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ORIGINAL ARTICLE

Analysis of differences in accuracy of positioning tied to various CORS networks in Poland: Case study

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Abstract

Network Real Time Kinematic (NRTK) measurements are currently the most popular surveying method in geodesy. In most countries, there are networks of Continuously Operating Reference Stations (CORS), which form the core of the terrestrial infrastructure that allows for NRTK measurements. In many countries, including Poland, several CORS networks operate in parallel and independently. The paper presents the characteristics of the CORS network in Poland. The results of several day NRTK and Real Time Kinematic (RTK) test measurements performed tied to five CORS networks operating in Poland: ASG-EUPOS, NadowskiNET, SmartNet, TPINETpro, VRSNet.pl, were subjected to a comparative analysis. VRS, FKP, MAC and POJ streams were used in the test measurements. The research mainly concerned the possibility of the occurrence of systematic errors when NRTK and RTK measurements were tied to different CORS networks for the survey of the same points. Conclusions from the comparative analysis of the accuracy and precision of the NRTK and RTK measurement results for each coordinate were also included.

Key words: CORS, RTK, NRTK, VRS, FKP, MAC, CORS, accuracy, precision

1 Introduction

Currently, in geodesy, static satellite measurements are most frequently used to accurately determine the coordinates of geodetic control points, and NRTK (Network Real Time Kinematic) measurements are used for a fairly wide range of surveying issues due to their satisfying positioning accuracy and excellent efficiency of these measurements. The accuracy of NRTK measurements is commonly estimated at ± 3 cm for position on a plane and ± 5 cm for height, for which a confidence interval of $\pm 95.0\%$ is declared. In many cases, the use of NRTK measurements assumes slightly better accuracy. Some NRTK measurement contractors may be convinced of better quality of their measurement results because of the spatio-temporal correlation of errors and the quality factor of the real-time kinematic measurement result, which is always displayed on the controller screen. In practice, it is commonly still regarded as an indicator of measurement accuracy, not precision. A problem with the reliability of the coordinate quality (CQ) indicator was noted in Edwards et al. (2010) when the measurement conditions are not ideal. The limited reliability of the CQ indicator was also pointed out in Janssen and Haasdyk (2011).

The quality of NRTK measurement results has been the subject of research since the development of this measurement method in 1999 (Schrock, 2010). The vast majority of papers in which the authors analyse the accuracy of NRTK measurement results focus on the results obtained in different measurement variants, but tied to one CORS network (Grejner-Brzezinska et al., 2005; Berber and Arslan, 2013; Gumus, 2016; Dabove, 2019).

Papers analysing the results of NRTK measurements referenced to at least two different networks and carried out under a single test procedure (Edwards et al., 2010; Garrido et al., 2012; Uznański, 2017; Specht et al., 2017; Koivula et al., 2018; Gillins et al., 2019; Prochniewicz et al., 2020) are few in number compared to papers presenting the results of measurements referenced to a single network. The authors used a variety of test procedures, the primary purpose of which was to determine the accuracy and precision of NRTK measurement results or individual reference data streams, although other aspects were also tested, such as the importance of

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positioning support with GLONASS (Martin and McGovern, 2012; Bae et al., 2015; Öğütcü and Kalayci, 2016) system satellites.

Many aspects of the test procedures employed can be compared and analysed. Comparing procedures is most often difficult as the authors highlight some factors and not others. As a result, some information is given, some has to be inferred, some can be seen in the accompanying pictures and some is not present, making comparative analysis of results significantly more difficult.

In Edwards et al. (2010), measurements were made with reference to SmartNet and VRS Now (UK). In the procedure used, a characteristic of some test measurements may be noted, which consists in mounting several receivers on some kind of metal flat bar at a distance of only a few to at most a few dozen centimetres. In this case, only one receiver can be centrally positioned. In Öğütcü and Kalayci (2016), no receiver was centrally positioned. The two main drawbacks in such a case are the proximity of the receivers, which does not occur outside the test measurements, and the need to determine the orientation of a survey apparatus.

An essential problem of key importance in test procedures for determining the quality of NRTK measurement results is the reference coordinates. Already in the paper Uznański (1999) an important conclusion of the report Baran and Zieliński (1997) concerning the intrinsic homogeneity of the static solution of the network and the occurrence of systematic errors between static solutions for points of the same network was noted. It is very problematic to interpret papers in which the reference coordinates were derived from a catalogue and not from own calculations. This problem was also noted in Garrido et al. (2012), where the NRTK measurements were referenced to two networks, RENEP (Portugal) and RAP (Spain), and the differences between the coordinates of the points of the national reference network from the catalogue and own study were estimated at 1–2 cm.

In the context of point coordinates, it should also be noted that many papers do not indicate whether the receiver was reinitialised before each successive measurement and so the correct interpretation of the results is difficult, as the initialisation error will be systematic throughout the kinematic chain. This is particularly crucial in tests to determine the effect of horizon obscurations on the quality of the NRTK position. There are also papers in which observations were recorded automatically, which generally results in the lack of reinitialisation of the receiver before each subsequent measurement (Gordini et al., 2006).

In many papers, the test procedures were designed to determine whether extending the NRTK measurement would improve the quality of the result (Edwards et al., 2010; Bae et al., 2015). The experience of two decades shows that in practice NRTK measurements last several epochs, and it is not uncommon for surveyors to take measurements lasting 1 second (1 epoch). In the research carried out, measurement in five one-second epochs was planned as the most commonly encountered in practice.

An analysis of the effect of reference station density on the quality of NRTK positioning is presented in Koivula et al. (2018). Measurements were made in Finland with reference to the FinnRef, Trimnet and HxGN SmartNet networks. In the conclusions formulated, it was found that the distance to the nearest reference station effects clearly the root mean square (rms) in the extrapolation network in all the configurations. Horizontal rms weakens to 0.9–3.5 mm per kilometre outside the reference station network. It was also found that the quality of the NRTK position depends more on the chosen NRTK correction method than on the distance between stations in the reference network. No deterioration in the quality of the NRTK position was found when extrapolating up to 60 km, based on measurements carried out in the borderland between Portugal and Spain (Garrido et al., 2012).

In Prochniewicz et al. (2020), an average measurement accuracy of 1 cm horizontally and 2 cm vertically was reported, but with the observation that twice as low an accuracy occurred for some networks and streams (reaching up to 4 cm for the height component). In contrast, the results of a study published in Garrido et al. (2012) demonstrate that positioning accuracy is approximately 2 cm horizontally and 4 cm vertically. The measurements presented in Specht et al. (2017) were taken with reference to 4 CORS networks for a point that was outside the interpolation area of the reference data of each CORS network. Position errors of the test point were estimated in-plane in the range of 0.008 m when referenced to the SmartNet network, to 0.035 m for the ASG-EUPOS network. Reference stations of the SmartNet network (JAGA) and the ASG-EPOS network (WLAD) were close to the ROZE test point. The largest extrapolation of network data had to occur for the VRSNet.pl network (GDSK was the closest station), but the calculated error of the ROZE point in the horizontal plane was 0.022 m. In Kudas and Wnęk (2019) includes results of tests carried out at the location most similar to the one in the tests presented in this paper. The results of MAC stream tests of the NadowskiNET network were compared to Uznański (2017), where all available streams in all CORS networks operating in Poland were tested and differences in results were noted.

The paper analyses the accuracy of NRTK measurement results tied to various CORS (Continuously Operating Reference Stations) networks operating in Poland. The practice of free access to network data streams offered by sellers of satellite receivers to their customers and the introduction of fees for the use of the state-owned CORS network in Poland have resulted in using various CORS networks in NRTK measurements. Free access to data of the state network ASG-EUPOS since 2 October 2022 did not significantly reduce diversification in this regard.

