

A new Approach for GNSS Analysis in a Multi-GNSS and Multi-Signal Environment

Research article

Erik Schöнемann^{1*}, Matthias Becker¹, Tim Springer²

1 Institut für Physikalische Geodäsie, Technische Universität Darmstadt, Germany

2 PosiTim, Seeheim-Jugenheim, Germany

Abstract:

Over the coming years GPS and GLONASS will be modernised, whilst at the same time new systems like QZSS, Galileo, and Compass are launched. The modernisations of the existing and the deployment of new Global Navigation Satellite Systems (GNSS) will make a whole range of new signals available to the users.

The anticipated improvements will strongly depend on our understanding and handling of the biases that will inevitably exist between the different systems and signals. Furthermore the extremely high stability of the future satellite clocks means, that any form of differencing observations to cancel out the satellite clock offsets, effectively leads to a very significant loss of information.

The fundamentally new aspect of our approach for GNSS analysis in a multi-GNSS and multi-signal environment is that it avoids the formation of differences as well as of linear combinations. Thus all available observations from all GNSS systems as observed by all the receivers in a network are incorporated in the parameter estimation. The fact that all observations are analysed without any pre-selection of observation types, needed for linear combinations or observation differences, leads to an enormous simplification of the processing.

Keywords:

GNSS • Ionosphere • TEC • DCB • UPD • Multi frequency • Multi GNSS

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1. Introduction

The two GIOVE A and B, as well as the launch of the first GPS Block IIF satellite are first concrete signs of the ongoing changes in the GNSS environment. In the near future the GPS dominated GNSS market will evolve into a true multi GNSS environment, providing a broad variety of frequencies and signals. This evolution can be seen as a driver to further enlarge the field of GNSS applications whilst at the same time improving the existing applications. The main advantage, coming along with the greater number of satellites and frequencies, is the ability to better mitigate and resolve atmospheric effects.

Over the recent years we have had the opportunity to work with some of the new data from the GIOVE-A and -B satellites and the latest GPS satellites with G5 (L5 GPS) capabilities. Based on these first experiences with the new signals we recognized that the current commonly adopted approach in GPS and GLONASS analysis is at best sub-optimal in a multi-GNSS and multi-frequency environment. There are two main reasons for this, firstly the availability of highly stable satellite clocks and secondly the high number of different raw observables which all may, or rather will be delayed with respect to each other, e.g., inter-system and inter-frequency biases (Hegarty et al. 2005, Phelts 2007).

Due to the limitation in separating the individual error sources in dual frequency GNSS, today GNSS processing uses signal differences and combinations, such as double differences (DD), single differences (SD) and ionosphere free linear combinations for error mitigation. These procedures are based on the assumption of identical signals tracked comparably in different receivers and

*E-mail: schoenemann@ipg.tu-darmstadt.de

therefore of similar biases. Taking into account the variety of future signals, a combination of all signals on the basis of differences will become practically impossible. Especially for Double Differences (DD) observations the advantages of the future signal diversity may be limited, as not all receivers will track the same signals. Also different receiver types may track identical signals differently. In RINEX 3.01 such observations are denoted as channel "X" (Gurtner and Estey 2009). Hence to access the true capabilities of the future heterogeneous GNSS environment it will be essential to treat the signals and the corresponding corrections individually.

The fundamentally new aspect of our approach for GNSS analysis in a multi-GNSS and multi-frequency environment is that it completely avoids the formation of differences and linear combinations. Undifferenced approaches for the GPS have already been presented, such as de Jonge (1998) and Odijk (2002), but all of them they still makes use of SD within the processing. Furthermore the extension to arbitrary signals and systems comes a long with numerous new difficulties which need to be solved such as signals specific Uncalibrated Signal Delay (USD) in both satellites and receivers. Our approach makes use of all available observations from all GNSS systems, as observed by all the receivers in a network; incorporated in a single parameter estimation. This leads to an enormous simplification in the data pre-processing as no pre-selection, differencing, nor forming of linear combinations is required. The price to be paid is a significant increase of the number of parameters to be estimated. Hence numerous, currently ignored biases, now needs to be considered, but the most significant increase is the estimation of ionospheric delays for each epoch for each receiver-satellite combination. This article describes our new estimation approach with a strong focus on the problems that may be caused by interfrequency and intersystem biases (Hegarty et al. 2005).

2. Basic Considerations

2.1. Clock Stability

GNSS solutions have reached an amazing level of accuracy. The GPS orbit estimates of the International GNSS Service (IGS) agree to within 10 mm and at the same time the weekly station positions agree at the 1 mm level horizontally and 4 mm vertically. Even with the enhancements of the Russian GLONASS system and the advent of the European Galileo system it is not very probable that these systems will increase these unsurpassed accuracy levels any further without significant changes in the data analysis strategies. One of the areas where significant improvements may be achieved is the clock modeling. In most GNSS analysis the GNSS transmitter and receiver clocks are estimated fully independently for each epoch. This approach ignores the facts that all GNSS transmitter clocks are derived from highly stable atomic clocks, and that within the IGS network a significant amount of receivers are connected to atomic clocks such as hydrogen masers. Furthermore, the clocks

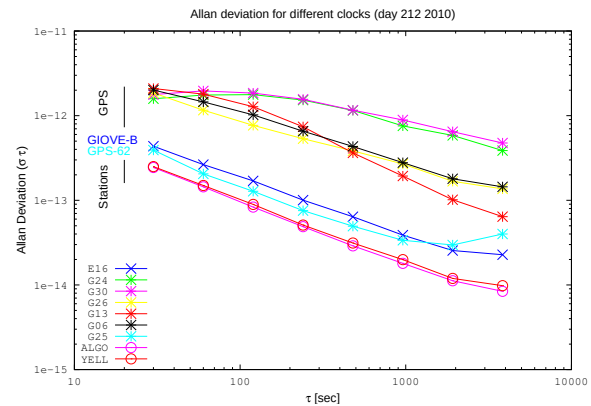


Figure 1. Stability of different satellite/station clocks (day 214 2010)

on board of the Galileo satellites are expected to be extremely stable, being the first passive hydrogen masers to be flown in orbit on GNSS satellites. Enhanced clock modeling has the potential for an extreme reduction of the number of estimated parameters (clocks) in undifferenced GNSS processing. The potential accuracy improvements are very significant and may constitute a true revolution in the GNSS analysis.

