GLONASS Inter-frequency Biases and Their Effects on RTK and PPP Carrier-phase Ambiguity Resolution

Nico Reussner, Lambert Wanninger
Geodetic Institute, Technische Universität Dresden (TU Dresden), Germany

BIOGRAPHIES

Nico Reussner is a member of the GNSS research group at the Geodetic Institute of TU Dresden. He received his Dipl.-Ing. in geodesy from TU Dresden in 2009.

Lambert Wanninger is a professor of geodesy at TU Dresden. He has been involved in research on precise GNSS positioning since 1990. He holds a Dr.-Ing. degree in geodesy from University of Hannover, Germany, and a habilitation degree in geodesy from TU Dresden.

ABSTRACT

GLONASS uses frequency division multiplexing (FDMA) to make the signals from individual satellites distinguishable. Thus, in both frequency bands the receiving equipment has to deal with up to 14 different frequencies. Due to code and carrier-phase inter-frequency biases in the receiving equipment, data processing gets more difficult as compared to GPS.

The carrier-phase inter-frequency biases mainly depend on the receiver type and can be modeled and corrected based on a linear function of the signal's frequency. The code inter-frequency biases are more difficult to handle since they mostly seem to be receiver individual and of non-linear character.

GLONASS Real-Time Kinematic (RTK) positioning is very similar to GPS RTK as long as ***a priori*** corrections for the carrier-phase inter-frequency biases are applied. Precise Point Positioning (PPP), however, usually uses dual-frequency code observations to resolve widelane ambiguities with the Melbourne-Wübbena linear combination. Due to the code inter-frequency biases this technique does not work for the present GLONASS receiving equipment and it must be substituted by a pure carrier-phase widelane ambiguity resolution technique.

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INTRODUCTION

Unlike GPS, GLONASS uses frequency division multiplexing (FDMA). This technique requires unique carrier frequencies for all satellites. In the two frequency bands L_1 and L_2 they are defined by:

$$\boldsymbol{f}_{1,\boldsymbol{k}} = \boldsymbol{f}_{0,1} + \boldsymbol{k} \cdot \Delta \boldsymbol{f}_1 = 1602 + \boldsymbol{k} \cdot 0.5625 \quad [\boldsymbol{MHz}]$$
$$\boldsymbol{f}_{2,\boldsymbol{k}} = \boldsymbol{f}_{0,2} + \boldsymbol{k} \cdot \Delta \boldsymbol{f}_2 = 1246 + \boldsymbol{k} \cdot 0.4375 \quad [\boldsymbol{MHz}]$$

where k is the frequency channel number selected from the range [-7,6]. The limitation to 14 different frequencies in each band made it necessary that satellites in antipodal positions share the same frequency (ICD 2008).

FDMA of the present GLONASS signals causes inter-frequency biases in the receiving equipment and in both primary observables namely code and carrier-phase. These biases are able to complicate or prevent carrier-phase ambiguity fixing.

Starting this year new GLONASS signals are added that will use code division multiplexing (CDMA) like GPS does (Revnivykh 2010). But for the next decade or so only GLONASS FDMA-signals will be able to provide continuous dual-frequency coverage.

RTK (Real-time Kinematic) positioning requires (an almost) complete and reliable fixing of the carrier-phase ambiguities in the baseline between reference station and rover station (Hofmann-Wellenhof et al. 2008). Ionospheric effects are greatly reduced due to differential positioning in baselines and more and more by regional modelling of the ionosphere with Network RTK techniques. Thus the ambiguity resolution algorithms need not to be so called ionosphere-free techniques, but integer ambiguities may be estimated using e.g. the widelane linear combination of L1 and L2 carrier-phase observations and subsequently the L1 (or narrowlane) carrier-phase ambiguity.

