Journal of Global Positioning Systems (2002)
Vol. 1, No. 1: 40-47

Journal of Global Positioning Systems
2002

Accuracy Performance of Virtual Reference Station (VRS) Networks

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Received: 24 February 2002 / Accepted: 30 May 2002

Abstract. Recent developments in differential GPS (DGPS) services have concentrated mainly on the reduction of the number of permanent reference stations required to cover a certain area and the extension of the possible ranges between reference and rover stations. Starting from networked DGPS stations where all stations are linked to a central control station for data correction and modeling, the most advanced technique nowadays is based on the virtual reference station (VRS) network concept. In this case, observation data for a non-existing "virtual" station are generated at the control center and transmitted to the rover. This leads to a significant improvement in positioning accuracy over longer distances compared to conventional DGPS networks. This paper summarizes the various DGPS architectures and the corresponding accuracy. This is followed by a description of the models and algorithms used for the VRS station concept. Practical examples of correction data services in Europe are given to highlight the achievable positioning accuracy. The results of an analysis of test data in a virtual reference station network in southern Germany show that always a horizontal positioning accuracy in the order of ± 5 cm can be achieved for baselines with a length up to 35 km.

Key words: GPS, DGPS, VRS, RTK

1 DGPS NETWORK ARCHITECTURES

1.1 Single reference station concept

Figure 1 shows the architecture for the single reference station concept. In this case, a reference station in a DGPS network consists of the following main components: a GPS antenna/receiver assembly; a wireless data communication link to the user (usually a radio link); the reference station software on a PC which performs station monitoring, DGPS data correction model estimation and data archiving; interfaces and communication links for data transfer to the user [Landau, 2000]. For integrity monitoring, a reference station usually consists of 2 independent GPS receivers to guarantee against system failure. The user receives either DGPS corrections for code positioning or real-time kinematic (RTK) GPS data for carrier phase positioning in RTCM (Radio Technical Commission for Maritime Services) format. As the observation errors and biases are not modelled in the network, the error budget shows a distance dependent growth as the user-to-station separation increases [Retscher and Moser, 2001].

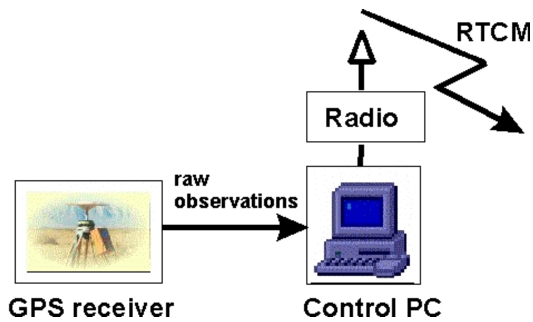


Fig. 1 Single reference station design

1.2 Multiple station concept

In the second concept, multiple reference stations are connected to a central control station using a data communication link (wireless radio link or cable connection via local area network (LAN) or Internet). Additional equipment at the reference station includes a modem for data transfer and modification of the station software package. The data transfer protocol employed between each reference station and the control center is usually RSIM (Reference Station Integrity Monitor messages). Further information about the data format standards may be found in [Moser, 2001]. On the control station, software is used to monitor several reference stations simultaneously.

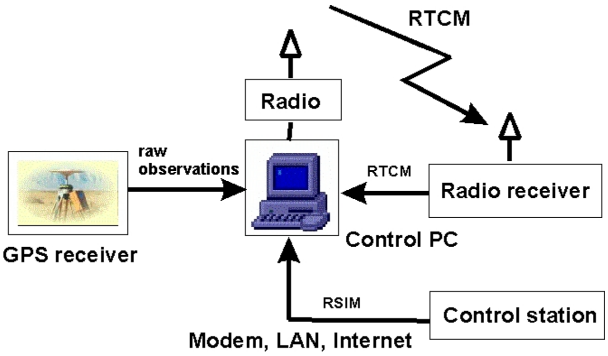
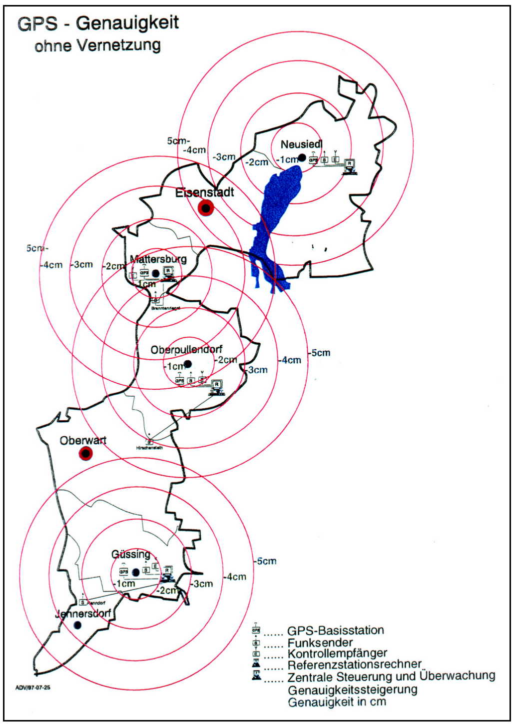


