# The New L2 Civil Signal

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## BIOGRAPHIES

Richard Fontana is the GPS Joint Program Office (JPO) Deputy Program Manager representing the Department of Transportation. In this capacity, he is responsible for civil GPS issues at the JPO, including implementation of civil GPS modernization efforts. Previously, as Chief of Testing at the Coast Guard Command and Control Engineering Center, he was responsible for ensuring all Coast Guard Command and Control systems were operationally acceptable prior to fielding. Prior to this he was program manager for the Shipboard Command and Control system, which replaced the entire combat information system on the Hamilton Class Cutters. He holds a BSEE from the United States Coast Guard Academy and an MSEE with a concentration in communications from George Mason University.

Wai Cheung is a Senior Systems engineer with Science Applications International Corporation (SAIC) in Torrance, CA, supporting the GPS Joint Program Office in the development and implementation of civil GPS system capabilities. At the Northrop Corporation he was involved in development of the Inertial Measurement Unit (IMU) for the PeaceKeeper missile program. At TRW he participated in research and development of an electronically controlled steering system for automotive applications and managed space vehicle propulsion and space vehicle bus structure projects. Mr. Cheung also was a systems engineering consultant on information technology programs at Lockheed Martin and both a systems engineer and a technical director in the development of internet based video technology at Global Webnet/Clearview Networks Inc. Mr. Cheung holds a BS in Mechanical Engineering from California State University, Los Angeles.

Paul Novak is a Senior Systems Engineer with SAIC in San Diego, CA, where he leads the team supporting the Civil GPS Applications Deputy Program Manager at the GPS Joint Program office. He joined SAIC in 2000 after 26 years in the U.S. Navy as a pilot and an acquisition program manager. He was the Navy's Navigation Systems Major Program Manager responsible for the integration of GPS into Navy, Marine Corps, and Coast Guard aircraft, ships, and submarines. He holds a B.S. in Biology from Stonehill College and an M.S. in Computer Systems Management from the Naval Postgraduate School, Monterey, CA.

Tom Stansell heads Stansell Consulting. Previously he was a Vice President of Leica Geosystems involved in technology development and strategic relationships. He received his BEE degree in 1957 and MEE degree in 1964, both from the University of Virginia. At the Johns Hopkins University Applied Physics Laboratory he participated in development of the Transit Navigation Satellite System, including the world's first surface ship satellite navigation receiver and the world's first portable Doppler geodetic survey receiver. At Magnavox, he led the development of many Transit and GPS products and their underlying technologies, including integrated navigation systems, Transit navigation and survey equipment, and GPS and GPS/GLONASS navigation and survey equipment. He retired from Magnavox as a Staff Vice President. He was technical program chairman ('84, '86, and '88) and general chairman ('94, '96, and '98) of IEEE PLANS conferences, and he served as technical program chairman of ION GPS-91 and general chairman of ION GPS-92. In 2000 Mr. Stansell was a member of the WAAS Independent Review Board, and in 2001 he led technical development of the new GPS L2 civil signal. He received the ION Weems Award in 1996, was elected a Fellow of the ION in 1999, received the IEEE PLANS Kershner award in 2000, and is a member of the GPS World editorial advisory board.

## INTRODUCTION

This paper and a companion article in the September 2001 issue of GPS World Magazine[(1)] describe the new L2 civil signal (L2C) which will be transmitted by modernized IIR (IIR-M) and all subsequent GPS satellites. The first IIR-M satellite is scheduled to be launched in 2003.

This paper covers seven main topics: the development framework, the signal description, signal acquisition and code tracking, code tracking accuracy, message sequencing options, relative signal performance, and the L2C design tradeoffs. The paper concludes with a discussion of why the two new GPS signals will affect future product design choices in significant ways, concluding that L2C could become the most widely used GPS signal of all.

Both L2C and L5 recently were described at an L2/L5 Industry Day public presentation on 5/02/01 at the Aerospace Corporation in El Segundo, CA, and again at an L2/L5 Public Forum on 6/29/01 at the Federal Aviation Administration (FAA) in Washington, DC. The charts presented at these events and the draft signal specifications have been posted on the NAVCEN web site (www.navcen.uscg.gov) under the modernization topic and on the GPS Joint Program Office (JPO) web site (https://gps.losangeles.af.mil, under GPS Library, Public Documents, Documents).

## DEVELOPMENT FRAMEWORK

Development of L2C was framed by the following requirements and realities:

### Tight Schedule

Although considerable work was subsequently required, and is continuing, to document and coordinate the signal design decisions within the GPS JPO, the Air Force Systems Command, the Interagency GPS Executive Board (IGEB), Lockheed-Martin, and Boeing, actual development of L2C required only three technical meetings, on 1/17/01, 1/26/01, and 2/9/01, after extensive technical preparation for each one. This compressed schedule was absolutely vital in order to meet critical deadlines for development of the IIR-M and IIF satellites, and it was possible only because of the background and experience of the key participants and the support of the GPS JPO and the Space Vehicle manufacturers.

### Limited Chip Rate

The chip rate of L2C was limited to 1.023 MHz, although the new L5 signal will employ two codes, each with a chip rate of 10.23 MHz. The clock rate limit is required to maintain spectral separation between the civil signal and the new military M code. (There is no M code on L5.) Fig. 1 illustrates this by showing the C/A code spectrum (1.023 MHz clock) and the effect on GPS noise floor of a strong M code signal. The civil signal is centered very intentionally in a null of the new military signal.

### Bi-phase Signal at Lower Power

L2C is limited to a single bi-phase signal component, unlike the new L5 signal which consists of two bi-phase components in phase quadrature. This is because L2C must share the L2 frequency with the military P/Y code.

