# Origin and Compensation of GLONASS Inter-frequency Carrier Phase Biases in GNSS Receivers

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## ABSTRACT

It is well known that centimeter-level inter-frequency biases are a major source of problems for the GLONASS carrier phase ambiguity resolution.

As already postulated by much research, these biases depend linearly upon the frequency number, change very little with time and temperature, and are almost equal for L1 and L2 bands when they are expressed in units of length.

Although the general properties of the GLONASS inter-frequency carrier phase biases are well studied, their origin in the receiver processing chain has remained largely unexplained. It is typically assumed that the biases are generated in the analog hardware of receivers, and hence are difficult to tackle without specialized laboratory equipment.

This paper presents an analysis of the possible sources of inter-frequency carrier phase biases in GNSS receivers and proposes a theory which explains all actually observed characteristics of the biases, in particular their linearity, stability and equal values for L1 and L2.

The paper begins with the analysis of inter-frequency carrier phase biases generated in the analog hardware. It is shown that these are too small and cannot account for the observed centimeter-level values. Next, we proceed to the DSP section and show that the major cause of linear inter-frequency carrier phase biases is a difference in the receiver clock bias term applicable to code and carrier phase measurements, the so called "code-phase bias".

We identify two specific causes of code-phase biases in the DSP. First, it is a common practice to adjust code measurements by some constant offset in the receiver firmware. If this is done without corresponding adjustment to the carrier phase measurements, code-phase biases are created. The second cause of biases is found in the receiver's digital signal processing chip, where reference code and phase signals may have different delays.

It is shown that the DSP-induced code-phase biases are the primary cause of inter-frequency biases in GLONASS RTK. Being caused by digital processing and firmware, they are perfectly stable in time, do not change with temperature, and do not vary from unit to unit.

It is also shown that, if the values of the code-phase biases are known, carrier phase measurements can be corrected for the most significant portion of the inter-frequency

biases, which significantly simplifies GLONASS RTK operation.

## INTRODUCTION

GLONASS currently uses a frequency division multiple access (FDMA) technique to distinguish the signals coming from different satellites in the Russian GNSS constellation. The GLONASS L1 and L2 bands are divided into 14 sub-bands, and each satellite transmits in one of these.

The sub-bands are identified by frequency numbers *k*, from -7 to 6. The GLONASS L1 and L2 carrier frequencies, in Hertz, at a frequency number *k* are defined by:

$$\begin{aligned} f_{L1}^{k}[Hz] &= 1602\cdot 10^{6} + k\cdot 562500 \\ f_{L2}^{k}[Hz] &= 1246\cdot 10^{6} + k\cdot 437500 = f_{L1}^{k}[Hz]\cdot 7/9 \end{aligned} \quad (1)$$

It has been known for a long time that the use of the FDMA technique causes significant inter-frequency biases in carrier phase measurements of GLONASS satellites. As already postulated in early GLONASS developments [3], these biases can be well modeled as a linear function of the frequency number *k*, and are very similar on L1 and L2 when expressed in units of length. It has also been shown that these biases tend to be the same for all receivers of a given brand, but significantly differ between brands [8][9]. The fact that the biases depend on the GLONASS frequency number and are not the same between brands significantly complicates the RTK ambiguity resolution process in heterogeneous base-rover combinations [1][6][10].

Although the general properties of the GLONASS inter-frequency carrier phase biases (linearity with respect to *k*, homogeneity within a given brand, and equality between the L1 and L2 bands) are well known and documented, the origin of these biases in the receiver signal processing chain has remained largely unexplained. The widely accepted hypothesis is that the biases originate in the analog hardware, and hence are difficult to tackle without specialized laboratory equipment.

This paper provides new insights into this question. Our analysis demonstrates that the major cause of inter-frequency carrier phase biases is not to be found in the analog RF part of the receiver, but rather in the way the measurements are generated in the digital part of the receiver. This opens new perspectives and new hope for the calibration of the biases between receivers: it is shown that the biases can be compensated to millimeter-level in an absolute sense.

## DEFINITIONS

Most existing research on inter-frequency carrier phase biases has been concerned with differential biases in the form of single and double differences, which reflects the form in which the biases appear in differential positioning algorithms, such as RTK. Instead, this paper addresses the source of biases inside a single GNSS receiver, and for that purpose it is more convenient to concentrate on non-differenced observations and non-differenced biases.

