Analysis of the System Performance of LADGPS and WADGPS Services in Europe

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Abstract

As the achievable accuracy for single point positioning with GPS is insufficient for many applications, DGPS services have been established all over the world. They can be distinguished into so-called Local Area DGPS services (LADGPS) for small areas such as a country and Wide Area DGPS services (WADGPS) for larger areas such as a whole continent or even worldwide. All of them have in common that for the DGPS services, distinct methods for generating differential GPS corrections have been developed. However, the main disadvantage of LADGPS Services is that position accuracy of a user degrades as the reference-to-user separation increases. The spatial decorrelation of the error sources, i.e., the atmospheric propagation and satellite orbit errors, are the main causes for the degradation of position accuracy. The combination of the measurements of several reference stations can be used to model these error components separately.

Starting from the discussion of the mathematical connections and the illustration of the main error sources on pseudo range measurements, this paper will concentrate on the essential features and differences of LADGPS and WADGPS services. For that purpose, also the characteristics of existing correction data services in Europe of each of these groups are analysed. The focus of these analyses will lie on the error modelling and the estimation of correction data in connection with the achievable accuracies. In the following, possibilities for embedding the common solution strategies of WADGPS concepts in LADGPS are discussed. Finally, practical studies of one of these possibilities, the virtual reference stations concept, using data of a test network in Germany will be presented.

1 Introduction

Local DGPS services have been established in many countries all over the world for many different kind of applications. However, the main disadvantage of Local Area DGPS Systems (LADGPS) is that position accuracy of a user degrades as the reference-to-user separation increases. Therefore research efforts have been concentrated on the development of precise long-range navigation. The main reasons for investigations on so-called Wide Area DGPS Systems (WADGPS) are (after Colombo, 1998):

a) Positioning on the decimetre level for large area surveys from aircraft, vessels and vehicles is required (e.g. for airborne altimetry, laser depth sounding, remote sensing and photogrammetry, SAR interferometry). Very precise survey data are usually post processed, however, for the survey a precise real-time navigation is required.
b) Improvement of GPS navigation at all distances. Methods are developed that can be used reliably in most applications employing advanced technologies and receiver hardware.

The precise long-range DGPS positioning requires the extension of existing DGPS navigation methods. Additional sources of errors that do not cancel out entirely as on short baselines have to be estimated. Errors that do not cancel out on long baselines due to the spatial decorrelation of the error sources are (Colombo et al., 1995):

a) Uncertainties in the GPS satellite orbit (i.e., 6 orbit parameters per satellite),
b) Uncertainties in the position of reference stations (i.e., 3 states per station) and

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c) Uncertainties in the correction of the ionospheric and tropospheric refraction (i.e. at least 1 state per station).

The main causes for the degradation of position accuracy are the atmospheric propagation and satellite orbit errors. The combination of the measurements of several reference stations can be used to model these error components separately. To achieve position accuracy better than 5 m (at 95 % probability level) the satellite orbits have to be determined with an accuracy of the order of 10 m using pseudorange data from at least three different reference stations and atmospheric models need to be estimated. For real-time positioning the orbit and atmospheric models need to be predicted ahead (see e.g. Ashkenazi et al., 1997). However, relative clock errors and ionospheric refraction can be eliminated by double-differencing the ionospheric free linear combination of L1 and L2. Therefore dual frequency equipment is necessary (Colombo, 1998).

2 LADGPS and WADGPS services

2.1 LADGPS Services in Austria

LADGPS services are designed to provide DGPS corrections in a local area. Apart from corrections for pseudorange measurements, also OTF differential data messages have been included in the RTCM format which is usually employed as standardized data transfer format (see also Retscher, 1999). To give examples of LADGPS services, firstly a DGPS reference network covering entire Austria and secondly a network in a federal state of Austria are described briefly.

