Analysis of GPS L2C Signal Quality and its Impact on PPP Performance

Rodrigo F. Leandro[1,2], Thatchineswaran Thirumurthi[1], Liliána Sükeová [1], Richard B. Langley[1], and Marcelo C. Santos[1]

[1]Geodetic Research Laboratory, Department of Geodesy and Geomatics Engineering,
University of New Brunswick, Fredericton, Canada

[2]Trimble Geomatics and Engineering Group – Trimble Terrasat GmbH
Hoehenkirchen, Germany

BIOGRAPHIES

Rodrigo Leandro is a Ph.D. candidate of the Department of Geodesy and Geomatics Engineering, University of New Brunswick (UNB), Fredericton, Canada, where he has been a student since 2004. Mr. Leandro is also a GNSS Research and Development engineer of Trimble Terrasat, Germany. He holds an M.Sc.Eng. in civil engineering from the University of São Paulo, in São Paulo, Brazil, and has been involved in research in the fields of geodesy and satellite positioning. Mr. Leandro has received a best student paper award from the Canadian Geophysical Union and a student paper award from The Institute of Navigation, both in 2004. In 2006, Mr. Leandro also received a best presentation award from The Institute of Navigation (ION).

Thatchineswaran Thirumurthi is a graduate student in the Department of Geodesy and Geomatics Engineering, UNB. He graduated from the Department of Electrical and Computer Engineering, UNB, with a B.Sc.E. in 2007.

Liliána Sükeová is an M.Sc.E student in the Department of Geodesy and Geomatics Engineering, UNB. She graduated from the Slovak Technical University, Bratislava, in 2005. She is a member of ION.

Richard Langley is a professor in the Department of Geodesy and Geomatics Engineering at UNB, where he has been teaching and managing research since 1981. He has a B.Sc. in applied physics from the University of Waterloo and a Ph.D. in experimental space science from York University, Toronto. Prof. Langley has been active in the development of GPS error models since the early 1980s and is a contributing editor and columnist for GPS World magazine. He is a fellow of ION and was a co-recipient of the ION Burka Award for 2003. He is also a fellow of the International Association of Geodesy and the Royal Institute of Navigation. In 2007, Prof. Langley received the ION Satellite Division's Johannes Kepler Award.

Marcelo Santos is an associate professor in the Department of Geodesy and Geomatics Engineering at UNB. He holds an M.Sc. in geophysics from the National Observatory in Rio de Janeiro, and a Ph.D. in geodesy from UNB. He has been involved in research in the fields of space and physical geodesy, GNSS, and navigation. Dr. Santos is the president of the Geodesy Section of the Canadian Geophysical Union and president of the International Association of Geodesy Sub-Commission 4.3 on remote sensing and modelling of the atmosphere.

ABSTRACT

University of New Brunswick researchers have actively participated in the research community's efforts to investigate the new GPS signal which is being broadcast by Block IIR-M satellites: the so called L2C signal. This participation has been carried out in several ways. UNB was one of the first institutions to have an active station participating in the International GNSS Service (IGS) L2C Test Network. UNB personnel have also contributed to the organization and management of the data, providing feedback to NASA's Crustal Dynamics Data Information System (CDDIS), which is responsible for the L2C Test data archiving. UNB's primary L2C station, which is called UNB3, has also been continuously used by several centers for different purposes, involving the modernization signal or not. However, perhaps the most substantial contribution from UNB for the L2C activities has been the research on the performance of the new signal, which has been carried out since early 2006. In this paper we present the latest results from our L2C signal analysis, which involves not only the investigation of the signal's quality, but also the impact of its use on positioning.

INTRODUCTION

Under the GPS modernization program, two new civil signals are being added to the legacy signals transmitted by the GPS satellites. The new signals are L2C, or L2 civil, and L5.

The L2C signal is to be transmitted on the L2 carrier frequency by all Block IIR-M and Block IIF satellites along with the legacy P(Y)-code and the new M-code. The L2C signal is already being transmitted by the five Block IIR-M satellites now in orbit (see Table 1 and Figure 1). Three more Block IIR-M satellites are scheduled to be launched this year.

Table 1. In-orbit Block IIR-M satellites

Satellite	PRN	SVN	Launch Date	Date Set Healthy for Users
IIR-M-1	17	53	26-Sep-2005	16-Dec-2005
IIR-M-2	31	52	25-Sep-2006	12-Oct-2006
IIR-M-3	12	58	17-Nov-2006	13-Dec-2006
IIR-M-4	15	55	17-Oct-2007	31-Oct-2007
IIR-M-5	29	57	20-Dec-2007	2-Jan-2008

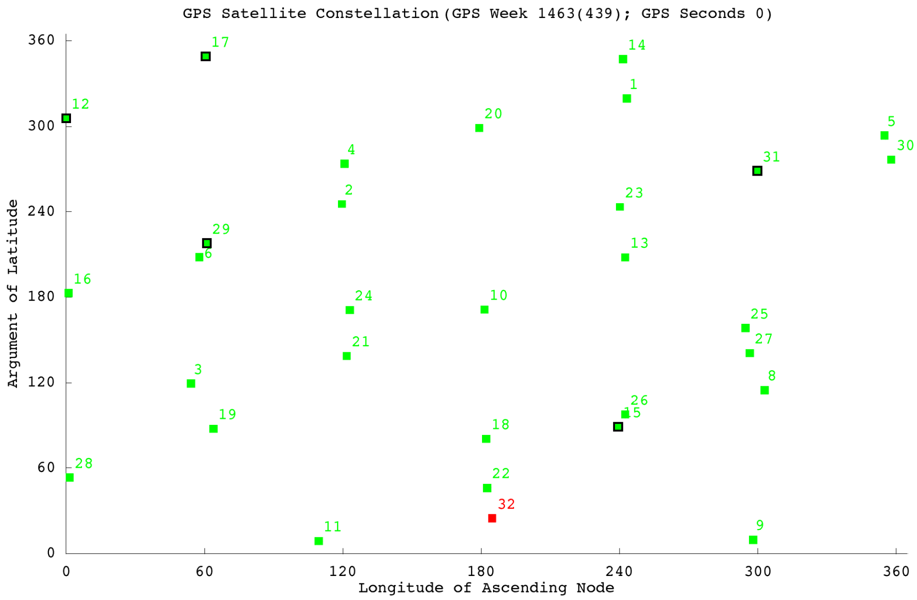

Figure 1. The current GPS satellite constellation. The Block IIR-M satellites are highlighted by black squares.

