Geo++® White Paper

Some Thoughts on Satellite Induced Phase Shifts aka "the L2C Quarter Cycle Problem" and the Impact on RINEX and RTCM

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Garbsen, 30. January 2009

Introduction

The modernization of GPS will provide several new signals for civil and military applications. The new signals are challenging and will have an impact on a variety of different applications. Already now, the first new civil signal L2C is transmitted by six modernized GPS Block IIR-M satellites.

This brings back an old issue of phase shifts induced by the satellite for signals on the same carrier. Before L2C signals became available, multiple phase measurements on the same carrier frequency were possible for L1 C/A- and P-Code signals only. Since both signals are available for all satellites a receiver or application could choose one signal for further processing. The RINEX standard did support only one phase for L1. Thus, the phase shift bias was identical for all satellites and could easily be estimated or eliminated through differencing and did not cause serious problems.

However, the phase shift of signals is a general problem for new signals. Since GNSS modernization is done satellite by satellite a mixture of phase measurements from different signals is obtained. The phase shift bias between such signals cannot be eliminated through simple differencing and must be handled separately. We are currently facing a quarter cycle phase shift for L2C, which already caused problems in GNSS applications.

The phase shift is introduced at the satellite and is in most cases a constant term but also variable phase shifts are possible. In addition satellite induced signal delays or phase biases have to be considered as well as receiver hardware biases which are associated with different signals and tracking modes of the signals. At the receiver level even mixed mode tracking of two or more signals is possible. These biases are gaining much more importance with more signals from the satellites, more tracking features of receivers and more GNSS systems.

Data format standards like RINEX and RTCM must consider how to handle phase shifts. The formats have to be unambiguous and flexible enough to cover all present and upcoming signals. The formats must maintain all signal properties to allow optimized processing with high accuracy requirements.

Therefore a closer look at satellite induced phase shifts and associated biases is necessary. The following discussion is primarily addressing GPS and the ¼ cycle phase shifts between the in-phase and quadrature signals, but the issue of satellite induced phase shifts applies also for other phase shifts and other GNSS systems.

Signal Generation at the Satellite

The quarter cycle phase shift is a satellite dependent parameter. A phase signal Φ_0 for the nominal frequency f is derived from the satellite clock with time t_0 according to

$$\Phi_0 = f \cdot t_0 \ . \tag{1}$$

The in-phase signal component (I) transmitted by the satellite can be described as

$$\Phi_I = \Phi_0 + b_I \ . \tag{2}$$

The quadrature signal component (Q) is phase shifted by $\delta\Phi_Q$. This phase shift is specified for GPS in IS-GPS-200D to be ¼ cycles with the Q-signal carrier lagging the I-signal by 90 degrees. The phase of the Q-signal transmitted by the satellite is

$$\Phi_Q = \Phi_0 + b_Q + \delta\Phi_Q \ . \tag{3}$$

The terms b_I and b_Q account for satellite phase biases induced by signal generation hard- and/or software.

For GPS the P-Codes are modulated on the in-phase carrier of L1 and L2 respectively and the C/A or L2C Codes are modulated on the Q-phase carrier.

The in-phase and quadrature-phase relationship is defined for GPS in the IS-GPS-200D. However, it is also stated, that the two L2 carrier components can be in same phase (so-called “Flex Power mode”). This means that the term $\delta\Phi_Q$ in (3) can be switched from 90 degrees to 0 and vice versa from time to time and for individual satellites.

In 2008 there have been some non-official statements about the future of the Flex Power mode for L2C in the sense that it might not be switched on or it might not be switched on unless a bit indicating this is available in the Navigation Message.

The specification for the accuracy of the phase quadrature in IS-GPS-200D as well as IS-GPS-705 (L5) and IS-GPS-800 (L1C) is:

$$|b_I - b_Q| \leqslant 100\, mrad \tag{4}$$

(IS-GPS: “Signals shall be in phase quadrature within +/- 100 mrad”).

