Implementation of a GPS Reference Network for Precise Real Time Positioning in Recife, Brazil

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BIOGRAPHIES

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ABSTRACT

Initiated through the SIRGAS project the Continuous Brazilian Monitoring Network (RBMC) with now 11 active GPS reference stations has been established by the Instituto Brasileiro de Geografia e Estatística (IBGE). The average spacing of the RBMC stations is about 500 - 1000 km and hence by far too large for precise real time applications. Local GPS reference networks are a means to provide cm-level positioning accuracy in real time for densely populated areas and important economic regions. Local, in this case, involves at least four reference stations and distances up to 100 km between them. Such a network was implemented for the urban area of Recife, in the Northeast of Brazil, and was operated for about three weeks during November 2000. Besides investigating the multi-station positioning approach under the particular ionospheric conditions in equatorial regions the network was used for several marine applications as well as geodetic control surveys, cadastral and GIS surveys, and car navigation. This project is part of the Bilateral Science and Technology Cooperation between the University of Hannover, Germany, and the two brazilian Universities Universidade Federal de Pernambuco (UFPE), Recife, and Universidade Federal do Paraná (UFPR), Curitiba.

Distance dependent errors, introduced by ionosphere, troposphere and orbit, limit the applicability of standard RTK systems to a radius of less than 10 km from the base station. When setting up a network of permanent reference stations it is necessary to extend the station spacing as much as possible. Only a real time multi-station solution that models the distance dependent errors allows then the fast, reliable, and precise real time positioning. One approach to achieve

this is the approximation of the ionospheric, tropospheric, and orbit residuals at all neighbouring reference stations by a plane or a polynomial of higher order. After parameterisation of the plane, the parameters are transmitted to the user. Using his approximate coordinates the user derives corrections from the parameters that will improve - compared to the standard RTCM based differential positioning - the ambiguity fixing process as well as the coordinate estimation process.

The paper focuses on the real time multi-station positioning algorithm. The network architecture and implementational issues regarding hardware and software are also adressed. The high ionospheric activity in the equatorial region requires even for shorter distances multi-station solutions. Such results are without exception faster, more reliable, and more precise, but cannot compensate for severe tracking problems because of strong ionospheric scintillations.

INTRODUCTION

In more than 25 years of cooperation between the University of Hannover and universities and institutions in Brazil various common projects related to satellite positioning have been performed. After participating at the SIRGAS campaign in 1995 and 1997 an initiative was started to establish active reference stations for precise real time positioning with GPS. At that time, the Instituto Brasileiro de Geografia e Estatística (IBGE) had already set up seven GPS reference stations throughout Brazil as part of the Continuous Brazilian Monitoring Network (RBMC) (Fortes *et al.*, 1997). With an average spacing from 500 km to 1000 km it is too extensive for a precise DGPS service, and the dissemination of GPS corrections has not been considered yet. Hence, a concept for local GPS reference networks that includes the RBMC has been developed.

The motives and features of the local GPS reference network concept are comparable to those of the High-Precision Permanent Positioning Service (HPPS) project (Augath and Jahn, 1998). After first investigations by the State Survey Authority of Lower Saxony a station spacing from 50 to 70 km was defined (Fröhlich, 1994), which matches well the range of the 2 m radio link (Martin and Jahn, 1998). The first real time test network was then installed with a few stations from Hannover towards the south-west of Lower Saxony. It was in this time when the configuration of reference station networks was designed. The software components necessary for a continuous operation were developed, that are now known as GNSMART.

Even in the first phase it was clear that RTK networking is necessary, because of the distance dependent errors and especially for the increasing activities of the ionosphere in view of the upcoming maximum of the solar cycle 23. In the test network near Hannover as well as some other networks a simple linear model for distance dependent errors in the form of FKP was realized (Wübbena *et al.*, 1996). Owing to the projects in Brazil it was thought to gain experiences in software design especially in the area of the high equatorial influences.

