The Performance of Virtual Reference Stations in Active Geodetic GPS-networks under Solar Maximum Conditions

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BIOGRAPHY

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ABSTRACT

In order to use fast static or real-time kinematic (RTK) cm-accurate positioning over larger distances, active GPS reference receiver networks have been established in parts of Germany with station distances of 30 to 50 km. Within these networks, the distance dependent error sources, like ionospheric and tropospheric refraction and broadcast orbit errors, are modelled satellite-by-satellite and with high temporal resolution. This procedure leads to the concept of virtual reference stations whose observations are computed from the data of the surrounding real reference stations and which are located at the user's approximate position.

The modelling algorithm for distance dependent errors in GPS-networks assumes that these errors can be linearly interpolated, i.e. that their spatial wavelength is much larger than the distances between reference stations. This, however, is not the case for Medium-Scale Travelling Ionospheric Disturbances (MSTIDs), which have horizontal wavelengths of 100 to several hundred km. Whereas the number of observed MSTIDs over Europe was small in the solar minimum years (1994 - 1998), the situation dramatically changed with the commencement of the MSTID winter season 1998-1999. From October 1998 to March 1999 their occurrence produced adverse effects on classical baseline positioning and also on the quality of virtual reference stations.

It is found that even in the presence of MSTIDs most of the relative ionospheric errors can be modelled and corrected for in regional GPS reference networks. Nevertheless some ionospheric effects remain in the short baseline between virtual reference station and rover receiver. Ambiguity resolution and coordinate estimation of this baseline have to take these ionospheric effects into account.

1 INTRODUCTION

With the establishment of active GPS-reference networks with station distances of 30, 100 or more km a new era of cm-accurate GPS positioning has begun. Such networks have been or will be established in e.g. Germany (Hankemeier, 1996), the Netherlands (Marel, 1998), Austria (Döller and Auzinger, 1998) and Sweden (Hedling and Jonsson, 1996). Centimeter-accurate fast static or real-time kinematic (RTK) positioning will no longer be performed relative to one single reference receiver but relative to several reference stations, i.e. within a network (Han and Rizos, 1996; Wübbena et al., 1996; Wanninger, 1997; Raquet et al. 1998). This concept has several advantages. Observation errors can be reduced by error modelling in the network. This enables faster and more reliable ambiguity resolution and more accurate coordinates. Furthermore, redundant observations of several reference stations improve the reliability of the reference station data. In the end, the network of active reference stations makes the use of temporary local reference stations obsolete (Wanninger, 1997).

The reduction of differential ionospheric refraction effects is the most important step for the improvement of ambiguity resolution. Although these effects can effectively be removed with dual-frequency corrections, they adversely affect ambiguity resolution.

Modelling of distance dependent errors using the observation data of several reference stations can only be performed successfully if the spatial extensions of the disturbing features are of larger scale than the station distances. With station distances of some 50 km this is al-ways the case for the effects of orbit errors and also for a large portion of the tropospheric errors and large-scale features of the ionospheric refraction. But with the increase of solar activity small and medium-scale features of the ionospheric electron content become more intense. In mid-latitudes (central Europe) we rarely have to deal with small-scale ionospheric disturbances causing phase scintillations. But medium-scale travelling ionospheric disturbances (MSTIDs) occur frequently. So the question arises whether we are able to model and correct for MSTIDs with sub-centimeter accuracy in active GPS-networks with station distances of about 50 km.

2 VIRTUAL REFERENCE STATIONS

One method to use the full information content of simultaneous observations of several reference stations is to combine them in such a way that an optimum set of code and carrier phase observations of a virtual reference station is obtained, which can then be used to determine the position of a rover receiver in baseline-mode (Fig. 1). Since some of the observation errors depend on the horizontal position differences of the rover receiver in relation to the reference stations, the rover's approximate position has to be known. Absolute GPS-code-positioning is sufficiently accurate for this purpose. The virtual reference station is assumed to be located at the rover's approximate position or in the immediate vicinity of the rover (Fig. 1).