Figure 1 shows the network of reference stations covering Austria by summer 2000. The data are broadcasted in RTCM SC-104 format using the DARC (Data Radio Channel) data channel of the Austrian radio broadcasting network of the ORF (Österreichischer Rundfunk: Austrian radio broadcasting network). Three different services are provided (see Table 1). In a distance of up to 20km from the GPS reference stations a positioning accuracy of better than 10cm can be achieved using the so-called “Prämium” service; in a radius of 70km from the reference station a positioning accuracy of better than 1m ("Profi" service). For larger distances the accuracy is within 10m in the "Standard" service (Ahrer and Auzinger, 1999).

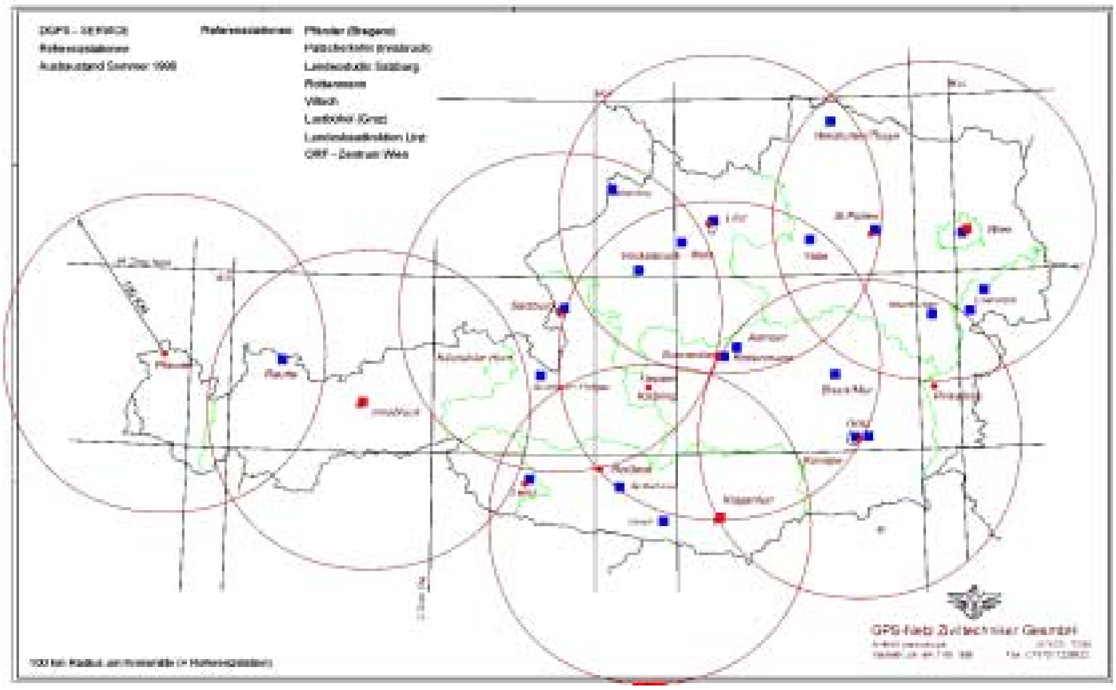

Figure 1: DGPS network in Austria (Summer 2000) (after DARC-dgps, 2000)

Table 1: Service types of the Austrian DGPS service
(Specifications from dgps Datenverbreitungsgesellschaft M.B.H., Austria)

1. STANDARD (< 10 m)	2. PROFI (< 1 m)	3. PRÄMIUM (< 0,1 m)
Guaranteed position accuracy of 10 m	Guaranteed position accuracy of 1 m using modern DGPS beacon receivers	RTK solution with dual frequency GPS receivers
Applications: Vehicle navigation, dispatch systems, GIS data acquistion, agricultural surveying, recreation, etc.	***Applications:*** Used by professionals for e.g. GIS data acquistion, machine guidance, intelligent vehicle navigation systems, etc.	***Applications:*** Used by professionals in surveying, land mangement and engineering surveying

