Investigations concerning the reliability and the external accuracy of GPS Real-Time Measurements

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Key words: real time, GPS, network adjustment, horizontal position, height, external accuracy

ABSTRACT

In a local area network for engineering purposes the external accuracy of different RTK-techniques is analysed in detail. Three different solutions for the network are produced by varying the kind of the necessary reference station. First of all a local reference station resulting in very short baselines is used for the RTK-measurements. A second solution for the network is produced by using the nearest SAPOS reference station (SAPOS: Satellite Positioning Service of the German National Survey) resulting in an average baseline length of about 6.8km. At least so called virtual reference stations – derived from a network solution of the surrounding SAPOS-stations – are used for a third RTK-solution.

For each solution every point of the network is occupied at least six times by using different ambiguity solutions, by varying the observation time after the successful initialisation from 10sec up to 60sec and by using a different satellite geometrie. The three network solutions are computed by using strong adjustment procedures as well for the horizontal positions as for the height component of the points of the network. Hereby the RTK positions and heights together with the corresponding variance-covariance matrices are introduced as pseudo-observations. Finally these adjustment results are analysed and compared to a more precise network solution resulting from terrestrial measurements of very high accuracy.

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1. INTRODUCTION

The new fair Karlsruhe covers 50,000 square meters of hall surface in four exhibition halls as well as 10,000 square meters of exhibition surface in the open area. One of the halls is conceived as multi-function hall for up to 14.000 visitors, in order to be able to execute concerts, sport and large meetings as well as TV productions. The costs of the fair amount to approximately 150 millions €. Basic condition for the problem-free solution of the subsequent surveying tasks is an accurate, reliable and unconstrained position and height reference network. The determination of this basic network took place in August 2001 in the further described measuring and evaluation procedure.

In the Federal Republic of Germany the satellite positioning service of the German land surveying (SAPOS) is in construction. One method to use this service is to consider an individual SAPOS station as reference station, which is suited for applications in small area networks because of the distance-dependent error influences of the GPS signals. The individual user needs only one GPS receiver, which means a substantial saving of investment costs. On the other hand one can use data from multiple reference stations to compute so-called virtual reference stations, which should reduce the effect of distance-dependent errors influencing the real-time solutions of GPS *(Wübbenea et. al., 1996; Wanninger, 1999).*

While so far the precise DGPS applications were limited to projects with a precision demand of one ore some centimeters, in this project it is investigated whether the accumulation of redundant RTK solutions can improve the external accuracy to a level of some millimeters. Three different versions of the RTK technique, i.e. the application of a single local reference station in the survey area, the use of the nearest SAPOS station and the principle of so-called virtual reference stations, are applied and the results compared to each other and to a reference solution resulting from very accurate terrestrial measurements.

2. MEASUREMENTS

The basic network of the new fair Karlsruhe, which has an expansion of approx. 625m x 625m, consists of altogether 24 netpoints. Four of these points are realized as observation pillars (M1 - M4) and 15 points are marked as brass pins, whose centers were indicated by approx. 1mm large holes. Further 5 points of the Geodetic Survey of Germany (587, 863, 864, 994, 995) were included into the network, in order to ensure a controlled link to the national network. In order to enable GPS independent comparisons of the obtained results, the network in consideration was additionally determined by classical terrestrial observations.

2.1 Terrestrial measurements

Before the measurement of the network an interactive planning of the network configuration with the software **NETZ2D** of the Geodetic Institute was performed. The observations had to be planned in such a way that the network fulfilled the demands of accuracy and reliability. For the measurements the total station TCRA 1103 of the company Leica was used, whose accuracy specifications of 2mm for the distances and 1mgon for the directions were introduced in the network planning. The final computation supplied an average accuracy of 1,7mm for the horizontal position of the netpoints with the maximum value of 4,3mm for point 587. The calculated redundancy numbers for the observations ranged between the values of 28% and 90%.

For the practical measurements the force centering method was applied and the planned network design could be realized to a large extent. The measurements were executed by two persons within one day. The possibility of the automatic target acquisition of the TCRA 1103 (in position 2 all targets were automatically recognized and observed) proved to be a substantial facilitation of observing the network. Since the height component of the RTK measurements should be examined likewise, all points of network were levelled additionally using the DINI 10T (Zeiss). So, heights with a quality better than 1mm were available for a critical comparison of the height component of the GPS-RTK results.

Fig. 1: Terrestrial measurements with the Leica TCRA 1103

2.2 Precise Real-Time DGPS measurements

The GPS measurements were carried out on the 15th and 16th August 2001 with Leica SR530 receivers in three versions: Use of a temporary local reference station in the network center, use of the nearest SAPOS station Karlsruhe (approx. 7.0km far from the network) as well as testing the SAPOS reference station network concept with virtual reference stations. In each version all points were observed with occupation times of 10sec, 30sec and 60sec. For each observation time two datasets resulting from a different satellite geometry were stored. So, six completely independent sets of coordinates including the corresponding variance-covariance information are available for following network adjustments of the different versions .