This value corresponds to the following metric values for GPS L1, L2 and L5:

$$\begin{aligned} L1 &\approx 3.0\, mm \\ L2 &\approx 3.9\, mm \\ L5 &\approx 4.1\, mm \ . \end{aligned} \tag{5}$$

For GLONASS the relationship is not as clearly specified as for GPS for the civil community, but empirical analysis shows currently a phase difference of 1/4 cycles between the GLONASS P and C/A phases on both L1 and L2. A specification for the phase quadrature accuracy is not available. It is not known whether similar techniques like the GPS Flex Power mode are implemented or intended for GLONASS.

Signal Tracking in a GNSS Receiver

The mathematical model for a phase measurement of a GNSS receiver can be formulated as follows.

The actual phase φ measured by a receiver is the phase difference between the phase of the received signal and the phase of a reference signal Φ_R generated in the receiver ("beat signal"). The reference signal is generated with the nominal frequency f of the satellite signal from the main receiver oscillator and can be written as

$$\Phi_R = f \cdot t_R \ , \tag{6}$$

where t_R is the receiver clock time.

In the following it is assumed that the same reference signal is used for the in-phase and quadrature-phase measurements. This assumption is implicitly also made in all the discussions so far within the RINEX and RTCM groups, although it is not a required property of a GNSS receiver to track the signals.

Receiver bias terms $b_{R,I}$ and $b_{R,Q}$ as well as the integer ambiguity terms N_I and N_Q and measurement error terms (including noise and multipath) ϵ_I and ϵ_Q are added accordingly. The I- and Q-phases measured by the receiver can be expressed as

$$\varphi_I = (\Phi_I - \Phi_R) + N_I + b_{R,I} + \epsilon_I \ \text{ and} \tag{7}$$

$$\varphi_Q = (\Phi_Q - \Phi_R) + N_Q + b_{R,Q} + \epsilon_Q \ . \tag{8}$$

It should be noted that the term $(\Phi_I - \Phi_R)$ contains $f(t_0 - t_R)$, which is the negative (pseudo-)propagation time of the signal in carrier cycles. Multiplying (7) or (8) with the wavelength and changing the sign results in the so-called PhaseRange measurement.

Substituting equations (2) and (3) into (7) and (8) yields

$$\varphi_I = (\Phi_0 + b_I - \Phi_R) + N_I + b_{R,I} + \epsilon_I \ \text{ and} \tag{9}$$

$$\varphi_Q = (\Phi_0 + b_Q + \delta\Phi_Q - \Phi_R) + N_Q + b_{R,Q} + \epsilon_Q \tag{10}$$

and after reordering

$$\varphi_I = (\Phi_0 - \Phi_R) + \qquad N_I + b_I + b_{R,I} + \epsilon_I \ \text{ and} \tag{11}$$

$$\varphi_Q = (\Phi_0 - \Phi_R) + \delta\Phi_Q + N_Q + b_Q + b_{R,Q} + \epsilon_Q \ . \tag{12}$$

The difference between the two measured phases is

$$\varphi_Q - \varphi_I = \delta\Phi_Q + (N_Q - N_I) + (b_Q - b_I) + (b_{R,Q} - b_{R,I}) + (\epsilon_Q - \epsilon_I) \ . \tag{13}$$

The ambiguity difference $(N_Q - N_I)$ can easily be solved and eliminated. After correcting the ambiguity difference and eliminating corresponding terms, the phase difference can be expressed as

$$\varphi_Q - \varphi_I = \delta\Phi_Q + (b_Q - b_I) + (b_{R,Q} - b_{R,I}) + \epsilon_Q - \epsilon_I \ . \tag{14}$$

The dominant term in this equation is the phase shift $\delta\Phi_Q$ which must be accounted for if the phase measurements from different signals (I, Q) and different receivers are combined within one application. However, even after a correction of $\delta\Phi_Q$ the satellite and receiver dependent bias terms are still existing and cannot be ignored for precise applications. Double differencing of phases from different carrier components will not completely eliminate the satellite and receiver dependent biases. As can be seen from (5) the term $(b_Q - b_I)$ can be in the order of +/- 3 mm to +/- 4 mm for GPS. The magnitude of the bias difference in term $(b_{R,Q} - b_{R,I})$ is receiver type dependent and cannot be specified in general. This means that a simple exchange of one phase by the phase-shift corrected phase of the other carrier component results in loss of accuracy if the biases are not treated carefully.

