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Cross-correlation Performance Comparison of L1 & L2C GPS Codes for Weak Signal Acquisition

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BIOGRAPHY

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Andrew G. Dempster is the Director of Research in the School of Surveying & Spatial Information Systems at UNSW. He led the team that developed Australia's first GPS receiver in the late 1980s and has been involved with satellite navigation ever since. His current research interests are GNSS receiver design, GNSS signal processing, and new location technologies.

ABSTRACT

The GPS constellation now contains six fully-operational Block IIR-M satellites. Each of these modernized satellites transmits the second GPS civil signal L2C. One of the key objectives of the L2C signal is to offer high cross-correlation protection, allowing weak signal acquisition in the presence of strong GPS signals in environments such as inside buildings and in urban canyons. The L2C signal achieves this by using longer spreading codes.

The L2C signal is composed of CM and CL codes multiplexed together on a chip-by-chip basis. The CM code is 20 milliseconds long while the CL code has a length of 1.5 seconds. The worst-case cross-correlation performance of CM and CL codes is about 27 dB and 45 dB respectively while that of C/A code is about 21 dB. While these figures immediately suggest L2C as the preferred choice for weak signal acquisition, they are based on the fundamental code period (e.g. 1 millisecond for the C/A code). However, the cross-correlation noise in a GPS receiver also depends on the size of signal observation interval. Hence, for cross-correlation performance comparison, the signals must be observed over the same duration. This leads to an interesting situation, where the cross-correlation characteristics of signals are significantly affected by the relative Doppler offset (between the local and incoming satellite signals).

This paper presents a detailed comparison of the cross-correlation performance of L1 and L2C signals under diverse conditions. The paper reveals that a GPS receiver observing the L2C signal is likely to suffer significantly more cross-correlation noise (hence requiring more acquisition effort) than when observing the L1 signal over the same duration. It is concluded that while the new modernized GPS civil signal L2C is specifically designed to replace the L1 signal, in weak signal environments in fact the L1 signal could be the preferred option for signal acquisition in such environments.

INTRODUCTION

L2C is the second GPS civil signal, now available on all of the six operational Block IIR-M satellites. The structure of the L2C signal was designed to meet the needs of positioning in weak signal environments such as inside buildings, in urban canyons and along tree-lined roads. In a weak signal environment, strong GPS signals coexist with weaker ones and high cross-correlation protection is therefore required for weak signal acquisition. The cross-correlation protection (or performance) of the L1-C/A code is about 21 dB, considered to be insufficient for weak signal acquisition [1] [2]. This cross-correlation margin means that a cross-correlation noise value will exceed the auto-correlation peak 'only' when it is more than 21 dB stronger than the desired weak signal. The L2C signal has used longer spreading codes to offer larger cross-correlation margins. The L2C signal is composed of CM (20ms) and CL (1.5s) codes having a cross-correlation performance of approximately 27 dB and 45 dB respectively [2] [3]. Use of longer codes in L2C signal, however, requires increased observation intervals in the GPS receiver. On the other hand, if the L1-C/A signal is observed over longer intervals, the C/A code starts recurring and the cross-correlation noise is averaged out by the offset-carrier (between the local and incoming satellite signals). Consequently, if the two signals (L1 & L2C) are observed over equal intervals, the L1 signal offers superior cross-correlation performance and therefore requires less acquisition effort than the L2C signal. It is shown that in fact the L1-C/A signal can be the preferred choice for satellite acquisition in GPS receivers working in weak signal environments.

This paper is organized as follows. The cross-correlation assessment of C/A and L2C codes is described in the beginning. Cross-correlation performance comparison of the two signals, as observed in the GPS receiver, is then discussed in detail. The two signals are then evaluated in the weak signal environment. Finally, some concluding remarks are given.

THE L2C SIGNAL STRUCTURE

The L2C signal is composed of two codes, L2 CM and L2 CL. The L2 CM-code is 20 milliseconds long and has 10230 chips while the L2 CL-code is 1.5 seconds long and has 767250 chips. The CM-code is modulo-2 added to data (i.e. it modulates the data) and the resultant sequence of chips is time-multiplexed with the CL-code on a chip-by-chip basis. This multiplexed sequence modulates the L2 (1227.6 M Hz.) carrier [4]. With the L2C signal structure, three basic options can be used as local replica code. As shown in Figure 1, the three options differ on choice of alternate chips.

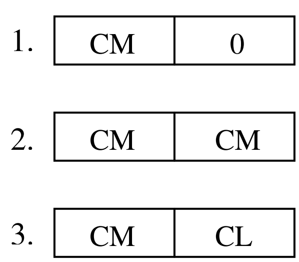


Figure 1. Choices of local replica code for observing the L2C signal (only two chips are shown)

The first option replaces CL chips in the L2C code with zeros and consequently the local code alternates between CM chips and zeros (also known as return-to-zero CM code). In the second option, a CM chip is extended to the duration of two chips to make it a non-return-to-zero CM code. The third option however retains original CL chips in place, as in the L2C code sequence [2] [5].