On the one hand it should be investigated whether different observation times influence significantly the quality of the point determination, and on the other hand the variation of the coordinates resulting from identical occupation times should be documented. The observations of the local version as well as the measurements under use of the SAPOS station Karlsruhe were carried out strictly simultaneously influenced by identical satellite constellation and atmospheric conditions, while the version with virtual reference stations was measured independently.

Fig. 2: Real-Time DGPS measurements with the Leica SR530

For each observation time of the local version (data communication by radio) the points were once observed maintaining the phase ambiguities solved before and another time the phase ambiguities were resolved for each point independently. For the two other versions (data communication by GSM) the communication with the reference station was always interrupted after the measurement of a point from cost reasons. Thus the phase ambiguities had to be resolved for each point independently.

During the measurements the phase initializations of the rovers succeed always in a few seconds, so that the time for solving the phase ambiguities was not of great importance. Also the dialing of the SAPOS reference stations proved as unproblematic and was not very time-consuming in comparison with the use of the local reference station with constant radio communication. Using only one rover the successive determination of all 24 netpoints lasted approx. 1,5h independently of the RTK-version. Converted to a average time for the determination of one point 3,75Min were needed including the time to drive between the points, the time to setup the equipment and the time to take the measurements.

For the occupation of the points poles with constant heights and strut tripods with clamping mechanism for a fast handling were used (see Fig. 2). In order to reduce the effect of phase center eccentricities the GPS antennas were always aligned to the same direction.

3. EVALUATION AND RESULTS

For the analysis and network adjustment of the terrestrial and the GPS-measurements the software **NETZ2D** of the geodetic institute of the University of Karlsruhe was used. According to the Karlsruhe approach *(Illner, 1995)* the threedimensional geocentric GPS-coordinates (X, Y, Z) were separated into the horizontal position components (E, N) and into the height component (h). Applying the law of error propagation the variance-covariance matrices of the threedimensional GPS-coordinates were also transformed into the position and height components. These accuracy informations were used for the adjustment of the corresponding horizontal and height networks. In the final adjustment computation of each RTK-version six sessions were introduced, that are two measurements of 10sec, 30sec and 60sec for every point of the network.

For the analysis of the different RTK-results the horizontal coordinates of a unconstrained network adjustment of the terrestrial measurements are defined as reference solution and the quality of the RTK-solutions can be directly derived from the resulting coordinate-differences of the netpoints. For the height component the differences between the heights resulting from GPS and the results of the levelling height network were analysed. Therefore the ellipsoidal GPS heights had to be transferred to the levelling height system. The difference between these two height systems was modelled by a bilinear polynomial function *(Illner, Jäger; 1995)* using the the levelled heights of the points 863, 864, B8, B13, M3, M4 (stochastical fixpoints) for the determination of the polynomial coefficients.

3.1 Terrestrial measurements

The unconstrained network adjustment of the terrestrial observations results in a mean point error of 0,9mm with the maximum value of 3,4mm for point 587. No blunders in the observa-