The extremely high stability of future satellite clocks, was demonstrated on the experimental Galileo satellite GIOVE-B (Waller et al. 2008, Schönemann et al. 2009) and the modernized GPS satellites. Figure 1 shows the Allan deviation, a measure for clock stability, for different satellite and station clocks. An Allan deviation of 1 ns corresponds to a range error of 0.3 m. Hence to allow a proper modeling (prediction) of GNSS clocks in accordance with up-to-date GNSS orbit and clock accuracy of 1.2 - 1.8 cm (Griffiths and Ray 2009) a clock stability better than 40 ps is needed.

Already the up to date GPS clocks can be divided in two groups the worse Cesium (e.g. G24, G30) and the better Rubidium (e.g. G26, G13, G06) clocks, with still insufficient stability. However the precursors of future GNSS clocks, as the passive H-Maser on board of GIOVE-B and the new Rubidium on board of GPS-62 (G25) shows a superior clock stability, close to the clock specs and close to the active H-Maser clock employed at ground stations (e.g. ALGO, YELL). The expected high clock stability means that any form of differencing observations to cancel out the satellite clock offsets effectively leads to a significant loss of information. Therefore satellite differences should be avoided in order to obtain the highest possible accuracies from the new and modernized systems. This, however, is not really a new trend, as undifferenced (also called zero-differenced) processing is not really uncommon, but the availability of highly stable satellite clocks makes the case for undifference processing even stronger.

2.2. Ionospheric effects

In GNSS analysis commonly ionosphere-free linear combination of the observations forms the basic observable for the parameter estimation. With just two frequencies on both GPS and GLONASS and a more or less de-facto standard that all receivers deliver the phase observations from the same code observations (i.e. from P1 and P2, rather than C/A or lately C2) the situation is (more or less) clearly defined. However, in a multi-GNSS, multi-frequency and multi-signal environment, with receivers tracking different codes differently, the number of possible linear combinations grows very rapidly. If one looks into the RINEX-3 standard (Gurtner and Estey 2007) one can see 19 different observables for both the GPS and the GALILEO system. The number of possible linear combinations becomes mind-boggling whilst at the same time the likelihood that two different receivers provide the same observables becomes very small. The large number of different raw observables and the biases between these observables renders the formation of ionosphere linear combinations rather useless or at least cumbersome. The number of possible signal combinations, the difficulty to define an optimal signal combination and the variability of the biases, calls for an approach that is more flexible than differencing and forming pre-defined linear combinations.

Rather than forming the ionosphere free linear combination our approach uses the "raw" observations and estimates one ionospheric delay parameter per epoch for each station-satellite pair. In the case of only two available signals this approach is exactly equivalent to forming the ionosphere-free linear combination, provided the ionosphere parameters are estimated completely free (Mervat 1995). With more than two signals available there is considerably more information that can be exploited at the cost of additional parameters in the estimation process. In our approach it would be possible to constrain the estimated ionosphere parameters, which could strengthen the solution significantly.

2.3. Inter signal biases

For each signal included in the parameter estimation a bias may, and most likely will, have to be estimated. Depending on the individual signal this bias may be satellite, receiver, and/or time dependent. Like the clock estimation in the undifferenced analysis where a reference clock has to be selected, in this analysis a reference observation type will have to be selected. For this "reference signal" no bias will be estimated. Consequently all the biases will be relative to this "reference signal" and also the clocks will be relative to this signal and to the selected reference clock. In addition, as explained above, ionospheric delay parameters will have to be estimated, as no ionosphere free linear combinations are formed for mitigation.

To enable the processing of single frequency measurements the code observations need to be adjusted by the utilization of so-called Differential Code Bias (DCB) (Schaer 1999, Schaer 2008). Since not only the code measurements, but also the phase mea-

surements are affected by hard- or software delays (Blewitt 1989), resulting in Fractional-Cycle-Bias (Ge et al. 2008), the integer nature of the undifferenced phase observations are destroyed. Different approaches for the recovery of the integer nature have been presented by Ge et al. (2008), Laurichesse et al. (2009), Collins et al. (2008), Henkel et al. (2010). All of these approaches take advantage of ionosphere free signal or ionospheric combinations to mitigate or estimate (Spits and Warnant 2008, Spits and Warnant 2011) the ionospheric effect on the measurements. But considering the number of possible differences in future, the application of differential corrections will become very difficult (Schaer and Dach 2010).

Also the current IGS orbit and clock products, as in general used for Precise Point Positioning (PPP) processing, are based upon GPS ionosphere free observations. Hence the application of IGS products is strictly speaking only correct for the processing of the same ionosphere free linear combination of the P1 and P2 pseudo range measurements and the corresponding phase observations. In this case the corresponding hardware biases in the satellite are the same at the provider and the user side and therefore they can be neglected. Note that this is only true when the user also uses the P1 and P2 observables. Alternatively the user may correct, or rather convert, C1 observables to P1 observables using the so-called P1-C1 biases, delivered by the IGS. For C2-P2 a similar problem exists but no products exist from the IGS that enables a corrective conversion, of C2 to P2.

