Carrier Phase Multipath Corrections Based on GNSS Signal Quality Measurements to Improve CORS Observations

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Abstract— **Carrier phase multipath caused by reflections in the vicinity of GNSS stations is a major error source of precise differential positioning. Detection and mitigation of carrier phase multipath errors can be based on signal quality measurements, i.e. signal-to-noise ratio (*S*/*N*) or carrier-to-noise ratio (*C*/*N*), as provided by GNSS receivers. Variations of the signal quality oscillation frequency are caused by changes of the reflected signal's additional path length. Calculating carrier phase multipath corrections from signal quality time series is not simple. Most published algorithms need various interim results, e.g. phase shift or attenuation factors, to calculate the final correction value. Our algorithm, however, directly estimates carrier phase multipath corrections from signal quality measurements. In order to validate the potential of this multipath mitigation method in practice, GPS/GLONASS observation data sets of six continuously operating reference stations (CORS) of the German SAPOS network were corrected. All these stations are equipped with receivers for which the signal quality based multipath mitigation performs similarly well for both frequencies. Thus multipath mitigation may even improve coordinate results based on the ionosphere-free linear combination. We present a detailed analysis of the effects of carrier phase multipath corrections on positioning results in this CORS subnetwork.**

GNSS; carrier phase multipath; signal-to-noise; signal quality; CORS

I. INTRODUCTION

Ideally, a signal transmitted by a satellite arrives at a receiving antenna on its direct path. However, the direct signal is superimposed by indirect signals, which are either reflected in the receiver antenna surroundings or at the transmitting satellite. This causes the received signal to become a composite signal whose phase is shifted when compared to the direct signal. Assuming a single reflected signal the amplitude A_c of the composed signal and the carrier phase error due to multipath interference $\delta\varphi$ can be described as indicated in [1] and [2] by

$$A_c = A_d \cdot \sqrt{1 + 2\alpha \cos \Delta\varphi_r + \alpha^2}\,, \qquad (1)$$

$$\delta\varphi = \arctan\left(\frac{\alpha \sin \Delta\varphi_r}{1 + \alpha \cos \Delta\varphi_r}\right). \qquad (2)$$

A_d denotes the amplitude of the direct signal (as voltage ratio), α the ratio of the amplitude of reflected and direct signal ($0 \leq \alpha \leq 1$) and $\Delta\varphi_r$ the phase shift with respect to the direct signal. The theoretical maximum carrier phase error occurs for $\alpha = 1$ and $\Delta\varphi_r = \pi$. This yields maximum phase range error of 4.8 cm and 6.1 cm for Global Positioning System (GPS) L1 and L2, respectively.

In addition to carrier phase and code observables Global Navigation Satellite System (GNSS) receivers record information concerning the signal quality. Signal quality is a generic term which describes the ratio of signal power to noise power. Signal-to-noise ratio can usually be found in the context of signals as baseband using the power of the modulated signal at correlator output [3]. As shown in [3] and [4] the quality of a received GNSS signal is commonly described by its carrier-to-noise ratio using the power of the unmodulated carrier at the receiving antenna. Nevertheless, signal quality is given either as signal-to-noise ratio (*S*/*N*) or as carrier-to-noise ratio (*C*/*N*). In order to ensure comparability among various GNSS receivers, signal quality is often normalized to a specific loop bandwidth, e.g. 1 Hz. This yields to signal-to-noise power density ratio (S/N_0) and carrier-to-noise power density ratio (C/N_0) [5].

The link between oscillations in the recorded signal quality and carrier phase multipath is described in detail in e.g. [6], [7] and [8].

This paper describes the effect of carrier phase multipath corrections based on signal quality measurement on GPS/GLONASS observation data sets of six continuously operating reference stations (CORS) of the German SAPOS network. The following section outlines the model for estimating carrier phase error due to multipath. The third section will give a short overview of the network stations used for analysis. Results of the data analysis are described in section four.

