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Antenna specific IfE-Robot based Code Phase Delays and its Impact on Positioning and Navigation

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Abstract
The Institut für Erdmessung (IfE) is an official IGS calibration institution, calibrating phase centre variations (PCV) for receiver antennae routinely in the field, using the actual GNSS satellite signals in space. Current research activities focus on the antenna code phase calibration with the Hannover Concept of absolute antenna calibration. The receiving antenna as a part of a reception chain can introduce systematic effects, currently known as Group Delay Variations (GDV), i.e. azimuth and elevation dependent code-phase delays. This error introduces additional range variations along the line-of-sight for every satellite depending on the corresponding incident angle in the antennas body frame. Depending on the antenna design, suitable for specific applications, GDV can degrade the accuracy of code based applications, such as precise landing approaches as well as for time and frequency transfer.
The paper can be subdivided into two major parts: In the first part, we focus on the current investigations on receiver antenna GDV calibration. Beside the theoretical background of a concept to determine GDV for different GPS antennae based on the Hannover Concept of absolute antenna calibration, the obtained GDV from several antennae with different characteristics will be presented and critically discussed. The second part focuses on the consequent analysis of the impact of the determined GDV on position and navigation applications. The contribution of GDV on the observation and position domain can be shown by using a special experimental set-up. In addition, GDV for a real C/A based autonomous navigation approach are investigated and critically discussed.

Keywords
Codephase Variations (CPV) — GNSS — phase centre variation (PCV)

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1. Introduction

The Federal Aviation Administration (FAA) is driving the research and development for the utilization of Global Navigation Satellite Systems (GNSS), like GPS, for precise aircraft landing approaches. The key system is the receiving element containing the antenna and the receiver on the moving platform. Inevitably, signal biases and systematic effects are introduced by the antenna and receiver. The key effects at the receiving antenna are the carrier phase centre variations (PCV) as well as group delay variations (Code Phase Variations, GDV).

The impact on the code-based navigation is of special interest, since this kind of observation type is licensed for aviation applications, for example in curved landing approaches and other aviation based approaches like sea-based landings on aircraft carriers. As shown in studies by [1], GDV affects the observations and degrades the precision at Controlled Reception Pattern Antennae (CRPA) at Joint Precision Approach and Landing Systems (JPALS). Further studies are concentrated on the requirements and importance of GDV with respect to the Local Area and Wide Area Augmentation

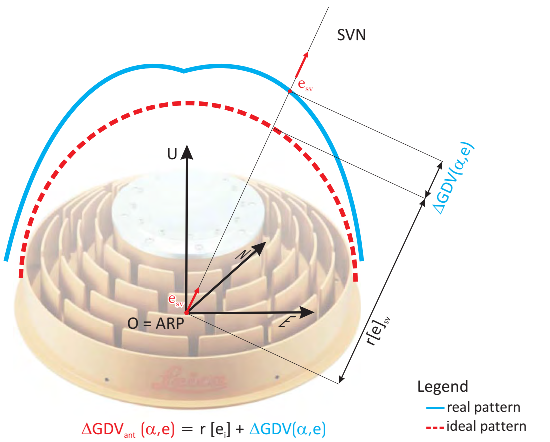


Figure 1. Scheme for Group Delay Variations (GDV) at a GNSS antenna.

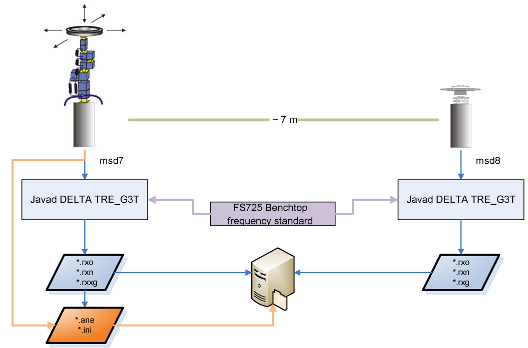


Figure 2. Scheme of antenna calibration based on the Hannover Concept.

System (LAAS and WAAS) as analysed by [2].

But also the precise orbit determination (POD) for several low earth orbiter (LEO) satellite missions could be affected, [3] if the GDV reaches significant values in the coordinate domain.

During the renewal of an updating of the Minimal Operational Performance Specifications (MOPS) [4], GPS antennas show unexpectedly large variations in GDV of some nanoseconds, with respect to azimuth and elevation of the incident ray, cf. [5] and [6].

