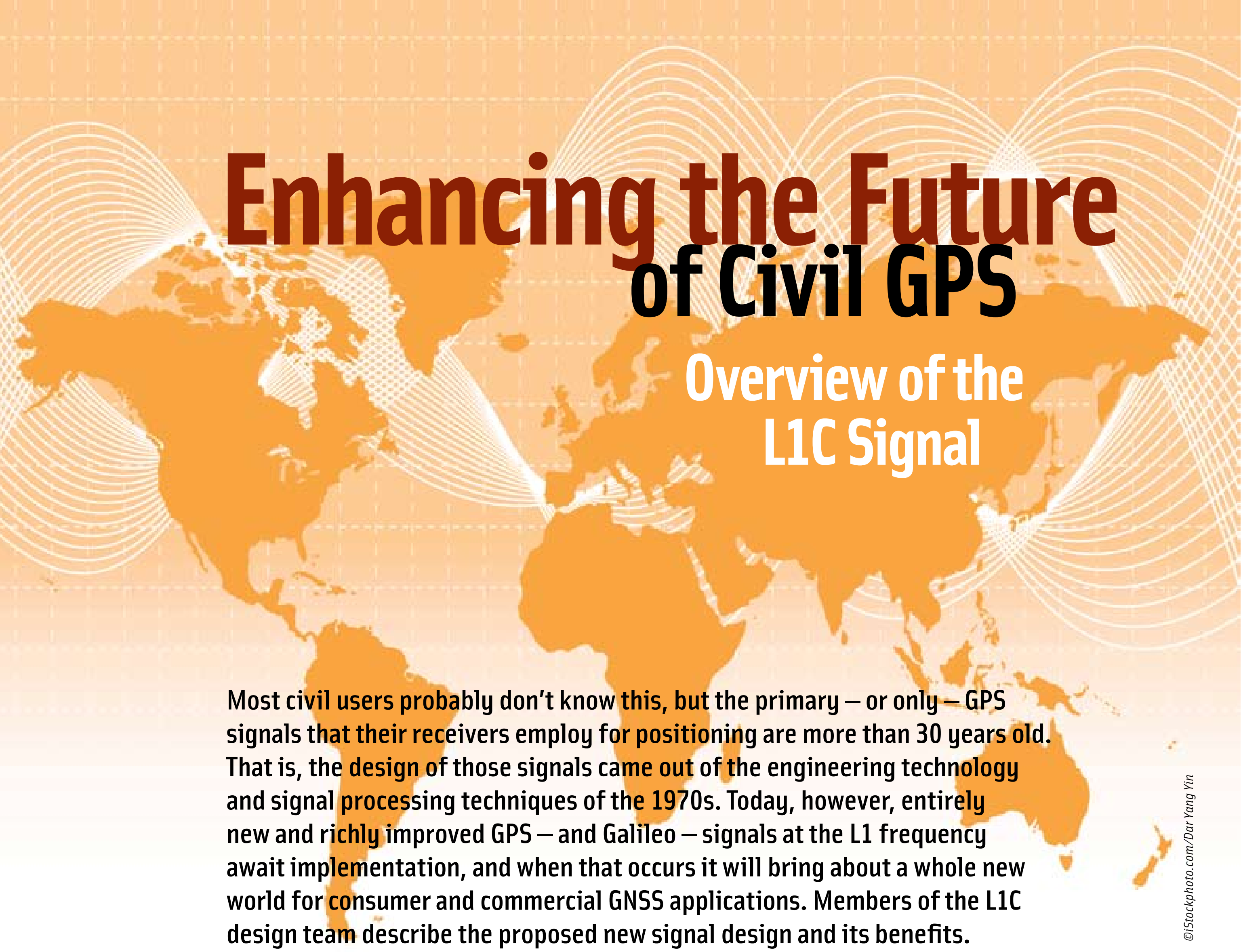
Enhancing the Future of Civil GPS

Overview of the L1C Signal



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Most civil users probably don't know this, but the primary — or only — GPS signals that their receivers employ for positioning are more than 30 years old. That is, the design of those signals came out of the engineering technology and signal processing techniques of the 1970s. Today, however, entirely new and richly improved GPS — and Galileo — signals at the L1 frequency await implementation, and when that occurs it will bring about a whole new world for consumer and commercial GNSS applications. Members of the L1C design team describe the proposed new signal design and its benefits.