Several processing steps have to be performed in order to transform the carrier phase observations of the network of real reference stations to carrier phase observations of a virtual reference station (Wanninger, 1997, Fig. 2). They include the resolution and removal of the double-difference carrier phase ambiguities. This step is a prerequisite for all further error modelling and reduction. If ambiguity resolution fails for any observation, this observation has to be excluded from further data processing. Since the coordinates of the reference stations in the network are precisely known, ambiguity resolution is much simpler to

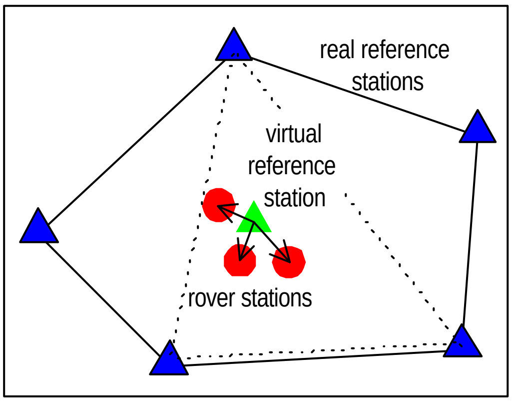

Fig. 1: Virtual GPS reference station in a regional network. The observations of the virtual station are computed from the observations of three or more real reference stations.

perform than for unknown baselines. On the other hand, distance dependent errors limit the complete ambiguity resolution to maximum distances between reference stations of 50 to 100 km.

After the successful ambiguity removal, error models are calculated from the carrier phase observations. The ionospheric model is based on the ionospheric linear combination and the geometric model, which contains the tropospheric and orbit errors, is based on the ionosphere-free linear combination. The differential effects of these distance dependent errors are modelled directly, i.e. no mapping to zenith direction is performed. We use bilinear surfaces to describe the errors (Fig. 3). Each such plane is determined by two parameters: its inclinations in two defined directions, e.g. north-south and east-west. The correction models are produced for each satellite and with a high temporal resolution. A minimum number of three reference stations is required. With four or more stations a best fitting plane is determined by least-squares adjustment and thus station dependent errors (mainly multipath effects) are mitigated by averaging.

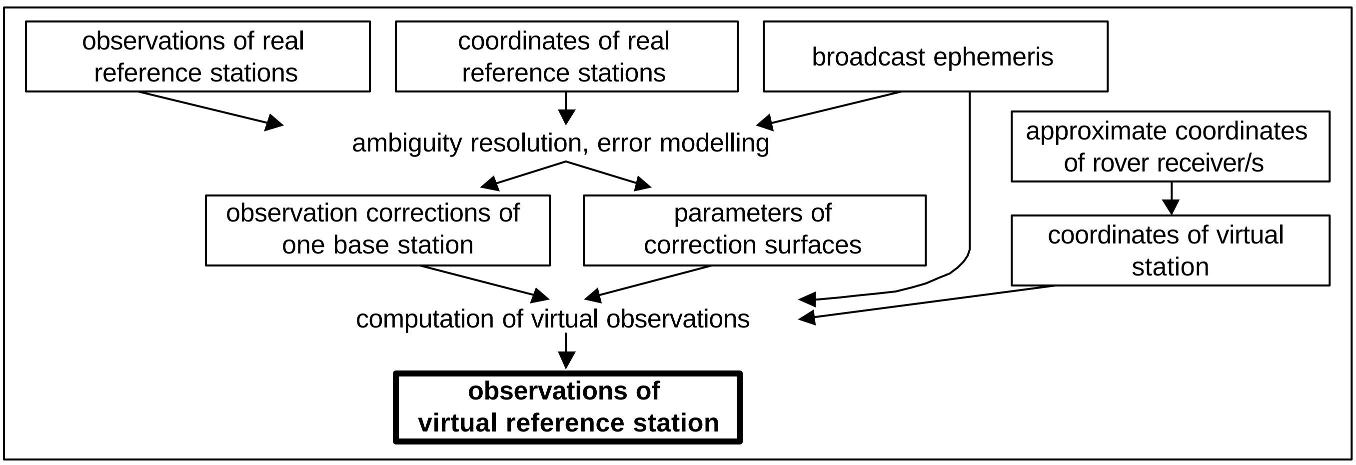

Fig. 2: Computation of carrier phase observations of a virtual reference station in a regional GPS-network.

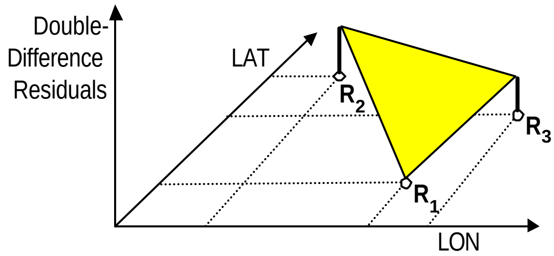

Fig. 3. Error modelling using bilinear surfaces are depicted best for double differenced observables. The actual algorithm is based on undifferenced observables.