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II. CARRIER PHASE MULTIPATH ESTIMATION BASED ON MEASURED SIGNAL QUALITY

The algorithm used in this paper to improve CORS of the German SAPOS network is described in [9]. At first, the ratio Q_A of the amplitude of the composite signal A_c and the amplitude of the direct signal A_d is obtained from (2)

$$Q_A = \frac{A_c}{A_d} = \sqrt{1 + 2\alpha \cos \Delta\varphi_r + \alpha^2}\,. \tag{3}$$

The direct signal amplitudes A_d were determined by polynomial fits to the raw signal quality measurements.

Afterwards the carrier phase multipath error is obtained by differentiating Q_A with respect to $\Delta\varphi_r$

$$\delta\varphi_{sq} = -\arcsin\left(\frac{dQ_A}{d\Delta\varphi_r}\right). \tag{4}$$

A simple geometric situation of one almost horizontal reflector below the antenna horizon is assumed. Then changes of $\Delta\varphi_r$ over time can be estimated by

$$\frac{d\Delta\varphi_r}{dt} = \frac{2\pi}{\lambda} 2h \cos el \frac{del}{dt}. \tag{5}$$

Changes of the satellite's elevation angle over time (del/dt) can easily be computed from broadcast ephemeris. The vertical distance h between antenna and horizontal reflector must be known. λ denotes the GNSS wavelength.

The algorithm was tested using data sets of two Leica GRX1200GG Pro receivers. In contrast to older Leica receivers tested in [7], with GRX1200 receivers, L2 carrier phase multipath corrections from signal quality observations perform as well as L1 corrections. Earlier tests showed that a large amount of the carrier phase multipath effect can be removed and thus, carrier phase multipath corrections could improve positioning results [9].

A successful multipath mitigation using the aforementioned technique is restricted to certain applications and multipath environments. These restrictions include: observations collected in static mode, multipath caused by geometrically well-defined reflectors. Furthermore, if there is more than one well-defined reflector, estimating the carrier phase multipath corrections as shown above is expected to fail.

III. CORS NETWORK SAXONY-ANHALT

In order to further validate the potential of this multipath mitigation method in practice, GPS/GLONASS observation data sets of six CORS of the federal state of Saxony-Anhalt, a subnetwork of the German SAPOS network, were used. Fig. 1 gives an overview of the CORS location within the subnetwork of Saxony-Anhalt. Horizontal reflectors dominate the station surroundings of these six CORS. All CORS are equipped with Leica receivers and choke ring antennas (see Fig. 1 for details). The antennas are mounted on the roof of the buildings with a vertical distance antenna – reflector between 0.7 m and 4.2 m (see Fig. 2). The network baselines vary between 36.2 km and 139.9 km.

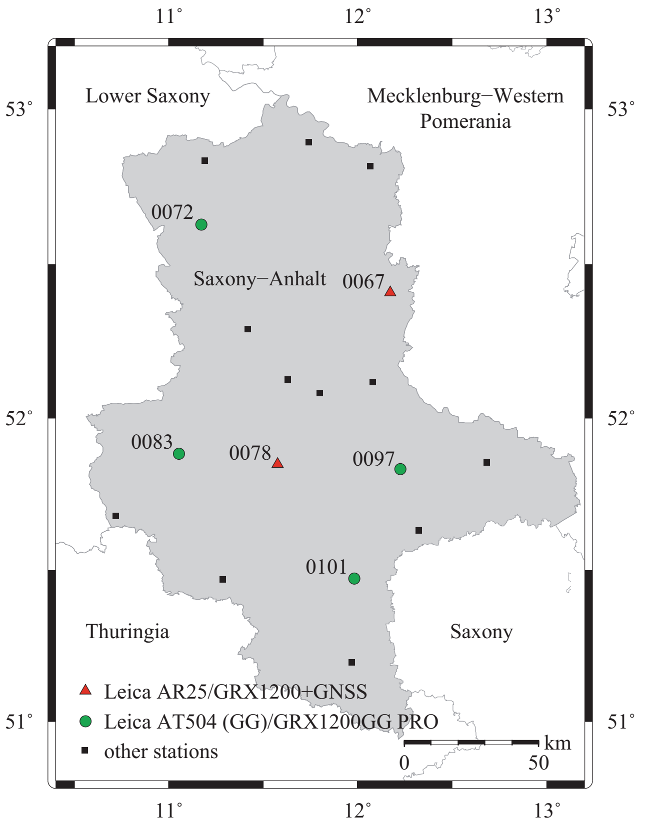

Figure 1. CORS of the SAPOS subnetwork of Saxony-Anhalt used for the data analysis.

