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ORIGINAL ARTICLE

Correction of apparent position shifts caused by GNSS antenna changes

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Abstract Antenna changes at GNSS reference stations frequently produce discontinuities in the coordinate time series. These apparent position shifts are mainly caused by changes of carrier-phase multipath effects and different errors in the antenna phase center corrections. A monitoring method was developed and successfully tested, which requires additional GNSS observations from a local, temporary reference station. Changes of carrier-phase measurement errors due to the antenna change are determined and stored in L1 and L2 phase maps. These phase maps provide corrections to be applied either to the observation data obtained before the antenna change or to the observation data obtained after the antenna change. The observation corrections are able to remove coordinate discontinuities independent of the selected coordinate estimation algorithm.

Keywords GNSS · Reference stations · Antenna change · Multipath · Phase center

Introduction

Permanent GNSS reference stations, often also called continuously operating reference stations (CORS), play an important role in present-day geodesy and satellite-based positioning. They fulfil several tasks. Among these are: the realization of the geodetic reference frame, control points for monitoring the earth's dynamics, reference station for precise differential GNSS positioning. These tasks require that the positions of the reference station markers are determined with millimeter accuracy.

Continuous time series of station coordinates, as they are produced by analysis of reference station network observations, indicate that this high level of accuracy is achievable even in global networks. In the event of a GNSS antenna change, however, discontinuities in the coordinate time series occur frequently. They can reach up to few centimeters in the height component and pose a major challenge for the realization of a reference frame and also for monitoring the earth's crustal dynamics.

These apparent position shifts are mainly caused by changes of carrier-phase multipath effects due to the antenna change. As a solution to this carrier-phase multipath problem it was suggested to perform in situ calibrations of GNSS reference stations (Böder et al. 2001; Park et al. 2004b). So far, none of these techniques has proved to be practicable.

The international GNSS service (IGS) and also the EUREF permanent network (EPN) recommend, when antenna changes are planned, to operate both the new and old antennas at the same time first, if an additional monument and receiver are available (IGS 2008; EPN 2007). This additional observation data should ensure that old and new stations are part of the network solution for some time and thus, a transition from old to new antenna is ensured.

In this paper a different approach is suggested, tested, and discussed. It consists of additional local GNSS observations at a temporary station for some time before and after the antenna change. The new reference antenna should be positioned vertically above the same marker as the old reference antenna. Any shift of the antenna reference point (ARP) must be recorded with sub-millimeter accuracy. Usually only a shift in height should occur. It can easily be determined by leveling or other appropriate

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measurement techniques. Based on the observation data, phase maps are produced which contain any changes in carrier-phase multipath and antenna phase center corrections. They can either be applied in a re-processing of the observation data of the old antenna or as correction to the new observation data.

It should be noted that this approach does not enable the correction of multipath or remaining antenna phase center errors in an absolute sense. The phase maps produced contain the difference of errors between old antenna and new antenna. They can thus only be used for removing this difference on the observation level and subsequently on the parameter level as well. Nevertheless, they ensure continuous time series of reference station coordinates that are not affected by antenna changes.

Effects of GNSS antenna changes

In recent months several antenna changes have been monitored with the observation technique and data processing algorithms described below. Most of these antenna changes took place in the German SAPOS network (http://www.sapos.de) and were necessary because the older GPS-capable equipment was replaced by GPS/GLONASS equipment. All the collected data sets so far come from roof-top reference stations with no (or hardly any) reflectors above the antenna horizon and often strong reflectors below the antenna horizon.

Table 1 gives an impression of how large apparent position shifts due to antenna changes are. The table contains the maximum position shifts for ten changes of geodetic-type antennas at GPS reference stations. These shifts were computed for a specific kind of coordinate solution which is the one usually used in regional and global sized networks: ionospheric-free linear combination with estimation of tropospheric zenith delays (L0+T).

Largest apparent position shifts are experienced in the height component. They can reach up to some centimeters. In the north and east components they usually do not exceed a few millimeters.

Apparent position shifts depend very much on the kind of coordinate solution employed. A single-frequency solution as it is commonly used in short baseline relative positioning is affected much less than any solutions based on the ionospheric-free linear combination of dual-frequency phase observations. The apparent height shifts further increase if parameters for tropospheric zenith delays are estimated as well.