JOHN W. BETZ
THE MITRE CORPORATION

MARIO A. BLANCO
THE MITRE CORPORATION

CHARLES R. CAHN
INDEPENDENT CONSULTANT

PHILIP A. DAFESH
THE AEROSPACE CORPORATION

CHRISTOPHER J. HEGARTY
THE MITRE CORPORATION

KENNETH W. HUDNUT
UNITED STATES GEOLOGICAL SURVEY

VIPADA KASEMSRI
THE MITRE CORPORATION

RICHARD KEEGAN
INDEPENDENT CONSULTANT

KARL KOVACH
ARINC ENGINEERING SERVICES

CAPT LAWRENCE S. LENAHAN
UNITED STATES AIR FORCE, GLOBAL POSITIONING SYSTEMS WING

HOWARD H. MA
THE MITRE CORPORATION

JOSEPH J. RUSHANAN
THE MITRE CORPORATION

DEAN SKLAR
THE AEROSPACE CORPORATION

THOMAS A. STANSELL
STANSELL CONSULTING

CHARLES C. WANG
THE AEROSPACE CORPORATION

SOON K. YI
ARINC ENGINEERING SERVICES

The Global Positioning System is undergoing continual modernization, providing ongoing improvements for users worldwide. Although various enhancements in system features have been under development since the mid-1990s, modernization first benefited civil users when Selective Availability — a security-motivated technique for "dithering" the open L1 signal to reduce positioning accuracy — was set to zero in May 2000.

Subsequently, other improvements in accuracy have been obtained through enhancements to the capabilities and operation of the control and space segments, still based on the original set of GPS signals with spectra shown in the first row of **Figure 1**.

The launch of the IIR-14(M) (modernized replenishment satellite) in 2005 began a new era with transmission of the L2 civil (L2C) signal, along with the modernized military M-code signal. The second row of Figure 1 shows the L2C and M-code spectra. A third civil signal, called L5, will be transmitted from Block IIF satellites, with spectra shown in the third row of Figure 1.

All the while, improvements in monitoring, satellite technology (for example, the on-board atomic clocks) and operations yield continuing increases in accuracy. The United States plans to continue providing these capabilities free of user fees. It will continue to complement this pricing policy by providing free and open signal descriptions and other technical information needed for development of receivers and services using civil signals.

In the meantime, development of the next generation of satellites, called GPS III, and a modernized control segment (OCX) continues, which will lead to greatly enhanced capabilities beginning early in the next decade. An integral part of the GPS III capabilities being developed is a new civil signal, called L1C, which will be transmitted on the L1 carrier frequency in addition to current signals, as shown in the bottom row of Figure 1.

Approximately one year ago, the U.S. Air Force released the initial draft of Interface Specification IS-GPS-800, describing L1C. Novel characteristics of the optimized L1C signal design provide advanced capabilities while offering to receiver designers considerable flexibility in how to use these capabilities.

The development of L1C represents a new stage in international GNSS: not only is the signal being designed for transmission from GPS satellites, its design also seeks to maximize interoperability with Galileo's Open Service signal. Further, Japan's Quazi-Zenith Satellite System (QZSS) will transmit a signal with virtually the same design as L1C. [1]

L1C has been designed to take advantage of many unique opportunities. Its center frequency of 1575.42 MHz is the pre-eminent GNSS frequency for a variety of reasons, including the extensive existing use of GPS C/A code, the lower ionospheric error at L1 band relative to lower frequencies, spectrum protection of the L1 band, and the use of this same center frequency by GPS, Galileo, QZSS, and satellite-based augmentation system (SBAS) signals for open access service and safety-of-life applications.

Other unique opportunities that the L1C design leverages include advances in signal design knowledge, improvements in receiver processing techniques, developments in circuit technologies, and enhancements in supporting services such as communications. The L1C design has been optimized to provide superior performance, while providing compatibility and interoperability with other signals in the L1 band.

L1C provides a number of advanced features, including: 75 percent of power in a pilot component for enhanced signal tracking, advanced Weil-based spreading codes, an overlay code on the pilot that provides data message synchronization, support for improved reading of clock and ephemeris by combining message symbols across messages, advanced forward error control coding, and data symbol interleaving to combat fading.

The resulting design offers receiver designers the opportunity to obtain unmatched performance in many ways. This article will give an overview of the L1C signal design, highlighting the features that will benefit receiver designers and, ultimately, end users. The following section provides background on L1C and its design process, from its beginnings in 2003.

Subsequent sections then provide an overview of the signal structure, details of the signal's spreading codes and overlay codes, spreading modulation, data message structure, and encoding and decoding of message information.

Finally, we will provide a summary of L1C's unique features and their benefits. Although more complete details are provided in IS-GPS-800, we will outline the most significant characteristics here.

Origins of L1C

The Interagency GPS Executive Board (IGEB) commissioned the L1C signal design project in August 2003. The IGEB has since been superseded by the National Space-Based Positioning, Navigation, and Timing (PNT) Executive Committee consistent with the updated U.S. policy on GPS announced in December 2004.

At the time that the L1C project was initiated, neither the desirability nor the feasibility of an L1C signal for GPS had been established. A final report issued on July 30, 2004 and authored by K. W. Hudnut and Capt. B. M. Titus documents the resulting effort over the initial 11 months of the L1C Project. A paper by J. W. Betz et al., "L1C Signal Design Options," presented at the 2006 National Technical Meeting of the Institute of Navigation also summarizes the results of this Phase I study. (See Additional Resources section near the end of this article for full details on both papers.)

The primary technical challenge involved what the L1C final report terms the "Message Data Rate Dilemma." When asked whether they preferred a data rate of 25, 50, or 100+ bits per second (bps), 41 percent of the respondents wanted 25 bps and 41 percent wanted 100 bps or higher.