Mixed Mode Tracking

The RINEX 3.00 document specifies mixed modes of signal tracking like (L1X, L5X, L7X, L8X and L6X). In this case the GNSS receiver tracks a combination of the I and Q signals. According to Jean-Marie Sleewagen from Septentrio such a tracking mode is not clearly defined. It can be any arbitrary combination of the two signals:

$$\varphi_X = \alpha(\Phi_I - \Phi_R) + \beta(\Phi_Q - \Phi_R) + \gamma + N_X + b_{R,X} + \epsilon_X \tag{15}$$

where α, β, γ are receiver type dependent constants. Substituting (2) and (3) into (15) yields

$$\varphi_X = (\alpha+\beta)(\Phi_0 - \Phi_R) + \alpha b_I + \beta \delta \Phi_Q + \beta b_Q + \gamma + N_X + b_{R,X} + \epsilon_X \ . \tag{16}$$

If $(\alpha+\beta)=1$ this signal has the same frequency (Doppler) as the original components. In this case the difference of this phase to the I-phase in (11) is:

$$\varphi_X - \varphi_I = \beta \delta \Phi_Q + \gamma + (N_X - N_I) + (\alpha b_I + \beta b_Q - b_I) + (b_{R,X} - b_{R,I}) + (\epsilon_X - \epsilon_I) \tag{17}$$

or with $b_X = \alpha b_I + \beta b_Q$ and reordering

$$\varphi_X - \varphi_I = \beta \delta \Phi_Q + \gamma + (b_X - b_I) + (b_{R,X} - b_{R,I}) + (N_X - N_I) + (\epsilon_X - \epsilon_I) \ . \tag{18}$$

In equation (16) the I-Q phase shift $\delta \Phi_Q$ is multiplied by the term β and a constant γ is added so that the phase shift of this arbitrary signal can be written as

$$\delta \Phi_X = \beta \delta \Phi_Q + \gamma \ , \tag{19}$$

i.e. the phase shift is a receiver type dependent linear combination of the original phase shift.

A manufacturer can choose β and γ for signals with constant $\delta \Phi_Q$ so that $\delta \Phi_X = \beta \delta \Phi_Q + \gamma = 0$ and thus the resulting phase is in-phase with the I-signal. However, for varying phase shift signals like GPS L2C in Flex Power mode such a constant relation does not work.

The satellite dependent bias in above equations is a linear combination of the original satellite based signal biases: $b_X = \alpha b_I + \beta b_Q$ or $b_X = b_I + \beta(b_Q - b_I) \forall (\alpha+\beta)=1$. Such biases could be called “receiver type dependent satellite biases”.

Such mixed mode signals are expected to yield better accuracy compared to the individual signals. However, the processing of such signals in combination with other signals on the same carrier frequency or with measurements from different receiver types is challenging because of the arbitrary mixture of biases. In order to use the potential of better accuracy of such signals, the bias issue must be treated carefully. For data exchange formats like RTCM or RINEX the inclusion of the receiver type dependent parameters α, β, γ should be considered.

For code measurements (pseudoranges) the situation is similar. However, the constants α, β, γ might be different and the bias terms are bigger compared to the phase biases.

Handling of Satellite induced Phase Shifts

Although the quarter cycle phase shift originates from the satellite, a correction of the term $\delta \Phi_Q$ to be applied to phase measurements before putting the measurements into the standard format is now under discussion for the RINEX and RTCM standards. This is in contradiction to the existing standards which do not allow the correction of external effects.