In the south-eastern part of Austria a network with four reference stations has been established by the local power supply company BEWAG (Burgenländische Elektrizitätswerke AG). The network concept of SATVB (Satellitenvermessung Burgenland) was developed in cooperation with the Department of Theoretical Geodesy of the Vienna University of Technology, Austria and the German company Geo++ GmbH (Figure 2). The aims which led to the establishment of the SATVB reference station network can be summarized as follows (Titz and Weber, 1998):

a) Precise real-time measurement capabilities with homogeneous accuracy at the 1 to 3 cm-level over the whole area of Burgenland,
b) Support of post processing applications by providing all users with RINEX data of the reference stations,
c) Transmission of code DGPS corrections for low precision surveys, GIS applications and navigation,
d) Full integration of the BEWAG geographic information system,
e) Serving as a research platform for the use of new technologies (GPS/GLONASS combination, Galileo, …) and
f) Serving as fundamental component in modern academic education.

Because of the high precision requirements for real-time positioning, at the moment the reference stations have been equipped with dual frequency combined GPS/GLONASS receivers and are networked to the central control station in Eisenstadt.

Figure 2 shows also the positioning accuracies which can be achieved due to the networked solution. The corrections are transmitted in RTCM data format in the 4m-band with a power of 6W. For total coverage only four radio transmitters placed at topographic optimal regions are used. With the transmission rate of 9600 bit/s, GPS and GLONASS code and phase data for all satellites in view can be transferred with an update rate of 1second.

2.2 European WADGPS Networks

Commercial WADGPS services providing full coverage of Europe are available from Fugro OmniStar and Thales (former Racal) LandStar (see Retscher and Moser, 2001). As an example, Figure

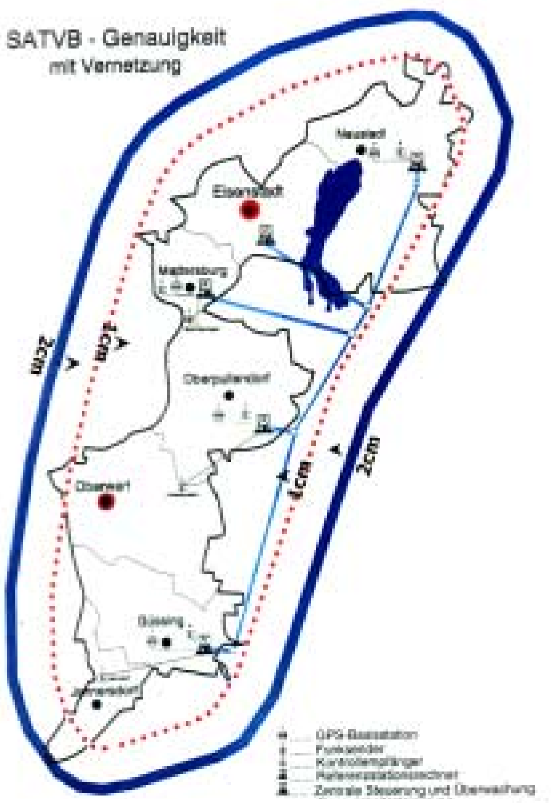

Figure 2: Networked DGPS reference station network SATVB in Burgenland, Austria (after Titz and Weber, 1998)

3 shows the worldwide LandStar-DGPS coverage map. The correction data is broadcasted via geostationary satellites of the INMARSAT satellite communication network.

2.3 Virtual Reference Station Networks

Currently the most advanced approach for increased spatial separation of permanent stations and error modelling is the so-called virtual reference station (VRS) network concept. The development of this concept was driven by the development of WADGPS services and the need to obtain higher position accuracy for larger distances. In a LADGPS service, the concept was firstly introduced in a part of the German reference station network SAPOS (Landau, 2000; Spectra Precision/Terrasat, 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 required initialization time for determination of the carrier phase ambiguities.