This context is depicted in Figure 1. Some antennae show a homogeneous response like indicated by the dashed line in Figure 1, whereas other antennae show a more pronounced pattern with respect to the LOS of the incident GNSS signal, which corresponds to the solid line in Figure 1. If a correction table parametrized in the azimuth and elevation is given, this effect can be interpolated and eliminated from the original observation.

2. GDV Determination Method

First results using the Hannover Concept of absolute antenna calibration to determine elevation dependent Code Phase Variation (GDV) were discussed in [7] and [8] for several geodetic GNSS antennae and receiver.

In this contribution the GDV are determined by an extended post-processing method that is based on the operational Hannover Concept of absolute antenna calibration, cf. [9], [10]. The set-up is depicted in Figure 2. On a short baseline of approx 7 m a reference station (msd8) and a kinematic station (msd7) are located. Both stations are connected to the identical receivers (Javad TRE_G3T) with identical firmware as well as one unique external frequency (FS 725 Benchtop Stanford rubidium frequency) supporting one second Allan Variance of $\sigma_y^2 < 2 \cdot 10^{-11}$. The kinematic station is represented by a precisely calibrated robot arm, which is regularly calibrated at the Geodetic Institute Hannover (GIH) with an accuracy of 0.25 mm, [11]. The robot is used to change the antenna's orientation on subsequent epochs (< 5 seconds) by well known and predefined steps in azimuth as well as in elevation.

The antenna calibration is carried out using the actual modulated and available GNSS satellite signals in space. The post-processing of the GDV antenna calibration is based on time differenced single differences.

2.1 Observation Model

The code phase observation P_A^j from a satellite j to a station A can be modelled by

$$\begin{aligned} P_A^j = \rho_A^j + c \cdot (\delta t_A - \delta t^j) + T_A^j + I_A^j + REL_A^j \\ - d_c^j + d_{A,c} + MP_{A,c}^j + GDV_A^j(\alpha, e) + \varepsilon_A^j \end{aligned} \quad (1)$$

with the geometric distance ρ_A^j, the synchronization error in meters $c \cdot (\delta t_A - \delta t^j)$ between the system time scale and the receiver clock, the tropospheric T_A^j and ionospheric I_A^j path delay, the relativistic correction REL_A^j, the hardware delays at the satellite d_c^j and the receiver $d_{A,c}$, multipath effects $MP_{A,c}^j$ and possible code phase variations $GDV_A^j(\alpha, e)$ as well as additional observation noise ε_A^j.

Forming inter-station single differences $SD_{AB_c}^j$ per each epoch ι leads to

$$\begin{aligned} SD_{AB_c}^j(t_\iota) = c \cdot \Delta\delta t_{AB}^j(t_\iota) + \Delta GDV_{AB}^j(\alpha, e, t_\iota) \\ + \Delta MP_{AB_c}^j(t_\iota) + \varepsilon_{AB}^j(t_\iota) \end{aligned} \quad (2)$$

with the differential receiver clock error $c \cdot \Delta\delta t_{AB}^j$ in meters, the differential GDV of both antennas on the baseline $\Delta GDV_{AB}^j(\alpha, e, t_\iota)$, the differential multipath $\Delta MP_{AB_c}^j$, and additional error sources $\varepsilon_{AB}^j(t_\iota)$. However, all the satellite and distance dependent error sources like orbital errors, troposphere and ionosphere are similar for both stations and can be eliminated by differentiation.

Since the geometry of visible satellites in the antenna's body frame will not change significantly between two subsequent epochs with maximum delay of less than 5 seconds, the $\Delta GDV_{AB}^j(\alpha, e, t_\iota)$ in equation (2) will also be similar for each epoch, so that GDV would be cancelled out by differentiation