The code observations are processed in a similar way. But here, no ambiguity resolution is required and the precise correction models obtained from the carrier phase observations are used to remove distance dependent errors.

Data processing can either be performed at a central computing facility or it can be divided between central facility and users. In the first case, the rover's approximate position has to be known to the central facility. In the second case, virtual observations are computed for a selected base station and they are broadcast together with the error models to the user. It is then his task to apply corrections to the (virtual) base station observations in order to obtain the observations of his virtual reference station.

The error modelling algorithms and the computation of virtual observations have been implemented into the post-processing software Wa-Soft which is now in operational use in a German 16 station network covering an area of 130 km x 160 km.

3 IONOSPHERIC CONDITIONS

The parameters of the ionospheric correction surfaces provide valuable information on the differential ionospheric errors which are caused either by the undisturbed ionosphere or by ionospheric disturbances. In the mid-latitude region of central Europe the determining factors are:

- large-scale horizontal gradients in north-south direction between the high electron content of the equatorial region and the low content of the northern polar region, and also east-west gradients due to diurnal variations,
- the vertical electron content (VEC),
- medium-scale disturbances, which are the most common form of ionospheric irregularities in mid-latitudes and which mainly occur during daylight hours in winter months in years of maximum solar activity (Velthoven, 1992; Jacobsen et al. 1995; Warnant, 1998),
- small-scale disturbances which cause amplitude and phase scintillations but which are rarely experienced in mid-latitudes.

In Figure 4 three samples of ionospheric surface parameter sets are presented. If VEC is low ($<20 \cdot 10^{16} el/m^2$), if no large-scale horizontal gradients occur, and if no ionospheric disturbances exist, these parameters do not exceed 1 ... 2 ppm for L_1-observations. If, however, VEC is high ($40...50 \cdot 10^{16} el/m^2$) or large-scale horizontal gradients exist, maximum values reach about 5 ppm (L_1). Even larger values (10 ppm (L1) and more) are caused by ionospheric distur-