The L2C signal normally includes two pseudorandom noise ranging codes of different lengths: CM or civil-moderate (a moderate-length code) and CL or civil-long (a long code). The CM code consists of 10,230 chips and repeats every 20 milliseconds, giving it a chipping rate of 511.5 kcps. The CL code consists of 767,250 chips and repeats every 1.5 seconds, giving it the same chipping rate as the CM code. Therefore, there are exactly 75 repetitions of the CM code for every cycle of the CL code. The CM and CL codes are combined in a chip-by-chip multiplexer so that the overall chipping rate is the same as for the legacy C/A code, 1.023 Mcps, with the same overall null-to-null bandwidth of 2.046 MHz. The equivalent chip width of about 0.9775 µs is also the same as the C/A code and so code ranging precision is similar. And since it has a similar overall code structure as the C/A code, L2C has similar multipath characteristics. Although not intended for normal operations, it is possible for satellites to alternatively transmit the C/A code on L2 instead of the CM and CL codes.

Unlike the C/A code, the CM and CL codes are not Gold codes. In fact, they possess some superior properties to the C/A codes. The CM and CL codes are perfectly balanced; i.e., they have the same number of ones and zeroes. But more importantly, because they are longer codes, they have better autocorrelation and crosscorrelation properties than the C/A code. The better crosscorrelation performance means that the reception of weak GPS signals is much less affected by simultaneously received strong GPS signals, which can be of significant advantage in difficult signal reception conditions.

Each satellite is assigned a unique pair of CM and CL codes. Thirty-seven pairs of codes were initially defined, 32 of which were reserved for GPS satellites. However, an additional 80 codes have now been defined, 26 of which are reserved for future satellites but not Block IIR-M or IIF satellites (ARINC, 2006).

A navigation message is nominally combined with the CM code whereas the CL code is dataless; i.e. it is not combined with data bits. There is a significant threshold advantage in tracking a dataless signal which means that measurements can be made at lower C/N_0 values than would otherwise be possible. A new navigation message format has been developed for use with the L2C and L5 signals – the Civil Navigation message or CNAV – which will provide more accurate and more frequent message data than the legacy navigation message (NAV). The possible L2C signal combinations that a Block IIR-M satellite can transmit upon command by the GPS control segment are:

(i) L2 CM $\oplus$ D(t) with L2 CL
(ii) L2 CM $\oplus$ D'(t) with L2 CL
(iii) L2 CM $\oplus$ $D_c(t)$ with L2 CL
(iv) L2 CM with L2 CL
(v) C/A $\oplus$ D(t)
(vi) C/A

where:
D(t) = NAV data at 50 bps;
D'(t) = NAV data at 25 bps with forward error correction (FEC);
and
$D_c(t)$ = CNAV data at 25 bps with FEC.

There are no flags or bits in the navigation message to directly indicate which signal option is being broadcast for L2C; this must be determined by the receiver itself. According to Marquis (2007), the Block IIR-M satellites currently in orbit are broadcasting L2C signals with signal option (iv); i.e., in dataless mode with no navigation message data modulated onto the carriers. This mode actually enhances acquisition of the new signals.

The L2C signal is modulated onto the L2 carrier using binary biphase modulation and nominally combined with the legacy L2P(Y) signal in phase quadrature. Although the L2C signal was baselined to be weaker than the L1 C/A-code signal (minimum received power of -160 dBW (or -161.4 dBW according to the spacecraft contractor) compared to -158.5 dBW for the C/A code), its new signal structure more than compensates for this. Furthermore, the use of a new transmitter module and antenna panel on the Block IIR-M satellites has resulted in actual received L2C signal strengths several dBW higher than the baseline minimum performance requirement. We present our own signal strength analyses later in this paper.

The L5 signal (ARINC, 2005) will be transmitted on a new carrier frequency at 1176.45 MHz and, being in a protected spectrum band, is intended for safety-of-life applications, such as aircraft navigation. However, the signal will be of advantage to other users, particularly precise positioning users who will benefit from using the signals on all three GPS frequencies. The L5 signal will be transmitted by Block IIF satellites. However, the new Wide Area Augmentation System satellites (Anik F1R and Galaxy XV) are already transmitting L5 signals and a GPS Block IIR-M satellite to be launched in 2008 has been modified to transmit L5 signals. As this paper is concerned with the analysis of the modernized civil signals currently transmitted by Block IIR-M satellites, the L5 signal will not be discussed further.

The main tool which is used in this work is our precise point positioning (PPP) package, called GAPS (GPS Analysis and Positioning Software). GAPS has been developed at UNB over the past 3 years, and its main advantage is that it is not only a positioning application, but also a data analysis tool. GAPS capabilities have been already discussed by Leandro et al. [2007b], for example, and it has been actually already used for L2C signal bias analysis [Leandro et al., 2007a]. This highlights the fact that our PPP software has been enhanced to handle L2C data, which allows us to make use of it in this particular research.

L2C SIGNAL TRACKING AT UNB

The primary UNB L2C tracking station is called UNB3 and it has been active since the January 2006. Initially, a Trimble R7 receiver was used, but in November 2006 it was replaced by a Trimble NetR5 receiver, both of them loaned by Trimble Navigation Ltd. UNB3 shares the UNBJ IGS station (currently a Javad Legacy receiver) antenna (a Javad RegAnt choke ring) by means of a splitter. This setup is advantageous because it allowed early quality checks, knowing that the two receivers share the same antenna phase center. Data from UNB3, as well as reports on its availability, can be found on the CDDIS ftp server [Noll, 2007].

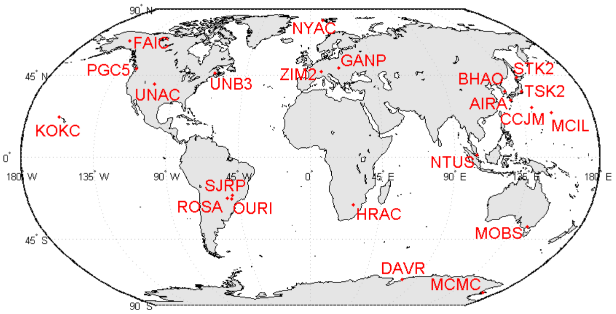

Figure 2. Stations of the L2C Test Network.

As mentioned earlier, UNB3 is also part of the IGS L2C Test Network, which has included as many as 22 stations to date. Figure 2 shows the distribution of the L2C Test Network stations.

UNB3 has been contributing to the research community in many different ways since it became part of the L2C Test Network. Its hourly and daily 30-second observation and navigation RINEX files have been made available on the CDDIS ftp server making it possible for its data to be used all over the world. High-rate (1 Hz) RINEX files of UNB3 data are also available for download from the CDDIS ftp server. Moreover, UNB3 data has also contributed to the generation of IGS products, such as IONEX maps.

One of the advantages of the Trimble NetR5 receiver, besides tracking the modernized L2C signal, is its capability to track GLONASS satellites. These GLONASS observations have been continuously used by Center for Orbit Determination in Europe researchers for GLONASS data analysis.