Seven days (2 – 8 October 2009) of GPS/GLONASS data collected at 15 s sample intervals were used for the analysis. This set of data was recorded especially with signal quality resolution of 0.25 dB-Hz and 0.05 dB-Hz respectively. Usually the resolution of SAPOS signal quality values is 1 dB-Hz only. The data were collected with a 0° or 5° elevation mask.

IV. PHASE MULTIPATH ESTIMATION AND DATA ANALYSIS

GPS and GLONASS carrier phase multipath corrections were estimated for the six CORS from signal quality using the algorithm presented in section two. The phase corrections were applied to the raw phase observations stored in RINEX format (RINEX – Receiver Independent Exchange Format).

In a second step, the original and the corrected data were analysed in a baseline mode with the baseline processor Wa1. Precise GPS/GLONASS orbits from ESOC (European Space Operation Centre) and antenna phase centre corrections were taken into account.

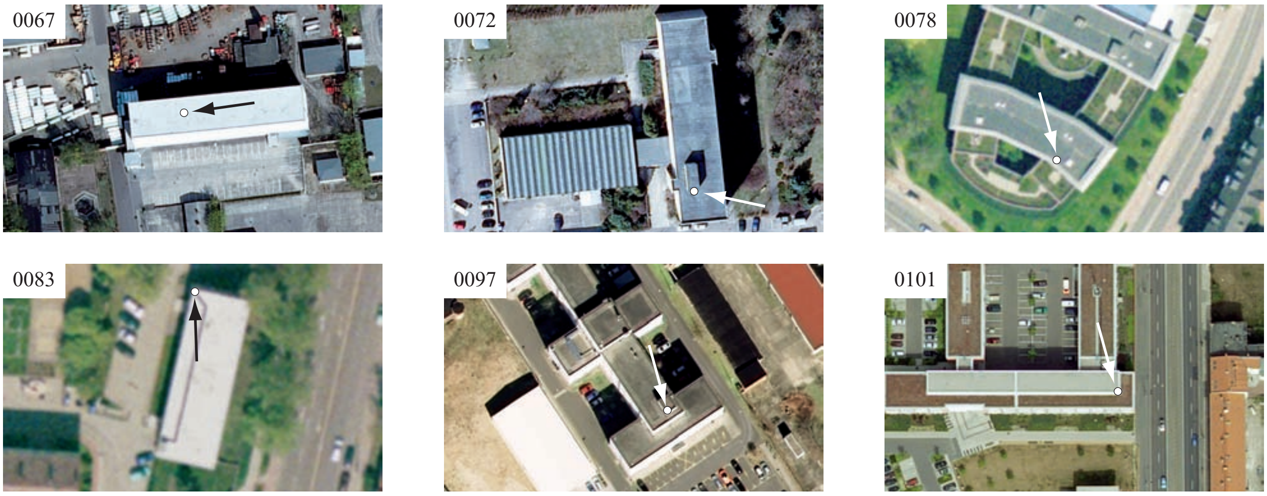

Figure 2. Aerial photos of the station surroundings of the CORS used in this study (source: Federal Agency for Cartography and Geodesy).

Single epoch baseline coordinate solutions were computed for the ionosphere-free linear combination. Because of the length of the baselines, tropospheric zenith delays had to be estimated. To ensure the comparability of the results, all baselines were computed with a 5° elevation cut-off.

Tab. I summarises the change of the standard deviation from ionosphere-free single epoch coordinate residuals (separately for the horizontal components and height) in per cent. The lower triangular matrix shows the change for the GPS/GLONASS solution, whereas the upper triangular matrix shows the change for the GPS solution. Implementing GPS and GLONASS L1 and L2 carrier phase multipath corrections for phase data leads to improvement of the positioning results, especially for the height component it can be up to 13%. This is remarkable, because all stations are equipped with a conventional choke ring antenna or a conical choke ring antenna (see Fig. 3 and Fig. for details). Nonetheless, deterioration especially in the horizontal components up to –6.5% can also be seen.