The analyses carried out in this research paper were aimed at determining whether the use of NRTK and RTK measurements tied to different CORS networks by contractors when implementing a fragment of the same investment or performing cyclical measurements by contractors using different CORS networks, in practice poses the risk of the occurrence of systematic errors. The test measurement procedures were designed to allow the accuracy and precision of the results to be tested.

The measurement results were compared to a similar measurement campaign carried out in 2017, the results of which are presented in Uznański (2017).

2 CORS networks in Poland

There are currently 5 nationwide CORS networks in operation in Poland (Figure 1): the state-owned ASG-EUPOS (GUGiK) and private ones: SmartNet (Leica Geosystems Polska), TPINETpro (TPI Sp. z o.o.), VRSNet.pl (VRSNet.pl Sp. z o.o.), RtkNet (ArtGeo) and one regional network (Figure 2) NadowskiNET (Instrumenty Geodezyjne Tadeusz Nadowski Sp.J.). ArtGeo, a distributor of Chinese instruments and the owner of the youngest network in Poland, has not made its network available for testing.

Each network's Ntrip caster can provide two types of reference data streams for surveying:

a) Streams with network data (NRTK measurements):

- VRS (Virtual Reference Station),
- MAC (Master Auxiliary Concept),
- FKP (Flächen Korrectur Parameter).

b) Streams with data from physical network reference stations (RTK measurements):

- POJ, in which the network server software selects the reference station closest to the user's location based on the position sent by the rover in the GGA message of the NMEA protocol,
- XXXX, any user-selected reference station, where XXXX is a 4-character denotation of the city or town where the CORS station is located, adopted inNtrip protocol (Networked Transport of RTCM via Internet Protocol).

In addition, in some networks, their operators provide streams

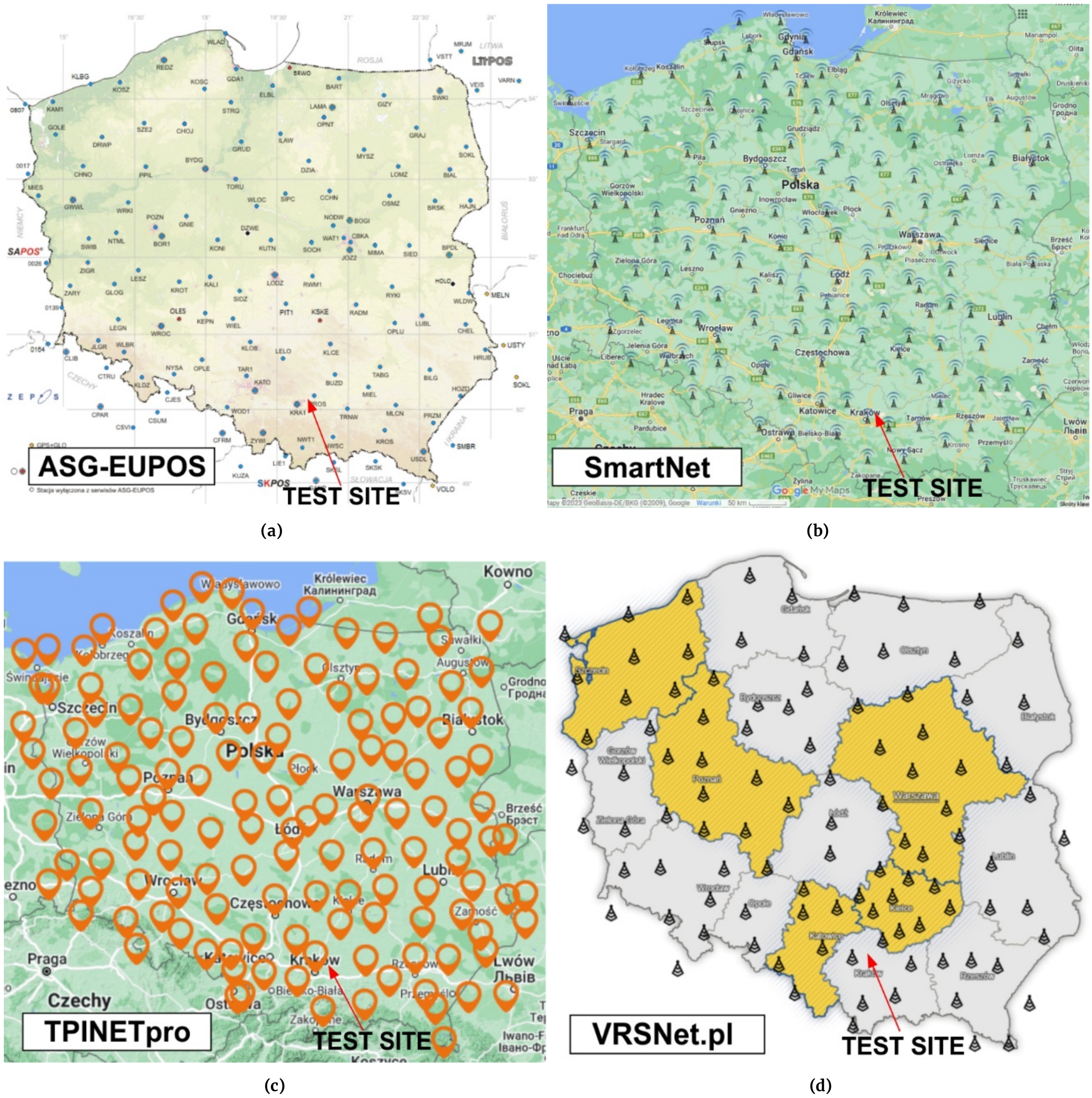

Figure 1. Location of reference stations of nationwide CORS network in Poland: (a) www.asgeupos.pl, (b) https://pl.nrtk.eu/, (c) https://tpinet.pl/, (d) http://vrsnet.pl/

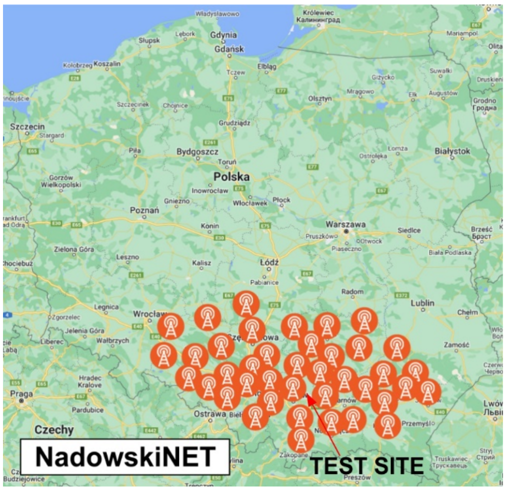

Figure 2. Location of reference stations of regional CORS NadowskiNET network (http://nadowski.pl/)

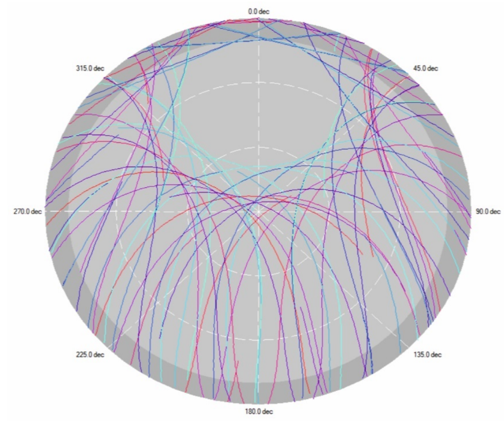

Figure 3. Sky plot for the measurement site

with DGNSS code data. CORS networks also provide observations in RINEX format.

