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# ON GNSS STATION CALIBRATION OF NEAR-FIELD MULTIPATH IN RTK-NETWORKS

Gerhard Wübbena, Martin Schmitz, Andreas Prüllage

## INTRODUCTION

A major error source for precise GNSS applications are station dependent errors arising from multipath effects. An in-situ station calibration approach has been proposed by Wübbena et al. (2011), based on a combination of several strategies to separate the near-field (NF) multipath for a single station to the best. However, there is still need to get calibrations for stations which are not easily accessible or not adequate for in-situ calibrations.

The basic station calibration concepts of analyzing observation residuals can also be applied to data from reference stations in RTK-networks. Based on elevation and azimuth dependent residuals (EAR) the calibration patterns as well as variance component estimates (VCE) are derived for each individual station. The EAR-VCE station calibration uses phase, code and signal-to-noise observables for every GNSS frequency. The station calibration results can be applied in the GNSS processing to improve the network performance as well as the performance of rovers utilizing the different network services.

The concepts, application and benefits of the EAR based VCE approach for station calibration of near-field multipath in a RTK-network are discussed. Calibration results and the effect while applying the corrections to stations are demonstrated within a RTK-network.

## GENERAL

Station calibration has been investigated by several research groups (e.g. Hurst, Bar Sever 1998, Iwabuchi et al. 2004, van der Marel 2006, Granström, Johansson 2007, Moore et al. 2012) and is still under study. Generally the phase residuals from a data processing of longer time spans are used to derive residual maps through so-called residual stacking. The residual maps account mainly for multipath effects and the investigations generally focus on time series of permanent reference stations.

A flexible concept to determine and correct near-field effects for a broad variety of GNSS applications consisting of different methods, e.g. for RTK-networks, has not been presented so far.

## STARTING POINT AND GOAL

Station dependent errors, which consists mainly of antenna and multipath effects, do have a significant influence on GNSS applications. Currently, the multipath effects are the major limiting factor. For a rover site, it is the user's responsibility to handle such errors. For reference stations, the provider (e.g. while choosing an adequate station design) or the GNSS application software can account for these effects.

It has been proposed by Wübbena et al (2006a, 2006b) to separate station dependent errors dS into antenna phase variations (PCV) and two different multipath parts MP, namely the near-field and far-field multipath:

$$dS = PCV + MP_{near\text{-}field} + MP_{far\text{-}field}$$

The justification for a near-field and far-field multipath term are their different properties, which allow different strategies to account for them. Tab. 1 gives an overview of station dependent errors and their basic characteristics and treatments (see also Wübbena et al. 2006a, 2011).

| | *Error* | *Characteristic* | *Treatment* |
|---|---|---|---|
| Antenna | PCV | elevation and azimuth dependent PCV | calibration of PCV using robot |
| Multipath | $MP_{near\text{-}field}$ | long-periodic, systematic effect, bias, close reflectors | calibration of near-field effects using robot/in-situ station calibration |
| | $MP_{far\text{-}field}$ | short-periodic, systematic effect, remote reflectors | averaging over time, absolute station calibration or weighting (CN0), sidereal differences (GPS only) |
| Station Uncertainty | | unstable underground, setup, monumentation | analysis of time series |

*Tab. 1: Different treatment of station dependent errors*

PCV of a GNSS antenna can be precisely determined by the absolute field calibration with a robot (Wübbena et al. 2000, Schmitz et al. 2008) and applied as a correction.

The theoretical existence of near-field multipath was first described in 1995 (Elosegui et al. 1995). The experimental verification of near-field effects for GNSS antennas has been demonstrated in 2003 using the absolute GNSS antenna calibration system (Wübbena et al. 2003).

Near-field multipath is caused by the close vicinity around a GNSS antenna. The GNSS signals are subject to signal diffraction and reflection, but also to effects like imaging and electromagnetic interaction. Furthermore, the antenna near-field impact depends on antenna type, mount/setup of the antenna, site design and properties as well as weather condition. Basically any changes or additional matter in the near-field around the antenna might influence the reception characteristic and consequently the GNSS signals tracked.