UNB3 has also been used by UNB to assist BKG (Bundesamt für Kartographie und Geodäsie) in Frankfurt with the improvement of the Networked Transport of RTCM via Internet Protocol (NTrip) for modernized GNSS data. UNB3 real-time data in RTCM 3.0 format is available via IGS Real-time Network, as mountpoint UNB30. BKG creates the UNB3 high-rate RINEX files from this data stream and submits the files to CDDIS.

Research which has been carried out at UNB, to a certain extent, helped the assessment of new versions of Trimble's NetR5 firmware and data conversion utilites.

For the work reported in this paper, we have used data almost exclusively from station UNB3. The main reason for that is the fact that the NetR5 receiver has the advantage of tracking simultaneously L2C and L2P(Y) signals. This characteristic is fundamental for the analysis of the improvements brought by the use of L2C, since the legacy and modernized signals are observed under the exact same conditions. UNB has even made data available containing simultaneous observations of carrier phase, code, and signal-to-noise ratio for the two signals. This was possible by using a specific in-house station setup, plus the capability of creating files in RINEX 3.0 format (in fact UNB3 was, to our knowledge, the first station to have data available in that format) [Langley and Leandro, 2007].

L2C signals are also tracked at UNB by a Topcon NET-G3 and a NovAtel ProPak-V3 (OEMV-3) using the same antenna as UNBJ and UNB3.

HANDLING L2C DATA IN GAPS

As we have mentioned, the off-line version of GAPS is capable of handling L2C data. The acquisition of the data is simple, because the software was made capable of reading files in RINEX 2.11 format [Gurtner and Estey, 2007], with very basic modifications. These modifications include not only reading the file, but making sure it does not neglect the C2 (as L2C code is called in RINEX 2.11 format) observations, and use them only when required/requested.

The main issue in using L2C is the fact that there are biases between the L2C code and the P2 code for both receiver and satellite (P2 is the designation for L2P(Y) code measurements in RINEX nomenclature).

To better understand the impact of such biases, we can take a look at the general ionosphere- (iono-)free pseudorange equation for a Trimble NetR5 receiver (or any other receiver which provides only C1 and P2 observations, such as the NovAtel OEMV-3 receiver), as used in GAPS:

$$\begin{aligned} P_{if(C1,P2)} &= \rho + T + c(dT - dt) \\ &\quad - \alpha \cdot b_{P1-C1} + m_{P_{if(C1,P2)}} + e_{P_{if(C1,P2)}} \end{aligned} , \qquad (1)$$

where ρ is the geometric range, T is the tropospheric propagation delay, dT and dt are the receiver and satellite clock offsets, respectively, $m_{P_{if(C1,P2)}}$ is the iono-free multipath combination, and $e_{P_{if(C1,P2)}}$ is the combined noise and residual error term. The factor α is the coefficient for the L1 measurement in the iono-free combination equation:

$$P_{if(C1,P2)} = \alpha \cdot C1 - \beta \cdot P2 , \qquad (2)$$

and can computed as:

$$\alpha = \frac{f_1^2}{f_1^2 - f_2^2} , \qquad (3)$$

while β can be computed as:

$$\beta = \frac{f_2^2}{f_1^2 - f_2^2} . \qquad (4)$$

The satellite code bias parameter (b_{P1-C1}) is needed because GAPS makes use of IGS clock products, and those products are based on P1 code, rather than C1. It is not necessary to account for the receiver-dependent bias, because it is actually absorbed by the receiver clock parameter, under the assumption that this bias is common for all receiver channels. Another condition for the receiver-dependent bias to be absorbed by the clock parameter is that the same code types (in this case, C1 and P2) are being observed for all satellites.

Similarly to (1), we can derive the equation for the iono-free pseudorange created using C1 and C2:

$$\begin{aligned} P_{if(C1,C2)} = {} & \rho + T + c(dT - dt) \\ & - \alpha \cdot b_{P1-C1} + \beta \cdot B_{P2-C2} \\ & - \beta \cdot b_{P2-C2} + m_{P_{if(C1,C2)}} + e_{P_{if(C1,C2)}} \end{aligned} , \qquad (5)$$

which is very similar to (1), with the addition of the two C2 bias terms, one for the receiver (B_{P2-C2}) and the other for the satellite (b_{P2-C2}). The satellite biases are needed because, as with the situation involving P1 and C1, IGS clock products are based on P2 measurements. Regarding the receiver, one should consider that there are only five satellites currently broadcasting L2C, and those might not even be visible simultaneously. Having said that, we should consider that the receiver clock is based on P2 measurements. However this assumption is not entirely true, unless we actually force the receiver clock to be based on P2, otherwise, it will be based on a P2 and C2 combination, depending on the weight each observation type/satellite pair has for a given epoch of observations. This requirement (forcing the receiver clock to be based on P2) is met in GAPS by means of a stochastic modeling.

GAPS uses an elevation angle dependent weighting scheme, where the *a priori* variance of the pseudorange is given by:

$$\sigma_p^{\ 2} = \frac{\sigma_{p,0}^{\ 2}}{\sin^2(e)}, \qquad (6)$$

where $\sigma_{p,0}$ is the zenith pseudorange standard deviation, and e is the satellite elevation angle. In case a pseudorange which uses a combination with C2 is used, the weighting is switched to:

$$\sigma_{p,C2}^{\ 2} = \frac{\sigma_{p,0}^{\ 2}}{\sin^2(e)} + \sigma_{P2C2}^{\ 2}, \qquad (7)$$

where the term σ_{P2C2} is used to account for the fact that the receiver and satellite biases are unknown, and thus these code measurements have nearly no impact on the receiver clock reference. This is done for code measurements only, and the carrier-phase measurements receive weights based on the same scheme regardless of the type of code that was used to generate them. This is possible because in GAPS carrier-phase measurements have a float ambiguity term to be solved, which inevitably includes all bias-like terms. Assuming (7) is used to weight C2-based measurements, we can rewrite (5) as:

$$\begin{aligned} P_{if(C1,C2)} = {} & \rho + T + c(dT - dt) \\ & - \alpha \cdot b_{P1-C1} + m_{P_{if(C1,C2)}} + \tilde{e}_{P_{if(C1,C2)}} \end{aligned} , \qquad (8)$$

where we have now modified the noise and other errors term, which will now also incorporate the un-modeled biases. The major part of this term (noise and other errors) is represented by the residuals of the PPP adjustment, once the solution has converged to a certain level. Figure 2 shows an example of $P_{if(C1,C2)}$ code residuals for IIR-M satellites, as used with the procedure above in GAPS for UNB3 data, DOY 358 of 2007.