In contrast to Germany, where State Survey Authorities build up the Satellite Positioning Service SAPOS (Hankemeier, 2000) with more and more stations covering the entire state territory, Brazil has to restrict to small local networks. That means in this particular case at least four reference stations and distances up to 100 km between them. For finacial reasons only densely populated areas and important economic regions can be covered.

For both Germany and Brazil a desirable aim of GPS reference services is to cut down the numbers of marked control points. In addition, the service should be designed for multifunctional use, i.e. for as many as possible users also outside the classical geodetic field. In principle the applications are not so different in both countries, but the geodetic sector in Brazil is not as large. Concerning the operation and use of reference station services a much higher need for continuing education programs is noticeable. Therefore, seminars on this topic are another important aim of the cooperation project (Willgalis and Krueger, 2000).

After a test in 1997 in Pontal do Sul (Krueger *et al.*, 1997) as well as a case study in Hannover 1998 the first reference station network (field test) was set up in April 1999 around the Bay of Paranagua (BRASnet99). This network was used for several marine applications (Krueger *et al.*, 2001) as well as geodetic control surveys. A second network was implemented for the urban area of Recife, in the north-east of Brazil, and was operated for about three weeks during November 2000 (BRASnet2000). Besides investigating the multi-station positioning approach under the particular ionospheric conditions in equatorial regions the main emphasis was put on cadastral and GIS surveys. But also geodetic control surveys, GPS heighting, and several marine applications were tested.

NETWORK IMPLEMENTATION

The reference network covered the city of Recife with four GPS reference stations (Fig. 1). The receivers were located on top of high buildings (SOLA, UFPE) and towers. One station was situated in the barracks of the 3rd topography unit (3aDL), and for station TELE the grounds of a training school of the telecommunication company TELEBRAS was used. The central reference station UFPE was set up on the highest buildung on the campus of the Universidade Federal de Pernambuco (UFPE). Just $400\ m$ apart was the RBMC station RECF placed on the library tower.

All four reference stations were equipped such that they could work as a single base for RTK positioning. The set up for each station inluded a geodetic dual-frequency GPS receivers with an absolute calibrated geodetic antenna, a UHF radio modem with antenna, a PC with OS/2 operating system, and the GNSMART software modules. Power supply, no-breaks, and converters completed the

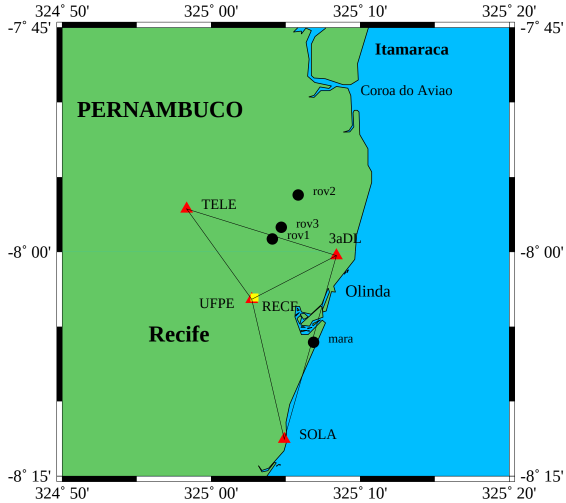

Figure 1: GPS reference network Recife with the coastline of Pernambuco. The RBMC station (square), reference stations (triangles), and permanent rover (circles) are plotted.

equipment. With one exception (SOLA), all GPS antennas have been mounted on pillars. The absolut antenna calibration was required, since different receiver and antenna types (ASHTECH Geodetic I, Geodetic II, Marine, Trimble Geodetic L1/L2) were used during the campaign.

In order to enable post processing the GPS measurements were stored in compressed RINEX format at each station. In addition, also the disseminated PDGPS corrections computed at each station by the software module GNRT were archived. Operating the network from November 9th (DOY314) to 27th (DOY 332) 2000, about 1.5 GB data was collected.