The huge benefit of our approach, if the IGS or any other GNSS service provider would adopt it, would be that all biases between all signals would be available. In this case the user will be completely free in his way of processing GNSS observations. It allows the user to process single signals, form signal differences, or any signal combination. This flexibility offers the chance to optimally cope with the future signal multiplicity. The user only must ensure that he applies the appropriate biases to the signals he uses.

2.4. Bias stability

The vital point for future multi frequency GNSS processing will be the stability of the different inter signal biases. This holds no matter if the signal processing is based on signal combinations or on undifferenced observation. First analyses already demonstrated the existence of inter-frequency drifts and even periodic variations (Montenbruck et al. 2010c). The difficulty of these variations becomes visible, when plotting the differences of the corrected (ionospheric delay plus mean phase bias removed) individual phase measurements against the mean range. Figure 2 shows these differences for the phase observations on G1/G2/G5 for the GPS-62 satellite. In this case range differences up to 20 mm (GPS L(G2) vs. L(G5)) appear, dependent on the frequency used. The magnitude of the phase variation shown, compared to previous publication (100 mm) (Montenbruck et al. 2010b) is discussed in section 4.2.

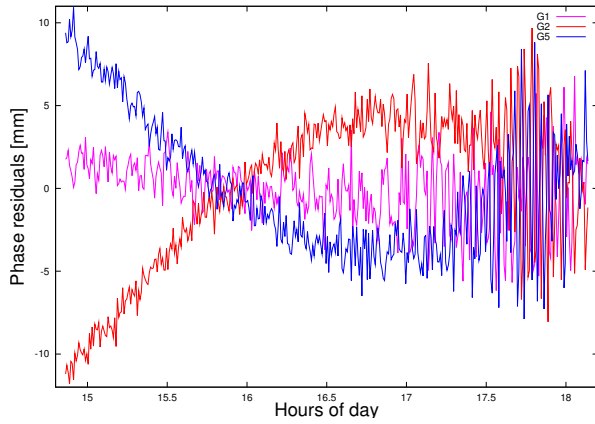


Figure 2. Phase residuals (wtx2 211 2010 [mm]).

2.5. Time system definition

Apart from that, there is still the issue of how to combine all available signals in a reasonable way. The major issues for the combination of different measurements are the signal dependent biases, resulting in an apparent signal specific clock offset. Figure 3 demonstrates the situation for multiple GNSS and signals, processed in a single time system. It shows the system time, which is in general defined by the mean over all clocks, or a selection of clocks. Each individual real clock in the processing has its own offset (true clock offset). Due to the presence of hardware biases the clock estimate depends on the applied signal or signal combination. In order to provide universal clocks, supporting as much users as possible, it is necessary to find a reasonable clock definition. In Figure 3 the satellite and the receiver clocks are defined as mean clock offset over all available signals. However, it would also be feasible to refer the clock to a single signal tracked by all receivers, or at least by most of them.

After the proper definition of the clock all signal specific clock offsets are referred to this clock definition. The resulting offsets are known as Uncalibrated Phase Delays (UPD) or Fractional-Cycle-Bias (FCB). Uncalibrated Signal Delays (USD), covering both Uncalibrated Code Delays (UCD) as well as UPD, gives a more general description. The USD absorb all signal specific delays, as for example transmitter and receiver hardware delays and the remaining relicts of the corrected or estimated ionospheric effect.

2.6. Processing Time

The approach to utilize all available, code and phase signals will allow a better decoupling of the different error sources, but will increase the computational power needed. Given that today a large IGS like (24 hours, ≈ 150 Stations) GNSS estimation process merely takes about 1 hour of CPU time using 2GB of RAM and

considering that it will take at least a decade to complete the modernisation and/or build the new systems we are confident that the speed of computers and the size of their RAM will be more than sufficient to support our fundamentally new approach.

3. Mathematical Background

Contrary to the current estimation strategies the new approach makes use of all raw observations, estimating ionospheric delay and USD in a single Least-Squares (LSQ) estimation. This means no signal differences or combinations are used to derive the phase ambiguities or the ionospheric delay.

$$\begin{aligned}
 P(\text{sig}, t)_{\text{rec}}^{\text{sat}} = & \rho_{\text{rec}}^{\text{sat}} + c * (\delta t(t)_{\text{rec}} - \delta t(t - \tau)^{\text{sat}} \\
 & + \delta t_{\text{rel}} + \delta t_{\text{sac}}) + \delta \text{rel} + \delta \text{pco}(\text{sig})^{\text{sat}} \\
 & + \delta \text{pcv}(\text{sig})^{\text{sat}} + \delta \text{pco}(\text{sig})_{\text{rec}} + \delta \text{pcv}(\text{sig})_{\text{rec}} \\
 & + \delta \text{coord} + \delta \text{trop} + \delta \text{ucd}(\text{sig})^{\text{sat}} \\
 & + \delta \text{ucd}(\text{sig})_{\text{rec}} + \delta \text{ion} + \delta \text{mp}(P(\text{sig})) \\
 & + \varepsilon(P(\text{sig}))
 \end{aligned} \quad (1)$$