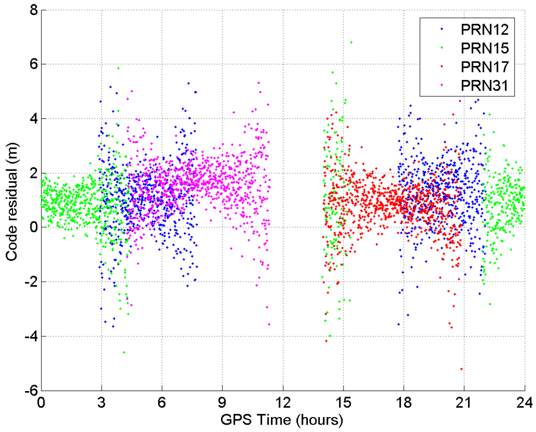

Figure 3. Block IIR-M satellites $P_{if(C1,C2)}$ code residuals from GAPS

It is possible to notice in Figure 3 that the residuals time series for each satellite is not zero-mean, due to the presence of un-modeled code biases. The drawback of de-weighting code measurements is that these observations do not contribute with the same strength as others (non IIR-M satellites) for the solution. It is important to remember that IIR-M carrier-phase measurements receive the same treatment as for other blocks of satellites, and thus GAPS takes full advantage of them.

ANALYSIS OF L2C CODE MEASUREMENTS

In this section we investigate the quality of the L2C code measurements. We have previously made preliminary analyses [e.g., Sükeová et al. 2007]. Our previous work has been mainly based on signal-to-noise ratio and noise level analysis. In the present paper, we are looking into lower frequency components of the code error. Again, we are using GAPS to do so. As mentioned earlier, GAPS residuals r provide a measure of the code un-modeled errors, which is true for P2 or C2 measurements, where:

$$r_{if(C1,P2)} = m_{P_{if(C1,P2)}} + e_{P_{if(C1,P2)}} , \tag{9}$$

and:

$$r_{if(C1,C2)} = m_{P_{if(C1,C2)}} + \tilde{e}_{P_{if(C1,C2)}} . \tag{10}$$

Equation 10 can be also written as:

$$\begin{aligned} r_{if(C1,C2)} = {} & \beta \cdot B_{P2-C2} - \beta \cdot b_{P2-C2} \\ & + m_{P_{if(C1,C2)}} + e_{P_{if(C1,C2)}} \end{aligned} , \tag{11}$$

The information in which we are interested in the equations above is the combination of multipath (m) and other errors (e) terms, mainly for low elevation angle satellites, where these terms are more strongly present. Figure 4 shows an example of P1/P2 iono-free code multipath plus noise (M+N) level for IGS station UNBJ (a Javad Legacy receiver which shares its antenna with UNB3) for different elevation angles and azimuths, where it can be clearly noticed that greater M+N levels are obtained at lower elevation angles, as expected. These values were derived from GAPS.

One effect which might be an object of concern for the un-modeled errors term is the residual neutral atmosphere. It is important to have in mind that we have simultaneous measurements of (9) and (11), thus these observations are subjected to the exact same conditions. Since we know that for high elevation angles there is very low impact of multipath and residual atmosphere, we can use (9) and (11) from observations above a certain elevation angle threshold (in this work we have neglected the first and last 10 minutes of data in each satellite pass – this time interval was determined empirically for this particular data set) to derive an estimate of the receiver-satellite bias combination of (11), according to:

$$\beta \cdot B_{P2-C2} - \beta \cdot b_{P2-C2} = r_{if(C1,C2)} - r_{if(C1,P2)} . \tag{12}$$

Alternatively, this derivation can be carried out with the raw measurements, as:

$$\beta \cdot B_{P2-C2} - \beta \cdot b_{P2-C2} = P_{if(C1,C2)} - P_{if(C1,P2)} , \tag{13}$$

since other effects are common for both measurement types. Figure 5 shows the values for $r_{if(C1,C2)}$ and $r_{if(C1,P2)}$ for PRN 17(Station UNB3, DOY 358 of 2007).

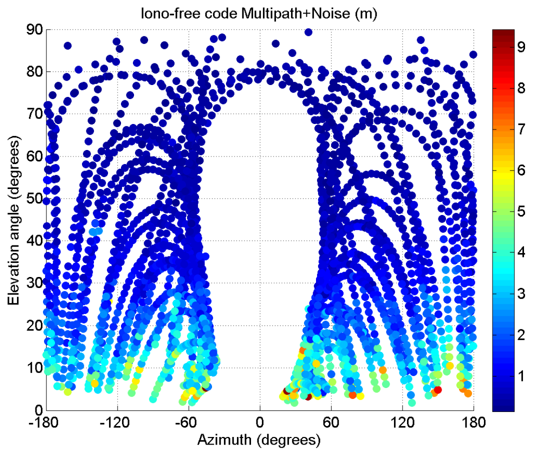

Figure 4. Code noise level for station UNBJ (DOY 340 of 2007)

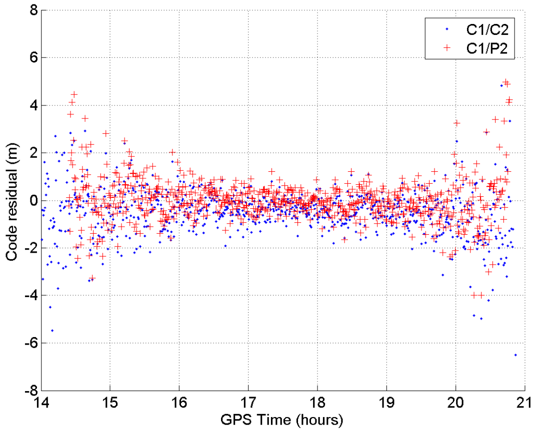

Figure 5. Code residuals for C2- and P2-based iono-free code observations.

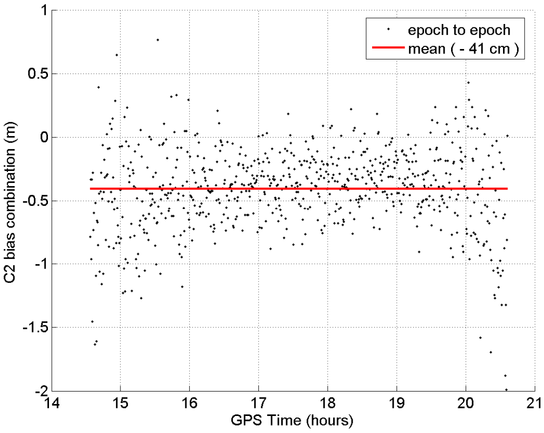

Figure 6. Receiver-satellite C2-P2 bias combination derivation.

Figure 6 shows the values computed for the bias combination, epoch by epoch (black) and the mean value computed for it (same data as Figure 5), which is around -41 cm for PRN 17.