The correlation with other parameters makes the near-field impact complex and manifold. It reveals itself often without being recognized as such. The actual differences in range caused by near-field effects may only be some millimeter, but the coordinate bias may reach centimeters. An increase by a factor of three is generally due to the use of the ionospheric free linear combination (L0). Furthermore, biased estimates for other parameters such as e.g. tropospheric zenith delay, tropospheric gradients, carrier phase ambiguities result in coordinate errors, mainly in the height component. Finally, the satellite constellation and elevation mask influence the positioning error, which give an additional time and spacial dependency. For details refer to Wübbena et al. (2006a, 2006b), Dilßner et al. (2008).

The effects of far-field multipath is generally known. It can be reduced in static applications with sufficient observation time or by carrier-to-noise (CN0) weighting in dynamic applications. Station uncertainties are listed in Tab. 1 for completeness and are not further discussed.

Near-field effects, however, are currently the most important not modeled station dependent error source and its complex interaction reduces the performance of GNSS applications (accuracy, availability, reliability). Therefore the demand for strategies to deal with near-field effects exists.

## APPROACHES AND METHODS TO DETERMINE NEAR-FIELD EFFECTS

Geo++ developed and analyzed different approaches and methods to determine, handle and correct near-field effects (Tab. 2). The approaches separate the near-field multipath for a single station.

The difference between a standard antenna calibration and a calibration with a representative mock-up of the setup/mounting is an explicit determination of the near-field impact on an antenna. It is not always possible to resemble the site setup in all its complexity in such a near-field calibration. But even in the case of remaining differences to the actual setup conditions, it generally gives a representative and good approximation (e.g. Schmitz et al. 2008).

| # | ***Approach*** | ***Method*** |
|---|---|---|
| 1 | explicit determination | robot calibration (since 2002) (e.g. Schmitz et al. 2008) |
| 2 | noisifying multipath | station calibration using robot (Böder et al. 2001) |
| 3 | averaging multipath | multiple station setup (Wübbena et al. 2006b) |
| 4 | determine near-field correction and weighting from L1 & L2 residuals | in-situ station calibration with calibrated, multipath free equipment (# 1) – **CaNF** (Wübbena et al. 2011) |
| 5 | determine near-field correction and weighting from L0 residuals in redundant setups | in-situ station calibration/ NF compensation within a network of GNSS reference stations - **CoNF** |
| 6 | combination of approaches | use of some in-situ calibrated stations (# 4) and apply it to constrain # 5 - **CNF** |

*Tab. 2: Different approaches to determine near-field effects of a reference station*

In-situ station calibration, however, provides access to the actual and complete near-field of a site. First, a single site calibration using a robot has been investigated (Böder et al. 2006) very efficiently, but effort and costs complicate this technique to become an operational method. The separation of multipath between stations was achieved through nosifying the impact for one station with the robot.

Another method averaged near-field mutipath using differently chosen station setups to separate the actual impact on a reference station. This approach was theoretically feasible, but showed up to have not enough control and reliability for high quality results (Wübbena et al. 2006b).

## CALIBRATION OF NEAR-FIELD EFFECTS (CaNF)

A synergism from the previously analyzed methods is the in-situ station ***ca***libration of ***n***ear-***f***ield with calibrated equipment (CaNF) presented in Wübbena et al. 2011. Several calibrated station setups free of near-field and with low far-field impact are operated over short distances at a reference station site to access the GNSS observable. Phase and code corrections for the original observable (e.g. L1, L2) as well as weighting schemes for near-field multipath are derived from a combined processing for the reference site. The approach is scalable and uses redundancy to obtain e.g. the complete GNSS visibility of the reference station.

There are often stations which are not easily accessible or not suited for an in-situ calibrations. Therefore a method is required to determine corrections and weighting schemes to compensate near-field effects from a network of reference stations. Basically, the concept of the CaNF method is applied to GNSS data in a redundant RTK-networks. Instead of the original observable, the ionospheric free linear combination has to be used. Therefore the method is termed compensation of near-field effect (CoNF). It will be presented in the following paragraphs.