Precise Point Positioning (PPP) as an absolute positioning technique has to deal with larger ionospheric effects. Here, ionosphere-free techniques should be applied in ambiguity fixing and coordinate estimation. Usually the widelane ambiguities are fixed using the Melbourne-Wübbena-combination of code and carrier-phase observations and afterwards the narrowlane ambiguities are fixed using the ionosphere-free linear combination of the carrier-phase observations. Ambiguity resolution with PPP requires information of the fractional-cycle biases (FCB) which must be determined utilizing a network of reference stations. For more information on PPP ambiguity resolution and FCB see e.g. Banville et al. (2008), Collins (2008), Ge et al. (2008), Laurichesse et al. (2008), Geng et al. (2010).

OBSERVATION EQUATIONS

In order to explain the differences between GPS and GLONASS signals we look at the observation equations of code $\boldsymbol{C}$ and carrier-phase Φ. In general and especially for GLONASS they may be written as:

$$\boldsymbol{C}_a^i = \boldsymbol{R}_a^i + \boldsymbol{c}_0 \cdot \left(\Delta t_a + h_{a,C}^{System,i} - \Delta t^i\right) + \ {}_{a,C}^{i}$$
$$\Phi_a^i = \boldsymbol{R}_a^i + \boldsymbol{c}_0 \cdot \left(\Delta t_a + h_{a,\Phi}^{System,i} - \Delta t^i\right) + \ \cdot \boldsymbol{N}_a^i + \ {}_{a,\Phi}^{i}$$

where subscript $\boldsymbol{a}$ stands for the station involved, the superscript $\boldsymbol{i}$ specifies the individual satellite and the superscript ***System*** indicates the GNSS satellite system. Furthermore, $\boldsymbol{R}$ [m] is the satellite-receiver range, c_0 [m/s] is the vacuum speed of light, Δt_a [s] is the receiver clock error, $\boldsymbol{h}$ [s] is the receiver hardware delay of the signal, Δt^i [s] is the satellite clock correction,   [m] is the signal wavelength, $\boldsymbol{N}$ [-] is the carrier-phase ambiguity, and   [m] is the sum of all uncorrected systematic and random errors affecting the observable. Unknowns to be determined are the coordinates of the receiving antenna X_a, Y_a, Z_a hidden in the satellite-receiver range $\boldsymbol{R}$, the receiver clock error Δt_a plus the receiver hardware delay h_a, and in case of the phase observations the ambiguity $\boldsymbol{N}$. Δt_a, h_a, and $\boldsymbol{N}$ are linearly dependent and thus lead to singularities, i.e. they can not be fully separated from each other.

In case of GPS with all satellites transmitting on the same frequency, the receiver instrumental delays h_a are identical for all signals and thus we merge them with the receiver clock error to the satellite system specific receiver clock errors $\Delta t_{a,C}^{GPS}$ and $\Delta t_{a,\Phi}^{GPS}$:

$$\boldsymbol{C}_a^{GPS,i} = \boldsymbol{R}_a^i + \boldsymbol{c}_0 \cdot \left(\Delta t_{a,C}^{GPS} - \Delta t^i\right) + \ {}_{a,C}^{i}$$
$$\Phi_a^{GPS,i} = \boldsymbol{R}_a^i + \boldsymbol{c}_0 \cdot \left(\Delta t_{a,\Phi}^{GPS} - \Delta t^i\right) + \ \cdot \boldsymbol{N}_a^i + \ {}_{a,\Phi}^{i}$$

GLONASS INTER-FREQUENCY BIASES OF THE CARRIER-PHASE OBSERVATIONS

The detailed analysis of the carrier-phase inter-frequency biases of various GLONASS receivers (Wanninger and Wallstab-Freitag 2007, Zinoviev et al. 2009, Wanninger 2011) leads to the following conclusions:

