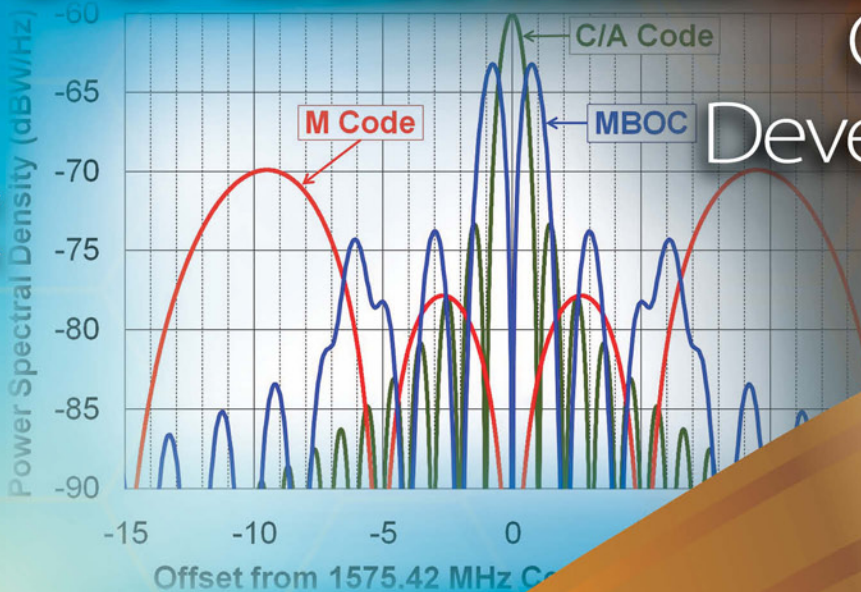# GPS World

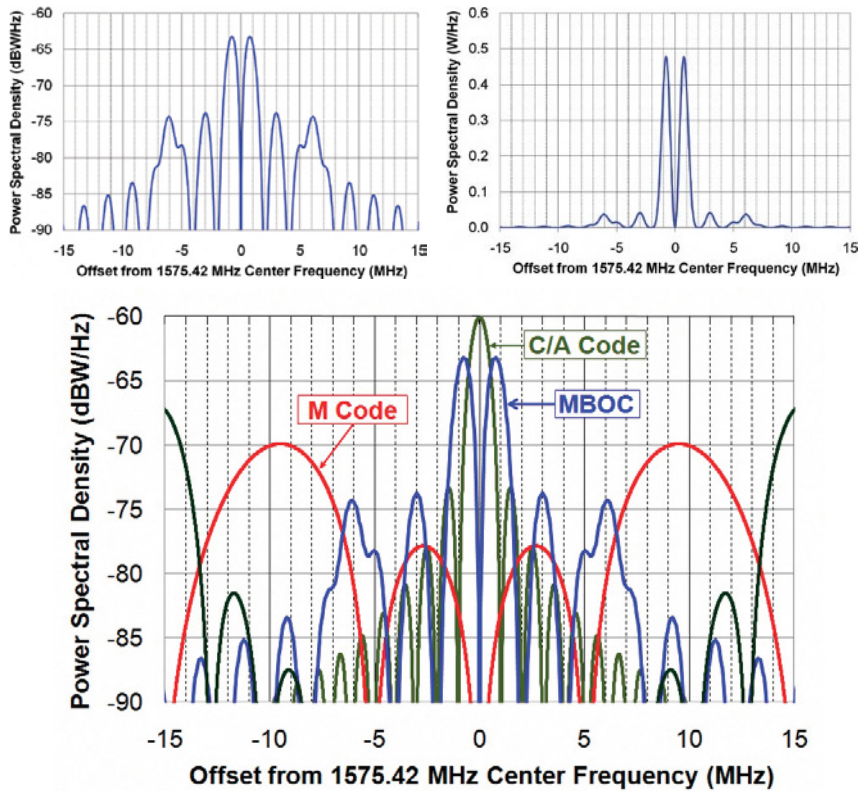## THE BUSINESS & TECHNOLOGY OF GNSS

APRIL 2011

MODERNIZATION

GPS
L1C
OCX

GLONASS
Development
Strategy

PLUS
• Lightsquared Interference
• Spoofing Protection

▲ **FIGURES 1, 2, AND 3** (clockwise from top left.)

Future Wave
L1C Signal Performance and Receiver Design

The new GPS L1C signal will be broadcast by the Block III satellites, with first launches as early as 2014. L1C innovations significantly enhance PNT performance as well as interoperability with other GNSS signals. The authors describe the benefits of its new features and how best to make use of each one.

Thomas A. Stansell, Kenneth W. Hudnut, and Richard G. Keegan

A highly evolved racehorse of a signal with outstanding technical performance, L1C was designed to significantly improve autonomous navigation, and to be interoperable with L1 signals from other GNSS providers. Its structure evolved from the earliest GPS signals: it shares with the C/A signal the L1 center frequency of 1575.42 MHz, coherence between the carrier frequency, the code clock rates, and the data rate, and the provision of a navigation data message.

