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Virtual Reference Stations for Centimeter-Level Kinematic Positioning

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BIOGRAPHY

Lambert Wanninger graduated and obtained his doctor´s degree in Geodesy from the University of Hannover, Germany. He spent several years lecturing and doing research in the field of GPS at the Dresden University of Technology. In 2000 he started Ingenieurbüro Wanninger and has since been working as developer of software for precise GPS applications.

ABSTRACT

Advanced positioning techniques pre-process the observations of regional reference station networks in order to provide individual virtual reference station (VRS) observations. These virtual observations enable users to perform cm-level positioning in baseline mode, even with the real reference stations situated in distances of several 10 km.

This paper extends the concept of static VRS to that of a semi-kinematic VRS to be used in such cases of kinematic positioning, when the rover receiver moves across long distances. Test data sets were used to evaluate the performance of this new kind of VRS. The results demonstrate its superiority to static VRS in large-scale kinematic applications.

1 INTRODUCTION

Centimeter-level positioning in an array of reference stations (RS) with a station spacing of 30 to 100 or even more kilometers can be achieved using virtual reference station (VRS) observations optimized for the user´s position. Precise correction models for dispersive (ionospheric) and non-dispersive (tropospheric and orbit) distance-dependent biases are obtained from the real reference data and used in the calculation of the virtual observations (Wanninger 1997).

This concept is often realized by setting up a central computing facility collecting the RS observation data and performing a pre-processing to obtain correction models for distance-dependant biases. The user transmits his approximate position to the central computing facility and by return he receives VRS observations based on the real RS data and the correction models (Trimble 2001).

This concept was developed for static users or users moving through fairly small areas. On such conditions one approximate user position, provided at the login to the computing facility, is sufficient for the complete positioning task.

If the user is moving over longer distances, however, frequently updates of the approximate position are necessary and the VRS should not been fixed but be moved along the user´s trajectory. Baseline processing softwares have not accepted moving reference stations as yet. Therefore a new type of VRS has been developed for kinematic applications in order to overcome this difficulty.

2 VRS POSITIONING

Pre-processing of RS array observations for VRS-positioning includes two necessary steps: ambiguity resolution in the network of RS and interpolation of the distance-dependent biases. Several interpolation algorithms have been suggested in recent years. Comparisons indicate that the performance of most of these methods is similar (Dai et al. 2001).

Usually the interpolation algorithms are separately applied to the dispersive (ionospheric) and to the non-dispersive (geometric, i.e. tropospheric and orbit) biases. The correction model parameters are known as area correction parameters (in German *Flächenkorrekturparameter*, abbreviated FKP).

VRS observations are then computed from one set of observations (or observation corrections as defined by the RTCM-format description, see RTCM (2001)) and the FKP to correct distance-dependent biases. In this paper the one set of observations is referred to as observation set of a master RS. It either consists of the observations of one selected real RS or it is obtained by combining the observations of a group of RS and referring them to any chosen position. In the second case multipath mitigation algorithms can be applied and data gaps can be filled.

The quality of VRS observations mainly depends on two aspects: firstly on the amount of station-dependent biases in the original RS observations mostly caused by carrier phase multipath and secondly on possible ionospheric and tropospheric disturbances. Small-scale and medium-scale spatial features in ionospheric and tropospheric refraction may not be completely represented by the correction models of distance-dependent biases. Remaining errors affect ambiguity resolution and positioning accuracy of the baseline between VRS and rover station (Wanninger 1999). The size of these biases and thus the quality of the VRS observations is estimated together with the correction model parameters. The VRS observation quality has to be taken into account in the baseline processing.