At the central reference station UFPE the PDGPS corrections received by UHF radio link together with the corrections generated for the station UFPE itself were fed to the real time multi-station algorithm implemented in the GNNET module, that is described more detailed in the next section. At first, cycle slips have to be detected and eliminated before the ambiguities can be estimated together with the complete state vector in a simultaneous dual-frequency adjustment. Following the state space estimation, the representation of the error states by simple mathematical means is required. The spatial variations of the residuals are approximated by a low-order surface model, and the coefficients of this model (area correction parameters, FKP) are disseminated in the RTCM message type 59 together with the carrier phase corrections (RTCM message type 20/21) and all other necessary RTCM messages.

The PDGPS corrections including the network coefficients were broadcasted via VHF radio. Because of the high elevation of the VHF radio transmitter and the fairly flat topography of Recife, corrections could be received in almost all tested parts of the city. With VHF waves distances of 70 km can be reached, so that the university buildung is an ideal location for broadcasting corrections in a permanent PDGPS service. The cellular phone system was not suited at that time for data transmission and could therefore not be used.

All the implementational and operational issues of an active reference network were investigated and testet with a group of graduate students during a project seminar at the Universität Hannover (Willgalis, 2000). A concept for test measurements in the network was developed that is based on a permanent rover. Setting up a rover for several hours, even days, yields the most conclusive results on the accuracy, reliability, and availability of the posititioning service. Such rover were placed at the edges of the network (mara) and beyond (rov1-rov3, see Fig. 1), in order to test how far the network corrections can be extrapolated. Other rovers were used for static as well as kinematic applications, mainly to study and demonstrate the practical use of RTK networks.

A good absolute datum and very accurate reference coordinates are in general a prerequisite for GPS data processing, but for real time multi-station positioning it is especially important. Unfortunately, the coordinates of the four reference stations were not sufficiently accurate. Also the UHF data links sometimes did not work reliable, hence the decision was made to post process the RINEX data in order to derive very accurate reference coordinates tied to ITRF (Kewes, 2001), and to reprocess the archived data with GNSMART, i.e. to carry out a real time simulation. It has been proven already with data from the German SAPOS stations that the real time simulation yields comparable results. But it has the advantage, that the simulation can be repeated with different options and parameters can be optimized. This knowledge, in turn, can be transferred back to optimize the existing networks.

MULTI-STATION SOLUTION IN REAL TIME

For processing the real time multi-station solutions the software GNSMART (Geo++ GmbH) was employed. The algorithms of the software are based on the parameter estimation concept. In the undifferenced observation equation

$$PR^i_{s,j} = |\mathbf{R}^i_j| + \delta B^i_{s,j} + \lambda_s N^i_{s,j} + \varepsilon^i_{s,j} \tag{1}$$

all bias parameters $\delta B^i_{s,j}$, the ambiguity term $N^i_{s,j}$, and station parameters included in the geometric range $|\mathbf{R}^i_j|$ are estimated together. The advantages of this approach compared to the more common parameter elimination concept have been discussed by Wübbena and Willgalis (2001).

With regard to RTK networks it is important to separate the bias term in (1) into clock related errors $\delta C^i_{s,j}$, station dependent errors $\delta S^i_{s,j}$, and distance dependent errors $\delta D^i_{s,j}$.

$$\delta B^i_{s,j} = \delta C^i_{s,j} + \delta S^i_{s,j} + \delta D^i_{s,j} \tag{2}$$

The signal transmission time at the satellite and the signal reception time at the receiver are distorted by clock errors ($\delta t^i, \delta t_j$) and signal delays ($\delta d_s^i, \delta d_{s,j}$) in the hardware of the satellite and the receiver respectively:

$$\delta C_{s,j}^i = (\delta t^i + \delta d_s^i) - (\delta t_j + \delta d_{s,j}) \tag{3}$$