$$\begin{aligned}
 L(\text{sig}, t)_{\text{rec}}^{\text{sat}} = & \rho_{\text{rec}}^{\text{sat}} + c * (\delta t(t)_{\text{rec}} - \delta t(t - \tau)^{\text{sat}} \\
 & + \delta t_{\text{rel}} + \delta t_{\text{sac}}) \\
 & + \delta \text{rel} + \delta \text{pco}(\text{sig})^{\text{sat}} + \delta \text{pcv}(\text{sig})^{\text{sat}} \\
 & + \delta \text{pco}(\text{sig})_{\text{rec}} + \delta \text{pcv}(\text{sig})_{\text{rec}} + \delta \text{coord} \\
 & + \delta \text{trop} + \delta \text{upd}(\text{sig})^{\text{sat}} + \delta \text{upd}(\text{sig})_{\text{rec}} - \delta \text{ion} \\
 & + \lambda(\text{sig}) * N + \delta \text{mp}(\text{sig}) + \varepsilon(L(\text{sig}))
 \end{aligned} \quad (2)$$

Equation (2) shows the general observation equation for code $P(\text{sig}, t)_{\text{rec}}^{\text{sat}}$ and phase $L(\text{sig}, t)_{\text{rec}}^{\text{sat}}$ signals (sig) dedicated to a satellite (sat) receiver (rec) link at a single epoch (t) in the adopted time system.

The constant c stands for the speed of light and $\lambda(\text{sig})$ for the wavelength of the phase signal. The symbols P and L denote the raw code and phase observation, tracked by the receiver at system time (t). As the signal emission took place in advance to the reception the satellite parameter needs to be adjusted for the travel time (τ). The true geometric range ($\rho_{\text{rec}}^{\text{sat}}$) can be written as the distance between the satellite position at transmission time ($x(t - \tau)^{\text{sat}}$) and the receiver position at reception time (x_{rec}) in the Earth Centred Earth Fixed (ECEF) coordinate system. The following parameters can be sufficiently described by adequate models:

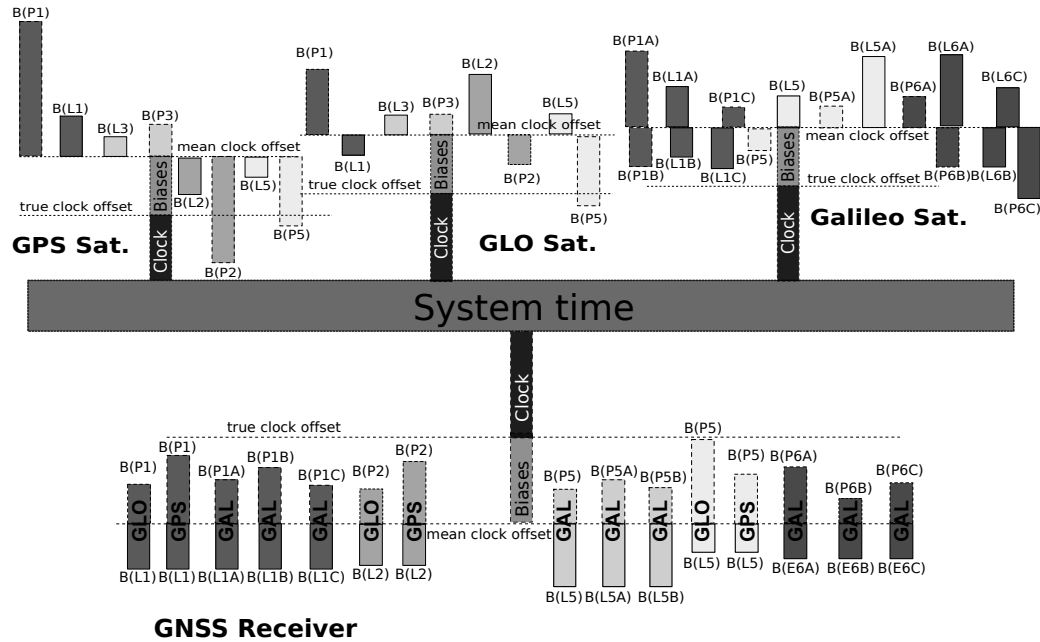


Figure 3. Clock definition in a future multi - GNSS, - signal environment.

$\vec{x}_{rec}$	Satellite position (ECEF)
$\delta t(t - \tau)^{sat}$	Satellite clock error (t- τ)
δt_{rel}	Relativistic effect due to eccentricity of the satellite orbit
δt_{sac}	Sagnac effect
δrel	Relativity (satellite signal)
$\delta w(sig)$	Phase wind up
$\delta pco(sig)$	Phase centre offset (PCO)
$\delta pcv(sig)$	Phase centre variation (PCV)
$\delta coord$	Coordinate variations (Tectonic movements, tidal, loading effects)

Finally remaining error sources, as multipath $\delta mp(sig)$ and the measurement noise $\varepsilon(sig)$. Besides the pure measurement noise $\varepsilon(sig)$ will also absorb modeling errors. The remaining parameters to be estimated are:

$\vec{x}_{rec}$	Receiver position (ECEF)
$\delta t(t)_{rec}$	Receiver clock error
$\delta ucd(sig)$	USD for code signal (sat./rec.)
$\delta upd(sig)$	USD for phase signal (sat./rec.)
$N(sig)$	Phase ambiguity
δion	Ionospheric delay
$\delta trop$	Tropospheric delay

Contrary the general processing strategy the observation equations include USD to align the different code and phase observations, as well as the herewith strongly correlated ionospheric delay. The ionospheric delay can be described, according to Hofmann-Wellenhof et al. (2008) as: $\delta ion = TEC \frac{40.28}{f_{sig}^2}$. Where the

Total Electron Content (TEC) is defined as the number of electrons in a tube along the Line-Of-Sight (LOS) with an aperture of 1 m^2 . In the rest of this article the TEC is given in $10^{16} \text{ electrons/m}^2 = 1 \text{ TEC Unit (TECU)}$. Finally the observation equation can be solved for the unknown parameters by the least squares approach.

