*2nd URSI AT-RASC, Gran Canaria, 28 May – 1 June 2018*

# On the Accuracy of the GPS L2 Observable for Ionospheric Monitoring

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## Abstract

The recent introduction of the modern Global Positioning System (GPS) signals, like L2 Civil (L2C), have the potential to improve measurements relevant to the ionospheric research community. Recent publications have outlined issues with the new L2 signal when comparing its results to the encrypted, legacy L2 Precision (L2P(Y)) signal. A difference in the high rate carrier phase residuals between the L2P and L2C carriers are determined to be caused by L1-aided tracking techniques. It is shown that L1-aided tracking degrades the accuracy of the phase residuals. L1-aided tracking is necessarily used in tracking the L2P carrier, therefore, the accuracy of the L2P carrier phase residuals is suspect. It is not necessary to use L1-aided tracking for the modern L2C carrier; however, it is shown that many receivers use it, thus resulting in discrepancies in the L2C carrier phase residuals between receivers.

## 1. Introduction

New GPS signals have been introduced as part of the modernization of the GPS constellation. This includes adding the Civil code to the L2 carrier, providing the public with an open code on the L2 frequency. Previously, only the encrypted Precision code was available on the L2 carrier. The open access to the L2C code should provide receivers the opportunity for more robust tracking techniques which will likely improve the accuracy of the observables, including those used in ionospheric research.

The L2 carrier phase is an important observable in GPS-based ionospheric research and monitoring, specifically in Total Electron Content (TEC) and scintillation research [1,2,3]. With the L2C carrier being transmitted on 19 operational satellites as of April 2017, the ionospheric research community can begin using its observables. However, with the introduction of new data sources, we must always ensure we understand the limitations and advantages of these observables to ensure they are used appropriately.

Work has already begun in analyzing the validity of the L2C carrier phase observables, by way of analyzing the Rate of Change of TEC (ROT) and the ROT index (ROTI) [4]. TEC is defined as the integral number of electrons within a m$^2$ column centered along the ray path, and is calculated using the following method [5]:

$$TEC = \frac{f_1 f_2}{40.3(f_1 - f_2)}(\Phi_1 - \Phi_2) \tag{1}$$

where $f_1$ and $f_2$ are the L1 and L2 carrier frequencies (in Hz) respectively, and $\Phi_1$ and $\Phi_2$ are the carrier phase observables (in meters) respectively. The L2 carrier phase observable can be taken from either the L2C or L2P(Y) signal, resulting in L2C-derived TEC or L2P(Y)-derived TEC. The ROT and ROTI are defined as follows [6]:

$$ROT = \frac{TEC_i - TEC_{i-1}}{\tau_i - \tau_{i-1}} \tag{2}$$

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2} \tag{3}$$

where $i$ is the epoch corresponding to the TEC estimation, $\tau$ refers to the time at the corresponding epoch, and the angle brackets represent an average, typically taken over five-minute intervals.

In the work presented by [4], it was shown that the L2C- and L2P(Y)-derived ROTI differed significantly for certain receivers. Since the L2C and L2P(Y) codes are modulated on the same carrier frequencies, they should follow the same path through the ionosphere and thus be affected in the same way. Therefore, these differences are likely not ionospheric in nature. Effects due to the receiver are then assumed to the be the cause of these differences.

## 2. L2 Tracking

It is important to discuss the tracking of the encrypted L2P(Y) signal, as it is likely to have an impact on the final carrier phase observable and is relevant to the results presented in [4]. We note that due to the proprietary nature of GPS receivers, the full extent of the tracking techniques employed by the receivers cannot be known. This is an unfortunate realization for GPS-based ionospheric research and monitoring as it forces the community to use the receivers as semi-black boxes. However, using published work regarding GPS tracking techniques and the information that is provided by the manufacturers, appropriate conclusions can be made about the techniques employed by these receivers.

