Lockheed Martin

Correlators for L2C
Some Considerations

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With the launch of the first modernized GPS Block IIR satellite in September 2006, GNSS product designers have an additional, fully open signal to use in their work: L2C. But the new signal also has different parameters than the L1 C/A-code signal available for the last 30 years. What does that mean to the people who are designing the correlators for new generations of GNSS receivers?

The term "Correlator" is often used in discussions of GPS and GNSS receiver design. It has been used to describe devices as simple as a single exclusive OR gate through to complete "baseband" chips that include a microprocessor.

Most usually, and in this article, the term describes the hardware or software that produces all of the required correlation data for a single signal from a specific GNSS satellite signal. This is also sometimes termed a "channel."

With the open GPS civil signal at the L2 frequency (L2C) now becoming available on Block IIR-M satellites, receiver designers have the opportunity to work with a markedly different GNSS signal resource. The first IIR-M spacecraft (designated SVN53/PRN17) was launched September 25, 2005, and the second is scheduled to go into orbit on September 14, 2006. (IIR-Ms also transmit the new GPS L1/L2 military (M-code) signal, but we will not treat this issue here.)

Against that historic backdrop, then, this article examines some of the novel elements of the L2C signal and its implications for GNSS receiver correlators. Our focus will be on a technically challenging aspect of receiver operation: initial acquisition of the signal and its processing by the correlator. But first we will review some of the key functional aspects of GNSS correlators and some of the signal parameters that affect their operation.

Correlators' Essential Role

The GPS L1 signal is a code-division-multiple-access (CDMA) signal. Each of the signals transmitted by different satellites in the L1 band has a distinct pseudorandom noise (PRN) code, which is a 1,023-chip sequence of 1s and 0s. (It's called "chip" rather than "bit" because the code sequence carries no information)

These chips are BPSK-modulated (where BPSK is binary phase-shift key in which only 0° and 180° phases are used); so, rather than 1s and 0s, the code could be considered to be 1s and –1s "multiplied" by the 50-bps data signal. The code rate is 1.023 Mchip/sec, which means that the very narrowband data signal is spread into a significantly wider bandwidth. This process is also known as direct sequence spread spectrum. (Editor's note: For discussion of spread spectrum and GNSS codes, see the Working Paper's column beginning on page 46.)

The role of the correlator circuit is to "despread" this signal and recover the original narrowband signal. This is achieved by aligning a replica of the transmitted code with the received signal. In this process, the 1s multiply by 1 and the –1s multiply by –1; so, the original data signal is effectively multiplied by 1, i.e., it is recovered.

We can more easily explain the role of a correlator if we examine its two functions separately. In a GNSS receiver, correlation is used in two distinct activities:

- **Acquisition.** Before the receiver knows whether it can receive a certain satellite's signal, it must "search" for it using the correlation in an ordered but relatively indiscriminate way. Effectively, many correlation trials are run for each of many code delays and Doppler frequency offsets.
- **Tracking.** Once acquired, the receiver must still despread the received signal in order to receive data and measure pseudoranges. Several correlators are usually used to keep the local code as closely aligned to the received code as possible. To do this, a "delay-locked loop" is used, with the correlators operating within the loops, some typically ahead of the received code ("early") and some behind ("late").

In other words, correlation is used both to "get" the signal and to "keep" it. These actions should be considered quite separately. In this article, we concentrate on the acquisition process.

The equation of the correlation of the received signal $r(t)$ and the locally generated code $s(t)$ is:

$$R(\tau) = \int_0^T r(t)s(t+\tau)dt \qquad (1)$$

Several points of interest appear in this equation. First, if the carrier and data are successfully stripped from the received signal, $R(\tau)$ is nearly an autocorrelation such as is shown in Figure 1. (If $r(t)$ had infinite bandwidth it would be even nearer.) When tracking we would like to keep the delay τ at "0", or an integer number of code lengths, so that the value of $R(\tau)$ is maximized, that is, we stay at the peak of the correlation function (see Figure 1b)). During acquisition, it is this delay that is varied in search of the peak.