To focus on the inter-frequency phase biases, we shall purposely ignore in our formulas all other error sources such as atmospheric delays, multipath or tracking noise. We also ignore inter-frequency code biases, which shall not be discussed in this paper. Under these idealized assumptions, the code and carrier phase measurement generated in a GNSS receiver would differ only by an integer number of wavelengths:

$$\varphi_{Li,ideal}^{k} = \frac{C^{k}}{\lambda_{Li}^{k}} + N_{Li}^{k} \quad (2)$$

where $\varphi_{Li}^{k}$ is the phase measurement, in units of cycles, for the frequency band *Li* (*i*=1 or 2) and for a GLONASS satellite transmitting in a frequency channel *k*, $C^{k}$ is the code measurement, $N_{Li}^{k}$ is an integer phase ambiguity and $\lambda_{Li}^{k}$ is the carrier wavelength, defined as $\lambda_{Li}^{k} = c / f_{Li}^{k}$ with *c* being the speed of light (299792458 m/s) and $f_{Li}^{k}$ defined by equation (1).

In this paper, we will use the symbol "$\varphi$" for phase measurements expressed in cycles and "$\Phi$" for phase measurements expressed in meters. To convert $\varphi$ to $\Phi$, it is sufficient to multiply it by the carrier wavelength $\lambda_{Li}^{k}$.

Equation (2) represents an ideal non-biased case. If biases affect carrier phase measurements, equation (2) must be rewritten as:

$$\varphi_{Li}^{k} = \frac{C^{k}}{\lambda_{Li}^{k}} + N_{Li}^{k} + \Delta\varphi_{Li}^{k} \quad (3)$$

where $\Delta\varphi_{Li}^{k}$ is the carrier phase bias term, in cycles. It is dependent on the frequency number, hence the superscript *k*. The GLONASS inter-frequency carrier phase bias is commonly defined as the difference of the bias at frequency number *k* with respect to the bias at frequency number 0. In this paper, we will denote the inter-frequency carrier phase bias as $\Delta\varphi_{Li}^{k,0}$ when expressed in units of cycles, and $\Delta\Phi_{Li}^{k,0}$ when expressed in units of length:

$$\Delta\varphi_{Li}^{k,0} = \Delta\varphi_{Li}^{k} - \Delta\varphi_{Li}^{0} \quad (4)$$

and

$$\Delta\Phi_{Li}^{k,0} = \Delta\varphi_{Li}^{k} \cdot \lambda_{Li}^{k} - \Delta\varphi_{Li}^{0} \cdot \lambda_{Li}^{0} \approx \Delta\varphi_{Li}^{k,0} \cdot \lambda_{Li}^{0} \qquad (5)$$

The approximation in equation (5) is accurate to a sub-millimeter level and hence is valid in all practical cases.

Figure 1 shows the L1 and L2 GLONASS inter-frequency carrier phase biases ($\Delta\Phi_{L1}^{k,0}$ and $\Delta\Phi_{L2}^{k,0}$) as a function of the frequency number $k$ for Septentrio's PolaRx3 receivers running firmware version 2.2. This figure illustrates that the inter-frequency biases are linear functions of the frequency number, and, when expressed in units of length, are almost equal for L1 and L2.