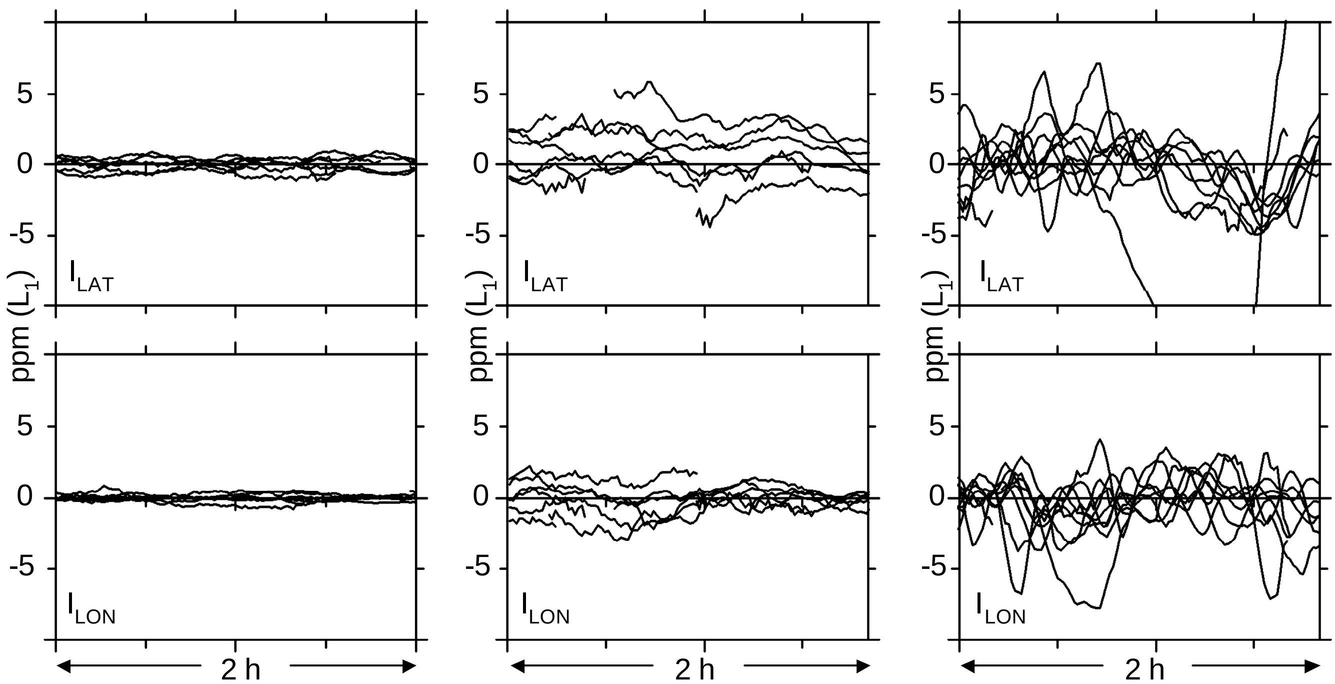

Fig. 4. Parameters of ionospheric correction surfaces in north-south (I_{LAT}) and east-west (I_{LON}). Each line connects the parameters of a single satellite. Left panels: low vertical electron content (VEC) $<10 \cdot 10^{16} el/m^2$, no disturbances. Center panels: high VEC ($40...50 \cdot 10^{16} el/m^2$), no disturbances. Right panels: low VEC ($<15 \cdot 10^{16} el/m^2$), MSTIDs.

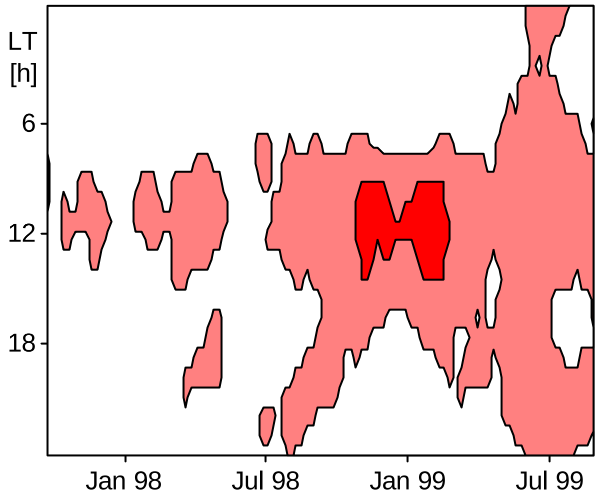

Fig. 5: Weekly averages of hourly I_{95}-Index values calculated for a three station network (30 km x 40 km) in central Europe.

bances. Then the time series of inclination parameters reveal typical periods of 10 minutes to 1 hour. This kind of ionospheric refraction features are attributed to Medium-Scale Travelling Ionospheric Disturbances (MSTIDs).

In order to condense the information content of the parameters describing the ionospheric correction surfaces we combine each two corresponding parameters by

$$I_G = \sqrt{I_{LAT}^2 + I_{LON}^2}$$

and thus neglect any information on the gradient's direction. We then define an index I_{95} of the ionospheric differential errors by

$$I_{95} \text{ with } 95\% \text{ of } I_G < I_{95}$$
$$\text{and } 5\% \text{ of } I_G > I_{95}.$$

This index describes the effects of ionospheric refraction on kinematic or fast static positioning. It is based on single epoch ionospheric corrections. The 95% limit was selected because it is expected that GPS carrier phase processing softwares are able to select and neglect those observations which are affected most.

Two years of observations collected at three German reference stations were post-processed and hourly values of the I_{95}-index were calculated. Figure 5 shows weekly averages of these index values in a coordinate system of date and local time. The figure reveals that the largest differential ionospheric errors occurred between November 1998 and March 1999 around local noon. No similar effects could be detected in the winter of 1997/98, which can be explained with the then still lower level of solar activity.

In order to further investigate the cause of this differential error maximum, we also determined the vertical electron content and large-scale horizontal gradients from dual-frequency observations of a single GPS-station in the network. These parameters were determined by fitting low order polynomials in latitude and local time to hourly blocks of the ionospheric linear combination of phase observations (Georgiadou and Kleusberg, 1988).

Both, VEC and the size of the gradients, increased in the two year period due to the approach of a solar activity maximum (Fig. 6 and 7). Because of seasonal variations, they both do not reach maximum values in the winter pe-

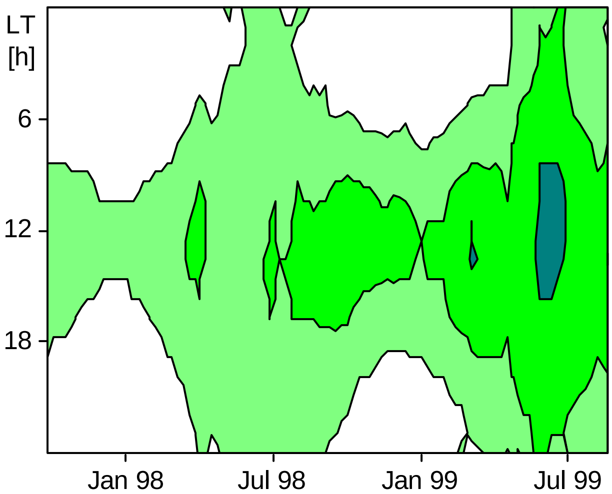

Fig. 6: Weekly averages of vertical ionospheric electron content (VEC) over Central Europe determined from dual-frequency GPS phase observations of a single reference receiver.