The availability of these real-time reference data streams varies across networks. That is why it was not possible to compare the results from tying measurements to all types of streams in all networks. Streams are made available in different versions of the RTCM protocol, occasionally in the CMR protocol, and they are generated based on observations from two (NAVSTAR GPS, GLONASS) or four satellite navigation systems.

The VRS, MAC and FKP methods obviously have the same terrestrial infrastructure in the form of the CORS network (Fotopoulos and Cannon, 2001; Rizos, 2002; Wanninger, 2002), Ntrip communication (RTCM, 2004, 2011; Lenz, 2004) and all use some kind of interpolation algorithm. Those most frequently mentioned in the literature include Linear Combination Model, Distance-Based Linear Interpolation Method, Linear Interpolation Method, Lower-Order Surface Model, Least-Squares Collocation (Dai et al., 2001; Wei et al., 2006; Cui et al., 2018).

However, these methods differ in positioning concepts. In the VRS method (Schrock, 2010; Landau et al., 2002; Vollath et al., 2002; Wanninger, 2002), the effect of distance-dependent errors is reduced by shortening the reference station–rover vector by creating a virtual reference station at the location given by the rover in the GGA message of the NMEA protocol. In the FKP method, an adjustment plane for distance-dependent errors is defined and its coefficients are transmitted in the reference data (Wübbena et al., 1996; Wubbena et al., 2001; Wübbena and Bagge, 2002). In the MAC concept, the rover sets its position tied to a physical reference station, and auxiliary stations enable it to interpolate distance-dependent errors (Euler et al., 2001; Brown and Keenan, 2005; Brown et al., 2006). The positioning accuracy is not differentiated depending on the network data stream used.

Table 1 summarises the basic information about the networks whose data was used in the test measurements. The nationwide networks also use data from selected CORS stations operating in neighbouring countries to enable interpolation of distance-dependent errors for surveys performed in border areas of Poland. The NadowskiNET network is a regional network covering the belt of southern Poland. For the measurement site, the NadowskiNET network had the most densely located reference stations.

Ntrip protocol stream names are provided by the CORS network operator. In most networks, this is done transparently and intuitively. Relatively the greatest problems may be encountered by the user with the selection of the right stream in the TPINETpro network, which provides all 84 streams on one port 2101, but only 7 streams can be used in Poland, the descriptions of which are very general. The TPINETpro network does not make FKP and MAC streams available and does not allow for free selection of the reference station.

Table 2 summarises the availability of types of real-time reference data streams for land-surveying in individual CORS networks. POJ stream means data from a physical reference station selected by the CORS network server software. Most networks allow for selecting any reference station.

3 Material and methods

The tests were carried out approximately 20 km east of Krakow in May/June 2021. For the test measurements, one of the 5 points of the test base was selected, monumented in the field and with an unobscured horizon, slightly rising towards the north. No attempt was made to investigate the impact of obstacles on the quality of positioning. The nominal sky plot for the test site is shown in Figure 3. It can be assumed that there is a blind spot of approximately 40° to the north resulting from the construction of the space segment of the NAVSTAR GPS and GLONASS systems. Table 3 summarises the number of satellites whose signals were used by the receiver to determine the NRTK position and the values of the DOP coefficients. The minimum number of satellites tracked by the GNSS receiver during the measurements was 10 and the maximum was 20.

Figure 4 shows the location of the test site in the context of the location of the nearest CORS network reference stations to which the NRTK measurements were referenced. A detailed report template prepared for the measurements shows how many reference stations were involved in the solution. Naturally, the information is only effective for the MAC stream, as in the other streams only one reference station is reported. The number of reference stations participating in the MAC solution reached a maximum of 8 and this is the number included for the networks that provide this stream. The VRS algorithm assumes the use of data from up to 6 reference stations. For this reason, it was decided to analyse the distances of only the 6 closest reference stations in Table 4 in order to make the included data more comparable. The significance of more distant stations for the solution should be less. Based on the data of Table 4, 2 groups of CORS networks can be identified in the test area: the denser SmartNet and NadowskiNET networks and the sparser networks: ASG-EUPOS, TPINETpro and VRSNet.pl. Indicatively, the difference between these two groups can be estimated at 26%. The geometry of the CORS network for the test measurement site is shown in Figure 4. Based on (Garrido et al., 2012; Specht et al., 2017; Koivula et al., 2018), it could be assumed that the density of the network is of little importance. However, the vast majority of studies consider the geometry of the network at the measurement site to be an important factor for the quality of the NRTK measurement

Table 1. Basic information on reference networks in Poland

Network	Caster IP	Ports	Number of REF stations
ASG-EUPOS	91.198.76.2 system.asgeupos.pl	NRTK: 2101, 8080 RTK: 8086 (RTCM 3.2), 8082, 8083 (RTCM 3.1) DGNSS 8081	**129** = 105PL+7CZ+5DE+4LT+6SK+2UA
NadowskiNET	213.241.57.10 nadowski.net	NRTK: 2101, 8080 RTK: 2101 (POJ), 8082	**40**PL
SmartNet	69.64.185.160 smartnetleica.com	NRTK: 2101, 8080 RTK: 8082	**187** = 166PL+6CZ+9DE+6SK
TPINETpro	88.86.116.1 rtk.topnetlive.com	NRTK, RTK: 2101	**141** = 118PL+10CZ+5DE+1LT+7UA
VRSNet.pl	178.73.5.200 siec.vrsnet.pl	NRTK: 8080, 2101, 2102 RTK: 8081, 8082 NRTK, RTK (regions of PL): 2112, 3113, 4114, 5115, 6116, 7117	**98** = 87PL+2DE+5CZ+1SK+3UA

Table 2. Availability of types of data streams in CORS networks in Poland

System\stream	VRS	FKP	MAC	POJ	REF own choice
ASG-EUPOS	✓	✓	✓	✓	✓
NadowskiNET	✓	✓	✓	✓	✓
TPINetpro	✓	–	–	✓	–
VRSNet.pl	✓	✓	–	✓	✓
SmartNet	✓	–	✓	✓	✓

Table 3. Number of satellites and DOP values

	GPS	GLONASS	GDOP	PDOP	HDOP	VDOP
Mean	8	5	1.9	1.5	0.8	1.2
Min.	6	3	1.2	0.9	0.5	0.8
Max.	11	9	7.3	5.8	2.2	5.6

results.

The marker of the measuring point were stainless steel screws selected so that their cross enabled bisectional centring using a precise Leica GZR3 plummet (0.3 mm centring accuracy). The centring accuracy, estimated at approximately 0.5 mm, was also checked after the end of the measurements on a given day. Measurements were performed with a Leica GS16 receiver set on a LEICA GTS120-9 beech tripod. NAVSTAR GPS and GLONASS system signals were used above 10° above the antenna horizon.

All accuracy analyses were based on differences in reference coordinates and NRTK surveys. The stabilised test network consisted of 5 points, which allowed a quality analysis of the results of the static measurement calculations using reliability theory Baarda (1967, 1968). The reference coordinates of these points were determined from three 12-hour static sessions taken with Leica GS16 receivers with reference to the ASG-EUPOS state network. Based on the differences in coordinates determined from each session separately, the accuracy of the reference test point coordinates was estimated at 1–2 mm for x, y coordinates and 2–3 mm for ellipsoidal height. For the point where NRTK surveys were performed, the maximum differences in coordinates from static sessions were Δx = 1.1 mm, Δy = 1.1 mm, Δh = 0.7 mm. For the analyses, these coordinates were assumed to be true, i.e. error-free. All test measurements were carried out by one person in 5 one-second epochs. They were intended to serve different types of analysis. Data from 4 days of measurements were used for the analysis in terms of positioning for the different CORS networks in Poland, which are the subject of this paper.