As stated as the last method in Tab. 2, a flexible and therefore very promising strategy is the combination and integration of the different methods.

## COMPENSATION OF NEAR-FIELD EFFECTS (CoNF)

The station calibration concepts is based on analyzing GNSS observation residuals. In RTK-networks the L0 residuals are the primary signal for near-field corrections. The original observable L1, L2 and L5 are not fully accessible due to non-distinguishable ionospheric effects.

Nevertheless, the basic concept of the CaNF calibration can be applied: ***e***levation and ***a***zimuth dependent non-differenced ionospheric free signal ***r***esiduals (EAR) are used to determine correction models and weighting schemes. As the algorithm is using different observables (phase, code and carrier-to-noise for every GNSS frequency) and their properties, the weighting is comparable to a ***v***ariance ***c***omponent ***e***stimates (VCE). A EAR-VCE model is estimated for each individual station.

One central task is to separate individual near-field effects of one station and reducing correlation with any other station while using a network of stations. Sufficient redundancy in the network utilizes the compensation of near-field for all network stations. The combination of different methods from Tab. 2 can in addition constrain the separation of effects, which is addressed further below.

The GNSS data of the network allows the analysis of the site's near-field multipath and the actual determination of single station near-field multipath. The EAR-VCE model can be applied in the GNSS processing to improve the network performance as well as the performance of rovers utilizing the different network services.

## RESIDUAL ANALYSIS IN RTK-NETWORK

A set of 20 reference stations from the BKG* GREF network was selected and a real-time GNSS networking was setup with the software package Geo++ GNSMART. The RTK-network covers complete Germany with an average station distance of about 160 km and is depicted in Fig. 1.

An automatic procedure estimates EAR-VCE correction and weighting and also automatically applies them in the GNSS networking. The system is designed adaptive, which means that the EAR-VCE models are permanently estimated based on current observations and regularly updated. Hence, the compensation model is steadily improved and adopts changes at a site (currently on a daily basis).

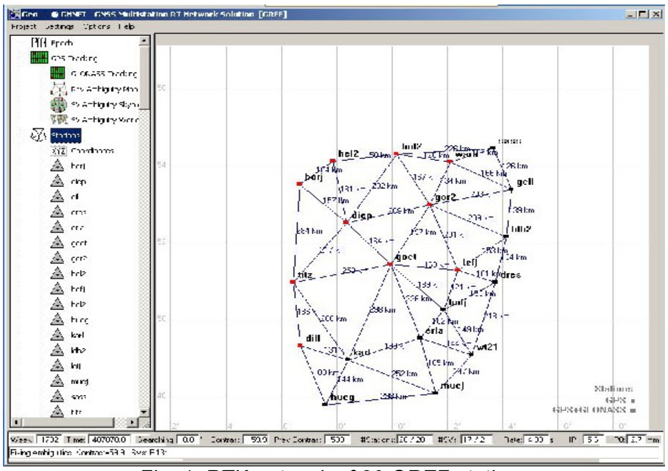

*Fig. 1: RTK-network of 20 GREF stations*

Two different stations are presented as an examples for the residual analysis from the network. The antenna of station GOET is mounted on a pillar with a clear surrounding (Fig. 2), while the antenna of station HUEG is located on a mast attached to a building (Fig. 3). The orientation of the antennas can be exploited from the cable connectors (oriented North for GOET, South for HUEG).

The residual plots in Fig. 4, Fig. 5, Fig. 6 are derived from the automated and iterative estimation in the 20 station GREF network and reflect the situation in October 2011 (doy 277) from several days of observations.

*Fig. 2: GREF station GOET*

*Fig. 3: GREF station HUEG*

There is basically no obstructions detectable for station GOET from the GPS L0 residuals (Fig. 4). A prominent band of larger residuals is visible in EW direction up to ~30°-60° zenith distance in the 2D plot. The example also shows, that high elevations are not necessarily free of multipath.