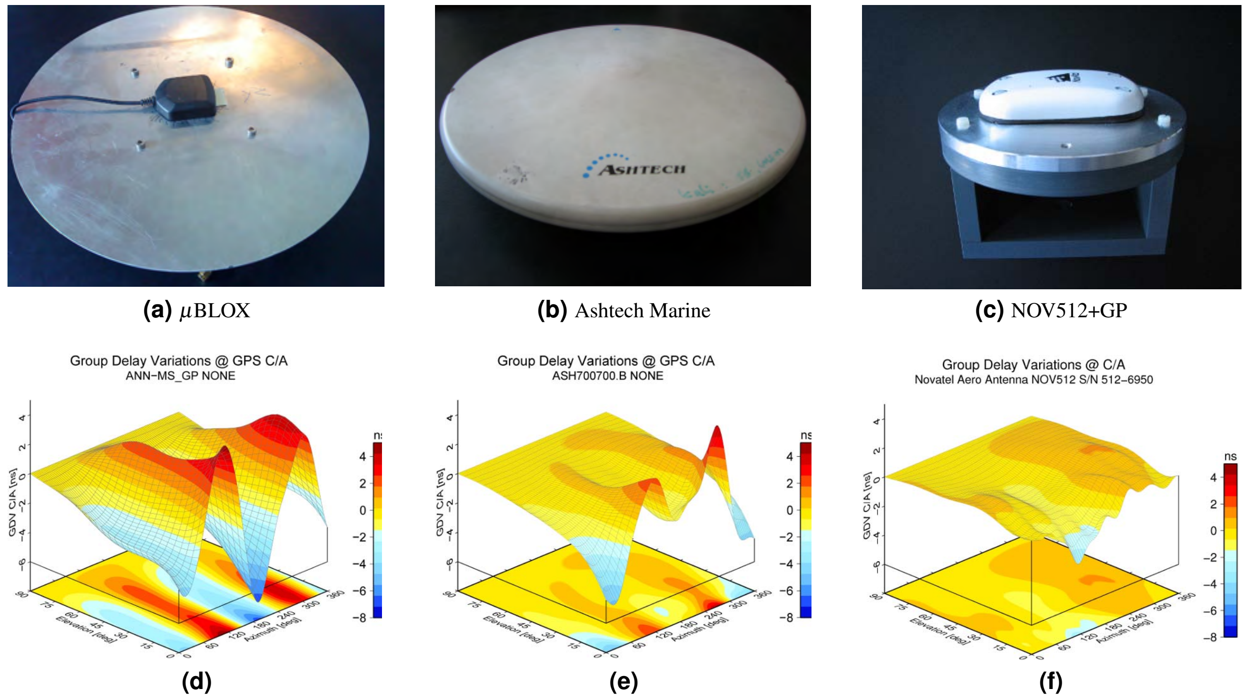


Figure 3. Determined GDV based on GPS C/A code observations for several GNSS navigation antennas.

of subsequent epochs. Consequently, the orientation of the antenna has to be changed between subsequent epochs by well known and very pre-defined steps in azimuth and elevation. This is realized by a robot, so that the GDV can be estimated through time differenced single differences on a short baseline with an observation equation that reads

$$\begin{aligned} \Delta SD^{j}_{AB_c}(t_\iota, t_{\iota+1}) &= SD^{j}_{AB_c}(t_{\iota+1}) - SD^{j}_{AB_c}(t_\iota) \\ &= GDV^{j}_{A}(\alpha, e) + \varepsilon^{j}_{AB}(t_\iota, t_{\iota+1}). \end{aligned} \tag{3}$$

Since an external frequency standard is used for both receivers, the differential receiver clock error in equation (2) is stable over subsequent epochs and cancels out by differentiation. This is also true for the far field multipath. The impact of the near field multipath is currently analysed at the IfE in a separate study. However, this effect is a challenge at all antenna calibration facilities, chamber as well as robot based approaches.

2.2 Mathematical Model

GDV are expressed on a sphere by a spherical harmonic analysis

$$GDV(\alpha, e) = \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} \left\{ \begin{matrix} A_{nm}\,\bar{R}_{nm}(\alpha, e) \\ B_{nm}\,\bar{S}_{nm}(\alpha, e) \end{matrix} \right\}, \tag{4}$$

with unknown coefficients A_{nm} and B_{nm} and

$$\left\{ \begin{matrix} \bar{R}_{nm}(\alpha, e) \\ \bar{S}_{nm}(\alpha, e) \end{matrix} \right\} = \left\{ \begin{matrix} \cos(m\alpha) \\ \sin(m\alpha) \end{matrix} \right\} N_{nm} P_{nm}(\sin e)$$

with the fully normalized harmonics $\bar{R}_{nm}(\alpha, e)$ and $\bar{S}_{nm}(\alpha, e)$ and a to maximum degree n_{max} and order m_{max} truncated expansion. The harmonics are continuous and orthogonal base functions of elevation e and azimuth α in the antenna's body frame as shown in Figure 1. The normalization factor is denoted by N_{nm} and the associated Legendre functions by $P_{nm}(\sin e)$, as described in [12]. GDV were derived by a best linear unbiased estimator (BLUE) approach (least squares) as shown in [13].

3. Discussion of GDV Antenna Calibration

Exemplary, solutions of GPS C/A GDV are depicted as a rectangular plot for azimuth and elevation in Figure 3 for some typical GNSS navigation antennae.