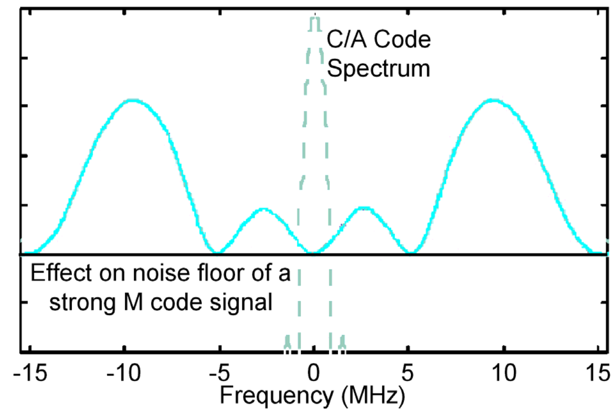


Fig. 1 – Spectral Separation of M Code and Civil Signal

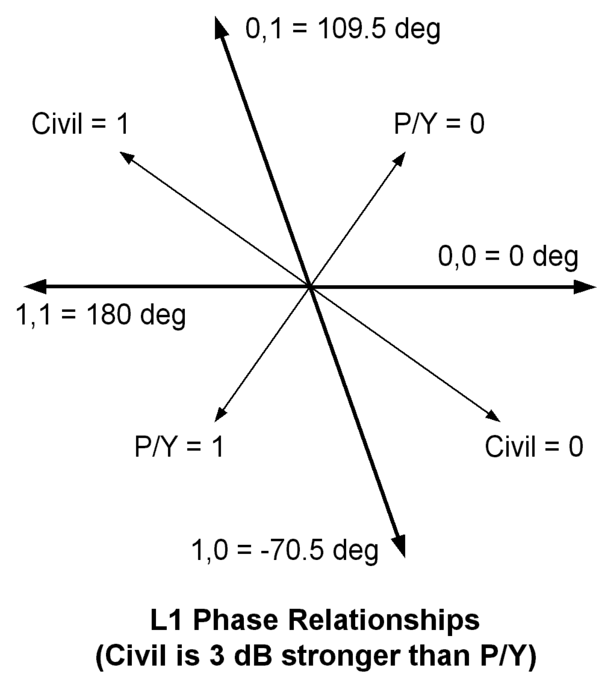


Fig. 2 – L1 Signal Component Vector Relationships

Figs. 2 and 3 illustrate this point. Fig. 2 shows the phase relationships of the current L1 signal components. The light vectors indicate the bi-phase civil signal (C/A code) in phase quadrature with the P/Y code. As illustrated, the civil signal is 3 dB stronger than the P/Y code. The heavy vectors are the vector sums for each of the four possible combinations of civil code and P/Y code (00, 01, 10, 11). Note that the heavy vectors are not in phase quadrature, but they do have a constant amplitude, which is important in achieving optimum transmitter efficiency. Fig. 3 is a plot of the L2 signals. As with L1, the civil and the P/Y signals are in phase quadrature and the heavy vectors have a constant amplitude, but in this case the civil signal is 0.4 dB weaker than the P/Y signal. As a result, civil users must cope with an L2 signal from all planned IIR-M and IIF satellites which is 2.3 dB weaker than the C/A code from L1, although the new signal structure more than compensates for this initial deficit. GPS III satellites could eliminate the inconsistency by providing substantially more L2C power.

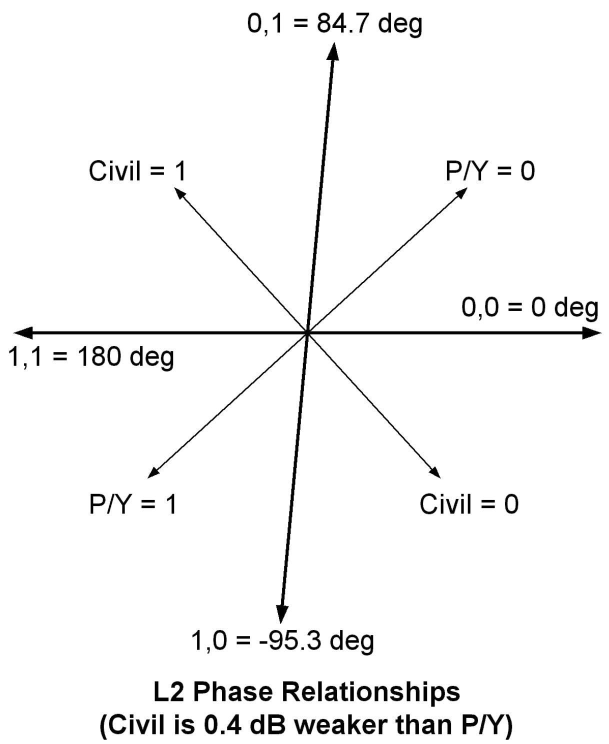


Fig. 3 – L2 Signal Component Vector Relationships

**Application Requirements**

A White House press release on March 30, 1998, announced that a civil signal would be added to the GPS L2 frequency. Instead of replicating the C/A code, as many expected, the modern L2C signal structure, better matched to 21st century capabilities and requirements, will be used. Although the new signal will be available for all GPS applications, two primary requirements drove the design.

Dual-Frequency Users – First, the signal must serve the current large and growing population of dual-frequency civil users, estimated to employ about 50,000 receivers for high value professional and commercial applications. Although this number seems small compared with handheld or automobile use, the purchase value of these receivers is about a billion dollars, not counting spares, application software, communication systems, and so on. More importantly, these products are at work adding value to society. Applications include:

- scientific projects to monitor earthquakes, volcanoes, continental drift, and weather
- cadastral and construction land survey
- guidance and control of mining, construction, and agricultural machines
- land and offshore oil and mineral exploration
- marine survey and construction, etc.

