Reducing Distance Dependent Errors for Real−Time Precise DGPS Applications by Establishing Reference Station Networks

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BIOGRAPHY

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ABSTRACT

Distance dependent errors limit the accuracy of high precision real−time DPGS applications to 1 to 10 ppm. The objective of this investigation is to improve the reliability and speed of On−The−Way (OTW) ambiguity resolution and to enhance the accuracy of the GPS solution by using data from multiple reference stations.

Extensive test measurements carried out in the northern part of Germany using the real−time processing software package GNRT with only one reference station clearly shows distant dependent errors of about 1 ppm and more. The postprocessing simulation of a reference station network reduces the effects to generally less than 1 cm without any distance dependencies.

1. Introduction

Precise real−time DGPS positioning currently becomes important in many surveying and navigation applications. The implementation of On−The−Way (OTW) ambiguity search algorithms in real−time software packages provides centimeter accuracy over distances of up to a few tens of kilometers between a reference station and mobile users. Distance dependent errors like atmospheric refraction and orbit errors limit the accuracy to 1 to 10 ppm.

Experiences with postprocessing results from multistation networks show that the reliability and speed of OTW ambiguity fixing, and the accuracy of the GPS solution is considerably improved by using data from more than one reference station. It is hence likely that the establishment of reference station networks should also reduce the distance dependent errors in real−time.

In the following a concept is elaborated which uses carrier phase information of several reference stations in order to improve the position solution in the field in real−time. The fundamental idea is to process carrier phase information from several local area reference stations simultaneously with a multistation adjustmentsoftware package, and to derive parameters of an appropriate error model which describes the distance dependent error situation in the working area. The model parameters are then disseminated to the users in real−time.

To this respect a project has been designed and test measurements were carried out in the northern part of Germany. In order to study the distance dependent effects present in real−time measurements the coordinates of nearly 25 stations with distances of up to 25 kilometers from a permanently operating reference station were determined using the receiver independent, real−time precise DGPS software package GNRT and the OTW−module GNRT−*K (Wübbena, Seeber 1995)*. Together with three additional temporarily operating receivers the reference network consists of four stations. Because of missing data links between the reference stations, the network solutions for this investigation have been simulated in post−processing. The postprocessing software uses the same mathematical models like the real−time software; hence the results should be comparable to a real−time approach.

In the sequel the basic concept of the approach, the test measurements, and the preliminary results are presented. The described work is a cooperative project between a GPS technology and software company, a University research group, and a State surveying authority

2. Concept and Software Design

2.1 Relevant Error Components

With standard DGPS and PDGPS most of the relevant error sources in positioning are covered. For DGPS with code observations no significant improvement seems achievable, since the limiting error source (besides of the ionosphere over longer distances) is the measurement noise of code observations. For Precise Differential (PDGPS) or real−time kinematic applications however, where the noise theoretically is lower than 1 millimeter, only some parts of the error sources are reduced. Among them are clock errors and the common part of atmosperic refraction and orbit errors. However, there are some significant remaining errors that make the quality of a DGPS result very dependent on the distance to the reference station. The distance dependent errors are the ionospheric and troposheric refraction and orbit errors, which limit the accuracy to 1 to 10 ppm.

There are some other errors that cannot be caught by the networking approach discussed in this paper. The first effect to be mentioned is the antenna phase center offset, which is at the millimeter level. The effect is not constant for every coordinate component, but it shows azimuth and elevation dependent parts. Another effect is multipath and imaging in the environment of the reference station antenna. Both effects are local and refer to a single reference station; they can be calibrated and corrected by special techniques *(Wübbena et al. 1996)*. The influence of tropospheric errors depends highly on the actual correlation between different stations.