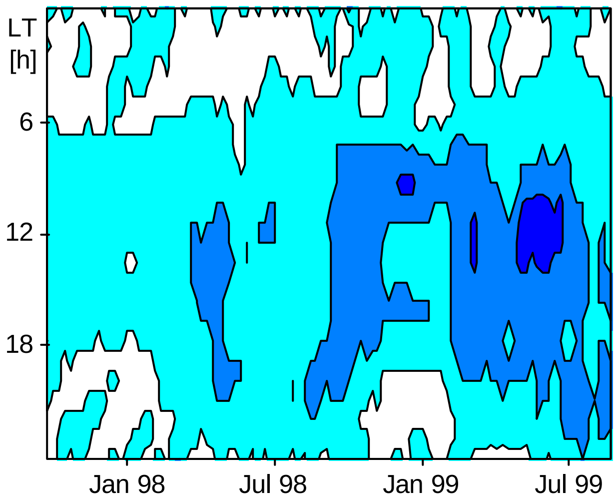

Fig. 7: Weekly averages of VEC gradients over Central Europe determined from dual-frequency GPS phase observations of a single reference receiver.

riod 1998/99 but rather around local noon in summer of 1999. Simulating the effects of VEC and large-scale gradients on I_{95}-index values by taking the satellite sky distribution into account showed that the undisturbed ionosphere causes less than 50 % of the index values around local noon in the winter of 1998/99. So they are not the main causes of relative ionospheric errors in this period.

Further analyses of the time series of I_{LAT} and I_{LON} revealed that on all affected days the parameter variations showed periods of 10 minutes to 1 hour, which are typical for MSTIDs. It can be concluded that MSTIDs are the main cause of the maximum of differential ionospheric errors around local noon in the winter of 1998/99. This local noon and winter maximum agrees with the results of studies on the seasonal and local time behavior of MSTIDs (Velthoven, 1992; Jacobsen et al. 1995; Warnant, 1998).

MSTIDs complicate ambiguity resolution of single-frequency and dual-frequency data even on baselines shorter than 10 km. In case of fast static and RTK-positioning, single-frequency coordinate errors can exceed 10 ppm of the baseline length (Wanninger, 1995). MSTIDs have horizontal wavelengths of 100 to several hundred km (Spoelstra, 1992). It can therefore be expected that even the satellite-by-satellite ionospheric corrections used in regional GPS-networks can not completely remove differential ionospheric effects caused by MSTIDs.

4 THE PERFORMANCE OF VIRTUAL REFERENCE STATIONS

In order to test the performance of virtual reference observations, sample data sets were selected from groups of German reference stations. In each case one reference station was considered as rover station and a virtual station was located close to it. The quality of the virtual observations could then be tested by processing the short baseline from the virtual station to the rover station. The computation of virtual observations and the baseline processing was performed using the author's software WaSoft.

The selected data sets show different levels of ionospheric disturbances, which can be demonstrated with the help of the I_G time series (Fig. 6). The first data set can be considered as collected under undisturbed ionospheric conditions (I_{95}-value of about 1 ppm (L_1), 1 - 6 LT on day 313/1998). In the period of the second data set severe ionospheric disturbances occurred (I_{95}-value of about 10 ppm (L_1), 10 - 15 LT on day 313/1998).

The results are presented in the form of RMS values of the double-difference residuals, i.e. on the level of observation errors. In the case of the ionosphere-free linear combination the observation errors are dominated by multipath effects, but they can also include (remaining) tropospheric