L1C inherited significant improvements from subsequent developments, specifically WAAS, L5, and L2C. WAAS was the first GPS-related signal to use forward error correction (FEC) for its data. L5 was the first open signal design to use longer spreading codes (10,230 chips), to have separate data and data-less (pilot carrier) signal components, to employ an improved navigation message structure (CNAV), and to employ overlay codes to achieve a longer equivalent code length, improve correlation performance, and

eliminate the need for bit synchronization. The L2C signal adopted most of these improvements but, instead of an overlay, substituted a much longer pilot carrier spreading code, not only to optimize correlation performance but also to decrease the number of time ambiguities after tracking the spreading codes.

L1C Signal Description
The official L1C signal description is given by IS-GPS-800; the most recent version A was released on June 8, 2010. **FIGURES 1** and **2** (left, top) show the L1C power spectral density with, respectively, a logarithmic (dBW/Hz) scale and a linear (Watts per Hz) scale. **FIGURE 3** (left, bottom) is the same as Figure 1 but also includes the C/A and M Code signals; it assumes both signals are transmitted with the same total power.

These plots illustrate three important aspects of the L1C spectrum. First, L1C is designed to have only a small impact on reception of the legacy C/A signal. This is important for the compatibility of signals with respect to each other. A good way to evaluate the impact of one signal on another is called the Spectral Separation Coefficient (SSC), which quantifies the amount of interfering power from one signal to another, under the assumption that each signal is transmitted with the same power but with different spreading codes.

The SSC between a C/A signal and the L1C signal is −68.3 dB/Hz. The spectral separation illustrated in Figures 1, 2, and 3 assures that L1C signals will have very little impact on acquiring and tracking the legacy C/A signals. Therefore, L1C is judged to be compatible with the C/A signal.

Figure 3 also illustrates that L1C and the M Code signals have very little impact on each other. The SSC between L1C and M Code is −82.8 dB/Hz. This
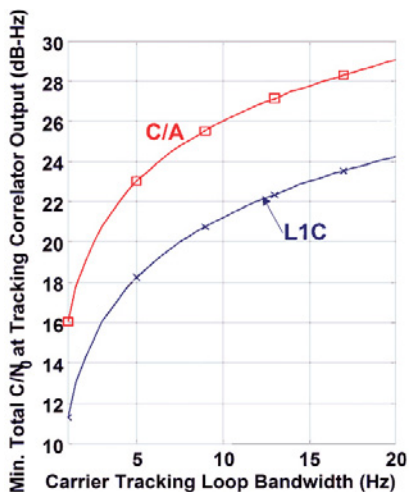
▲ **FIGURE 4** Required post Correlator C/N_0 versus tracking loop bandwidth.

is important because M-Code power may be substantially higher than the civilian signals, so a larger negative SSC is important to maintaining compatibility.

The third aspect of the L1C spectrum is the additional signal power at ±6.138 MHz. This component of signal power differentiates a binary offset carrier BOC(1,1) waveform from the L1C multiplexed BOC or MBOC waveform. Exactly 1/11th of the L1C signal power is a BOC(6,1) component, whereas 9/11th of the power is a BOC(1,1) component.

75 Percent in the Pilot Carrier. FIGURE 4, which shows the required post-correlator C/N_0 required to phase track either the L1C or C/A signals as a function of tracking loop bandwidth, illustrates the main advantages of having 75 percent of the L1C signal power in the pilot component. The carrier-tracking threshold for equivalent signal power using a Costas loop is 6 dB worse than tracking with a phase-locked loop (PLL). A Costas loop is needed for the C/A signal because it is modulated by data, whereas a PLL can be used for the dataless L1C pilot signal. This 6 dB advantage more than compensates for having only 75 percent (-1.25 dB) of the L1C power in the pilot. The vertical displacement between the two curves illustrates the 4.75 dB L1C tracking

threshold advantage.

The horizontal displacement of the curves shows another L1C advantage. For a given C/N_0 threshold, the L1C loop bandwidth can be increased by a factor of three. In turn, this allows tracking with G forces 3^2, or nine times higher. For third-order loops capable of tracking acceleration, this allows

tracking with 27 times higher jerk. Such differences are likely to be more important than tracking threshold for high-dynamic applications such as machine control.