For postprocessing applications, the common approach to reduce the effects of orbit errors is to introduce precise ephemeris, which are computed several days after the observation period and are available from services like the International Geodynamic Service (IGS) or from CODE. For real−time applications, however, precise ephemeris are currently not available and cannot be applied, because of the delay in computation, the need for a high bandwidth data link to the mobile user and the lack of adequate algorithms at the mobile users GPS equipment.

A similar problem exists for the ionospheric errors. This mainly concerns single frequency receivers, but also has some impact on dual frequency receivers. For real−time ionospheric corrections the ionosphere must be predicted, described in a parametric model, transmitted to the mobile user, and be introduced into the algorithms of the RTK solution. This is currently not practicable in real−time.

2.2 The Reference Station Software Package Geo++®−GNREF

For real−time practice Geo++ has developed the reference station software Geo++®−GNREF. GNREF is receiver independent, which means it works with any GPS (or GLONASS) sensor that provides raw measurement data for code and carrier phase. GNREF computes corrections for code and carrier and transmits them as RTCM message over radio link, GSM modem or any other communication line.

Standard DGPS corrections are transmitted in the format described in the 2.0 version of RTCM−SC104, PDGPS corrections are transmitted as message types 20 and 21 of the 2.1 version. The types 18 and 19 for raw data measurements have not been chosen because they have some severe disadvantages when compared with types 20/21. RTCM 2.1 allows both, type 18/19 and type 20/21, they both contain sufficient information for PDGPS applications.

The first advantage of using corrections instead of raw measurements is, corrections are less receiver dependent and therefore more general. This simplifies the use of heterogeneous receiver equipment in the participating reference stations and/or with the mobile user. Additionally it makes it possible to apply corrections for local errors like antenna phase center offsets, L1/L2 antenna offsets, or multipath errors. Corrections may also be derived from several receivers, which allows network concepts.

The second and main advantage is the required bandwidth to transmit the RTCM data from the reference station to the mobile user. Although both types have the same nominal data width, the types 20/21 corrections contain more redundant data, which yields to better compressibility. Geo++ developed a highly sophisticated data reduction and compression algorithm as an extension to the RTCM standard, called RTCM++. The compressed type 20/21 information is stored in a type 59 message, so RTCM++ is fully compatible with the RTCM format. With RTCM++ the entire PDGPS information for an all−in−view data set (12 satellites) fits into just 2400 bits. This allows, even at slow communication links (2400 bps), the transmission of one complete data set every second, which is sufficient for most, even high dynamical real−time kinematic applications. In contrast to this, types 18/19 or uncompressed 20/21 require a 9600 bps data link for the same task. At the mobile site the RTCM++ message may be decompressed into RTCM type 20/21 messages, either in the mobile processing software or in a separate converter box. For the mobile GPS equipment this is a fully transparent RTCM−2.1 signal.

2.3 Real−Time Concept of Geo++®−GNNET

GNNET is the real−time multi reference station adjustment program. It performs a real−time multiple station adjustment of several reference stations including the carrier phase ambiguity resolution. While the coordinates of the reference stations are held fixed, the DGPS corrections are to be estimated. Introducing a geometric model for the corrections, using the horizontal coordinates as parameters, the coefficients of the model may be estimated in an adjustment process. For a three station network, the model could be a simple inclined plane, for more stations the model may be a polynomial function of higher degree. GNNET chooses the optimal model type and polynomial degree either automatically or with respect to given constraints.

Both, the model type and the estimated coefficients describe the dependency of the (P)DGPS corrections on their geographical location. We call them *network coefficients*, because they are derived from the network adjustment of the reference stations. With the network coefficients it is possible to interpolate the (P)DGPS corrections for given location inside the area covered by the reference station network. To be compatible with RTCM defined corrections, the correction portion that comes from the network adjustment has to be treated separately from the corrections that are normally generated from a single reference station. This leads to a different set of network coefficients for every selected reference station. This fact, however, does not provide any inconvenience because every set provides the same result.