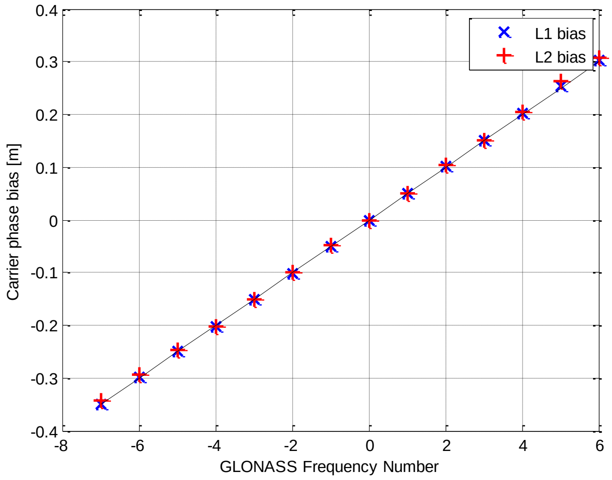


**Figure 1. Carrier phase bias in the GLONASS L1 and L2 bands for Septentrio's PolaRx3_v2.2 receiver.**

According to [9], GLONASS inter-frequency phase biases for a given brand can be characterized by a single parameter: the slope of their linear dependence upon the frequency number expressed in centimeters per frequency number. In the case of the PolaRx3_v2.2 receiver, the biases of which are shown in Figure 1, the slope is 4.9 cm per frequency number and is the same on L1 and L2. The value of the slope for other receiver manufacturers can be found in [9].

In the next section it will be shown that inter-frequency carrier phase biases consist of two components: biases caused by analog radio-frequency hardware and biases caused by the digital signal processing (DSP):

$$\Delta\varphi_{Li}^{k,0} = \Delta\varphi_{Li,HW}^{k,0} + \Delta\varphi_{Li,DSP}^{k,0} \qquad (6)$$

Although it is commonly assumed that analog hardware is a main source of biases, it will be shown in this paper that this is not the case: in reality, the digital signal processing is by far the dominant source of biases.

## EFFECT OF ANALOG FILTERS

It is well known that GNSS signals are subjected to a group delay and a phase shift when passing through the analog components of the antenna and the receiver. This effect is frequency dependent, and hence is not the same for the different GLONASS frequency channels.

The phase response of an analog filter characterizes the phase shift introduced by the filter as a function of the carrier frequency. The phase response for a particular receiver can be computed *a priori* if the filter design is known, or can be accurately measured in an absolute sense using specialized laboratory equipment such as a network analyzer.

As an example, Figure 2 shows the phase response across the GLONASS L2 band for the L2 analog filter of the PolaRx3 receiver, the bias of which is shown in Figure 1. In this figure, the effect of the frequency-independent delay introduced by the filter has been removed.

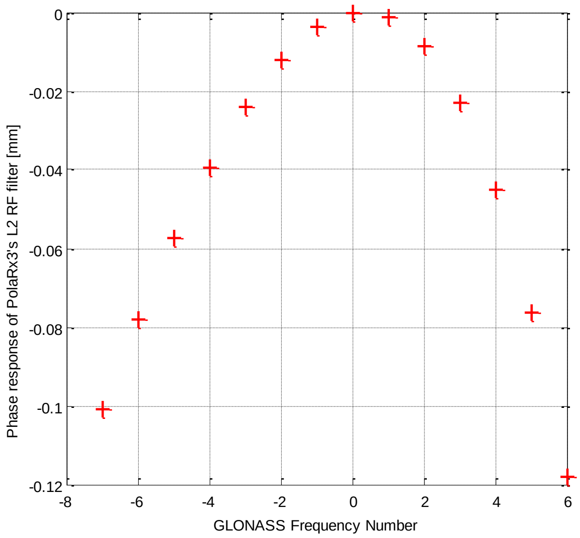


**Figure 2. Phase response of the analog filter in a Septentrio's PolaRx3 receiver across the GLONASS L2 band. Note that the scale of the Y-axis is in millimeters, while the scale in Figure 1 was in meters.**

It can be seen that the phase shift variation caused by that RF filter is very small (sub-millimeter level) and cannot account for the decimeter-level biases shown in Figure 1. More generally, it is clear that the observed properties of the inter-frequency carrier phase biases do not correspond to what would be caused by analog filters:

- Analog filters would not systematically cause the same bias on L1 and L2;
- Analog filters would not systematically produce linear biases;

- Analog biases are sensitive to temperature, while no temperature effect has been observed so far [9].

## BIASES FROM THE DIGITAL SIGNAL PROCESSING

In GLONASS RTK processing, it is common practice to use code measurements to estimate the single difference between the clock biases of the rover and base receivers [4][5], and it is assumed that the single-difference receiver clock biases for code and carrier phase measurements are equal. An incorrect estimation of the single-difference receiver phase clock bias is known to introduce large carrier phase residual errors when fixing GLONASS ambiguities [2][7].