Multipath ($\delta M_{s,j}^i$) and phase centre variations (PCV) of the receiver antenna ($\delta A_{f,j}^i$) are station dependent errors. Just for completeness, also phase centre variations ($\delta E_{f,j}^i$) and multipath (δW_s^i) at the satellite antenna have been considered in (4), although they are not yet used in practice. Since the station dependent error components are uncorrelated between stations, it is important to reduce or correct for these error terms.

$$\delta S_{s,j}^i = \delta A_{f,j}^i + \delta M_{s,j}^i + \delta E_{f,j}^i + \delta W_s^i \tag{4}$$

Signal delays caused by ionosphere ($\delta I_{s,j}^i$) and troposphere (δT_j^i) together with the orbit error vector $\delta \mathbf{o}^i$ make up the distance dependent biases:

$$\delta D_{s,j}^i = \pm \delta I_{s,j}^i + \delta T_j^i + \frac{\mathbf{R}_j^i}{|\mathbf{R}_j^i|} \delta \mathbf{o}^i \tag{5}$$

The estimation of these spatial and temporal correlated errors, which will not cancel out for baselines of more than 10 km, is the key issue for precise real time positioning. The successful modelling in a reference station network improves the ambiguity fixing with respect to the reduction of the time to fix ambiguity (TTFA), and increases reliability. Positioning with cm-level accuracy becomes then feasible also over longer interstation distances.

Optimal estimates of the various parameters of the undifferenced observation equation (1) are derived by means of a Kalman filter. The dynamic model

$$\mathbf{x}_{k+1} = \mathbf{T}_k \mathbf{x}_k + \mathbf{C}_k \mathbf{w}_k \tag{6}$$

descibes the change of the state vector $\mathbf{x}$ from time t_k to t_{k+1}. The transition matrix $\mathbf{T}$ represents the functional models, whereas the stochastic forcing function $\mathbf{Cw}$ maps the process noise $\mathbf{w}_k$ to the subsequent epoch $k-1$.

The corresponding measurement model (7) has already been introduced. The vector $\mathbf{l}$ encloses the linearized measurements, the linearized parameter vector $\mathbf{x}$ is related to the measurements by the design matrix $\mathbf{A}$, and a measurement error vector $\mathbf{v}_k$ need to be considered.

$$\mathbf{l}_k = \mathbf{A}_k \mathbf{x}_k - \mathbf{v}_k \tag{7}$$

The rather complex state vector (8) yields information that are important for the operation and monitoring of the RTK network. The information on individual error states can be used for the derivation of optimal corrections for field users within the network.

$$\mathbf{x} = [\mathbf{X}_j | \mathbf{N}_j^i | \delta \mathbf{t}_j | \delta \mathbf{t}^i | \delta \mathbf{o}^i | \delta \mathbf{T}_j^i | \delta \mathbf{I}_{s,j}^i | \delta \mathbf{M}_{s,j}^i]^T \tag{8}$$

The deterministic and stochastic models employed in the Kalman filter cannot perfectly describe the real dynamic processes. Significant residuals will remain at each reference station, which still contain non-modelled systematic errors. Different approaches have been developed ((Fotopoulos, 2000), (Wübbena *et al.*, 2001)) to model these residuals over the network area and to predict corrections for any user location.

The optimal but not yet available solution would be the dissemination of the estimated state parameters to the user. The corresponding error terms of the observation equation could be eliminated, and the user would derive a precise absolute position. The current RTK standards do not consider such state space domain corrections. Therefore, a simplified approach is used, in which the state parameters are reduced to observation domain corrections.