The network coefficients have to be enclosed in the RTCM message. Since there is no standardized message type available for the network coefficients in RTCM 2.1 nor in the upcoming 2.2, we decided to include the network coefficients into a proprietary type 59 message.

The network coefficients have to be transmitted to the mobile user. Generally the mobile user knows his approximate location (from GPS or even from a map) and can compute the improved (P)DGPS corrections for his actual position. These improved corrections may be reassembled into RTCM type 20/21 messages. For a GPS receiver equipment with RTCM−2.1 capability these corrections look like normal RTCM corrections, with the difference that they behave like from a nearby reference station. They hence give much better results than distant reference station without any networking. This positively affects the accuracy and also reduces the required time to fix the ambiguities at the mobile station. Even with single frequency receivers a reasonable accuracy level can be achieved, also over larger distances.

2.4 Data Flow

The first step in processing the network solution with GNNET is to collect the data of several reference stations at a processing center. This requires on−line connections from all participating reference stations.

In a centralized concept of a DGPS provider all GNNET computations may be performed at one central host computer. The network coefficients have then to be transmitted back to the individual reference stations where they are added to the individual RTCM message.

In a decentralized concept each reference station may run GNNET as an additional process, restricted to the data of nearby reference stations.

Existing radio broadcast links of sufficient range may be used for this purpose. Alternative concepts include leased line direct modem connections or wide area computer networks like the Internet. Only a limited bandwidth of 2400 bps is required if the RTCM++

format is used because it contains all necessary information.

2.5 Dynamics of network parameters

While the PDGPS corrections of a reference station have to be updated at least every second to provide centimeter accuracy also for high dynamic applications, the network coefficients may be expected to be of much smaller dynamics, as they contain mainly the differences of the effect of orbit errors and atmospheric refraction with respect to different locations.

From this reason it should be sufficient to recompute and transmit the actual network coefficients every 30 to 60 seconds. Or, a complete set of network coefficients may be decomposed into 30 or 60 subsets which are added to every RTCM message. Only a few bits per second are required for the complete set of network coefficients, and the full "network accuracy" is available after collecting 30 or 60 seconds of RTCM data.

3. Test Measurements in the Reference Station Network Hamburg

In order to prove the efficiency of the above described concept extensive measurements were carried out in the northern part of Germany. In a cooperation between the »Stadtvermessungsamt Hamburg« and the Institut für Erdmessung GPS nearly 25 points in Hamburg were observed. A central reference station (VAHH, see Fig. 1) broadcasts permanently correction data for real time applications. The station is part of the SAPOS system (»Satellitenpositionierungsdienst der deutschen Landesvermessung«), the Satellite Positioning Service of the Surveying and Mapping Authorities of the Federal Republic of Germany. The reference station software GNREF generates the correction data and provides them to the real−time users by radio link (VHF, 2−m band) or cellular phone. The observations are also stored in the RINEX−format.