The goal of the analysis described in the next section is the proof the practicability of our new approach. Therefore we focused our analyses on the satellites providing signals on at least three frequencies. There are currently two satellites, transmitting more than two frequencies, the first GPS Block-II/F (GPS-62) and the GALILEO test satellite GIOVE-B. Indeed GIOVE-B is not providing the ideal three frequency data set, as transmission is restricted to two frequency bands at a time and so three out of the four provided signals are part of the E5 frequency band (see Table 1).

Table 1. GNSS Frequencies (Gurtner and Estey 2007)

GNSS	RINEX	Freq. Band	Freq. (MHz)
GPS	G1	L1	1575.42
GPS	G2	L2	1227.60
GPS	G5	L5	1176.45
GALILEO	E1	E1	1575.42
GALILEO	E5	E5a	1176.45
GALILEO	E8	E5(E5a+E5b)	1191.78
GALILEO	E7	E5b	1207.14
GALILEO	E6	E6(not available)	1278.75

As it is not possible to solve the complete observation equation (Equation 2.6) with two satellites only, the number of unknown parameters needs to be reduced. Therefore the station position x_{rec} is assumed to be known and the tests are restricted to a single satellite and the estimation of the mean range ($R(t)$) and the TEC plus USD. For this simplified case the observation equation can be re-written as follows (Equation 3):

$$\begin{aligned} P(sig, t)_{rec}^{sat} &= +\delta ion(t) + R(t) + \delta ucd(sig) \\ &\quad + \delta cor(P) + \varepsilon(sig) \\ L(sig, t)_{rec}^{sat} &= -\delta ion(t) + R(t) + \delta upd(sig) \\ &\quad + \delta cor(P) + \varepsilon(sig) \end{aligned} \quad (3)$$

Due to the elimination of station coordinates the observation equation becomes solvable without linearization, using least squares. The corresponding design matrix A can be divided into different parts, for epoch-wise ionosphere parameters ei , epoch-wise range parameter er and the permanent parameters pp i.e. USDs.

$$A = \begin{pmatrix} ei_1 & 0 & 0 & er_1 & 0 & 0 & pp \\ 0 & \ddots & 0 & 0 & \ddots & 0 & \vdots \\ 0 & 0 & ei_n & 0 & 0 & er_n & pp \end{pmatrix}$$

The submatrices are set up as follows:

$$er = \begin{pmatrix} 1 \\ \vdots \\ 1 \\ 1 \\ \vdots \\ 1 \end{pmatrix} \quad ei = \begin{pmatrix} +TEC \frac{40.28}{f_{sig}^2} \\ \vdots \\ +TEC \frac{40.28}{f_{sig}^2} \\ -TEC \frac{40.28}{f_{sig}^2} \\ \vdots \\ -TEC \frac{40.28}{f_{sig}^2} \end{pmatrix}$$

Here the upper part of the submatrices contains the unknowns, corresponding to code and the lower part the derivatives for the phase observation equation. Normally the permanent matrix is supposed to be structured as follows:

$$pp = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & \ddots & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

However to obtain a bias level comparable to the actual ionospheric delays provided by e.g. IONEX files, the code biases were not

estimated. Instead the code observations were corrected using a priori code biases. The a priori code biases were computed as mean offset of each individual code signal against the mean of all code and phase signals. Therefore all signals were corrected a priori for the ionospheric delay by IONEX files, provided by CODE. For this approach the pp matrix can be written as follows:

$$pp = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Due to the small weight of the code observations compared to the phase observations (1/100) the error introduced by the a priori UCD, which is expected to be on centimetre level, can be neglected. For an analysis based on a single receiver, as in the test case, a separation of receiver and transmitter dependent USD is not possible. Hence the estimate will include a mixture of satellite and receiver USD. In future IGS may serve as a provider of USD biases, like now with the P1C1 and P1P2 biases.

4. Proof of Concept

In this section we demonstrate the new estimation approach with a strong focus on the characteristics of the expected intersystem and inter-frequency biases. We have selected the PPP approach (Zumberge et al. 1997) to demonstrate some of the interesting features in particular because the PPP approach was motivated by the idea of mitigating all individual error sources by adequate correction models. Furthermore, the PPP approach is very widely used and may suffer the most from the emergence of new signals because for this approach it is mandatory that the same observables are used on the "server" and "client" side. In a multi-GNSS and multi-frequency environment this may seldomly be the case. As a test site the GNSS station Wettzell (WTX), part of the CONGO was selected. WTX provides data of three different GNSS receivers connected to the same antenna. Therefore data and products, based on observations recorded by different receiver types can be easily compared and analysed. Even more the receiver clocks of WTX2 and WTX1 are steered by the same H-Maser. Although the receiver clocks are steered by the same H-Maser the measurements are not taken at the same time. Figure 4 compares the phase measurements of WTX2 and WTX1 receivers for the GIOVE-B satellite. It shows a significant clock variation, showing up as common inter receiver difference for all signals. This demonstrates that also receivers steered by stable external frequency standards need to be corrected for remaining clock differences introduced by the receiver electronics.