In the simplified model, corrections

$$\delta r_{FKP}(t) = \delta r_{s,j}(t) + \delta r_a(t) \tag{9}$$

for a user within the network are composed of range corrections

$$\delta r_s = R_{s,meas} - R_{s,comp} \tag{10}$$

and an additional correction

$$\delta r_a(t) = a_{\varphi,s}(t)(\varphi - \varphi_0) + a_{\lambda,s}(t)(\lambda - \lambda_0) \tag{11}$$

derived from the network. In order to distinguish between the two major error sources with different spatial and temporal correlations, the range errors δr_s are separated into residuals δr_I of the geometry-free linear combination L_I, and residuals δr_0 of the ionosphere-free linear combination L_0.

For the time dependent parameters a of the bilinear polynomial (11), which geometrically represent the inclination of a plane, the name area correction parameters, in German abbreviated with FKP, became the practice. They are estimated in a weighted least squares solution from the residuals 10) at each reference station. Two planes have to be computed for the error components δr_I and δr_0 individually for each satellite, and for each epoch. The pseudo ranges measured by the rover are corrected by deriving the network corrections δr_{FKP} for the approximate rover position and resubstitution of the ionospheric and the geometric components to L_1 and L_2 range corrections.

RESULTS

During the measurement campaign longer observation series have been made on several control points distributed inside and outside the reference network. These stations have been occupied between one and six hours. Operating as a permanent rover, real time solutions have been collected continuously. A complete reset of the rover system followed automatically ten seconds after each successful ambiguity resolution. Due to deficiencies of the communication links, the data have been reprocessed using the real time algorithms described before.

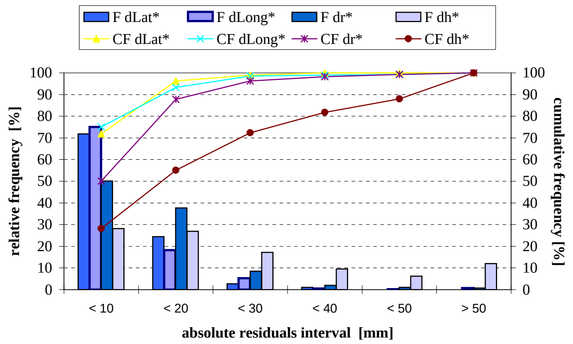

Figure 2: Positioning results for rover UFPE within the network 3aDL, SOLA, TELE based on 404 fixings (GPS week 1088, DOY 320, L_X solution, 10° elev. mask)

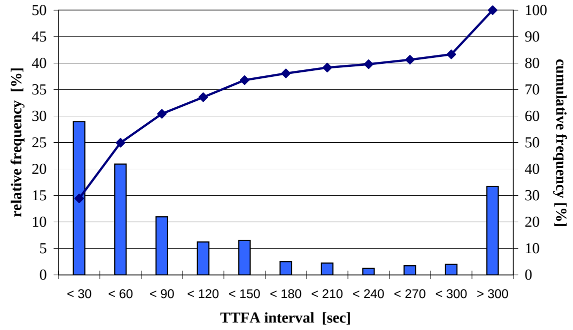

Figure 3: Time to fix ambiguities (TTFA) for rover UFPE

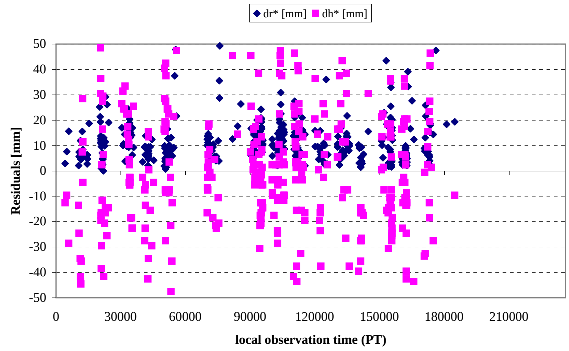

Figure 4: Availability and accuracy of network RTK solutions depending on local observation time

A comparison of RTK solutions with RTK network solutions for different baseline lengths gave no significant results for the pure RTK solutions. Beyond interstation distances of 12 km RTK solutions were hardly possible. More than 80% of these solutions exceeded the maximum treshold of 10 cm for the three dimensional position accuracy and the treshold of 5 min for the TTFA. From the few results, a distance dependent error of 21 ppm for the horizontal component, and of 16 ppm for the height component can be derived. The time required to fix the ambiguities (TTFA) grows by about 300 sec per 10 km increase in baseline length. The main conclusion from this first investigation is that for reliable, precise, and fast positioning results over baseline lengths longer than 10 km real time multi-station solutions are indispensable.