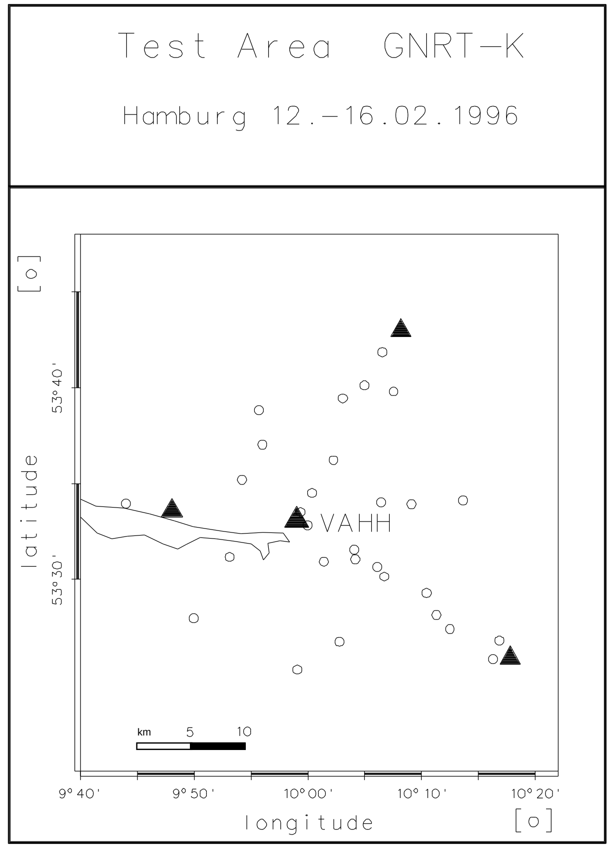

Fig. 1: Test area for the real−time measurements with GNRT, Hamburg 12.−16.02.1996

Three additional GPS receiver collected raw measurements on temporarily established reference stations. The distances between the central reference station (VAHH) and the mobile receiver range from 500 m to 23 km (see Fig 1).

The mobile station worked with the DGPS program system GNRT and the OTW−module GNRT−K. Correction data were provided from the reference station via radio link. For the computations a PC486DX with the operating system OS/2 was used.

All reference and mobile stations were equipped with dual frequency Ashtech Z12 receiver. The data sampling rate was 1 sec.

The following table gives a short overview of the hard− and software:

1 permanent reference station:

- Ashtech Z12 receiver, geodetic L1/L2−antenna
- transmitting radio data link (VHF, 2−m−band)
- PC486DX with the operating system OS/2
- reference station software GNREF
- RINEX data sampling

3 temporary reference stations

- Ashtech Z12 receiver, kinematic L1/L2−antenna

- raw measurement data sampling

1 mobile station

- Ashtech Z12 receiver, geodetic L1/L2−antenna
- receiving radio data link (2−m−band)
- PC486DX with the operating system OS/2
- real−time kinematic software GNRT with module GNRT−K
- RINEX data sampling.

3.1 Real−time processing

Each mobile point was observed in real−time as follows:

- start of the software package GNRT
- 1. reset of the carrier phase ambiguities
- measuring the time to fix the ambiguities (TTFA)
- storing the coordinates for each epoch with fixed ambiguities (about five minutes)
- 2. reset of the ambiguities
- ...

The resets of the carrier phase ambiguities were carried out four times on average. Fig. 2 shows the necessary »time to fix ambiguities« (TTFA) for each experiment. The TTFA value depends mostly on the number of observed satellites and the quality of the data link between reference and mobile station. The variations can be explained by the fact, that the observations and the quality of the data link were disturbed by buildings and traffic, especially in the center of Hamburg.

The TTFA values range from only a few seconds up to 5 and 10 minutes. A calculated mathematical regression in Fig. 2 clearly shows the expected distance dependent behavior. The TTFA numbers show a rise of about 100 seconds / 10 km.

