Real-Time Differential GPS Error Modelling in Regional Reference Station Networks[1]

Lambert Wanninger
Geodetic Institute, TU Dresden
D-01062 Dresden, Germany

Abstract

Observations of several GPS reference receivers in a regional network enable two kinds of error modelling and reduction. The spatially correlated errors (orbit, ionosphere, troposphere) are modelled epoch-by-epoch and satellite-by-satellite by 2-D linear interpolation. Furthermore, multipath effects are mitigated by averaging correspondent observations of several receivers. As a result, observations of a virtual reference station are created. It is assumed to be located at the rover's approximate position and its observations are used in the precise baseline positioning of the rover. This approach has been tested with several months of observations including data disturbed by ionospheric irregularities, large tropospheric gradients and large orbit errors. It considerably improved ambiguity resolution and reduced coordinate errors in the positioning of rover receivers.

Introduction

Precise (cm-accurate) GPS positioning uses carrier phase observations and requires the resolution of the double-differenced carrier phase ambiguities. It is usually performed in a baseline-mode with one receiver at a reference station and one rover receiver at a station whose position is to be determined. The effects of ionospheric refraction, orbit errors, and tropospheric refraction on the double-differenced observables grow with increasing baseline length and also depend on the baseline direction. Furthermore, station dependent errors like multipath show severest effects for observation sessions of just a few minutes or less. Therefore, it becomes increasingly difficult to resolve the ambiguities the longer the baseline length and the shorter the observation session. Fast and on-the-fly ambiguity resolutions are often limited to baseline lengths of 5 to 15 km, depending on the actual size of the observation errors and they require continuous observations for at least a few minutes.

In order to reduce the observation errors, GPS-measurements of a regional network of reference stations are used to model the baseline length and direction dependent errors (ionosphere, orbit, troposphere). As a consequence the distance dependence of ambiguity resolution and positioning accuracy is greatly reduced. A further improvement of the reference station observations is obtained through multipath mitigation

---

[1] Proceedings of the IAG Scientific Assembly, Rio de Janeiro, Sep. 1997, IAG Symposia 118, Springer Verlag, 86-92.

and quality control in the multistation reference network. As a result, we compute the observations of a virtual reference station located at the rover's approximate position.

Observation errors and their reduction

The dominant error sources in differential GPS positioning and the appropriate ways to model and reduce them in a reference station network will be briefly discussed below.

Although the effects of ionospheric refraction can effectively be removed with dual-frequency observations they adversely affect ambiguity resolution. The reduction of the differential ionospheric refraction is the most important step for the improvement of ambiguity resolution. Large-scale and medium-scale features of the differential ionospheric refraction can be modelled using latitude-differences and longitude-differences as parameters of a model consisting of two coefficients (inclined plane). The models are produced for each satellite at each epoch. A minimum number of three reference stations is required (Wanninger, 1995).

The differential effects of broadcast orbit errors also depend on the length and direction of the baseline. They can be corrected with a similar model to that described above (Wanninger, 1996; Wübbena et al., 1996). The differential effects of tropospheric refraction often do not only depend on the length and direction of the baseline but also on altitude differences. With small altitude differences in the reference station network a two-dimensional-modelling should be adequate, otherwise the model has to be extended to the third (height) dimension.

The size of multipath effects on both code and carrier phase observations depends on the station vicinity and the receiver/antenna-system. As long as no detailed information on the multipath occurrence at the various reference stations exists, multipath is considered to behave stochastically and its effect is reduced by averaging the corresponding observations of all reference stations.

Antenna phase centre offsets and variations should be pre-determined by calibration. No advantage is obtained by combining the observations of several reference stations.

Virtual reference station

Our objective is to combine the observations of several reference stations in such a way that an optimum set of observations of a virtual reference station is obtained, which can be used to determine the position of a rover receiver in baseline-mode. 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.