Within a short satellite path significant systematic residual changes occur covering the complete range of residuals. A comparable plot is derived independently from GLO L0 residuals. The inclination of the GLONASS satellites result into a smaller Northern hole with no satellite observations. Differences in the residuals are due to slightly different signal frequencies compared to GPS.

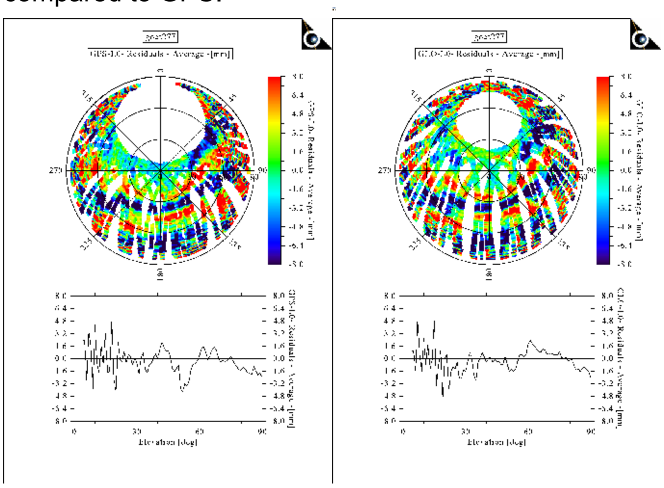

*Fig. 4: GPS L0 and GLO L0 residual station GOET (277, 2011)*

The GPS and GLO L0 residuals of GREF station HUEG are displayed in Fig. 5. No general obstruction is present. The station is less disturbed in high elevations, but near-field multipath is apparent in low elevations and especially in Northern directions. These pattern are caused by the roof and/or building edges/walls. Again, a similar pattern is obtained from the GLO L0 residuals.

The residual analysis clearly shows near-field effects on the two sites, which correlates with the station setup. The L0 residuals range from about -8 mm to +8 mm. Moreover, very critical gradients – large residual changes over small elevation ranges – are obvious. Therefore effects in the position domain can be expected, if no correction is applied.

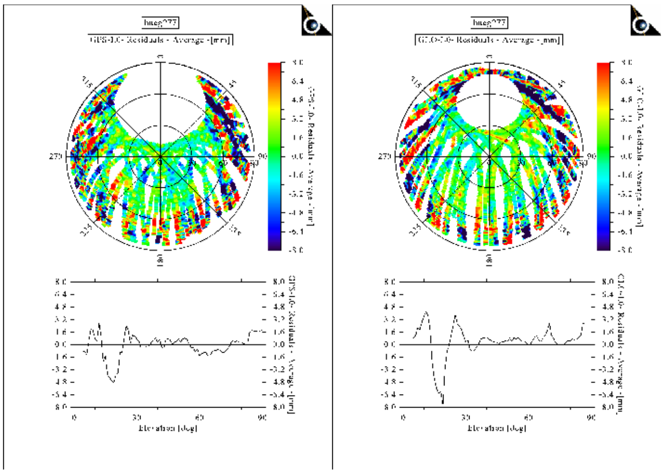

*Fig. 5: GPS L0 and GLO L0 residual station HUEG (277, 2011)*

In addition to the phase observable also the code observable are used in the EAR-VCE models. In Fig. 6 code GPS C1 residual for the two station GOET and HUEG are shown. The pattern differ compared to the L0 phase residuals due to the different signal properties.

