AN ATTEMPT TO APPLY GPS-RTK TECHNOLOGY FOR TOPOGRAPHIC SURVEYS WITHIN URBAN AREAS

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1. INTRODUCTION

The GPS-RTK (GLOBAL POSITIONING SYSTEM - REAL TIME KINEMATIC) method is considered the most useful method for topographic surveys between satellite survey technologies. Utilisation of that method for surveys of multi-functional networks, and, sometimes, also the detailed, 3rd order network, is becoming more popular. The basic feature of the RTK method is the possibility to obtain coordinates of surveyed points as early as within several seconds after initialisation of surveys. The factor, which makes surveys using the RTK measuring set more difficult within urban areas, is the presence of terrain obstacles, which limit the simultaneous communication of the basic receiver and the mobile receiver, with the same, five satellites.

The RTK method may be applied in three, basic forms:
1. Surveys by means of two receivers: the Base and the Mobile Station (the so-called Rover),
2. Surveys by means of one receiver, the Mobile Station with reference to the reference stations of the ASG-EUPOS System,
3. Surveys with the use of the Virtual Base Station.

Results of research, presented in the work, refer to the first method of surveys. Test RTK surveys were performed using the TOPCON GPS Hyper Pro measuring set (two receivers: Base and Rover) with the FC2000 Controller. The GPS and Glonass systems were used during the survey sessions.

Results of research, presented in the paper, are mostly the effect of survey experiments, performed within the master's theses of the students of the Faculty of Geodesy and Cartography, the Warsaw University of Technology [3], directed by the co-author of the presented work. The objective of this work was to compare the topographic survey results obtained by means of the GPS-RTK methods with results of tacheometric surveys. Research works were performed at the test site, established within the main campus of the Warsaw University of Technology.

2. CHARACTERISTICS OF THE TEST SITE

The main campus of the Warsaw University of Technology has been chosen as the test site (Fig.1). Many terrain features, which are classified into the first and the second accuracy groups, may be found within that area, which also reflects the diversification of urban areas. The local, two-functional network has been established within that area

(Fig. 2); the network is composed of very short tacheometric traverses and individual spans, which connect common points. The average length of sides equals to approximately 60m. Points of te networks were established in such a way, which allows for surveys of the maximum number of details in densely built-up areas. In the course of designing the network, the possibility to utilise the network points as stations of hybrid instruments (an electronic tacheometer connected to the GPS receiver), was also considered.

The electronic tacheometer TOPCON GTS225 was used for surveys of the network and the terrain features. The surveys of the tacheometric network were performed by means of the "three tripods" method with simultaneous surveys of elevation differences using the trigonometric levelling method. Values of angular and linear deviations and sums of elevation differences in particular loops are presented in Fig. 2.

Fig. 1. A copy of the topographic map of the test site (the original scale 1:500).

The network is characterised by the following parameters:
- the mean error of measurements of a horizontal angle m $= 20^{cc}$,
- the mean error of side measurements $m_S = 0.8mm$,
- the error of a typical observation after adjustment of the horizontal network $m_0 = 0,99$,
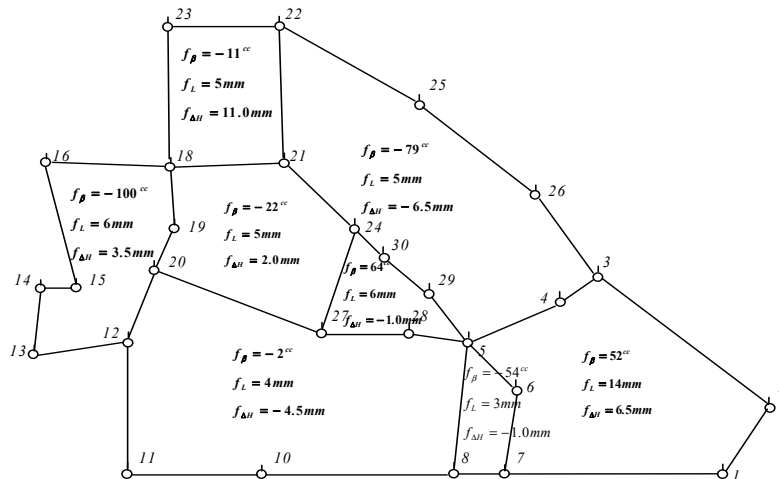- the mean error of elevation difference between the successive stations $m_H = 0,7mm$.