CROSS-CORRELATION PERFORMANCE EVALUATION

The cross-correlation protection or performance of a code-group is determined by the margin between its auto-correlation peak and the cross-correlation noise. The cross-correlation performance of L1 and L2C codes is shown in Figure 2. Each of the performance curves in Figure 2 represents the result of cross-correlation between corresponding 'raw' codes of PRN-1 & PRN-28. The horizontal axis of the figure represents the cross-correlation power with reference to the auto-correlation peak (i.e. 0 dB), while the vertical axis gives the cumulative probability distribution of the cross-correlation result. Consequently, as a performance curve moves towards the left, it indicates an improvement in the cross-correlation performance. In particular, we are interested in the top of this curve, where cross-correlations "start" to be a problem. This method of evaluating the cross-correlation performance is also used for the L1 signal in [6]. The term 'raw' code or 'code' refers to code sequences as they appear at the output of the corresponding code generator with 0s replaced by -1s and considering zero relative Doppler offset.

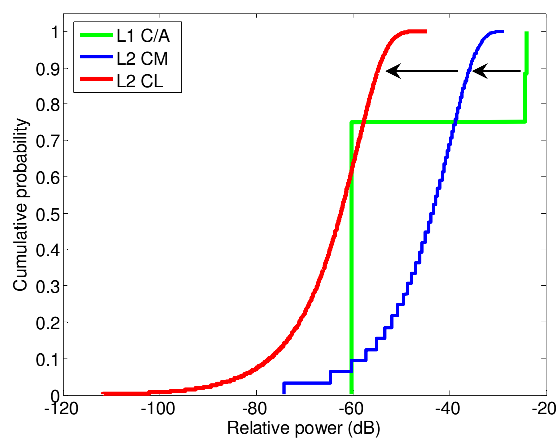


Figure 2. Cross-correlation performance of L1 & L2C raw-codes

It can be observed from Figure 2 that L2 CL code has the best cross-correlation performance followed by L2 CM and L1-C/A codes respectively. This relative improvement in the cross-correlation performance has been used to promote L2C as being a good weak signal [2] [3]. In fact this performance variation among different codes is due to their different lengths (code periods).

Figure 3 compares the cross-correlation performance of L2C replica raw code choices, discussed above. For each case in Figure 3, the L2C code (PRN-1) is observed over 20 milliseconds with the corresponding local code (PRN-28) and the resulting cross-correlation noise is plotted. As shown in the figure, the actual L2C code (choice 3 in Figure 1) sequence has the best performance, followed by the return-to-zero (RZ) CM code and non-return-to-zero (NRZ) CM code respectively, with a 3 dB relative difference in each case. The RZ CM code is preferred for acquiring the L2C signal as it allows signal searches across 20 milliseconds and it removes half (3 dB) of the cross-correlation noise between CM and CL chips [7].

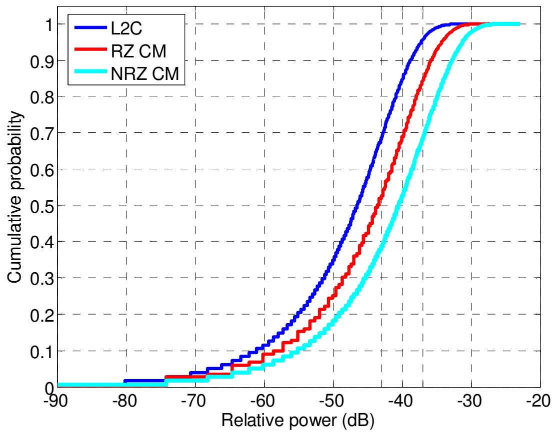


Figure 3. Cross-correlation performance of L2C local code choices, over the observation interval of 20-ms

For all experiments conducted in this research, RZ CM code is used for observing the L2C signal without the data modulation. Direct use of L2 CL code for acquisition, on the other hand, requires 1.5 seconds for each code phase search and is therefore not recommended.