The most important objective was to eliminate need for the marginal and somewhat fragile semi-codeless tracking technique now used to acquire L2 measurements. Simply having a civil code on L2 achieves this objective, so a C/A code replica would meet the requirement. However, L2C enhances performance by having no data on one of its two codes, which improves threshold tracking performance by 3 dB and provides 'full-wavelength' carrier phase measurements without having to resolve the phase ambiguity inherent in signals with bi-phase data modulation.

Single-Frequency Users – The second key objective was to make L2 valuable for a host of single-frequency GPS applications which so far have been served only by the L1 C/A signal. The primary need was to eliminate the unacceptable 21 dB crosscorrelation performance of the C/A code, which allows a strong GPS signal to interfere with weak GPS signals. L2C achieves this by having a worst case crosscorrelation of 45 dB (over 251 times better). Furthermore, L2C lowers the data demodulation threshold, making it possible to read the message when barely tracking the signal. As a result, L2C is likely to become the signal of choice for applications like wireless emergency 911 (E911) positioning inside buildings, personal navigation in wooded areas, or vehicle navigation along tree-lined roads. If so, embedded GPS in wireless phones alone would make L2C the most widely used of all GPS signals.

**Modern Technology**

An extremely important aspect of the development framework is that technology has advanced enormously since the 1970's when the C/A code was developed. Figs. 4 and 5 illustrate this point by first showing an old briefing chart touting GPS experience in 1984. In particular, the Phase I and Phase II receivers were rack-mounted and had only five analog channels. Control and display functions required a separate large box. In contrast, Fig. 5 shows two current-day consumer products, each with twelve digital channels, one with a color digital map display and the other priced at less than $100. In 1970 it was necessary to have a very short code for signal acquisition. In the 21st century, a long code can be acquired quickly by having a large number of digital correlators, even in GPS consumer products. Therefore, the outdated C/A code can and should be replaced with a modern code better matched to the demands of new and more challenging application environments.

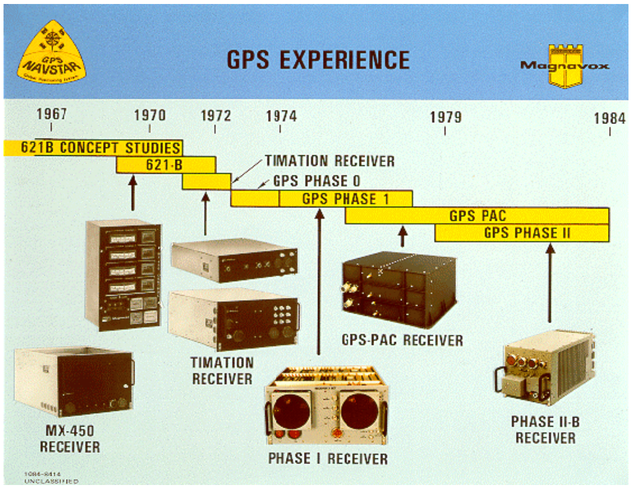

Fig. 4 – C/A Code Developed for 1970's GPS Technology

Fig. 5 – Dramatic Technology Progress Since the 1970's

### New Signal Availability

Development of L2C is in the context of an historic and dramatic change in the number of GPS navigation signals. Ever since 1974 when the first Block I satellite was launched, including today's IIR satellites, there have been only three GPS navigation signals, C/A on L1, P or P/Y on L1, and P or P/Y on L2. As illustrated by Fig. 6, this 29-year *status quo* will change dramatically in 2003 with launch of the first IIR-M satellite. The total number of navigation signals will double with the inclusion of M code on L1, M code on L2, and the new civil signal on L2. When the first IIF satellite is launched in 2005, the number of navigation signals will increase to seven by adding the L5 civil signal. These are dramatic changes, indeed.

Although the change is dramatic, Fig. 7 shows that it will not be sudden. The figure shows the increasing number of new civil signals in the GPS constellation. In the early years it is expected that only professional dual-frequency equipment will take advantage of L2C. The single

| Signal\SV | IIR | IIR-M | IIF |
|---|---|---|---|
| L1 C/A | ✓ | ✓ | ✓ |
| L1 P/Y | ✓ | ✓ | ✓ |
| L1 M | | ✓ | ✓ |
| L2 Civil | | ✓ | ✓ |
| L2 P/Y | ✓ | ✓ | ✓ |
| L2 M | | ✓ | ✓ |
| L5 Civil | | | ✓ |

Fig. 6 – Historic Increase in GPS Navigation Signals

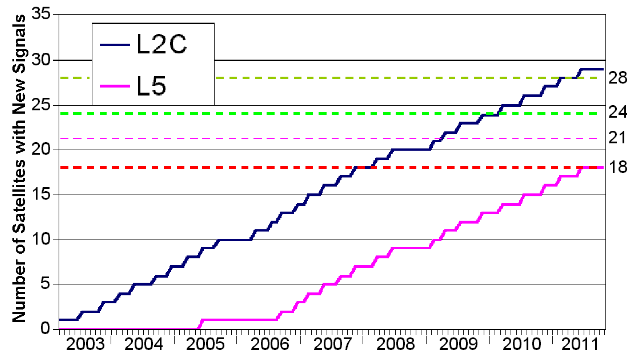

Fig. 7 – Expected Growth in L2C and L5 Signals (Assumes Modernization of 12 IIR Satellites)

frequency market for L2C receivers should grow very rapidly as the number of signals approaches 24. Signal choice may trigger a new era of expanding GPS applications.