Figure 3: LandStar-DGPS network and coverage map (after Racal, 2000)

To create the virtual reference station data for a certain RTK GPS rover station, the user has to send its approximate location resulting from code single point positioning to the network control center. Therefore a bi-directional communication link between the user and the control center is required. The communication is usually performed using cellular phones. The observations for the given location are estimated in the control center using real-time correction models (see section 3) and then transferred in RTCM format to the rover station. On the rover side, standard RTK GPS algorithms are employed to obtain the position fix. The performance and accuracy achievements of the virtual reference station concept were analysed in a study at our department and are presented in section 4.

3 Real-Time Correction Models for DGPS

The current trend of reducing the number of reference stations in LADGPS services and to increase the spatial separation between those requires the availability of real-time modelling of the main error sources. The errors which do not cancel out any longer in differential GPS positioning (e.g. using single, double or triple differenced data) over larger distances now must be estimated or reduced using advanced filter techniques to determine the current position of the rover receiver accurately. Because it is a more complex problem, the reliability and accuracy of long-range navigation is not as good as for similar applications of GPS navigation over distances of a few tens of kilometres. One source of error that cannot be differenced away over long baselines is ionospheric refraction, limiting the ability to deal with carrier phase ambiguities even when using more expensive dual frequency receivers. Another limiting factor for the positioning accuracy is the accuracy of the satellite orbit. In the following, both error sources will be discussed more in detail.

3.1 Satellite Orbits

For long-range DGPS the accuracy of the broadcast ephemeries is not enough to achieve position accuracies better than 5m (95%) as the accuracy of the broadcast ephemeries is only in the order of ±20m. Therefore precise ephemeries have to be used. Since 1994 precise satellite orbits are available from the global International GPS Service for Geodynamics IGS[1]. The IGS orbits are determined from a global network of 80 stations all over the world with measurement sampling rates of 30 sec over 24 hours. The orbits are calculated in seven different control stations. A final solution is issued two weeks later from the master control station and can be obtained from IGS. The final ephemeries for post processing have an accuracy of about ±5cm. For real-time applications also predicted ephemeries with an accuracy in the order of ±50cm can be obtained from IGS. Most RTK GPS receivers now available on the market, however, do not support the use of these IGS orbits in real-time.