CROSS-CORRELATION PERFORMANCE OF L1 & L2C SIGNALS IN THE GPS RECEIVER

In the GPS receiver, when a signal is observed for acquisition, the cross-correlation noise appears at the output of 'correlator' and it is given by:

$$\chi(\tau,\Delta\omega,T_c)=\left|\begin{array}{l}\int_0^{T_c}\sqrt{2}Ac_1(t)\cos(\omega_1 t)\left[\sqrt{2}\cos(\omega_2 t)c_2(t-\tau)\right]dt+\\ \int_0^{T_c}\sqrt{2}Ac_1(t)\cos(\omega_1 t)\left[\sqrt{2}\sin(\omega_2 t)c_2(t-\tau)\right]dt\end{array}\right| \quad (1)$$

Considering the double-frequency term in (1), filtered out by the integration process, the effective cross-correlation noise can be expressed as:

$$\chi(\tau,\Delta\omega,T_c)=\left|\begin{array}{l}\int_0^{T_c}Ac_1(t)c_2(t-\tau)\cos(\Delta\omega)tdt+\\ \int_0^{T_c}Ac_1(t)c_2(t-\tau)\sin(\Delta\omega)tdt\end{array}\right| \quad (2)$$

Where τ is the local code offset, T_c is the size of observation interval, $\Delta\omega=\omega_1-\omega_2$ is the carrier offset between the incoming and local signals, while $c_1(t)$ and $c_2(t)$ are the respective code sequences. And 'A' represents the incoming signal amplitude. Equation (2) indicates that the cross-correlation noise in a GPS receiver depends on the carrier offset $\Delta\omega$ and the size of the observation interval T_c.

The Relative Doppler Offset

In a GPS receiver, while the local carrier is adjusted to match with a desired signal, it causes an offset with signals of all other visible satellites. Consequently the cross-correlation between local and incoming signals is always associated with a carrier offset (or the relative Doppler offset). We observed the L1 and L2C signals over a wide range of relative Doppler offsets. For each relative Doppler offset, all code phases were trialed and the highest cross-correlation peak was recorded. Table 1 indicates the parameters used in the observations.

Table 1. Parameters used for L1 & L2C signal observations

Signal	Incoming PRN	Local PRN	IF (MHz)	Fs (MHz)	Δf (KHz)
L1	1	28	1.405	5.115	-5→5
L2C	1	28	1.405	5.115	-5→5

When L1 and L2C signals are observed over C/A and L2 CM code periods respectively, L2C performs better than L1 over the entire range of relative Doppler offsets used for signal observation, as shown in Figure 4.

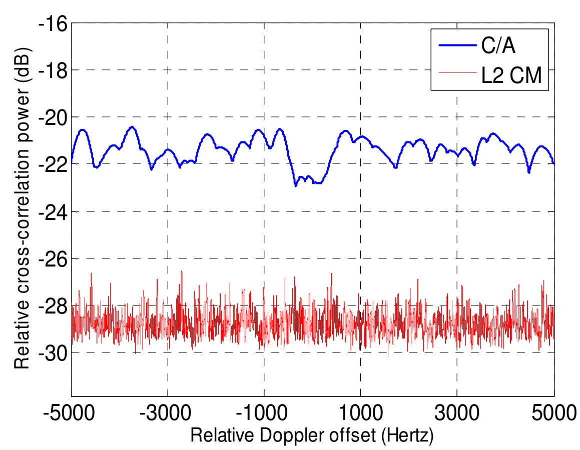


Figure 4. Highest cross-correlation noise observed in L1 & L2C signals, as a function of relative Doppler offset

In this case, L2C takes advantage of being observed over 20 times longer interval than the L1 signal. This, however, requires much greater acquisition effort for the L2C signal than that for L1. However, for a fair comparison, the two signals should be observed over the same duration. Figure 5 compares the worst (or highest) cross-correlation peaks for each relative Doppler offset, when L1 and L2C signals are both observed over a 20 millisecond interval. It can be observed from Figure 5 that in this case, the L1 signal outperforms L2C signal over about 93% of relative Doppler offsets.

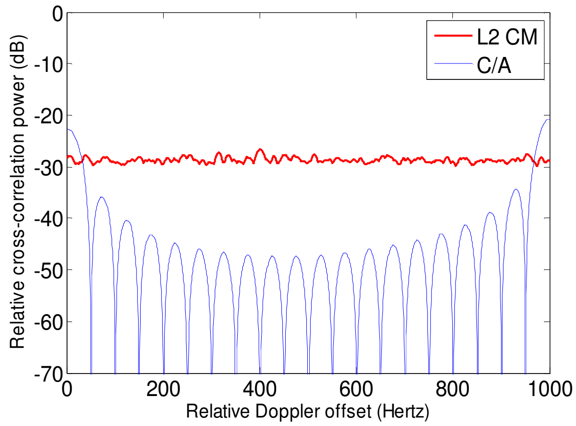


Figure 5. Highest cross-correlation noise observed in L1 & L2C signals for the observation intervals of 20 milliseconds, as a function of relative Doppler offset

The remaining 7% of the relative Doppler are, referred to here, "critical Doppler offsets", CDO. The reason for L1 superiority (in the specified range of relative Doppler offsets) is that, over a period of 20 milliseconds, the C/A code repeats 20 times and the offset-carrier (relative Doppler offset) has an un-correlated phase across each C/A code period. Consequently, when the integration is performed across 20 periods, the cross-correlation noise is averaged out. As illustrated in Figure 5, the reduction in cross-correlation noise will depend on the frequency of relative Doppler offset. For example, a relative Doppler offset of 500 Hz (see Figure 6), has an exactly opposite phase across adjacent C/A code periods and consequently when the integration is performed across 20 periods, the cross-correlation noise is completely cancelled out. On the other hand, a 1200 Hz offset adapts a different phase across each C/A code period and therefore the integration across 20 code periods, in this case, results in a different cross-correlation value. That is why for relative Doppler offsets that are integer multiples of 1 KHz, where the offset carrier has exactly same phase in each C/A code period, longer integrations can not reduces the cross-correlation noise.