The differences of the standard deviations from original and corrected positioning residuals are in the same order for the following days. Due to an inhomogeneous tropospheric influence the percentage improvement on several days is smaller than shown in Tab. I.

The baselines including station 0067 show the largest improvements for the combined GPS/GLONASS solution as well as for the GPS solution. The comparison of original with corrected single epoch coordinate residuals reveals that the effect of carrier phase multipath on the positioning results can be reduced (see sample in Fig. 4).

Fig 4 compares three hours of single epoch coordinate residuals of original and corrected data for the ionosphere-free linear combination from baseline 0067 – 0083. Particularly peaks in the single epoch coordinates height component (bottom row) can be attenuated. In general, the phase multipath corrections decrease, but not completely remove systematic errors in the positioning residuals.

TABLE I. CHANGE OF POSITIONING RESULTS FOR IONOSPHERE-FREE SINGLE EPOCH COORDINATE RESIDUALS (NORTH/EAST/UP) AS OF 2 OCTOBER 2009 FROM STANDARD DEVIATIONS FROM ORIGINAL AND CORRECTED DATA. THE UPPER TRIANGULAR MATRIX SHOW THE IMPROVEMENT IN PER CENT FOR GPS SOLUTION AND THE LOWER TRIANGULAR MATRIX FOR GPS/GLONASS SOLUTION.

CORS	**0067**	**0072**	**0078**	**0083**	**0097**	**0101**
		GPS solution				
0067	north/east/up	8.5/ 9.7/ 8.6	4.7/ 7.4/ 7.4	11.9/ 8.9/12.9	8.0/ 9.2/13.1	11.1/10.7/ 9.8
0072	9. 7/ 9.3/ 7.2		–2.3/ 2.8/ –0.6	6.8/–1.3/ 3. 8	2.3/–2.3/ 0.3	0.1/ 4.1/ 0.5
0078	6.7/ 6.6/ 8.7	–2.3/ 3.6/ –0.1		3.1/–0.5/ 2.7	0.0/ 1,8/–0.6	–2.2/ 5.8/ 0.6
0083	11.0/ 6.6/12.3	6.8/–2.5/ 3.0	–0.1/ –1.2/ 5.1		9.2/–1.3/ 4.7	4.6/ 3.4/ 5.6
0097	9.4/ 8.6/13.7	0.4/ 1.0/ 1.1	–4.1/ 3.1/ 4.6	5.7/–0.7/ 4.8		0.9/ 6.6/–1.3
0101	11.9/ 9.7/10.7	–0.3/ 4.6/ 0.5	–6.5/ 5.1/ 3.7	5.0/ 1.3/ 5.6	0.8/ 8.3/ 1.6	
	GPS/GLONASS solution					

Leica AT504 (GG) Leica AR25

Figure 3. Different Leica choke ring antenna models used in this study, the conventional choke ring antenna AT504 (GG) and the conical choke ring antenna AR25 (source: Leica Geosystems).

Tab. I reveals that the positioning change in other CORS combinations is negligible or negative in some cases. A thorough analysis of the data has shown that the station surroundings from CORS 0072, 0078, 0097 and 0101 do not conform to the model-based assumption of one well-defined reflector. As has shown in Fig. 2 these stations have more than one horizontal reflector below the antenna horizon. Only the CORS 0067 and 0083 will the model-based assumption of one well-defined horizontal reflector. The various reflectors of the other CORS cause false carrier phase multipath corrections.

To assess the impact of several horizontal reflectors on the carrier phase multipath corrections estimated from signal quality, the original as well as the corrected RINEX files were computed with WaSoft/Multipath [10]. In contrast to the algorithm presented in section one WaSoft/Multipath uses carrier phase observations to detect and to locate carrier phase multipath errors for the ionosphere-free linear combination [10]. The data basis comprises seven days of phase observations of the six CORS.