Fig. 2 Multiple reference station design with control center

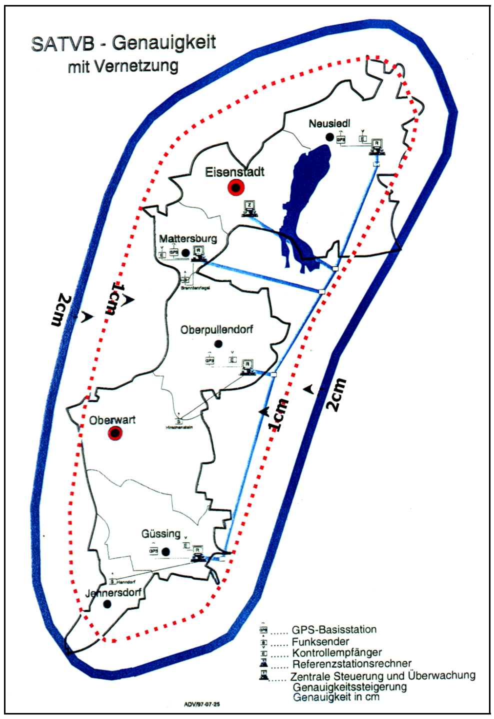
1.3 Networked DGPS system concept

Due to the use of networked DGPS system concepts, a reduction in initialization time for carrier phase positioning (i.e., time required for resolving the carrier phase ambiguities) and accuracy improvement for longer ranges is achieved. Additionally the reliability of the position solutions are improved allowing a larger reference-to-user separation. Thereby the system architecture is similar to the multiple reference station concept (Figure 2), only due to the software modification for data modeling in the control center a networked solution is obtained. The software modification includes new models for correction data estimation for modeling of the major error sources, i.e., the satellite orbit errors, ionospheric refraction as well as satellite and receiver clock errors. For the modeling observation data from at least three multiple reference stations are required. Then so-called area correction parameters [Wanninger, 1999] can be deduced for each triangle of three reference stations in a network.

Other advantages of a networked DGPS station network include the possibility for detecting station malfunction or failure. Figure 3 compares the positioning accuracies which are achieved over the SATVB reference station network in Burgenland, Austria [Retscher and Chao, 2000] for a standard DGPS network on the left (Figure 3 (a)) and the networked solution on the right (Figure 3 (b)). From the comparison it can be seen that due to the networked solution an accuracy of better than ± 2 cm can be achieved for the whole area of Burgenland using only 4 reference stations where the station separation ranges between 40 to 50 km. In the standard DGPS network the position accuracy degrades as the user-to-station separation increases and reaches values of ± 5 cm at a distance of 50 km from the nearest reference station.



(a) Standard DGPS solution for four independent reference stations



(b) Networked DGPS solution with an additional central control station

Fig. 3 SATVB network in Burgenland, Austria with 4 CORGS (Contiuous Operating Reference Geodetic Stations) [after Titz, 1999]

1.4 Virtual reference station network concept

Currently the most advanced approach for increased spatial separation of permanent stations and error modeling is the so-called virtual reference station (VRS) network concept. The concept was firstly introduced in a part of the German reference station network SAPOS [Landau, 2000; Trimble, 2001]. The name of this approach results from the fact that observations for a "virtual" non-existing station are created from the real observation of a multiple reference station network. This allows to eliminate or reduce systematic errors in reference station data resulting in an increase of distance separation to the reference station for RTK positioning while increasing the reliability of the system and reducing the initialization time.