Although Figure 4 assumes the L1C and L1 C/A signals have the same total power, the minimum received L1C signal power specified in IS-GPS-800A
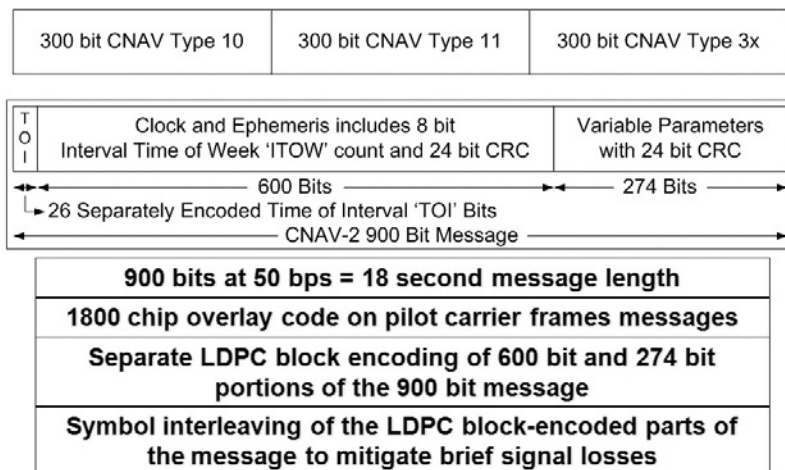
300 bit CNAV Type 10	300 bit CNAV Type 11	300 bit CNAV Type 3x

| T O I | Clock and Ephemeris includes 8 bit Interval Time of Week 'ITOW' count and 24 bit CRC | Variable Parameters with 24 bit CRC |

◄——— 600 Bits ———►◄——— 274 Bits ———►
└► 26 Separately Encoded Time of Interval 'TOI' Bits
◄——————— CNAV-2 900 Bit Message ———————►

900 bits at 50 bps = 18 second message length
1800 chip overlay code on pilot carrier frames messages
Separate LDPC block encoding of 600 bit and 274 bit portions of the 900 bit message
Symbol interleaving of the LDPC block-encoded parts of the message to mitigate brief signal losses

▲ **FIGURE 5** CNAV and CNAV-2 message structures.

is –157 dBW, and the equivalent for C/A in IS-GPS-200E is –158.5 dBW. In other words, the intent is for L1C to be transmitted with 1.5 dB more power than C/A. Therefore, the figure is conservative by 1.5 dB in evaluating the L1C advantages over C/A. Thus, the actual threshold advantage is 4.75 + 1.5 = 6.25 dB.

For narrowband or other receivers not punctual correlating the BOC(6,1) signal component, the pilot carrier is 29/33 or 0.56 dB weaker, so the net advantage is 4.75 – 0.56 + 1.5 = 5.69 dB.

LDPC Block Encoding

Low-density parity check (LDPC) encoding provides three key advantages. First, to demodulate the critical part of the L1C message with a bit error rate (BER) of 10^{-5} requires an E_b/N_0 (ratio of energy per bit to the noise power in a 1-Hz bandwidth) of 2.2 dB versus 96 dB for the C/A signal. When taking into account that only 25 percent of L1C signal power is in the data component, the required total power of the L1C signal can be 1.4 dB less than the C/A signal for an equivalent BER. As a result, this performance allows the pilot component of L1C to have 75 percent of the total L1C power.

Second, LDPC gives near-optimum performance with no intellectual property constraints. Third is the ability to block-encode Subframes 2 and 3 of the L1C message, described next.

CNAV-2 Message. FIGURE 5 compares the L5 and L2C CNAV message structure to the L1C CNAV-2 structure. CNAV was a major step forward compared to the original NAV message in terms of flexibility, precision, time to first fix (TTFF), and integrity. Instead of the fixed 30-second structure of the NAV message, CNAV consists of multiple six-second messages that are differentiated by a message-type number. The sequence of broadcast message types is defined by the GPS control segment, which greatly improves flexibility. The round-off error in the NAV message can affect pseudorange calculations by up to 40 centimeters, whereas the equivalent CNAV error contributes about 3 centimeters. Orbit and clock precision is substantially improved. Because a minimum of three message types are needed for the necessary orbit and clock parameters, as little as 18 seconds is needed to gather the necessary information after locking to a signal. On the other hand, if four message types are being sent sequentially, and the receiver locks just after the beginning of a message, it can take 30 seconds to gather the necessary data. TTFF typically is improved. Importantly, each CNAV message includes a 24-bit cyclic redundancy check (CRC) word that makes it practically impossible to have bit errors in a message that passes the CRC check.

CNAV-2 improvements to the CNAV structure all but guarantee an 18-second TTFF after signal acquisition. Message efficiency is improved by eliminating the need to identify each six-second message, to have complete time-of-week (TOW) information in each six-second message, and to have three rather than two 24-bit CRC words every 18 seconds. Even more important, GPS time is defined modulo 18 seconds upon acquisition of only one signal, and it is defined modulo two hours by decoding only one 26-bit, 0.52-second time-of-interval (TOI) word at the beginning of each message. In addition, TOI is so well encoded (52 symbols for nine data bits) that it can be demodulated in very weak signal conditions, which can be further enhanced by combining the identical TOI symbols transmitted by every satellite at the beginning of every 18-second message.