A correct handling of the phase shift issue must be achieved for all applications dealing with integer ambiguity resolution. In principle this is the task of the application software or the rover receiver which uses data from reference stations or networks. Current proposals try to solve the problem before the measurements are put into the standardized data formats. The idea is that the application software/rover shall be unburdened from this task.

A general requirement for the data format standards is that the properties of the signals are maintained and that no ambiguity is introduced through the corrections now and in the future.

First of all, the exact indication of signal and tracking mode is required to enable rigorous modeling of satellite and receiver biases. A “faking” of a signal is not allowed considering precise applications.

In case of the RINEX 2.11 standard, this exact indication is not possible because there is only one identifier for phase measurements on L1 or L2 respectively. Any carrier phase measurement for L1 is indicated as “L1” and any phase measurement for L2 is indicated as “L2” regardless of the underlying signal (I or Q).

In case of RINEX 3.00 the new observation identifiers allow an unambiguous identification of the signal and tracking mode.

In case of RTCM 2.3 the L1 C/A- and P-Code signals can be distinguished. But L2C cannot be identified in this format. Support for L2 carrier phases is only available for L2P.

In case of RTCM 3.1 an unambiguous identification of the signals and tracking modes for L1-C/A, L1-P(Y), L2-P(Y) and L2C is possible.

Without format extensions both RINEX and RTCM version 2 (V2) standards cannot be used for multiple and mixed signal modes.

Both version 3 (V3) standards can be used for the currently available signals. Both V3 standards clearly specify that no corrections should be applied with respect to the phase shifts. This means that both V3 standards are unambiguous today.

The limited applicability of V2 of the standards led to the fact that one manufacturer put a mixture of L2 phase measurements on L2P and L2C into the files or data streams respectively, although both V2 standards do not support this. In order to avoid problems with the phase shift in the receiving application, the L2C phases have been modified by correcting the ¼ cycles. For some reason the same practice has been used for the V3 standards, although this violates the standards and has not been necessary. The other manufacturers capable of tracking L2C did not do the corrections for the V3 files and streams, which is compliant with the standards. This situation resulted in interoperability problems between the different manufacturers and/or applications.

Instead of keeping the current RINEX and RTCM standards a discussion has been started to change the paradigm that “external effects shall not be corrected” to “phase shifts shall be corrected”.

One proposal from the RINEX group is to apply ¼ cycle corrections to one of the carrier phases in order to align all the phases of the same carrier frequency to the same phase shift. It shall be left to the manufacturer of the receiver or the author of conversion software or even to the user to choose the signals to be corrected.

Such an approach cannot be accepted unless the data files (or streams) contain the information about direction and amount of the correction. Otherwise the resulting phases are ambiguous by ¼ cycles in addition to the integer cycle ambiguity of phase measurements because it is not known to which signal the ¼ cycle correction has been applied. This will have an impact on non-difference or single-difference applications which determine clocks, use code-carrier combination methods or determine absolute ionosphere.

One argument against this objection is that such a ¼ cycle ambiguity cannot be distinguished from a receiver signal delay bias for the corresponding frequency and thus cannot hurt an application. This argument is only valid if the correction of phase shifts is done within the receiver before the phases are output to the communication interfaces. If the correction is done in a data format conversion tool (converter) the bias depends on the choice of the programmer or user of such a tool. This means that a "converter dependent bias" or even "user dependent bias" is introduced. Such converters can be implemented into the receiver but can also be external. If the converter is exchanged the bias might change and can no longer be called a receiver type dependent bias. Such a bias change is especially critical if, for instance, in real-time applications a switch between primary and secondary communication chains is performed where different converters are used. In such a situation the biases would jump by ¼ cycles which could cause severe modeling problems and possibly would result in arbitrary jumps in corresponding parameters like clocks or ionosphere estimates.

The bias issues are complex and challenging enough. One should not introduce additional arbitrary biases just because it seems to be a convenient approach to the problem.