Due to the encryption on the L2P(Y) code, certain techniques must be used to bypass the encryption and get information about the carrier signal. Popular methods include codeless and semi-codeless tracking techniques [7]. These techniques rely on using the L1 carrier dynamics to aid in tracking the L2 carrier. However, these L1-aided tracking techniques will lead to inaccuracies in the L2 dynamics. We have confirmed that the Septentrio receivers use L1-aided tracking of the L2P(Y) carrier, while the tracking of the L2C carrier uses an independent tracking technique. The effect of the L1-aided tracking on the L2P(Y) residuals with the Septentrio receivers is a damping effect on the magnitude of the L2P(Y) carrier phase residuals, causing them to be agree with the L1C/A residuals. This agreement is not observed with the L2C residuals; the L2C residuals are shown to be larger in magnitude than L1C/A, which is expected for refractive ionospheric effects.

It has been mentioned in previous works [9,10] that some receivers appear to be tracking L2C using L1-aided techniques, even though it is not necessary. This is likely done to ensure that the L2C tracking is more robust, as an L1-aided tracking technique is more resilient to loss of lock during deep signal fades and improves signal acquisition time [10]. These improvements are very useful in positioning, but are detrimental for ionospheric monitoring and research. We propose that the inaccuracies in the L2 carrier phase residuals which are tracked using L1-aided techniques are very likely the cause of the differences in the ROTI measurements presented in [4].

## 3. Results

Using data obtained from a Septentrio PolaRxS Pro and Trimble NetR9 GPS receiver, set up as a zero-baseline pair, we present and discuss the effects of L1-aided versus independent tracking of the L2 carrier phase dynamics. The receiver pair is in Repulse Bay, Nunavut, Canada, as part of the Canadian High Arctic Ionospheric Network (CHAIN) [11]. These effects will be discussed in relation to the results presented in [4], where the L2C- and L2P(Y)-derived ROTI from different receivers was examined.

An example event is presented using GPS satellite PRN 31, during UTC hour 0 on Day 346 of 2016. The presented example is representative of a larger data set analyzed for this study. We begin with a comparison of the L2P(Y) and L2C carrier phase dynamics. Figure 1 presents the L2C phase residuals in the top panels, the L2P(Y) phase residuals in the middle panels and the differences in the bottom panels. The phases obtained from the Trimble receiver is presented on the left-side panels and the phase obtained from the Septentrio receiver in the right-side panels. The residuals are obtained by detrending the raw carrier phase using a 0.1 Hz high-pass filter [8]. The differences between the L2C and L2P(Y) phase residuals obtained from the Septentrio receiver show significant magnitudes. This is not surprising since the Septentrio receivers are known to track L2C independent of L1. We observe near zero differences for the Trimble receiver, suggesting the L2C and L2P(Y) residuals are identical. This is typical behavior for receivers in which L2C is tracked using L1-aided techniques like L2P(Y). Thus, we suggest that the Trimble receiver is tracking L2C using an L1-aided technique.

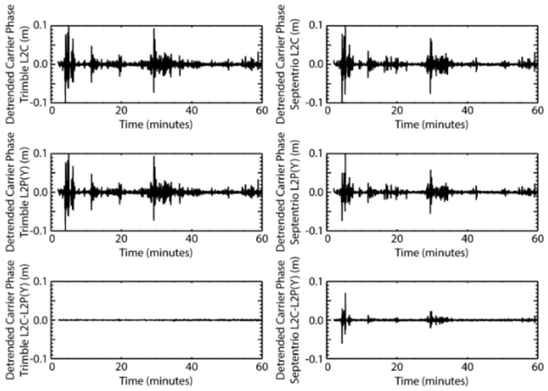

**Figure 1.** A typical example of detrended L2C (top) and L2P(Y) (middle) carrier phase for the Trimble NetR9 (left) and Septentrio PolaRxS Pro (right) receivers. The difference between the L2P(Y) and L2C carrier phases for each receiver are shown in the bottom panels.