The first antenna is a typical low cost navigation antenna, which was adopted with a ground plane as shown in Figure 3a. By post-processing of the GDV calibration, a very pronounced GDV pattern with magnitudes of up to 6 ns (1.7 m) could be determined. It indicates, that the elevation dependence of the GDV pattern is mostly driven by variation in azimuth.

The Ashtech Marine antenna, as depicted in Figure 3b is primarily used in marine navigation approaches. The antenna has a less pronounced azimuthal GDV pattern than the μBLOX antenna, but variations of up to ± 2 ns for elevations below 30° could be determined by the calibration. From Figure 3e a 180° rotation symmetrical behaviour of the azimuthal GDV can be identified, similar to the GDV symmetry of the μBLOX antenna.

For an aeronautical navigation antenna Novatel NOV512+GP with a special tripod and a modified groundplane as depicted in Figure 3c GDV patterns with smaller magnitudes of below 2 ns were determined. This context is depicted in Figure 3f. The Novatel NOV512 antenna has a more homogeneous GDV pattern with very small azimuthal variation of below ±1 ns.

The studies on GDV C/A calibration at IfE also confirm the analyses carried out by [6] where elevation and azimuth dependence of some nanoseconds were reported. However, all analysed GPS antennae show an individual and significant pattern. In addition, the study of Figures 3d - 3f suggests, that the elevation dependence is mostly driven by azimuthal variations. For all the tested antennae, no significant pure elevation dependence could be achieved.

4. Application of GDV

4.1 Observation Domain

To validate the determined GDV in the observation domain, a special experiment on the laboratory network at the IfE roof top was carried out on a short baseline (≈ 7 m) - very similar to the set-up shown in Figure 2 with the identical receiver (Javad TRE_G3T) connected to a Standford rubidium frequency FS725 as common clock. The baseline was equipped with a μBLOX antenna as shown in Figure 3a and a typical geodetic 3d Leica AR25.R3 choke ring antenna. The measurements were carried out by a 24 hours dataset with 15 seconds sampling interval on DOY 223 to DOY 224, 2012. The observations were studied on the basis of inter-station single differences (SD) in common clock mode. The observations and all error sources are described by equation (2).

In Figure 4 the observed minus computed (OMC) values are depicted versus the satellite elevation. The following conclusions can be drawn in the observation domain:

(1) SD OMC are influenced by a systematic effect that is obviously elevation-dependent,

(2) these variations seems to be azimuth dependent too, since the impact of GDV is not symmetrical to the elevation of the satellite and

(3) this effect is unique for each satellite in the antenna's body frame.

The GDV correction (solid line within the SD OMC) describes this systematic effect very good. The systematic signature can be removed from the observations by applying the corresponding GDV corrections and an improvement of up to 50% in the observation domain can be reached, when applying carrier phase smoothing. Table 1 summarizes the results for some selected PRNs.

4.2 Coordinate Domain

The impact of the GDV on the coordinate domain is analysed on the basis of an autonomous C/A based single point positioning (SPP) with the same 24 hours dataset and 15 seconds sampling rate, measured on DOY 223 to DOY 224, 2012 as described before. The coordinates were computed with 100 seconds carrier phase smoothed code observations and elevation weighting, [14]. Figure 5 presents the difference of two SPP derived time series, one with GDV corrected, one without GDV correction applied. Thus, the resulting difference describes the impact of the GDV on the coordinate domain.

The GDV impact is highly correlated with the current satellite geometry and the number of visible satellites in the antenna's body frame. The impact on the coordinate domain can be attributed to the very pronounced elevation and azimuth dependent GDV pattern.