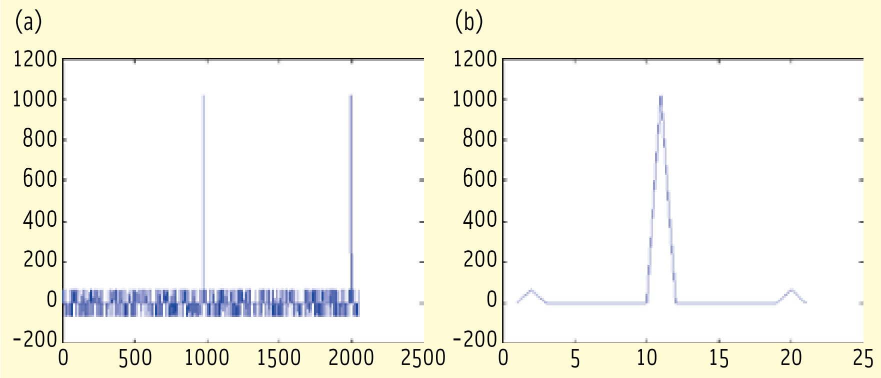

FIGURE 1 Autocorrelation of code for satellite 1 a) two periods, b) around the peak

The integration time T is the period that we observe the signal before calculating a value for $R(\tau)$. The longer this period, the better the signal-to-noise ratio becomes, as the signal is integrated coherently and the noise is averaged. (Non-coherent integration, which we mention later, refers to summing the magnitudes of several of these coherent integrations, a process during which the phase information is eliminated.)

The other important function appearing in Equation (1) is the multiplication of $r(t)$ and $s(t)$. Given that $s(t)$ can be a simple binary representation of the code, and $r(t)$ can be represented by signed arithmetic, this multiplication can occur in an XOR gate.

New Civil GPS Signals

When considering new GNSS signals, we have a range from which to choose. Galileo has begun transmitting a version of its signal selection, and GPS SVN 53 is now transmitting L2C and also M-code on both L1 and L2.

However, to identify some of the issues facing designers of correlators for new GNSS signals, here we just consider L2C, primarily because its full specification is available to civilians. The new signals' differences from L1 are of most interest here, and L2C is different enough to make an interesting discussion. The L5 signal introduces additional differences.

Various signal parameters affect correlation. These are listed for the three GPS signals in Table 1. Both L2C and L5 have dataless sub-signals which are time-multiplexed (CM and CL) and in quadrature (I5 and Q5), respectively. Both use longer codes than L1, while L5 has a higher chipping rate. L5 also has the added complication of Neuman-Hoffman codes, which will not be further discussed here.

Correlation Signal "Shape"

As discussed previously, the L1 civilian C/A-code signal is a single BPSK modulation. Despite the fact that the L2C signal is also BPSK, it introduces another layer of complexity by having the data-carrying and dataless signals multiplexed in time. Typically, the shorter (20-millisecond) data-carrying CM code will be acquired first, then the receiver would hand over to the longer (1.5-second) dataless CL code for tracking.

If we treat the L2C received codes as two-level signals (as they can be for L1), a problem arises with the correlation function. Consider a "non-return to zero" (NRZ) version of the CM code, where the value of CM in the local code is held for the length of both the received CM chip and the CL chip. Figure 2 illustrates this approach, which produces a flattened correlation shape. In other words, when the codes are aligned, there

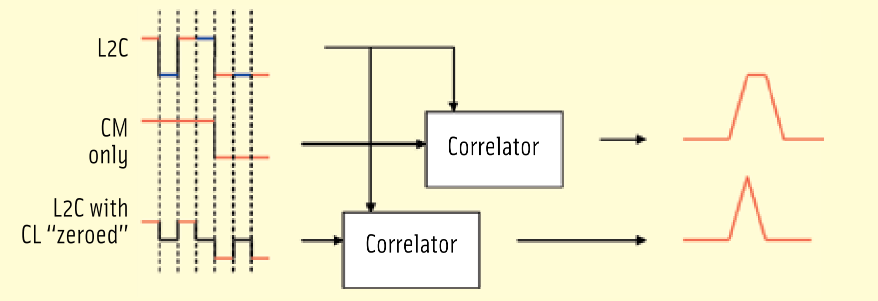

FIGURE 2 The correlation "shapes" arising when the L2C combined codes (CM is red, CL is blue) are "correlated" with the NRZ CM code (top), and with the combined codes with CL "zeroed" – an RZ code.

is a possible "slip" the width of one chip of the combined code or half a chip of the CM code alone.

This may not necessarily be seen as an insoluble problem, as the correlators used for tracking (the "early" and "late" correlators which sit on the shoulders of the correlation function) could simply be placed another (L2C) chip width apart. This idea has two flaws, however. The first is that multipath behavior will be poor (a classic solution to the multipath problem is the "narrow correlator" which places the early and late "fingers" very close together – spreading these fingers further will accentuate multipath vulnerability).