After the receiver-satellite bias combination is accounted for, it is possible to build a measurement of the difference in terms of un-modeled errors (which would be very similar to Figure 6, but shifted to have a zero-mean), according to:

$$r_{if(C1,C2)} - r_{if(C1,P2)} - \beta \cdot B_{P2-C2} + \beta \cdot b_{P2-C2} = \\ + m_{P_{if(C1,C2)}} + e_{P_{if(C1,C2)}} - m_{P_{if(C1,P2)}} - e_{P_{if(C1,P2)}} . \qquad (14)$$

Similarly, this comparison can be also made by means of the raw measurements. However there is a major advantage in using GAPS residuals rather than raw measurements. This is due to the fact that besides providing the magnitude of differences, the residuals also allow us to determine which of the two code types is providing better results, since better measurements should provide smaller residuals. Other information, which can be derived only from residuals, is the relative order of magnitude of the differences, with respect to the residuals themselves, which tells us whether the differences are actually negligible with respect to the residuals or not.

Figure 7 shows the two types (C2- and P2-based) of iono-free code residuals for station UNB3, DOY 358 of 2007, with respect to elevation angle for Block IIR-M satellites.

From the plot below, it is possible to see that, down to elevation angles of around 10 degrees, there is a very small difference between the spread of the residuals obtained using C2 or P2 codes. This means that, above 10 degrees, elevation angle both code types should provide results with a similar quality level. When we look at residuals at 10 degrees and below, it is clear that there are many more C2-based samples than P2-based samples. This is because L2C code typically can be tracked to lower elevation angles than L2P(Y) code. Besides that, the few samples of P2-based residuals below 10 degrees seem to have a somewhat worse quality than C2-based ones. This can be more clearly seen in Figure 8, which shows the rms of the residuals of Figure 7 for each elevation angle bin (for every 10 degrees).

In Figure 8, it can be noticed that down to the 20-30 degrees bin there is virtually no difference between C1/P2 and C1/C2 residuals rms. There is a small difference for bin 10-20, of around 25 cm, and a big difference (about 1.5 m) in the rms for the 0-10 degrees bin.

The shown plots lead us to the conclusion that for elevation angles above 10 degrees, the use of L2C does not bring any big advantage over the use of L2P(Y) code in terms of M+N level. It should be noted that this conclusion is valid only for situations when a reasonably clear sky is available. Surveys made in high multipath environments (such as under tree canopies or in urban areas) where there are potentially many losses of lock, might lead to different conclusions. Nevertheless, for lower elevation angles there is a sensible difference in M+N level, as well as a larger number observations realized when L2C is used.

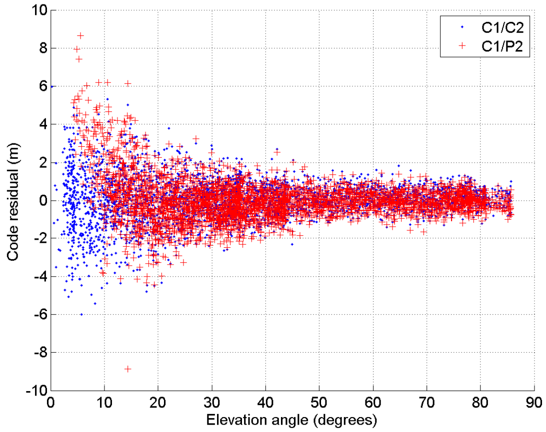

Figure 7. C2- and P2-based iono-free pseudorange residuals.

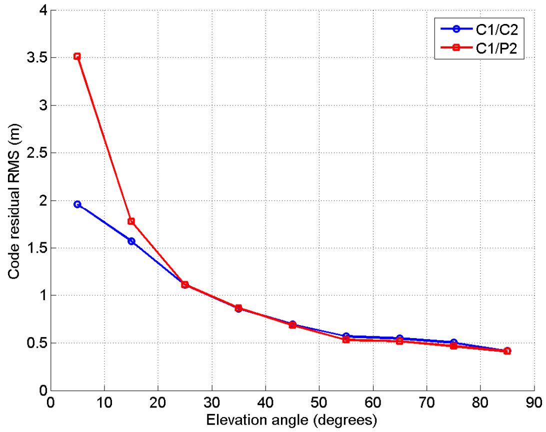

Figure 8. Rms of Figure 6 residuals for different elevation angle bins.

QUALITY OF ADDITIONAL MEASUREMENTS

In this section, we explore the fact that the L2C signal is more easily tracked than L2P(Y) signal. This difference is caused by a mixture of signal strengths and signal correlation techniques. L2C is a civil signal, and therefore its codes are known, which makes it possible to track it by means of direct correlation, rather than semi-codeless techniques which have to be used for P(Y) tracking in civil receivers. The outcome of this is that L2C observables are tracked to lower elevation angles, mainly when the satellite is rising, with earlier signal acquisition for a given receiver-antenna setup (as can be seen in

Figure 6). In this section we analyze the additional measurements provided by L2C tracking with respect to L2P(Y) measurements. The analysis consists of investigating the noise level of these measurements, as well as systematic effects present in them, such as residual atmosphere. The main objective of the analysis is to decide if these additional measurements can be effectively used, or if there are other limiting factors which should be taken into account.

As an illustration of the additional C2 measurements which are made with respect to P2 measurements, Figure 9 shows, for the same satellite at the same time, a comparison between C/N_0 based on P(Y) tracking and that based on L2C tracking by UNB3 on DOY 224, 2007, for PRN 12 (upper panel), where it can be seen that the signal-to-noise ratios are clearly higher for L2C tracking. In the same figure, in the bottom panel, the C/N_0 values only for the additional L2C measurements are shown. We must mention here, that the power of the signal feeding the UNB3 receiver might be slightly low due to its use with the Javad RegAnt antenna without the use of an additional preamplifier. Nevertheless, we can infer that for a given receiver-antenna setup, L2C signals may be tracked at lower elevation angles than L2P(Y). We examined this behavior in detail.

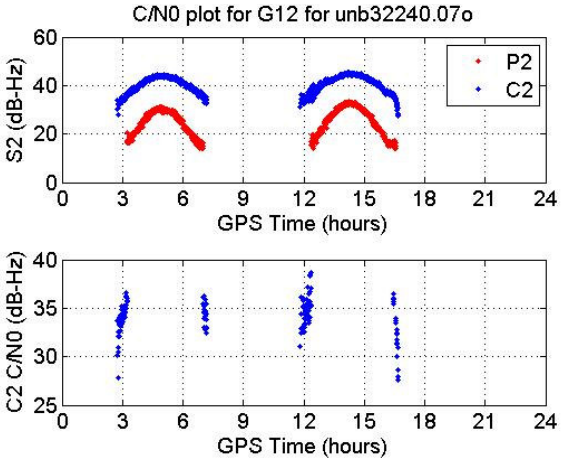

Figure 9. UNB3 C/N_0 values for PRN 12, for L2C and P2(Y) tracking for DOY 224 of 2007.