### L2C SIGNAL DESCRIPTION

The L2C signal contains two codes of different length, one of which provides a data message structured like that planned for L5. However, options are available in case the L5-like message cannot be supported in early satellites. The following definitions are used:

- CM – the L2C moderate length code contains 10,230 chips, repeats every 20 milliseconds, and is modulated with message data
- CL – the L2C long code contains 767,250 chips, repeats every 1.5 second, is synchronized with the 1.5 second Z-count, and has no data modulation
- NAV – the legacy navigation message provided by the current L1 C/A signal
- CNAV – a navigation message structure like that adopted for L5

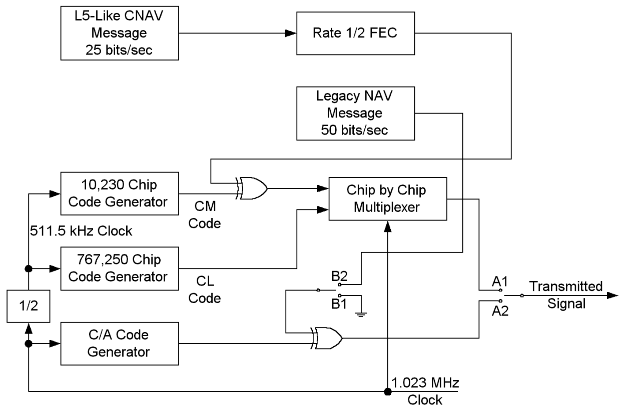


Fig. 8 – L2C Signal Options on IIF Satellites

Fig. 8 shows the L2 signal generation plan for IIF satellites. The signal options are controlled by two switches, A and B. In both cases, the preferred switch position is ‘1’. The A-2 position permits the old C/A code to be transmitted as an option. With switch B in the ‘2’ position, the C/A code is modulated by the legacy NAV message, creating a replica of the current L1 C/A signal. However, the preferred position is B-1, which transmits the C/A code with no data modulation. This is better because dual-frequency users can track the signal with a simple phase locked loop rather than needing a Costas (squaring) loop, thus improving tracking threshold by 6 dB. Also, the phase locked loop makes whole-cycle phase measurements rather than having to use message content to resolve the 180-degree phase ambiguity inherent in a Costas loop. Furthermore, there is no known civil interest in an L1 C/A replica signal on L2. Relative to L1, L2 has 2.3 dB less received power and 65% more ionospheric refraction error, which discourage use of C/A code on L2 as a single frequency alternative to L1.

The A-2 switch position is only an option, so it is expected the A switch normally will be in the preferred ‘1’ position. In this case, note that the 1.023 MHz clock is divided by two in order to drive two code generators at 511.5 kHz each. These generate the CM code with 10,230 chips and the CL code with 767,250 chips. As shown by Fig. 8, the CM code is modulated by message data and the CL code is not. The CNAV message format is like that adopted for L5. However, in this case the data rate is 25 bits per second (bps) rather than the conventional 50 bps. Furthermore, a forward error correction (FEC) is applied, like that used on the Wide Area Augmentation System (WAAS) and planned for L5. (The FEC is rate 1/2 convolutional coding with an encoding constraint length of 7.) As a result, 50 symbols per second modulate the CM code. The reasons for these choices will be explained later.

The modulated CM code and the unmodulated CL code are combined in a chip by chip multiplexer. The CM chip is transmitted first, followed by the CL chip. As a result, the transmitted code has an overall chipping rate of 1.023 MHz, the same as the C/A code.

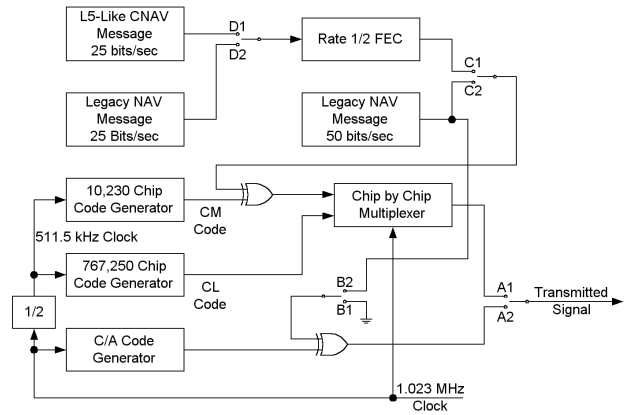


Fig. 9 – L2C Signal Options on IIR-M Satellites

Fig. 9 is the L2 signal generation diagram for IIR-M satellites. Except for two additional message format options, it is the same as Fig. 8. The additional options are controlled by switches C and D. These were added because it was not clear if there would be enough IIR memory to support the CNAV message with FEC, although at this time no problem is expected. Even so, the options will be retained, at least until all doubts are resolved and until Ground Segment support for the new signal structure is assured. The first additional option is with switch C in the ‘2’ position, which puts the legacy NAV message at 50 bps on the CM code. The second added option is with switch positions C-1 and D-2, which uses the NAV message but at 25 bps with FEC. Switch positions A-1, C-1, and D-1 in Fig. 9 provide the same signal as switch position A-1 in Fig. 8.

L2 receivers should be designed to detect whether the optional C/A code is being transmitted rather than L2C and which type of message is being sent. Eventually these options will not be used, but until then automatic detection is needed. By storing the last known signal type from each satellite in the receiver’s non-volatile memory, the next acquisition will be faster than having to repeat the search.