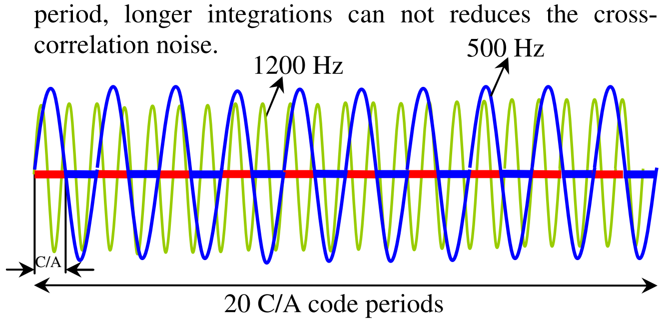


Figure 6. Examples of the offset carrier phase across C/A code periods

Figure 5 repeats for relative Doppler offsets beyond the selected 1 KHz range because of the 1 millisecond C/A code period, as explained later in the paper in equation 10).

Following discussion provides an analytical explanation of this cross-correlation behavior.

The codes-product '$c_1(t)c_2(t-\tau)$' in equation (2) is a random variable and consequently the integrals in eq (2) are not deterministic. However, over the coherent integration interval T_c, this codes-product theoretically fluctuates between +1 and -1 and can be decomposed as:

$$c_1(t)c_2(t-\tau) = c^+(t-\tau) + c^-(t-\tau) \qquad (3)$$

where $c^+(t-\tau)$ is a sub-code that replaces all -1s in the codes-product by 0s while $c^-(t-\tau)$ replaces all 1s in the codes-product by 0s. The two sub codes can be expressed as:

$$c^+(t-\tau) = \frac{c_1(t)c_2(t-\tau)+1}{2} \qquad (4)$$

and

$$c^-(t-\tau) = \frac{c_1(t)c_2(t-\tau)-1}{2} \qquad (5)$$

Equation (2) can now be simplified as:

$$\chi(\tau,\Delta\omega,T_c) = \left| \left[\int_0^{T_c} Ac^+(t-\tau)\cos(\Delta\omega)t\,dt + \int_0^{T_c} Ac^-(t-\tau)\cos(\Delta\omega)t\,dt\right] + \left[\int_0^{T_c} Ac^+(t-\tau)\sin(\Delta\omega)t\,dt + \int_0^{T_c} Ac^-(t-\tau)\sin(\Delta\omega)t\,dt\right] \right| \qquad (6)$$

$$= \left| \left[\int_0^{T_c} A\cos^+(\Delta\omega)t\,dt + \int_0^{T_c} A\cos^-(\Delta\omega)t\,dt\right] + \left[\int_0^{T_c} A\sin^+(\Delta\omega)t\,dt + \int_0^{T_c} A\sin^-(\Delta\omega)t\,dt\right] \right| \qquad (7)$$

$$= \left| \left[\frac{A\sin^+(\Delta\omega)T_c}{\Delta\omega} + \frac{A\sin^-(\Delta\omega)T_c}{\Delta\omega}\right] + \left[\frac{A\left(1-\cos^+(\Delta\omega)T_c\right)}{\Delta\omega} + \frac{A\left(1-\cos^-(\Delta\omega)T_c\right)}{\Delta\omega}\right] \right| \qquad (8)$$

Equation (8) states that, with reference to $\Delta\omega$, the cross-correlation noise eventually follows the "Sinc" function. The oscillation frequency of the "Sinc" function is:

$$\tilde{f} = \frac{2\pi}{T_c} \tag{9}$$

While the "Sinc" function replicates at:

$$\Delta\omega = \frac{2k\pi}{T_{code}} \tag{10}$$

where k is an integer and T_{code} is the fundamental code period. A CDO window exists for $\Delta\omega$ given by equation (10), and for given signals the size of this window is determined by the coherent observation interval. In Figure 4, the coherent integration interval equals the fundamental code period (i.e. T_c=T_{code}) and therefore no oscillations are observed. However, in Figure 5, in the case of the L1 signal, an oscillation frequency of 50 Hz can be observed. The L1 signal here takes advantage of the shorter code period, as it is observed over 20 code periods. This code recurrence in the signal observation interval improves the cross-correlation performance of the L1 signal.