FIGURE 6 illustrates the ability to combine message symbols from several sequential Subframe 2 data blocks so vital clock and ephemeris data can be demodulated at the weakest signal level the receiver can track. This feature is made possible because the symbols in subframe 2 will not change for at least 15 minutes (50 repeats) and typically no more often than one to two hours (200 to 400 repeats). This provides up to 8.4 dB of message demodulation improvement. The figure also shows other L1C improvements: 4.8 dB of carrier track threshold extension, and a TTFF of 18 seconds after successfully demodulating subframe 2 from the minimum number satellites for a position fix.

Subframe 3 of the L1C message contains less time-critical information such as almanac, ionospheric correction terms, and so on. This subframe also is LDPC block-encoded so it is quite robust, although it does not offer the ability to combine symbols from sequential messages.

Pilot Overlay Code

Figure 5 shows that the pilot overlay code consists of 1,800 chips that frame
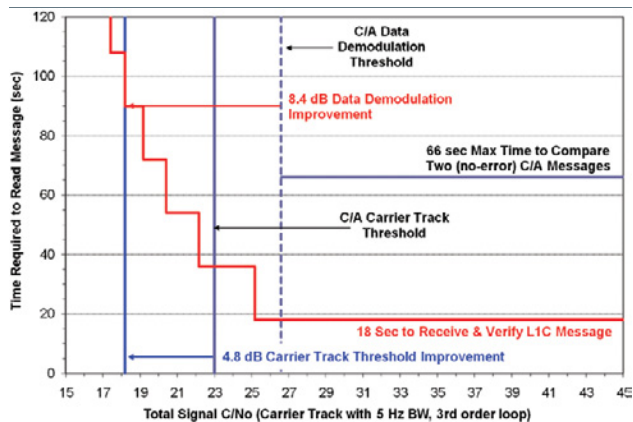
▲ **FIGURE 6** L1C and C/A performance comparison.
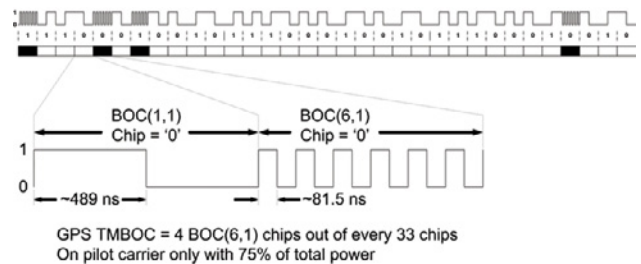

▲ **FIGURE 7** The GPS MBOC (TMBOC) modulation.

the 18-second message. In comparison with the L5 20-millisecond (ms) pilot overlay code, it not only is 900 times longer but also is unique to each satellite. This improves cross-correlation performance in general and particularly when two satellites have the same pseudorange.

The long L1C overlay code can be acquired reliably after only one or two seconds of signal lock. Its length does not cause a relevant delay in TTFF, but it provides many advantages. First, synchronizing to the overlay code on one satellite defines GPS time for all satellites modulo 18 seconds (in comparison to 1 ms with the C/A code). Even with infrequent use, the receiver's RTC, which typically is better than 5 parts per million (ppm), should have sufficient accuracy — better than ± 9 seconds — to completely resolve GPS time with one signal acquisition. In 24 hours with a clock frequency error of 5 ppm the time drift would be less than ½ second.

Even if the RTC is in error by several times 18 seconds, resolving accurate time can be done quickly by computing position fixes with multiple time hypotheses spaced 18 seconds apart. Pseudorange changes at rates up to ±1,440 kilometers per 18 seconds. Because some satellites are approaching, others are moving away, and all of them are changing range at different speeds (different Doppler frequencies), determining which position fix is correct out of several 18-second GPS time hypotheses will be straightforward since only one will be reasonable. (Care must be taken to avoid any extremely rare instances where two results may seem reasonable.)

The worst clock error with aided GPS (A-GPS) is ±2 seconds, which is adequate to completely resolve GPS time after acquiring only one L1C signal. This capability can aid acquisition of and navigation with other signals, such as C/A or signals from other GNSS providers. The 18-second overlay code will provide benefits as soon as even a few L1C signals are available.

The L1C overlay code, in conjunction with the repeating symbols of message subframe 2, also enables data demodu-lation to begin at any point within an 18-second message. It is not necessary to wait for the message frame to begin. The receiver can begin collecting data symbols at any time, and 18 seconds later it will have assembled all the subframe 2 clock and ephemeris information and can begin to navigate. An exception occurs when the satellite message is updated, between once every 15 minutes to once every two hours. This capability significantly improves TTFF whenever satellite messages are needed for navigation, for example, when they aren't still valid from a previous collection or aren't provided by an A-GPS service.