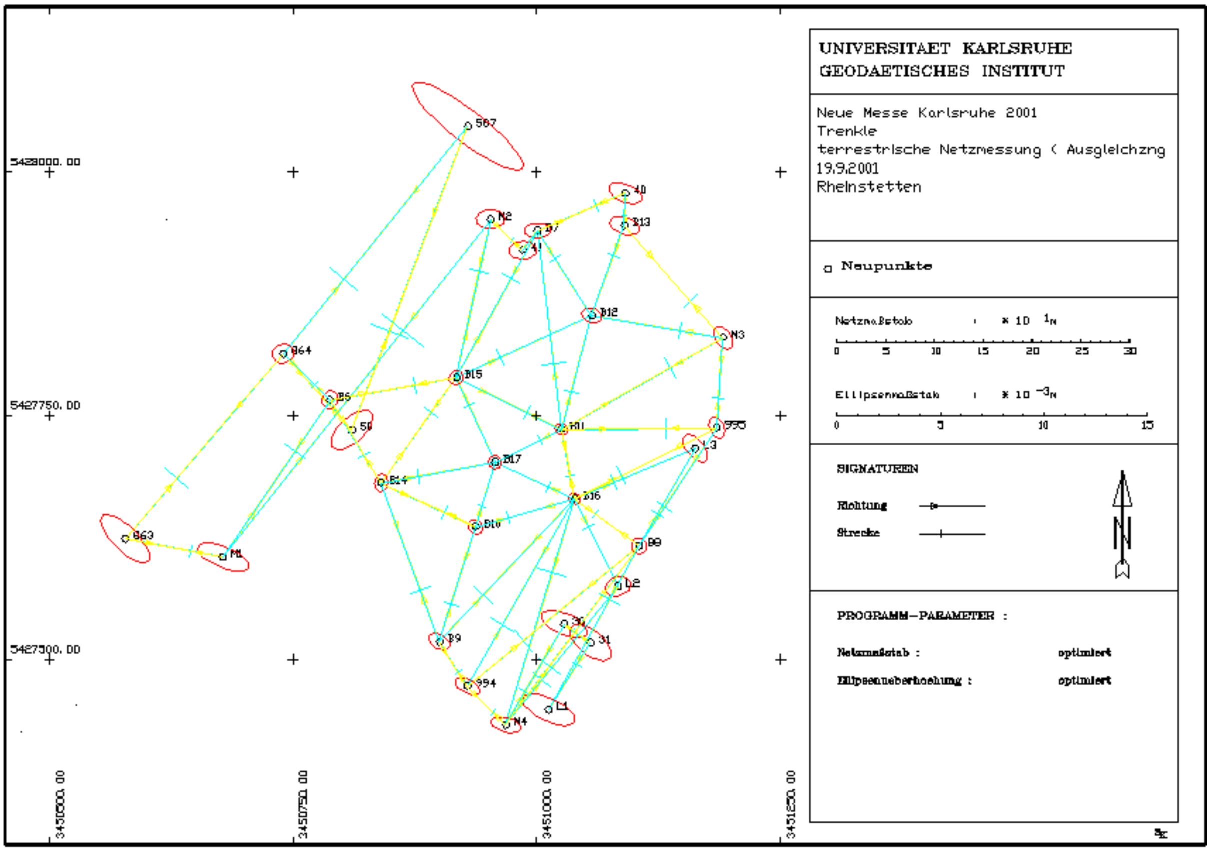

Fig.3: Results of the unconstrained network adjustment of the terrestrial measurements

tions were detected by the applied statistical testing procedures. The network design and the resulting error ellipses are shown in Fig.3. The geometry of the network is only fixed by the observations and it is not influenced by external constraints (e.g. fix points). So, the resulting coordinates are very well suited for a GPS independent comparison of the different GPS-RTK results.

3.2 Real-time DGPS measurements

The analysis of the GPS-RTK results showed, that all phases ambiguity solutions were correct and that no one position was wrong because of a incorrect phase ambiguty solution process. So, for the RTK-results using a local reference station no significant differences occur between the measurements maintaining the previous resolved ambiguities and those solving the ambiguities for every netpoint again.

To get an idea of the occuring differences between the RTK-coordinates using a different satellite constellation and a completly independent set up of the equipment the differences in (X, Y, Z) of two 10sec observations of the RTK-version with the local reference station are

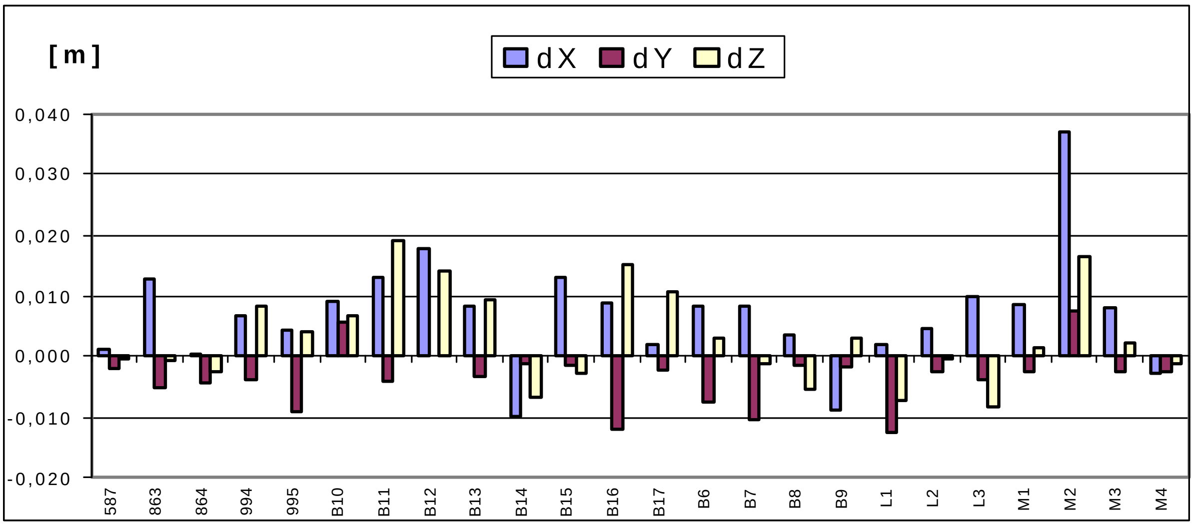

Fig. 4: Differences (dX, dY, dZ) between two 10sec measurements of the local RTK-version

listed in Fig.4. Obviously the discrepancies in the X- and Z-components exceed the corresponding values in Y. The reason for this is that the height component of GPS is less accurate than the horizontal components (Fig. 5), and for the geograpical latitude and longitude of the network in consideration the height component is mainly influenced by the X- and Z-components. While the differences in the horizontal coordinates (E, N) nearly not