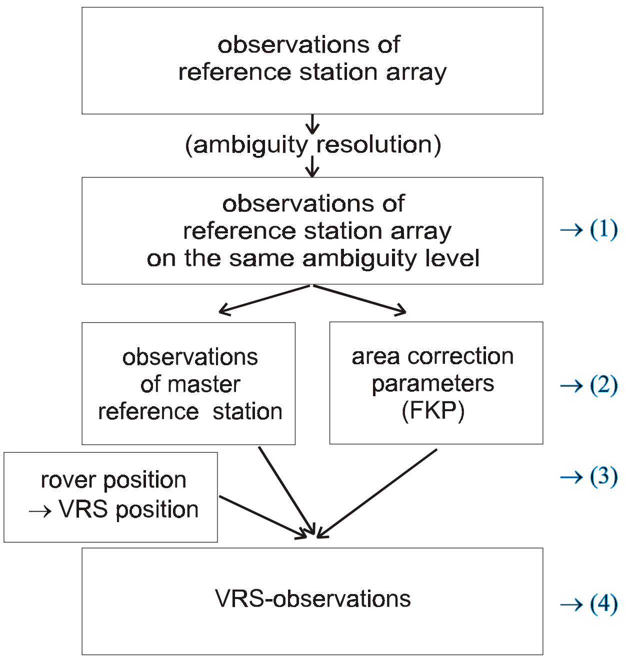

Fig. 1: Computation of VRS-observations.

Several methods have been suggested for the transfer of network information to the user (Fig. 1).

(1) Network observations on common ambiguity level: Broadcast of the observations of a master RS and observation differences between pairs of RS, all being on the same ambiguity level (Euler et al. 2001). The user performs the interpolation step on his own providing him with network corrections and valuable information on their quality. He computes VRS-observations and positions in baseline mode. The necessary data formats have not been standardized yet.

(2) FKP: Broadcast of the observations of a master RS and FKP (Wübbena et al. 2000). The user applies the FKP to the RS observation data set according to his position and thus obtains VRS-observations. The necessary data formats have not been standardized yet, although a manufacturer agreement exists on RTCM Type 59 proprietary message containing FKP information.

(3) Gridded corrections: Broadcast of the observations of a master RS and gridded corrections of the distance-dependent biases (Townsend et al. 2000). The user interpolates individual corrections within the grid and applies them to the observation data set in order to obtain VRS-observations. The necessary data formats have not been standardized yet.

(4) VRS: The user sends his approximate position to a central computing facility and by return receives VRS-observations to be used for baseline positioning. Whereas this approach uses existing data formats (RTCM, RINEX), in general no information is provided on the quality of the interpolation process. A two-way communication link is required.

Applying one of the first three approaches, the user is able to extract quality information of the virtual observations either from the interpolation step or directly from the FKP. He is thus able to estimate the size of remaining observations biases which need to be considered in baseline processing. Unfortunately no standardized data formats exist for any of these methods.

Existing data formats are used in the case of transferring VRS-observations to the user: RTCM for real-time applications, RINEX for post-processing. VRS observations, however, do not comply with the format standards because both standards state that observation data should not be corrected for any errors. Furthermore, these standards do not provide any formats for the transmission of VRS related quality information. The baseline processing software is not even able to notice that it processes virtual reference data. As a result the software will not come to optimal decisions in its baseline processing.

Nevertheless, as long as no other standard formats exist, transferring VRS-observations will stay the preferred method of providing pre-processed network information to the user. This will hold specifically true for post-processing applications since no extensions to the RINEX-format are under discussion.

3 VRS FOR KINEMATIC APPLICATIONS

The VRS concept was developed for static users or users moving through fairly small areas. On such conditions one approximate user position is sufficient for the complete positioning task. If the user is moving over longer distances, however, e.g. by car or airplane, he must frequently update his approximate position and the VRS should not be fixed but be moved along the user´ s trajectory. Baseline processing softwares have not accepted moving reference stations as yet. If new coordinates are assigned to a reference station it is assumed to be a new one and ambiguity resolution is restarted.

A new type of VRS has been developed for kinematic applications in order to overcome these difficulties. It refers to a fixed position, but the area correction parameters are applied according to the rover´ s trajectory (Fig. 2). Since this kind of VRS partly behaves like a static RS and partly like a moving receiver it is called semi-kinematic VRS.

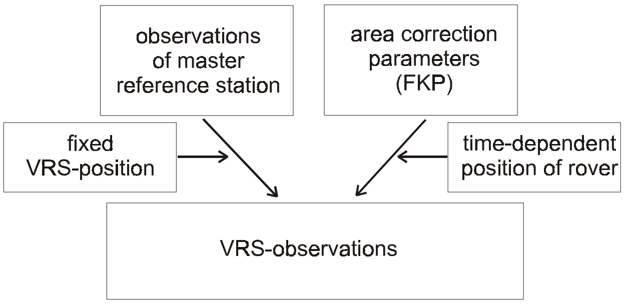

Fig. 2: Computation of the observations of a semi-kinematic VRS.