Several processing steps have to be performed in order to transform the observations of the network of real reference stations to the observations of the virtual

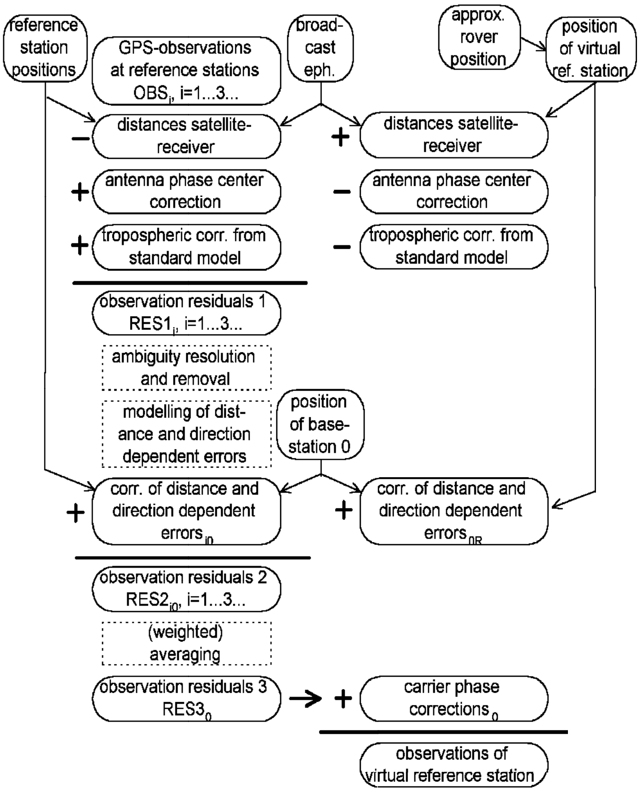

Figure 1:
Creation of the observations of a virtual reference station.

reference station (Fig.1). All processing steps are based on undifferenced carrier phase observables. In the first step the observations are reduced by the satellite-receiver distance computed from the broadcast ephemeris. Furthermore, antenna phase centre corrections and standard tropospheric corrections are applied. The resulting observation residuals are used to resolve and remove the double-differenced carrier phase ambiguities. This step is a prerequisite for all further error modelling and reduction. If ambiguity resolution fails for any observation, it 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 perform than for unknown baselines. On the other hand, distance dependent errors limit the complete ambiguity resolution to maximum distances between reference stations of some 50 km. Most of the difficulties are encountered for low-elevated satellites. From time to time, ambiguity resolution in the post-processing experiences difficulties with short, and typically low, satellite passes. Real-time processing sometimes also fails for the first minutes of data of a rising satellite.

After the successful double-differenced ambiguity removal, two linear combinations of the carrier phase observations are formed. The coefficients of the ionospheric model are calculated from the ionospheric linear combination and the coefficients of the geometric model, which contains the tropospheric and orbit errors, are calculated from the ionosphere-free linear combination.

Both kinds of models are applied to the reference station observations in such a way that the error budget of all reference stations refers to the position of a selected base station, e.g. at the "centre" of the network. Now, simultaneous observations of

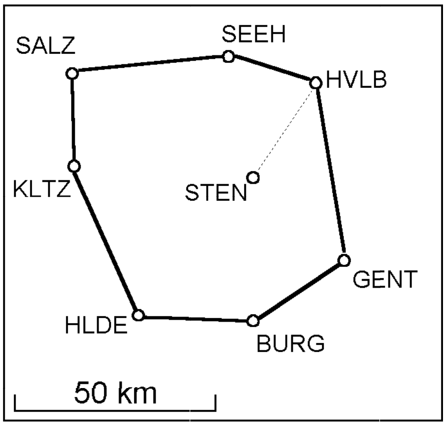

Figure 2: Northern part of the regional GPS reference station network in Sachsen-Anhalt, Germany.

different reference stations to a satellite should be identical with the exception of multipath, random errors, and the receiver clock error. An averaging process is performed for code and phase on the level of single-differences between satellites, nevertheless undifferenced observation residuals are stored. It reduces both multipath and random errors. In the end, one set of undifferenced observation residuals is obtained, which mainly contains satellite and receiver clock errors and the errors due to ionosphere, orbit and troposphere as they would be experienced at the selected base station.