A comparison of original with corrected carrier phase multipath maps for the different CORS used in this study is given in Fig. 5. It reveals that a large portion of the carrier phase multipath effects can be removed, especially for the stations 0067 and 0083. Both CORS match the model-based assumption of one well-defined reflector. For station 0078 phase multipath effects in the north–east direction could be removed. Phase multipath in the south–west direction, however, was increased. The false corrections are the result from a second horizontal reflector in the south–west direction near the antenna phase centre (see Fig. 6). The multipath maps, especially for stations 0067 and 0078 indicate that the conical choke ring antennas do not guarantee multipath free observation data from satellites with lower elevation.

V. CONCLUSIONS

Carrier phase multipath corrections for GPS and GLONASS were estimated using signal quality measurements. The carrier phase multipath corrections were applied to observation data from six continuously operating reference stations (CORS) of the SAPOS subnetwork Saxony-Anhalt. Comparing baseline solutions for the ionosphere-free linear combination

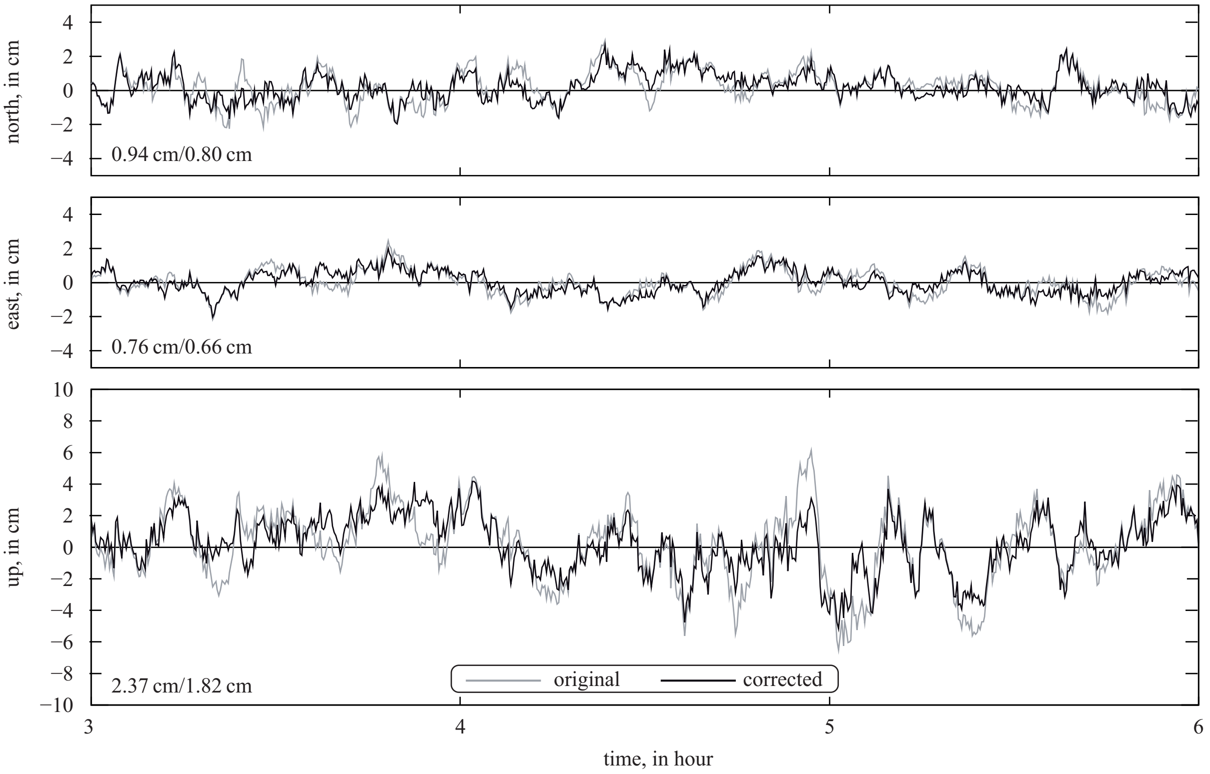

Figure 4. GPS single epoch residuals from original (grey) and corrected (black) data for baseline 0067 – 0083. Top row show residuals for north, middle row for east and bottom row for height component with standard deviations (original/corrected) for the given time range.