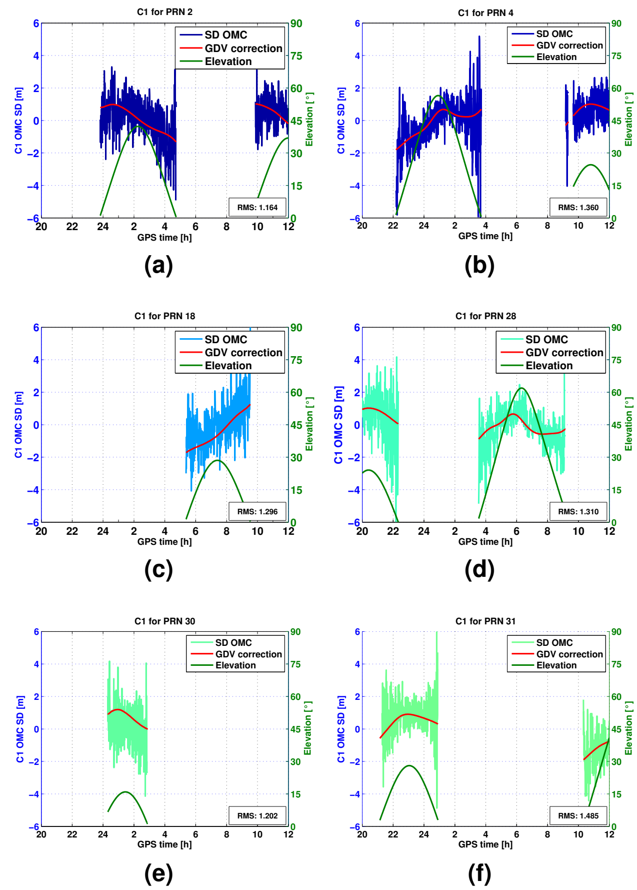


Figure 4. Observed-Minus-Computed (OMC) values of GPS C/A inter-station single differences (SD) on a short baseline for some selected satellites versus elevation and determined GDV correction for a representative 16 hour selection.

Table 1. Comparison of the Impact of GDV on the GPS C/A code observation with and without carrier phase smoothing for a short baseline in common clock mode.

	RMS in [m]						
	GDV	PRN2	PRN4	PRN18	PRN28	PRN30	PRN31
	no	1.164	1.496	1.296	1.310	1.202	1.485
	yes	1.010	1.310	1.095	1.168	1.159	1.117
		+13%	+12%	+15%	+10%	+3%	+24%
smoothed	no	0.699	0.773	0.623	0.647	0.942	0.764
smoothed	yes	0.362	0.348	0.432	0.485	0.400	0.440
smoothed		+48%	+54%	+31%	+25%	+57%	+42%

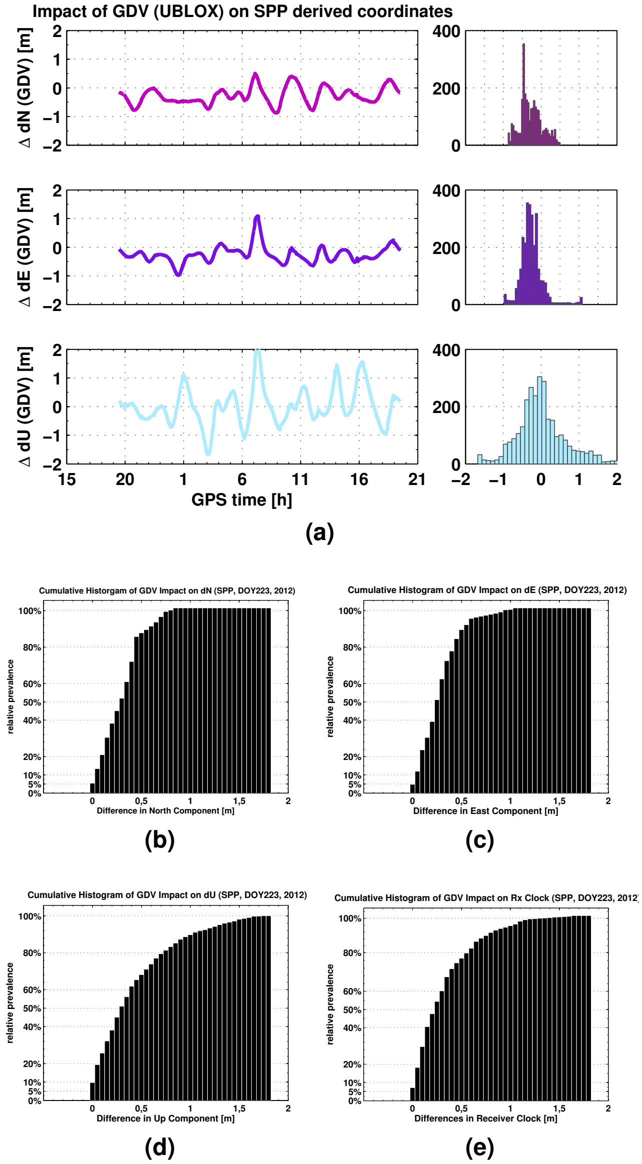


Figure 5. Impact of GDV on the coordinate domain within a 24 hour GPS C/A based single point positioning (SPP) approach with carrier phase smoothed code observations and elevation weighting (a) and cumulative histograms showing the impact of GDV corrections on the SPP derived position solution for the baseline on the laboratory rooftop network of IfE, DOY223, 2012 (b-e).