Fig. 2. An outline of the local network.

For any point of the local network, presented in Fig. 2 the mean errors of plane coordinates (m_x, m_y) do not exceed the value of 1.5 mm, and the mean errors of elevations of points of that network do not exceed the value of 3.4 mm. Those accuracies are sufficient for comparative analyses with the RTK method.

Topographic surveys of the test site has been performed by means of the object method [2]. The topographic map in the digital form was developed by means of *n4ce* software tools, basing on conventional surveys. The copy of that map is presented in Fig. 1.

In order to ensure repeatability of survey points of terrain features and to eliminate errors of point identification during the repeated GPS surveys, each of surveyed points was marked by a yellow spot of the diameter equal to 5-10mm.

For short aiming lines, which occur in tacheometric surveys within urban areas, the mean horizontal and vertical error is mostly influenced by the, so-called, setting-up errors: errors of centring of an instrument and erecting a pole on connecting points and on terrain details.

In order to evaluate mean horizontal and vertical errors of detail points surveyed by means of the tacheometric method, control distance field measurements, as well as measurements of elevation differences were performed about 100 detail points, determined by means of tacheometric method. Basing on differences between control surveys and their values calculated from coordinates, mean errors of planimetric and elevation location of the detail points were calculated: $m_P = 0,019m$, $m_H = 0,006m$.

Those accuracies are sufficient for further comparative analyses with results of surveys performed by means of the RTK method.

3. SURVEYS OF THE TWO-FUNCTIONAL NETWORK BY MEANS OF THE RTK METHOD

It has been initially assumed that surveys of the network, which require special care, will be preceded by selection of the optimum time of surveys, where the PDOP coefficient would have the most advantageous value. The TRIMBLE PLANNING software tool was used for planning the time of observations. It was also assumed that for each point the waiting time for the FIX solution should not exceed 10 min.

Three cycles of measurements were planned: the first two of them during winter (with no leaves on trees) and the third one–during the spring-and-summer period (with leaves on trees). In those cycles, measurements were performed for various locations of the Base station. The location of the Base station is presented in Fig. 3-5 by the symbol ⩕ .

The first two surveys (Called the *Base 1* and the *Base 2*) refer to locations of the base stations in the Politechnika Square (Fig. 3 and Fig. 4), in the periods of various configurations of satellites. The third measurement (the *Base 3)* was performed for the satellite configuration, similar to the first measurement, but the location of the base point was changed into the location covered from the South, inside the campus (Fig. 5).

Values of coordinates, obtained from measurements performed by the RTK method, were compared with corresponding results of conventional surveys. Calculated differences of coordinates *ΔX, ΔY, ΔH,* due to high accuracy of the network, measured by the conventional method, may be considered as true errors, which reflect the accuracy of measurements performed by means of the RTK method. Figures 3,4 and 5 present the quasi-true values of errors of position of the network points: in black for the horizontal plane, and vertical in grey.

Only 8 out of 30 network points could be measured during the *Base 1* measurements. The highest values of quasi-true errors were obtained for point no. 3. Outstanding observations were noticed for that point only. This results from the location of that