In June 2004, in parallel with the activities related to the GPS L1C Project's Phase 1 study, the United States and the member states of the European Community signed an "Agreement on the Promotion, Provision, and Use of Galileo and GPS Satellite-Based Navigation Systems and Related Applications." As part of this agreement, the United States agreed to provide a future GPS III civil signal centered at 1575.42 MHz — in effect, the L1C signal. Thus, L1C unequivocally became part of the GPS III signal set.

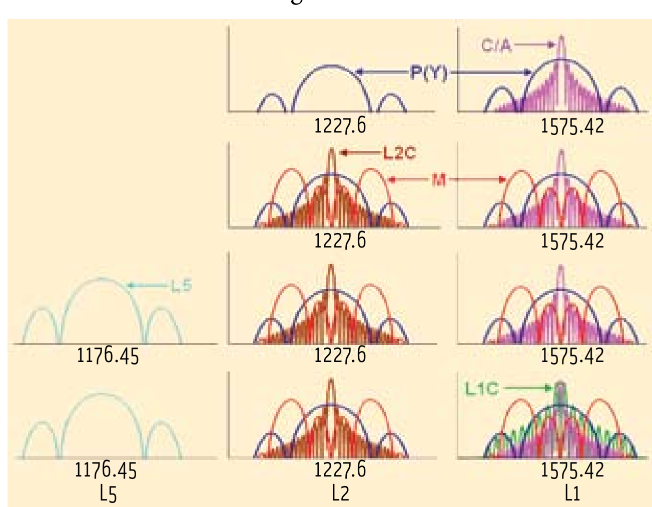

FIGURE 1 Evolution of GPS Signal Spectra (from top): Original, Block IIR-M, Block IIF, Block III

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The IGEB funded the L1C Phase 2 activity in late 2004, and the development of a detailed L1C design progressed throughout 2005. Among the many aspects of signal design addressed during Phase 2, data message issues remained pivotal. Perhaps the most persistent issue was the future of out-of-band (OOB) data messages (that is, provision of data messages by means other than the L1C signal-in-space, such as the Internet, broadcast using terrestrial transmitters including communications network assisted GNSS techniques, broadcast by other satellite systems, and so forth).

Although the L1C design team believed that the availability of OOB data messages is likely to increase, it struggled to predict with confidence which types of users might be able to rely on those data sources. The availability of OOB data messages to users in challenged environments (such as indoors) would alleviate the need to provide robust messaging in L1C.

In contrast, if OOB data messages were available to users who desire fast clock and ephemeris data (CED) or information that provides very high accuracy positioning, that would ease the need for the GPS system itself to provide high rate messages. Simultaneously, feedback from the user community indicated an interest in providing the most robust signal tracking performance.

Picking a Favorite

The L1C design team evaluated various options involving many different aspects of signal design, while assessing performance associated with these diverse aspects. Ultimately, it became clear that some aspects of the signal design were universally desirable, while tradeoffs were involved with other aspects.

The team assembled a large number of signal design options that included the universally desirable aspects with various combinations of the other aspects. Through performance assessments, a downselection process identified a set of five candidate design options for further consideration. Each candidate signal design represented a particular combination of features that the team thought might appeal to certain important classes of users.

The "L1C Signal Design Options" paper mentioned earlier describes these design criteria and the five design options and their performance. As summarized in Table 1 and more fully described in the paper, these design options differed in the number of data components, the power allocation among pilot and data components, and the data rates.

The five options contain two data rates, 50 and 75 bits per second (bps), and three options of how to split power between the pilot carrier and data. These include the "traditional" 50/50 power split, a pair of options with two data channels, and an option with 75 percent of the power in the pilot carrier and 25 percent in a single data channel at 50 bps. The Table 1 options with dual data channels have names beginning with a "D," while names of those with single data channels begin with "S."

The design team presented these options to GNSS experts around the world. Many of the 33 survey presentations were in person, and the rest were by telephone and the Internet, at times to multiple locations. The survey produced 81 responses (some representing a group of opinions) from the following countries: Japan, United States, Russia, United Kingdom, Canada, Australia, Finland, Germany, Switzerland, and Taiwan.

The percent of responses which favored each option were: S50/25% = 61.7 percent, D50/25% = 13.6 percent, S50/50% = 12.3 percent, D75/25% = 9.9 percent, and S75/50% = 2.5 percent. The S50/25% option was the clear worldwide winner, and 83.3 percent of the responses from North America also preferred S50/25%. The L1C Project technical team evaluated the results of these surveys in January 2006, which guided the finalized design for L1C.