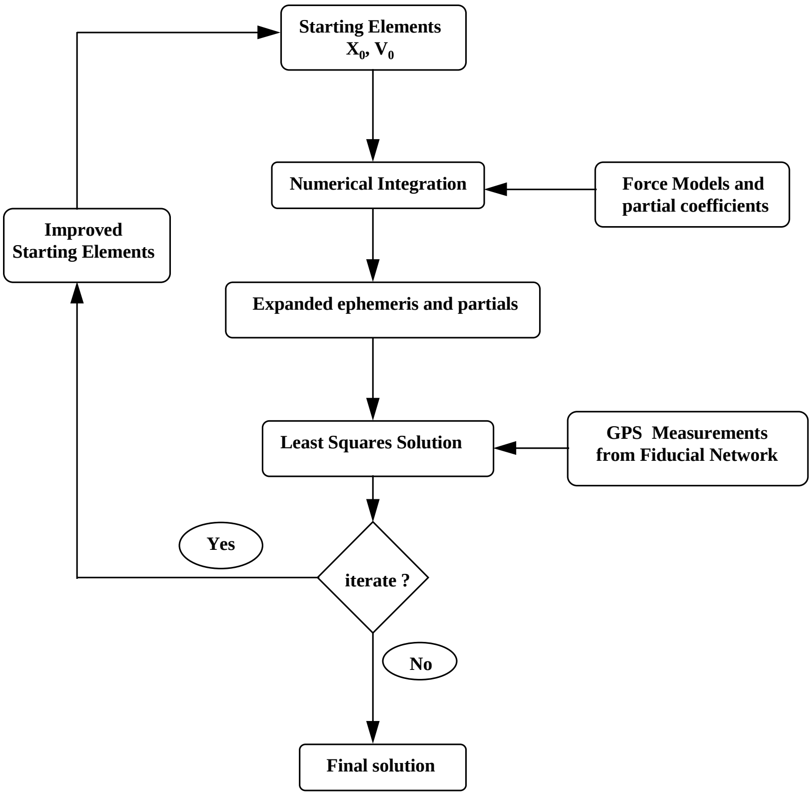

Figure 4: Dynamic orbit determination flow diagram

For real-time applications it is therefore necessary that the satellite orbits are predicted ahead using pseudorange observations of a multiple reference station network. Mostly an accuracy in the order of 10m or better for the satellite orbit parameters is required (see Ashkenazi et al., 1997). The algorithm incorporates a complete dynamic orbit determination by using pseudorange data from a fiducial tracking network. A frequently updated satellite state vector (position and velocity)

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[1] IGS Website: http://igscb.jpl.nasa.gov/

resulting from a Kalman filter solution is transmitted to the user at regular intervals to replace the broadcast ephemeries totally. The processing flow of the dynamic orbit determination is illustrated in Figure 4.

The dynamic orbit determination involves the precise definition of the force model consisting of all the forces acting on a satellite. The resulting acceleration is integrated once to give the velocity and twice to give the position of the satellite as a function of time. The initial starting values of the orbit (position and velocity) need not to be very accurate as the position will be improved by introducing observations from the fiducial network data in a least squares process. Depending on the accuracy of the starting values, an iterative procedure can be involved to further improve the solution.

In a European test network consisting of three or four multiple reference stations (i.e., Hammerfest in Norway, Cadiz in Spain, Cyprus and Aberdeen) the orbit prediction algorithm was tested (see Chao, 1997; Retscher and Chao, 2000). The main results of the test are summarized in Table 2. Using dual frequency raw pseudorange data and a data span of 72 hours in the orbit determination process a satellite orbital accuracy in the order of 10 m r.m.s. with three stations and 5 m r.m.s. with four stations was achieved over baselines from 2,000 to 3,500km. The IGS precise ephemeries were taken as the true ephemeries to evaluate the accuracy of the recovered satellite orbits, by comparing the discrete satellite positions every 5 minutes over a 24 hours period. The test has proven that the satellite ephemeris can be estimated very economically using the dynamic orbit determination approach.

Table 2: Orbit recovery obtained from dual frequency pseudorange observations (Retscher and Chao, 2000)

r.m.s. Error (m)	**3 stations**	**4 stations**
Mean	10.0	5.1
Best	2.0	1.6
Worst	18.6	9.0

3.2 Ionospheric Models

The main error source for long-range GPS is caused by the propagation error of the signal in the ionosphere. As the theory of ionospheric refraction is well known, only some important points will be summarized in the following.

The ionosphere is made up of several layers of ionized gas enveloping the earth, produced mainly by the ultra-violet radiation of the sun acting on the upper atmosphere. The mean height of these layers is about 400km and they are irregular in density. The GPS signals are dispersed by the ionosphere causing a group delay to pseudorange and a phase advance to carrier phase measurements. As a result, ionospheric refraction affects pseudorange and phase measurements on the same extent, but with opposite signs. Phase measurements of the distance are always to short while pseudorange measurements are always to long. In addition, as the ionosphere is a dispersive medium, the ionospheric refraction also varies across the radio-wave spectrum in dependence of the frequency of the carrier phase signal. Therefore it is not the same for the carrier phase signals L1 and L2. Proper modeling of ionospheric effects is very important for high accuracy positioning over long baselines for which the effects are significant and do not cancel out using differencing techniques. Due to ionospheric effects, the detection capability of cycle slips and the success of the carrier phase ambiguity resolution is also reduced.