point, close to high buildings, at the back of the Main Building of the Warsaw University of Technology, which covers the major part of the southern horizon.
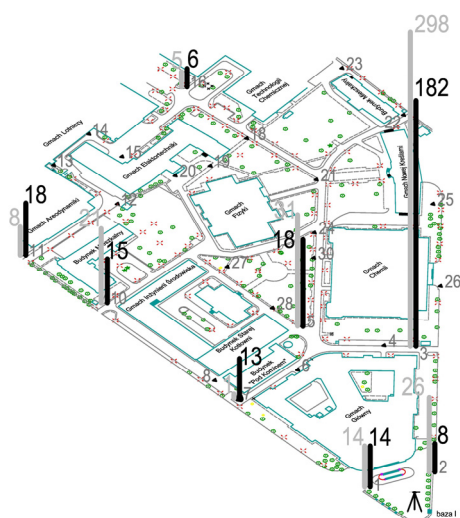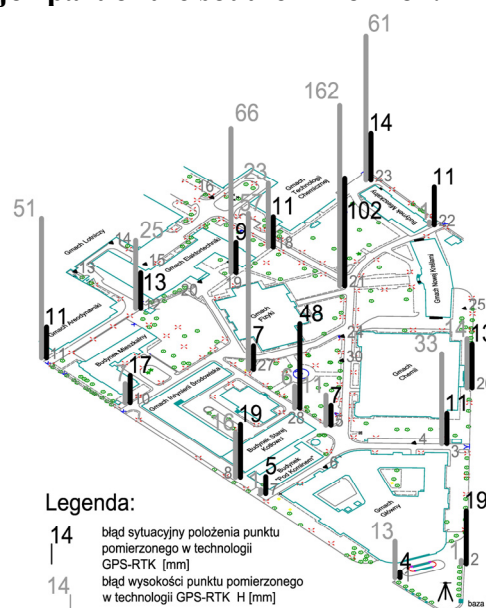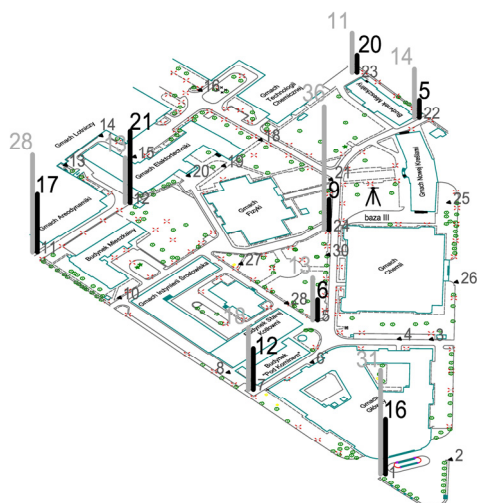

Fig. 3. The *Base 1.*

Fig. 4. The *Base 2.*

Fig. 5. The *Base 3*

Legend:

| 14 error of point measured using the RTK technology, X,Y plane [mm]

14| error of point measured using the RTK technology, H plane [mm]

Table 1. The *Base I* – quasi-true errors of coordinates of the network points (ΔX, ΔY, ΔH, d components), number of GPS and GLONASS satellites and PDOP, HRMS, VRMS coefficients

Baze I									
True errors	**|ΔX| [mm]**	**|ΔY| [mm]**	**|ΔH| [mm]**	**d [mm]**	**PDOP**	**Nr of satellites**		**HRMS**	**VRMS**
						GPS	**GLONASS**		
Mean value	14	18	50	24	3,0	6,0	2,4	0,048	0,038
Max	65	64	298	91	3,4	5	3	0,037	0,047
Min	3	5	5	6	4,8	5	2	0,023	0,042

The smallest number of GPS satellites was observed in the course of measurements of that points – only five of them – what resulted in the higher value of the PDOP coefficient value. For point no.16 similar survey conditions may be also observed, however, the deviation from coordinates obtained from the conventional method, is considerably lower. At the point no.3 the system was looking for the FIX solutions, which „guarantees" the high accuracy of performed measurements, for the very long time, equalled to seven minutes.

In the case of the *Base II* measurements, for the identical position of the base station in the square, in front of the Main Building of the Warsaw University of Technology, but for another configuration of satellite, it was possible to measure the highest number of satellites, i.e. 17. Surveys of every point, with the exception of point no.12, lasted for about one minute.

Table 2. The *Base II* – quasi-true errors of coordinates of the network points (ΔX, ΔY, ΔH, d components), number of GPS and GLONASS satellites and PDOP, HRMS, VRMS coefficients

Baza II									
True errors	|ΔX| [m]	|ΔY| [m]	|ΔH| [m]	d [m]	PDOP	Nr of satellites		HRMS	VRMS
						GPS	GLONASS		
Mean value	12	12	32	19	3,8	5,6	2,5	0,038	0,037
Max	57	84	162	102	4,4	5	0	0,038	0,060
Min	4	3	1	5	2,8	7	2	0,026	0,016

For that measurement, coordinates of point no. 21 were determined with the lowest accuracy. The distance $d = 10,2cm$ and the error of the elevation of the station $H = 16.2cm$ exceed the recommendations of the G-4 Instruction, which refer to errors of position of points of the two-functional network, which are determined with the poorest accuracy. This resulted from difficult field conditions. During the measurements, the high van stayed close to point no.21. which excluded GLONASS satellites from observations. However, measurements were not repeated, since the HRMS, VRMS and PDOP coefficients pointed to correctness of performed observations.