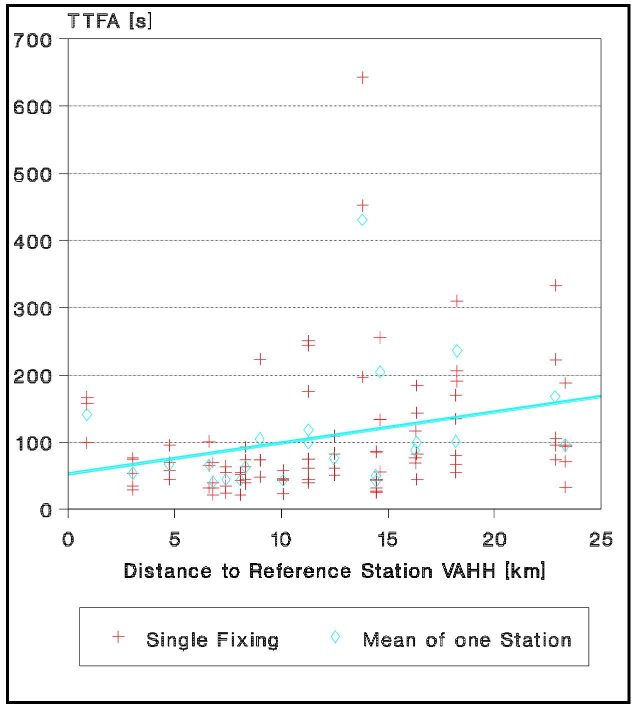

Fig. 2: TTFA value of each fixing, real−time experiment with GNRT, Hamburg 12.−16.02.1996

The mean value of a 5 minute data set gives the position for one reset, the mean value of four resets was used to calculate the final GNRT−K position. Fig. 3 shows the standard deviation for each GNRT−K position in the components latitude, longitude and height as well as for the 3D−position. The accuracy is generally better than 4 cm and mostly better than 2 cm. The calculated regression shows an increase in the 3D−standard deviation of about 1 cm + 0,6 ppm. The height component is less accurate than the horizontal components. Because of geometric conditions in the northern part of Germany the GPS derived latitude is less accurate than the longitude component.

These first results show the distance dependent effects based on the real−time positions. Please note, that the regression results only show a tendency of the effects and should not yet be taken as a valid rule of thumb.

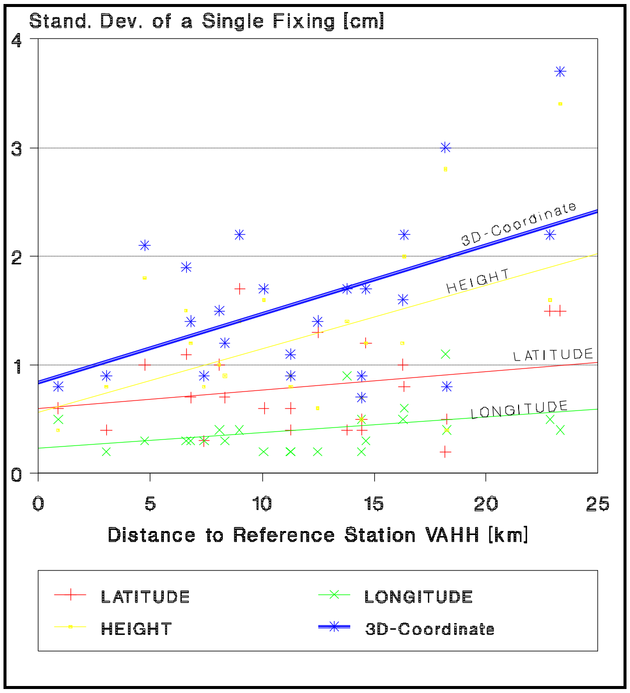

Fig. 3: Standard deviation of each fixing, real−time experiment with GNRT, Hamburg 12.−16.02.1996

3.2 Postprocessing

For further investigations, a reference solution for each field station was calculated with the observations of all four reference stations using the program system GEONAP in postprocessing. Because of the long observation periods, the multipath effects can be neglected.

The algorithms in GEONAP are very similar to those, which are implemented in the GNRT software. From this reason it is possible to consider the postprocessing results as a simulation of the the real−time measurements.

Remaining differences between the real−time solution with GNRT and the postprocessing simulation with GEONAP (see Fig. 4) come from a different data rate in the postprocessing solution (10 sec) and occuring problems with the data link during the real−time measurements. Nevertheless, both solutions clearly show the distance dependency in the accuracy of the 3D−coordinates, with an increase to 1,4 ppm in the postprocessing simulation. The deviations in Fig. 4 are calculated between the reference solution and the real−time GNRT solution (Mean 1) and between the reference solution and the simulated real−time GEONAP solution (Mean 2) without using the network concept.