Table 1 Maximum apparent position shifts of ten antenna changes, coordinate solution L0+T

	Apparent position shifts (mm)
Δ_{north}	−3.2 to 10.7
Δ_{east}	−0.8 to 2.9
Δ_{up}	−11.0 to 36.5

The main reasons for apparent position shifts are differences of carrier-phase multipath effects and antenna calibration errors between old and new station equipment. Carrier-phase multipath effects strongly depend on signal reflectors in the antenna surroundings (Elósegui et al. 1995; Park et al. 2004a). Although these reflectors do not change their characteristics just because of a substitution of the receiving antenna, their effects are often altered because of (slightly) different physical dimensions of old and new antenna, or a (slightly) different height of the antenna above the marker. Even small geometrical changes may have large effects on the affective multipath signals. Furthermore, antennas and receivers vary with respect to their sensitivity to multipath signals and thus a change of equipment causes apparent position shifts.

More differences may be introduced by the antenna calibration data sets used in the data processing. There are several different sources of calibration values (antenna type specific corrections, individual corrections) and several methods for performing calibrations (chamber measurements, field calibration without or with antenna rotation/tilting) (Mader 1999; Menge et al. 1998). Furthermore, antenna/radome combinations which have not been calibrated at all are still in use in some reference station networks. Systematic differences on the millimeter-level are quite common between pairs of antenna calibration values. These differences contribute to apparent position shifts.

Modeling on coordinate level and observation level

The monitoring technique applied requires additional local GNSS observations. A temporary second reference station has to be installed close to the existing reference station where an antenna change is intended. Ideally the distance between the two antennas lies in the range of a few meters and several 10 m. The temporary station is run for a period before and after the antenna change (Fig. 1). Experience shows that data collection of a few days before and a few days after the antenna change is sufficient if the data sets are complete and of good quality.

It is expected that old and new antennas of the reference station are mounted vertically above the station marker. The vertical distance between marker and the ARPs, i.e., the antenna heights, may change due to a different antenna setup or different antenna construction. The antenna heights must be measured and taken into account in the modeling of the apparent position shifts.

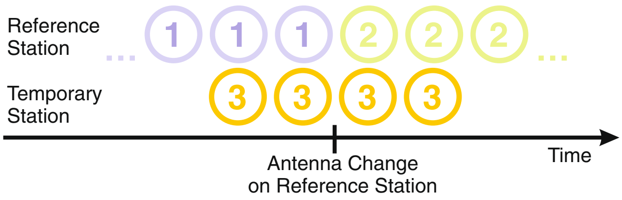


Fig. 1 Basic principle of monitoring the effects of an antenna change at a reference station with three antennas involved: (*1*) old antenna at reference station, (*2*) new antenna at reference station, and (*3*) antenna of temporary station

Two kinds of modeling have been performed. Modeling the apparent position shifts on the coordinate level consists of computing coordinates of the baseline between temporary station and reference station before and after the antenna change. The difference of these coordinate sets gives the apparent position shifts. Since these position shifts are signal frequency and algorithm dependent, this estimation has to be performed for several different kinds of positioning solutions:

- L1 solution: the coordinate estimation in short baselines is often based on L1 carrier-phase observations only, please note: ambiguity resolution is often performed using dual-frequency observation in a preceding processing step.
- L2 solution: a coordinate solution based on L2 carrier-phase observations is seldom used in practice.
- LN solution: a narrow lane coordinate solution requires dual-frequency carrier-phase observations and is often the most precise one on short baselines.
- L0 solution: ionospheric-free coordinate solution as used in longer baselines (longer a few km).
- L0+T solution: if the baseline length exceeds about 10 km, unknowns for the tropospheric zenith delay may have to be estimated as well.
- L0+T_float solution: standard Precise Point Positioning (PPP, e.g., Kouba and Héroux 2001) results are based on the ionospheric-free linear combination of dual-frequency carrier-phase observations with estimation of tropospheric zenith delays but without ambiguity resolution.

Besides these differences in observations and algorithms used one has to take into account the fact that the apparent position shifts also depend on other characteristics of the processing software and its parameters setting: for example,

- elevation mask,
- weighting function for carrier-phase observations, e.g., weighting according to elevation angle, and
- tropospheric mapping function.

Thus, the apparent position shifts determined with a specific software package and particular parameter settings should not be used as corrections for coordinate results obtained with other software or other parameter settings.

This disadvantage of corrections on the coordinate level can be overcome by producing corrections on the observation level. In a first processing step one set of coordinates for the baseline between temporary station and reference station is estimated. ARP heights above marker and antenna phase center corrections are taken into account. These coordinates are held fixed in the further processing steps. Two models based on carrier-phase residuals after ambiguity fixing are computed: one for the baseline between temporary station and reference station before the antenna change and one for the baseline after the antenna change.