During the design process, the United States and its international partners in Japan and the European Union (EU) collaborated with regular interactions and exchanges of ideas and plans. During 2005 and 2006, a series of several meetings of the U.S.-Japan GPS-QZSS Experts' Working Group — and also of the U.S.-EU GPS-Galileo Working Group on Compatibility and Interoperability — took place to coordinate

Option Name	% Pilot Power	Full Accuracy & Variable Messages		Fast Start Messages	
		Data Rate (bps)	% Power	Data Rate (bps)	% Power
S50/25%	75	50	25	-	0
S50/50%	50	50	50	-	0
S75/50%	50	75	50	-	0
D50/25%	50	50	25	50	25
D75/25%	50	50	25	75	25

TABLE 1. Summary of L1C Design Options

on interoperable GNSS signal designs. In some cases, members of the Japan and European signal design teams also joined meetings of the L1C Project technical team.

A clear and positive outcome from these meetings: it is now certain that these future GNSS satellites will broadcast interoperable signals at L1. The L1C signal design described in IS-GPS-800 and in this article will be broadcast by GPS, and with minor modifications also by QZSS.

Galileo has designed and will broadcast an interoperable signal with the same signal spectrum as L1C, yet with many different characteristics motivated by different design objectives. A draft Galileo Open Service Signal in Space Interface Control Document (OS SIS ICD) issued May 23, 2006, describes the technical parameters of the corresponding Galileo L1C signal referred to as E1 OS. SBAS and other satellite navigation systems may also transmit L1C-like signals in the future.

By April 2006, all aspects of the L1C signal design had been finalized and described in the interface specification. Additional reviews preceded public release of IS-GPS-800 on April 19, 2006. The GPS Wing initiated the public Interface Control Working Group (ICWG) review process at this time and provided official public notification of L1C through the Federal Register and worldwide through diplomatic channels. IS-GPS-800 is now in the full regular ICWG review process.

L1C Signal Overview

The GPS III satellites will broadcast the L1C signal at the L1 carrier frequency of 1575.42 MHz.

The unequal power split, with 75 percent in the pilot component and 25 percent in the data component, improves pilot tracking thresholds by 1.8 dB compared with a 50/50 power split.

The 75/25 power split is enabled by two breakthroughs. First, the powerful forward error control (FEC) coding provides an improvement in data demodulation threshold of more than 7 decibels (dB) compared to signals without FEC, such as the C/A code signal.

Second, the L1C message structure allows data symbol combining across sequential messages, enabling demodulation of vital clock and ephemeris information at even lower carrier-to-noise values (C/N_0).

Signal generators on board the satellites will multiplex the L1C pilot and data components onto the L1 carrier, along with the P(Y) code signal, the M code signal, and the C/A code signal. The phase relationships between the two components of L1C and between the L1C components and C/A code are not specified in advance, but instead will be specified in the broadcast data message. This arrangement provides flexibility for the most efficient signal combining on the satellite.

Codes: Spreading and Overlay

Length-10230 sequences are used to spread both the pilot and data components of L1C, with a repetition period of 10 milliseconds (ms) at the 1.023 MHz chip rate. Different spreading sequences are used for each satellite and for each component (data and pilot).

The pilot component is also modulated by a length-1800overlay code unique to each satellite or space vehicle (SV). These overlay codes provide further correlation separation and aid in synchronization to the data message boundary. Each bit of the overlay code is applied to one repetition of the spreading sequence, e.g., over 10-ms intervals.

A new family of spreading codes was created for L1C that provide lower autocorrelation and crosscorrelation sidelobes while still being very practical to implement. We will next describe these new spreading and overlay codes in further detail.

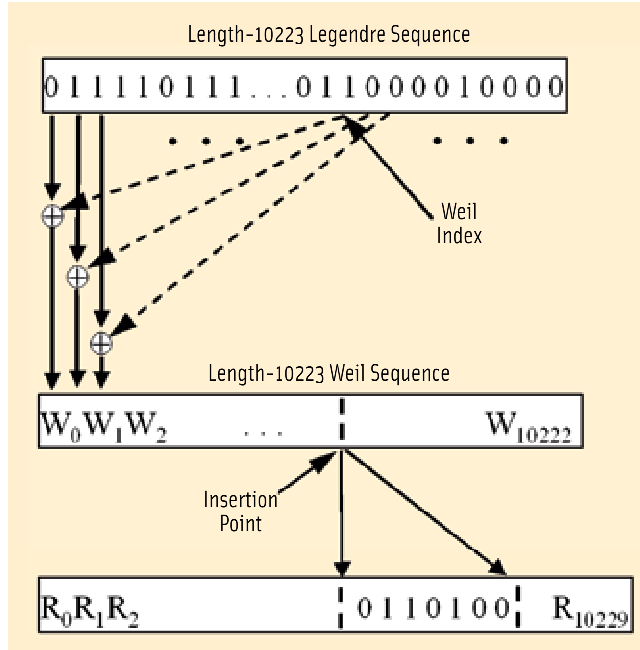

FIGURE 2 Construction of Length-10230 Weil-Based Spreading Codes. The figure shows construction of Weil Sequences from a single Legendre sequence, then extension to 10,230 bits by inserting seven additional bits, all using simple logical operations.

Spreading Codes. The new family of spreading codes is based on Weil sequences (described in the paper by J. J. Rushanan, cited in Additional Resources), which in turn are derived from the length-10223 Legendre sequence. Each Weil sequence is the component-wise exclusive-or of the Legendre sequence and a circular shift of the Legendre sequence. The value of this shift is the *Weil index*. The resulting Weil sequence is also length-10223.