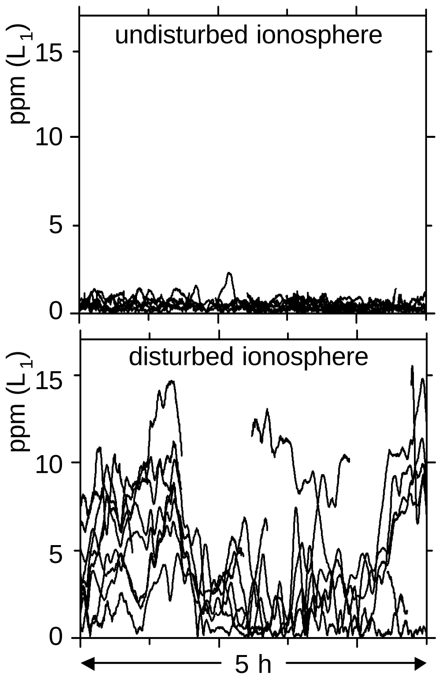

Fig. 6: I_G-values of two periods of time on day 313/1998.

and orbit error effects. L_1 double-difference residuals are less affected by multipath, but they are additionally affected by ionospheric refraction errors.

The first samples originate from German reference stations with station distances of about 60 km. In one case the rover station is located close to the center of the network, in the other case the rover station lies close to a real reference station (Fig. 6). The observations of the virtual reference stations were computed in two ways: based on the observations of four real reference stations and based on the observations of just three reference stations. Using more than three reference stations, it can be expected that multipath effects are mitigated by averaging. With just three stations however, the area to be covered by the correction surfaces becomes smaller and thus smaller-scale

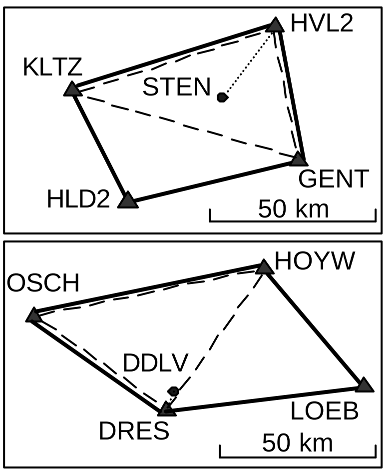

Fig. 7. Two sub-networks with reference station distances of about 60 km.

features (of e.g. the ionosphere) can be modelled more accurately. For reasons of comparison, the results of the baseline between the rover station and the closest reference station are also presented (Table 1).

Table 1. RMS [cm] of double-difference residuals in cm for baselines reference station - rover station in the networks of Figure 7.

Baseline	undisturbed ionosphere iono.-free	undisturbed ionosphere L_1	disturbed ionosphere iono.-free	disturbed ionosphere L_1
rover station close to center of network				
closest ref. sta. (29 km)	2.0	2.2	2.1	12.0
virtual station (3 ref. sta.)	1.5	0.9	1.6	2.3
virtual station (4 ref. sta.)	1.4	0.8	1.6	2.2
rover station close to one real reference station				
closest ref. sta. (6 km)	1.3	0.9	1.4	2.7
virtual station (3 ref. sta.)	1.1	0.6	1.2	0.8
virtual station (4 ref. sta.)	1.0	0.7	1.0	3.4

The following conclusions can be drawn from the results presented in Table 1:

- On a short baseline (6 km) the L_1-observables are usually less affected by observation errors than the ionosphere-free linear combination. This is not true if severe ionospheric disturbances occur or if the baseline length exceeds 10 to 20 km.
- The L_1 observation errors in the baseline virtual reference station - rover station are in general much smaller than in the baseline from the closest real reference station to the rover station. This shows that most of the ionospheric errors can be removed using the bilinear correction surfaces. But in the presence of ionospheric disturbances, in a network of four stations, and the rover station being close to a real reference station, the ionospheric correction fails. Here, the ionospheric disturbances are smaller in size than the reference station distances. The use of three stations, however, produces excellent results, because now the observations of the closest real reference station are introduced into the correction modelling algorithm with a very high weight.
- The ionosphere-free observables produce slightly better results using four reference stations as compared to three stations. This is due to multipath mitigation by averaging.

More results of the same kind have been produced in three-station-networks of different sizes (Fig. 8, Table 2). Here again, all baselines using the virtual reference station are less affected by observation errors than the baselines to real reference stations. In the 60 km and 100 km networks the L_1 results have smaller observation errors than