All further results are derived from RTK network solutions, where the reference station UFPE was used as permanent rover in the refence network built by the three stations 3aDL, SOLA, and TELE. For all four stations, absolute calibrated antennas have been used. For the reference stations an elevation mask of 8.5° and of 10° for the rover was pre-set. The parameter estimation employed a simultaneous dual-frequency adjustment of the L_1 and L_2 frequencies (L_X solution) with stochastic modelling of the remaining ionospheric residuals, unless otherwise stated. The results are compared to reference coordinates, which have been derived from data of the whole campaign in post processing. In the following, exemplary results from DOY 320 in GPS week 1088 (Nov. 15th, 2000) are presented.

Figure 2 shows the relative as well as the cumulative frequency of absolute residuals for 1 cm intervals between zero and 5 cm. 90% of all solutions deviate less than 2 cm, which is an important treshold for cadastral surveys, in the horizontal component from the reference coordinate. More than 70% of the latitude and longitude components are even better than 1 cm. In the height component, 50% of the solutions are better than 2 cm, and 90% are within 5 cm. About 1% of all fixings must be considered as blunders with deviations much larger than 10 cm.

The distribution of TTFA values is shown by Fig. 3. Half of all fixings occur in less than one minute. 83% of all solutions are successful within five minutes, which means that 17% take more time to fix the ambiguities, sometimes up to 30 minutes. There are also times during the day, when ambiguity fixing is impossible for a few hours. It should be mentioned, that solutions which require more than five minutes are not necessarely less accurate. But all solutions yielding blunders exhibit long TTFA values. Hence a TTFA treshold of about five minutes will protect against most blunders.

Availability is another important performance factor of real time muti-station positioning. Looking at the distribution of residuals (dr, dh) as a function of observation time (Fig. 4), periods with a larger number of solutions are just as recognizable as periods without any solution. These results are highly correlated with sunrise (at about 5:30 local time), and sunset (at 18:00 local time), when high gradients of ionospheric delay occur. Even worse, from sunset until midnight the level of ionospheric activity is so high, that no network RTK solution can be produced. With decreasing ionospheric activities after midnight the network software resumes its normal operation until sunrise. Another distinct period with a lower number of fixings occurs in the afternoon when the highest level of electron content is reached. In Fig. 4 the horizontal vector component (dr) of the residuals and the residual height component (dh) are plotted. The majority of horizontal residuals are below 2 cm, whereas the height residuals are evenly scattered

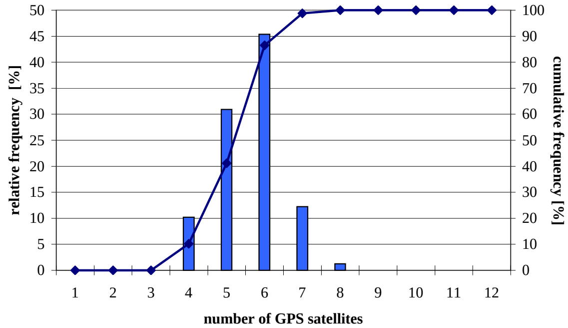

Figure 5: Number of satellites with network corrections for each of the 404 fixings