It is not commonly known that the fundamental assumption that code and carrier phase measurements share the same clock bias is generally incorrect. There exist at least two mechanisms by which the measurement generation algorithm in the receiver's DSP can induce a difference in code and carrier clock bias.

First, it is a common practice to adjust code measurements by some constant offset. For instance, this adjustment is performed to compensate for group delay effects in the reception chain, in order to align the time at which the pulse-per-second strobe (PPS) is generated. This adjustment is done in the receiver firmware by adding a constant term $\delta PR_{Li}$ to all raw code measurements within frequency band *Li*. This adjustment, being constant for all satellites, is seen as a code clock bias by the positioning algorithm. If it is applied to code measurements only, it obviously introduces a difference between code and phase clock biases.

The second cause of code-phase bias is to be found in the correlation process that takes place in the digital hardware. Signal tracking involves maximizing the correlation between the incoming signal and local signal replicas generated by code and carrier generators implemented in the receiver's digital circuits. This process is illustrated in Figure 3.

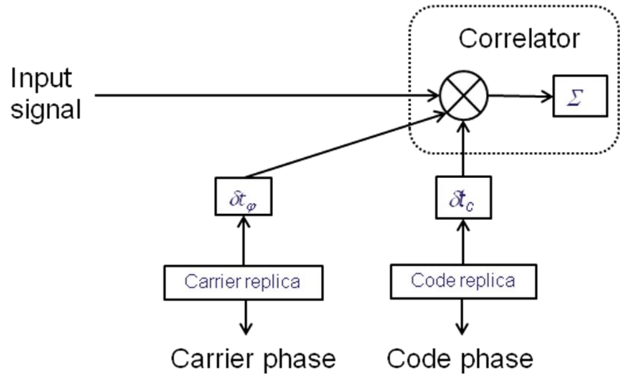


**Figure 3. Correlation process in a tracking channel of a GNSS receiver and related code and carrier delays.**

There exists a delay $\delta t_C$ from the code generator to the correlator, and a delay $\delta t_\varphi$ from the carrier generator to the correlator. These delays are fixed for a given receiver architecture, and do not depend on temperature. Typically, they are multiples of the sampling interval used by a particular receiver design. Depending on the chip architecture, the delays $\delta t_C$ and $\delta t_\varphi$ are not necessarily equal. Any difference between these delays is directly translated into a bias between the code and carrier phase measurements.

With the code measurement adjustment term $\delta PR_{Li}$ and the delays $\delta t_C$ and $\delta t_\varphi$ introduced above, equation (2) does not hold anymore and must be rewritten as follows:

$$\varphi_{Li}^k = \frac{C^k}{\lambda_{Li}^k} + N_{Li}^k + \frac{c\cdot\left(\delta t_C - \delta t_\varphi\right) - \delta PR_{Li}}{\lambda_{Li}^k} \qquad (7)$$

The third term in the right-hand side of equation (7) is the DSP-induced carrier phase bias defined in equation (3):

$$\begin{aligned}\Delta\varphi_{Li,DSP}^k &= \frac{c\cdot\left(\delta t_C - \delta t_\varphi\right) - \delta PR_{Li}}{\lambda_{Li}^k} \\ &= \frac{CPB_{Li}}{c}\cdot f_{Li}^k\end{aligned} \qquad (8)$$

where

$$CPB_{Li} = c\cdot\left(\delta t_C - \delta t_\varphi\right) - \delta PR_{Li} \qquad (9)$$

is the aggregate code-phase bias (CPB) induced by the digital processing in the *Li* band, expressed in units of length. Using the values of $f_{Li}^k$ defined in equations (1), we can now rewrite the DSP-induced L1 and L2 carrier phase biases as follows:

$$
\begin{aligned}
\Delta\varphi^{k}_{L1,DSP} &= \frac{CPB_{L1}}{c}\cdot f^{k}_{L1} \\
&= \frac{CPB_{L1}}{c}\cdot\left(1602\cdot 10^{6}+562500\cdot k\right) \\
&= \Delta\varphi^{0}_{L1,DSP}+CPB_{L1}\cdot\frac{562500}{c}\cdot k \\
\Delta\varphi^{k}_{L2,DSP} &= \frac{CPB_{L2}}{c}\cdot f^{k}_{L2} \\
&= \frac{CPB_{L2}}{c}\cdot\left(1246\cdot 10^{6}+437500\cdot k\right) \\
&= \Delta\varphi^{0}_{L2,DSP}+CPB_{L2}\cdot\frac{437500}{c}\cdot k
\end{aligned} \tag{10}
$$