The second problem is that by integrating during the non-useful CL chips, extra noise is added so that signal-to-noise ratio is also worse than necessary. Ideally the CL chip periods should not contribute to the correlation.

If instead the CL contribution to L2C is replaced by zero, producing a "return to zero" (RZ) chip shape, then a sharp correlation function results, and the unwanted noise during the CL chips is also avoided. However, this introduces a 3-level code signal, multiplication with which cannot be simply implemented as a XOR gate. A practical implementation of this may use two-bit arithmetic for the CM code as illustrated in Figure 2 with the integration part of the circuit disabled by a signal synchronized to CL.

L2C Acquisition

The traditional way that GPS receivers have acquired the L1 signal is to take digital samples of the downconverted signal and "multiply" them by a sampled local code as they arrive, in real time. This is the multiplication in Equation (1). After a period of observation, known as the "integration time", *T*, a relatively large number of these individual multiplications are produced, often in both I and Q channels. These are added together (the integral in Equation 1), turned into an $\sqrt{I^2+Q^2}$ envelope, and compared to a threshold.

Much has been made of the benefits in the L2C signal design for data extraction and signal tracking. Despite each of the CM and CL parts of the signal being 5.3 dB weaker than L1, there is a 0.7-dB tracking advantage. This is because a phase-locked loop (PLL) rather than a Costas loop can be used to track CL, gaining 6 dB. There is also a 2.7-dB data extraction advantage (due to data arriving at 25 bps, gaining 3dB, and the use of forward error correction, gaining 5dB).

However, these advantages only manifest themselves once the signal is acquired. The acquisition process still suffers the full effect of the 5.3 dB weaker signal.

There are various ways to analyze the acquisition process, but if we take a "typical" received L1 signal with C/N_0 = 37.0dB, with the detection threshold set such that probability of false alarm P_{fa} = 16 percent, then a 1-ms integration period gives a reasonable probability of detection P_d of 93 percent.

For the CM (or CL) code received from the same satellite with its 5.3 dB weaker signal, P_d = 49.7 percent for a 1ms integration period and to achieve the same P_d of 93%, the integration period must grow to at least 3.4ms (i.e. 5.3dB "longer"). (For a full presentation of these calculations, see page 222 of the text by Elliot Kaplan and C.J. Hegarty, eds, cited in the Additional Resources section at the end of this article.)

To achieve the same acquisition performance as for L1, the L2C signal(s) must be integrated for a longer period. This is partly because the L2C signal is 2.3 dB weaker. Moreover, if the RZ CM code in Figure 2 is used, then we can clearly see that for half of the time nothing is being integrated; so, integration

Parameter	L1	L2		L5	
	C/A	CM	CL	I5	Q5
Received Power (dBW)	-157.7	-163.0	-163.0	-157.0	-157.0
Chipping Rate (chip/s)	1.023M	0.5115M	0.5115M	10.23M	10.23M
Data Rate (bit/s)	50	50	-	100	-
Code Length (chips)	1023	10230	767250	10230	10230
Code Length (s)	1m	20m	1.5	1m	1m
Neuman-Hoffman Clock Rate (Hz)	-	-	-	1k	1k
Neuman-Hoffman Length (symbols)	-	-	-	10	20
Neuman-Hoffman Repetition Rate (Hz)	-	-	-	100	50

TABLE 1. Signal parameters affecting the correlator performance. Note: i) that the two codes on L2C and L5 are assigned half of their signal's total received power each, ii) that the data rates shown for L2C and L5 are the rates apparent to the correlation process; because of forward error correction the actual data transmitted arrive at half those rates.

time must be doubled. These two factors give a constant factor of 3.4 longer integrations for L2C over L1. (If the NRZ version of the CM code is used from Figure 2, the signal-to-noise ratio is reduced by 3 dB and, hence, integrations must be further doubled, to 6.8 times as long as for L1.)

During acquisition of the spread signals, the search occurs not only in the "delay" domain, testing the different values of τ in Equation (1), but also in the frequency or "Doppler" direction. Different trial frequencies must be used for the final downconversion step, with the aim of completely removing the carrier and leaving a binary signal for the despreading to work with.

Errors in these trial frequencies leave some residual carrier in the signal, which needs to be kept down to less than a cycle (say 2/3 of a cycle) during the integration period. If the integration period becomes longer, the steps between these frequency trials must be made proportionally shorter, in order to ensure that this 2/3 cycle limit is not exceeded.