In [4], the L2P(Y)- and L2C-derived ROTI was examined for the following receivers: Septentrio PolaRxS Pro, Leica GR10, Septentrio PolaRx4, Javad TRE-G3TH DELTA, and a Trimble NetR9. The differences between the L2P(Y)- and L2C-derived ROTI for the Trimble and Leica receivers showed near zero differences; moderate differences were observed for the Javad receiver, and significant differences for the Septentrio receivers. Based on the results presented, near zero differences in the L2C- and L2P(Y)-derived carrier phase residuals, and thus the ROTI, suggests L1-aided tracking for both L2P(Y) and L2C. Therefore, the Trimble and Leica receivers are very likely using L1-aided tracking for the L2C carrier; this agrees with our result for the Trimble receiver.

The significant differences observed between the L2C- and L2P(Y)-derived ROTI with the Septentrio receivers agrees with our results as well, indicating the receivers are tracking L2C independent of L1C/A, unlike L2P(Y).

The Javad receiver presented differences significantly greater than zero, but less than those observed for the Septentrio receivers. Comparing the Septentrio PolaRx4 and Javad receivers in a very-short baseline configuration results in significant differences between the Septentrio L2C-derived ROTI and the Javad L2C-derived ROTI. Although this is not conclusive, this result suggests the Javad receiver is tracking L2C using an L1-aided technique, which has less of an impact on the accuracy of the phase residuals than those used by Trimble and Leica.

### 3.1 Accuracy of the Residuals

### 3.1.1 Ionosphere Free Linear Combination

Based on the work presented in [12], ionospheric-induced variations in the carrier phase observable which are not accompanied by significant signal fades are likely refractive. Since refractive variations are deterministic, combinations like the Ionosphere-Free Linear Combination (IFLC) can be used to determine or eliminate the refractive effects. Ignoring higher order effects, the refractive effects of the ionosphere on the carrier phase follow an inverse frequency-squared relationship [13]. The IFLC exploits this feature, creating a linear combination which eliminates the refractive variations:

$$\Phi_{IFLC} = \frac{\Phi_1 f_1^2 - \Phi_2 f_2^2}{f_1^2 - f_2^2} \tag{4}$$

Equation 4 assumes the carrier phase variations are accurate, as inaccurate variations will not follow the inverse frequency-squared relationship and thus result in larger residuals in the IFLC. Therefore, using carrier phase variations during which no significant signal fades occur, we can use the IFLC as a measure of the accuracy of the carrier phase residuals. We present such an event in Figure 2, using the Septentrio and Trimble receiver pair within CHAIN. The top panel presents the detrended L2C signal power for the Septentrio receiver, with no significant variations throughout the presented hour. The middle panels present the IFLC using the detrended L1C/A- and L2P(Y)-derived carrier phases, and the bottom panel presents the IFLC using the L1C/A- and L2C-derived carrier phases. The combinations obtained using the Trimble receiver are presented on the left-side, while the combination obtained using the Septentrio receiver is presented on the right-side. For the Trimble-derived combinations, we observe significant variations in both the L2P(Y)- and L2C-derived IFLC, thus suggesting inaccuracy in both residuals. For the Septentrio combinations we observe similar variations in the L2P(Y)-derived IFLC. For the L2C-derived IFLC, we observe little to no variations. Recalling that the Septentrio L2C carrier phase is independently tracked, we conclude that the independently tracked carrier phase residuals are more accurate that those obtained through L1-aided tracking.

### 3.1.2 Using Phase Wind-Up Effects to Characterize the L2 Tracking Accuracy

We can further assess the accuracy of the tracking techniques of the L2 carriers by examining the artificial effects of phase wind-up. Rotating a GPS antenna about its vertical axis induces wind-up effects which manifest as a divergence in the L1 and L2 carrier phase observables [14]. As observed by the receiver, the effects of phase wind-up are comparable to ionospheric effects. If the antenna is rotated a full rotation, the carrier phase observables will change by a full wavelength. This results in a change of roughly 24.4 cm in the L2 carrier and 19.0 cm in the L1 carrier. Therefore, under quiet conditions, the difference between the L1 and L2 carrier phase observables will exhibit a 5.4 cm change due to a full rotation of the antenna.