The inter-frequency biases, as defined in equation (4), read:

$$
\begin{aligned}
\Delta\varphi^{k,0}_{L1,DSP} &= CPB_{L1}\cdot\frac{562500}{c}\cdot k \\
\Delta\varphi^{k,0}_{L2,DSP} &= CPB_{L2}\cdot\frac{437500}{c}\cdot k
\end{aligned} \tag{11}
$$

In units of length, they become (see equation (5)):

$$
\begin{aligned}
\Delta\Phi^{k,0}_{L1,DSP}[m] &= CPB_{L1}\cdot\frac{562500}{c}\cdot k\cdot\lambda^{0}_{L1} \\
&= \frac{CPB_{L1}}{2848}\cdot k \\
\Delta\Phi^{k,0}_{L2,DSP}[m] &= CPB_{L2}\cdot\frac{437500}{c}\cdot k\cdot\lambda^{0}_{L2} \\
&= \frac{CPB_{L2}}{2848}\cdot k
\end{aligned} \tag{12}
$$

Equation (12) shows that the DSP-induced inter-frequency biases, when expressed in meters, are linear functions of *k*. The slope of the linear function is proportional to $CPB_{Li}$.

The worst-case inter-frequency bias is when differencing frequency number k=-7 and k=6. This worst-case bias amounts to:

$$
\max\Delta\Phi_{Li,DSP}=\frac{CPB_{Li}}{2848}\cdot(6+7)=\frac{CPB_{Li}}{219.1} \tag{13}
$$

The value of $CPB_{Li}$ depends upon the receiver brand and typically ranges from zero to a few hundreds of meters. The resulting inter-frequency carrier phase biases, as computed from (12), may amount to a few centimeters per frequency number.

In the case of the PolaRx3 receiver running firmware version 2.2, the bias of which was shown in Figure 1, the CPBs are known to the authors: $CPB_{L1} = CPB_{L2} = 142.4$m. Equation (12) shows that this causes an inter-frequency carrier phase bias of 0.05m per frequency number on L1 and L2. This closely matches the bias of 4.9cm per frequency number reported in [9].

## DIFFERENCE BETWEEN $CPB_{L1}$ AND $CPB_{L2}$

$CPB_{L1}$ differs from $CPB_{L2}$ if the DSP applies a different adjustment to the L1 code measurements than to the L2 code measurements, i.e. if $\delta PR_{L1} \neq \delta PR_{L2}$. This may be done to compensate for a possible differential group delay between the L1 and the L2 RF filters.

Typically, the differential group delay between L1 and L2 RF filters does not exceed about ten meters, and therefore the difference between $CPB_{L1}$ and $CPB_{L2}$ typically ranges from zero to about ten meters. Equation (12) shows that the resulting difference in the slope of the inter-frequency carrier phase bias on L1 and L2 is relatively small: it is at the level of a few millimeters per frequency number. This explains why the inter-frequency carrier phase biases are almost equal on L1 and L2 for all receiver models, as reported in [9].

It is important to realize that the presence of RF filter group delays in itself does not imply the presence of code-phase biases. Code-phase biases only appear when the DSP attempts to compensate for such group delays by adjusting the code measurements while keeping the phase measurements uncorrected.

As a side note, it would be wrong for the RTK engine to assume that the single-difference receiver clock bias is the same on L1 and L2. As the estimated clock bias, being computed from code measurements, contains a group delay component, it may differ between L1 and L2. Using the L1 single-difference receiver clock bias for fixing the L2 carrier ambiguities generally results in millimeter-level inter-frequency biases, even when $CPB_{L1}$ and $CPB_{L2}$ are equal, or when there are no code-phase biases at all.

## DIFFERENCE BETWEEN C/A AND P

GLONASS signals in the L1 and L2 bands contain two components: a C/A component and a P component. A receiver may report carrier phase measurements from the C/A and/or the P component. Depending on the receiver brand, raw C/A and P carrier phase measurements are either aligned (modulo one cycle), or they differ by a quarter cycle (modulo one cycle). The quarter cycle issue has been widely addressed within the GNSS user community and is not relevant to the topic of inter-frequency biases: the quarter cycle bias, if it is present, is a constant offset, independent on the GLONASS frequency channel.