- Receivers of the same type and usually even of the same manufacturer show very similar inter-frequency biases.
- The inter-frequency biases can be modeled very well as a linear function of frequency (or the channel number $\boldsymbol{k}$):

$$\Phi_a^i = \boldsymbol{R}_a^i + \boldsymbol{c}_0 \cdot \left(\Delta t_{a,\Phi}^{GLONASS} + \boldsymbol{k} \cdot \boldsymbol{IFB}_a - \Delta t^i\right) + \ \cdot \boldsymbol{N}_a^i + \ {}_{a,\Phi}^{i}$$

  where IFB [s] is the GLONASS inter-frequency bias per Δf or per $\boldsymbol{k}$.
- For most receivers L1 and L2 carrier-phase inter-frequency biases (IFB) have very similar values, thus a single value per receiver is enough to pre-correct the effects of the inter-frequency biases.
- Such a pre-correction (see Tab. 1) is necessary to allow a complete and reliable RTK ambiguity fixing in receiver-mixed baselines. After ambiguity fixing IFB values should be estimated from the present observations separately for L1 and L2 (or at least for the selected linear combination used for coordinate estimation).
- IFB values do not only depend on the receiver but sometimes also on the selected antenna. The often expected sensitivity of the carrier-phase IFBs to temperature changes could not be confirmed (Wanninger 2011).

Tab. 1: Proposed ***a priori*** corrections of L1 and L2 GLONASS carrier-phase inter-frequency biases IFB for receivers of 9 different manufacturers (Wanninger 2011)

receiver manufacturer	***a priori* IFB corrections [cm]**
Trimble	–0.7
Ashtech (old), Javad, JPS, TPS	0.0
Ashtech (new)	0.4
Leica, Novatel	2.3
Septentrio	4.9

Utilizing ***a priori*** IFB values (Tab. 1) in RTK positioning enables GLONASS ambiguity resolution and fixing to be performed very similar to the one with GPS signals. After ambiguity fixing coordinate solutions should be estimated together with receiver individual IFB values.

In PPP data processing the ***a priori*** corrections of Tab. 1 should be applied when fractional-cycle biases (FCB) are estimated. They must also be applied on the rover side so that GLONASS carrier-phase ambiguity fixing can be performed. Afterwards individual IFB values should be estimated. Unfortunately, standard PPP ambiguity resolution and fixing differs from that of RTK, since code observations play an important role in the ambiguity estimation of the Melbourne-Wübbena linear combination. Here, it is not enough to deal with GLONASS carrier-phase IFBs, but the code IFBs have to be taken into account as well.

GLONASS INTER-FREQUENCY BIASES OF THE CODE OBSERVATIONS

The code IFBs play an important role in PPP. First of all they must be taken into account in the coordinate estimation based on the ionosphere-free linear combination of the code observations. Furthermore, code observations are used for widelane ambiguity estimation based on the Melbourne-Wübbena linear combination.

We estimated mean code residuals of the ionosphere-free linear combination P_0 (based on P_1 and P_2) in PPP data processing of 2 weeks of observations (GPS week 1627 and 1628) for several reference stations. In case of GPS all these estimates are close to zero, i.e. no satellite specific delays exist. In case of GLONASS, however, mean delays reach up to several meters (Fig. 1). These estimated delays also depend on the GLONASS clock products introduced into the data processing. The examples shown in Fig. 1 were computed with the orbit and clock corrections of the European Space Operations Centre (ESOC), Darmstadt, Germany.

Figure 1 shows the GLONASS delays for 4 selected stations of the EUREF Permanent Network (EPN, http://www.epncb.oma.be) as a function of the GLONASS channel number ***k*** and thus of the signal frequency. In general a frequency-dependence is obvious; however no simple linear modeling seems to fit. The delays appear to be very much receiver-individual. There are some exceptions of the pure frequency-dependence: e.g. at station/receiver GARI and for channel number k = 0 the estimated delays for the two antipodal satellites R11 and R15 differ by about 2 m.