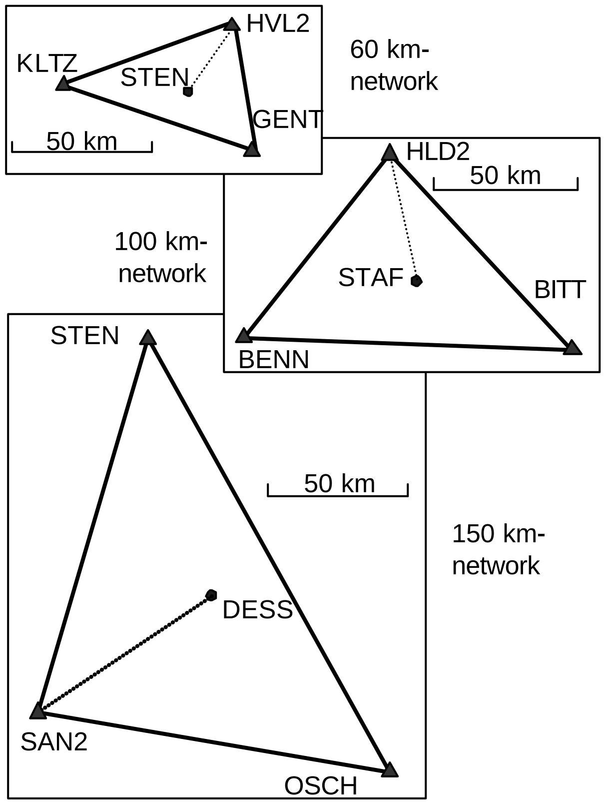

Fig. 8. Three sub-networks with reference station distances of about 60 km, 100 km and 150 km.

the ionosphere-free results. But this is not true any more if the reference station distances are larger than 100 km or if ionospheric disturbances occur. It can be concluded, that the ionospheric correction removes most of the ionospheric refraction effects. For network sizes larger than 100 km and in the presence of ionospheric disturbances some differential ionospheric error remains.

The occurrence of ionospheric disturbances can easily be detected by interpretation of the inclination parameters for the ionospheric correction surfaces. If they exceed certain thresholds (e.g. I_{95} > 4 ppm for L_1) it is recommended to

Table 2. RMS of Double-Difference Residuals in cm for baselines reference station - rover station in the networks of Figure 8.

Baseline	undisturbed ionosphere iono.-free	undisturbed ionosphere L_1	disturbed ionosphere iono.-free	disturbed ionosphere L_1
60 km-network				
closest ref. sta. (29 km)	2.0	2.2	2.1	12.0
virtual station	1.5	0.9	1.6	2.3
100 km-network				
closest ref. sta. (50 km)	2.2	3.2	1.7	23.8
virtual station	1.0	0.8	0.9	3.5
150 km-network				
closest ref. sta. (75 km)	1.7	3.8	2.1	21.4
virtual station	1.4	1.8	1.4	8.5

process the baseline between virtual station and rover station using an ambiguity resolution algorithm which can handle some ionospheric effects and to compute the coordinates with the ionosphere-free linear combination.

Furthermore, the results show that in the presence of ionospheric disturbances and in sparser networks the coordinate accuracy obtainable is lower than in times of an undisturbed ionosphere and in denser networks.

5 BASELINE PROCESSING USING VIRTUAL REFERENCE STATIONS

Even in the presence of MSTIDs, most of the ionospheric refraction effects can be modelled and removed in a regional reference station network with station distances of about 60 km. Nevertheless, some refraction modelling errors remain in the calculated observations of the virtual reference station. The very short baseline between virtual reference station and rover receiver is not completely free of ionospheric errors as it could be expected for a real baseline of this length. Thus, the algorithms used for ambiguity resolution and coordinate estimation in the baseline between virtual reference station and rover station have to cope with observation errors they are not necessarily prepared for.

The latest versions (April 1999) of three widely used GPS-post-processing software-packages have been tested for their ability to resolve ambiguities and for coordinate accuracy when using virtual reference station observations.

The test data were taken from the network KLTZ-HVL2-GENT with STEN being considered as rover station (Fig. 8). The observations of a virtual reference station located at the position of STEN were computed from the observations of the real reference stations. Ten hours of observations of day 313/1998 (1-6 h and 10-15 h LT, Fig. 6) were divided into observation-blocks of 5 minutes each. Thus, the tests were performed using 60 samples collected under undisturbed ionospheric conditions and another 60 samples disturbed by MSTIDs.

Three criteria have been defined to describe the quality of the baseline results:

- **correctness of ambiguity resolution:** ratio of the number of correct solutions to the number of baseline samples. Each coordinate estimation of the rover station STEN is compared to the precisely known coordinates of this station. If the difference vector is shorter than 8 cm the ambiguity fixing is considered as being correct.
- **reliability of ambiguity fixing:** ratio of correct solutions to the number of solutions with ambiguities being fixed. The reliability figure shows how often the software is not able to detect an incorrect ambiguity fixing.
- **accuracy of baseline coordinates:** RMS of horizontal (2D) and vertical coordinate differences between baseline solutions and precisely known coordinates.