In contrast to a static VRS the observations of a semi-kinematic VRS should not be used for baseline processing of any rover stations situated in the vicinity of the VRS but only for the specific rover whose trajectory was used in the VRS computation. In case of real-time VRS computation at a central computing facility, the rover has repeatedly to transmit his approximate positions. Thus, a continuous two-way communication link is required.

In the subsequent baseline processing between semi-kinematic VRS and rover it has to be taken into account that the reference observations are based on network data, i.e. the apparent baseline length is irrelevant. On the other hand a small but not negligible amount of remaining ionospheric and tropospheric biases have to be considered. There size depends on the actual refraction conditions, the reference station separations, the actual number of reference stations used and on the selected interpolation algorithm.

4 TEST DATA SETS

Two kinematic test data sets have been selected which make it possible to compare baseline solutions between different kinds of reference stations and rover receivers. In both cases a permanent regional reference station network exists with station spacing in the order of 50 km. Local reference stations were employed temporarily, because in the original set-up it was not intended to make use of the permanent RS network.

Four kinds of kinematic baseline solutions have been analyzed based on the observations of different reference stations:

- **closest permanent reference station**: these are the preferred reference observations if no local RS exists and VRS-technique is not applied.
- **local reference station**: it is set up in the center of the area of interest so that the maximum distances to the rover are as short as possible. The objective of reference station networks is to make such temporary local RS obsolete.
- **static VRS:** It is based on the observations of the surrounding three permanent RS. Its position is selected, keeping the maximum distances to the rover as short as possible. These distances are even shorter than those from the local reference station to the rover, since no other restrictions apply to the VRS-position selection.
- **semi-kinematic VRS**: It provides the optimal VRS observations for the positioning of the rover. Its fixed position can be selected freely. For both test data sets the position of the static VRS is also used as the fixed position of the semi-kinematic VRS.

The VRS observations were computed in post-processing mode using the software package WaSoft/Virtuell (see http://www.wasoft.de). This software uses undifferenced observables and is thus especially suited for network applications. For the processing of the test data sets, the computation of static VRS observations has been extended to semi-kinematic VRS observations. VRS observations are provided in RINEX-format. Thus, the subsequent baseline processing can be performed with any post-processing software package. In the case of the test data sets presented here, the baseline processing was performed with WaSoft/K.

In order to reduce station-dependent biases, antenna phase center corrections were applied for the permanent and local RS. Using the corrections of elevation-dependant phase center variations for the rover antennas, the VRS were assigned antennas similar to those of the rovers. Thus the baselines between VRS and rovers are free of elevation-dependent phase center variations.

The elevation mask chosen was 10 degrees for all processing steps.

4.1 TEST DATA SET 1: FREEWAY A9

The first data set was collected on the German freeway A9 south of Berlin on November 24, 1999. The GPS observations contributed to the data acquisition of a freeway inventory. Two GPS antennas were mounted on top of the roof of a van at a fixed distance of 0,70 cm. One antenna was connected to a Trimble 4700 and the other to a Trimble 4000 SSE.

The van entered the freeway at the southern end of the stretch, traveled north for 12.5 km and returned to its starting point (Fig. 3). Its average speed was 50 km/h. The van used the left most lane in order to avoid signal obstructions by trees. Nevertheless, signal reception was repeatedly interrupted either by overpasses or by trees. The shortest time span with continuous observations lasted about 100 s, the longest span reached several minutes. The Trimble SSE lost signals more often and took a longer time to reacquire them. On its way back the van stopped four times to determine positions of control points in static mode. These static data have neither been included in Figure 5 nor in Table 1.

