Using residual stacking to mitigate site-specific errors in order to improve the quality of GNSS-based coordinate time series of CORS

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Abstract

Within the last decades, positioning using GNSS (Global Navigation Satellite Systems; e.g., GPS) has become a standard tool in many (geo-)sciences. The positioning methods Precise Point Positioning and differential point positioning based on carrier phase observations have been developed for a broad variety of applications. Focussing on high precision applications, a lot of effort was invested to mitigate important error sources (see Table 1). Therefore, within processing of data of CORS (continuously operating reference sites) equipped with geodetic hardware using a sophisticated strategy, the latest products and models nowadays enable positioning accuracies at low mm level.

Despite the considerable improvements that have been achieved within GNSS data processing, a generally valid multipath model is still lacking. Therefore, site-specific multipath still represents a major error source in precise GNSS positioning. Furthermore, the calibration information of receiving GNSS antennas, which is for instance derived by robot or chamber calibrations, is valid only for the location of the calibration. The calibrated antenna can show a slightly different behaviour at the CORS due to multipath effects especially. One very promising strategy to mitigate multipath effects as well as imperfectly calibrated receiver antennas is to stack observation residuals of several days. Thereby, observation residuals are analysed for respective signal direction, to find and reduce systematic constituents.

Error source	Mitigation
Satellite orbits and clocks	Advanced models and reprocessing campaigns
Satellite and receiver antennas	Improved models and calibration methods
Ionosphere/troposphere	Improved models in processing software
CORS hardware	New receivers and antennas

Table 1: Error sources and mitigation methods for GNSS positioning.

GNSS Upper Rhine graben Network (GURN)

GURN actually (April 2014) includes German, French and Swiss continuously operating GNSS sites (see Figure 1).

The data of the German sites is mainly provided from SAPOS® Baden-Württemberg and SAPOS® Rheinland-Pfalz. Most sites are enabled to track GPS and GLONASS data and are actually updated to be capable for future GNSS signals (e.g., Galileo).

The data of the French sites have several origins: RENAG (universities and research institutes), RGP (network of IGN), Teria, Orpheon, EOST. Thus, the sites were established for scientific resp. business purposes.

Additionally, one IGS site (HUEG), one EPN site (KARL) and two GREF sites (DILL, BFO1) are included. A further extension of the network in northern direction is planned.

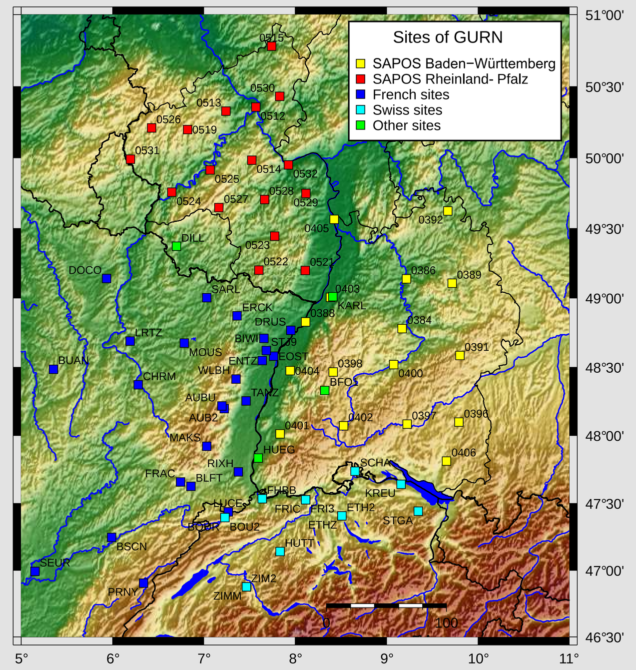

Figure 1: Map of GURN in the actual configuration (March 2014) with sites in Germany, France, and Switzerland.