For the *base III* the position of the BASA receiver was changed (Fig. 5) to the place with the partial cover of the Southern horizon. Measurements were performed with the slightly modified configuration of satellites with respect to the *Base I.* For such located base station, the lowest number of the network points, i.e. 8, were measured, but gross errors did not occur in those observations.

Table 3. The *Base III* – quasi-true errors of coordinates of the network points (ΔX, ΔY, ΔH, d components), number of GPS and GLONASS satellites and PDOP, HRMS, VRMS coefficients

Baza III									
True errors	|ΔX| [m]	|ΔY| [m]	|ΔH| [m]	d [m]	PDOP	Nr of satellites		HRMS	VRMS
						GPS	GLONASS		
Mean value	10	6	21	12	3,9	5,5	2,8	0,037	0,037
Max	15	15	36	22	4,3	5	2	0,046	0,059
Min	6	2	13	6	2,3	6	3	0,026	0,028

As it turns out from above tests, location of the base station, as well as positioning the mobile station is very important for obtaining correct results of the RTK measurements. Even the single obstacle may be the source of considerable survey errors. Therefore, repeated control surveys should always be performed in measurements of networks, and they should be referenced to various locations of the base station. Observations obtained after long waiting time for the FIX solution, were characterised by high values of true errors. Even in the case of many attempts, it was impossible to measure 8 network points. Locations of those points result from the needs to survey terrain features by means of the tacheometric method. Any terrain features could not be measured by means of the RTK method around those points. The main reason was the close neighbourhood of tall buildings, composing the densely built-up areas.

4. SURVEYS OF TERRAIN FEATURES, WHERE THE RTK RECEIVER COULD BE PLACED

In the case of surveys of detail points, the so long waiting time for the FIX solution cannot be accepted, as in the case of network measurements, since this would result in the high increase of costs, and, therefore, measurements would turn to be ineffective comparing to conventional tacheometric surveys. Still, at each surveyed points, the survey attempt lasted for 2 minutes, as the maximum.

Only 122 detail points were measured by means of the GPS-RTK, including 69 points measured in the Politechnika Square. Other 53 detail points were measured around the Southern part of the Main Building and at the central part of the campus, where low and scattered buildings occur, surrounded by tall green vegetation. Any detail points could be measured in the North-Western part, where densely built-up areas occur.

The measurement of characteristic terrain features was measured into two groups:
- directly measured detail points (sink-holes, curbs etc.).
- detail points measure by means of the offset method (trees, street lamps, corners of buildings etc).

The largest group of detail points (90) were measured directly, i.e. after positioning the mobile receiver (rover) on terrain features. For that points it was possible to determine differences of three coordinates from the RTK measurements and from tacheometruic surveys.

Direct measurements were performed in the Politechnika Square, where all interesting terrain features could be measured. Synthetic results of those measurements are presented in Table 4. The direct method was also used to measure protruding corners of footings of some buildings (Table 5), as well as street and park details at the central part of the campus (Table 6).

Table 4. Comparison of tacheometric and RTK measurements for points located in the Politechnika Square (the receiver directly on points)

Measurements directly on points of terrain features in the Politechnika Square			
True errors	$|\Delta X|$ [mm]	$|\Delta Y|$ [mm]	$|\Delta H|$ [mm]	D [mm]
Mean value	11.2	16.7	77.2	22.0
Max	58.0	70.0	247.0	78.7
Min	0.1	0.0	36.7	1.4