Figure 10 shows the elevation angle of L2C-based and P(Y)-based observations for PRN 12 (UNB3, DOY 358 of 2007). In the plot we can notice that in terms of elevation angle the L2C tracking starts reasonably earlier than L2P(Y) tracking. In Figure 11, it is possible to see that this is a common effect for all IIR-M satellites. We should point out that the UNB3/UNBJ antenna has a clear view to close to a zero-degree-elevation-angle horizon except towards the south and west where it is several degrees by virtue of the hillside setting of the UNB Fredericton campus. Also, in these plots only epochs with simultaneous measurements on both L1 and L2 frequencies are considered.

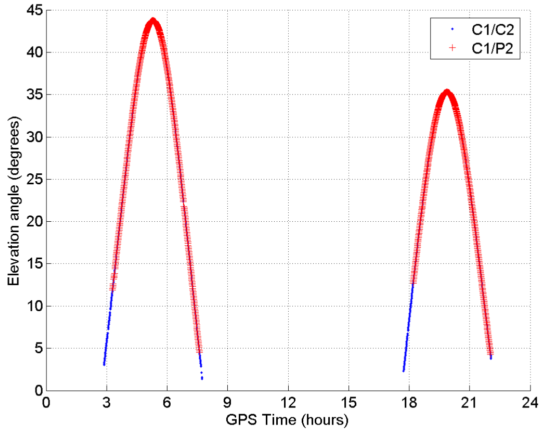

Figure 10. Elevation angle for PRN 12's L2C-based and L2P(Y)-based observations.

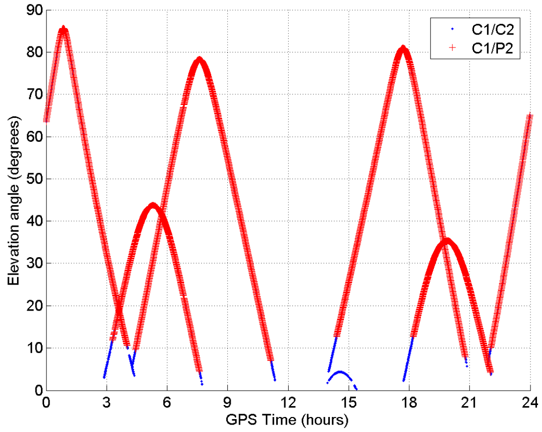

Figure 11. Elevation angle for IIR-M satellites' L2C-based and L2P(Y)-based observations (UNB3, DOY 358 of 2007).

As mentioned earlier, there is an obvious question which should arise from this analysis, related to the quality of these additional measurements. Are they really bringing useful information inside the GNSS engine which processes this data? Looking at Figures 7 and 8, it is possible to notice that the additional code measurements have a noise level which is quite reasonable for such low elevation angles. However, we should note that the noise of the code measurements will hide some effects which will have a clear impact on more precise measurements, in particular, carrier-phase measurements.

Similarly to Figure 7, but now using carrier-phase measurements (from the same data set), Figure 12 shows the two types (L2C- and L2P(Y)-based) of iono-free carrier-phase residuals, with respect to elevation angle for Block IIR-M satellites.

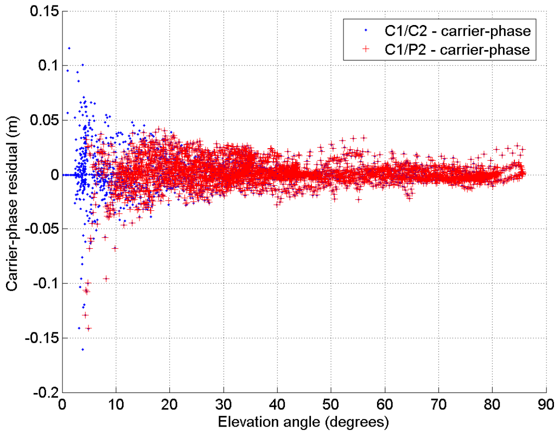

Figure 12. L2C- and L2P(Y)-based iono-free carrier-phase residuals.

In the plot, we can see that L2C-based and L2P(Y)-based phase residuals follow pretty much the same pattern down to about 5 degrees, even though there are fewer L2P(Y)–based observations between 5 and 10 degrees, and almost none below 5 degrees. The zero values that can be seen in the plot correspond to the first measurements of the current satellite arc, when the ambiguity parameter has yet to be resolved and absorbs all of the random error. Figure 13 shows the rms values for each elevation angle bin.

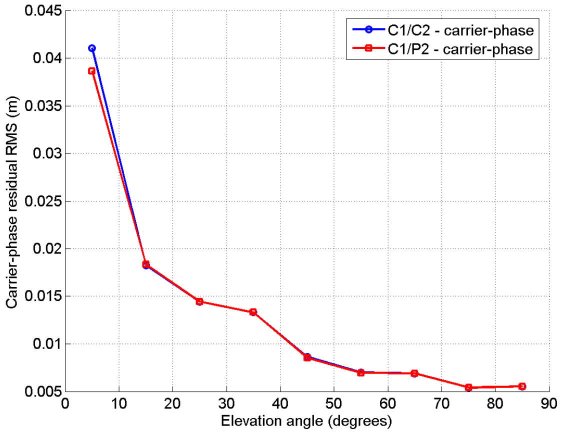

Figure 13. Carrier-phase residual rms of Figure 12for different elevation angle bins.

According to the plot, it looks like as long as the signal is being tracked, there is no significant difference in terms of quality for the carrier-phase measurements between the different code types being used. It seems that the major difference regarding the carrier-phase measurements is the additional observations which are made available thanks to the earlier/later signal tracking with L2C codes.

IMPACT OF L2C ON POSITIONING

In this section we analyze the impact of using L2C-derived measurements (i.e., code and phase) on PPP.

As previously shown, the major difference between L2C and L2P(Y) tracking has been the additional measurements that can be made, since the noise level (as evidenced by analysis residuals) is relatively comparable. Taking this into account, before starting to analyze results in position space, it is interesting to analyze the contribution of these additional observations in observation space. Here we have studied the impact the extra observations have in terms of their weight in the overall satellite pass. For this, we will consider a weighting scheme where the weight is inversely proportional to a reference variance and directly proportional to the square of the sine of the elevation angle, thus:

$$W \propto \frac{(\sin el)^2}{\sigma^2} . \tag{15}$$

If the reference variance is chosen so that a weight equal to one corresponds to the weight of an observation made at the zenith, (15) can be simplified to:

$$W = (\sin el)^2 . \tag{16}$$

The data used in this analysis (UNB3, DOY 358 of 2007) was observed at 0.5 Hz, and no correlation between observations was considered. Figure 14 shows the accumulated weights for each of the IIR-M satellite passes, which are the same as the ones shown in Figure 10.