The system architecture is shown in Figure 4. To create the virtual reference station data for a certain RTK GPS rover station, the user receiver's approximate location accurate to about 100 m is transmitted to the network control center. As a result,a bi-directional communication link between the user and the control center is required. The communication is usually performed using cellular phones (Global System for Mobile Communication GSM, in future Universal Mobile Telecommunication Service UMTS). The observations for a given location are estimated in the control center using real-time correction models and then transferred in the RTCM format to the rover station. On the rover side, standard RTK GPS algorithms are employed to obtain the position fix.

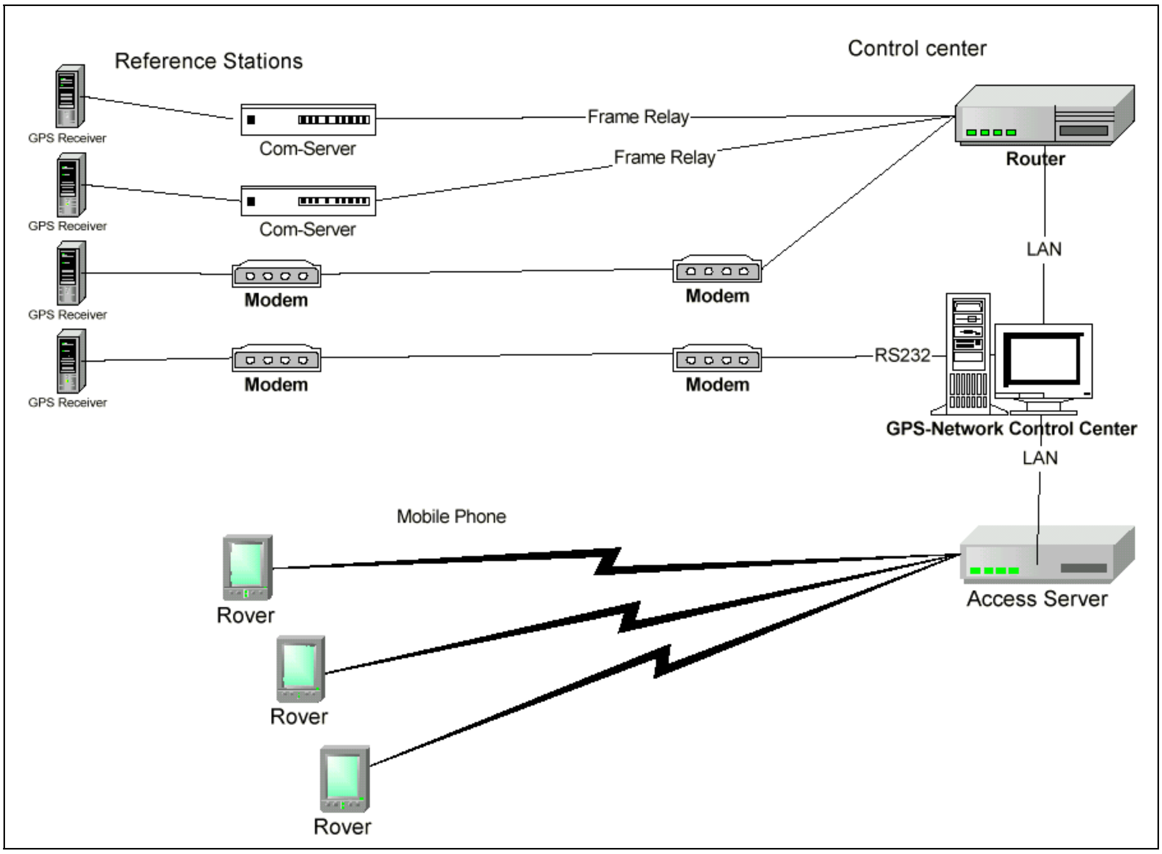


Fig. 4 System architecture of the virtual reference station concept [after Trimble, 2001]

1.5 Virtual reference cell concept

Another possibility for networked DGPS solutions is the virtual reference cell (VRC) concept. Here the correction models are not estimated for a specific user on request as in VRS concept, but the models are estimated for a given gridded DGPS service area. The rover receiver is assigned to a cell and there is no need for the virtual station to follow the movement of the rover station. When the rover leaves a VRC cell, then it is assigned to a new cell. The main advantage using this concept is that there is no limitation in the number of users and no bi-directional communication link between the rover and the control center is required. The positioning accuracy, however, is lower than the accuracy which can be achieved using the VRS approach. The VRC concept is therefore mostly employed in WADGPS (Wide Area DGPS) networks, such as the services provided by Thales and Fugro. Further information about this services may be found in e.g. [Moser, 2001], [Retscher and Moser, 2001].