Size of Observation Interval

Shorter observation intervals are desired in order to minimize the acquisition effort in a GPS receiver. The size of the observation interval is gradually increased to acquire weaker signals.

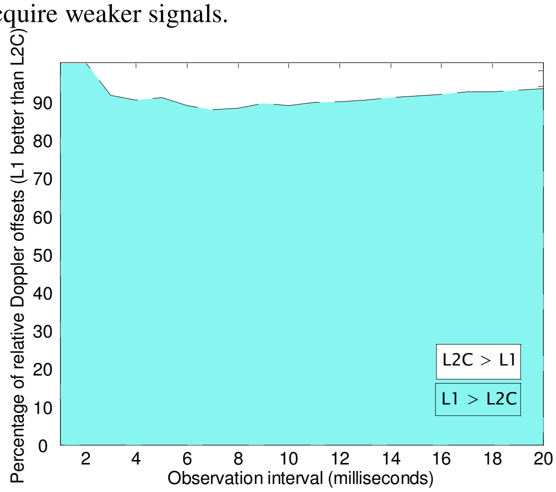


Figure 7. Cross-correlation performance comparison of L1 & L2C signals ("L1>L2C" indicates superior performance by L1)

We observed L1 and L2C signals over equal intervals of different sizes. For each observation interval, 1000 relative Doppler offsets were trialed and the percentage of relative Doppler offsets for which the peak cross-correlation noise in L1 signal remains below the peak cross-correlation noise in L2C signal was recorded. In other words, we are measuring the CDO window size for each observation interval. This gives us an overall impression of the L1 signal's superiority over the L2C signal (see Figure 7). The blue (shaded) area in Figure 7 represents L1 superiority over L2C, when the entire range of relative Doppler offsets is considered for each observation interval. For observation intervals of 1 millisecond and 2 milliseconds, L1 relatively retains the Gold code characteristics, offering superior cross-correlation performance over L2C for all relative Doppler offsets. For these shorter periods though, the cross-correlation of L2C looks like "random data".

It is important to understand that for L2C observation intervals shorter than 20 milliseconds, although the number of searches remains the same as for the 20 milliseconds observation interval, computations per search are significantly reduced, hence minimizing the L2C acquisition effort. The two signals were therefore compared for observation intervals of 1 to 20 milliseconds.

Cross-correlation Noise Sink

It was identified that when L1 and L2C signals are observed over a particular interval, for a certain percentage of relative Doppler offsets, the cross-correlation noise drops well below the auto-correlation peak such that it can be considered as effectively eliminated. A percentile of -35 dB was selected to observe this cross-correlation sink as a function of size of observation interval, for both the L1 and L2C signals. The -35 dB figure translates to acquisition of weak signals as low as 28 dB Hz, as was used in [8] and [9]. Figure 8 shows this cross-correlation sink for the L1 and L2C signals.

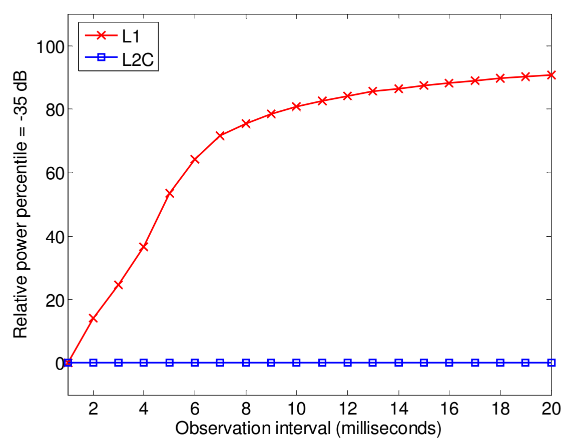


Figure 8. Comparison of the cross-correlation sink in L1 & L2C signals for a percentile of -35 dB

It can be observed from Figure 8 that as the size of the observation interval increases, the L1 signal can sink more and more cross-correlation noise, while the L2C gives a flat response. This indicates that the relative cross-correlation performance of L1 signal improves as the observation interval is increased.

Sampling Rate

So far in this paper, a synchronous sampling rate of 5.115 MHz, as shown in Table 1, was considered. Synchronous sampling rates are integer multiples of the code chipping rate and consequently they produce exactly the same number of samples per code chip. However, asynchronous sampling rate of 5.714 MHz, such as used by the Zarlink chipset GP2015 ([11]), is used in practice and so the cross-correlation performance for that rate is compared with the synchronous case. It can be observed from Figure 9 that L1 retains its superiority over L2C for both the synchronous and asynchronous cases.