A fixed seven-bit sequence is inserted into a Weil sequence to create a length-10230 L1C spreading code, which is specified by the value of the Weil index and the insertion point. All spreading codes are based on the Legendre sequence and the same seven-bit sequence. The construction, summarized in Figure 2, involves simple logical operations on the Legendre sequence and the seven-bit sequence.

An extensive search was conducted to produce 210 pairs of Weil-based spreading codes for BOC(1,1), each pair consisting of a pilot code and a data code. The search was repeated to find a different set of Weil-based spreading codes for a time-multiplexed (TMBOC) version of BOC(1,1). Because of the larger allocation of power to the pilot component, codes with the best correlation properties were allocated to pilot components. Each pilot/data pair was chosen to have very low mutual cross-correlation at zero lag.

Overlay Codes. Each overlay code is 1,800 bits long, aligned to the data message boundary. Overlay codes indexed 1 to 63 are reserved for GPS and are truncated m-sequences. The remaining overlay codes indexed 64 to 210 are truncated Gold sequences. The codes were also chosen to have good correlation properties for small window sizes. These low side-lobes enable more reliable synchronization to an interval, and thus to the data message.

Spreading Modulation

Two spreading modulation variants are under consideration, both using the spreading code chip rate of 1.023 MHz. The baseline spreading modulation is a binary offset carrier (BOC) modulation with 1.023 MHz spreading code chipping rate and 1.023 MHz square wave subcarrier frequency, sine phased, which is denoted as BOC(1,1) and described in further detail in the Institute of Navigation (ION) *NAVIGATION* article by J. W. Betz cited in Additional Resources.

The alternative spreading modulation, called multiplexed BOC (MBOC) and recommended by the GPS-GALILEO Working Group on Interoperability and Compatibility, has a spectrum produced by 10/11 of the total signal power in a BOC(1,1) component, and 1/11 of the total signal power in a BOC(6,1) component:

$$\Phi_{MBOC}(f)=\frac{10}{11}\Phi_{BOC(1,1)}(f)+\frac{1}{11}\Phi_{BOC(6,1)}(f)$$

where $\Phi_{BOC(1,1)}(f)$ is the normalized (unit power) power spectral density of a BOC(1,1) signal, and $\Phi_{BOC(6,1)}(f)$ is the normalized power spectral density of a BOC(6,1) signal. (See the article by G. Hein et al. cited in Additional Resources.)

The L1C implementation of MBOC is called time-multiplexed BOC (TMBOC), and is produced by replacing four of each 33 spreading symbols in the pilot component with BOC(6,1) spreading symbols, while retaining BOC(1,1) for all other spreading symbols in the pilot and also for all of the data spreading symbols. The result is then (4/33) × (3/4) = 1/11 of the total power in BOC(6,1), and the remaining 10/11 of the total power in BOC(1,1), consistent with the desired MBOC spectrum.

Figure 3 compares the power spectral densities (PSDs) of L1C pilots using BOC(1,1) and TMBOC, compared with C/A code's BPSK-R(1) spectrum. The increase in higher frequency power is evident.

A discussion of relevant characteristics of both alternatives summarized in a paper by J. W. Betz et al., "Description of the L1C Signal," (see Additional Resources citation) and presented at ION GNSS 2006 indicates that a BOC(1,1) spreading modulation offers advantages over a hypothetical BPSK-R(1) spreading modulation for L1C in almost all areas, except for performance of double-delta processing against multipath. A TMBOC pilot extends most of those advantages, several of them by more than 1 dB over BOC(1,1).

The United States has indicated that GPS will follow Galileo's lead in choosing between MBOC and BOC(1,1); so, the EU's decision also affects GPS and potentially other satellite navigation signals such as QZSS and SBAS. European authorities are still assessing whether near-term programmatic aspects allow adoption of MBOC.

Message Structure

Figure 4 shows the basic L1C data message structure. A frame is divided into three subframes that provide time, non-variable data, and variable system data. Multiple frames (i.e., a superframe) are required to broadcast the complete set of data messages.

Each frame consists of 9 bits of "Time of Interval" (TOI) data (describing the index of this next message frame within the two-hour interval) in subframe 1; 600 bits of "non-variable" clock and ephemeris data with cyclic redundancy check (CRC) in subframe 2; and 274 bits