The network covers the whole URG region homogeneously with about **80 permanently operating sites**. The mean distance between the sites is **40 - 60 km**. The database of GURN starts in the year 2002, when SAPOS® Baden-Württemberg began to archive their data. The data archive of SAPOS® Rheinland-Pfalz begins in 2004. Most of the French sites were established after 2006, swisstopo provides data for GURN since 2009. Hence, the time series comprise max. **12 years**. The archived observations have a tracking rate of at least 30 s.

The **main goal of GURN** is to determine a **revised, sophisticated geodynamical model for the region of the Upper Rhine Graben** using results of GNSS data processing. In this area, site velocities in the range of mm or even **sub-mm per year** are expected. Therefore, a long data history of high quality GNSS data and a sophisticated data processing strategy is of fundamental importance.

Figure 2 left: site ERCK (operated by EOST), right: site 0528 (operated by SAPOS® Rheinland-Pfalz).

The permanently operating sites of GURN were established for different purposes. Some few sites were explicitely installed in order to monitor geodynamic processes with a good coupling to the ground using a massive fundamentation and a pillar type setup (e.g., ERCK, see Figure 2 left). Most GURN sites were installed to be used as reference stations for positioning services which enable users to achieve realtime positioning. Therefore, the sites are mainly located on roof tops in order to guarantee obstacle-free signal tracking (e.g., 0528, see Figure 2 right). For more details to GURN see Mayer et al. (2012).

GNSS data processing challenges within GURN

The **individual environment** of each GURN site causes **individual site-specific effects;** including especially **multipath** effects, which occur when the satellite signal is reflected on its way to the antenna. These effects can cause direction-related positioning errors in the range of several cm (see Figure 3). A temporally changing environment (e.g., vegetation) of the sites may result in pseudo coordinate changes of stable sites which imply pseudo movements.

Equipment changes on the sites (e.g., antenna) can cause jumps in single coordinate components and thus interupt the time series. Therefore, from the geodynamic point of view, CORS should be operated as long as possible with identical equipment. This is contrary to the demands of GNSS RTK service providers which are interested in supplying the most recent techniques to their customers.

Further, the monumentation of the site can imply **seasonal signals** in the coordinate time series (see Figure 4 left) and shadowing by variable vegetation may result in stronger **noise** (see Figure 4 right).

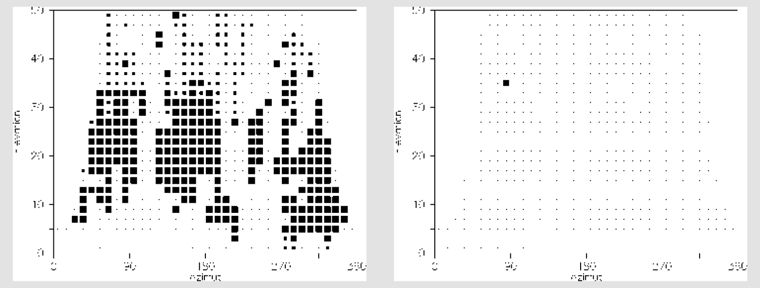

Figure 3: Multipath maps estimated using WaSoft/Multipath; left: site 0387 representing strong impact of multipath; right: site 0403 showing no significant impact of multipath. Small/medium/large dots: no/small/large impact of multipath => RMS of the ionosphere-free linear combination <5 mm/<15 mm/>15 mm.

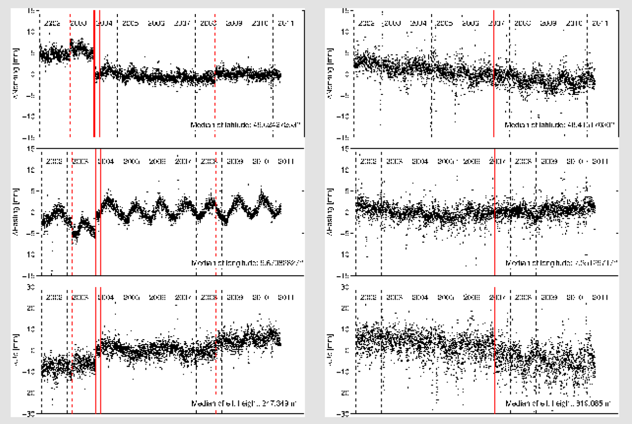

Figure 4: Coordinate time series of two GURN sites. Coloured vertical lines mark equipment changes. Left: site 0392, strong seasonal signal on easting component; right: site WLBH, strong scattering due to shadowing by vegetation.