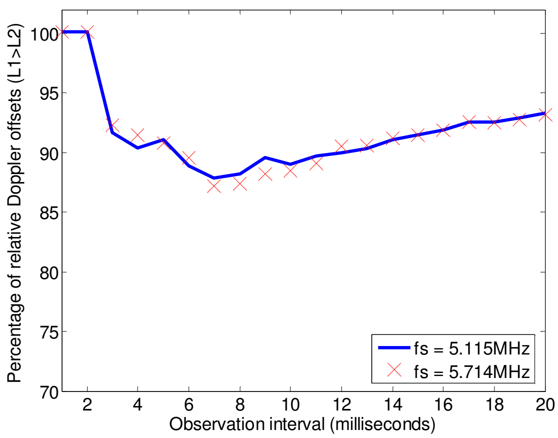


Figure 9. L1 superiority over L2C with synchronous and asynchronous sampling rates

CROSS-CORRELATION PERFORMANCE IN WEAK SIGNAL ENVIRONMENTS

A weak signal environment refers to situations where some of the satellite signals seen by a GPS receiver are stronger than others. Such situations occur, for example, when a GPS receiver is working indoors or in urban canyons. A strong GPS signal can either prevent the acquisition of a desired weak signal or it can lead to false acquisition [9]. High cross-correlation performance is desired for weak signal acquisition in such environments. The cross-correlation performance of L1 and L2C signals is evaluated in the presence of one, two, three and four interfering (causing cross-correlation) satellite signals.

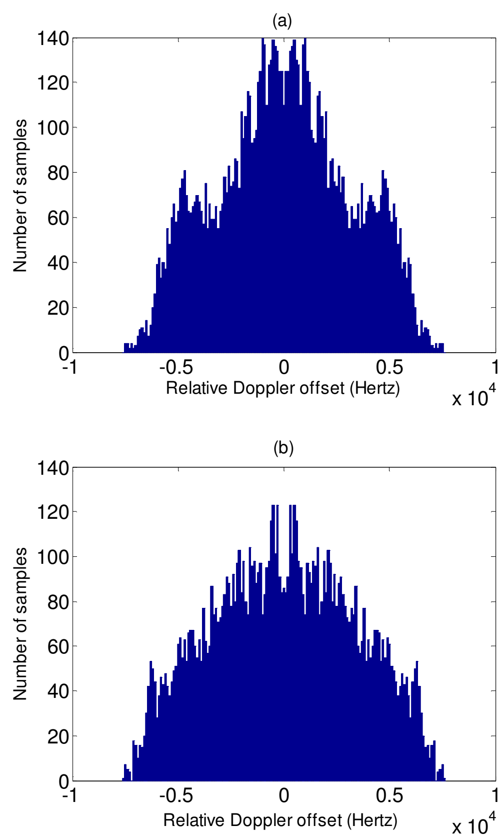
Doppler Offset Assignment

The distribution of relative Doppler offset between two satellites was computed for a number of geographically dispersed locations, using the almanac data. The cumulative probability of relative Doppler offset is then computed for each of these distributions. For each location, the Doppler of all visible satellites above 10 degrees elevation was observed every 10 minutes over the course of 24 hours. The relative Doppler offset between all possible pairs of visible satellites is then computed. Table 2 summarizes the data set used for the observations.

Table 2. ECEF coordinates of the locations used for Doppler observation and observed CDO

Location	X	Y	Z	CDO (%)
Sydney	-4644468.695	2549957.976	-3538921.13	10
Paris	4229481.535	161741.023	4755371.006	9
Singapore	-1434445.575	6213266.401	134890.627	9.9
Brasilia	3603134.231	-5145808.97	-1100248.547	10
Toronto	885646.252	-4556254.98	4359896.076	9.7

Figures 10 and 11 give the distribution and cumulative probability of relative Doppler offset for each location, respectively.



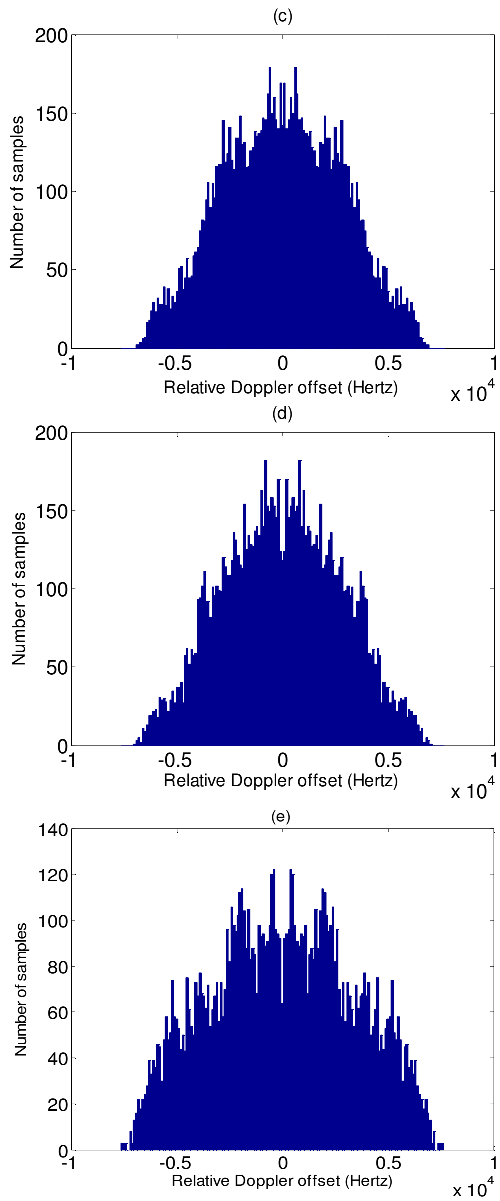
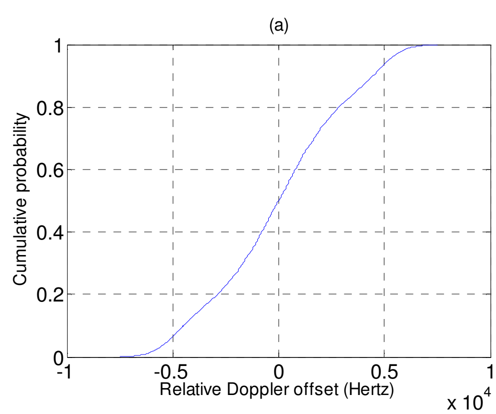