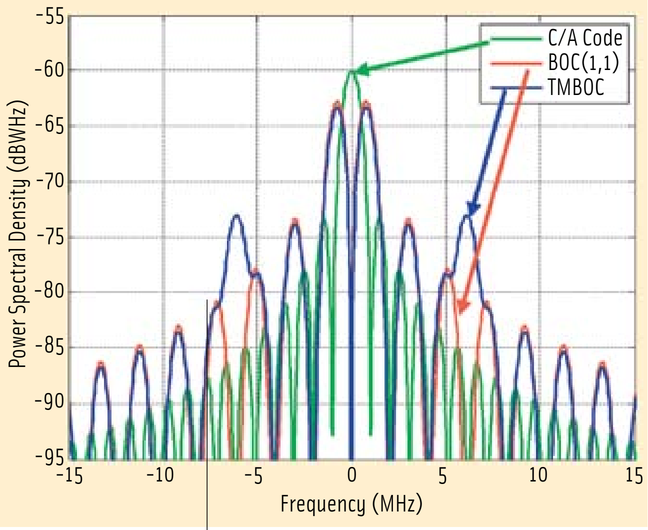

FIGURE 3 Unit Power PSD of L1C Pilots using BOC(1,1) and TMBOC Spreading Modulations, Compared to C/A Code PSD, Showing the Increases in Beneficial High Frequency Power

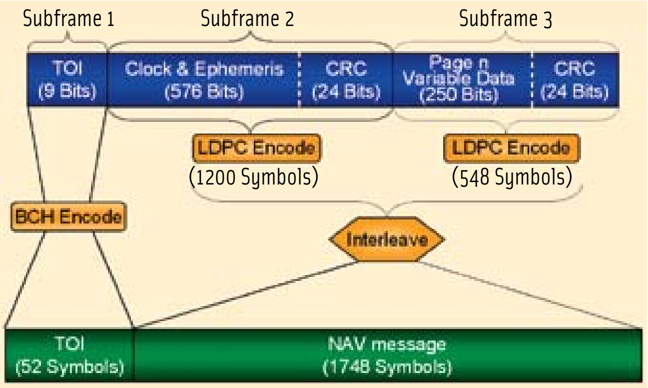

FIGURE4 Data Message Structure

of “variable” data with CRC in subframe 3.

The content of subframe 3 nominally varies from one frame to the next, and each subframe 3 is also identified by a page number. The content of subframe 2 is nominally invariant over a period of multiple frames lasting nominally two hours, allowing subframe 2 symbols to be combined over multiple messages for demodulation at lower C/N_0 values.

The TOI data in subframe 1 corresponds to the time epoch at the start (leading edge) of the following frame. This TOI data, together with Interval Time of Week data in subframe 2, specify the satellite time within a GPS week with a resolution of 18 seconds. The 9-bit TOI data is encoded into 52 symbols using Bose, Chaudhuri, and Hocquenghem (BCH) coding described in the following section.

The 24-bit CRC scheme used in subframes 2 and 3 is the same as used for L2C, L5, and SBAS navigation data. Each of the two subframes (2 and 3) is further encoded using low density parity check (LDPC) FEC coding and interleaving, as will be described in a subsequent section. The resulting 1,800 channel encoded symbols, representing one message frame, biphase modulate the spread data component at 100 symbols per second.

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TOI Error Correction

The TOI word changes in every message frame and is encoded for error correction separately from the other contents of the data message. Because an interval may last for up to two hours, or 7,200 seconds, there may be up to 7,200/18 = 400 frames in an interval. Hence, the TOI must be represented by nine bits.

The error-correcting code for TOI provides a low probability of error at the C/N_0 that allows one repetition of the fixed message to be decoded with a low message-error rate. To get a low probability of error for TOI, the error-correcting code must have a high redundancy. The code selected for TOI is a BCH(n,k) linear code with a large minimum Hamming distance. Here, n is the number of coded bits and k is the number of data bits in the block.

A search of BCH codes listed in Appendix D of *Error-Correcting Codes* by W. Peterson and E. Weldon (see citation in Additional Resources) yielded an attractive candidate for the nine-bit TOI: a BCH(51,9) with minimum distance 19. A 51-bit code word is generated by an eight-stage linear shift-register generator (LSRG) defined by the polynomial $x^8 + x^7 + x^6 + x^5 + x^4 + x + 1$. Appending an overall parity extends the BCH(51,9) code with odd minimum distance to a (52,9) code with minimum distance 20, for which the weight distribution is: $A(20) = 51$, $A(24) = 204$, $A(28) = 204$, $A(32) = 51$, and $A(52) = 1$. The resulting 52-bit code word occupies a duration of 26 data bit periods in the message frame.

The receiver can readily generate the replica code words using a linear shift-register generator (LSRG) with the requisite feedback connections (discussed further in *Error-Correcting Codes*). It can then perform maximum-likelihood decoding by correlating the stored received soft decisions of the coded bits against all possible candidate TOI code words.

This “brute-force” decoding is relatively simple because it is done at low speed, and the decoder has to retain only the single candidate code word that produced the maximum correlation. Moreover, sensitivity can be improved through code combining (summing or otherwise using repeated soft decisions) over identical TOI words received from different satellites.

LDPC Codes and Interleaving

Subframes 2 and 3 of the transmitted L1C message consist of 1,748 interleaved error control coded symbols, produced by separately encoding the 600 and 274 raw, CRC-protected NAV information bits contained in subframes 2 and 3, followed by interleaving of the symbols from both subframes. LDPC FEC codes were selected for L1C due to their block structure, superior performance, low implementation complexity, and non-proprietary technology. A brief overview of LDPC codes is provided in the appendix to “Description of the L1C Signal,” by J. W. Betz et al.