The carrier-phase residuals are mainly caused by:

- multipath effects at the temporary station,
- multipath effects at the reference station before (or after) the antenna change,
- errors of the phase center corrections of the antenna at the temporary station, and
- errors of the phase center corrections of the antenna at the reference station before (or after) the antenna change.

These effects are frequency dependent and thus have to be modeled separately for L1 and L2. They vary due to the signal incident angles and thus are best modeled as a function of azimuth and elevation angle of the satellites. One appropriate mathematical model, the one used in this paper, is based on spherical harmonic expansion.

It is assumed that multipath effects (for specific incident angles) and errors of the antenna corrections do not change with time. This will be certainly true for the errors of the antenna corrections. Multipath effects, however, partly depend on rainfall or snow cover.

The effects caused by the temporary station cancel out when taking the difference of the two models. Only the differential effects at the reference station caused by the antenna change remain:

- differences of the multipath effect at the reference station before and after the antenna change, and
- differences of the errors of the phase center corrections of the antenna at the reference station before and after the antenna change.

The resulting phase maps can then be used to correct observations of this reference station for those effects which are caused by the antenna change.

Application of correction model

Basically, there are two ways to apply the phase maps produced as described above. One could correct the observation data obtained before the antenna change or one could correct the observation data obtained after the antenna change. Both applications have in common that the effects of the antenna change are minimized, i.e., time series of the reference station coordinates do not show discontinuities. But the true coordinate level remains unknown. We may still be off the truth by a centimeter or even up to a few centimeters.

Correcting the observation data which were collected before the antenna change can only be used in post-processing applications. Such a re-processing of the observation data produces improved estimates of station velocities.

On the other hand, correcting the observation data after the antenna change can be performed even in real-time data processing. The realization of a geodetic datum can be maintained even if antennas had been changed. Disadvantages are that no corrections exist for new signal frequencies (e.g., GPS L5) and that some extrapolation of the GPS phase corrections is needed in the case of GLONASS signals, which come from satellites with higher inclined orbits.

Presently there is no data format for phase maps available which is understood by the common software packages. Therefore, the ANTEX format (Rothacher and Schmid 2006) was adapted to store these corrections. Actually, antenna phase center correction and phase maps were merged into one correction data set stored in ANTEX format. The corrections are thus readily available to be applied with most GNSS processing software.

Example

One example has been selected from the antenna changes which were processed so far. It is the one with the largest position shift. It occurred due to an antenna change at the European permanent network (EPN) reference station DRES on 22 January 2003. The antenna of type “TRM22020.00+GP DOME” was replaced by a choke ring antenna of type “TRM29659.00 NONE”. The antenna height and also the receiver of type “TRIMBLE 4000SSI” remained unchanged. The EPN time series of the station coordinates of DRES can be found on the EPN-website (http://www.epncb.oma.be). It is shown here as Fig. 2. Red vertical lines indicate changes of the antenna, green vertical lines indicate changes of the receiver hardware or firmware. EPN estimates offset values in the coordinate times series if a position shift is suspected. The offsets caused by the antenna change in January 2003 were estimated by one of the EPN analysis centers to be 5 mm in north, −2 mm in east and 32 mm in the height component.

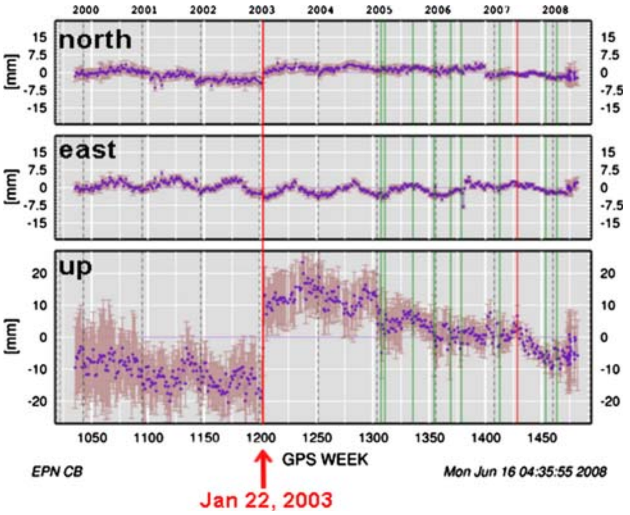


Fig. 2 EPN time series of station coordinates of DRES (source: http://www.epncb.oma.be, 2008)

Simultaneously, a second permanent GNSS station was employed on the same roof-top: the IGS station DREJ. The distance between the two antennas was just 1.4 m. This station was considered to be a temporary reference station. The short baseline DREJ–DRES was computed starting day of year (DoY) 14/2003 until DoY 31/2003. The observations of one day (DoY 26/2003) had to be ignored because they were incomplete, so that observation data sets of 8 days before and 8 days after the antenna change were used.