Figure 10. Distribution of relative Doppler offset for geographically dispersed locations. (a) Sydney, (b) Paris, (c) Singapore, (d) Brasilia and (e) Toronto. Note the low incidences of CDO, as given in Table 2.



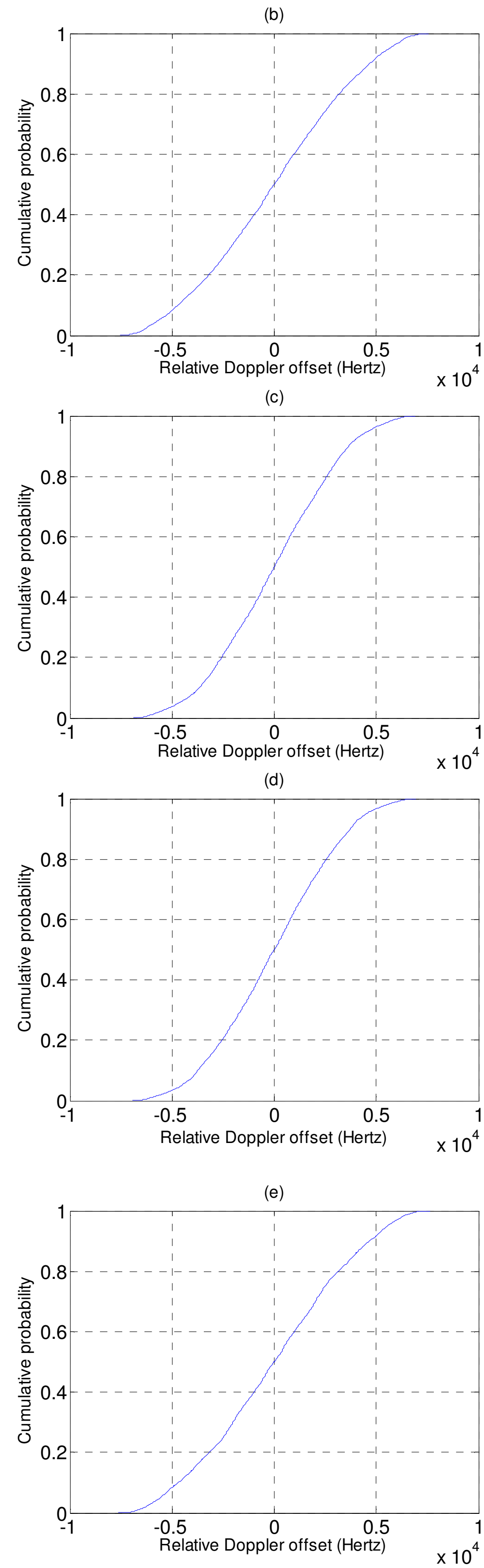


Figure 11. Cumulative probability of relative Doppler offset for different locations. (a) Sydney, (b) Paris, (c) Singapore, (d) Brasilia and (e) Toronto.

Desired relative Doppler offsets for experiments were then chosen by reading off the horizontal axis for uniformly distributed points along the vertical axis, of the cumulative probability curves. Table 3 gives the data set used for the experiments.