A total of 2,887 measurements tied to different CORS networks were analysed. The number of samples from each test day is presented in Table 3. On the first day of testing, the surveying procedure lasted 14h 25m 40s (from 6:24:59.7 am to 8:50:38.9 pm) and as many as 1,194 measurements were carried out. During the day, the average time needed to change the network was 67s. At that time, substantive activities related to the measurement were performed: the receiver was reconfigured for every second measurement, consisting in changing the network and data stream, the point name template with the introduction of the value of the current measurement number in the series, and initialisation of the receiver in the new network. This time also included the necessary short breaks resulting from the duration of the measurements of almost 14.5 hours. It was a very exhausting experiment and in the following days of testing it was not possible to carry out such a large number of measurements. They were performed in series and required a lot of concentration; yet, in such a large number of measurements on the first day of testing, only 6 measurements included in the measurement procedure were accidentally omitted.

The majority of the measurements were performed according to a procedure that involved initialising the receiver in reference to a CORS network, taking a measurement at 5 epochs, storing the position, measuring again at 5 epochs, storing the position, reconfiguring the receiver, initialising it in the next network and taking two measurements in the same manner. Successive CORS networks were selected in an alphabetical order. A series of 30 duplicate measurements were taken with reference to each CORS network, after which the reference data stream (VRS, MAC, FKP, POJ) was changed and the measurement sequence repeated. Table 7 shows the availability of reference data streams in each CORS network. If any stream was not available in the CORS network (MAC, FKP), it was replaced by the VRS stream.

On the second day of tests, measurements were also performed according to a different procedure, without the second measurement after initialisation; the measurement was performed 30 times with reference to a given CORS network with each time the measurement being reinitialised, after which the network was changed to the next one and the other 30 measurements were performed again.

On the fourth day of measurements, the measurement procedure was also changed. The lack of MAC and FKP streams was not replaced by measurements using the VRS stream available on all networks. There were 5 double measurements to all networks using the VRS stream and then 3 double measurements to the networks providing the MAC stream (ASG-EUPOS, NadowskiNet, SmartNet).

Table 5 demonstrates the number of measurements carried out immediately after the initialisation of the receiver and then subsequent ones, without reinitialisation. The measurements with initialisation formed the basis for the analysis of the accuracy of test measurement results. The aim of the second measurement,

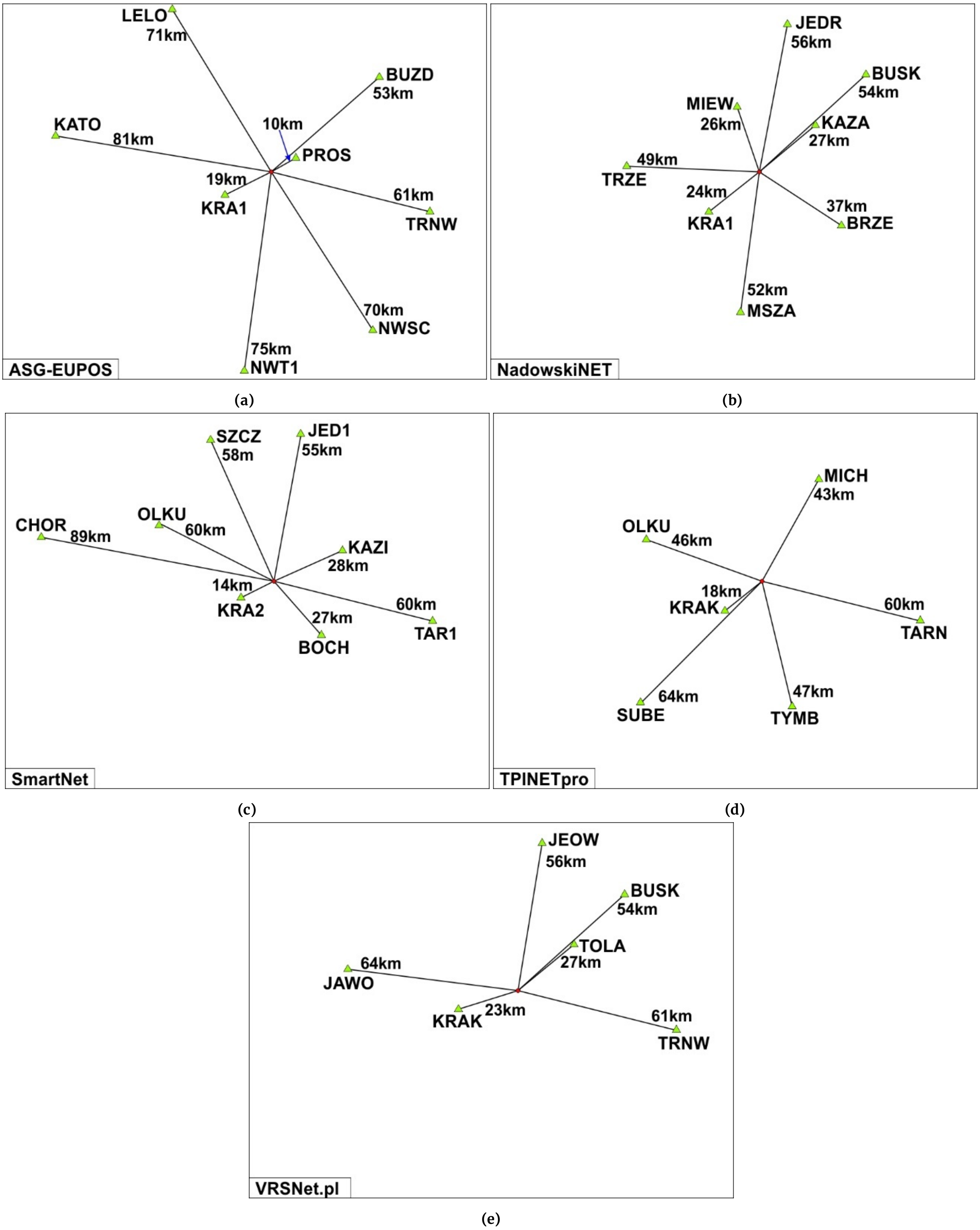

Figure 4. CORS network geometry for the test measurement site: (a) ASG-EUPOS, (b) NadowskiNET, (c) SmartNet, (d) TPINETpro, (e) VRSNet.pl

Table 4. Distances of the measurement site from the reference stations of the CORS networks

ASG-EUPOS		SmartNet		NadowskiNET		TPINETpro		VRSNet.pl	
Id	[km]	Id	[km]	Id	[km]	Id	[km]	Id	[km]
PROS	10	KRA2	14	KRAK	24	KRAK	18	KRAK	23
KRA1	19	KAZI	28	MIEW	26	MICH	43	TOLA	27
BUZD	53	BOCH	27	KAZA	27	OLKU	46	BUSK	54
TRNW	61	JED1	55	BRZE	37	TYMB	47	JEOW	56
NWSC	70	OLKU	48	TRZE	49	TARN	60	TRNW	61
LELO	71	TAR1	60	MSZA	52	SUBE	64	JAWO	64
sum of distances from reference stations [km]									
284		232		215		279		284	

Table 5. Number of analysed measurements from successive test days

Day	1	2	3	4	Total
Number of all measurements	1,194	687	562	444	2,887
Number of 1st measurements after initialisation	598	420	281	222	1,521
Number of measurements without reinitialisation	596	267	281	222	1,366

without reinitialisation, was only to enable analysis of the precision of the measurement results.