Spreading and Overlay Code Designs

The L1C MBOC waveform (time-multiplexed BOC, or TM-BOC), shown in **FIGURE 7**, enabled GPS and Galileo to have open-service L1 signals with an identical spectrum, although implemented quite differently. L1C places all the BOC(6,1) chips in the pilot carrier. This is because the BOC(6,1) component is intended to improve code-tracking performance by increasing code loop signal-to-noise ratio (SNR) and by allowing advanced multipath-mitigation techniques to have the advantage of more code transitions. Because these measurements are made almost exclusively on the three times (4.8 dB) more powerful pilot signal, there is no reason to lose the code tracking benefit by having BOC(6,1) chips in the data signal component. In addition, narrowband receivers such as those predominantly used for consumer applications cannot process BOC(6,1) chips, so it would be undesirable to deny full message signal power to such receivers.

For receivers tracking only the BOC(1,1) component of L1C MBOC, there are on average 43.5 code transitions per 33 chips. For those tracking both components, there are on average 89.5 code transitions per 33 chips. This provides up to 3.1 dB of improvement in code loop SNR for wideband receivers code tracking with both types of chips. (The amount of improvement depends on receiver RF bandwidth.)

Classic multipath-mitigation techniques such as the double-delta don't work well with the BOC(6,1) waveform, but recent advances promise improvement by using the extra transitions in the MBOC signal. Some developers worry that the full benefit may not be achieved unless code symmetry and time alignment of the two components is better than the signal specification permits. If the satellites cannot

provide the needed signal symmetry and alignment, such problems likely can be overcome by ground calibration of these characteristics, either directly by each receiver or indirectly by an observing network.

Symbol Interleaving. Symbol interleaving means that before a message is transmitted, the satellite scatters the 10-ms message data symbols from subframes 2 and 3 throughout these subframes in a fixed and known pattern. After a receiver has demodulated (or otherwise measured) the symbols belonging in a subframe, they are reassembled into the proper order before the LDPC block decoding is performed. In other words, the scattering done in the satellite is undone by the receiver. The objective is to provide a measure of protection against certain types of signal fading. For example, if a sequence of symbols from the satellite is lost because the receiver passes behind an object such as a tree, only half the symbols in this part of the message would be affected if the adjacent symbols in the original message are received either before or after the signal blockage. Thus, with reasonable signal levels and the benefit of powerful LDPC block encoding, the entire message could be reconstructed.

Performance Metrics and Comparison

A main objective for the L1C signal structure was to significantly improve the autonomous navigation capability for GPS users. Key weaknesses in the current C/A signal include the thresholds for bit synchronization, message synchronization, and data-bit demodulation. To achieve navigation at very low signal levels, users of the L1 C/A signal had to employ external sources for time synchronization, data acquisition, and, to extend the tracking loop threshold, external data-bit aiding to enable phase-locked tracking rather than Costas tracking of the C/A signal. The new signal structure addresses all of these shortcomings and provides a robust autonomous navigation system

that requires no external aiding for most commercial applications.

Message Frame Synchronization and Time of Transmission. For autonomous navigation, frame synchronization has two important roles. The first is to set GPS time, modulo frame duration, which is required to establish the unambiguous time of transmission. Frame synchronization, or knowledge of frame start, also enables assembly of the received bits into the appropriate data words. In both L1 C/A and L5, frame synchronization is accomplished by recognizing a synch word within a data subframe, which requires accurate demodulation of data bits. For L1C, frame synchronization is inherent in the signal structure and does not require demodulation of data bits. This is very important for two reasons. The first is to establish GPS time of transmission very quickly, especially when the satellite message is not needed, for example, if it was acquired previously or obtained by other means. The second is when satellite ephemeris data is necessary, but the signals are very weak. The L1C message structure facilitates this capability.

Overlay Code on Pilot Carrier. One frame of data consists of 1,800 symbols modulated onto the data carrier which, at 100 symbols per second, is 18 seconds long. However, synchronized to this 18-second data frame is a pseudorandom code modulated on the dataless pilot carrier. This 100 chips per second overlay code is a linear-shift-register code that is truncated to be 1,800 chips long. The overlay codes were chosen to have very low minor auto-correlation and cross-correlation peaks so a very short segment of the code can be used to establish its underlying code phase.

If a 100-chip segment of the received code is correlated over a replica of the entire code, the proper correlation peak would be easily distinguished, thus establishing the GPS time epoch at the start of the code. Since this code epoch and the start of the data frame are synchronized, the start of the entire data frame is established, modulo 18

seconds. The start of the data frame by definition establishes the GPS time of transmission, also modulo 18 seconds. This is accomplished without decoding a single data bit by using the power advantage of the pilot carrier.

However, using the message to resolve the 18-second time ambiguity often is not needed. For example, the receiver's real time clock (RTC) is likely to be accurate to within ±9 seconds. Alternately, almost any source of external aiding can provide time to within ±2 seconds. In either case, if the receiver already has a valid satellite ephemeris, navigation can begin after receiving a little over 1 second of the stronger pilot carrier signal. Ephemeris data can be available in a number of ways, including prior reception from the satellite, from a separate communications channel, or from one of several predicted ephemeris sources.