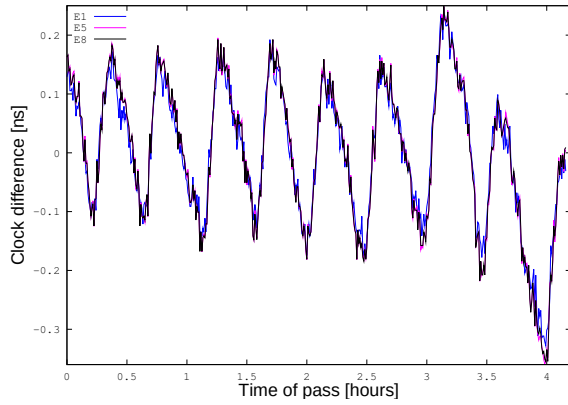


Figure 4. Δ Receiver clock WTX1 - WTX2 (GIOVE-B, day 212 2010).

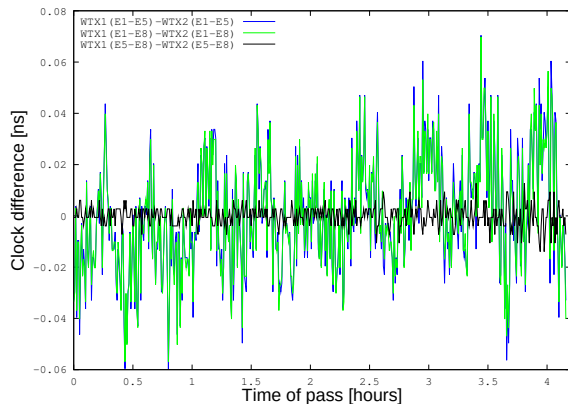


Figure 5. Δ Receiver/signal WTX1 - WTX2 (GIOVE-B, day 212 2010).

In order to examine the stability of the receiver dependent USD the inter receiver-signal double differences (RSDD) were computed, where Ea and Eb denote the signals to be analysed:

$$RSDD(t)_{Eab} = +(Ea(t)_{WTX1} - Eb(t)_{WTX1}) - (Ea(t)_{WTX2} - Eb(t)_{WTX2}) \quad (4)$$

Due to double differencing the receiver and satellite clock offsets, as well as the satellite dependent USDs are removed. Hence the remaining difference can be attributed to inter frequency phase variations. These phase variations include the variations of both receivers and cannot be assigned to an individual one. Unlike phase measurements in the same frequency band (E5/E8), Figure 5 shows systematic frequency variations between E1 and E5 phase measurements.

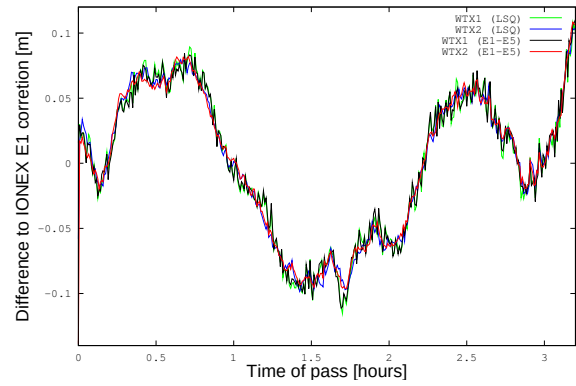


Figure 6. Ionospheric delay estimates vs. IONEX (GIOVE-B 213 2010).

4.1. Ionosphere Estimation

The first point of interest is the ability of the new approach to derive the ionospheric effect. Therefore the ionospheric correction conventionally derived of E1 and E5 by the ionospheric combination, is compared to the ionospheric delay estimated in the proposed Least-Squares approach. Figure 6 shows the difference of the computed ionospheric E1 corrections against the corrections taken from the IONEX file. It demonstrates the good performance of all solutions and also of both receivers (≈ 10 mm).

Apart from that it shows the limitations of the ionospheric corrections taken from IONEX-files. Hence even under regular conditions the corrections, taken from the IONEX-file, show differences up to 0.10 m vs. the true ionospheric correction on E1 frequency. The smaller number of signals tracked by WTX1 explains the increased noise level of its LSQ solution. WTX2 tracked all available signals whereas WTX1 did not track E7. However even with six observations per epoch, three code and three phase signals, and a non-optimal frequency spacing the LSQ approach provides a reasonable estimate of the ionospheric delay.

The most important parameter in the estimation procedure is the satellite-receiver range. Since the measured range is depending on tracking time, the clock difference needs to be removed before the comparison. Figure 7 is divided into three parts. The first part shows the receiver clock difference. The second part shows the difference in the estimated range, where the inter receiver clock difference is clearly visible in the range difference. Hence to better compare the estimated ranges the clock signal is removed (part three). Although there are still remaining systematic effects between the receivers (Figure 5), as well as remaining multipath errors, the rms of the range difference is mostly below 15 mm.

The performance of the individual phase measurements is demonstrated in Figure 8. It shows the original phase measurements, corrected by the respective USD and the corresponding ionospheric correction. For a better visualisation the estimated range

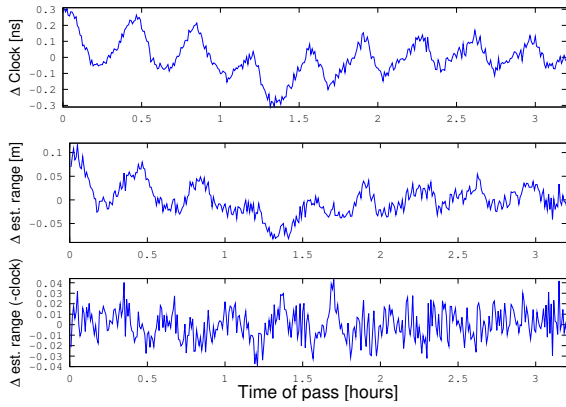


Figure 7. Range difference WTX1 vs. WTX2.