The observations of the virtual reference station can then be constructed as shown on the right hand side of Figure 1. With the help of the ionospheric and geometric error models the distance dependent errors are shifted from the base station position to the position of the virtual reference station.

The 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, the virtual observations are computed for the 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.

Test data set and results

Three months of observations of a regional German GPS-network (Fig.2) with distances between adjacent reference stations of 23 to 40 km have been processed in order to verify the concept of virtual reference stations. The receiver at station STEN has been considered a rover receiver, all other receivers were used as reference receivers. Observations of a virtual reference station at STEN were computed and used to position the receiver at STEN. Ionospheric and geometric error models of the complete data set were evaluated in order to find periods with standard conditions (undisturbed) and disturbed periods of time. Examples of error models are shown in Fig.3. For each epoch and satellite four model coefficients are computed from the reference observations: latitude and longitude components of the ionospheric and of the geometric model. The numbers are given in units of ppm - parts per million of the coordinate difference

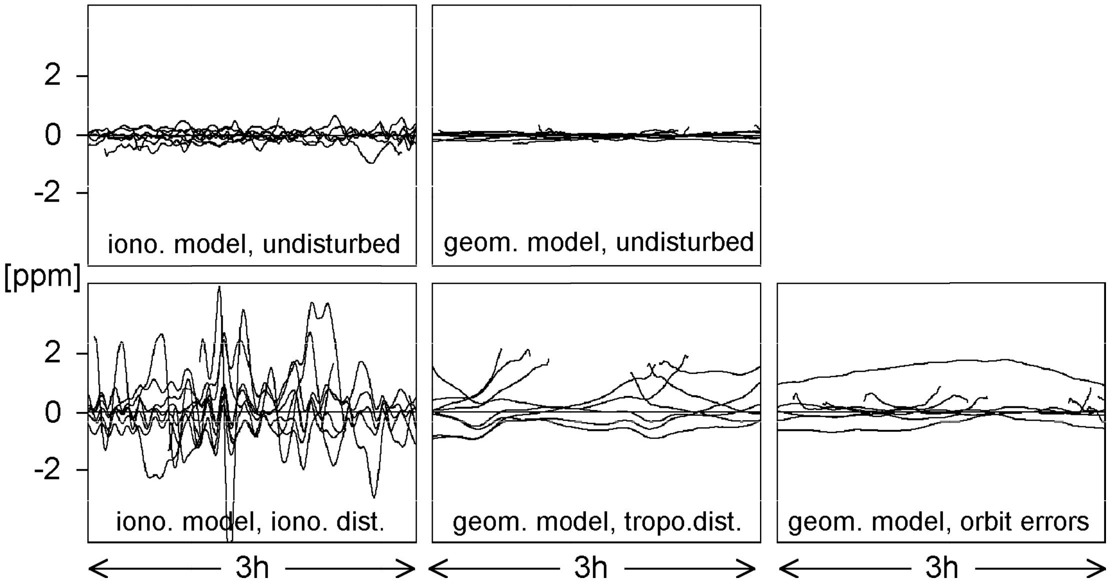

Figure 3: Examples of ionospheric and geometric error models under standard conditions (undisturbed) and under disturbed conditions. Each line represents the time series of model coefficients of a specific satellite. Each example shows either the latitude component or the longitude component of an error model.

for the specific component. The ionospheric model is scaled to the ionospheric effect on L_1-observations.

Most of our data (80-90%) were free of severe disturbances and can be considered as observed under standard conditions. Nevertheless, three kinds of disturbances were detected in the time period from November 1996 to January 1997:

- Medium-scale travelling ionospheric disturbances (MSTIDs), which in mid-latitudes mainly occur during day light hours of winter months (Wanninger, 1995), were found on many days of the November and December data. The error models reveal the characteristic apparent MSTID-periods of 10 to 30 minutes. Maximum rates of change of the error model coefficients can be found in the presence of these disturbances. They reach up to 1.5 ppm/minute.
- Severe tropospheric disturbances due to large humidity and temperature gradients occurred once in the three month period and lasted for more than 24 hours. Observation errors exceeded 1 ppm of the baseline length and mainly affect the height component of the baseline coordinate differences.
- Large broadcast orbit errors of 30 to 50 m were detected for about one satellite pass per week. They produce observation errors of more than 1 ppm of the baseline length.