A temporary local reference station (Trimble 4000 SSI) was employed close to the freeway (Fig.3) at a site almost free of multipath. Observations of three permanent RS were made available by the state survey departments of Brandenburg and Sachsen-Anhalt (Fig. 3). A static VRS

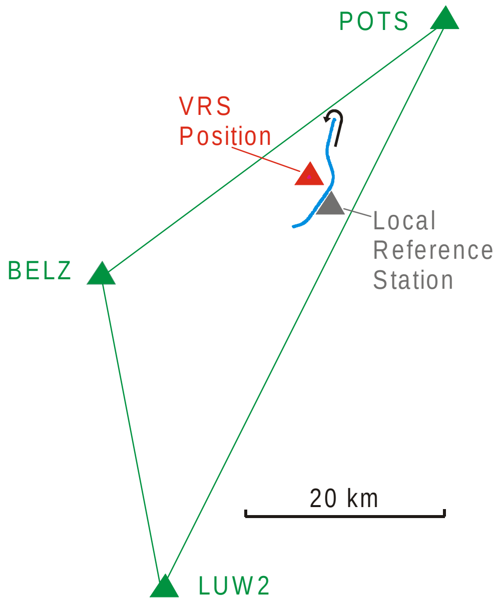

Fig. 3: Rovers trajectory and reference stations of test data set 1.

and a semi-kinematic VRS were computed based on these reference observations.

The FKP show the size of temporal variations of the differential ionospheric, tropospheric and orbit errors. Whereas the non-dispersive differential biases are fairly