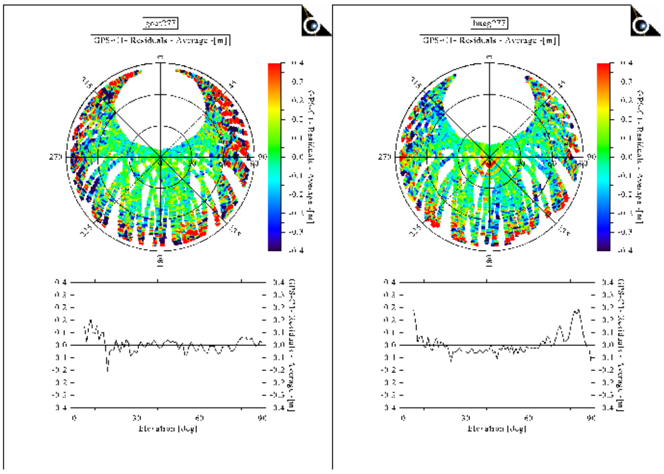

*Fig. 6: Code GPS C1 residual station GOET, HUEG (277, 2011)*

## VERIFICATION EXPERIMENT

A special real-time experiment was executed over 51 days to verify the CoNF results in the position domain. Two identical real-time sub-networks of seven GREF stations around HOFJ were setup. The sub-network design is shown for one of the two networks in Fig. 7.

The data streams of all stations including HOFJ were duplicated. For one network, the data streams were uncorrected, for the other network the EAR-VCE models were applied for all stations. Station HOFJ served as a rover station.

The coordinates of the reference stations were introduced as known, while station HOFJ was kept free to evaluate the effect of the EAR correction. In both sub-networks a filter reset of all station dependent parameters of station HOFJ (e.g. ambiguities, coordinates, etc.) was simultaneously executed every 5 minutes based on absolute time. This procedure provided comparable positioning results. The troposphere was estimated. The coordinate estimation from the RTK positioning were analyzed.

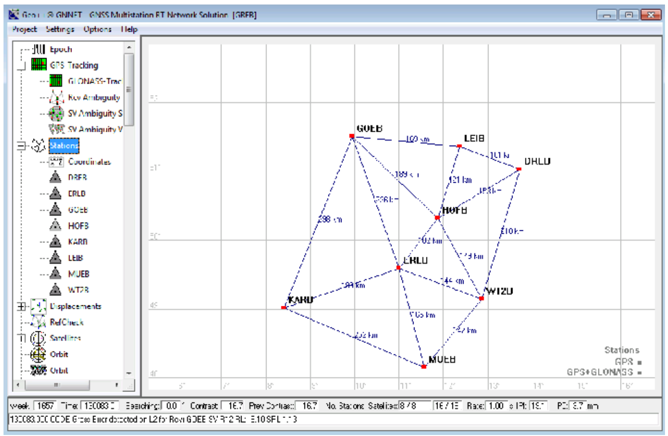


*Fig. 7: Free station HOFJ (renamed HOFB) within seven GREF station sub-network (fixed coordinates)*

Comparing Fig. 8 without correction and Fig. 9 with EAR-VCE corrections reveals a significant improvement in both, horizontal and height coordinate components. The differences to a reference position amount for the uncorrected experiment are up to 4 cm in Northing, 2.5 cm in Easting and up to 14 cm in height. The corrected experiments shows generally smaller differences (height up to 6 cm) for the 5 minutes RTK positioning solutions.

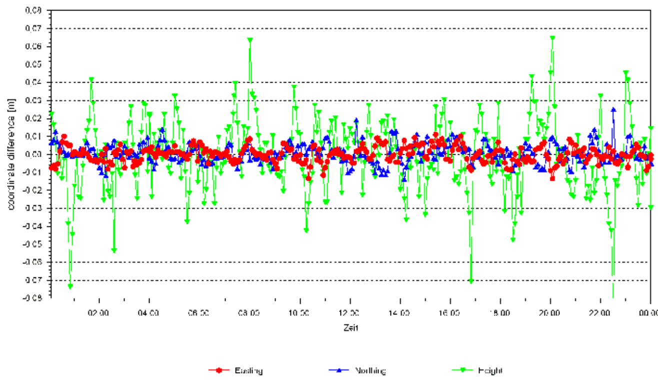

*Fig. 8: Coordinate differences station HOFJ without EAR correction over 24 h (288, 2011)*