Single differences in the number of measurements in Table 5 result from the accidental omission of a measurement planned according to the measurement procedure.

Table 6 presents the number of measurements in relation to individual networks. The variation in these figures is mainly due to three factors:

- Problems with data transmission (SmartNet 33 measurements, TPINETpro 2 measurements, VRSNet.pl 50 measurements), which resulted in the need to remove several dozen measurements from the analysed sample (column 6 in Table 6). Measurements were performed in series of 30, in the case of problems with obtaining a solution in a given network; two attempts to connect to Caster Ntrip were made, usually unsuccessful, after which the measurement in the series was skipped;
- Accidental omission of a measurement tied to a given network (column 6 of Table 6): ASG-EUPOS (1), NadowskiNet (9), SmartNet (2), TPINETpro (8), VRSNet.pl (5);
- Non-disclosure of some reference data streams (MAC, FKP) by some networks (TPINETpro, VRSNet.pl), column 2 of Table 6. As mentioned above, measurements were generally performed assuming no significant differences in the accuracy of the position determined from any stream of a given network. If the tested stream was not provided by the given network, it was replaced by the VRS stream. On the fourth test day, a series of measurements tied to the MAC stream was performed, in which networks that did not provide this stream were omitted.

A summary of the number of measurements carried out using individual reference data streams is presented in Table 7. In order to compare positioning tied to various networks operating in Poland, it was necessary to focus on the VRS stream, which is the only one made available by all networks. For this reason, the VRS stream is most represented in Table 7. The VRS, MAC, and FKP streams are for NRTK positioning, and the POJ stream is for RTK positioning.

Test measurements were performed in accordance with different procedures, as they were to be used for various tests and analyses. Therefore, the work analysed some of them, which concerned measurements in relation to various reference networks using different reference data streams. The basic measurement procedure consisted in initialising the receiver in a given network of reference stations, repeating the measurement without reinitialisation, changing the network to the next one and repeating two measurements. It was assumed that the series performed in this way would consist of 30 measurements. Due to the performance of a very large number of monotonous measurements every day, starting from almost 1,200 measurements on the first day to over 500 on the following days, errors occurred, such as the omission of one of the networks in the measurement or the omission of the second measurement after initialisation of the receiver. The created import template file of the measured points made it possible to obtain a detailed report from the CS20 controller, based on which it was possible to determine the causes of all differences in measurements from the assumed procedure of their implementation (all errors, measurements carried out in the absence of reference data).

4 Results and Discussion

The differences in the coordinates of 2887 NRTK test measurements and the reference coordinates calculated from three 12-hour static sessions formed the basis for the comparative analyses. The measurements performed immediately after the initialisation of the receiver in a given CORS network were analysed. Figure 7 shows the scatter of all results on the (x, y) plane and Figure 6 for ellipsoidal height h on the time axis, with the axis described by the number of measurements. The scales of the axes for the results tied to the individual networks in the figures have been standardised to enable a reliable comparison. In Figure 4, the results of the measurements tied to the ASG-EUPOS and SmartNet networks seem to be the most accurate, though a systematic error of several millimetres is noticeable. The results of the measurements in the VRSNet.pl network seem to be the most dispersed, as there is no clear concentration of coordinate difference values around any value. Table 8 confirms that, in the interval of ± 1 cm, the largest number of measurement results were found tied to the ASG-EUPOS and SmartNet networks, and the least for the VRSNet.pl network. When compared to the ASG-EUPOS network, there were 22% fewer values in this range for differences in the y-coordinate and as many as 52% for differences in the x-coordinate (Table 9), identically as for the TPINETpro network. In relation to the generally accepted accuracy of NRTK measurements at the level of ± 3 cm, greater differences in the x-coordinate occurred only in 4 out of 1,521 measurements. A slightly lower accuracy of the x-coordinate was noticeable in the NRTK measurement results. There were 28 differences in the coordinates of this coordinate greater than ± 3 cm. The data in Table 9 demonstrates a tendency to assume too small values for the x-coordinate in the NadowskiNet, SmartNet and TPINETpro networks. For the results in the VRSNet.pl network, the scatter of differences in the x-coordinate is greater than in the y-coordinate and it is symmetrical to the mean value.

Figure 6 compares the accuracy of the NRTK measurement results with their precision. In most of the procedures, two measurements were made with one initialisation of the receiver in order to analyse the precision of the NRTK measurement results regarding

Table 6. Summary of the number of measurements tied to individual networks

Network	All measurements	Measurements with initialisation	Cumulative number	% in sample	Missing and removed	% in sample (2+6)
1	2	3	4	5	6	7
ASG-EUPOS	621	325	621	21.5	1	20.75
NadowskiNET	613	322	1,234	21.2	9	20.75
SmartNet	587	309	1,821	20.3	35	20.75
TPINETpro	553	293	2,374	19.2	10	18.79
VRSNet.pl	513	272	2,887	17.8	55	18.95