Our conclusion is that inter-frequency biases of the GLONASS code observations exist that are mainly frequency dependent but seem to be receiver individual and can not be modeled with a simple modeling function. Thus, we must expect a lower code positioning accuracy as compared to GPS. Furthermore, we can expect difficulties in the PPP widelane ambiguity fixing with the Melbourne-Wübbena method. The second aspect is discussed below.

There may be a chance to calibrate the GLONASS code-delays of individual receivers to improve the code positioning accuracy, but we have not checked for their long-term and temperature stability.

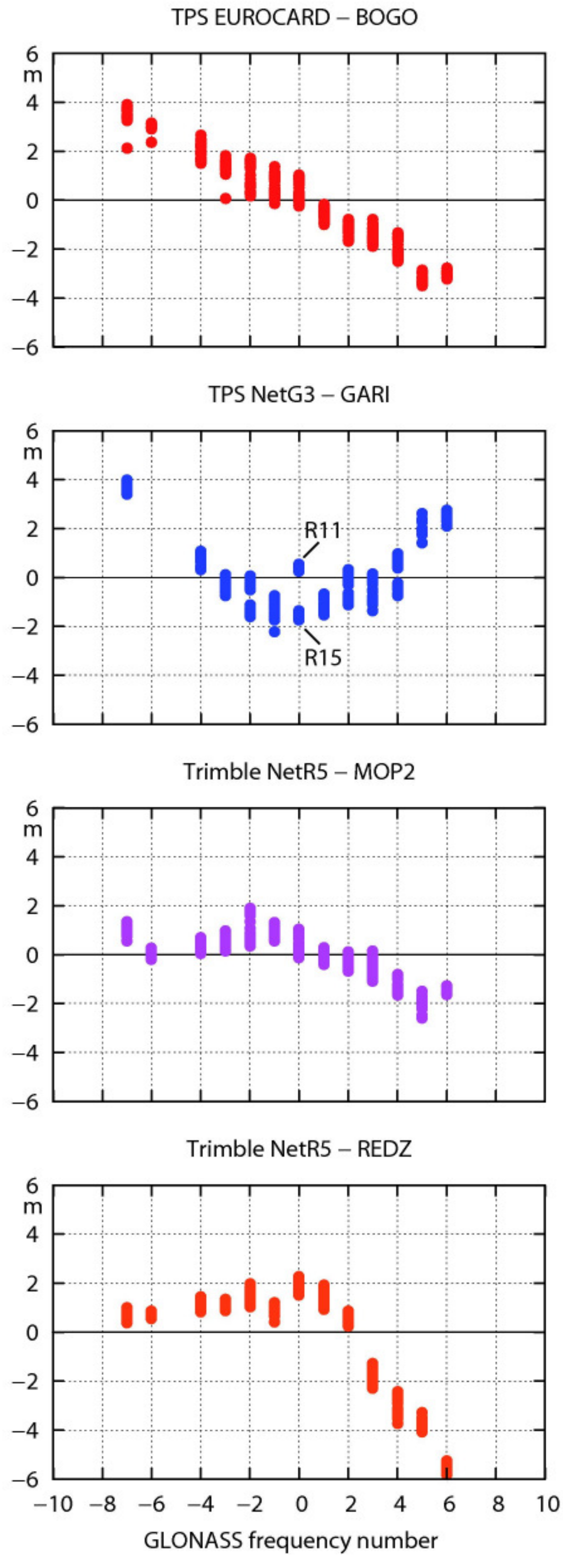

Fig. 1: Mean GLONASS ionosphere-free code delays as a function of GLONASS channel number k for 4 different stations with 3 different receiver types.

GLONASS WIDELANE AMBIGUITY RESOLUTION

There are two ways to resolve the widelane ambiguities in PPP data processing. Usually it is done in comparison with dual-frequency code observations (Melbourne-Wübbena method). This approach has the advantages that it is not affected by the atmosphere (ionosphere and troposphere) and also not by geometric aspects like orbit errors and estimates of the rover position. Major drawbacks, however, are code multipath and noise.