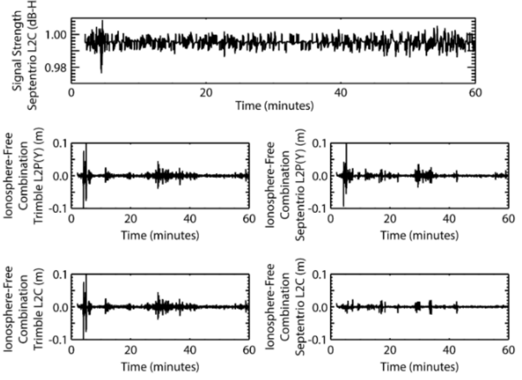

**Figure 2.** Detrended L2C signal intensity for the Septentrio receiver is presented in the top panel. The middle panels present the L1C/A- and L2P(Y)-derived IFLC and the bottom panels present the L1C/A- and L2C-derived IFLC, using data from the Trimble receiver (left) and the Septentrio receiver (right).

This experiment was performed using a Septentrio PolaRx5S and a Trimble BD982 receiver, connected to a single antenna. A representative example, using a high elevation satellite, is presented in Figure 3. The differences of the L2P(Y)- and L2C-derived carrier phases with the L1C/A carrier phase are presented for both the Septentrio and Trimble receivers. Note that the combinations are DC offset to zero for clarity. The rotation of the antenna begins just before 2 seconds and last only a fraction of a second.

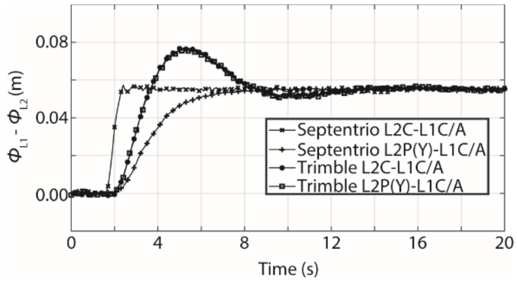

**Figure 3.** Phase wind-up effect on the L2-L1C/A combinations for a Septentrio and Trimble receiver, caused by a full-turn rotation of the shared antenna.

The Septentrio L1C/A-L2C combination presents the expected effect, as is expected with the independent tracking of L2C. The Septentrio L1C/A-L2P(Y) combination shows a slow reaction to the phase wind-up effects, taking roughly 7 seconds to converge to the expected value.

For the Trimble receiver, we observe that the L1C/A-L2P(Y) and L1C/A-L2C combination are nearly identical, as we expect with L1-aided tracking used for L2C. The combination takes roughly 10 seconds to converge to the expected value. It is interesting to note that the Trimble receiver first overestimates the effects of the phase wind-up, followed by a ringing effect before settling on the expected value.

## 4. Conclusion

L1-aided tracking techniques are beneficial for GPS receivers when positioning is the intended use. However, for the ionospheric research and monitoring community, the use of L1-aided tracking can be detrimental. Accuracy in the carrier phase residuals is vital in works examining ROT and ROTI, high rate TEC dynamics, IFLC dynamics, and those studying phase scintillation. In the past, these works would use the L2P(Y)-derived carrier phase observable, as it was the only available option; however, its long use in the community does not ensure its accuracy. It is necessary to ensure that the L2 carrier phase observable is not affected by L1-aided tracking techniques. To the knowledge of the authors, only Septentrio receivers use independent tracking for the L2C carrier phase. We suggest future works be wary of the impact of L1-aided tracking and clearly state when it is used. We also note that the effects of the L1-aided tracking on the ROTI measurement may have a significant impact on the proposed ROTI maps by the International GNSS Service (IGS) [15].

It is important for the ionospheric community to be aware of the impacts of the receiver on the observables used in research and monitoring. When subjected to rapid variations in phase, the L2 observables tracked using L1-aided techniques tell more about the implementation of the receiver than of the actual ionospheric phenomenon.

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