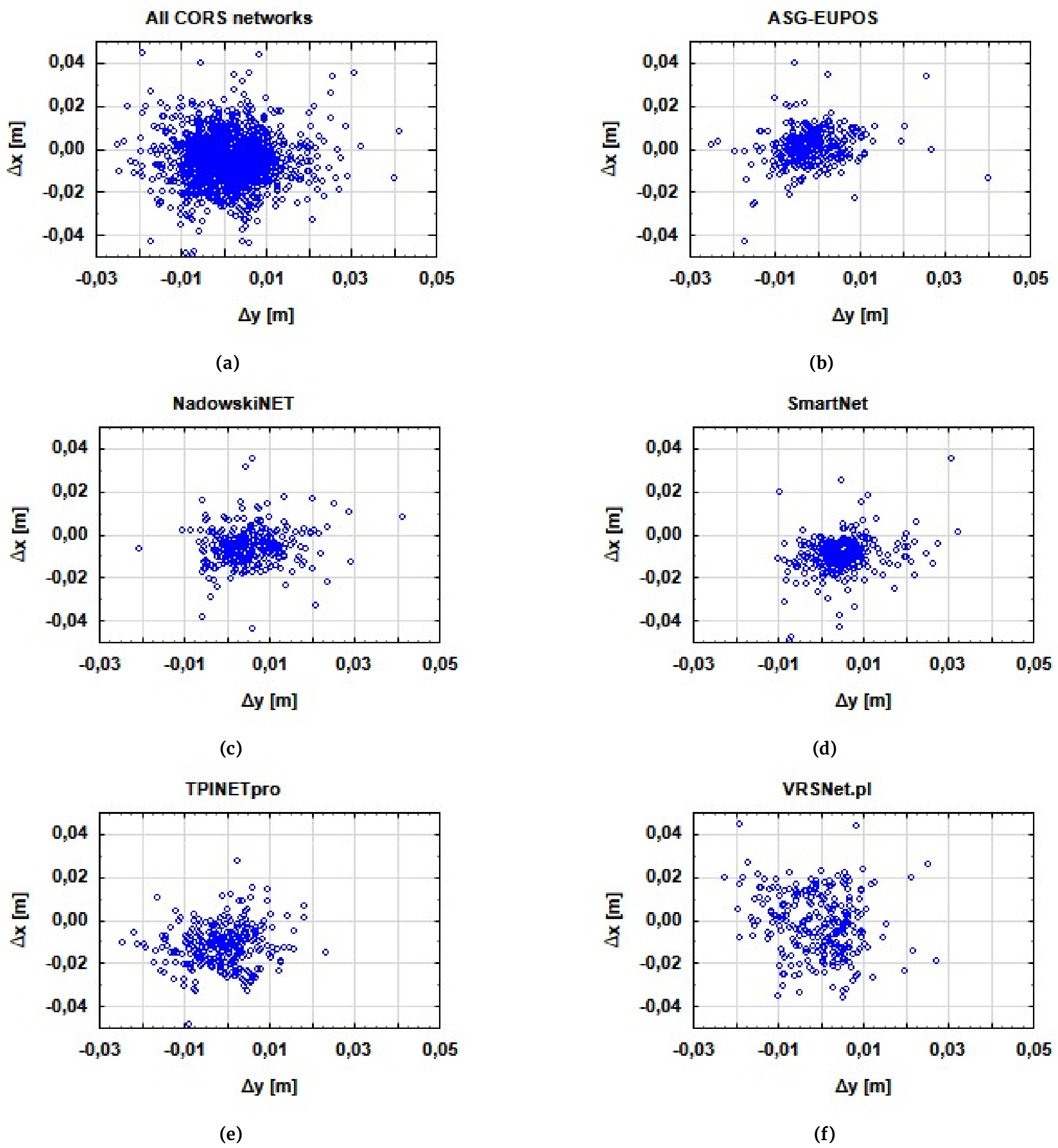

Figure 5. Scatter of (x, y) measurement positions: (a) All CORS networks, (b) ASG-EUPOS, (c) NadowskiNET, (d) SmartNet, (e) TPINETpro, (f) VRSNet.pl

Table 7. The number of measurements in relation to individual reference data streams

Stream	All measurements	1st measurement after initialisation
VRS	1540	847
MAC	466	233
FKP	296	148
POJ	585	292

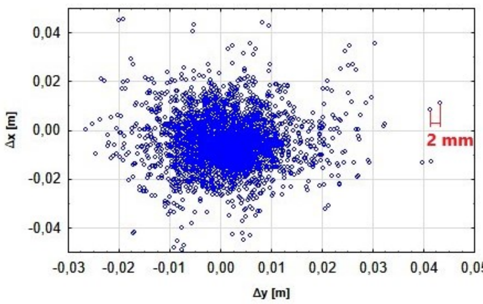

Figure 6. Summary of the scatter (x, y) of all measurements

their accuracy relative to the reference coordinates from static measurements. Figure 6 illustrates characteristic pairs of points. The difference between the coordinates of such a pair and the reference coordinates can be as much as a few centimetres, but the difference between the coordinates of points in the pair was most frequently < 4 mm for the x-coordinates (93%), < 3 mm for the y-coordinate (92%) and < 8 mm for the ellipsoidal height (92%). In this case, performing a series of measurements without reinitialising the receiver would therefore result in a false positive belief about the high accuracy of the NRTK measurement results.

The analysis of ellipsoidal height differences confirms the generally accepted statement that they are less accurately determined in satellite measurements than the x, y coordinates (Figure 7). The differences in reference coordinates determined from static measurements and coordinates from NRTK measurements formed the basis for the analyses. The analysis of coordinate differences clearly demonstrated their differentiation depending on the coordinate. It is generally accepted that the quality of positioning based on satellite surveys is about two times less accurate for ellipsoidal heights than for x, y coordinates. The results confirmed this statement. This was the consequence of limiting the horizon for the reception of satellite signals by the GNSS antenna in the vertical plane from 360° to 160° (assuming a minimum horizontal height of satellites at 10°). The measurements also presented the differences in their accuracy for the x and y coordinates. The sky plot analysis showed that for the y-coordinate there was the symmetry of the satellite trajectories, and for the x-coordinate there was a dead zone for satellite signals at the latitude of the measurements and in the terrain rising from the north (Figure 3), for which the angle of aperture could be estimated at about 40°.

Similarly to the x and y coordinates, the scale is unified for all networks in Figure 7. The ASG-EUPOS and SmartNet networks seem to produce the most accurate results. The NadowskiNET has a greater scatter of results but there are no outliers, which are most noticeable for the TPINETpro and VRSNet.pl networks. The data in Table 10 present a clear decrease in the number of ellipsoidal height differences in the interval of ±1 cm for each of the networks compared to such values calculated for horizontal coordinates. In this comparison, the SmartNet network performs the worst, although Figure 7 illustrates that its data has a relatively small scatter, smaller than that of the TPINETpro and VRSNet.pl networks. Height differences in the NadowskiNET network are quite clustered around the average, but they exhibit a systematic factor which, however, is dealt with in the results of measurements tied to each CORS network. The numbers of height differences within ±1 cm for the remaining networks differ very little from each other. The heights in all networks tend to be too large relative to the reference height and the scatter of the results is much greater than for the x, y coordinates. Occasionally, outliers of up to ±1 decimetre can be expected. The most outlier results occurred in the TPINETpro and VRSNet.pl networks. However, 75% of the height differences fell within ±3 cm. The most measurement results here were tied to the ASG-EUPOS network (268), and the fewest to the VRSNet.pl (200) and SmartNet (205) networks, accounting for a difference of 25%.

Table 11 summarises the basic descriptive statistics of NRTK measurements with respect to different networks. The rows are ordered by type of coordinates to make comparison easier. In general, the results vary depending on the coordinate. The measurement results for the y-coordinate are the least scattered while they are noticeably more scattered for the x-coordinate, and the height traditionally differs from the x, y coordinates in the statistics. The average values coincide with the medians or differ by a maximum of 1 mm. The standard deviation of the y-coordinate for all networks is practically the same, and for the three networks it is also the same for the x-coordinate. For the TPINETpro and VRSNet.pl networks, for the x-coordinate, the standard deviations are higher, and for the VRSNet.pl network it is higher by 75% compared to the best networks in this criterion.

In Table 11, the confidence intervals for the mean and standard deviation are ±99.7% (3s). The limit values for the confidence intervals of the average x, y coordinate difference change in relation to the mean value by 1 mm, and for the SmartNet, TPINETpro, VRSNet.pl networks by a maximum of 2 mm. For the ellipsoidal height, the analogous value is at the level of 2–3 mm.

Figure 8 allows for the comparison of the measurement results in all networks for all the coordinates. The dot stands for the median value, which practically coincides with the mean value, the bar represents 90% of the measurement results, and the whiskers indicate the extreme values. The results for the x, y coordinates without the systematic factor are noticeable for the ASG-EUPOS network, which performed best in all analyses, but also for the VRSNet.pl network, whose results were characterised by a relatively large scatter, and in the case of the x-coordinate, even the largest. The data analysis demonstrated that there were relatively rare outliers, and the vast majority of coordinate differences for x, y coordinates did not exceed ±2 cm, and for height it was half of the results. The analysis of the average value of the coordinate differences indicated the existence of differences in the results of different networks. For the y-coordinate, there was a systematic factor of 5 mm for two networks: NadowskiNET and SmartNet. For the x-coordinate, only the results in the ASG-EUPOS and VRSNet.pl networks could be considered unbiased by a systematic factor. For the results in the NadowskiNET network, the value of 5 mm occurred again, but with the opposite sign, and for the results in the SmartNet and TPINETpro networks the systematic factor doubled in relation to the y-coordinate and amounted to -9 mm and -11 mm. The analysis of ellipsoidal height differences demonstrated that, on average, the smallest differences were obtained in the TPINETpro and VRSNet.pl networks – average values of 8 mm and 9 mm, respectively. Paradoxically, in these networks, the results had the largest height scatter measured by the standard deviation value and the most outliers, including extreme ones for this coordinate.