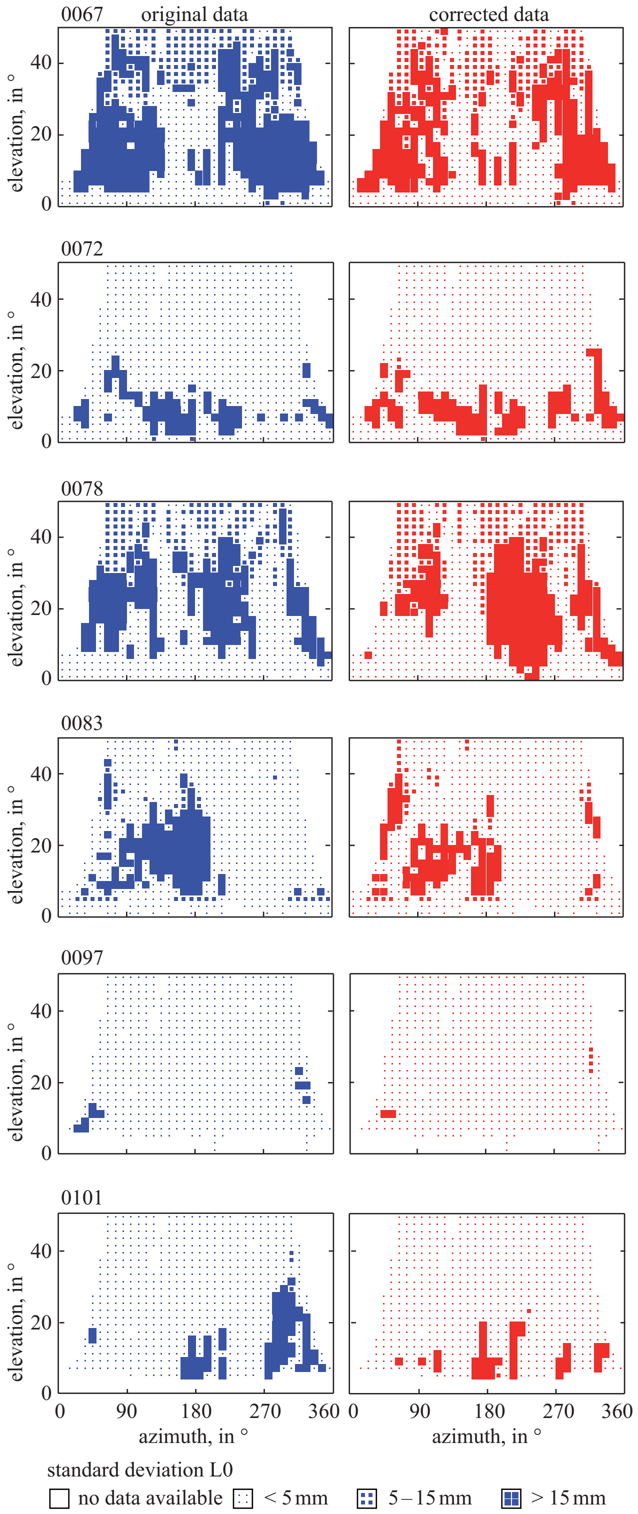

Figure 5. Carrier phase multipath maps estimated with WaSoft/Multipath from original (left) and corrected (right) phase data (data from 2 – 8 October 2009) for the CORS used in this study.

before and after applying phase multipath corrections shows an improvement in the single epoch coordinate standard deviation up to 13%.

Figure 6. Detail picture of the station surrounding of CORS 0078 (facing west) before the change to a choke ring antenna. The balustrade on the left causes false carrier phase multipath estimation.

Our experience in applying the described technique of computing phase multipath corrections to CORS observation data indicates that extracting corrections requires a careful station selection. Due to several restrictions, the described method cannot be used for multipath mitigation in general. Nevertheless, the results presented in this paper suggest that if signal quality measurements are available for GNSS stations on both frequencies with an appropriate resolution, this technique could be useful to remove carrier phase multipath errors for GNSS sites with a simple well-defined multipath environment.

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