If a phase shift correction has to be applied the phase shift between the different carrier components of the same frequency must be known. This phase shift can be determined from

- a priori known information for constant phase shifts, i.e. from Interface Control Documents of the corresponding GNSS, e.g. between GPS L1-P and L1-C/A,
- parallel tracking of the corresponding signals on at least one receiver or
- an indicator in Navigation Message or Almanac, e.g. GPS L2C.

The correction of constant phase shifts are simple and can be easily defined.

However, the correction of phase shifts for the "Flex Power" signals is complicated.

For L2C it has been stated that Flex Power will not be switched on unless bits in the Navigation Message, probably the Almanac, are available which indicate the status. If the standards require corrected phase shifts then all receivers and converters must be capable to decode and apply the information correctly. A receiver or converter probably must wait until the corresponding Almanac page has been received before the phase measurements can be put into the file or sent to the data stream. In case the Almanac is unreliable or old the bits may not indicate the correct status and the correction might be false.

Since the specification of a new Navigation Message format with L2C "signal phase" bits is not available yet, a converter written today cannot use the L2C bits and thus cannot determine the correct phase shift. This means that it is impossible to write an application or data format converter today which is reliably compatible with the standard and future applications. The only way to achieve this is to leave the phases uncorrected for the standardized data formats.

If other GNSS systems apply similar techniques like GPS Flex Power mode but do not publish this information or do not make it available in the navigation data, the strategy of correcting the phase shifts before generation of standard formats may not work at all.

Parallel tracking of signals is only possible if enough channels are available and the necessary tracking modes are implemented in the receiver.

If no correction is applied to the data put into the standardized formats the generating receiver/process can immediately put the phases to the file/stream without knowing the phase shift status. The receiving application can immediately use the measurements if other receivers track the same signal (e.g. phase shift eliminated through single differencing) and/or if the application is capable of estimating the phase shift or if other receivers are involved which track other signals of the same frequency and thus allow the direct determination of the phase shift.

One argument used in favor of corrections are the mixed mode signals which might have an arbitrary phase shift which is known only to the manufacturer and should therefore be corrected ("receiver type dependent satellite phase shift"). The better solution for this problem is the inclusion of the receiver dependent parameters into the standards (see above) because they also affect the phase biases ("receiver type dependent satellite biases") and must be known in order to correctly model such biases.

Conclusion

Satellite based phase shifts between different carrier components of the same frequency can affect the performance of precise GNSS applications and must be treated carefully. An approach is under discussion to leave it to the receiver or conversion software manufacturer to correct for the phase shifts. This procedure is unreliable and ambiguous. Thus, it is highly recommended to leave the phases uncorrected. This is already the status of the existing RINEX and RTCM standards. No changes are needed!

A critical situation arises for cases with variable phase shifts as for GPS L2C in Flex Power mode. Even if Flex Power for GPS might not be switched on in the future the potential possibility to have variable phase shifts on GNSS signals exists. Variable phase shift corrections cannot be reliably applied by the receiver or data conversion software due to insufficient information. It should be left to the final application software to deal with this issue. Even in the Flex Power case the final application should be able to handle the situation by either choosing a compatible (i.e. the same) signal, determining the bias from parallel tracking of other signals on some receivers, by estimating the bias or by neglecting the measurement. Only the final application should have the responsibility for the correct handling of the issue.

Without variable phase shifts the issue can easily be handled if the phase relation between different carrier components is documented. In this case a known constant correction has to be applied. This could be done in the receiver, the data converter or final application. None of the approaches has principle advantages. The correct identification of the signal is required for external converters and final applications. But this requirement holds also for the satellite and receiver dependent phase bias issue.

In case of mixed mode tracking the issue becomes more complicated. Additional information about the internal generation of the measurements in the receiver is necessary to handle the phase shift as well as the signal delay biases of satellites and receivers. The standard formats RINEX and RTCM probably need extensions for the inclusion of corresponding parameters.

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