Fig. 10 shows the linear shift register logic used to generate the CM and CL codes. Each shift register has 27 stages with twelve feedback taps. If not short-cycled, this logic would produce a maximal length code of 134,217,727 chips. However, the CM and CL codes are produced by initializing the shift register to the specified initial state and short-cycling back to that state after the defined chip count or after detecting the specified final state. A total of 100 each CM and CL codes have been defined, of which 37 pairs are published in the proposed revision to ICD-GPS-200. As an example, Tables I and II list the octal beginning and end states for the first few CM and CL codes, respectively. Because the chip length of each code (10,230 for CM and 767,250 for CL) is an even number, all codes were selected to be perfectly balanced, i.e., to have precisely the same number of ones as zeros. Also, note that there are exactly 75 repetitions of the CM code for every cycle of the CL code.

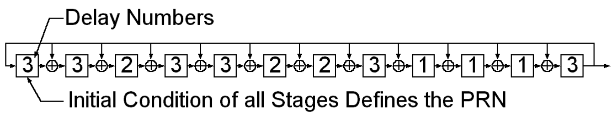

Fig. 10 – Shift Register Logic for L2C Code Generators

Table I – First Ten CM Code Definitions

| Period=10,230 Chips | | |
|---|---|---|
| CM Code States (Octal) | | |
| PRN | START | END |
| 1 | 742417664 | 552566002 |
| 2 | 756014035 | 034445034 |
| 3 | 002747144 | 723443711 |
| 4 | 066265724 | 511222013 |
| 5 | 601403471 | 463055213 |
| 6 | 703232733 | 667044524 |
| 7 | 124510070 | 652322653 |
| 8 | 617316361 | 505703344 |
| 9 | 047541621 | 520302775 |
| 10 | 733031046 | 244205506 |

Table II – First Ten CL Code Definitions

| Period=767,250 Chips | | |
|---|---|---|
| CL Code States (Octal) | | |
| PRN | START | END |
| 1 | 624145772 | 267724236 |
| 2 | 506610362 | 167516066 |
| 3 | 220360016 | 771756405 |
| 4 | 710406104 | 047202624 |
| 5 | 001143345 | 052770433 |
| 6 | 053023326 | 761743665 |
| 7 | 652521276 | 133015726 |
| 8 | 206124777 | 610611511 |
| 9 | 015563374 | 352150323 |
| 10 | 561522076 | 051266046 |

## SIGNAL ACQUISITION AND CODE TRACKING

Because the CL code is 75 times longer than the CM code, initial acquisition of the L2C signal normally will employ only the 10,230 chip CM code. Frequency tracking or a Costas loop may be employed for acquisition and tracking during this process. Once acquired, a quick search of the 75 possible time relationships between the CM and CL codes will allow acquisition of the CL code and use of a phase locked loop to track the signal with improved threshold performance. With adequate signal strength, it is reasonable to acquire most if not all the satellite signals this way.

However, for very weak signals it may be better to acquire the CL code directly. Having acquired at least one CL code, the uncertainty in time of arrival of all other CL codes is about 18.7 milliseconds, which is the difference in propagation delay of a satellite at the horizon versus one at the zenith. Therefore, the total search range is about $(18.7 \times 10^{-3}) \times (1.023 \times 10^{6}) =$ 19,130 chips. Although about twice as long as the 10,230 chip CM code search range, the CL code has no data modulation which, in principle, allows use of coherent integration beyond the 20 msec data symbol boundaries to lower the signal detection threshold. To achieve this, however, requires an excellent estimate of the signal frequency, noting that only a 12.5 Hz frequency error causes a quarter cycle rotation in 20 msec. Direct CL acquisition becomes increasingly possible either as the search range is reduced through better knowledge of the satellite and user position and velocity, e.g., for reacquisition of a recently tracked signal, or by use of techniques such as a Fast Fourier Transform (FFT) to detect the satellite frequency after an extended sampling interval. Having no data modulation enhances the effectiveness of these techniques.

Although it is possible to track both the CM and CL codes concurrently, the advantage is slight. Therefore, this discussion concentrates on tracking only one of the codes. To illustrate the difference between tracking a continuous code and a code which is chip by chip multiplexed with another, Fig. 11 shows two cycles of a 15-chip code and the corresponding “narrow correlator” early-minus-late gates aligned with each code transition. Shown in this example are 16 narrow correlator gates (the first and last half-gates count as one). Each code transition is from a +1 to a -1 state, or the inverse.

In contrast, Fig. 12 shows the equivalent process when tracking one of two chip by chip multiplexed codes. Since the second code is effectively unknown, its chips are represented by the zero state. Because the CM code is perfectly balanced, it is precisely correct to assume the CM code chips average to zero when tracking the CL code. The 15-chip code illustrated in Fig. 11 also is used in Fig. 12, but because the clock rate for the multiplexed code is half that of the continuous code, only one cycle of the code appears in Fig. 12. This corresponds to the 511.5 kHz clock for CM and CL compared with the 1.023 MHz clock for the combined codes or for a C/A code.