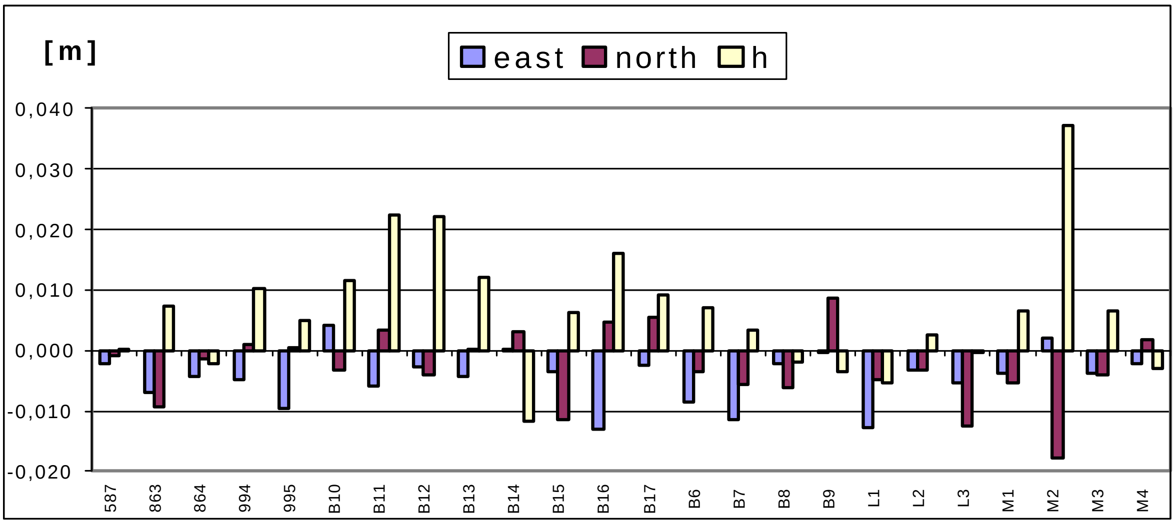

Fig. 5: Differences (dE, dN, dh) between two 10sec measurements of the local RTK-version

exceed 1cm the largest ellipsoidal height difference of 3,7cm is indicated for point M2. This value may be caused by obstructions because of a large office building nearby the point. A careful analysis of all the coordinate differences cannot indicate a significant increase of accuracy by extended observation times.

3.2.1 Analysis of the RTK-results using a local reference station

Horizontal components

The horizontal coordinates of the RTK-solutions are treated as pseudo-observations and introduced into a common network adjustment. The variance-covariance matrices - resulting from the law of error propagation applied to the coordinate transformation (X, Y, Z) → (E, N, h) - are introduced as stochastical model. The unconstrained adjustment of the six observation sessions leads to a mean accuracy of 2,1mm for the horizontal position of the netpoints with the maximum value of 3,0mm for the position of M2. One blunder detected by data snooping had to be removed from the list of observations. While the single RTK-positions show differences of about 1cm and more (Fig. 5), the accumulation of several RTK-observations and their common adjustment can obviously provide more accurate results.

In order to get a convincing measure for the obtained external accuracy of this GPS-network it is neccessary to compare the geometry of the network with the corresponding results of the terrestrial reference solution. Fig. 6 shows the resulting discrepancies between the horizontal positions of both networks. Point B14 is excluded from this comparison because his position