The estimation of 3D positions based on GNSS observations of permanently operating sites with an accuracy of few cm is nowadays state-of-the-art. mm-level position qualities can be achieved using a sophisticated data processing strategy based on adequate handling of limiting effects using appropriate models (e.g., atmosphere), external data (e.g., satellite orbits) and calibration values (e.g., antenna modelling).

Despite the considerable improvements that have been achieved within GNSS data processing, a generally valid **multipath model is still lacking**. Most of the GNSS receiving **antennas** of GURN are individually calibrated on absolute level. Strictly speaking, these calibration values are valid only at the location of the calibration due to remaining effects of the environment. Thus, these effects have to be taken into account as well in order to prevent their impact as artefacts propagating into coordinate estimates. Therefore, site-specific effects (e.g., multipath, receiving antenna) represent still a major error source in precise GNSS positioning affecting coordinate estimates. Aiming for velocities on mm to sub-mm level per year implies the demand of best-possible coordinate time series, and therefore the elimination of these effects.

Residual stacking in space domain to mitigate site-specific effects

One very promising strategy to mitigate site-specific effects is to stack the observation residuals with respect to their signal **direction** (elevation, azimuth). Due to the slow variation of the geometry satellite-reflector-antenna in static GNSS positioning, signals from **similar directions** cause **identical artefacts** in residual time series. The residuals are affected by various factors, the most prominent ones are shown in Figure 5. **Partitioning the antenna hemisphere** in single **cells** using azimuth and zenith distance increments, a stacking of the residuals of these cells over several days enables to detect and reduce **systematic effects** (e.g., multipath, receiving antenna). Random errors (e.g., atmosphere) are negligible due to averaging over an appropriate chosen time span.

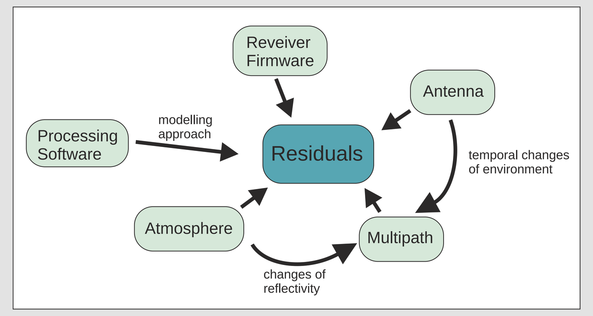

Figure 5: Aspects affecting GNSS residuals.

Figure 6 illustrates the scheme of the **stacking procedure** within the iterative GNSS data processing using the Bernese GNSS Software. In the first processing step, phase residuals for each single site and each processed day are calculated. They comprise the systematic signature of the environment (e.g., multipath-based) and remaining systematic errors of the antenna model especially. Mean values of the residuals in given cells are determined using spacial stacking of these residuals over an appropriate number of days.

The determined site-specific **mean residual map** represents corrections for certain directions (elevation, azimuth) from the site to the satellite. Introducing this stacking map as correction into a second processing step, systematic errors can be significantly reduced.