The maximum values of differences of plane coordinates *ΔX* i *ΔY* and the distance *d* of points directly measured in the Politechnika Square do not exceed the criterion of the mean error of location of point, $m_P < 10$ cm, permitted by the G-4 Instruction. In the case of 20% of observed points, differences of the distance *d* do not exceed the 2/3 of that value. Unfortunately, any of measured points, met the requirements of the technical instruction, concerning the determination of elevation of the features of the I group $m_H < 1$ cm. Comparison of results obtained using the GPS-RTK method with tacheometric measurements are presented in Fig. 6. Much worse results of elevation measurements (in grey) may be noticed comparing to planimetric measurements (in black).
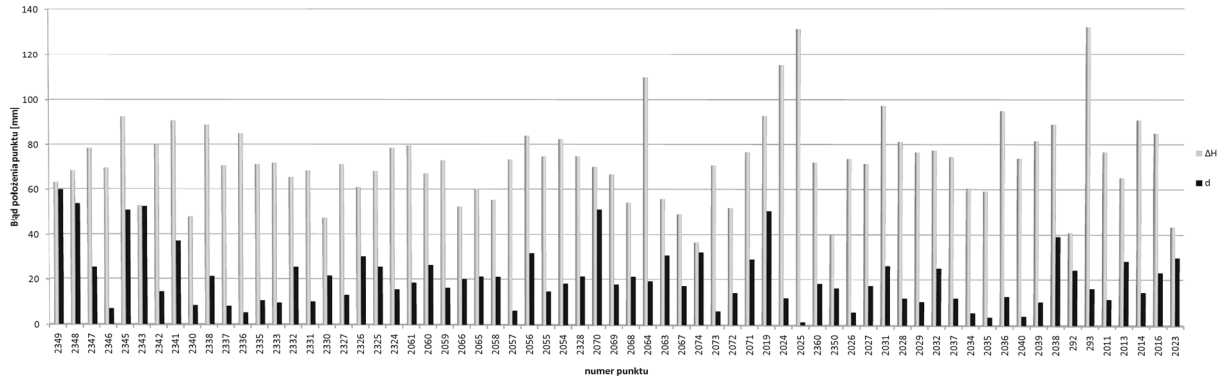

Fig. 6. Comparison of results of measurements performed by means of the RTK and tacheometric methods [mm].

The direct method was successfully used for measurements of the part of the Main Building (the antenna adjoining the building). Unfortunately, results of measurements of the corners of that building, to which the antenna was touched, were highly unsatisfactory. Out of 4 measurements, characterised by correct X,Y coordinates, gross errors of the H coordinate, reaching up to *1m* were observed. They probably result from disadvantageous influence of multi-way signal distribution, scattered by walls of the building. Synthetic results of that measurement are presented in Table 5.

Table 5. Comparison of tacheometric and RTK measurements.

Measurements with an antenna adjoining building corners on the southern and eastern side				
True errors	|ΔX| [mm]	|ΔY| [mm]	|ΔH| [mm]	D [mm]
Mean	21.3	18.5	118.6	30.0
Max	74.0	40.7	1002.8	75.0
Min	4.2	2.1	0.007	5.1

Table 6. Comparison of tacheometric and RTK measurements.

Measurements on points at the central part of the campus				
True errors	|ΔX| [mm]	|ΔY| [mm]	|ΔH| [mm]	d [mm]
Mean	21.5	17.8	52.0	31.2
Max	66.9	71.3	107.5	79.0
Min	1.3	0.6	0.9	5.0

The last area, where direct GPS-RTK measurements could be performed, was the square between the Main Buildings and the Buildings of Physics and Chemistry. Only 18 points were measured within that area, out of 100 points measured by means of the tacheometric method. Synthetic values of differences of the GPS-RTK and tacheometric measurements, are presented in Table 6.

Results of topographic measurements obtained in that square meet the criterion of the technical instruction referring to the mean horizontal error of the detail point. Only 2 points, for which the „*d*" value exceeds 5.0 cm occurred in that group. However, only one measured elevation had the value ∆H ≤ 1 cm.

In the conclusion for that part of experiments, which covered the direct topographic measurements in the GPS-RTK technology, it may be stated, that this method is useful for topographic measurements, if terrain conditions allow for that. However, one cannot trust the results of elevation surveys of characteristic terrain features, performed by means of the RTK method.

5. MEASUREMENTS OF POINTS OF TERRAIN FEATURES INACCESSIBLE FOR DIRECT MEASUREMENTS (OFFSET SURVEYS)

In some cases, using both, the GPS-RTK and tacheometric method, offset measurements of terrain features, must be applied. In conventional methods, such measurements are performed, when the pole, or the pole with the mirror, cannot be positioned on the surveyed point, or when the point is not visible from the measurement station. In the case of GPS measurements, such situations also include places when some parts of sky are hidden behind surveyed buildings or tree crowns. In such cases, it is sufficient to recoil from the surveyed details to such a distance, that it is possible to perform observations on two points, which will create the baseline. Depending on the way of point determination, distances to the inaccessible point should be measured from one or two points of the baseline.