Different rate-½ irregular LDPC codes are used for the two subframes, because of the different subframe lengths. Subframe 2 contains identical, repeating bits for each interval (lasting up to 2 hours), while subframe 3 can change with each message. Because subframe 2 is encoded separately from subframe 3, the subframe symbols — even after being dispersed by the interleaver — remain invariant over the interval. Phase tracking of the pilot component does not have a 180-degree ambiguity; therefore, the receiver can then readily perform code combining of subframe 2 symbols over multiple messages to read clock and ephemeris at progressively lower values of C/N_0.

To mitigate correlated errors within a NAV frame, the 1,748 encoded symbols of subframes 2 and 3 are combined and

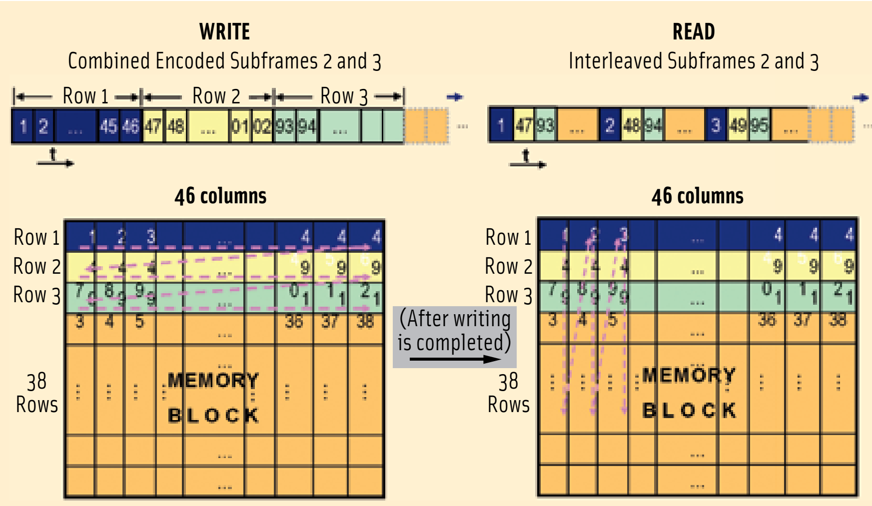

FIGURE 5 Block Interleaving of Subframes 2 and 3

interleaved using a block interleaver. The block interleaver can be visualized as a two-dimensional array of 46 columns and 38 rows depicted in **Figure 5**.

Encoded symbols are sequentially written into the interleaver from left to right starting at Row 1. After Row 1 is filled, symbols are written sequentially into Row 2 in the same manner, starting from the left-most cell. This process continues until the 1748th symbol is written into the rightmost cell of the last (38th) row.

Once all 1748 symbols are written into the array, the symbols are sequentially read out of the array from top to bottom starting at Column 1. After reading out the last (38th) symbol in Column 1, the symbols from Column 2 are read out in the same manner starting at the top and moving downward. This process continues until the last symbol in the (38th) cell of the last (46th) column is read out. Because the interleaving is the same for each message, the interleaved symbols from Subframe 2 occur at the same locations.

Summary of Benefits

L1C has been designed with unique, innovative, and powerful new features to enhance its robustness for all users, especially in difficult environments.

The signal structure alone, with the spreading code and the overlay code, provides exact GPS time, modulo 18 seconds. Alignment to the spreading code provides bit synchronization and alignment to the overlay code provide frame synchronization, making these receiver functions simple and robust.

For high-precision (e.g., survey) use, the pilot carrier removes the half cycle phase ambiguity, and the larger RMS bandwidth of the new spreading modulation has the potential to improve tracking performance, especially multipath mitigation. With the combination of improved carrier tracking of the pilot component, segmentation of clock and ephemeris in the data message, and FEC design, an autonomous navigator can demodulate the satellite clock and ephemeris whenever the signal can be tracked.

The improved cross-correlation of the new codes will also improve the performance of high-sensitivity receivers. Performance will also improve as a result of the new message format that allows code combining across satellites for the TOI and code combining of the near constant sub-frame 2 ephemeris data across multiple frames. International collaboration and outreach have assisted in producing a truly international signal with capabilities that will serve users for decades to come.

Acknowledgments

The Interagency GPS Executive Board provided major funding for the L1C Project, with matching support provided through significant contributions from the Air Force and Federal Aviation Administration. MITRE's work was supported by the Air Force under contract FA8721-04-C-0001 and by the Federal Aviation Administration under contract DTFA01-01-C-00001. Work by Stansell Consulting, Dr. Cahn in part, and Mr. Keegan was supported by the U. S. Geological Survey under Purchase Order 05WRCN0005. Aerospace's work and part of Dr. Cahn's work was supported by the Air Force under contract number FA8802-04-C-0001. ARINC's work was supported by the Air Force under contract number F04701-00-A-8002.