Stacking procedure

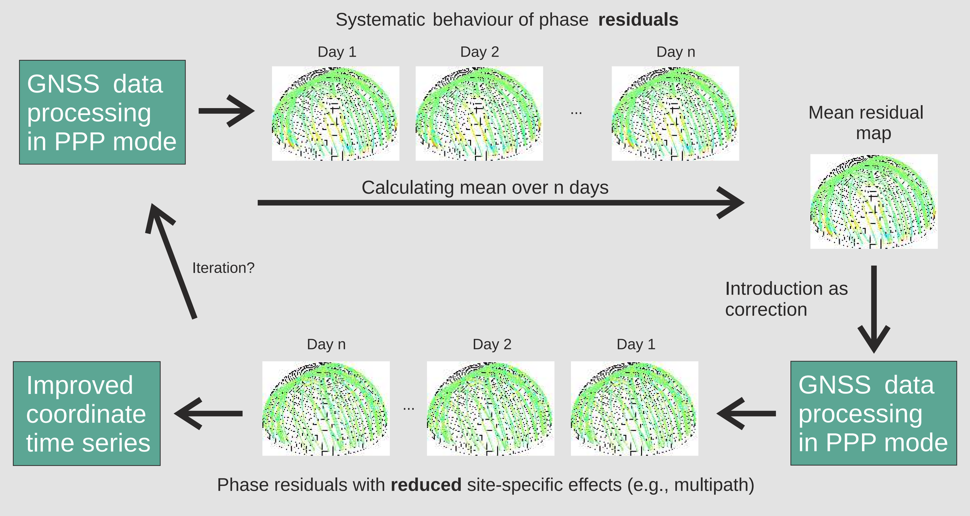

Figure 6: Scheme of stacking procedure within GNSS data processing.

Formerly, the GNSS data processing in GURN was carried out in differential mode (see Fuhrmann et al., 2013). Actually, we use **PPP** to generate site-related stacking maps.

During the stacking process, estimated residuals within one cell are statistically checked. Within an iterative process, **outliers** are eliminated. In order to determine cell-related stacked values, a minimum number of residuals must remain in one cell. Finally, the **significance** of the systematic behaviour is checked: Is the determined value above a certain significance level?

Implementation

As a first step towards the correction of site-specific effects using residual stacking, an easy-to-implement procedure to introduce the stacked residuals was developed. Since the calibration information consisting of PCO (phase center offset) and PCV (phase center variation) for each individual antenna is introduced into the data processing anyway, the basic idea is to **add the stacking-derived corrections to the PCV** for each antenna separately. Since the PCV are given on L_1-resp. L_2-level and the residuals are calculated using the ionosphere-free linear combination L_3, a conversion from L_1 resp. L_2 to L_3 and vice versa is mandatory. Based on PCV-values on L_1- and L_2-level, the corresponding L_3-PCV-values are calculated using

$$L_3 = \frac{1}{f_1^2 - f_2^2}(f_1^2 L_1 - f_2^2 L_2)$$

(see Beutler et al., 1988).

The reconstruc/tion from L_3 to L_1 resp. L_2 is carried out using the assumption $PCV(L_2) = 0$ in order to be able to combine L_1-resp. L_2-PCV and L_3-residuals (see Figure 8). A test processing of data using original and transformed PCV (L_1 resp. L_2 => L_3 => L_1 resp. L_2 with $PCV(L_2) = 0$) proofs the correctness of our approach.

For a first investigation, a simple stacking procedure using the grid resolution of the corresponding PCV (5° x 5°) was used to calculate the mean value for each grid cell based on the cell-related residuals for ten consecutive days. Later on, finer grid resolutions are going to be used (e.g., see Fuhrmann et al., 2014).

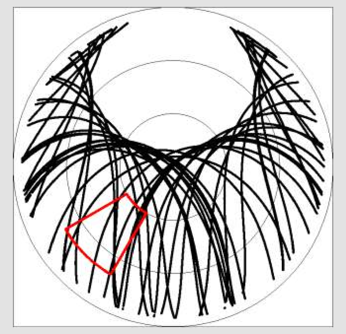

Figure 7: Skyplot for the GPS satellites of site 0384 for DoY2013: 200 with modified PCV sector in red.