In effect, the spacing required in the Doppler domain is inversely proportional to the integration period and, hence, to search the same two-dimensional space (code delay and Doppler), an increase in the integration period of 3.4 means that there are 3.4 times more Doppler trials to perform. (If the NRZ version of the code in Figure 2 is used, each integration period is 6.8 times as long and there are 6.8 times as many Doppler trials).

Searching in the code domain usually occurs at half-chip intervals in order to make sure that the search does not "step over" the peak of the correlation function. For the L1 C/A code, this means 1,023 × 2 = 2,046 trial delays are required at each Doppler trial value. The L2C CM code has 10,230 chips to search; however, the correlation function for the RZ code in Figure 2 is half the width of one of these chips. Consequently, to avoid "stepping over" a chip, the code search must be at half-chip intervals of the combined CM/CL codes. This means there are 10,230 × 2 × 2 = 40,920 trials for each Doppler trial value, 20 times more than for L1 C/A.

So, the search time required for L2C CM code, if performed sequentially, is 3.4 × 3.4 × 20 = 231.2 times longer than for the same type of search for L1 C/A code. To search for CL would take a further 75 times longer. (If the NRZ code from Figure 2 was used, single CM chip steps can be used, so the increase over L1 C/A is 6.8 × 6.8 × 10 = 462.4 times longer – so the RZ method is still preferred).

"Search engines" replace sequential correlation by simultaneous integration in massively parallel circuits. The numbers of correlation operations evaluated in the preceding discussion apply whether done serially or in parallel; so, if search engines are used, the ratios of effort remain the same.

When approaching the direct acquisition of L2C, designers so far have opted for a strategy that acquires the shorter CM code first, then the CL code.

Auto- and Cross-Correlation

When approaching the direct acquisition of L2C, designers so far have opted for a strategy that acquires the shorter CM code first, then the CL code. The CL code is then used for tracking, because it is data-free. But for acquisition in the strong-signal case, we are typically examining the CM code alone.

The L1 C/A code can often be acquired by examining integration periods of one epoch of the 1,023-chip code, i.e., 1-ms integrations. In one millisecond, only 511.5 chips from CM or CL are available. Using the C/A Gold codes, autocorrelation peaks, such as those visible in Figure 1, and cross-correlation peaks are restricted to about –24 dB and –60 dB.

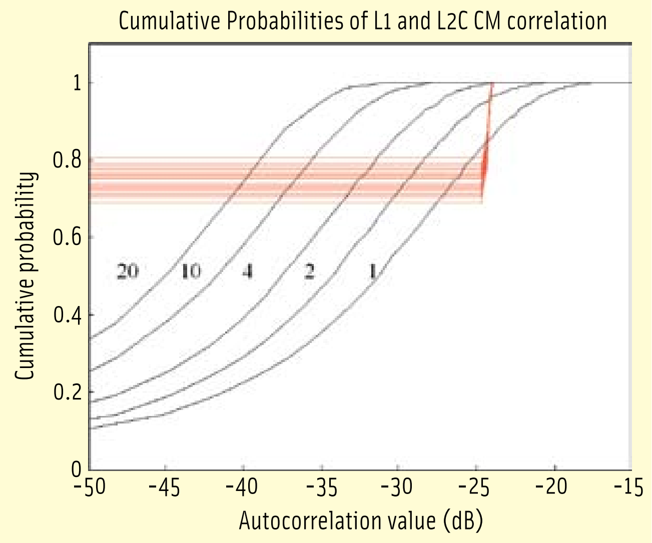

FIGURE 3 Probabilities of Auto- (and Cross-) Correlations in the L1 C/A codes (red – all codes shown), and the L2C CM code using integration times, i.e., code sub-sections, of length 1, 2, 4, 10, and 20 ms.

Figure 3 shows the probabilities of autocorrelation peaks for the C/A codes and for short sub-code lengths up to the CM code length of 20 ms. For integrations longer than 20 ms, the behavior is similar to 20 ms. Cross-correlation plots would be almost identical.

Cross-correlation behavior of L2C has often been highlighted as being far superior to L1, with cross-correlations restricted to the –60dB level. This is because the CL code has been used for those comparisons. The 1.5s CL code if shown on Figure 3 would have the same shape as the 20ms curve, but about 19dB to the left. (For further discussion of these and other aspects of L2C, see the article by R. D. Fontana et al listed in the Additional Resources section.)