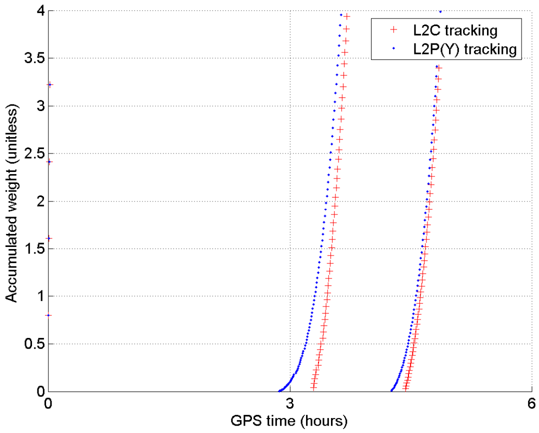

Figure 14. Accumulated weight for each IIR-M satellite pass (UNB3, DOY 358 of 2007).

As can be seen in Figure 14, within the plot scale, it is very hard to see any difference between L2C-based and

L2P(Y)-based accumulated weights. In Figure 15, we have zoomed in for the period between 2 and 6 hours.

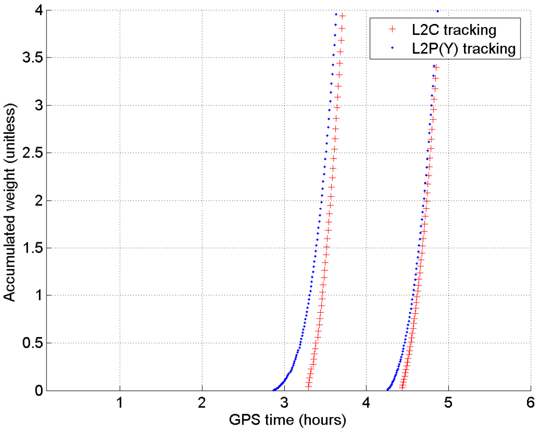

Figure 15. Accumulated weight for each IIR-M satellite pass (UNB3, DOY 358 of 2007) – zoomed view.

In this figure, it is easy to notice that L2C-based observations, as expected, start to accumulate weight earlier than L2P(Y)-based observations. Although it cannot be clearly seen in this plot, once L2P(Y)-based measurements start to be made, the difference in accumulated weight is constant over time, since the elevation angles are the same for both observation types. This can be seen more clearly in Figure 15, where the differences between accumulated weights are shown for each satellite.

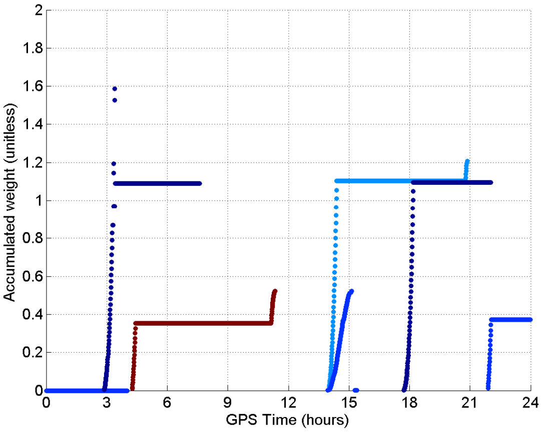

Figure 16. Differences between accumulated weights for L2C and L2P(Y) tracking (UNB3, DOY 358 of 2007).

As can be seen in the figure, the difference in the accumulated weight for this geometry reaches its maximum at near 1 weight unit. If we look back at Figure 13, we can see that this difference (1 unit) usually becomes a negligible amount of contribution after some time, which might take several minutes. Nevertheless, at this point the impact of the additional observations provided by L2C tracking on the overall solution looks to be minimal. We'll comment further on the usefulness of additional observations provided by L2C tracking following an analysis of the actual impact of the observations on our current test scenario in position space.

It is important to remember that, even though this is a very interesting analysis, it is based on only four satellites, and the results (and conclusions) we have gotten here in terms of performance might change as more modernized satellites are launched. Nevertheless, it provides an early estimate of what to expect from a full modernized constellation under a more-or-less ideal observing scenario. Figure 17 shows the convergence of coordinates for a 24-hour GAPS-PPP solution (for UNB3, DOY 358 of 2007) for the two tracking techniques. This was a static run, where the antenna is supposed to be static, i.e., one single set of coordinates is computed for the whole 24 hours period but interim updated solutions are provided at each data epoch. The plot actually shows the difference between GAPS' solution and the IGS SINEX solution for the same week of the observations (considered as "truth" here) in the horizontal plane. As can be seen, the two solutions are very close to each other, reaching an error of less than 5 mm at the end of the day, with a negligible difference between them.

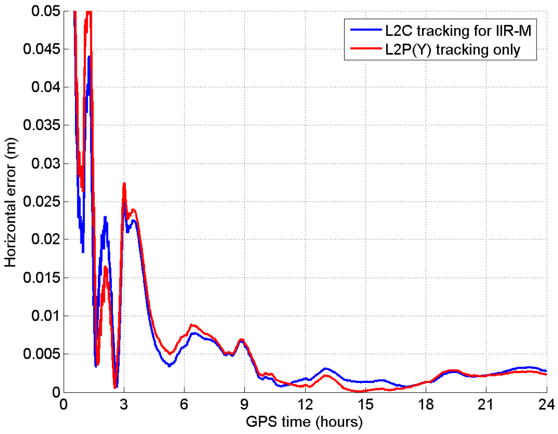

Figure 17. PPP convergence of coordinates in static mode (UNB3, DOY 358 of 2007).

The two solutions are overall very similar when looking at the whole 24-hour period, it being hard to distinguish any significant performance difference. Similar behavior can be seen for the height component (Figure 18).

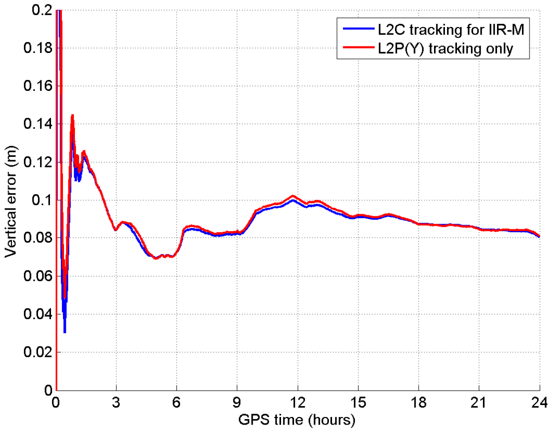

Figure 18. PPP height convergence in static mode UNB3, DOY 358 of 2007).