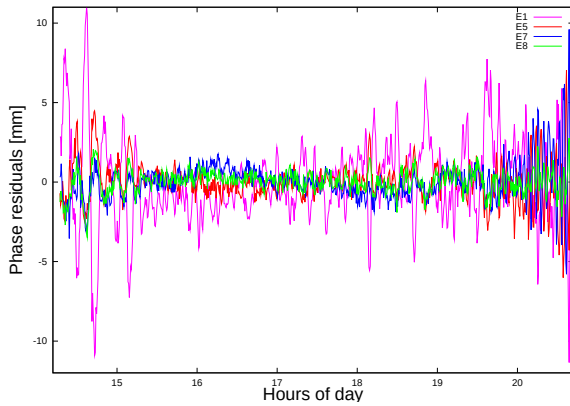


Figure 8. Phase residuals (GIOVE-B on WTX2).

is removed. It is seen, that all residual phase observations are in the range of a few millimeters.

The unexpected high noise for the E1 phase measurements can be explained by the strong weight of the E5 frequency band due to three close-by observations (E5/E7/E8) in the LSQ estimation. Hence the phase variation between E1 and E5 frequency band deteriorates the quality of the corrected E1 measurements. For a future operational use of this approach the correlations and weighting need to be refined and considered correctly. A significant improvement is expected when using reasonable ionospheric constraints to replace the epoch-wise link parameter estimation. Possible candidates for ionosphere models reach from piecewise linear (along track) functions, to ionospheric station gradients (north-south/east-west) up to global models. Up to now the demonstration concentrates on the client site processing, where no satellite parameters need to be estimated. In order to allow the recovery of the integer nature of the phase observations, the introduced satellite clocks, provided from an external service like the IGS, need to be constraint to specific values within the LSQ.

4.2. Stability of phase biases

Up to now all analyses present are based on GIOVE-B observations. The reason for this decision is the stability of the phase biases in the satellite. In contrast to the GIOVE-B phase biases, GPS-62 observations show significant sub-daily phase variations (Table 1 and Montenbruck et al. 2010b). These variations make it considerably more difficult to model the USD and to combine the different measurements. Montenbruck et al. (2010b) discovered phase variations on the G5 vs. the G1 and G2 phase observations with an amplitude of 100 mm. In order to enable a correct modeling of the GPS satellite's USD further analyses were carried out.

Understanding of the relative signal behaviour and its effects on the results is the key issue for a correct multi-signal processing. First of all different ionospheric estimates were compared. In general the ionospheric delay is estimated, using smoothed code observations on two different frequencies. To mitigate the impact of the code noise on the results this test is based on corrected phase observables instead of smoothed code observations. The phase observations were corrected for the phase ambiguities, offsets and the receiver clock errors. In the following all these corrections, taken from the LSQ estimation, are denoted as δ_{cor} . Consequently the G1 ionospheric correction $\delta_{ion}(t)$ can be computed as follows:

$$\delta_{ion} = \left(\frac{((L(G1,t) + \delta_{cor}(G1,t)) - (L(G2,t) + \delta_{cor}(G2,t)))}{\frac{40.28}{freq(G2)^2} - \frac{40.28}{freq(G1)^2}} \right) * \frac{40.28}{freq(G1)^2} \quad (5)$$

Figure 9 shows the $L(G1)$ range residual as response to different ionospheric correction models, whereby the range residuals $\delta R(t)$ were computed as follows:

$$\delta RG1(t) = L(G1; t) + \delta_{ion}(t) + \delta_{cor}(G1; t) \quad (6)$$

The best result is obtained for the ionospheric model, making use of all signals within the estimation process. Even if the range was estimated together with the TEC, this seems to be the most reasonable solution, as this solution includes all code and phase signals. In case the G1 phase measurements are corrected by the ionospheric delay, derived from the two ionosphere combination G1-G2/G1-G5 the corrected measurements show a clear signal, but with opposite sign. Consequently the use of the ionospheric correction derived from G2-G5 reinforces the variation.

In a next step signal combinations based on two different frequency pairs were estimated and compared in Figure 10. There are no significant variations in the residuals derived from the LSQ based on G1/G2 and the G1/G5 signals, whereas a clear signal pattern can be found for the signals on G2/G5. That conforms previous analyses (Montenbruck et al. 2010a, Montenbruck et al. 2010b). In summary, it can be stated that a single phase variation can be absorbed by the receiver clock estimate, whereas variations in additional signals will result in a doubtful solution that includes a

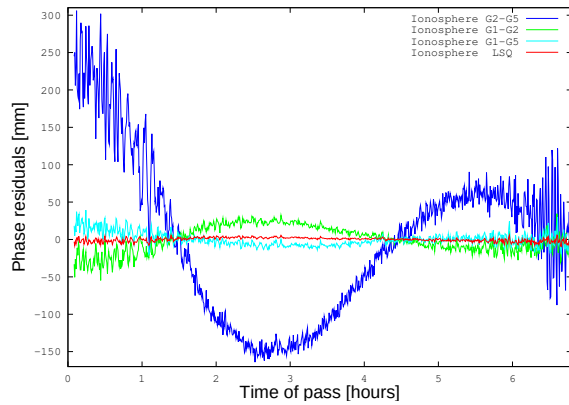


Figure 9. G1 phase residuals, referred to different ionosphere corrections.