For the discussed 24 hour dataset it can be summarized that GDV introduce a mean offset of -0.5 m in the north and a mean offset of -0.25 m in the east component for the ($SPP_{GDV} - SPP$) time series. The height component is influenced by variations due to the changing satellite geometry with maximum magnitudes of up to 2 m, which can be attributed to the pronounced GDV pattern, ref. Figure 3d. For the up component an offset of up to 2 m can be expected for a weak satellite coverage. In addition, the histograms illustrates the scatter of the coordinates. Further studies have shown, that this is also valid for different observation weightings within the SPP algorithm.

In Figure 5 cumulative histograms are depicted for the analysis of the GDV impact on the static autonomous SPP. Due to the high correlation of the up component and the receiver clock estimates, the similar behaviour can be expected for the receiver clock, as shown in Figure 5e.

For this studies it can be summarized, that for antennae which have a pronounced GDV pattern, a significant impact on the observation and therefore on the derived coordinate domain is unavoidable. Taking the GDV correction into account the effects on the observation and coordinate domain can be controlled and reduced.

For the north and the east component, the impact of the GDV on positioning is smaller than 0.5 m in 80% and smaller than 0.75 m in 90% of all cases. For the up component the deviation is smaller with 0.5 m in 65% of cases, 1 m in 90% and 1.5 m in 99% of the 24 h data set. It should be noted that these values are valid at mid-latitudes.

5. Application to Navigation

In addition to the studies of the GDV impact on the coordinate domain, a precise autonomous GNSS code-based navigation of an air plane during a real test flight on DOY 192, 2011 was analysed.

5.1 General Set-up

The trajectory of the test flight was carried out in collaboration with the Institut für Flugführung (IFF) of the University of Braunschweig (TU Braunschweig) and is shown in Figure 6. The IFF has a scientific research aircraft (Dornier 128-6 D-IBUF) that provides the 70 minutes test flight with typical flight manoeuvres for curved approaches, cf. Figure 6b. In fact, the test flight was carried out to validate the concept of a virtual receiver, cf. [15]. During the flight a dual frequency aero antenna Novatel NOV512 as depicted in Figure 3c was used in the front section of the air plane, were only few obstructions are expected for non curved flight approaches.

The GDV for this antenna were determined after the flight using a special tripod to calibrate the Novatel antenna on the antenna calibration unit.

The skyplot in Figure 6a indicates that a stable satellite geometry of high and low satellites could be achieved.

5.2 Computation of the Trajectory and Nominal Solution

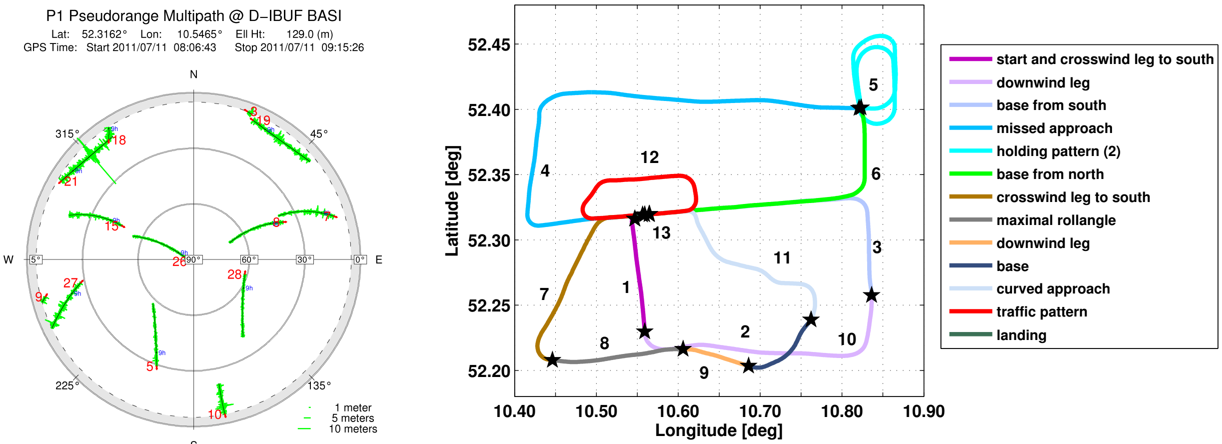
The data of the 70 minutes test flight was collected using 1 second sampling rate. The processing of the data set was performed using elevation dependent-weighted, 100 seconds carrier-phase smoothed code observations and with an elevation mask of 5°, as indicated by Figure 6a. The autonomous SPP solution was derived using a software developed at IfE.

The reference solution was derived by using the two orders more accurate dual frequency carrier phase data within a PPP software also developed at IfE as described in [16].