In the next two figures (Figures 19 and 20), we show the PPP performance in kinematic mode (the station is supposed to be moving, so a new set of independent coordinates is computed at every data epoch), for horizontal and vertical directions, respectively.

As before, it is very hard to point to any significant difference in performance for the "kinematic" run, for either the horizontal or vertical components.

In terms of overall statistics, there is very little difference between the two tracking techniques, even though the results obtained with L2C tracking seem to be consistently very slightly better, as can be seen in Table 2.

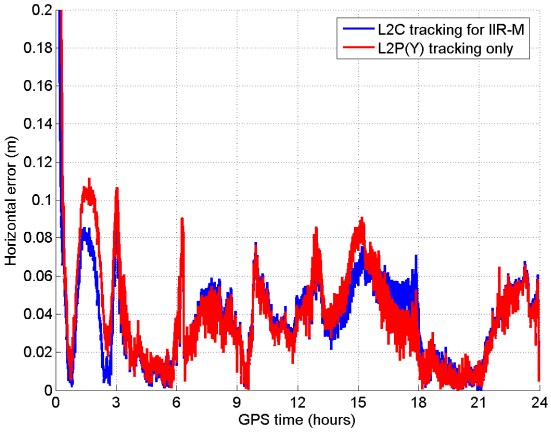

Figure 19. PPP horizontal error in kinematic mode (UNB3, DOY 358 of 2007).

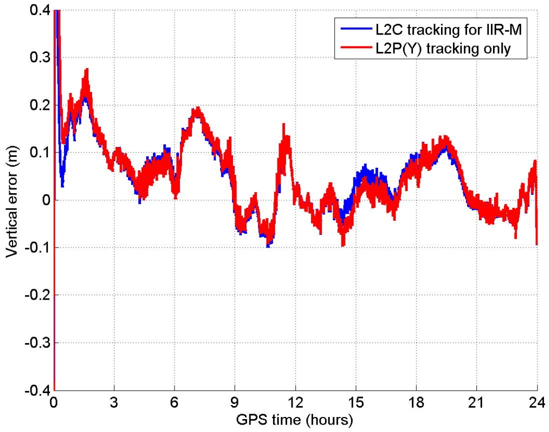

Figure 20. PPP vertical error in kinematic mode (UNB3, DOY 358 of 2007).

Table 2. Statistics for the "kinematic" run. All values in cm.

	Horizontal		Vertical	
	RMS	Max. error	RMS	Max. error
L2C	4.1	9.5	7.3	19.5
L2P(Y)	4.2	10.7	7.3	19.7

CONCLUSIONS AND FUTURE WORK

In the analysis of the L2C-based code measurements, we found that the noise level is similar to code measurements from L2P(Y), down to at least 10 degrees. For station UNB3, with observations below 10 degrees, there are several additional measurements when using L2C tracking as opposed to L2P(Y) tracking. The noise level of these additional measurements follows the same pattern as the others, with an increasing noise level as the elevation angle decreases. We have seen that the main difference between L2C- and L2P(Y)-based observation has not been the noise level, but the amount of additional data which can be collected when using L2C, when tracking becomes difficult using L2P(Y).

When looking into the positioning scenario, we have demonstrated that in case of UNB3, the additional L2C-based measurements don't bring much weight for the solution, accounting for the number of additional measurements and their respective elevation angles (in this case, using an elevation-angle-dependent stochastic model). From that, we take that for an open sky and low to moderate multipath environment, L2C does not bring any significant improvement for positioning solutions. As mentioned before, it should be pointed out that we are looking at a benign observing scenario and that under more difficult reception conditions, the additional observations provided by L2C tracking might be critical for successful dual-frequency positioning

Although we could identify only a minor improvement in the position solution, it is quite clear that L2C has an improvement in tracking robustness over L2P(Y), which might be a crucial characteristic for a different environment. Our future work will be based on data collected in challenging environments, so the improvement brought from the L2C tracking robustness can be more adequately assessed.

ACKNOWLEDGMENTS

The research reported in this paper has been developed under the auspices of the GEOIDE Network of Centres of Excellence project "Next-generation Algorithms for Navigation, Geodesy and Earth Sciences Under Modernized Global Navigation Satellite Systems (GNSS)". Support also provided by the Natural Sciences and Engineering Research Council of Canada.

We would like to acknowledge Carey Noll from the Crustal Dynamics Data Information System for her great efforts in managing the L2C Test Network, as well as for her help in assuring the completeness of UNB3 stored data.

REFERENCES

ARINC, 2005. "Navstar GPS Space Segment / User Segment L5 Interfaces", IS-GPS-705. ARINC Engineering Services, LLC, El Segundo, CA, September.

ARINC, 2006. "Navstar GPS Space Segment/Navigation User Interfaces", IS-GPS-200D. ARINC Engineering Services, LLC, El Segundo, CA, March.

Gurtner W. and L. Estey, 2007. "RINEX: The Receiver Independent Exchange Format Version 2.11". Document available at http://www.aiub-download.unibe.ch/rinex/rinex211.txt.

Langley, R.B. and R.F. Leandro, 2007. "[IGSMAIL-5632]: RINEX 3.00 Initiative." Message sent to IGSMAIL e-mail list on 20 August of 2007. Available at http://igscb.jpl.nasa.gov/mail/igsmail/2007/msg00112.html.

Leandro, R.F., R.B. Langley, and M.C. Santos, 2007. "Estimation of P2-C2 biases by means of Precise Point Positioning." *Proceedings of ION 63rd Annual Meeting*, Cambridge, Massachusetts, 23-25 April 2007, pp. 225-231.

Leandro, R.F., M.C. Santos, and R.B. Langley, 2007. "GAPS: The GPS Analysis and Positioning Software – A Brief Overview." *Proceedings of ION GNSS 2007*, the 20th International Technical Meeting of the Satellite Division of The Institute of Navigation, Fort Worth, TX, 25-28 September 2007, pp. 1807-1811.

Marquis, W., 2007. "Working Without a Net – Operating the Modernized GPS Block IIR space Vehicles Prior to OCX." *Proceedings of ION GNSS 2007*, the 20th International Technical Meeting of the Satellite Division of The Institute of Navigation, Fort Worth, TX, 25-28 September 2007, pp. 2466-2477.

Noll, C., 2007. "[IGSMAIL-5644]: More on RINEX V2.11 and L2C data archiving at CDDIS." Message sent to IGSMAIL e-mail list on 21 September 2007. Available at http://igscb.jpl.nasa.gov/mail/igsmail/2007/msg00124.html.

Sükeová, L., M.C. Santos, R.B. Langley, R.F. Leandro, O. Nnani, and F.G. Nievinski, 2007. "GPS L2C Signal Quality Analysis." *Proceedings of ION 63rd Annual Meeting*, Cambridge, Massachusetts, 23-25 April 2007, pp. 232-241.