In order to verify the effect of the suggested procedure, a test scenario was designed. Within this scenario, the sector of the PCV pattern ([Azi: 210° - 240°; Ele: 20° - 60°]; see Figure 7) was modified stepwise within the range of 0 ... 30 mm on L_3-level for selected sites to generate „well-known errors“ and introduced in a first processing run. According to Georgiadou and Kleusberg (1988), the maximum theoretical range error due to multipath can reach l/4. According to the subroutine DEFREQ.f of the Bernese GNSS Software, the wavelength for L_3 is calculated to 10.70 cm. Hence, the maximum range errors due to multipath on L_3 can reach 27 mm. The stacking of the raw residuals was performed in the resolution of the PCV grid. Therefore, the PCV were converted to L_3. Finally, the combined PCV and stacked residuals are converted back to L_1 resp. L_2 and introduced into a second processing run. The scheme of the stacking procedure is given in Figure 8.

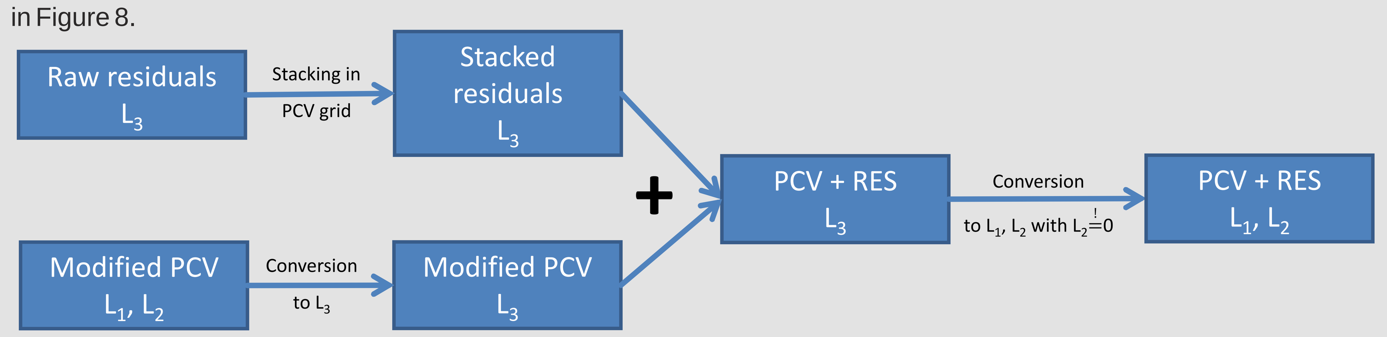

Figure 8: Scheme for the combination of the stacked residuals with the PCV.

The test scenario was applied in the period DoY2013: 199 - 208 for the sites 0384, BFO1 and KARL which provide different antenna types, site environment and shadowing level.

Results of test scenario

In order to quantify the impact of the residual stacking in space domain, the mean residuals for the chosen timespan are compared. In Figure 9, the results of different processing versions for DoY2013: 199 for site 0384 are given. The positive effect on the residuals due the integration of stacked information is clearly visible.