Under standard conditions single epoch ambiguity resolution succeeded for more than 99% of the observations, and produced incorrect results for just 0.01% of the data. Under disturbed conditions the success rate decreased to about 95%, with the percentage of incorrect results increasing to about 0.5%.

Table 1: Ambiguity resolution and positioning errors with 5-minute-samples of observations (GPSurvey 2.20).

Baseline		# of samples	Success Rate Ambiguity Resolution	Positioning Errors RMS dN/dE/dH [cm]	
				L_1	L_0
HVLB–STEN (29 km)	Standard Cond.	864	89%	–	1.1/0.7/2.5
	Iono. Disturb.	119	87%	–	1.3/0.8/2.8
	Tropo. Disturb.	106	89%	–	1.6/0.8/7.8
	Large Orbit Err.	126	97%	–	1.3/0.8/2.7
Virt. Ref. Station – STEN	Standard Cond.	864	98%	0.9/0.6/1.9	1.0/0.6/2.4
	Iono. Disturb.	119	96%	1.5/0.9/2.7	1.1/0.7/2.7
	Tropo. Disturb.	106	100%	1.4/0.7/1.7	1.4/0.6/2.4
	Large Orbit Err.	126	99%	0.8/0.7/1.7	0.9/0.6/2.2

Table 1 summarizes the results of positioning with 5-minute-blocks of data as performed with the post-processing software GPSurvey 2.20. It compares the baselines from STEN to the closest real reference station HVLB (29 km) to the positioning of STEN with a virtual reference station. The success rate of ambiguity resolution could be improved from about 90% to about 98%. The position estimation of a 29 km baseline is usually performed with the ionospheric-free linear combination L_0. For the positioning with the virtual reference station, however, ionospheric errors have already be considerably reduced, so that an L_1-solution would be more accurate than an L_0-solution because of its lower sensitivity to multipath and random errors. And in fact, the positioning errors are not only smaller using the virtual reference stations as compared to the 29 km baseline, in most cases an L_1-solution is more accurate than an L_0-solution. The only exception that was found was in the presence of ionospheric disturbances. Here, the ionospheric error model removes most of the effects but it does not perform as well as the dual-frequency ionospheric correction.

Conclusions

Combining the observations of several reference stations of a regional GPS-network to create observations of a virtual reference station greatly improves ambiguity resolution and reduces positioning errors. This improvement is mainly achieved by modelling the differential errors of ionospheric refraction, broadcast orbit errors and tropospheric refraction. The redundant data of the reference network are also used for mitigation of multipath and random errors and for a quality control of the observations.

The main prerequisite for the calculation of virtual reference station observations is successful ambiguity resolution for the reference station network. In general, this requirement presents no difficulty for distances between reference stations up to about 50 km, even for data processing in real-time, because the reference station coordinates are well known.

Acknowledgement. The GPS observations were made available by the state survey department of Sachsen-Anhalt, Germany.

References

Wanninger, L. (1995): Improved ambiguity resolution by regional differential modelling of the ionosphere, *Proceedings of ION GPS-95*, pp. 55-62.

Wanninger, L. (1996): Fehlermodellierung in regionalen Referenzstationsnetzen, *41. DVW-Fortbildungsseminar: GPS-Anwendungen und Ergebnisse '96*, Potsdam, Nov. 7-8, 1996, DVW-Schriftenreihe 28/97, pp. 206-218.

Wübbena, G., Bagge, A., Seeber, G., Böder, V., Hankemeier, P. (1996): Reducing distance dependent errors for real-time precise DGPS applications by establishing reference station networks, *Proceedings of ION GPS-96*, pp. 1845-1852.