2 ERROR BUDGET AND MODELING

The main error sources and the models employed in WADGPS networks have been discussed in detail in [Retscher and Chao 2000]. The models can be adapted to suit the requirements for correction data estimation in networked DGPS services or in the virtual reference station network concept. As usual, the main error sources that have to be dealt with are the satellite orbit errors, ionospheric refraction as well as satellite and receiver clock errors. For the error budget see [Kaplan, 1996] and for a detailed discussion of the error modeling see [Ashkenazi et al., 1997; Retscher and Moser, 2001; Whitehead et al., 1998]. In general, the approaches can be classified into the following three types:

- Estimation of range corrections: In this case, networked solutions are used to estimate the range corrections from weighted observations of a multiple reference station network. The main disadvantage is that the positioning accuracy gets worse depending on the distance between the user and the central point of the multiple reference station triangle.
- Estimation of position corrections: Position dependent algorithms estimate the position correction from the weighted average of the rover positions derived from each reference station. The accuracy degrades in a similar way to the method using the range correction approach.
- Estimation of corrections for the cell area: In the third approach, the range error is divided into different components that are estimated in a cell area independently from the baselines between the reference and rover stations. The user receives DGPS corrections that are separated into several components and must combine them to determine a position solution. The calculation of the corrections is an iterative process. This approach is most commonly applied and has many advantages compared to the first two algorithms named above. The disadvantage, however, is that the corrections have to be applied at the rover and a modification of standard DGPS algorithms would be necessary. This problem has been solved using the VRS approach.

For real-time applications, these error models have to be predicted ahead. An approach for a dynamic orbit determination has been introduced in [Retscher and Chao, 2000]. It can be summarized that then the satellite orbits can be obtained with an accuracy of better than 10 m r.m.s. using dual frequency raw pseudorange data from only three reference stations. The accuracy is further improved using data from more than three multiple reference stations. In the dynamic orbit determination algorithm also ionospheric correction parameters can be estimated in an integrated Kalman filter approach. Thereby the TEC (Total Electron Content) is estimated using modified standard single layer models (e.g. a modified Klobuchar model) [Klobuchar, 1986; Kleusberg, 1998]. The clock errors are depending on the other two error sources. They are estimated in an iterative process and due to the improvement of the estimates of the other error sources their impact is reduced. Site-specific errors (e.g. multipath) can not be taken into account as it has to be assumed that the reference stations are situated at ideal locations and at the user site these error sources are also minimized.

3 RESULTS OF TEST IN A VIRTUAL REFERENCE STATION NETWORK

The performance and accuracy achievements of the virtual reference station concept were analysed and presented in [Retscher and Moser, 2001]. The main results are summarized here. The VRS test network in southern Germany of the company Trimble (Terrasat) is shown in Figure 5. For the analysis presented here, the observation data for three stations (Virtuell 1 to Virtuell 3, see Figure 6) in the VRS network was downloaded from the website of the company Terrasat[1]. In total, 112 measurement epochs have been processed. To analysis the distance dependance of the result, the station Höhenkirchen was chosen as reference station in all tests. In the first analysis, the accuracy of the solution was investigated, followed by an analysis of system performance and the overall precision of the result.