The second method estimates the widelane ambiguities from the carrier-phase observations directly. Here, we do not have to cope with code multipath but with atmospheric effects (ionosphere and troposphere) and geometric errors (orbit errors, errors in the rover position estimates). In fact, the second method requires ionospheric corrections, e.g. the Global Ionospheric Maps (GIM) produced by the International GNSS Service (IGS). But still, remaining ionospheric effects may prevent a successful widelane ambiguity fixing.

In order to test GLONASS ambiguity resolution we determined fractional-cycle biases (FCB) at selected reference stations for three linear combinations:

- Melbourne-Wübbena linear combination,
- widelane carrier-phase linear combination, and
- ionosphere-free carrier-phase linear combination.

We then applied these FCB at rover stations and tried to fix the carrier-phase ambiguities. Here, we will concentrate on the GPS and GLONASS widelane fixing with the two methods discussed above. Fig. 2 and 3 show fractional parts of the widelane ambiguity estimates of rover stations, Fig. 2 of the Melbourne-Wübbena linear combination, Fig. 3 of the widelane carrier-phase linear combination. Both figures present GPS results as a function of PRN number and GLONASS results as a function of channel number ***k***. The fractional-cycle biases (FCB) were calculated from observations of one reference station and the fractional parts of widelane ambiguities were estimated with observations of another station. The results shown are based on observation data from day-of-year 166/2011. Ambiguities were estimated for

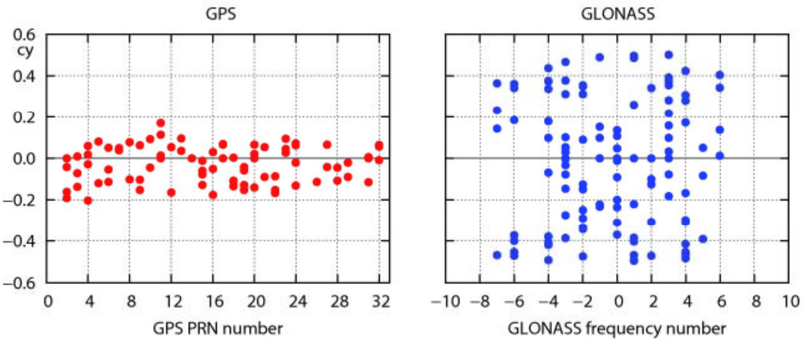

Fig.2: Fractional parts of the PPP widelane ambiguity estimates using the Melbourne-Wübbena linear combination.

observation durations of 2 hours, i.e. 12 independent estimations were produced from the 24 h data set.

In case of the Melbourne-Wübbena method (Fig. 2) the FCB were estimated with observations of the Slovakian station MOP2 at Modra-Piesok and they were applied to the Polish station REDZ at Redzikowo. Both stations were equipped with Trimble NetR5 receivers. All GPS fractional parts of estimated widelane ambiguities are well below 0.2 cycles, so that a successful ambiguity fixing can be performed. But the GLONASS fractional parts vary between -0.5 and +0.5 cycles so that the true integer value can not be found. The GLONASS ambiguity estimates are biased by code and carrier-phase inter-frequency delays which are larger than the widelane wavelength (cf. Fig. 1).