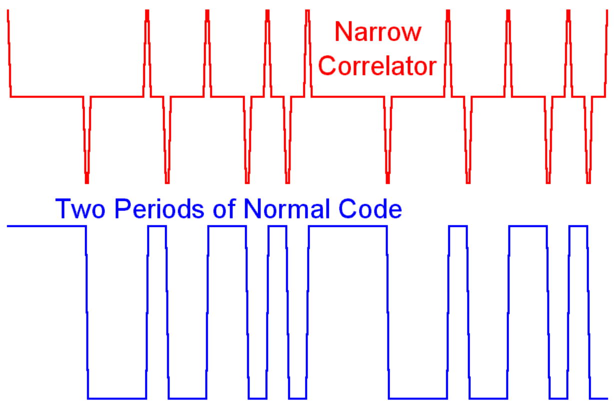


Fig. 11 – Tracking Continuous Code with a Narrow Correlator

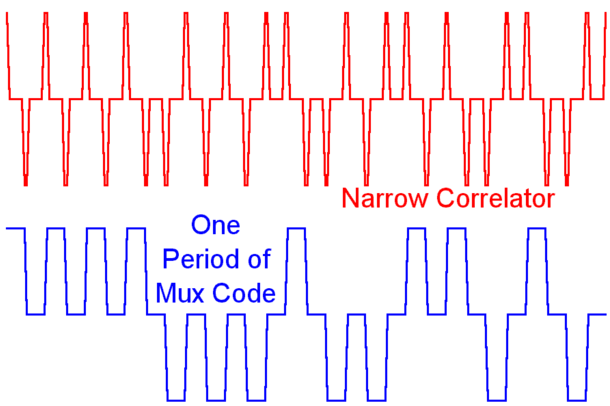


Fig. 12 – Tracking Chip by Chip Multiplexed Code with a Narrow Correlator

Whereas Fig. 11 has 16 code transitions and 16 corresponding narrow correlator gates, Fig. 12 has 30. This is because, with alternate states of zero, there is a code transition at every clock. (For longer codes, in which the number of code transitions essentially is half the number of chips, the transition ratio is two.) Therefore, the narrow correlator gate is turned on twice as often when tracking a chip by chip multiplexed code as compared with tracking a single continuous code. This allows twice as much noise power to enter the tracking loop, for a -3 dB reduction in signal to noise ratio (S/N). In addition, each transition has half the voltage amplitude, which reduces the S/N by a factor of four, or -6 dB. On the other side of the ledger, having twice as many transitions improves the S/N by a factor of four, or +6 dB. The net difference is a 3 dB reduction in loop S/N when tracking a chip by chip multiplexed code as compared with tracking a continuous code, which is appropriate because only one of two codes is being tracked.

**CODE TRACKING ACCURACY**

The effect of clock rate on code measurement accuracy is an important subject. For example, concern has been expressed that reducing the clock rate of the CM and CL codes would adversely affect navigation accuracy, compared not only with the C/A code but also with L5 codes which are clocked at 10.23 MHz. For example, when using the same narrow correlator gate width, a 10.23 MHz code has a 10 dB better code loop S/N than a 1.023 MHz code, thus a 13 dB better S/N than a 511.5 kHz code.

Two factors not only mitigate but effectively eliminate this concern. The first is code tracking bandwidth. Because the code loop can be aided almost perfectly by the carrier tracking loop, it is not required to track vehicle, satellite, or oscillator dynamics. As a result, there is no reason to have a code loop bandwidth greater than about 0.1 Hz. In many receivers the tracking bandwidth is further reduced by carrier aided code smoothing to minimize multipath noise. Even a modest amount of code smoothing will use 2 to 5 minute time constants, for an equivalent bandwidth of 0.008 to 0.003 Hz. On zero baseline tests (one antenna connected to two receivers), where all error sources are common except the tracking loop S/N, C/A code measurements agree with each other within a few centimeters. In other words, the S/N in these narrow bandwidths is already so good there is little practical benefit to increasing S/N with a higher code clock rate.

The other important factor is that in most practical cases code noise is dominated entirely by multipath, which is not affected by loop S/N. In the past it certainly was true that a higher code clock rate significantly reduced the impact of multipath. Fig. 13 dramatically illustrates this point. It plots the envelope of code measurement error caused by one multipath signal with half the voltage amplitude of the direct satellite signal as a function of multipath time delay. Both axes are scaled in fractions of a C/A code chip, with one chip being approximately one microsecond or 300 meters. The actual error varies as a function of the relative carrier phase of the two signals, touching the upper curve when the signals are exactly in phase and touching the lower curve when the two signals are exactly out of phase. One of the earliest ways to track a code was with a wide early minus late correlator, which produces the largest multipath error. An important innovation was the narrow correlator which significantly reduces the amplitude of the multipath error as well as eliminating its effect for delays just greater than one chip. In this example the width of the narrow correlator is 0.1 of the wide correlator. The amplitude reduction improves as the correlator width is further narrowed, although the improvement ultimately is limited by the bandwidth of the incoming signals.

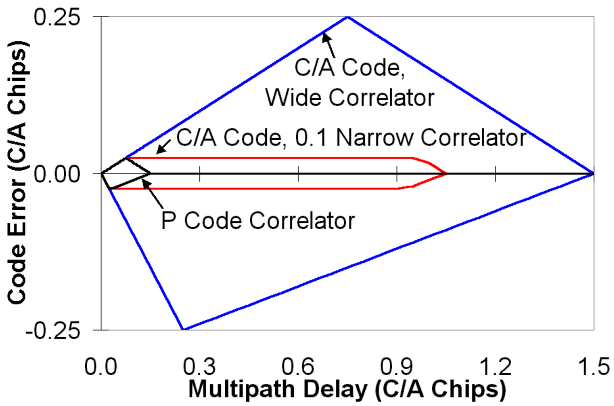


Fig. 13 – Multipath Error for Three Correlator Types

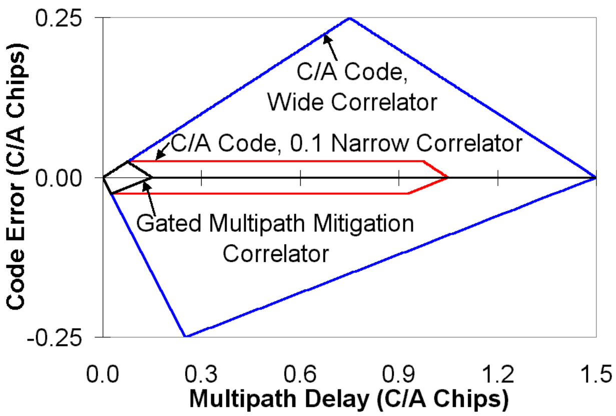


Fig. 14 – Gated Multipath Mitigation C/A Code Correlator Provides the Same Performance as a High Code Clock Rate