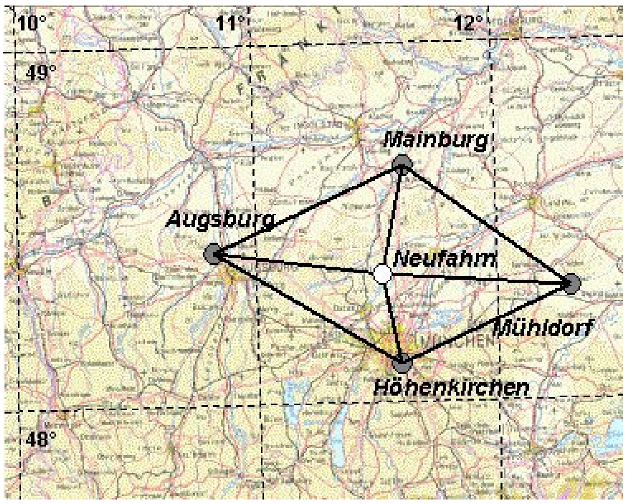


Fig. 5 VRS test network of the company Trimble (Terrasat) in Bayern, Southern Germany (Map not to scale)

[1] Website for Download of VRS observation data: www.virtualrtk.com

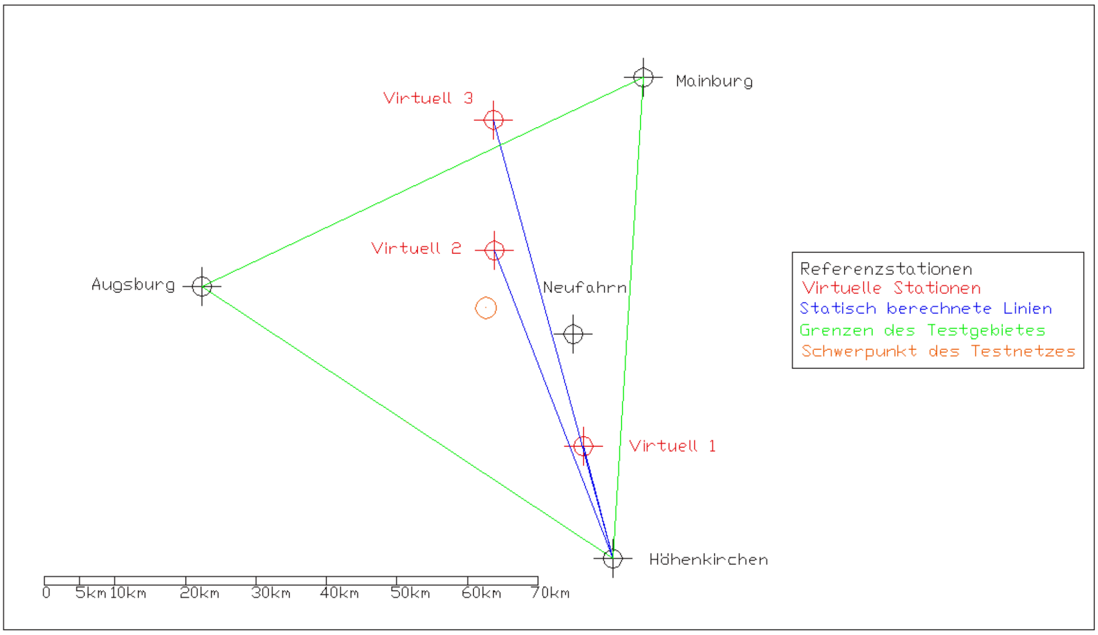


Fig. 6 Virtual reference station locations (Virtuell 1 to Virtuell 3)

3.1 Accuracy of the solution for the VRS stations

Table 1 shows the standard deviations of the processing results for the VRS stations (Virtuell 1 to Virtuell 3). The observations have been treated as kinematic observations and positions were processed independently for each measurement epoch. Figure 7 shows a classification of the standard deviations of the horizontal coordinates using a class interval of 10 cm. As expected, it can be seen from Table 1 that the standard deviation increases over larger distances from the reference station (i.e., station Höhenkirchen). On the other hand, surprisingly, the standard deviations of station Virtuell 2 and Virtuell 3 have nearly the same value, although the station Virtuell 3 is 18 km further away from the reference station Höhenkirchen than Virtuell 2. The reason for this phenomenon may be the fact that the station is located outside the triangle of the three multiple reference stations (see Figure 6) which are used to estimate the correction parameters in VRS reference station network.