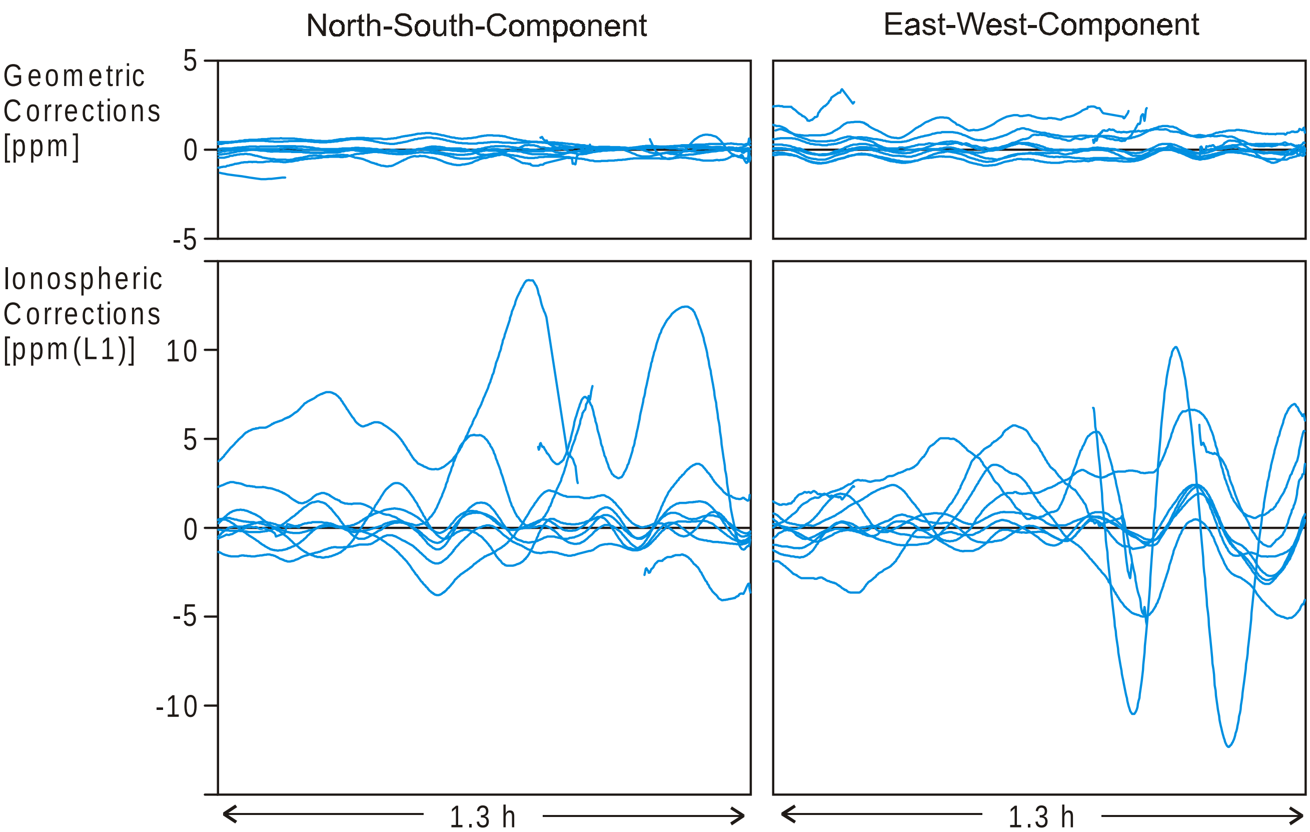

Fig. 4: Parameters of non-dispersive (geometric) and dispersive (ionospheric) correction models for test data set 1.

small, large medium-scale ionospheric disturbances are observed affecting the signals of 6 out of 11 satellites (Fig. 4). The ionospheric corrections reach more than 10 ppm(L1) of the distance components. Medium-scale disturbances causing such great errors indicate that a noticeable amount of residual ionospheric biases can be expected to be present in the baseline between VRS and rover receiver.

Ambiguity resolution could successfully be performed in the baselines between the local reference station or VRS stations and the Trimble 4700 rover receiver. The ambiguities of the long baseline between POTS and the Trimble 4700 receiver could only be resolved by introducing precise rover coordinates as provided by the other baselines.

Double-differenced residuals of four independent baseline solutions are shown in Figure 5. Residuals of the ionospheric-free linear combination of phase observations are dominated by station-dependent error sources, namely multipath effects. These residuals are smallest in the baseline to the local RS. This indicates that the local RS is less affected by multipath than the permanent RS, which are all located in multipath-rich environments on top of buildings. Ionospheric-free residuals are independent of baseline length revealing that for this example differential tropospheric and orbit errors are of minor importance.

Double-differenced L1-residuals are affected by both differential ionospheric refraction and station-dependent biases. The large ionospheric effects in the long baseline to the closest permanent RS (POTS) severely deteriorate successful ambiguity resolution (compare Table 1). Smallest L1-residuals are found in the baseline to the local RS, which is most probably due to the smaller multipath effects at the local RS.

It is important to note that the L1-residuals in the baseline to the semi-kinematic VRS are smaller by almost 10% compared to those in the baseline to the static VRS. Although the maximum distance between static VRS and rover does not exceed 6 km only, the semi-kinematic VRS shows a better performance than the static VRS

Coordinate solutions have been obtained for all 8 baselines between the 4 different kinds of RS and the 2 rover receivers using WaSoft/K. The correctness of the ambiguity fixing was tested with the help of the fixed distance between both rover antennas. Ambiguity fixing failed more often for the Trimble 4000 SSE rover receiver as compared to the Trimble 4700 receiver.

Tab. 1: Percentage of epochs with correctly resolved ambiguities for the baselines to both moving receivers.

reference station POTS	81
local reference station	95
static VRS	93
semi-kinematic VRS	93

As it was to be expected from the interpretation of the observation residuals of Fig. 4, the percentage of successful ambiguity fixing is lowest for the long baseline to the permanent reference station POTS and highest for the