To some extent, the ionospheric refraction is predictable in time and can be interpolated in space. One strategy would be to use of observations from all receivers available within a given area to predict what the ionospheric refraction at any given time and location might be. Then this prediction could be used to correct the phase measurements making them “ionospheric free”. For the estimation of the ionospheric delay then the total electron content (TEC) of the free electrons in the ionosphere along the signal path is necessary. Several different models are available to describe the ionospheric refraction (see e.g. Hamoui, 1996; Kleusberg, 1998). In general, a so-called single layer model is applied where the vertical electron content (VTEC) is estimated from a layer with high electron density (so-called ionospheric layer) in a height of 350 to 450 km above ground (Klobuchar, 1986).

The ionospheric effect normally cancels out at the sub-centimetre level when forming the ionospheric free linear combination of the carrier phases L1 and L2 (usually called L3). Together with the ambiguities another unknown value, i.e., the ion-free bias, is then estimated in the processing step. Over long baselines many observing epochs are needed to estimate the ion-free biases with enough accuracy to achieve sub-decimetre positioning. The estimation usually requires post processing and is limited for real-time applications. The Kalman filter can be applied to estimate the variation of the ionospheric refraction in real-time. Thereby the TEC distribution has to be estimated from the measurements of multiple reference stations and its variation in time and space is predicted using the Kalman filter. The estimation of the TEC model is based on a regular grid spaced coordinate frame. The state vector includes the ionospheric delay of the reference stations and their variation in time. From the original dual frequency observations the geometry free linear combination L4 is used for the update step in the filter process. This approach can be either used for code pseudorange measurements, carrier phase measurements or combined code and phase measurements (Kutterer et al., 1998; Leinen, 1997).

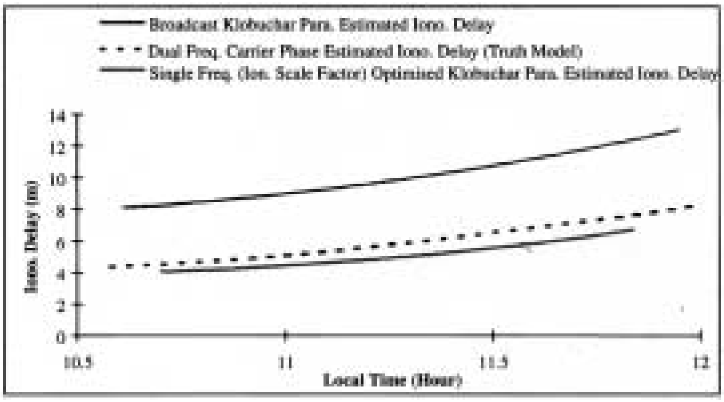

Figure 5: Comparison of ionospheric corrections estimated from different models (after Chao et al., 1998)

An improvement of this approach can be achieved by introducing a scale factor for the ionospheric delay of each reference station. Then the model error caused by the difference between the true and the estimated ionospheric delay can be described by scale factors which are estimated as additional unknowns in the least squares adjustment of the dynamic orbit determination. Afterwards the corrected ionospeheric delays of all multiple reference station will be used in the Klobuchar model to obtain estimates for the user sites. Figure 5 shows the achievable improvements using the scale factors compared to a standard Klobuchar model. Using the standard model the differences to the true ionospheric delays were in the range of 4m, with the improved approach less than 0.8m (Chao et al., 1998). An additional advantage is that this approach can also be used if on the user site only single frequency GPS receivers are employed.

4 Performance and Accuracy Test in Virtual Reference Station Network Concept

The concept of virtual reference station networks was briefly described in section 2.3. The main results of a study on the performance and accuracy achievements of the virtual reference station concept will be summarized in the following (Retscher and Moser, 2001). The VRS test network is shown in Figure 6. The observation data for 3 stations (Virtuell 1 to Virtuell 3) in the VRS network was downloaded from the website of the company Terrasat[2]. In total, 112 measurement epochs have been processed. 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.