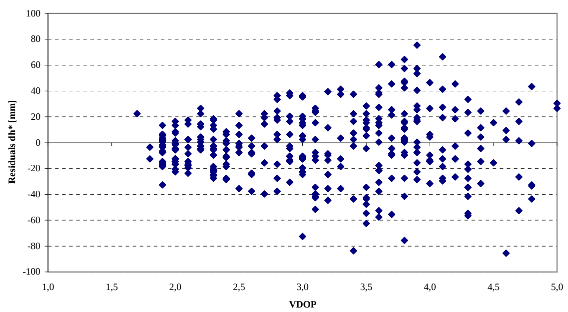

Figure 6: Dependency of height residuals on VDOP values

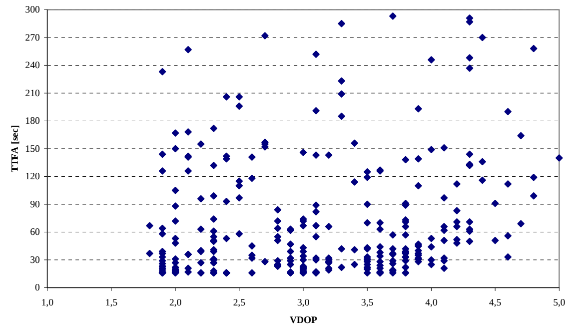

Figure 7: Relation between TTFA and VDOP

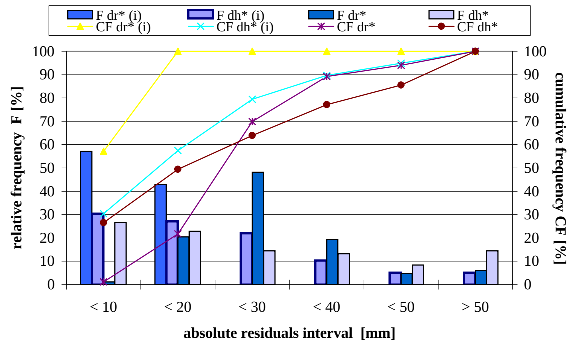

Figure 8: Improvement of positioning results through stochastic modelling of ionospheric residuals (Rover MARA, 120 fixings)

within the treshold of $\pm$ 5 cm. As far as precision is concerned, no distinct dependency on the observation time is visible, as long as a network RTK solution is feasible. This statement is also true for the TTFA values.

Besides the influence of the ionosphere the network performance also depends on the satellite geometry, which is at first a function of the number of available satellites. As soon as a satellite rises above the horizon, the network RTK algorithm starts to estimate the satellite state parameters. The goal is to have an estimate by 8.5° elevation, so that the area correction parameters (FKP) can be derived and broadcasted to the user before the satellite passes the 10° cutoff angle. In the real time simulation more time is needed to estimate the satellite state. FKP are not available below an elevation of 10° to 15°, occasionally 20° to 25° elevation. The consequence is that from 8-10 satellites above the horizon only up to 7 satellites FKP are available (Fig. 5). In this investigation, 90% of all solutions have been computed with only 6 satellites.

Since the standard deviation of the position is a function of the standard deviation of the pseudo range and the DOP value, an effect of the satellite geometry on the residuals can be expected. As shown in Fig. 6 the height residuals increase from about $\pm$ 2 cm up to $\pm$ 8 cm with growing VDOP values between 1.8 and 4.5. A similar, but less distinct correlation can be recognized for the horizontal residuals. Interestingly, the TTFA is independent of any DOP value (Fig. 7).

All solutions presented are based on a simultaneous dual-frequency adjustment with stochastic modelling of the remaining ionospheric residuals. With one parameter for each receiver-satellite combination, the vertical ionospheric delay is mapped to the individual line of sight between the receiver and the satellite (Euler and Ziegler, 2000). This allows the modelling of ionospheric disturbances, that cannot be removed by standard models. The renunciation of the stochastic modelling yields larger residuals which are also much more spread over the residual intervals (Fig. 8) than the solutions with the additional ionospheric parame-