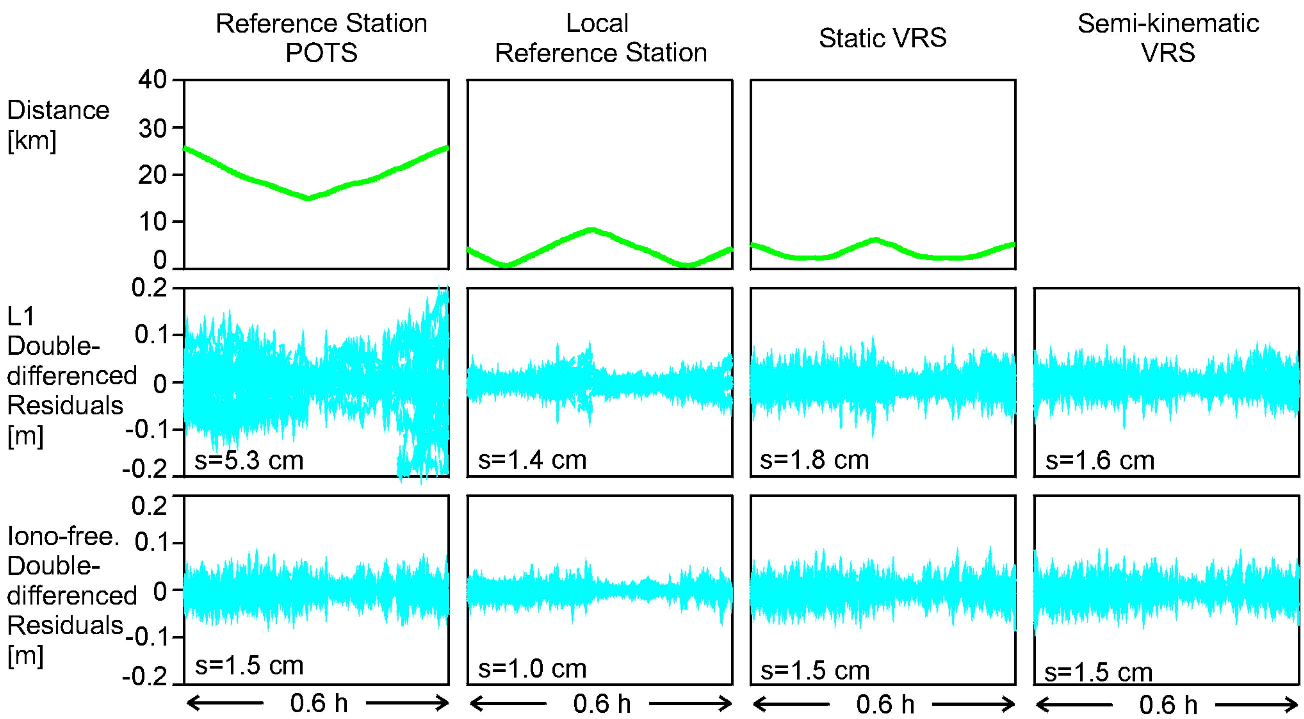

Fig. 5: Four different baseline solutions for the observations of test data set 1: distances to the reference stations, double-differenced residuals in the baselines from the reference stations to the rover.

baseline to the local RS (Tab. 1). The performances of the two VRS are almost as good as the performance of the local RS.

Improved VRS observations could be obtained if the station-dependent biases, namely carrier phase multipath, were reduced at the permanent reference stations. Nevertheless, even in the present situation VRS-observations are able to substitute local RS data.

4.2 TEST DATA SET 2: TEST FLIGHT VAIHINGEN

The second data set originates form a test flight over Vaihingen/Enz near Stuttgart, Germany, on June 6, 2000. A GPS-receiver (Ashtech UZ-12) and an inertial system operated on board the aircraft. The results presented here are based on the GPS observations only. Besides a temporary local RS in the center of the test area, three permanent RS were included in this test (Fig. 6). Four baselines from different kinds of reference stations to the rover receiver onboard the aircraft are compared: the baseline form the closest permanent RS (STUT), the baseline from the local RS, the baseline from a static VRS, and the baseline from a semi-kinematic VRS.

The flight data are of extraordinary good quality with respect to the continuity of the phase observations. Only few cycle-slips occurred during the 2.3 h flight so that all observations belong to the same ambiguity block. As a consequence ambiguity fixing could be performed successfully in all 4 baselines.

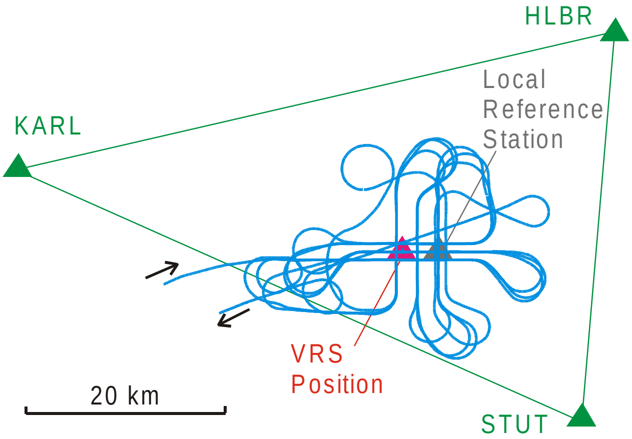

Fig. 6: Rovers trajectory and reference stations of test data set 2.