The analysis of the NRTK and RTK measurement results revealed that, on average, they did not differ significantly in accuracy. Nevertheless, the percentage values of differences of individual coordinates in the intervals ±1cm, ±2 cm and ±3cm and for height in the interval ±5 cm (Table 12) were never greater for the RTK measurements than for the NRTK measurements.

In 2017 (Uznański, 2017), 3345 similar measurements were taken. When comparing the 2021 NRTK measurements with the 2017 results, there is a very high similarity in the difference values

Table 8. Number of differences of the y-coordinate in the intervals

y	Number	%	A	N	S	T	V
-0.03<y<=-0.02	7	0.46	2	1		3	1
-0.02<y<=-0.01	91	5.98	24	1	1	29	36
-0.01<y<=0.01	**1269**	**83.43**	**286**	**246**	**270**	**245**	**222**
0.01<y<=0.02	125	8.22	9	64	28	15	9
0.02<y<=0.03	25	1.64	3	9	8	5	4
0.03<y<=0.04	3	0.20	1		2		
0.04<y<=0.05	1	0.07		1			

Network names are abbreviated to the first letter of their full name, e.g. A – ASG-EUPOS, etc.

Table 9. Number of differences of the x-coordinate in the intervals

x	Number	%	A	N	S	T	V
-0.05<x<=-0.04	6	0.39	1	1	3	1	
-0.04<x<=-0.03	14	0.92		2	3	3	6
-0.03<x<=-0.02	84	5.52	4	5	12	44	19
-0.02<x<=-0.01	329	21.63	14	61	92	111	51
-0.01<x<=0.01	**954**	**62.72**	**266**	**240**	**194**	**127**	**127**
0.01<x<=0.02	106	6.97	32	11	2	6	55
0.02<x<=0.03	20	1.31	5		2	1	12
0.03<x<=0.04	5	0.33	2	2	1		
0.04<x<=0.05	3	0.20	1				2

Network names are abbreviated to the first letter of their full name, e.g. A – ASG-EUPOS, etc.

Table 10. Number of differences of the h-coordinate in the intervals

h	Number	%	A	N	S	T	V
-0.15<h<=-0.14	1	0.07				1	
-0.11<h<=-0.10	1	0.07				1	
-0.10<h<=-0.09	2	0.13				1	1
-0.08<h<=-0.07	1	0.07					1
-0.07<h<=-0.06	5	0.33		1			4
-0.06<h<=-0.05	2	0.13				1	1
-0.05<h<=-0.04	19	1.25	1	5	1	6	6
-0.04<h<=-0.03	22	1.45	4	2	1	9	6
-0.03<h<=-0.02	47	3.09	4	14	5	18	6
-0.02<h<=-0.01	79	5.19	15	14	10	24	16
-0.01<h<=0.01	**458**	**30.11**	**115**	**97**	**50**	**96**	**100**
0.01<h<=0.02	288	18.93	89	55	54	47	43
0.02<h<=0.03	266	17.49	45	67	86	33	35
0.03<h<=0.04	178	11.70	32	37	54	23	32
0.04<h<=0.05	87	5.72	11	16	24	20	16
0.05<h<=0.06	39	2.56	9	10	13	5	2
0.06<h<=0.07	19	1.25		4	8	6	1
0.07<h<=0.08	4	0.26			3		1
0.08<h<=0.09	2	0.13				1	1
0.11<h<=0.12	1	0.07				1	

Network names are abbreviated to the first letter of their full name, e.g. A – ASG-EUPOS, etc.

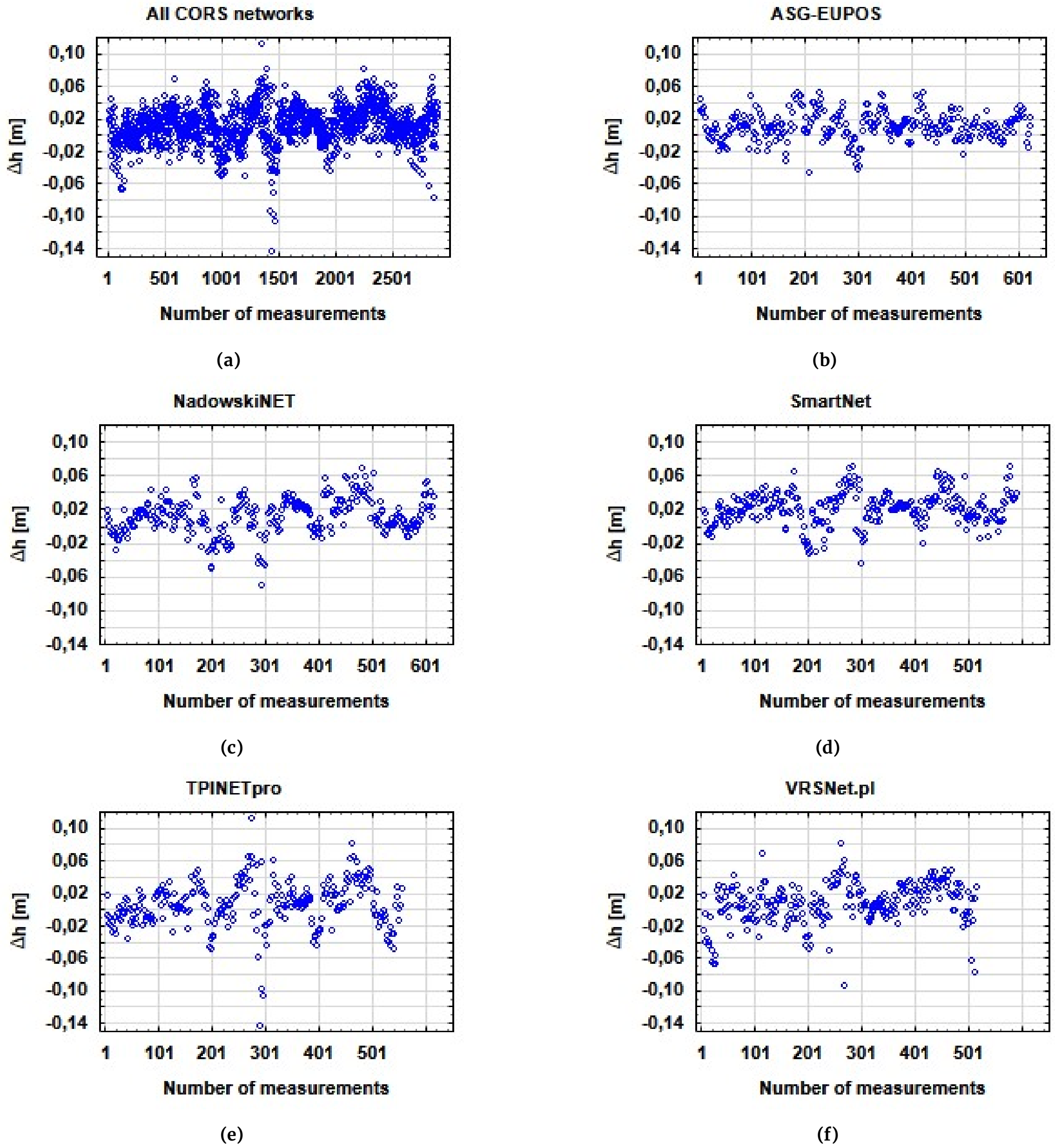

Figure 7. Scatter of heights on the timeline (described by the number of measurements): (a) All CORS networks, (b) ASG-EUPOS, (c) NadowskiNET, (d) SmartNet, (e) TPINETpro, (f) VRSNet.pl