Tab. 1 Standard deviations of the kinematic solution for the VRS stations Virtuell 1 to Virtuell 3

Point No.	Standard deviations in [cm]	
	horizontal coord.	Height
Virtuell 1	+/- 2.0	+/- 4.3
Virtuell 2	+/- 34.4	+/- 65.2
Virtuell 3	+/- 37.1	+/- 68.8

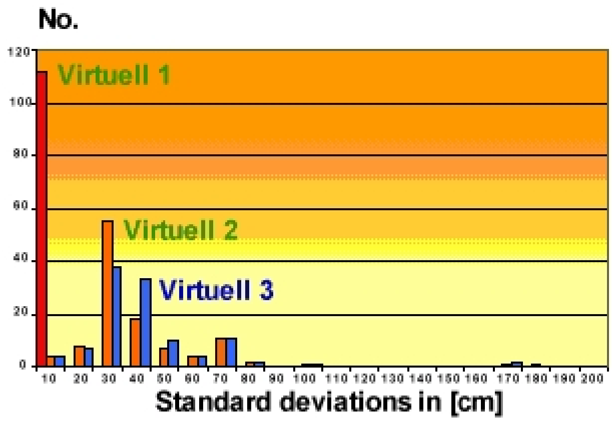


Fig. 7 Standard deviations of horizontal coordinates of the virtual reference stations (classification with intervals of 10 cm)

3.2 Overall precision of the result for the VRS stations

The overall precision of the result was obtained by comparing the solution for the VRS stations with the true values of the coordinates used to download the observation data. Figure 8 shows a classification of the deviations of the horizontal components X and Y for the stations Virtuell 2 and Virtuell 3 where again a class interval of 10 cm is used. As expected, the deviations for station Virtuell 1 are very small and are not displayed in Figure 8. The deviations follow a Gaussian distribution which proves that no systematic errors occur in the data sets.

(a)

(b)