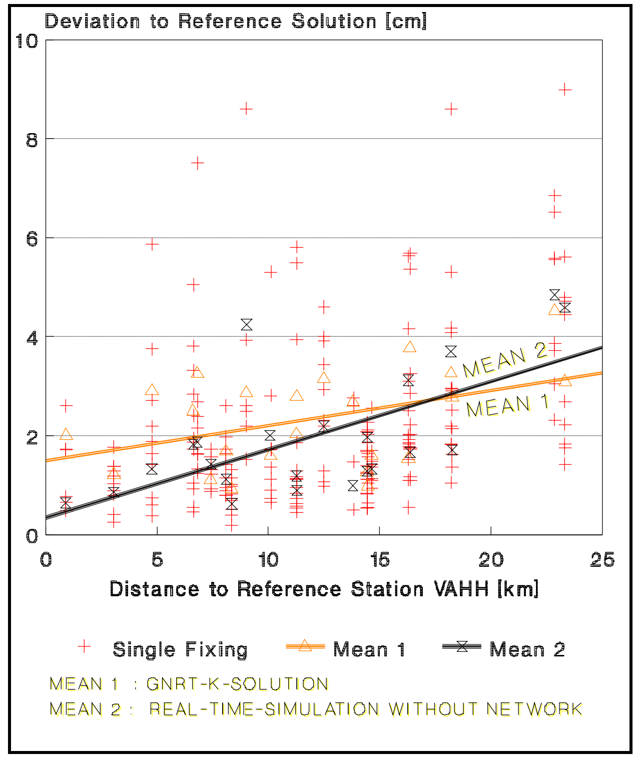

Fig. 4: Deviations of the GNRT real−time solution and the GEONAP solution (without network concept) from the reference solution, Hamburg 12.−16.02.1996

In a further step the GEONAP solution simulates the concept of the reference station network, as outlined above, by estimating additional orbit parameters for each satellite with a drift model. As a result the distance dependency disappears (see Fig. 5). The difference between the reference solution and the simulated network is generally smaller than 2 cm.

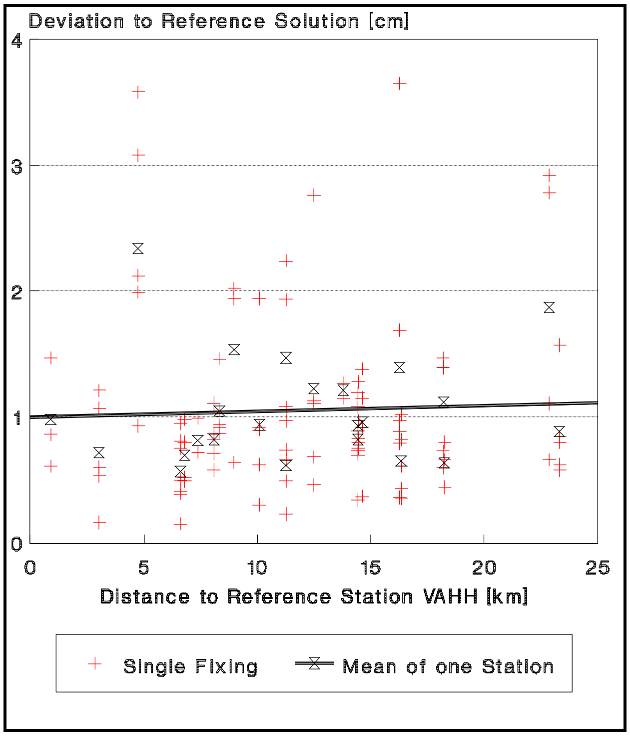

Fig. 5: Difference between the reference solution and the GEONAP solution with the simulation of the network concept, Hamburg 12.−16.02.1996

The difference between both approaches is demonstrated in Fig. 6. Again the mean values of the individual 3D−fixings are compared with the reference solution. The distance dependency is clearly present in the approach without a network concept, whereas the mean positions of the simulated network solution do not show any distance dependency, and differ less than 1 cm from the reference position. The mean discrepancy is only 0.6 cm.