Trajectories derived from SPP with and without applying GDV corrections are compared to the PPP solution. When applying the GDV correction on the test flight scenario, the corresponding satellite geometry has to be expressed in the topocentric antenna body frame for each epoch. The azimuth and elevation values for consistent transformation between global Earth Centred Earth Fixed (ECEF) and antenna body frame are derived by additional aeronautical instruments.

5.3 Results for Navigation Approach

The impact of GDV on the SPP algorithm is analysed by comparing the differences of the SPP solution with and without applying the corrections. The impact on the topocentric coordinates are mostly



(a) (b)

Figure 6. Skyplot of visible satellites during the test flight of the Do128-6 D-IBUF (a) and trajectory with colored maneuvers (b).

reflected by offsets and a high correlation with the currently visible satellite geometry inside the antenna's body frame. This is underlined by sudden jumps of the GDV impact, which are directly assigned to the changes of flight direction within the test flight, as described in Figure 6b.

A continuous impact is mainly detectable for the up component, which is also indicated by the histograms of the coordinate differences. As shown by the cumulative histograms in Figure 8 the impact of GDV on the test flight is mainly smaller than 0.30 m in 90% of cases for the north component. The east component shows smaller magnitudes since in 90% of all cases the impact on the coordinate domain is below 0.25 m. For the up component 90% are smaller than 0.3 m and all deviations are smaller 0.5 m. Consequently the used antenna design already reduces the maximum coordinate variations compared to the before analyzed μBLOX antenna.

Finally for the current GNSS signals and requirements of the CAT approaches, the GDV of the analysed antenna are not an issue. This situation may change in future for different antennae and with more precise GNSS signals.

When comparing both SPP solutions versus the PPP derived coordinate series, it indicates by Figure 8 that an offset seems to be introduced. But also some variation could be reduced by applying GDV corrections during the SPP algorithm as depicted in Figure 7b. This fact is supported by the results from Table 2, too. It points out that GDV can refine the code based autonomous navigation - since the mean values of the time series for all 3 components could be improved by up to 10% for horizontal components and up to 84% for height component.

Table 2. Comparison of Differences of SPP versus PPP derived trajectory with and without GDV corrected code observations.

	GDV	Δnorth	Δeast	Δup	Δ3d point
mean	no	0.178	0.130	-0.242	1.076
RMS		0.383	0.367	1.01	0.487
mean	yes	0.157 (+11.8%)	-0.118 (+9.2%)	-0.045 (81%)	1.086 (-0.9%)
RMS		0.491	0.332	1.020	0.502

The statements in this study are valid for mid-latitudes. It should be noted, that for a difficult satellite constellation these GDV introduced impacts can reach significant and mainly position and navigation degrading values, for example especially in northern and southern pole regions, where GNSS satellite coverage is very difficult.

6. Conclusions

In this contribution it could be shown that code observations are affected by systematic errors, which are introduced by the antenna specific reception behaviour for the code observations. These code-phase variation (GDV) can depend on the elevation and azimuth of the incoming GNSS satellite signal. By an experimental extension of the Hannover Concept of absolute antenna calibration, these GDV can be determined in a post-processing. GDV are calculated on a sphere by a least squares estimation with time differenced single differences (ΔSD).

The study shows that GDV are an antenna specific property, as well as frequency dependent. For a μBLOX antenna elevation and azimuth dependent variations of up to 6 ns (1.7 m) could be determined for the C/A code. For some navigation antennas C/A code GDV with magnitudes of up to 1-2 ns (0.3-0.4 m) could be shown.

Within an analysis on a short baseline, it could be shown, that GDV have an significant impact on the code observation at some antennae. Single differences (SD) on a short baseline with common clock and 100 seconds carrier smoothing could be improved by up to 50% when applying GDV corerections.

In the second part it was carried out by intensive studies, that GDV affects the code-based positioning. Offsets of up to -0.5 m for the north component and -0.25 m for the east component could be determined. The up component is affected by variations of up to 2 m due to high correlation of GDV impact and changing satellite geometry.