Two basic methods of measurements of inaccessible points are distinguished:
-   the method of extension on a line,
-   the method of linear intersections.

The evaluation of usefulness of offset measurements has been empirically performed using the test site, which was prepared earlier. Coordinates obtained from tacheomatric measurements were compared with coordinate of the same points, repeatedly measured by means of linear intersections and extensions on a line. Results of those comparison are listed in Table 7. Differences of X,Y coordinates between points from tacheometric measurements and from offset measurements using the GPS-RTK method do not exceed 6.7 cm for any point surveyed by means of both methods.

Table 7. Differences of coordinates between points measured in the RTK mode by means of the line extension and linear intersection methods and tacheometric measurements

True errors	Line extension method		Linear intersection method	
	$|\Delta X|$ [mm]	$|\Delta Y|$ [mm]	$|\Delta X|$ [mm]	$|\Delta Y|$ [mm]
Mean value	19	28	17	20
Max	56	67	36	57
Min	1	1	3	2

Therefore it may be stated that offset measurements, performed using the RTK method allow to achieve the accuracy compliant with the requirements of the G-4 Technical Instruction concerning measurements of terrain features of the fist accuracy group, i.e. $m_P < 10$cm. However, it should be stressed, that the linear intersections method proved to be much faster than the method of extensions.

Unfortunately, the basic disadvantage of both methods is lack of possibility of the sufficiently accurate determination of the elevation coordinate.

The method of linear intersections has been also used to measure a dozen or so trees, classified as terrain features of the 2nd accuracy group. For that group the mean error of point location should not exceed 0.30 m. This group of points has been specially distinguished, since problems related to explicit identification of a terrain feature centre (a tree centre) occurred. Still, satisfactory results of measurements in the RTK mode were obtained. Differences of coordinates from tacheometric measurements and the GPS-RTK measurements are listed, in synthetic form, in Table 8.

Table 8. Comparing of results of trees by means of the tacheometric and RTK method

True errors	ΔX [m]	ΔY [m]	ΔH [m]	d [m]
Mean	102,9	70,4	-	135,8
Max	259,2	127,9	-	289,0
Min	0,6	17,6	-	53,3

All observed points meet the criteria of the G-4 Technical Instruction concerning measurements of terrain features of the 2nd accuracy group, i.e. $m_P < 30cm$. Unfortunately, only less than 20 trees could be measured by means of the linear intersection method, out of several dozens trees existing within the main campus of the Warsaw University of Technology.

6. CONCLUSIONS

During the survey performer in a typical urban areas, out of 2220 detail points measured by the tacheometric method only 122 detail points could be surveyed by the RTK method, what equals to 5,5 % of planned observations.

Considering economic aspects, as well as requirements of the contracting party, it is difficult to practically plan measurements in such a way that it would be possible to adjust the schedule of measurements to the optimum configuration of satellites. Besides, due to terrain obstacles which exist in urban areas it is difficult to increase the accuracy of measurements performed using the GPS-RTK technology, as a result of observation planning activities.

The obstacles which turned to be impossible to overcome, which occurred in the central part of the test site, were trees in the vegetation period.

Direct measurements of corners of building should be avoided; instead, the antenna should be attached to those corners due to occurrence of multi-way distribution of signals.

The RTK measurements can be performed with satisfactory accuracy only when the „fast" FIX type solution can be found. Then those measurements meet the requirements specified in the G-4 Technical Instruction concerning the terrain features.

Offset measurements in the X,Y plane meet the criteria of the G-4 Technical Instruction. Both, the line extension method, as well as the linear intersection method, are sufficient with respect to accuracy requirements concerning surveys of terrain

features. <u>Unfortunately, Topcon has not included the faster and more accurate method of linear intersections into their software tools.</u>

The basic disadvantage of offset surveys is to obtain the value of elevation at the position, where a point is inaccessible for direct measurements; this is practically impossible or time consuming. Any point, for which it was possible to measure the H ordinate, does not meet the accuracy criteria of the G-4 Technical Instruction.

In order to determine coordinates of the network point by means of the RTK method, repeated surveys must be performed with reference to various positions of the base station. This also refers to tacheometric stations, established by means of the RTK method in the case of hybrid measurements.

At present, utilisation of GPS receivers for the needs of measurements using the GPS-RTK technology within urban areas, cannot be recommended.

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