In case of the widelane method (Fig. 3) the FCB were esti-

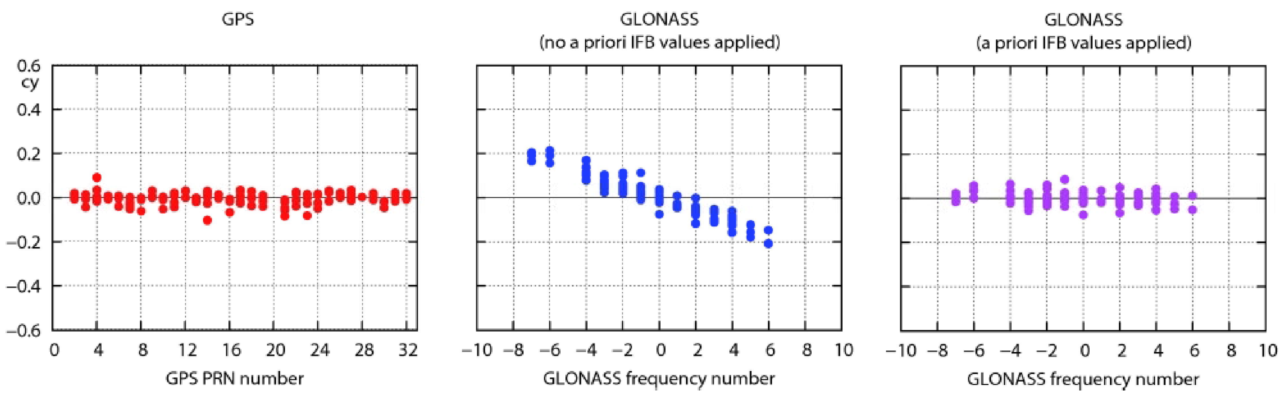

Fig. 3: Fractional parts of PPP ambiguity estimates of the carrier-phase widelane linear combination. The third panel shows GLONASS results with ***a priori*** corrections of Tab. 1 being applied to the observation data.

mated from observations of the British station HERS at Hailsham equipped with a Septentrio PolaRx3eTR receiver and applied to a second station at Hailsham, HERT, equipped with a Leica GRX1200 GG PRO receiver. By purpose we decided to show results of such a very short "baseline". Here, remaining ionospheric effects in the widelane FCB do not show up in the fractional parts of the estimated ambiguities since they cancel out by "differencing". Thus, the effects of the carrier-phase inter-frequency biases (IFB) dominate and they are clearly visible in the central panel of Fig. 3. The third panel of Fig. 3 shows the fractional parts of PPP widelane ambiguities when the appropriate ***a priori*** IFB values of Tab. 1 are applied in both processing steps: FCB estimation (Septentrio receiver at HERS) and PPP ambiguity estimation (Leica receiver at HERT).

In practice, this method of widelane ambiguity estimation and fixing requires ionospheric corrections. But still, remaining ionospheric errors will affect FCB estimation and will complicate ambiguity resolution. The size of the remaining ionospheric errors depends very much on the actual ionospheric conditions and of course on the quality of the ionospheric model. After a successful widelane ambiguity fixing, the ionosphere has no further significant influence on the PPP results, since the second ambiguity fixing step and the coordinate estimation is performed with the ionosphere-free linear combination of the carrier-phase observations.

SUMMARY AND CONCLUSIONS

GLONASS carrier-phase and code observations are affected by receiver hardware delays which cause inter-frequency biases. Carrier-phase inter-frequency biases are very similar within groups of receivers of the same type (or even from the same manufacturer). Furthermore, inter-frequency bias differences between two individual receivers can be modeled very well as a linear function of the signal's frequency.

GLONASS code inter-frequency biases are much more difficult to handle. They show large differences even between receivers of the same type. These differences mainly seem to be a function of frequency but a simple linear modeling is insufficient.

As long as no code observations are directly involved in ambiguity resolution and fixing, GPS and GLONASS fixing algorithms are very similar. In case of GLONASS, however, carrier-phase inter-frequency bias corrections must be applied to the observations data. On the other hand, ambiguity resolution algorithms which use code observations (Melbourne-Wübbena method) do not work at all or at least not as good with present GLONASS observations as compared to GPS observations. They must be substituted by other algorithms which are independent of the code observations but usually have its own shortcomings.

We conclude that standard RTK ambiguity resolution works as good for GLONASS as for GPS. In PPP ambiguity resolution, however, FDMA-GLONASS signals observed with present receiving equipment are at a disadvantage as compared to CDMA-GPS signals..

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