In addition, the studies on GDV have also shown significant impacts on the code-based aviation navigation, like for example in curved landing approaches. Therefore a code based real test

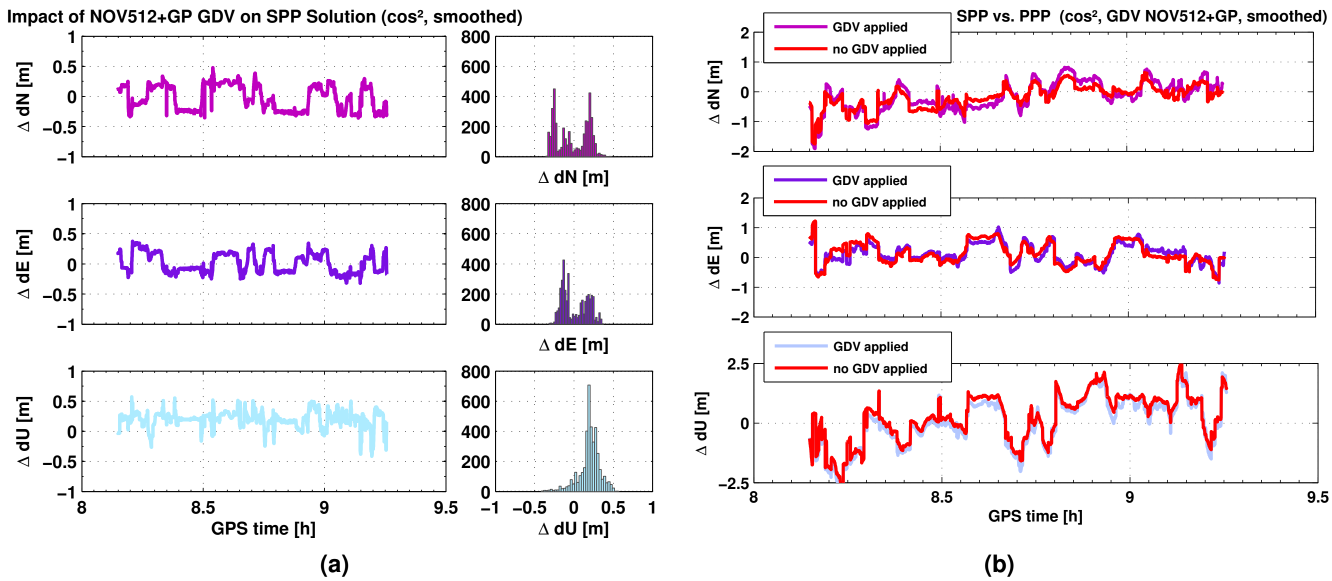


Figure 7. Impact of GDV on autonomous code based SPP navigation approach for an air plane (a) and comparison between PPP derived solution versus SPP w/o GDV correction (b).

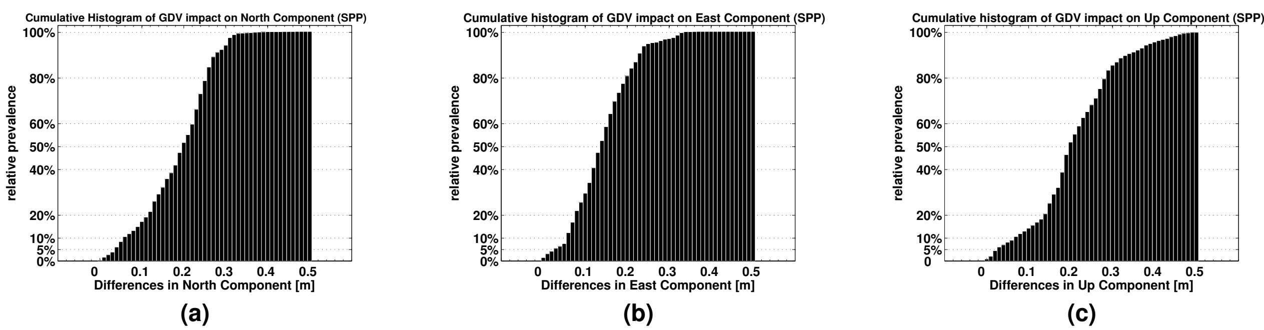


Figure 8. Cumulative Histograms showing the impact of GDV corrections on the SPP derived Navigation trajectory for the three topocentric components for the test flight on DOY192, 2011.

flight was analysed with and without GDV correction applied. Both solutions were compared to a PPP derived nominal solution. It points out that GDV can improve the up-component of up to 80% and the horizontal components of up to 10%, although the euclidean distance (Δ3d point) could not be improved.

Further studies of GDV are concentrated on the analysis of the near field impact on the derived GDV. In addition, the amount of GDV with nearly one cycle and sometimes more of a carrier phase wavelength encourages the further analysis of possible improvements within ambiguity fixing.

Disclaimer

Although the authors dispense with endorsement of any of the products used within this study, commercial products were named for scientific transparency. Please note that a different receiver / antenna unit of the same manufacturer and type may show different characteristics.

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