VRS observations were computed based on the observations of the three permanent RS. They refer to a common position on the ground. The horizontal components of the aircraft trajectory were used in the computation of the semi-kinematic VRS. The non-dispersive FKP corrections reached up to 3 ppm and the maximum ionospheric corrections amounted to 6 ppm(L1) (Fig. 7).

Double-differenced carrier phase residuals are largest for the long baseline to the permanent reference station STUT and smallest for the baseline to the semi-kinematic VRS (Fig.8). The performances of the local RS and the static VRS are indistinguishable. Existing differences are more pronounced in L1 and hardly recognizable in the iono-

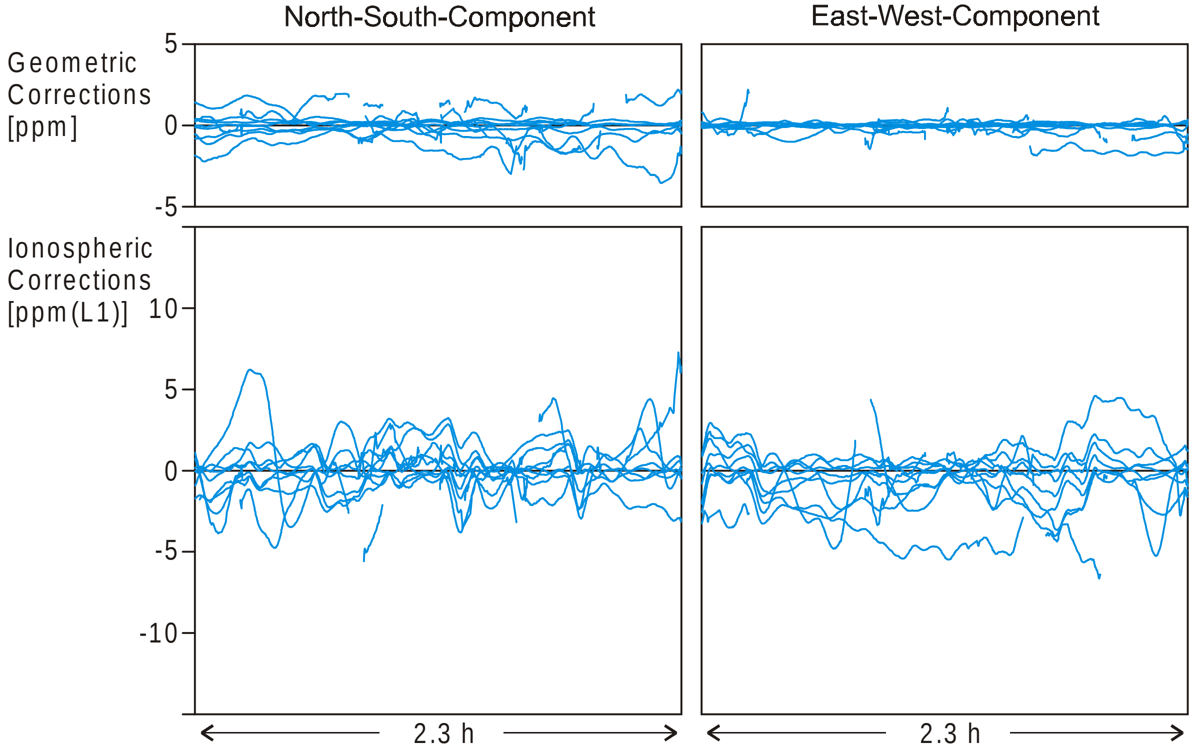

Fig. 7: Parameters of non-dispersive (geometric) and dispersive (ionospheric) correction models for test data set 2.