The small zone marked P Code Correlator represents the multipath error when tracking the P code with the equivalent of a wide P code correlator. Because the P code clock rate is ten times that of the C/A code, the dimensions of the P Code Correlator zone are 1/10 those of the wide C/A code correlator zone. This is why the peak P code correlator error is the same as the 0.1 narrow correlator error. Fig. 13 seems to indicate that a higher clock rate significantly reduces multipath error.

Fig. 14 looks exactly like Fig. 13, except the small zone is now labeled "Gated Multipath Mitigation Correlator". The small zone is obtained by tracking the C/A code with a new type of correlator designed to provide the same multipath mitigation performance normally associated with a higher clock rate. This level of performance also can be improved by further narrowing the correlator gates, limited only by the bandwidth of the incoming signals. (A gate must cover a significant part of the signal transition, e.g., its rise time. A wider bandwidth decreases rise time, allowing narrower gates, which provides better multipath mitigation.)

In summary, a higher code clock rate is not needed to achieve excellent code measurement accuracy. Wide bandwidth signal processing with an effective gated multipath mitigation correlator and use of carrier aided code smoothing to permit narrow bandwidth code tracking achieves equivalent performance. This is an important result, because the large spectral separation between the M code and the civil code, as shown in Fig. 1, requires a limit on civil code clock rate. Fortunately, this limit does not sacrifice code measurement accuracy.

## CNAV MESSAGE SEQUENCING OPTIONS

The CNAV message structure is basically the same as that adopted for the L5 GPS signal. It is both more compact and more flexible than the original NAV message. Instead of a fixed message format, CNAV allows the Control Segment to specify the sequence and timing of each message component. The components are 300 bit subframes, each with a message type designator. For L2C, which sends data at 25 bps, each subframe requires 12 seconds to transmit. The message types defined to date are:

- Type 1 = Ephemeris message part 1
- Type 2 = Ephemeris message part 2
- Type 3 = Ionosphere, time biases, health bits, etc.
- Type 4 = Almanac
- Type 5 = Free form text message

Over the next few months these messages will be reviewed and potentially revised in significant ways. For example, the Type 4 almanac message currently defines only one satellite orbit at a time. One proposal would add a Type 6 almanac message to provide orbit parameters for seven satellites in one subframe. In addition, alternatives are being considered which would replace the Type 1 and Type 2 ephemeris messages with only one subframe providing better accuracy and a longer validity period. Each of these changes will particularly benefit L2C users because of its 25 bps data rate, but the changes also will improve L5 message performance.

Although it is too early to define specific message sequences, two examples using the current message definitions may be instructive. Fig. 15 shows two ways to organize the message types. The upper diagram illustrates a 36 second frame consisting of the Type 1 and Type 2 messages plus one other message type. With this configuration an L2C ephemeris is available every 36 seconds, which is not much longer than today's 30 second interval between L1 C/A ephemeris messages. However, only one of the other message types would be available every 36 seconds. If the Type 3 message were transmitted in every other frame, alternating with Type 4 almanac messages, it would require 36 minutes to transmit a 30 satellite almanac. The lower diagram in Fig. 15 shows a 48 second frame which would reduce the almanac collection time to 18 minutes, still longer than today's 12.5 minutes, at the expense of a 48 second interval between ephemeris messages. By packing seven satellites in each almanac subframe and providing a complete ephemeris in another, it is clear that L2C message performance would be enhanced significantly.

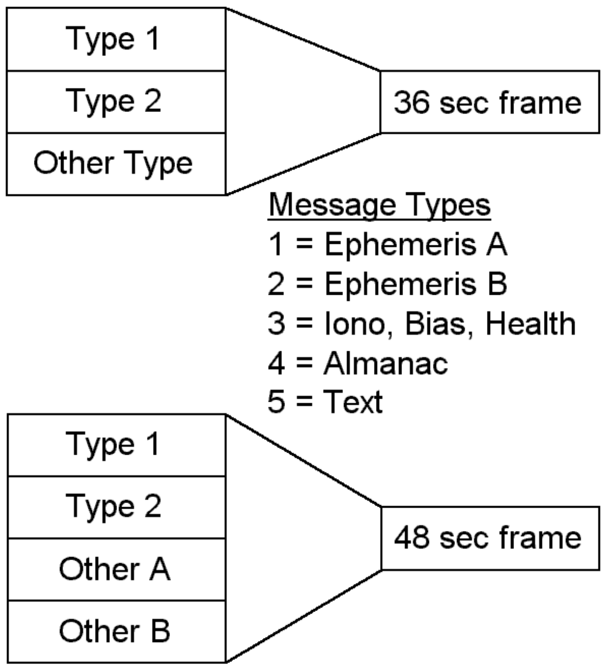


Fig. 15 – Two L2C Message Frame Alternatives

## RELATIVE SIGNAL PERFORMANCE

### L2C Compared With C/A on L2

As stated earlier, the original thought was to duplicate the L1 C/A code on L2. Therefore, the next few tables compare the L2C performance against a C/A code baseline.