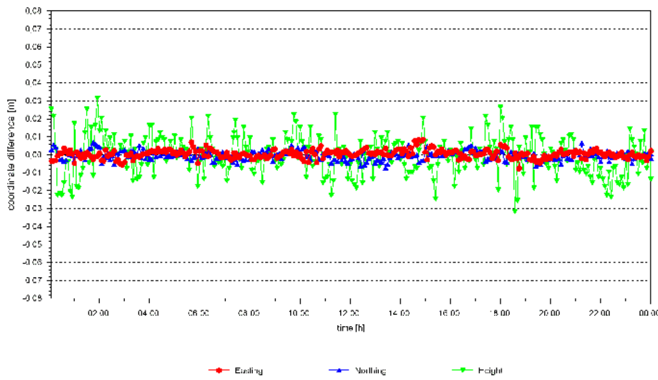

*Fig. 9: Coordinate differences station HOFJ, with EAR correction over 24 h (288, 2011)*

As expected by theory, the EAR-VCE improvement for the near-field multipath is largest for the height component. Fig. 10 shows the differences of the height component between the two data sets with and without EAR-VCE correction in more detail.

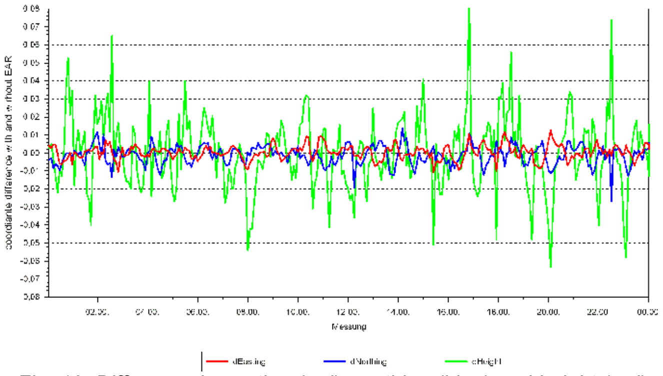

*Fig. 10: Difference in easting /red), northing (blue) and height (red) with/without EAR correction over 24 h (HOFJ 288, 2011)*

The histograms in Fig. 11, Fig. 12 and Fig. 13 show the distribution of the coordinate differences for station HOFJ to a reference for a time period of about 15 days. The sample size is about 4250 coordinate differences.

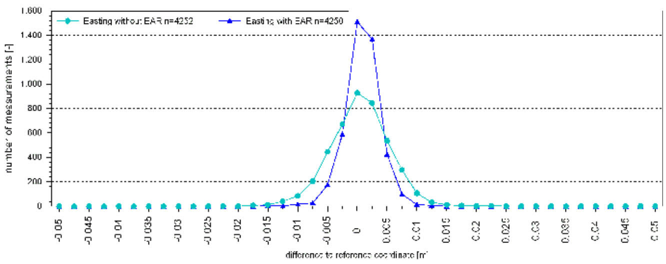


*Fig. 11: Coordinate difference in Easting with (triangle) and without EAR correction (circle)*

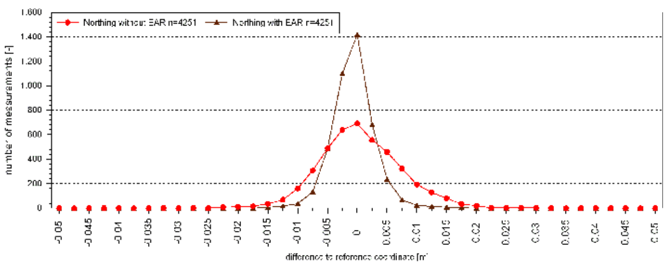


*Fig. 12: Coordinate difference in Northing with (triangle) and without EAR correction (circle)*

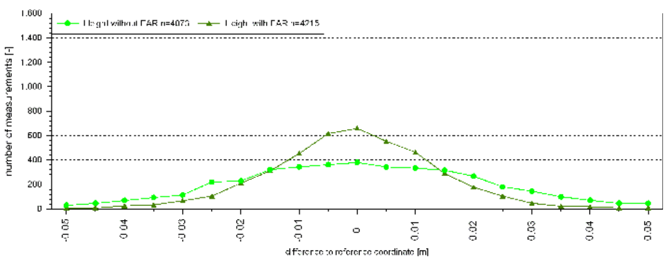

*Fig. 13: Coordinate difference in Height with (triangle) and without EAR correction (circle)*

An improvement in all coordinates components is clearly visible. The distribution around the reference is smaller for the coordinate differences with EAR-VCE correction and underlines the benefits.