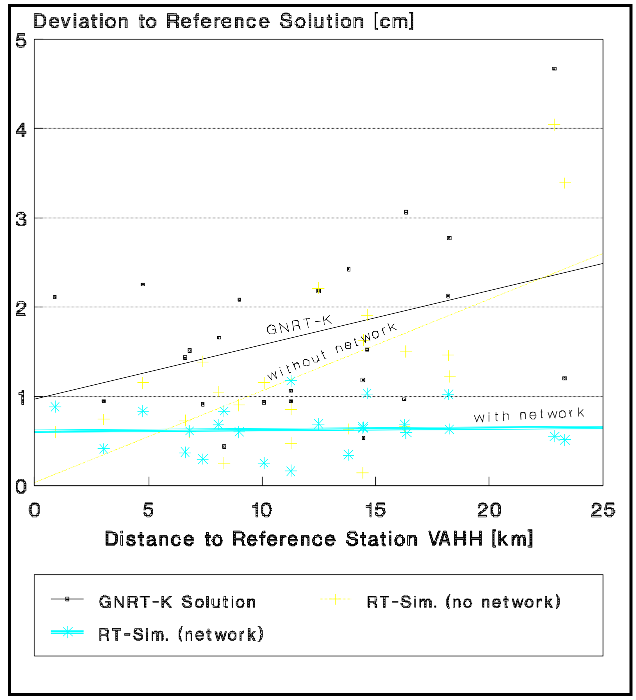

Fig. 6: Difference between the reference solution and the mean position of all stations calculated with GNRT−K, GEONAP real−time simulation without network concept and the GEONAP real−time simulation with network concept, Hamburg 12.−16.02.1996

These results prove the efficiency of the algorithm. For practical applications, however, the user needs the additional network correction in real−time at the mobile station. The SAPOS service transmits correction data every second with a communication rate of only 2400 baud via radio link. In order to decrease the amount of information to be transmitted it is necessary to investigate the dynamics of the network coefficients. GEONAP offers the possibility to analyze the calculated coefficients, which are shown in Fig. 7.