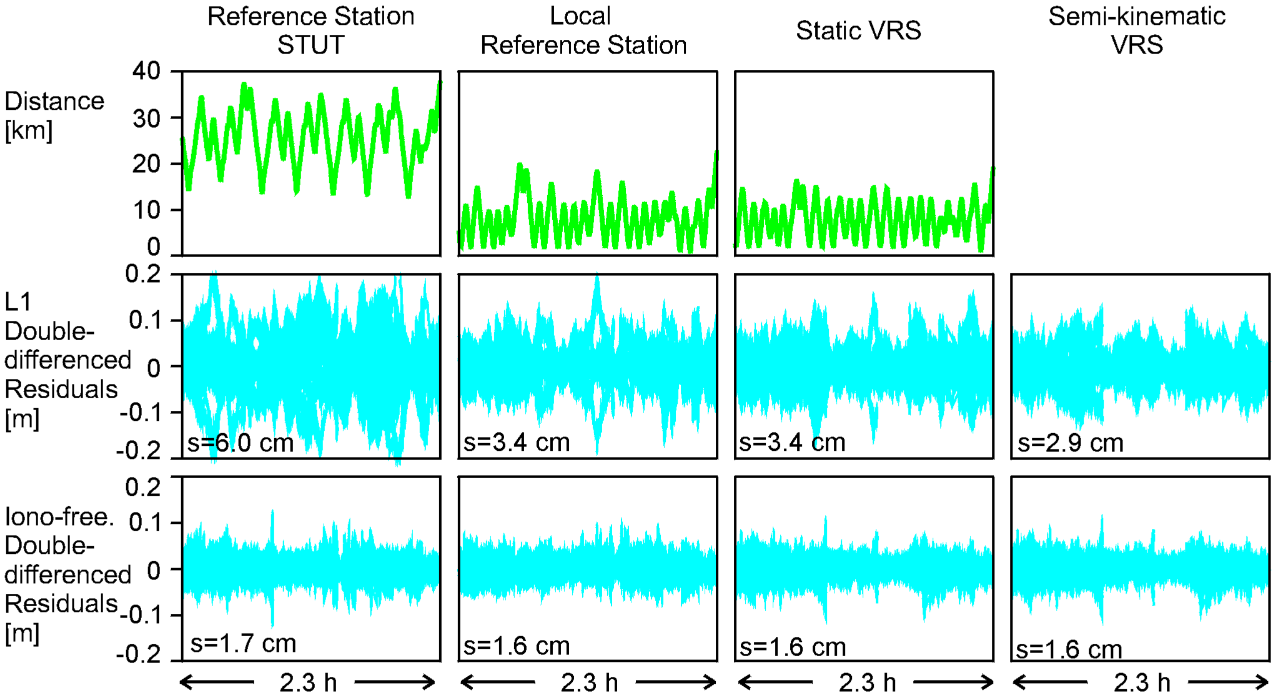

Fig. 8: Four different baseline solutions for the observations of test data set 2: distances to the reference stations, double-differenced residuals in the baselines from the reference stations to the rover.

spheric-free linear combination.

Smaller differential observation errors yield a faster and more reliable ambiguity resolution. Whereas no differences in the ambiguity resolution could be detected with the complete data set of 2.3 hours, the semi-kinematic VRS shows the best ambiguity resolution performance if we look at observation samples of 5 to 20 minutes (Tab. 2). In the long baseline from STUT ambiguity resolution could be successfully performed for less than 50% of the 5 minute samples. In case of the semi-kinematic VRS the percentage exceeds 90%. With a sample size of 20 minutes ambiguity resolution still fails for one block of observations in the baseline from STUT, but complete and correct ambiguity fixing is achieved for the other three kinds of reference stations.

Tab. 2: Percentage of epochs with correctly resolved ambiguities for the baseline to the moving receiver.

sample length [min]	5	10	20
number of samples	28	14	7
reference station STUT	46	64	86
local reference station	89	93	100
static VRS	89	93	100
semi-kinematic VRS	93	93	100

5 CONCLUSIONS

In an area of permanent reference stations with a station spacing of 30 to 70 km virtual reference stations (VRS) are able to substitute temporary local reference stations.

In the case of large-scale kinematic applications a semi-kinematic VRS leads to better positioning results than a static VRS. Especially the differential ionospheric biases are further reduced which enables a faster and more reliable ambiguity resolution.

An improved VRS performance could be achieved if carrier phase multipath effects were reduced at the permanent reference sites.

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The permanent GPS reference stations belong to the SAPOS-network of the German state survey departments. They were made available by the state survey departments of Brandenburg, Sachsen-Anhalt and Baden-Württemberg.

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