However, that C/A and P carrier phase measurements are aligned does not necessarily mean that inter-frequency biases for these two signals are equal. As explained above, the inter-frequency carrier phase biases depend on the way code measurements are generated.

It is not excluded that, in some receiver designs, the DSP applies a different adjustment to the C/A code measurements than to the P code measurements ($\delta PR_{Li,C/A} \neq \delta PR_{Li,P}$). The reason for doing so could be to compensate for small C/A-P differential group delays introduced by the RF filters.

The difference between the CPBs for C/A and P measurements, if any, is not expected to exceed one or two meters. Equation (12) shows that the resulting difference in the slope of the inter-frequency carrier phase bias is under the millimeter per frequency number, and hence will not be relevant in most practical cases.

## COMPENSATION OF CPB EFFECTS

Contrary to analog hardware biases, DSP-induced biases are perfectly stable in time and temperature. They are only dependent on the architecture of the digital signal processor, and hence do not vary from unit to unit.

The terms $\delta PR_{Li}$ are firmware parameters that can directly be retrieved from the source code of the DSP software. The code-phase correlator delay $\delta t_C$ - $\delta t_\varphi$ can be retrieved from the architecture of the baseband digital chip.

GNSS receiver manufacturers know the parameters applicable to their own design and therefore can compute their CPBs using equation (9). If the CPBs are not zero for their receivers, they could decide to apply formulas (11) or (12) to correct their carrier phase measurements. However, having receivers applying the correction by default is not necessarily recommended as some RTK rover engines rely on a hard-coded table of carrier phase biases per manufacturer (see for example the table in [9]). Changing the biases, even if it is to remove them, would introduce a backward incompatibility.

Another approach, which maintains backward compatibility, consists in keeping the carrier phase measurements intact while providing the applicable CPBs values to the user. In this approach, the user has the responsibility to correct the carrier phase measurements.

At most, up to four CPB values must be provided to the user:

1. $CPB_{L1P}$: bias between L1 phase and L1P code measurements;
2. $CPB_{L1CA}$: bias between L1 phase and L1CA code measurements;
3. $CPB_{L2P}$: bias between L2 phase and L2P code measurements;
4. $CPB_{L2CA}$: bias between L2 phase and L2CA code measurements;

Note that, for the phase measurement, there is no need to differentiate between C/A and P, as discussed in the previous section.

For many receiver designs, all these CPBs are equal. If they differ, they differ by small values only, as discussed above.

It is important to apply the right CPBs when correcting the carrier phase measurements. For the fixing of the ambiguities of L1 phase measurements (either L1CA or L1P phase), $CPB_{L1CA}$ is applicable if the single-difference receiver clock bias is computed from L1CA code measurements, and $CPB_{L1P}$ is applicable if it is computed from the L1P code measurements. The same applies for the L2 ambiguities.

## CONCLUSION

This paper provides new insights into the origin of GLONASS inter-frequency carrier phase biases in GNSS receivers. It is shown that the well-known centimeter-level linear biases affecting GLONASS carrier phase ambiguity resolution result from the erroneous assumption that the receiver clock bias is the same for code and for carrier phase measurements.

It is shown how the digital signal processing in GNSS receivers can introduce a significant code-phase bias and how this code-phase bias translates into large linear inter-frequency biases when fixing GLONASS carrier ambiguities.

Two major causes of code-phase biases are identified: (i) adjustment of code measurements in the receiver firmware, and (ii) differential delays between the signals from the code and carrier generators in the receiver's digital chip.

These DSP-induced code-phase biases are, by far, the major cause of GLONASS inter-frequency carrier phase biases, contrary to the common assumption that analog-induced biases are dominant. They are not dependent on temperature, they do not vary from unit to unit and they are stable in time. They can be derived in an absolute sense from the receiver firmware and digital chip architecture.

This means that no tedious empirical inter-receiver calibration is required, and the interoperability of GLONASS receivers can be ensured by relatively simple measures.

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