Additional Resources

[1] ____, "Agreement on the Promotion, Provision and Use of GALILEO and GPS Satellite-Based Navigation Systems and Related Applications," June 2004. Available at <http://pnt.gov//public/docs/2004-US-EC-agreement.pdf/>

[2] ____, "Galileo Open Service Signal in Space Interface Control Document (OS SIS ICD) Draft 0," 23 May 2006, available at <http://www.galileoju.com/>

[3] ____, "U.S. Space-Based Positioning, Navigation, and Timing Policy," December 15, 2004, available at <www.ostp.gov/html/ FactSheet-SPACE-BASEDPOSITIONINGNAVIGATIONTIMING.pdf>

[4] ARINC, *NAVSTAR GPS Space Segment/User Segment L1C Interfaces*, IS-GPS-800, ARINC Engineering Services, LLC, El Segundo, California, 19 April 2006, available at <http://gps.losangeles.af.mil/engineering/icwg/Docs/Draft%20IS-GPS-800%2019Apr06.pdf >

[5] Betz, J. W., "Binary Offset Carrier Modulations for Radio Navigation," *NAVIGATION: The Journal of the Institute of Navigation*, Vol. 48, No. 4, Winter 2001-2002

[6] Betz, J. W., et al., "Description of the L1C Signal," Institute of Navigation, Proceedings of ION-GNSS-2006, September 2006

[7] Betz, J. W., et al., "L1C Signal Design Options," ION-NTM-2006, Institute of Navigation, January, 2006

[8] Gibbons, G., et al., "BOC or MBOC? The Common GPS/Galileo Civil Signal Design: A Manufacturers Dialog, Part 2," *Inside GNSS,* Vol. 1 Number 6, September 2006

[9] Hein, G., et al., "MBOC: The New Optimized Spreading Modulation Recommended for Galileo L1 OS and GPS L1C," *Proceedings of The IEEE/ION Position, Location, and Navigation Symposium*, Coronado, California, April 2006

[10] Hein, G., et al., "Working Papers: The Galileo Code and Others," *Inside GNSS,* Vol. 1 Number 6, September 2006

[11] <http://gps.losangeles.af.mil/engineering/icwg/Docs/EC%20and%20US%20Joint%20Statement%20on%20GALILEO%20and%20GPS%20Signal%20Optimization%20-%20%2024%20Mar%2006.pdf>

[12] <http://gps.losangeles.af.mil/engineering/icwg/Docs/WGA%20Signed%20Recommendation%20on%20MBOC%20-%2023%20Mar%2006.pdf>

[13] Hudnut, K. W., and Capt B. M. Titus, "GPS L1 Civil Signal Modernization (L1C)," Final Report of Interagency GPS Executive Board Stewardship Project #204, July 30, 2004. Available at <http://pnt.gov/public/docs/L1C-report-long.pdf> and <www.navcen.uscg.gov/gps/modernization/>

[14] Japan Aerospace Exploration Agency, "Interface Specification for QZSS (IS-QZSS)," January 22, 2007, available at <http://qzss.jaxa.jp/is-qzss/index_e.html>

[15] Peterson, W., and E. Weldon, *Error-Correcting Codes*, 2nd Edition, The MIT Press, 1972

[16] Rushanan, J. J., "Weil Sequences: A Family of Binary Sequences with Good Correlation Properties," IEEE International Symposium on Information Theory, Seattle, Washington, July 9-14, 2006

[17] Stansell, T., et al., "BOC or MBOC? The Common GPS/Galileo Civil Signal Design: A Manufacturers Dialog, Part 1," *Inside GNSS,* Vol. 1 Number 5, July/August 2006

Authors

John W. Betz is a Fellow of The Mitre Corporation.

Mario A. Blaco is a is an associate section leader in the Communications and Networks Directorate of the C2 Center at the MITRE Corporation.

Charles R. Cahn is an independent consultant.

Philip A. Dafesh is the associate director of the Digital Communication Implementation Department at The Aerospace Corporation.

Christopher J. Hegarty is a director with The MITRE Corporation's Center for Advanced Aviation System Development.

Kenneth W. Hudnut is a geophysicist for the U. S. Geological Survey.

Vipada Kasemsri is a lead communications engineer in the Analysis and Application Communications and Networking Department of the MITRE Corporation's Command & Control Center.

Richard Keegan is an independent consultant.

Karl Kovach is a Fellow with ARINC Engineering Services, LLC.

Capt Lawrence S. Lenahan is the L1C Project Military Co-Chair and works for the GPS Wing (formerly GPS Joint Program Office) in its Engineering and Advanced Technology Branch.

Howard H. Ma is engaged in research in digital communications and coding for The Mitre Corporation.

Joseph J. Rushanan is a principal mathematician in the Signal Processing Section of the MITRE Corporation.

Dean Sklar is a senior member of the technical staff at The Aerospace Corporation.

Thomas A. Stansell is an independent consultant.

Charles C. Wang is the associate director of the Communication Systems Engineering Department at The Aerospace Corporation.

Soon K. Yi is a Systems Engineer for ARINC Engineering Services, LLC. IG