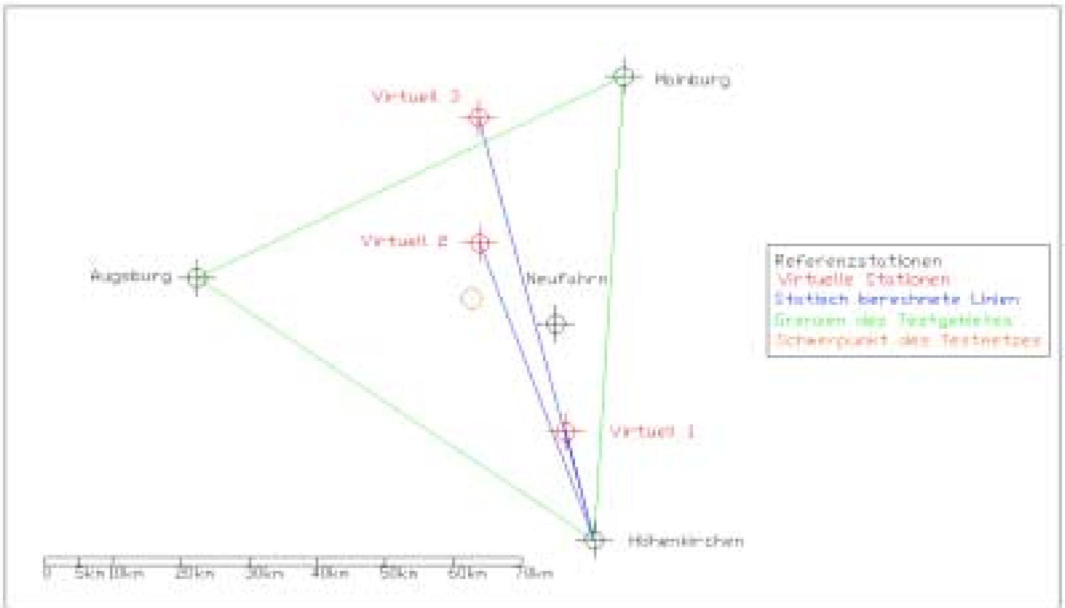

Figure 6: Virtual reference station (VRS) test network

4.1 Accuracy of the solution for the VRS stations

Table 3 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. As expected, it can be seen from Table 3 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 18km farer 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 3 multiple reference stations (see Figure 6) which are used to estimate the correction parameters in VRS reference station network.

Table 3: Standard deviations of the kinematic solution for the VRS stations Virtuell 1 to Virtuell 3

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

4.2 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 generate the observation data. Figure 7 shows a classification of the deviations of the horizontal components X and Y for the stations Virtuell 2 and Virtuell 3 using a class interval of 10cm. As expected, the deviations for station Virtuell 1 are very small and are not displayed in Figure 7. The deviations follow a Gaussian distribution which proves that no systematic errors occur in the data sets.