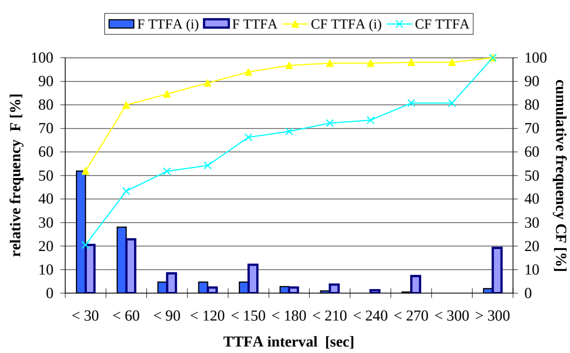

Figure 9: Improvement of TTFA through stochastic modelling of ionospheric residuals

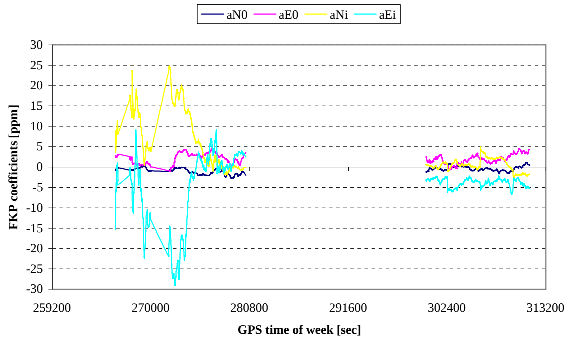

Figure 10: Network coefficients for satellite PRN 13 (left) and PRN 17 (right)

ter. The stochastic modelling has also a beneficial influence on the TTFA values (Fig. 9), the time required for ambiguity fixing is drastically reduced.

Finally, the temporal variations of network coefficients for two different satellite passes are presented in Fig. 10. Plotted are the four tilt parameter for the FKP planes, two for the geometric plane, and two for the ionospheric plane. The x-axis of the graph starts at 9 p.m. local time and ends at 3 p.m. the next day. Due to the high level of ionospheric activity during the night hours, the ionospheric coefficients for the satellite PRN 13 (to the left) reach up to $30\ ppm$. High variations of more than $10\ ppm$ within short time spans are also exhibited. In the afternoon, the ionospheric coefficients for PRN 17 (to the right) reach a maximum of only $5\ ppm$, but still show high frequency variations, which is typical for equatorial regions.

CONCLUSIONS

In large countries like Brazil it is for economic reasons neither possible nor necessary to cover the entire country with active reference stations for precise real time positioning. Instead, smaller local reference networks are an alternative. Even under the current conditions of the equatorial ionosphere precise positoning over baselines up to $40\ km$ is feasible, if multi-station solutions are employed. The multi-station algorithm used in this investigation is based on state space estimation. The parameter estimation improves with the number of available reference stations and with their spatial extension. Therefore further investigations are necessary on the combination of global state parameters, like satellite orbits and clocks derived in a nationwide network, with the regional and local parameters estimated in the local networks. If this can be done in real time, the combination of larger networks, e.g. the RBMC, and of local networks like the Recife net will be the most effective solution.

The BRASnet2000 project proofs that even with only few resources it is possible to provide precise real time positioning capability for a large city. In order to operate this active network as a permanent service, more efforts need to be put especially on the data communication aspects. Although almost the entire city could be covered with PDGPS corrections by VHF radio, an alternative distribution by cellular phone should be considered as soon as the technical prerequisites are fulfilled. A close cooperation with telecommunication companies is recommended.

The high equatorial ionospheric activities certainly are a drawback for precise real time positioning. Because of signal tracking problems during periods with fast changing rates of TEC, that are in this region highly correlated with sunrise and sunset, the network corrections are not continuously available. Nevertheless, during daytime the horizontal accuracy for more than 90% of all solutions is better than $2\ cm$. Half of these solutions can be achieved in less than a minute. Further refinement of the stochastic modelling of ionospheric residuals improves the results clearly.

ACKNOWLEDGEMENT

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