Tab. 3: Quality of baseline estimation using three post-processing software packages.

Post-Processing Software	Correctness [%]	Reliability [%]	Accuracy 2D/vertical RMS [cm]
undisturbed ionosphere default algorithms			
A	97	97	1.0/1.6
B	95	95	1.1/1.8
C	87	98	0.9/2.0
disturbed ionosphere default algorithms			
A	87	87	2.2/2.9
B	80	81	2.1/3.3
C	37	96	2.0/2.7
disturbed ionosphere algorithms for long baselines (ionosphere-free)			
A	97	97	1.5/2.8
B	83	86	2.2/3.5
C	37	96	1.4/1.8

Under undisturbed ionospheric conditions all softwares obtain good results with just 5 minutes of observations for the baseline between the virtual reference station and the rover station (Tab. 3). The correctness reaches 95 % and more for softwares A and B. With software C less than 90 % of all baselines results were correct, but the reliability of ambiguity resolution is somewhat higher than for the other two software packages. The RMS-values of horizontal and vertical position amount to about 1 cm and to less than 2 cm respectively.

In the presence of medium-scale ionospheric disturbances and thus some remaining ionospheric effects in the short baseline, the results get worse. The correctness figures drop to less than 90 % or even less than 40 % (Tab. 3). The ambiguity fixings are less reliable. And the ionospheric errors affect the coordinate accuracy: the RMS-values of horizontal and vertical position increase to about 2 cm and 3 cm respectively.

Some softwares also offer additional algorithms for long baselines which take some residual ionospheric effects into account. In case of softwares A and B, different algorithms can be selected for ambiguity resolution and coordinate estimation (ionosphere-free linear combination). They are activated automatically if the baseline length exceeds 10 or 30 km. This activation threshold can be lowered to 0 km by the user. Software C does not contain a special ambiguity resolution algorithm for longer baselines, but the ionosphere-free coordinates can be computed.

With these algorithms for long baselines, all softwares obtain better results. Software A produces results with correctness and reliability figures as high as under ionospheric undisturbed conditions. And the coordinates based on the ionosphere-free linear combination are more accurate than the L_1-results obtained with the standard algorithm. But they are not as accurate as the results from ionospherically undisturbed observations, because of the higher multipath sensitivity of the ionosphere-free linear combination. Software B shows some improvement in the correctness and reliability of the baseline results. The coordinate accuracy, however, does not improve, because many baseline results are now based on the widelane linear-combination. Software C uses the same ambiguity resolution algorithm as before. The improved coordinate accuracy is caused by the use of the ionosphere-free linear combination.

All three softwares can handle observations of virtual reference stations. But remaining ionospheric effects in the short baseline between virtual station and rover receiver makes ambiguity resolution more difficult and increases coordinate errors if standard algorithms are used. Then, better results are obtained if the software user changes over to long baseline algorithms. The decision when to use what algorithm can be based on the parameters describing the ionospheric correction surfaces e.g. in the form of I_{95}-index values.

But even if the remaining ionospheric effects are removed by dual-frequency corrections, the coordinate accuracy decreases in the presence of ionospheric disturbances, because now the higher multipath sensitivity of the ionosphere-free linear combination introduces additional errors.

CONCLUSIONS

Even in the presence of ionospheric disturbances (MSTIDs) most of the relative ionospheric errors can be modelled and corrected for in regional GPS reference networks located in mid-latitude regions. Nevertheless, the quality of the ionospheric corrections decreases with increasing network size and increasing ionospheric activity. Best results are achieved in sub-networks of just three stations.

Whereas under undisturbed ionospheric conditions and in case of a network size of about 50 km, the L_1 observables produce more accurate results than ionosphere-free linear combinations, this is not true any more if the ionosphere is disturbed or if the reference station distances exceed 100 km. In these cases remaining ionospheric errors adversely affect ambiguity resolution and coordinate estimation in the short baseline between virtual station and rover station.

Post-processing software packages handle virtual RINEX-observations without difficulties. In case of strong ionospheric disturbances and thus remaining ionospheric effects in the short baseline between virtual reference station and rover station, however, standard algorithms for ambiguity resolution increasingly fail. Then, better results are obtained using long baseline algorithms. But the achievable accuracy deteriorates due to the higher sensitivity of the ionosphere-free linear combination to multipath.

ACKNOWLEDGEMENTS

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