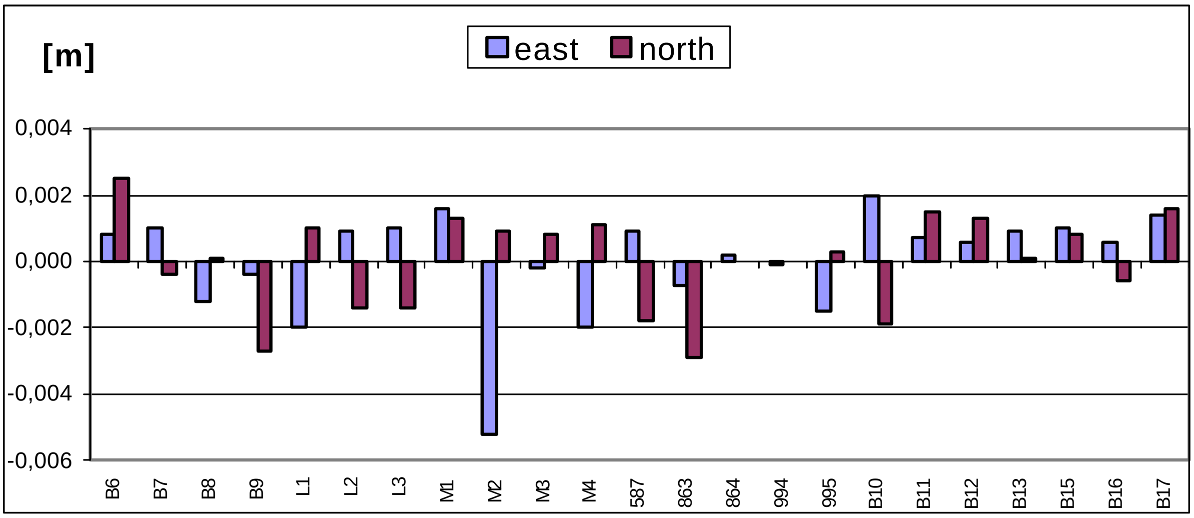

Fig. 6: Differences between the local RTK-results and the terrestrial reference solution

changed in the time between the terrestrial and the GPS-measurements due to building operations. The mean difference in the position amounts to 1,6mm and the maximum value of 5,2mm results for the east-component of M2 (obstruction problems). All other differences are smaller than 3mm. That means, with the exception of M2 we get a very good congruency for the horizontal positions of both networks.

Height component

After the removal of a blunder in the ellipsoidal height of M2, the unconstrained adjustment of the ellipsoidal heights yields a mean height error of 3,1mm. The maximum value of 4,4mm results again for the adjusted height of M2. This computation is not influenced by external constraints caused by fixpoints and/or by the method used to transform the ellipsoidal heights into the levelling height system.

Because the GPS user is not primarily interested in ellipsoidal heights but in heights referred to the national height system, a transformation of the ellipsoidal heights into the levelling height system was modelled by a bilinear polynomial function using the the levelled heights of the points 863, 864, B8, B13, M3, M4 (stochastical fixpoints) for the determination of the polynomial coefficients. The computation with the software **HEIDI** produces a formal accuracy of 3,1mm. This is the same value as it resulted for the unconstrained adjustment and it indicates that the change of the height reference system succeeded with no loss of accuracy. The comparison of the so determined heights with the levelling heights is presented in Fig. 7.

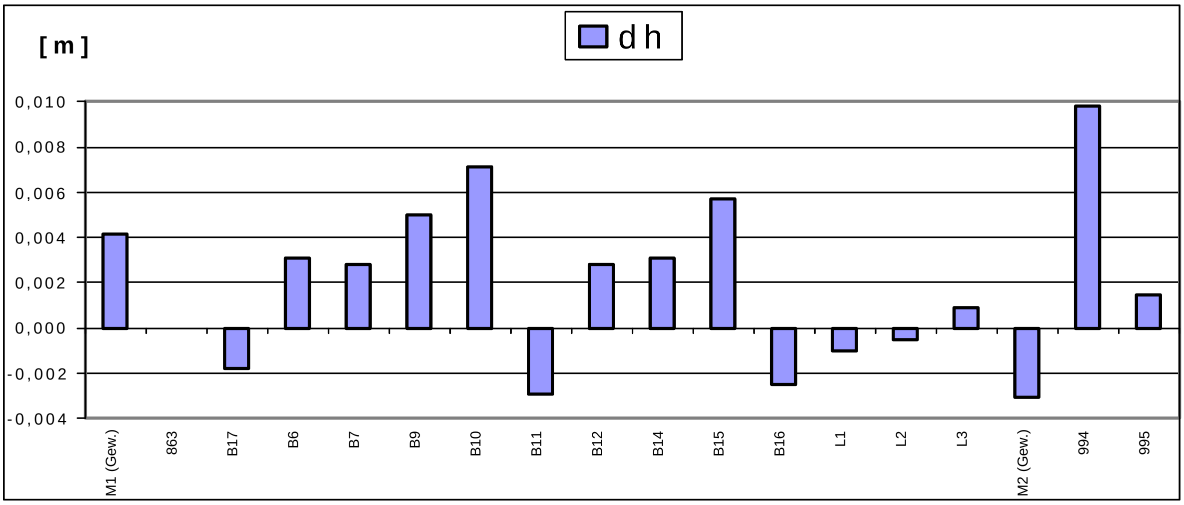

Fig. 7: Differences between the heights of the local RTK-version and the levelling heights

The mean difference amounts to 3,4mm and the maximum value of 9,8mm is obtained for point 994. Differences greater than 5,0mm only occur in 3 points. Because the residuals of the stochastical fixpoints do not exceed 0,1mm these points are not shown in Fig. 7. These results mean that the height component of the RTK-network using a local reference station also very good agrees with the heights of the levelling network.