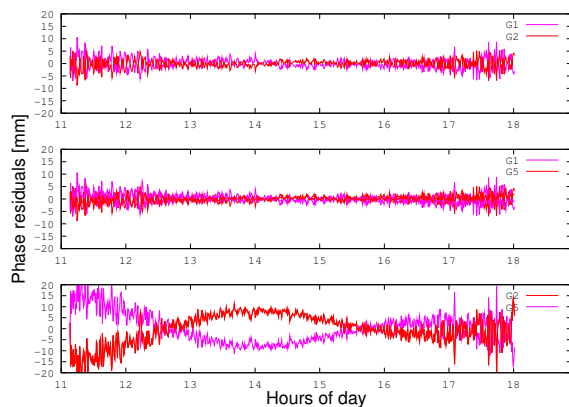


Figure 10. LSQ phase residuals for different input signals.

mixture of both biases. Furthermore the results indicate a variation on both, G2 and G5 phase signals rather than in the G5 only.

Due to the limitation of the presented analyses to a single site and two receivers a separation of receiver and satellite biases is not possible. Hence up to now a trace back of the phase variation to an explicit source, receiver or satellite, is not possible. The extension of this analysis to multiple receivers allows us an improved view to this problem. Figure 11 shows the G5 LSQ phase residuals for different, globally distributed stations. The agreement of the phase residuals derived on the different stations aligned over the time of day match perfectly and clearly indicate the satellite as source of the variation.

These results allow us to conclude that phase variations of GPS SVN 62 cannot be assigned to a single phase signal only. A more reasonable explanation is a variation of both the G2 and the G5 signals in relation to the G1 signal. Differences in the magnitude of the phase variation as compared to previous publications, can be explained by different TEC estimation/mitigation procedures.

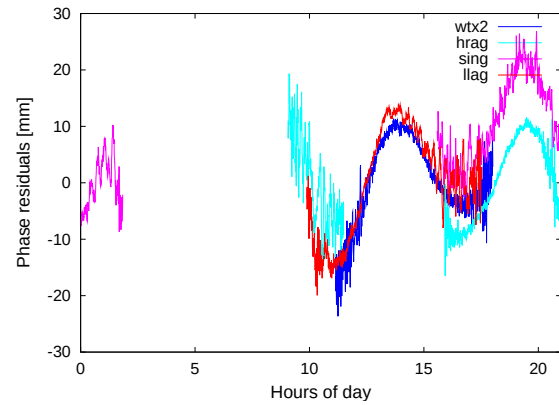


Figure 11. G5 phase residuals on different stations (G25, 213 2010).

So parts of the apparent phase variation are absorbed by the TEC estimate. These results highlight the importance to the currently employed processing approaches that make use of linear combinations and differences of the individual, biased, signals.

4.3. Outlook

Even if there are still numerous open questions, concerning the stability, variability and out of that the modeling and the provision of reasonable USD, the combination of all signals offers a great potential for improvement. Especially in view of the superior quality of the improved code modulations provided by the future GALILEO system.

Figure 12 shows the range residual δR for the different available GALILEO code modulations for a single satellite pass.

$$\delta R(t) = P(\text{sig}, t) - \delta \text{ion}(t) + \delta \text{cor}(\text{sig}, t) \quad (7)$$

The significant improvement for the new code modulations on E5, E7 and especially for the AltBOC on E8 is clearly visible. Hence, as soon as the issue of USD is solved the performance of the AltBOC (E8) code signal will allow decimetre positioning, using the GRAPHIC combination (Yunck 1993).

5. Conclusions

In this article we have proposed a new approach for GNSS analysis in a multi-GNSS and multi-frequency environment. The fundamentally new aspect of our approach is that it completely avoids the formation of differences as well as of linear combinations. Thus all available observations from all GNSS systems as observed by all the receivers in a network may be incorporated to the parameter estimation. This leads to an enormous simplification in the data analysis as no pre-selection of any observations is required. We demonstrated the ability to process all available signals (code and phase) in a single LSQ approach. The major advantage of this

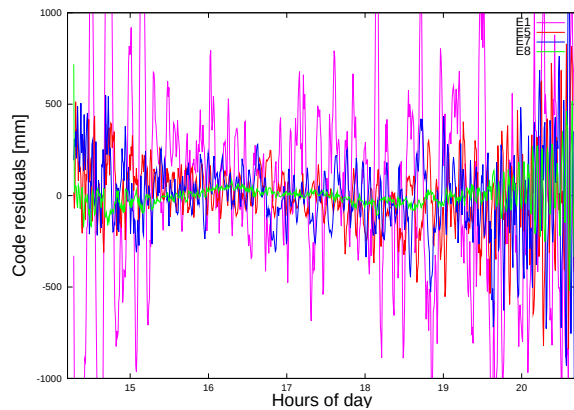


Figure 12. Corrected Code observations (GLOVE-B on WTX2).

approach is the optimal combination of all available information and the estimation of signal specific USD. The availability of the derived USD, as well as the corresponding TEC values allows the use of all signals and signal combination by any user having access to these estimated parameters. This is extremely important when considering for instance the PPP approach based on products from the IGS. In a multi-GNSS and multi-frequency environment the IGS will have to provide information regarding all signal biases in a clearly defined "bias reference frame" such that all users can use any signal in their processing by having access to the proper calibration and offset parameters estimated by the IGS. Besides the potential of the multi-GNSS, multi-signal processing this article also highlighted the problem of bias stability. The stability or better the ability to estimate or model the USD is the crucial part of future GNSS processing. With the large amount of different signals and observables it will be of prime importance that the biases between the signals both at the level of the satellites as well as at the level of the receivers are stable over time. If the biases are stable GNSS analysis in a multi-GNSS and multi-frequency environment will bring significant improvements compared to today's "dual signal" situation.

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