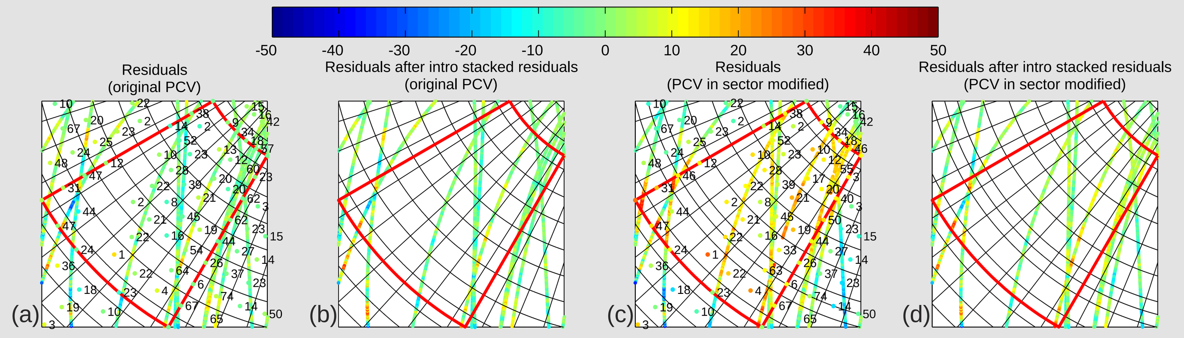

Figure 9: Colour-coded residuals after processing (see colourbar at top in mm) in different processing scenarios for DoY2013: 199 for site 0384; plots (c,d): PCV in red-bordered frame have been modified by 30 mm on L_3-level; figures in plots (a,c): number of residuals within this cell.

The improvement is also visible in Table 2, where the mean values over ten days for the number / min / max / mean residual value of the chose area for the complete antenna hemisphere / the modified sector / a reference sector (elevation >80°) are given. While the number of residuals in the modified sector is reduced with increasing modification values, the stacked version leads to almost constant numbers, as well as the mean residual value for this sector ranges near zero. The impact on coordinates is under progress.

	PCV mod.	intro stack.	PCV mod.	intro stack.	PCV mod.	intro stack.	PCV mod.	intro stack.	PCV mod.	intro stack.	PCV mod.	intro stack.	PCV mod.	intro stack.
modified by ... mm	0		5		10		15		20		25		30	
all residuals														
number	27206	27215	27202	27216	27199	27214	27192	27212	27168	27213	27124	27211	27015	27208
min	-136.4	-139.6	-135.7	-138.9	-137.3	-139.8	-140.2	-139.3	-139.3	-138.9	-139.3	-138.6	-139	-138.4
max	161.6	154.2	163.5	154.7	165.9	154.9	166.8	154.6	164.2	155.2	162.9	155.8	161.8	156.8
value	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1	0.3	0.1
residuals in modified sector														
number	981	981	981	981	979	981	975	980	963	980	940	980	858	980
min	-35.3	-28.7	-32.8	-28.2	-30.3	-27.8	-27.7	-27.3	-25.2	-26.9	-22.7	-26.5	-17.8	-26.8
max	30.6	30.3	33.6	31	36.1	32	38.1	32.9	39.7	33.9	43.3	35	44	36.2
value	-0.2	0.3	2.1	1	4.3	1.6	6.5	2.3	8.7	3	10.8	3.7	12.9	4.7
residuals in reference sector (zenith distance <= 10°)														
number	1272	1272	1272	1272	1272	1272	1272	1272	1272	1272	1272	1272	1271	1272
min	-11.2	-9.2	-11.5	-9.3	-12	-9.3	-12.6	-9.4	-13.2	-9.6	-13.4	-9.8	-13.4	-10
max	7.9	8.2	8.1	8.3	8.2	8.4	8.5	8.9	8.7	9	9.1	8.8	9.6	8.7
value	-1.6	-0.4	-1.6	-0.4	-1.6	-0.4	-1.6	-0.5	-1.6	-0.5	-1.5	-0.5	-1.4	-0.6

Table 2: Mean residual statistics for site 0384 over ten days (DoY2013: 199 - 208) for the complete antenna hemisphere, the modified sector (see Fig. 7) and the reference sector using modified PCV and after introduction of stacked residuals.

Conclusions and outlook

Using residual stacking in space domain and application of the stacked residuals by addition to the PCV works quite fine for the test scenario.

As next step, the direct improvement of the observations by adding the stacked residual on L_3-level within the GNSS data processing will be implemented. Further, a refinement of the actually used stacking grid is desirable. Finally, the impact of the stacking procedure onto coordinate time series compared to results without stacking is going to be analysed.

After finalizing the research focussing on stacking of PPP-derived residuals, an integration of PPP derived site-related stacked residuals in differential GNSS data processing is planned in order to combine the advantages of both strategies.

Literature and acknowledgement

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