Apparent position shifts were estimated using the baseline software processor Wa1. Antenna phase center corrections were taken into account. Baseline coordinate solutions DREJ–DRES were computed for each 24 h data set (left panel of Fig. 4) and combined into a baseline solution from DREJ to the old antenna at DRES and a second baseline solution from DREJ to the new antenna at DRES. The differences of these two baseline solutions and thus the apparent position shifts are presented in Table 2.

Five different kinds of solutions were produced from these short baseline observations (Table 2). The apparent position shifts are smaller in the horizontal components as compared to the height component where they reach some millimeters in L1 or L2. They get much larger when using the ionospheric-free linear combination L0. The height

Table 2 Apparent position shifts due to the antenna change at station DRES on 22 January 2003 computed from the short baseline DRES–DREJ with software Wa1, 10° elevation mask

	L1	L2	LN	L0	L0+T	L0+T_float
Δ_{north}	0.4	−0.6	0.4	4.0	3.5	3.5
Δ_{east} (mm)	2.7	1.2	1.2	1.3	1.1	1.2
Δ_{up}	3.8	−7.5	−1.0	23.3	36.5	34.1

component suffers even more when tropospheric zenith delays are estimated as additional unknowns. The maximum height shift amounts to about 3.5 cm for the ionospheric-free solution including estimation of tropospheric zenith delays.

The apparent shifts do not only depend on the selected kind of coordinate solution but also on software settings. Here, a 10° elevation mask was applied to the raw data. The coordinate shifts as shown in Table 2 are thus not applicable to data processing with other elevation mask values or other software.

This limitation can be overcome when corrections are produced on the observation level. Based on the same observation data, two models of the azimuth-elevation-dependence of the carrier-phase residuals were computed: one model for the baseline DREJ to the old antenna at DRES, a second model for the baseline DREJ to the new antenna at DRES. Taking the difference of these two models yields observation corrections as shown in Fig. 3. These phase maps for L1 and L2 observations were modeled based on spherical harmonic expansion with coefficients up to degree 8 and order 5. Hardly any information is available for the northern sky quadrant since the GPS satellite orbit inclination of 55° causes a “shadow” area in the sky from where no GPS signals arrive.

In this example the intention is to correct the observations of DRES with the old antenna in order to obtain a continuous time series of station coordinates free of apparent position shifts. Therefore, the antenna phase center corrections of the old antenna at DRES were merged with the phase maps of Fig. 3 to get combined corrections. These corrections were applied to the DRES observations obtained before the antenna change. Two data sets were selected for verification of the algorithm and its implementation.

First, the short baseline DREJ–DRES was re-processed, now with corrections applied (Fig. 4). This is an internal test, since the corrections are applied to exactly those observations which had been used to compute the corrections. The apparent position shifts of the L0+T-solution of 3.5/1.1/36.5 mm in north/east/up (left panel of Fig. 4) were reduced to below 1 mm in all three components (right panel of Fig. 4). This verification step confirms that L1 and L2 corrections on the observation level are able to remove apparent position shifts for all kinds of positioning

Fig. 3 Phase maps of observation corrections for the antenna change at station DRES on 22 January 2003, based on 16 days of observations of the short baseline DREJ–DRES