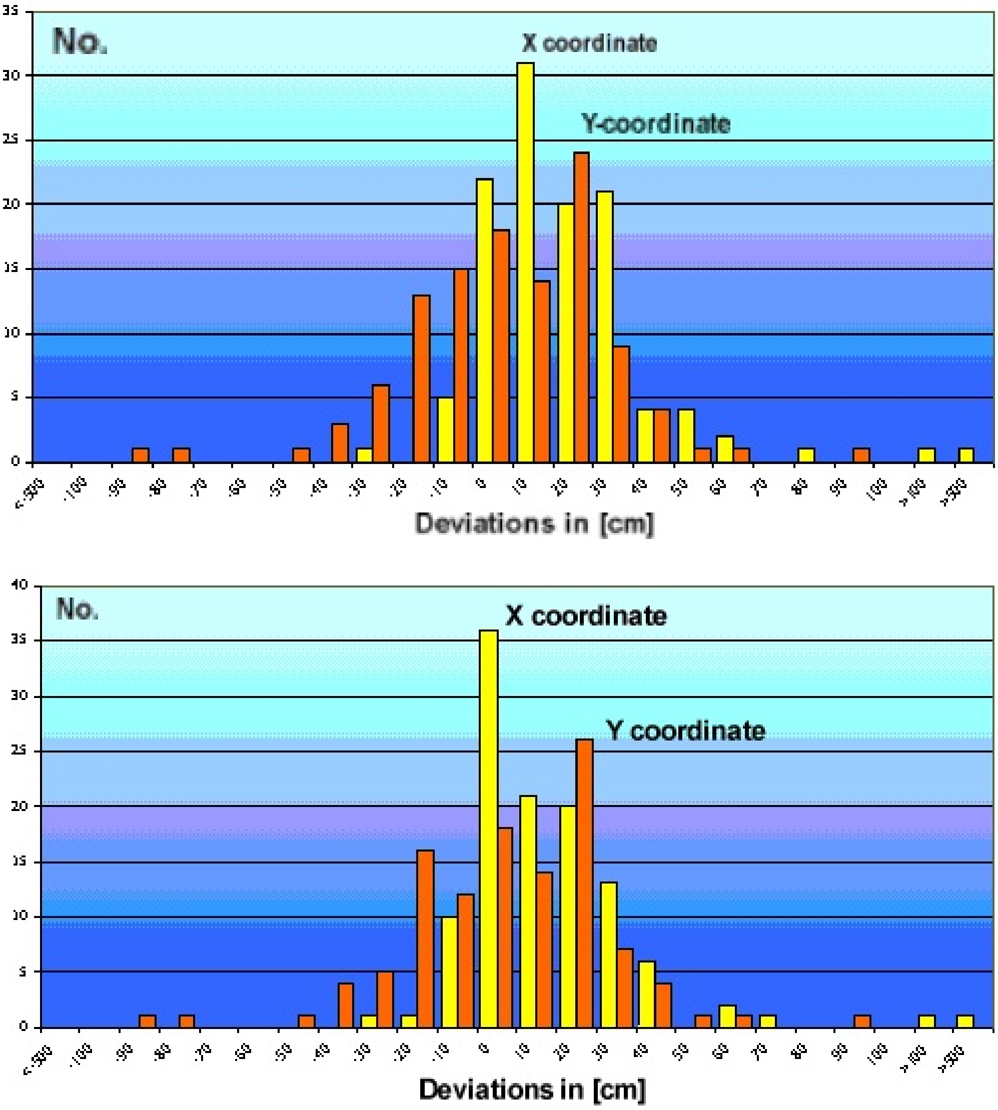


Fig. 8 Deviations of the horizontal component for the VRS stations Virtuell 2 (a) and Virtuell 3 (b) (classification with intervals of 10 cm)

The following major results can be summarized:

- The baseline accuracy of RTK GPS measurements is usually described by a constant and a distance dependent error, e.g. 5-20 mm ± 1-2 ppm. For a baseline with a length of 10 km we would therefore get an error of ± 40 mm in the worst case. In the analysed concept of the VRS network, the maximum baseline length is always very short as observations of a non-existing “virtual” reference station are sent to the rover station which is located nearby the rover. The baseline length is given by the square root of the square sum of the coordinate differences between the VRS and the rover station. In our investigation the maximum distance encountered was less than 1.05 m. Therefore the precision of the position solutions for the rover stations can be equated with the precision of the corresponding VRS station. The precision of the VRS station is given by the standard deviation of their differences to the true values.
- For a comparison of all results the standard deviations of the differences to the true values of the VRS stations are summarized in Table 2. To achieve comparable values at a probability level of 99%, the standard deviations of the measurements of 112 epochs have to be multiplied by a quantile of 1.211 which is obtained from a student probability distribution. The results show reasonable values for the standard deviations of the X and Y coordinates for distances up to 30 km from the network center point. In addition, the standard deviations are also compared to values published by the company Trimble (Terrasat) for the station Neufahrn. They have been obtained from a continuous RTK observation over a period of several hours. As can be seen from Table 2 similar results are obtained for the horizontal component, the standard deviations of the

height component, however, are much smaller. The reason for this may be the fact that a larger number of RTK results are available which are used to calculate the standard deviation as the length of the observation period was about 90 hours.

Tab. 2 Comparison of the standard deviations of four VRS stations

Distance to the network center point	Point No.	Standard deviations in [cm] of the differences at a probability level of 99%		
		X	Y	H
8km	Virtuell 2	<2.2	<2.9	<13.1
13km	Neufahrn	<2.6	<2.1	< 4.9
24km	Virtuell 1	<1.6	<0.4	<10.1
27km	Virtuell 3	<2.3	<2.9	<13.0

- The achievable precision for the horizontal component of the solutions are always within ± 5 cm, even for baseline length up to 35 km. Also for the height good results can be obtained where as usual the standard deviations are larger by a factor of 1.5 to 2 compared to the horizontal component. Therefore our tests could prove that a high precision increase can be achieved due to the employment of network station concepts.

4 CONCLUSIONS

Using the VRS station concept, similar accuracies can be achieved in distances of up to 35 km from the nearest reference station as for short baselines in the single reference station concept. Therefore the distances between the reference stations in a LADGPS network can be enlarged to 70 to 80 km which would result in large cost savings for the establishment and a maintenance of the permanent DGPS network. A further advantage of the VRS concept is that in the rover receiver standard RTK processing algorithms are employed and no modification of the receiver hardware or software is required. The communication link is performed using common mobile phone data links. Due to high density of mobile transmitters in Europe nearly a full coverage of most areas is guaranteed. For a global use of the data communication, however, a modification of the commonly used RTCM data protocol is still required. It can be expected that this problem will be solved soon. New networks in Austria, e.g. a new permanent DGPS network for Vienna which will be established by the power supply company Wienstrom, will employ the most advanced VRS station concept.

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