What these Figure 3 curves show is, firstly, that for 1-ms integrations the auto- and cross-correlation performance of the L2C codes are, in fact, far worse than for L1 C/A code. However, unlike C/A code, longer integrations can assist in reducing these effects.

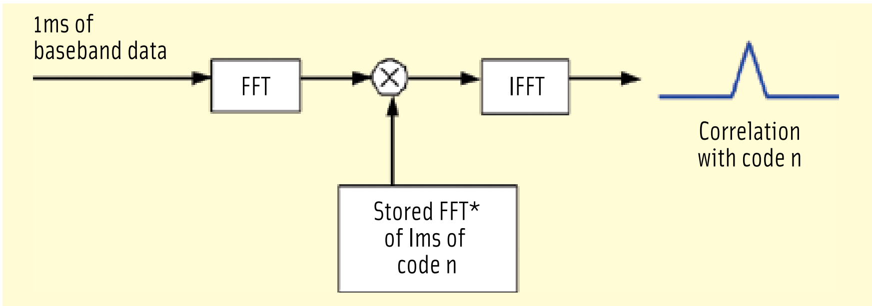

FIGURE 4 Block diagram of software acquisition

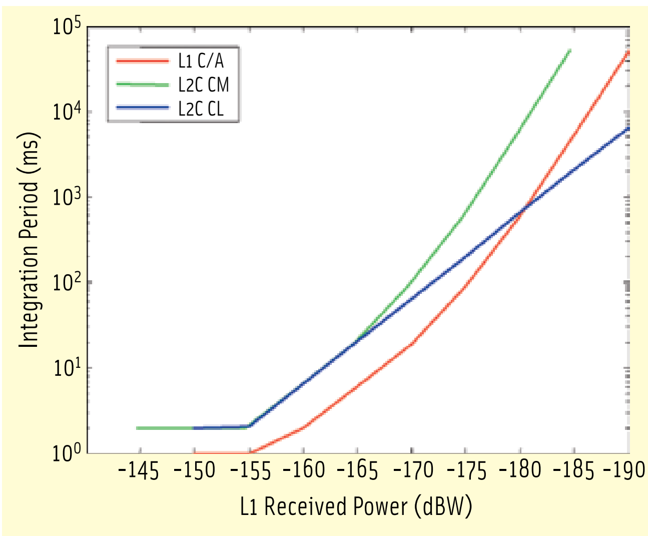

FIGURE5TheintegrationtimesrequiredforthecodesL1C/A,L2CCL,and L2CCM,atvariouslevelsofL1receivedpowerandassumingthesame attenuationappliestoL2C(i.e.,L2Cisalways2.3dBweakerthanL1). Nominalminimumtimesof1millisecondand2millisecondshavebeen assigned to L1 and L2C respectively.

Software Acquisition

Acquisition using the Discrete Fourier Transform (DFT) approach has been extremely effective when using software receivers. For L1 C/A, a single 1-ms code epoch of received data is transformed into the frequency domain and multiplied by the conjugate of the transform of 1 ms of the code in question.

Taking the inverse transform of this product produces in the time domain the whole correlation function (see Figure 4). This is highly desirable because a single epoch of data can then be used to acquire the signal.

Using the same approach in the L2C case throws up a number of problems. First, the CM code epoch is 20 milliseconds long; so, the algorithm used to calculate the DFT, for example, a Fast Fourier Transform (FFT), must deal with 20 times as much data if it is to use whole code epochs. If shorter data sets are used, then the benefits of "circular convolution" are lost.

The idea of circular convolution arises because, when a digital signal of say 1-ms length is "convolved" with another digital signal of the same length by multiplying their DFTs together, the output is in fact the convolution of the first signal with the second repeated indefinitely at a 1-ms repetition rate.

In our case, this is useful because the C/A code *does* repeat at 1-ms intervals. Therefore, the output in Figure 4 is the same as if the correlation had been performed in the time domain. (Note that the conjugation of the stored code FFT turns the convolution operation into correlation. See the discussion on this and other aspects of software receiver operation in the text by James B-Y Tsui cited in Additional Resources.)

The beauty of the exploitation of the circular convolution is that the code in the data does not need to be well aligned with the stored data— the whole point of acquisition, after all, is to perform this alignment. So, if the CM code was chopped up into pieces smaller than 20 milliseconds, this circular convolution would no longer reflect the time domain correlation, and a receiver would need to have many stored codes.