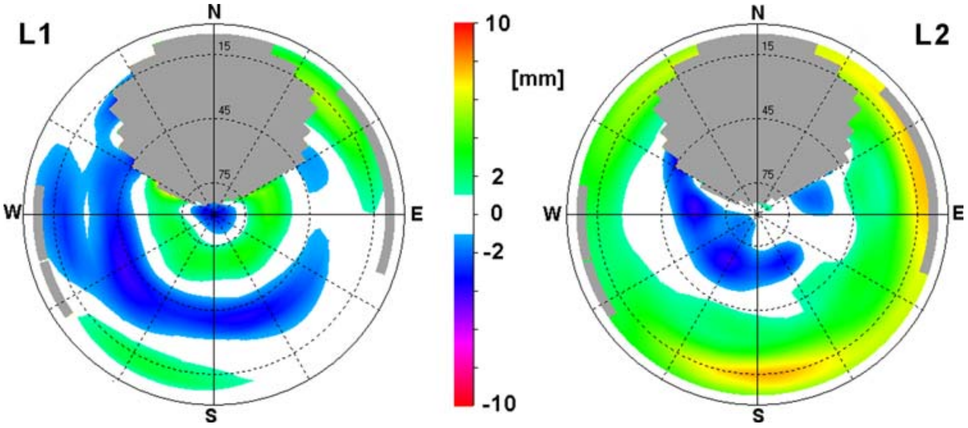
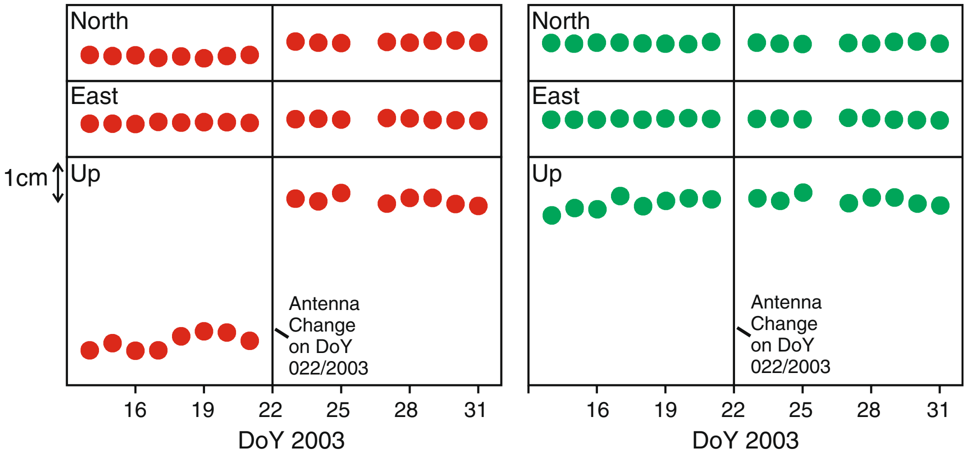


Fig. 4 Day-to-day repeatability of baseline coordinates DREJ–DRES, solution type ionospheric-free linear combination with estimation of tropospheric zenith delays (L0+T), no corrections for antenna change applied (*left panel*) and corrections applied to observations before the antenna change (*right panel*)



solutions, i.e., the developed algorithm and its implementation is correct.

The second verification step consists of a regional network solution with three reference stations (GOPE, LEIJ, and POTS) being held fixed and the coordinates of DRES being determined (Fig. 5). Weekly solutions were computed using the software package WaSoft/Netz. The reprocessing was performed for all available observations of the years 2002 and 2003. Figure 6 shows coordinate variations in north/east/up for two kinds of L0+T-solutions. Both solutions were obtained using antenna phase center corrections and an elevation mask of 5°.

The left panel of Fig. 6 shows the solution without any additional corrections. It is comparable to the EPN-solution of Fig. 2, although slightly different apparent position shifts are noticeable at the day of antenna change, since the two solutions are based on different selections of reference stations and were produced with different software packages and software settings. The right panel of Fig. 6 shows the coordinate results of DRES again, but now observation corrections according to Fig. 3 were applied to DRES observations obtained before the antenna change. The apparent position shifts were greatly reduced and are now less than 1 mm in the horizontal components and just about 2 mm in the height component (solution type L0+T).

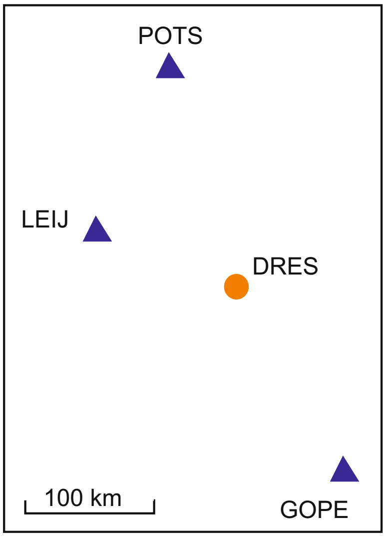


Fig. 5 Regional network of reference stations used for verification of observation corrections