Fig. 14 shows the standard deviation of the coordinate differences to the reference coordinate for 15 individual days. The improvement in 2D position and height demonstrates the good repeatability and consistency of the EAR-VCE corrections.

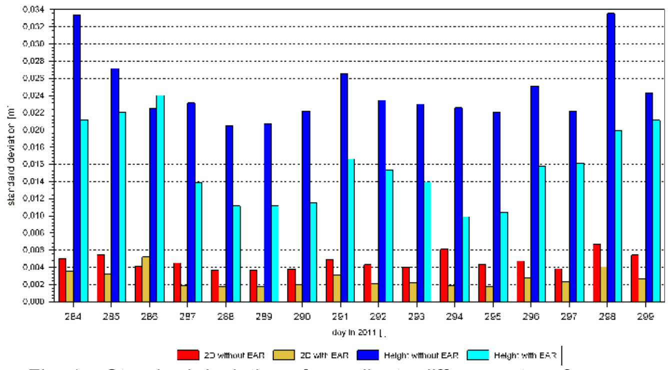


*Fig. 14: Standard deviation of coordinate difference to reference, station HOFJ with and without EAR correction, over 15 individual days*

## CNF – CALIBRATION + COMPENSATION OF NEAR-FIELD

A set of different methods has been developed and presented to determine near-field multipath effects. The methods can be combined in a flexible manner. All methods provide elevation and azimuth dependent correction/compensation and weighting models.

Considering a reference station network, the methods even allow the determination of near-field correction and weighting not only for L0, but also for the original signals. In this case, CaNF in-situ station calibrations are required for some selected sites in the network. The results for the original observable can then be used for constraining the CoNF method within a network of stations. The separation of the original signals from the ionospheric free signal L0 becomes possible through appropriate ionospheric modeling. As a result, L1, L2 and L5 correction and weighing scheme for all network sites can be derived.

This will be the topic of further investigations.

## SUMMARY AND DISCUSSION

Near-field multipath has a significant impact on GNSS applications and is essential for the separation of errors, performance of sophisticated modeling, reliability and accuracy of applications. A rigorous and flexible treatment for determination and correction of near-field effects for a variety of GNSS applications is required.

In-situ near-field calibration/compensation methods have been developed, which can be combined to best suit different tasks. The different approaches use robot calibrations to obtain near-field free equipment, single site in-situ calibration utilizing near-field free equipment (CaNF) and residual analysis in redundant GNSS RTK-networks to compensate near-field effects (CoNF). The combination of the CaNF and the CoNF methods is also feasible. The benefit of a combination is, that near-field correction and weighting models are obtained for all stations and signals.

The application of the correction and weighting in GNSS processing verified the models and demonstrated significant improvements. Further analysis and experiences with respect to e.g. environmental changes (e.g. weather condition) are meaningful. The currently implemented procedures in Geo++ GNSMART already use an adaptive approach. All addressed methods as well as in-situ station calibration equipment, analysis and processing software have been developed for operational use.

The benefits of near-field station calibration are obvious: an improvement of accuracy and reliability for a variety of GNSS applications.


## ACKNOWLEDGMENT

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Gerhard Wübbena, Martin Schmitz
Geo++®, Gesellschaft für satellitengestützte geodätische und navigatorische Technologien mbH

| | |
|---|---|
| Address | Steinriede 8, 30827 Garbsen, Germany |
| Phone | +49-5131-4689-0 |
| Fax | +49-5131-4689-99 |
| Web | www.geopp.de |
| E-mail | martin.schmitz@geopp.de |