3.2.2 Analysis of the RTK-results using the SAPOS-reference station Karlsruhe

In a second real time measurement series a single reference station of the Satellite Positioning Service of the German National Survey (SAPOS) was used. This station is about 7km far from the network in consideration. The measurements were taken with a second rover completely simultaneously to the observations referring to the local reference station in the network center so that the atmospheric conditions and the satellite constellation for both measurements series are equivalent. First of all unconstrained network adjustments of the horizontal positions (E, N) and of the ellipsoidal heights (h) were computed. No blunders in the pseudo-observations were detected. In a second step the ellipsoidal heights were transferred again into the levelling height system applying the model discussed above.

Horizontal components

The mean point error of the network resulting from the unconstrained adjustment of the six observation sessions amounts to 4,3mm. The maximum value of 5,3mm is again shown for M2. The results of the comparison to the terrestrial reference solution are shown in Fig 8.

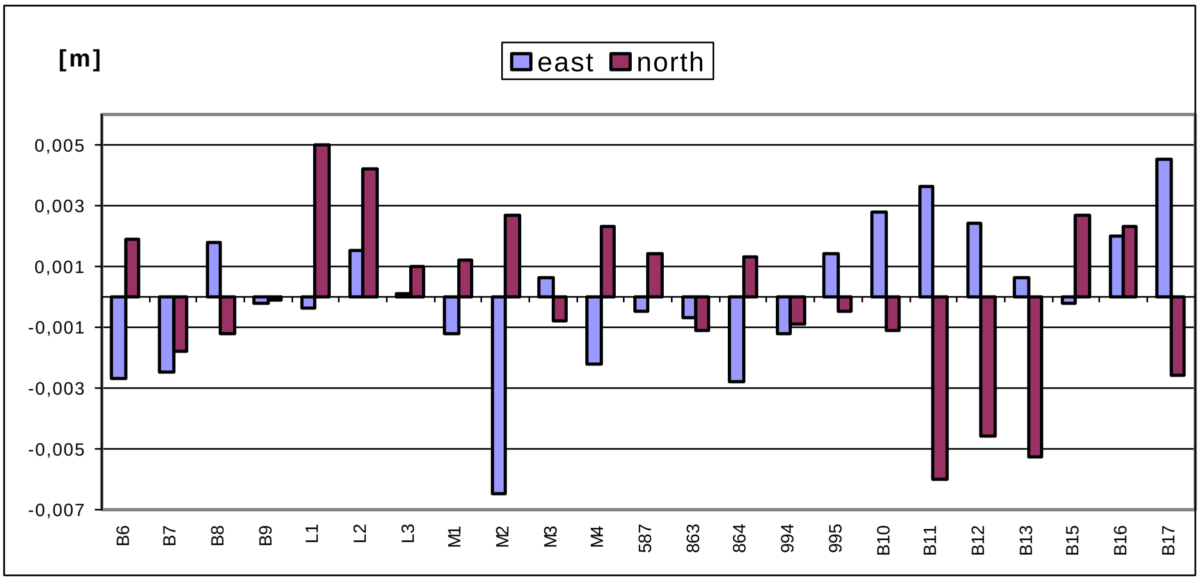

Fig. 8: Differences between the results using the SAPOS-station Karlsruhe and the terrestrial reference solution

The mean discrepancy between the horizontal coordinates is 2,8mm. The greatest difference of 6,5mm occurs again for the east-component of M2. Only three coordinate components show differences greater than 5mm. Therefore the horizontal position of this RTK-solution is also in a good agreement with the reference solution.

Height component

The mean height error of the unconstrained adjustment of the ellipsoidal heights results in 6,1mm. After the computation of heights referring to the national height system the mean difference between these GPS derived heights and the levelling heights reaches the value of 5,4mm. This time the maximum difference of 12,1mm is shown for point B9 (see Fig. 9). Three points show differences greater than 10,0mm and for seven points differences greater than 5,0mm occur. Both the formal accuracy of the adjustment and the external accuracy derived from the comparison with the levelling heights is nearly by the factor two worse than the RTK-results using the local reference station in the network center.