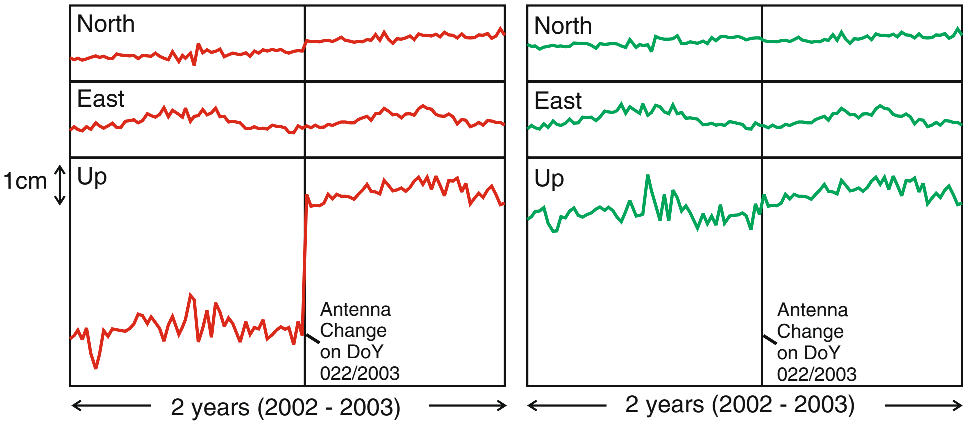
Summary and conclusions

Antenna changes at GNSS reference stations frequently produce discontinuities in the coordinate time series. A monitoring method was developed and tested which requires additional GNSS observations from a local, temporary reference station. Any changes in carrier-phase multipath effect and errors of antenna phase center corrections are determined and stored in L1 and L2 phase maps. These phase maps can be used to correct either the observation data obtained before the antenna change or the observation data after the antenna change.

Several antenna changes have been monitored and processed based on this approach. The one example with the largest apparent position shift was selected to illustrate this technique. It was shown that L1 and L2 phase maps can remove large apparent position shifts even in coordinate solutions based on the ionospheric-free linear combination and including the estimation of tropospheric zenith delays.

In the coming years many more antenna changes will be required in CORS networks in order to be able to use combined GPS/GLONASS receivers, GPS signals on L5-frequency, and also Galileo signals. The technique described in this paper guarantees a smooth transition from old to new antennas without any large discontinuities in the coordinate time series.

Fig. 6 Coordinate time series of weekly solutions for station DRES in regional network, solution type L0+T: no corrections for antenna change applied (*left panel*) and corrections applied to observations before the antenna change (*right panel*)



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References

Böder V, Menge F, Seeber G, Wübbena G, Schmitz M (2001) How to deal with station dependent errors—new developments of the absolute calibration of PCV and phase multipath with a precise robot. In: Proceedings of ION GPS 2001, pp 2166–2176

Elósegui P, Davis JL, Jaldehag RTK, Johansson JM, Niell AE, Shapiro II (1995) Geodesy using global positioning system: the effects of signal scattering on estimates of site position. J Geophys Res 100(B7):9921–9934. doi:10.1029/95JB00868

EPN (2007) Guidelines for EPN stations & operational centres, EUREF permanent network (EPN) Central Bureau, 15 May 2007. http://www.epncb.oma.be/_organisation/guidelines/guidelines_station_operationalcentre.pdf

IGS (2007) IGS site guidelines. 27 July 2007. http://igscb.jpl.nasa.gov/network/guidelines/guidelines.html

Kouba J, Héroux P (2001) Precise point positioning using IGS orbits and clock products. GPS Solut 5:12–28. doi:10.1007/PL00012883

Mader G (1999) GPS antenna calibration at the national geodetic survey. GPS Solut 3:50–58. doi:10.1007/PL00012780

Menge F, Seeber G, Völksen C, Wübbena G, Schmitz M (1998) Results of absolute field calibration of GPS antenna PCV. In: Proceedings of ION GPS, vol 98, pp 31–38

Park K-D, Nerem RS, Schenewerk MS, Davis JL (2004a) Site-specific multipath characteristics of global IGS and CORS GPS sites. J Geodesy 77:799–803. doi:10.1007/s00190-003-0359-9

Park K-D, Elósegui P, Davis JL, Jarlemark POJ, Corey BE, Niell AE et al (2004b) Development of an antenna and multipath calibration system for global positioning system sites. Radio Sci 39:RS5002. doi:10.1029/2003RS002999

Rothacher M, Schmid R (2006) ANTEX: the antenna exchange format version 1.3. ftp://igscb.jpl.nasa.gov/pub/station/general/antex13.txt

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