Message Frame – Data Format. A message frame consists of 1,800 symbols that comprise two distinct data types. The first data type, in subframe 1, is the Time of the Frame (TOI or Time of Interval) modulo two hours. The second data type is further separated into two blocks, subframe 2 containing data that is fixed for a period of time and subframe 3 containing data that can change from frame to frame.

Time of Interval Subframe. The TOI is a count of the number of 18-second message intervals in each 2 hour time period. Two hours is the maximum duration of any ephemeris message before being replaced by the satellite. (Fifteen minutes is the minimum.) There are 400 18-second intervals in 2 hours, so it requires 9 bits to represent the 400 intervals. These nine bits are block-encoded into 52 symbols using a BCH(51,8) code, where the 8 data bits are the least significant bits of the TOI. The most significant bit (MSB) of the TOI is then mod-2 added to the BCH codeword and also appended to the resulting codeword as its MSB, resulting in a 52-symbol codeword. This coding provides a BER of 10^{-5} for an E_b/N_0 of −1.9 dB per coded symbol or a C/N_0 of

+18.2 dB-Hz at the correlator output for the data channel. Since the data channel contains only 25 percent of the total L1C power, the C/N_0 of the composite signal would be +24.2 dB Hz. Symbol demodulation is performed using the pilot carrier tracked by a PLL as the phase reference. Since the pilot carrier contains 75 percent of the total power, its C/N_0 would be +23 dB-Hz. With a (single-sided) loop-noise bandwidth of 10 Hz, the loop SNR for the carrier channel PLL would be +10 dB.

Note that a 10^{-5} BER is not required for successful demodulation of TOI. Therefore, weaker signals can be used successfully if the PLL loop bandwidth can be smaller in such weak signal conditions.

The most straightforward method to decode the TOI is brute force maximum likelihood estimation. All possible code words for the 400 possible data words can be pre-computed. Each then can be compared (correlated) with the received code word. The data word that corresponds to the code word with the highest correlation would be the result of the decoding process.

Finally, since all satellites simultaneously transmit the same TOI, the received code word from several satellites can be combined to increase the effective Eb/N_0. The target BER of 10^{-5} thus can be achieved at an even a lower C/N_0 than the single satellite value. In this case, the decoding process described above can be performed on a composite code word derived from two or more satellite signals, weighted appropriately for the signal strength from each one.

As an example, consider a receiver with access to an external source of the ephemerides. By combining the TOI code word from five satellites, the average C/N_0 required per satellite would only be 17.2 dB-Hz, so time could be established to ±1 hour in slightly over 1 second.

Because of the 18-second overlay code, decoding TOI is not required for receivers with an internal clock good to ±9 seconds or with external time

aiding, the worst of which today is within ±2 seconds.

Data Subframes. The remaining data bits are separated into two additional subframes. (TOI is in the first subframe.) The second subframe contains data that does not change for at least 15 minutes, and typically for an hour or two. This subframe provides the satellite ephemeris and the interval time-of-week (ITOW) count, which identifies the start time of the two-hour interval since the beginning of the GPS week, which, in turn, frames the TOI count of 18-second intervals within each two-hour frame. The third subframe contains data that normally changes from frame to frame, such as the satellite constellation almanac.

The block of data containing the satellite ephemeris (subframe-2) consists of 576 clock and ephemeris bits along with a 24-bit CRC, for a total of 600 bits. These are encoded with a rate-½ LDPC Block code into 1,200 symbols. The block of data containing variable data (subframe-3) consists of 250 data bits along with a 24-bit CRC, for a total of 274 bits. These are also encoded with a rate-½ LDPC Block code into 548 symbols. The 1,748 symbols of the two data subframes are combined and interleaved using a simple 38 x 46 row-column block interleaver. These interleaved symbols plus the 53 TOI symbols make up the entire 1,800-symbol (900-bit) message frame.

Since both the LDPC codes and the interleaver operate on independent blocks of data, the resulting symbols for subframe-2 are identical and in the same location in each message frame for between 15 minutes and two hours. Since the data decoding uses the pilot carrier as the phase reference, the subframe-2 symbols can be coherently combined over many 18-second message frames before decoding to improve BER performance.

One reasonable subframe-2 strategy would be to check the CRC after LDPC-decoding the first received message to determine if there are any remaining bit errors. If errors are de-

tected, do the same with the second message. If errors exist in the second message, coherently combine the symbols from the two messages, properly weighted, LDPC-decode the combination, and check the resulting CRC for errors. If necessary, this process can be used on as many messages as needed to obtain a perfect result.

Framing the data messages with the pilot overlay code and the repeating characteristic of subframe 2 permits data collection over any arbitrary 18-second interval. It doesn't matter where data collection begins. The overlay code tells the receiver which symbol is which, and the repeating subframe-2 message can be compiled from any place in the previous message to the same place in the following message. The powerful CRC assures that a good message is perfect. When the ephemeris is needed from a satellite, rather than from an alternate source, these characteristics allow TTFF to be slightly over 18 seconds, with assurance the information is correct.