3.2.3 Analysis of the RTK-results applying the concept of virtual reference stations

For the third test-series of real-time measurements the multi reference station principle within the SAPOS-network was applied. Using the multistation solution software GNNET of the

Geo++® GmbH for PDGPS-reference stations for each rover point an individual virtual reference station nearby the point was computed and the rover coordinates were determined

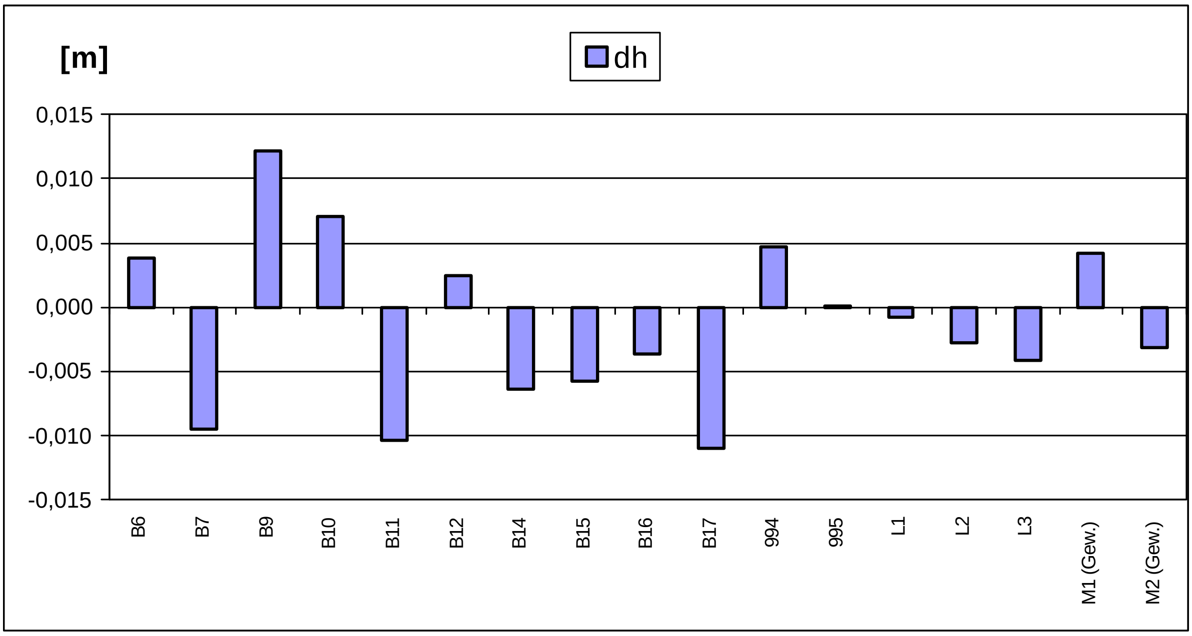

Fig. 9: Differences between the heights of the RTK-solution using the reference station Karlsruhe and the levelling heights

relative to these virtual reference stations.

Horizontal components

In the unconstrained adjustment procedure of the twodimensional RTK-positions two blunders were detected by data snooping. After the removal of these obeservations the mean point error of the network was estimated to 3,3mm. The differences between the resulting co-

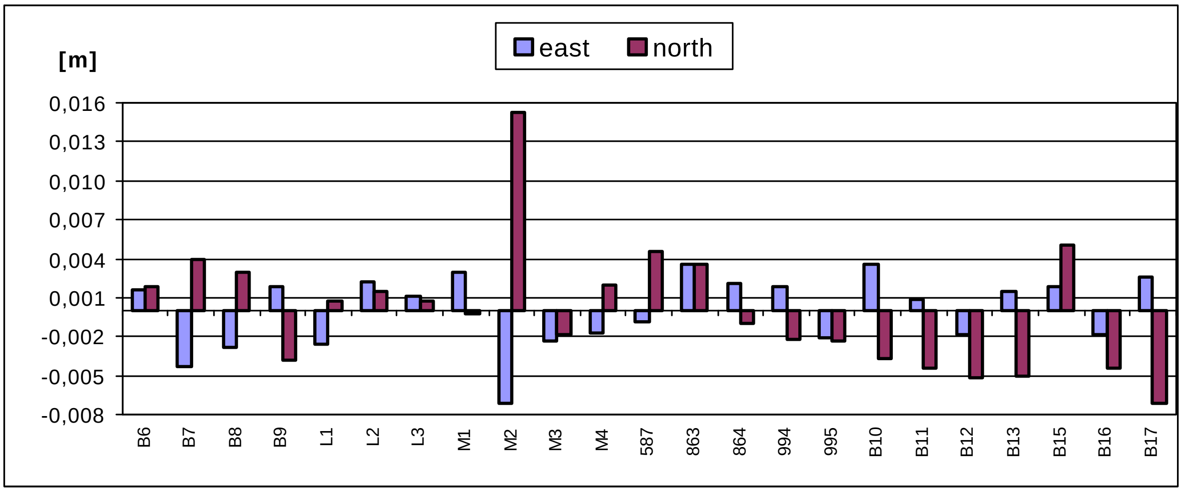

Fig. 10: Differences between the results using the multi reference station solution and the terrestrial reference solution

ordinates and the results of the terrestrial reference network are shown in Fig. 10. The mean value of all differences is 4,0mm with the maximum of 15,2mm for the north-component of M2. For points show differences greater than 5mm. That means that the results for the horizontal position of this RTK-version is a little bit worse compared to the other both versions.