Table 11. Basic descriptive statistics of point coordinate differences

Coordinates	Network	Mean	Confidence -99,7%	Confidence + 99,7%	Standard deviation	Standard deviation confidence level -99,7%	Standard deviation confidence level +99,7%
dy	all	0.001	0.001	0.002	0.008	0.007	0.008
dy	A	-0.002	-0.003	-0.001	0.007	0.006	0.008
dy	N	0.005	0.004	0.006	0.007	0.006	0.008
dy	S	0.005	0.004	0.006	0.007	0.006	0.007
dy	T	-0.001	-0.002	0.000	0.007	0.007	0.008
dy	V	-0.001	-0.002	0.001	0.008	0.007	0.009
dx	all	-0.005	-0.005	-0.004	0.011	0.010	0.012
dx	A	0.002	0.001	0.003	0.008	0.008	0.010
dx	N	-0.005	-0.006	-0.003	0.008	0.008	0.010
dx	S	-0.009	-0.010	-0.007	0.008	0.008	0.010
dx	T	-0.011	-0.013	-0.009	0.010	0.009	0.011
dx	V	-0.001	-0.003	0.002	0.014	0.013	0.016
dh	all	0.014	0.012	0.015	0.023	0.022	0.024
dh	A	0.013	0.010	0.016	0.017	0.015	0.019
dh	N	0.014	0.010	0.018	0.021	0.019	0.024
dh	S	0.023	0.020	0.026	0.019	0.017	0.022
dh	T	0.008	0.003	0.013	0.028	0.025	0.032
dh	V	0.009	0.004	0.013	0.025	0.022	0.028

Network names are abbreviated to the first letter of their full name, e.g. A – ASG-EUPOS, etc.

Table 12. Comparison of differences in coordinates of NRTK and RTK measurement results

Interval	± 1 cm		± 2 cm		± 3 cm		± 5 cm	
	number	%	number	%	number	%	number	%
x NRTK	776	63.19	1,120	91.21	1,205	98.13		
x RTK	178	60.75	269	91.81	288	98.29		
y NRTK	1,043	84.93	1,209	98.45	1,226	99.84		
y RTK	226	77.13	276	94.20	291	99.32		
h NRTK	379	30.86	690	56.19	940	76.55	1169	95.20
h RTK	79	26.96	135	46.08	198	67.58	275	93.86

Table 13. Percentage differences in the number of NRTK measurements in intervals – x-coordinate

Interval	-0.05 <x<= -0.04	-0.04 <x<= -0.03	-0.03 <x<= -0.02	-0.02 <x<= -0.01	-0.01 <x<= 0.01	0.01 <x<= 0.02	0.02 <x<= 0.03	0.03 <x<= 0.04	0.04 <x<= 0.05
Δ%	-0.1	0.1	2.7	9.7	**26.3**	**-36.8**	-2.0	-0.3	0.2

Table 14. Percentage differences in the number of NRTK measurements in intervals – height

Interval	-0.11 <h<= -0.07	-0.07 <h<= -0.06	-0.06 <h<= -0.05	-0.05 <h<= -0.04	-0.04 <h<= -0.03	-0.03 <h<= -0.02	-0.02 <h<= -0.01	-0.01 <h<= 0.01	0.01 <h<= 0.02	0.02 <h<= 0.03
Δ%	8.2	13.3	**22.7**	**25.7**	15.1	7.8	3.5	3	3.5	0.1

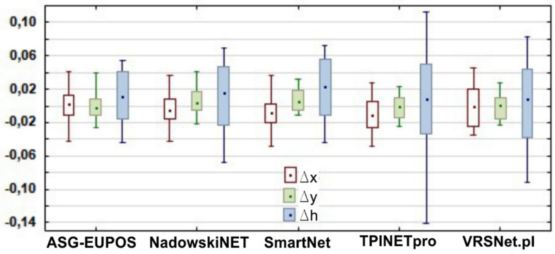

Figure 8. Whiskers box in [m]: median, bar: 90% of observations, whiskers: min-max

of the y-coordinate, which ranged from 0.5% to 3.3% for the individual ranges. In the case of the x-coordinate, a systematic factor of approx. -1 cm is visible (Table 13), and for height approximately -5 cm (Table 14). The analyses of the data in 2017 generally did not provide a satisfying explanation of the reasons for the occurrence of a westward and downward shift of the NRTK measurement results with respect to the reference coordinates. At that time, it was found that calculating the reference coordinates with reference to NadowskiNET reduced the absolute value of the systematic factor for height, but with a change in its sign.

In an analysis of the results of test measurements taken at virtually the same time, at a location approximately 30 km away (Kudas and Wnęk, 2019), a problem with a systematic factor for heights of approximately -10 cm can also be seen. The NRTK test measurements were referred to the NadowskiNET network and concerned only the MAC stream.

5 Conclusions

The surveys were performed tied to 5 CORS networks operating in Poland using VRS, MAC, FKP and POJ data streams. The differences in reference coordinates determined from static measurements and coordinates from NRTK measurements formed the basis for the analyses. Based on the NRTK measurements, it could not be unambiguously stated that tying the measurements to different CORS networks would cause systematic errors, which might pose a significant threat to the quality of positioning investments, periodic measurements, etc. Non-zero and varying values of mean coordinate differences were noted in the calculated coordinate differences. Estimating the accuracy of determining the reference coordinates of the test point at the level of 1–2 mm allowed for neglecting the values at this level as irrelevant. For the horizontal coordinates, average differences were determined at 1 mm - 5 mm for the y-coordinate, 1–11 mm for the x-coordinate and from 8 mm to 23 mm for ellipsoidal height. In each case, they fell within the positioning quality declared by the owners of the CORS networks in Poland (±3 cm for x, y coordinates and ±5 cm for ellipsoidal height at the 95% confidence level). In this context, there were no significant differences in the positioning accuracy when tying the NRTK measurements to each of the CORS networks in Poland (except for the RtkNet network, for which no conclusions could be drawn, as the owner did not make the network available for test measurements). The data analysis revealed that almost all differences in the y-coordinate (over 97%) fell within ±2 cm, and for the x-coordinate it was over 91%.

The aim of this work was to analyse the measurement results in terms of differences in positioning accuracy when using different CORS networks. The measurements were to enable various types of analyses. RTK measurements were also performed, tied to the reference station automatically selected by the CORS network server software, i.e. the closest location of the mobile GNSS receiver. The analysis of 2,302 NRTK positions, including 1,228 point positions immediately after the initialisation of the GNSS receiver, and 585 RTK positions, including 293 point positions immediately after the initialisation, allowed for the conclusion that the results were positively correlated, and the percentage values of differences of individual coordinates in the intervals were very close. This was an interesting observation because NRTK measurements were developed to overcome the weak point of RTK measurements consisting in the decrease in positioning accuracy with the increase in the distance between the reference station and the rover. The analysis of the location of reference stations of individual CORS networks in Poland (Figure 1, Figure 2) demonstrated that the mutual distances of neighbouring stations varied in some areas. Test measurements were carried out in one location. For these reasons, it was impossible to formulate a general conclusion that the accuracy of NRTK and RTK measurements was practically the same in Poland.

Despite finding no significant differences in the mean accuracy of the NRTK and RTK measurement results tied to different CORS networks in Poland, their differentiation was visible, but it was not unambiguous. For example, the lack of a systematic factor for the x-coordinate in the VRSNet.pl network was parallel with the greatest scatter of results for this coordinate in this network. A relatively small scatter of results in the NadowskiNET occurred together with a horizontal systematic factor of about 7 mm.

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