Therefore, software acquisition only makes sense for CM if 20-ms epochs are used. To establish how much extra work this requires from the processor, consider an RF front end sampled at 5.714 MHz such as those produced by Zarlink. One millisecond generates 5,714 samples, and if the same front end were used for the 20-ms L2C epoch, it would produce 114,280 samples.

This latter number makes for a very large FFT, requiring significant processing power and memory. Using the well-known "$n \log_2 n$" growth in FFT processing, this means there is about 27 times more effort to each CM software acquisition than with the L1 C/A code. Because the frequency search must also then be 20 times finer, as discussed earlier, 540 times as much computing will be spent on this process.

Weak Signal Performance

Because of L2C's poorer acquisition performance, the preceding calculations seem to suggest that dual L1/L2C receivers should be designed to acquire L1 first and then hand over to L2C, regardless of whether acquisition is performed using hardware or software techniques,

But this is not always true. The long L2C code, CL, carries no data and, therefore, can be used for long coherent integrations. Because L1 carries data, long integration periods can only be achieved by non-coherently summing the results (i.e., adding up the power outputs) of many shorter integration periods.

The latter process, however, leads to "squaring losses," which means that even longer integration periods must be used. This is illustrated in Figure 5 where the integration times for the two data-carrying codes C/A and CM increase rapidly with C/A always the better of these two, and the times for the dataless code CL increase linearly (admittedly on a log-log scale). (The data for the figure is drawn from the presentations by Rod Bryant and Frank Van Diggelen cited in the Additional Resource section.)

What Figure 5 tells us is that when the signals are attenuated such that the L1 signal is stronger than –180dBW, then L1 is easier to acquire. Where attenuation is greater than that, L2C CL is better. This continues to the point where a –190dBW L1 signal requires 51.5-second integration periods while the period for a similarly attenuated L2C signal (i.e. –192.3dBW or for just the CL component, –195.3dBW) requires integrations of only 6 seconds.

The point at which L2C CL becomes better can be pushed lower; for example, by using techniques described in the article by Rod Bryant, CL surpasses L1 at about –186 dB. Because the 20ms L2C CM code aligns with data bit boundaries, it can perform slightly better than as indicated in the figure. It is a weaker signal, however, and thus CM will always require longer integration periods than L1.

The preceding analysis shows that the CL code will be easier to acquire than L1 C/A in situations where signals experience significant attenuation. This weak signal advantage is enhanced because CL has superior cross-correlation properties for long integrations, meaning that if other strong L2C signals are present, they are much less likely to prevent the weaker signal from being acquired.

Power Considerations

Many GPS chipsets are optimized for operation in mobile telephone handsets and, as such, are aimed at minimizing the drain on handset batteries. For such applications, the large L2C acquisition overhead presents a serious problem because the increased effort factors discussed previously also apply to power consumption during acquisition, which for A-GPS is one of the primary power drains. Moreover, a parallel set of L2C circuitry will double the power consumption if both L1 and L2C are being tracked.

On the other hand, the ability to acquire the CL code in poor signal conditions makes the use of L2C attractive for indoor operation, where A-GPS is necessary. The consequences of this trade-off will be important for chip and system designers in the future but will not be considered further here.

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Tracking

The good news for signal tracking is that the performance of L2C is better than for L1. In a dual frequency receiver, the signal may be acquired using the following process: acquire L1 C/A, handover to CM, handover to CL. Then the receiver can track CL using a phase-locked loop rather than a Costas loop, which gives the L2C CL loop slightly better tracking performance than the L1 loop.

CL is also the better code to use for weak-signal tracking. So, in all cases tracking using CL is the best solution. Because of its signal-to-noise advantages (i.e., shorter integrations) and the better multipath performance, the RZ version of the code in Figure 2 should be used.

Conclusion

In this article, we have primarily examined the implications of signal acquisition for the new L2C signal. In a typical L2C-only receiver, significantly more effort is required to acquire the signal than is the case for L1 C/A code: more than 200 times higher in the hardware case and more than 500 times higher in the software case. However, because the long CL code does not carry any data, it can be used for the long integrations required for acquisition in a weak-signal environment.

Acknowledgments

The author wishes to acknowledge the useful suggestions made by Eamonn Glennon of Signav Pty Ltd.

Additional Resources

[1] Bryant, R., "subATTO Indoor GPS – Pitfalls, Solutions and Performance Using a Conventional Correlator," White paper, Signav Pty Ltd, www.signav.com.au

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