Table 3. Selected PRN (a) and relative Doppler offsets (b) for experiments

(a)

Satellite PRN				
2	4	7	9	23
5	11	8	6	28
19	12	18	16	24
3	10	27	21	31

(b)

Location	Relative Doppler Offsets (KHz)			
Sydney	0.6553	1.3483	2.2140	3.4207
Paris	0.7748	1.6629	2.5852	3.6552
Singapore	0.6386	1.3333	2.1174	2.8915
Brasilia	0.6657	1.3136	2.0825	2.9204
Toronto	0.8194	1.7120	2.4872	3.6565

The Test Process

For each of the one, two, three and four interferers cases, following steps are used to evaluate the cross-correlation performance:

a) A set of relative Doppler offsets is selected from the probability distribution curve of each location, using the method described above (Table 3-b).
b) For each scenario, five unique sets of interfering satellites are chosen from Table 3-a, on a random basis.
c) For each set of satellites, the cross-correlation is performed using relative Doppler offsets from all five locations.
d) The mean of the 25 results from the above steps is recorded. This mean is used to plot the cross-correlation performance curves.

The above test process is adapted to closely simulate the realistic scenarios. The cross-correlation performance of the L1 and L2C signals is evaluated under identical conditions for an observation period of 20 milliseconds using the test process described above. Figure 12 compares the cross-correlation performance of the two signals for different scenarios.

It can be observed from Figure 12 that L1 consistently performs better than L2C for all cases.

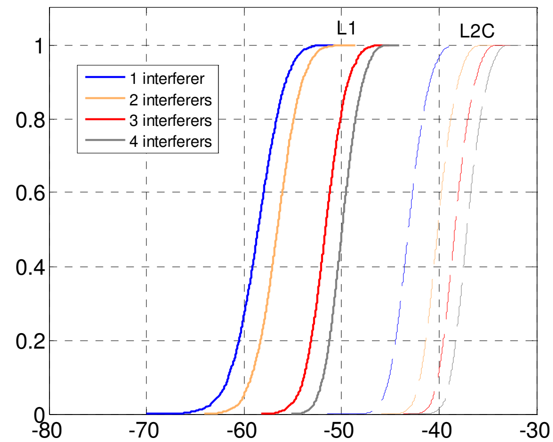


Figure 12. Cross-correlation performance comparison of L1 & L2C signals in weak signal environments for coherent integration of 20 milliseconds

Navigation Data Bit Transitions

The data bit length in both L1 and L2C signals is 20 milliseconds. Although the actual data rate in L2C signal is 25 bps, a half rate convolutional encoder is employed to transmit the data at 50 bps. The probability of having a data bit transition in L1 and L2C signals is therefore exactly the same. Presence of data bit transitions in the signal observation period prevents the use of longer coherent observation intervals, required for weak signal acquisition. Non-coherent integrations are typically used to deal with this issue. The cross-correlation performance of L1 and L2C signals is also evaluated in the presence of data bit transitions. For this purpose, a non-coherent integration of 20 milliseconds is performed with four coherent integration blocks of 5 milliseconds each.

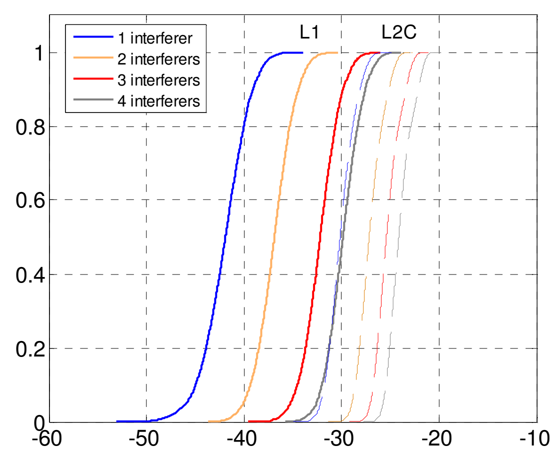


Figure 13. Cross-correlation performance comparison of L1 & L2C signals in weak signal environments, for non-coherent integrations

Using the test process described above, the performance of the two signals in this case is evaluated and shown in Figure 13.

It can be observed from Figure 13 that L1 performance is relatively degraded in this case as the phase information is lost due to 'squaring' across coherent blocks in the non-coherent integrations.

Acquisition Effort

A comparison of the acquisition effort required for the L1 and L2C signals is presented in [3]. When L1 and L2C signals are simultaneously observed over equal intervals, the L2C signal suffers significantly more cross-correlation noise than the L1 signal. Also, the fact that L2C signal is 2.3 dB weaker ([4] [9]) than the L1 signal and that the L2C signal requires search across at least 20 milliseconds for each code phase trial, make L2C acquisition a lot more difficult than that of the L1.

CONCLUSIONS

L2C is the new GPS civil signal now available on modernized Block IIR-M satellites. The structure of the L2C signal was specifically designed to replace the L1-C/A signal for weak signal acquisition in environments such as inside buildings and in urban canyons. It is shown that when the L1 and L2C signals are observed over the same duration, L1 offers much superior cross-correlation performance than L2C, and consequently the legacy L1 can offer a better solution for acquiring GPS satellite signals in weak signal environments.

ACKNOWLEDGEMENTS

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