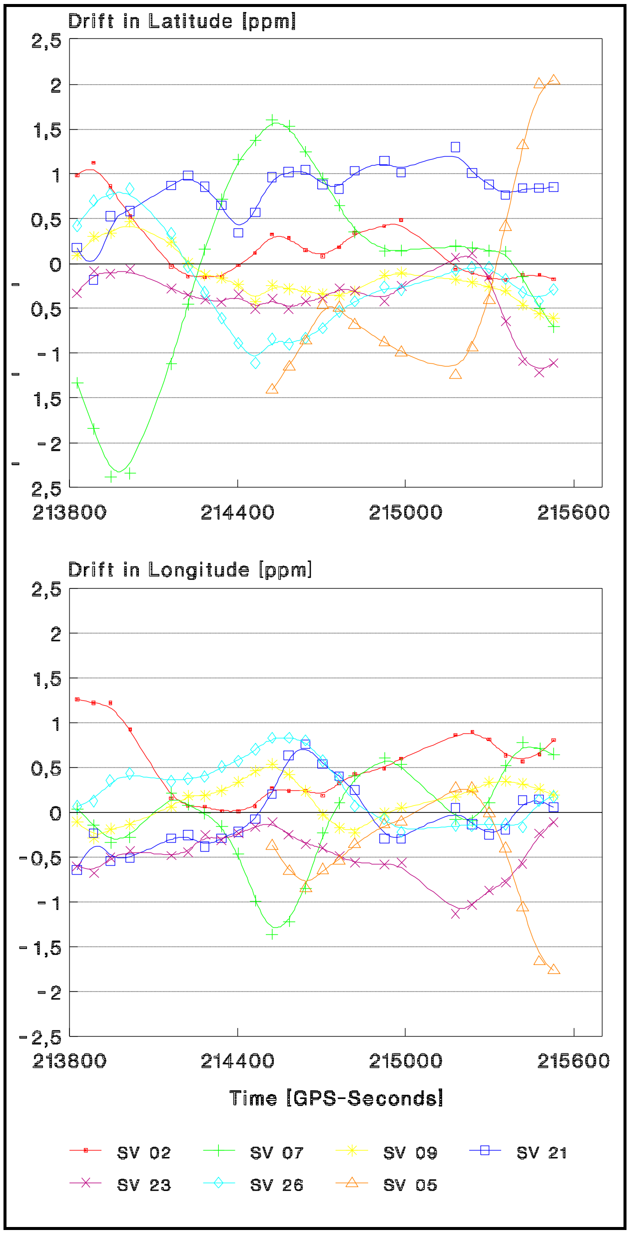

Fig. 7: Dynamics of the network coefficients, drift in longitude and latitude versus GPS time in seconds, station Moorfleet, Hamburg 12.−16.02.1996

The station Moorfleet is nearly in the center of the network. The coefficients are divided into longitude and latitude drift components, and they show a range between −2.4 ppm up to +2 ppm. The highest rate of change is visible in the latitude drift of satellite SV05 with nearly 3 ppm in 5 minutes (0.6 ppm in 1 minute) beginning at GPS second 215200.

In order to reach a high accuracy at the millimeter level also over larger distances, the accuracy of the network coefficients should be better than 0.1 ppm. In this case the satellite orbit error effects the coordinates less than 1mm/10 km according to a general rule of thumb (Seeber 1993).

In case of a maximum rate of change of 0.6 ppm per minute, network coefficients are required which are determined each 10 seconds. However, normally the rate of change is smaller and can be described with an additional parameter. Further investigations to reduce the amount of correction data have to be done.

4. Conclusions

This paper focus the distance dependency of real−time precise DGPS applications using the information of a only a single reference station. Test measurements in the network of Hamburg with the real−time software GNRT−K show, that the accuracy of the OTW−algorithms are limited by atmospheric refraction and orbit errors to a few centimeters.

Postprocessing simulations of the real−time measurements with the software GEONAP show, that a multiple station adjustment with calculated network coefficients reduces the errors to less than 1 cm over 25 km for the mean of a few fixings without any part of distance dependent error effects. It is expected, that also the necessary time to fix the ambiguity (TTFA) will decrease.

The real−time concept of GNNET performs a multiple station adjustment of several reference stations including the carrier phase ambiguity resolution. The concept of a multiple reference station network seems to be a promising way to produce PDGPS positions with an accuracy better than 1 cm for users of local or regional DGPS services. The RTCM message types can be used. This investigation need to be extended for more studies of the dynamics of the network coefficients.

For further improved results, the antenna phase center offsets, multipath and imaging effects in the reference antenna have to be calibrated and corrected.

5. Acknowledgements

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6. References

Hankemeier, P.: *The DGPS Service for the FRG −Concept and Status−*. In: Beutler u.a. (Hrsg.) GPS Trends in Precise Terrestrial, Airborne and Spaceborn Applications, IAG Symp. 113, 1996

Seeber, G. (1993): *Satellite Geodesy. Foundations, Methods, and Applications*. De Gruyter, Berlin, New York.

Wübbena, G., G. Seeber: *Developments in Real−Time Precise DGPS Applications −Concepts and Status−*. In: Beutler u.a. (Hrsg.) GPS Trends in Precise Terrestrial, Airborne and Spaceborn Applications, IAG Symp. 113, 1996

Wübbena, G., F. Menge, M. Schmitz, G. Seeber, C. Völksen. *A New Approach for Field Calibration of Absolute Antenna Phase Center Variations.* Contributed paper to the ION GPS−96, Kansas City, September 1996