Since LDPC FEC has been adopted by the current state-of-the-art wireless standards such as 802.11n and 802.16e, employing it in the latest GPS signal structure should be simple for the receiver designer. In fact, synthesizable cores are available for WiMax LDPC decoders from several sources, and LDPC decoders are as commonplace in wireless signal basebands as Viterbi decoders for the convolutional codes of L2C, L5, and SBAS have become in GPS basebands.

For subframe-2 data, the Eb/N_0 required to achieve a BER of 10^{-5} is approximately 2.2 dB. For subframe-3 data, the Eb/N_0 required for this same performance is approximately 2.7dB.

Signal Structure

The L1C signal is a composite of two signals that are phase/frequency coherent with synchronized spreading codes and symbol timing. The pilot signal has 75 percent of the total power, is a carrier-only signal, and is spread by a 10-ms long code plus an 18-second

		L1 C/A		L1C#
Reference Code FFT	4096 pt	49,152	65,536 pt	1,048,576
10 msec accumulations	2046 samples	20,460		
Candidate Code FFT	4096 pt	49,152	65,536 pt	1,048,576
Correlation	4096 pt	4096	65,536 pt	65,536
IFFT	4096 pt	49152	65,536 pt	1,048,576
Additional freq translation (10)	20,460 samples	204,600		†
10 msec accumulate (10)	2046 samples	204,600		†
Additional Candidate FFTs (10)	4096 pt	491,520		†
Additional Correlations (10)	4096 pt	40,960	65,536 pt	655,360
Additional IFFTs	4096 pt	491,520	65,536 pt	10,485,760
Total complex operations		**1,605,212‡**		**11,141,120‡**

† Frequency translation for L1C can be accomplished in the frequency domain since the bin spacing is 50 Hz whereas for L1 C/A, the bin spacing is 500 Hz.
‡ Approximately 7 times as many complex operations are needed for L1C as for L1 C/A though symbol (bit) sync is inherent in the process for L1C
# L1C BOC modulation additionally complicates FFT-based correlation

▲ **TABLE 1** Comparison of FFT-based correlation for L1C versus L1 C/A.

overlay code. The data signal has 25 percent of the total power, is spread by a 10-ms long code, and is data modulated with 10-ms symbols.

Spreading Codes. The spreading code for both L1C signals are 10,230 chip codes with a chip rate of 1.023 MHz, producing a 10-ms long code. This corresponds to one symbol for the data carrier and one chip of the overlay code for the pilot carrier. These codes are not linear shift register sequences like all other codes employed by GPS, but are pseudo-random sequences derived from Weil sequences of length 10223. This sequence is extended by a 7-bit sequence 0110100, which is the same for all satellites, to the required length of 10230. The location within the particular Weil sequence where the extension sequence is inserted is called the insertion index. A pair of Weil indices and a corresponding pair of insertions points then determines the pair of codes for each satellite.

Synchronization to one of these Weil-based codes can be accomplished with a standard time-domain correlator, but the number of potential hypotheses has increased by a factor of ten compared to the C/A signal. However, this is no different than time-domain correlation for an L5 code, which also are 10,230 chips long. Synchronization also can be accomplished using FFT-based frequency-domain correlation, however it does require an FFT of length 65,536 (for a standard radix-2 implementation) since the FFT must

span 2 full code periods at a minimum of 2 samples per code chip (40,920).

To compare L1C frequency domain correlation with L1 C/A, a frequency search window and integration time must be hypothesized. A simple example would be a 10-ms coherent integration time and ±250 Hz frequency uncertainty. **TABLE 1** compares the number of complex operations required for L1 C/A vs. L1C.

For cases where large search window uncertainties exist, and frequency domain correlation provides a computational benefit, an alternate approach to L1C synchronization would be to first obtain L1 C/A synchronization using an FFT-based search, providing frequency and 10 timing hypotheses (perhaps more with potential cross-correlations for L1 C/A). These L1C hypotheses could be tested by simple time-domain correlation that would benefit from the much better cross-correlation properties of the L1C codes.
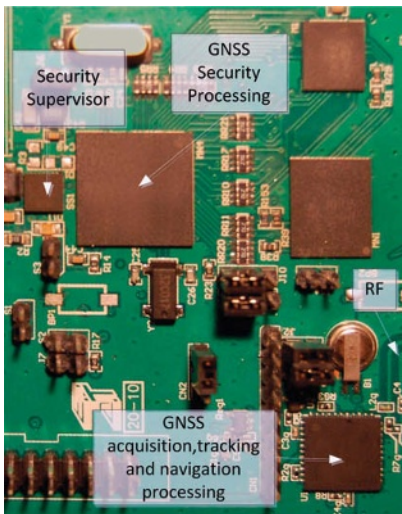
For cases where time uncertainty is not large, a time domain search of the L1C code would be no more difficult than the equivalent for L1 C/A. For cases where the time uncertainty is small but the frequency uncertainty is large, time-domain partial-period correlations could be combined in an FFT structure that would span a large frequency uncertainty with a single time hypothesis. For example, the 10,230 chips could be separated into 62 segments, each 165 chips long. The 62 segments could then be combined using a

zero filled 64-pt FFT to produce 64 full correlations spanning ±3 kHz.