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

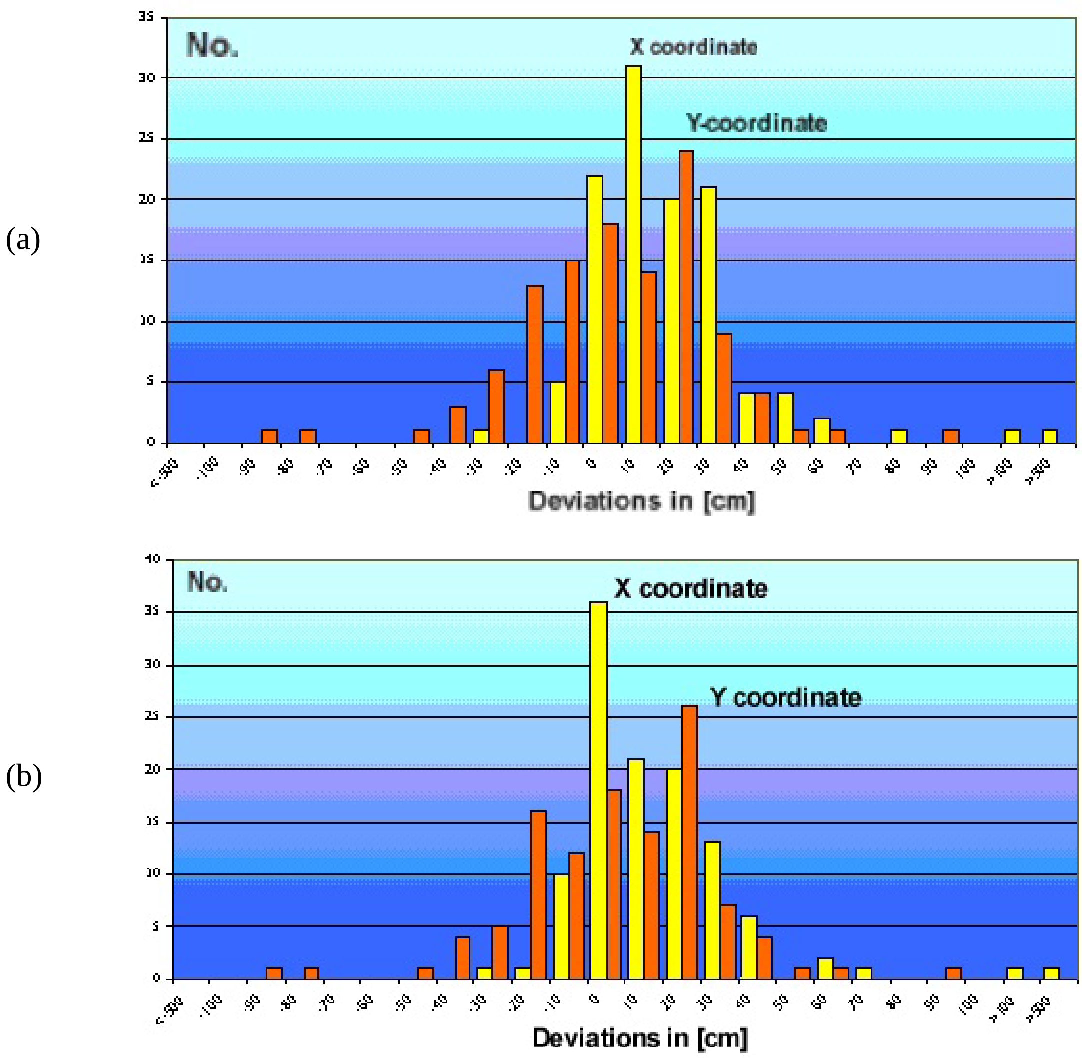

Figure 7: Deviations of the horizontal component for the VRS stations Virtuell 2 and Virtuell 3 (classification with intervals of 10 cm)

5 Conclusions

Finally the following results of our study can be summarized:

a) The baseline accuracy of RTK GPS measurements is usually described by a constant and a distance dependent error, e.g. 5-20mm ±1-2 ppm. For a baseline with a length of 10 km we would therefore get an error of ±40mm 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.

b) For a comparison of all results the standard deviations of the differences to the true values of VRS stations are summarized in Table 4. 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. In addition, the standard deviations are also compared to values published by the company Spectra Precision/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 4 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 observation period was about 90 hours.

Table 4: Comparison of the standard deviations of 4 VRS stations

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

c) The achievable precision for the horizontal component of the solutions are always within ±5cm, even for baseline length up to 35km. 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. Using the VRS station concept, similar accuracies can be achieved in distances of up to 30 to 35km from the next reference station. Therefore the distances between the reference stations in a network can be enlarged to 70 to 80km which would result in large cost savings for establishment and a maintenance of a permanent LADGPS network. A further advantage thereby 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 and Asia nearly a full coverage of most areas is guaranteed. For a global us of the data communication, however, still a modification of the commonly used RTCM data protocol is required. It can be expected that this problem will be solved soon. New networks in Austria, e.g. a new permanent GPS 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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