Height component

The unconstrained adjustment of the ellipsoidal heights leads to a mean height error of 4,9mm. In Fig. 11 the differences to the levelling heights are listed after the transformation of the ellipsoidal heights into the national height reference system. The mean difference comes

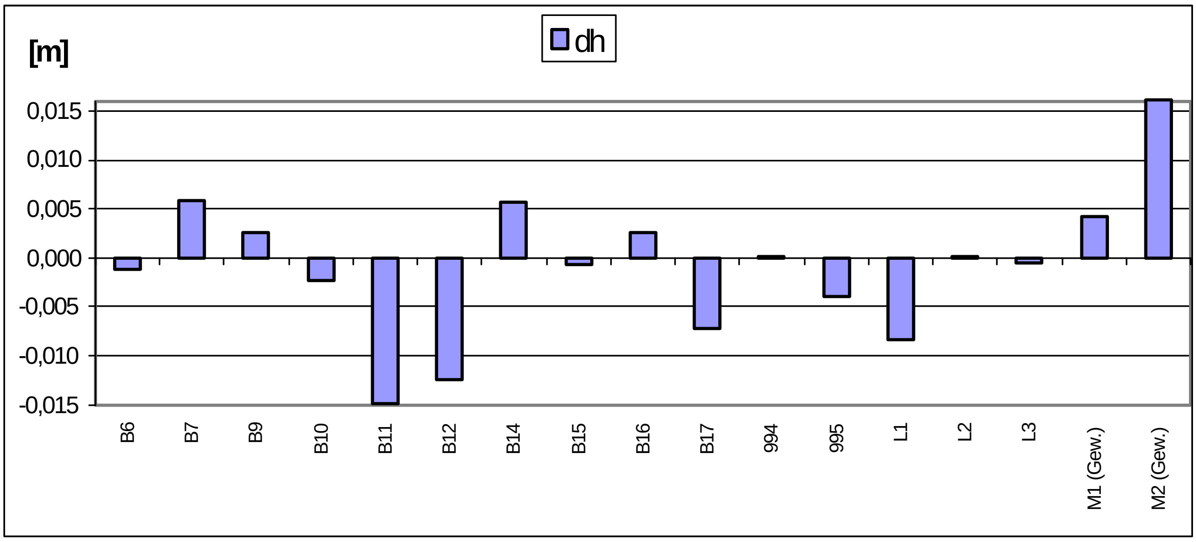

Fig. 11: Differences between the heights using the multi reference station solution and the levelling heights

to 5,2mm and the maximum difference of 16,0mm occurs again in M2. Altogether seven points show differences greater than 5mm. So, the quality of the height component is approximately the same as for the RTK-measurements using the single SAPOS reference station Karlsruhe. But the best results as well for the horizontal position as for the height component are obtained by the RTK-measurements using the local reference station.

4. CONCLUSIONS

The real time data of this local area network do not indicate a significant improvement of the attainable accuracy by extended observation times. The differences between the stored coordinates observed in an intervall of 10sec and 60sec are each of the same magnitude. The correct solution of the unknown integer phase ambiguities is the most important key for the attainable accuracy. On the other hand possible obstructions may reduce the accuracy considerably as it happened for point M2 of the network in consideration.

While two single RTK-datasets can show differences as well for the horizontal positions (E, N) as for the ellipsoidal heights (h) of about 1cm and more (Fig. 5), more accurate results can be obtained by a accumulation of several RTK-observations and their common adjustment. The obtained results of this example are summarized in Table 1. It is obvious, that real time

RTK- method	**formal accuracy (mm) of the unconstr. adjustment**		**differences to the reference solution (mm)**	
	horiz. comp.	height comp.	horiz. comp.	height comp.
Local reference station	2.1	3.1	1.6	3.4
SAPOPS station Karlsruhe	4.3	6.1	2.8	5.4
Multi reference station solution	3.3	4.9	4.0	5.2

Table 1:Summary of the obtained results

measurements related to a well chosen local reference station always will provide the best accuracy for the estimated coordinates. In the presented example the averaged difference to a terrestrial reference solution is less than 2mm in the horizontal position and about 3,5mm for the height component. But also the measurements using the SAPOS reference station Karlsruhe (about 7km far from the network) provide quite good results. This is of great importance because the user needs only one receiver and the costs for buying a second one can be dropped. The reason for the a little bit worse results of the RTK-solution using virtual reference stations may be that the construction of the SAPOS reference network is not yet completed and that the used reference stations did not neccessarily represent the local surroundings of the network sufficiently.

Because of the short observation times the multiple occupation of the netpoints using different satellite constellations is still an economic observation method especially suited for local engineering projects. Generally, the accuracy level better than 1cm can also be obtained for any other network determind by GPS-RTK measurements if the integer phase ambiguities can be successfully solved and if the netpoints are occupied for several times.

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