MBOC Waveform. The L1C spreading code is further modulated with a code clock synchronized 1.023 MHz square wave creating the BOC(1,1) signal that forms the majority of the L1C code symbols. This produces a code that appears as a 1 MHz square wave, synchronized to the Weil-based code edge, whose polarity indicates the state of the Weil-based code chip. This BOC(1,1) sequence modulates all of the data channel chips and 29 of every 33 pilot channel chips. The other 4 out of 33 Pilot channel chips are modulated by a BOC(6,1) code symbol in which a 6 MHz square wave is used instead of the 1 MHz square wave for the BOC(1,1) chips. (Recall that '1' signifies 1.023 MHz and '6' signifies 6.138 MHz.) For receiver designers who choose not to punctual correlate the BOC(6,1) component of the pilot carrier, the pilot carrier power will be reduced by ~0.6 dB.

The BOC(6,1) signal component provides an opportunity for better performance of advanced multipath mitigation techniques. The presence of multipath interference not only impacts the code-tracking process of a GPS receiver but also distorts the waveform seen by the phase-tracking process of the receiver. The distortion of the phase of the received signal is most problematic when the reflector creating the multipath signal is very close to the receiving antenna, because the path length of such a multipath signal changes very slowly. Since the path length changes very slowly, it appears as an almost constant bias error in the phase measurements. The only way to observe this distortion, and hence measure its impact on the phase measurements, is to observe the phase of the carrier very close to the code transitions. The estimate of this distortion obviously is better the more frequently it can be observed. This is particularly important because the distortion is not constant but slowly changes. The MBOC signal combination provides

▲ **FIGURE 5** TIGER hardware security components.

FUTURE WAVE *(continued from page 36)*
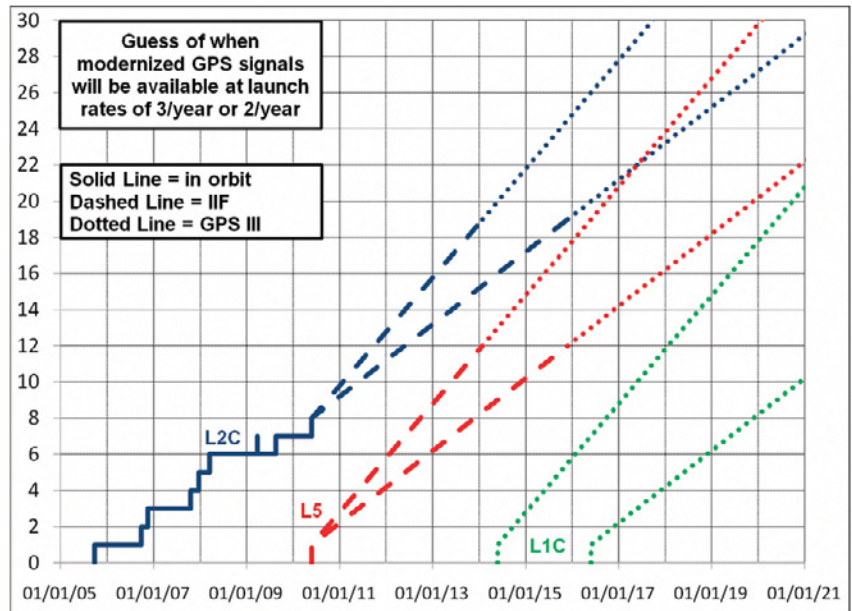
▲ **FIGURE 8** Guesstimate of modernized GPS signal availability.

Acknowledgment

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just over twice the number of transitions at which to observe the phase distortion than the BOC(1,1) signal alone, which is important for higher fidelity measurements during short intervals when the slowly changing distortion is highly correlated .

L1C Status

Companies already are designing L1C into their new chipsets, even though the first satellite to carry the signal is not expected before 2014. When will L1C be available from enough satellites to be meaningful? **FIGURE 8** is a guesstimate of how modernized GPS signals will become available over the next decade. The projections assume either two or three successful satellite launches per year, and many observers think two per year may be realistic. Because GPS only launches on need to sustain the constellation, the actual launch rate depends on the lifetime of the satellites now in orbit. The first launch of a GPS III may be delayed until all IIF satellites have been launched, or the first GPS III, if available, may be launched before the last IIF to test the new design in space as soon as possible.

Some L1C signal and message characteristics will significantly benefit us-

ers of C/A and other GNSS signals by, for example, quickly resolving time for all GNSS signals. Therefore, L1C will provide meaningful benefit as soon as even one signal can be tracked from any location on earth. That might be possible with as few as six GPS III satellites in orbit, depending on where in the constellation they are deployed.

Acknowledgment

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