The L2C signal structure divides the transmitted civil signal into two equal-power components, one with data and one without. In comparison, an L1 C/A replica places all the civil signal power in one code with data. Table III therefore defines the reference C/A code power level as 0.0 dB for the data channel and no power for a data-less channel. The two L2C signal components (channels) have half the total power, or -3 dB each relative to the C/A code signal. L2C takes a precious resource and cuts it in half.

Table IV compares the data demodulation and carrier tracking performance of each signal structure. Again, the reference values are defined as 0.0 dB each for the C/A code data recovery and carrier tracking thresholds. Although the L2C power devoted to data was half the total, its data recovery threshold performance is 5 dB better than C/A. This is because forward error correction improves threshold by 5 dB, and cutting the data rate in half improves threshold another 3 dB. Even after the 3 dB initial sacrifice, the data threshold performance is 5 dB better.

Table III – L2C Power Division Relative to L2 C/A

| | **Relative** Data Channel Power | **Relative** Data-Less Channel Power |
|---|---|---|
| L2 C/A | 0.0 dB | None (Costas) |
| L2C | -3 dB | -3 dB |

Table IV – L2C Performance Relative to L2 C/A

| | **Relative** Data Recovery Threshold | **Relative** Carrier Tracking Threshold |
|---|---|---|
| L2 C/A | 0.0 dB | 0.0 dB |
| L2C | +5.0 dB (FEC = 5 dB) (25 bps = 3 dB) | +3 dB (Phase locked tracking = 6 dB) |

Table IV also shows that the carrier tracking threshold is 3 dB better than with C/A. This is because the signal component without data modulation can be tracked with a simple phase locked loop, which has a 6 dB better tracking threshold than a Costas loop. In other words, L2C provides substantially better performance than would an L1 C/A signal replica.

Acquisition of L2C is a different matter. The CM code is ten times longer than the C/A code and it has only half the total power. Therefore, in an apples for apples comparison, signal acquisition should take 20 times longer with L2C than with a C/A code. Fortunately, receiver technology has come a long way since the 1970's when the C/A code was developed. Now it is possible to have hundreds of digital correlators in consumer GPS chipsets, and circuit densities will continue to improve over the next few years while waiting for enough satellites to provide a robust L2C single frequency service. Modern multiple correlator technology allows rapid acquisition of the longer codes needed for better crosscorrelation performance. This is a very important improvement, because the poor crosscorrelation properties of the C/A code allow strong GPS signals to block acquisition of weak signals or be tracked instead of the weak signals. The longer L2C codes eliminate this problem, and modern technology allows rapid acquisition of the longer codes.

**L2C Compared with L1 C/A and L5**

Table V shows the received signal power expected from IIR-M and IIF satellites for all three civil signals. For purposes of comparison, the received L2C and L5 power levels are shown relative to L1 C/A. L5 will be the strongest signal, and L2C will be the weakest, being 6 dB below L5.

Table V – Civil Signal Total Power Comparisons

| | Received Power | **Relative** Total Power |
|---|---|---|
| L1 C/A | -157.7 dBW | 0.0 dB |
| L2C | -160.0 dBW | -2.3 dB |
| L5 | -154 dBW | +3.7 dB |

Table VI compares the power in each of the two L2C and L5 signal components to the total power in the L1 C/A signal. Note that each component of the L5 signal still has slightly more power than L1 C/A, whereas each component of L2C has considerably less.

Table VI – Channel Power Comparisons

| | **Relative** Data Channel Power | **Relative** Data-Less Channel Power |
|---|---|---|
| L1 C/A | 0.0 dB | None (Costas) |
| L2C | -5.3 dB | -5.3 dB |
| L5 | +0.7 dB | +0.7 dB |

Table VII next compares the relative effectiveness of each signal for data demodulation and for carrier tracking threshold. Between the relative power levels in Table VI and the performance values in Table VII, there is a 5 dB gain in data recovery threshold for both L2C and L5 because of FEC, and L2C gains another 3 dB because its bit rate is 25 bps rather than 50 bps. As a result, although starting 5.3 dB behind in data channel power, L2C is 2.7 dB better than L1 C/A. Similarly, because of the 6 dB threshold advantage of a phase locked loop over a Costas loop, L2C is 0.7 dB better than L1 C/A in spite of its initial 5.3 dB handicap. Since L5 has 6 dB more power than L2C, it provides another significant boost in performance. We recommend and believe that future GPS satellites should eliminate this disparity by adding power to the L1 and L2 civil signals.

Table VII – Relative Signal Performance

| | **Relative** Data Recovery Threshold | **Relative** Carrier Tracking Threshold |
|---|---|---|
| L1 C/A | 0.0 dB | 0.0 dB |
| L2C | +2.7 dB (FEC = 5 dB) (25 bps = 3 dB) | +0.7 dB (Phase locked tracking = 6 dB) |
| L5 | +5.7 dB (FEC = 5 dB) | +6.7 dB |

## L2C DESIGN TRADEOFFS

### Two Codes

Use of two codes for a GPS civil signal was first adopted for L5. However, the fundamental concept dates back to the world's first navigation satellite system, which was Transit (the Navy Navigation Satellite System). Its development began in 1958 (triggered by launch of the first Sputnik the previous year), it became operational in 1964, and it was switched off at the end of 1996 after nearly 32 years of dependable service. As shown by Fig. 16, Transit did not use bi-phase data modulation. Instead, the carrier phase had three states, $0^o$, $+60^o$, and $-60^o$. The modulation pattern put 44% of the signal power into data, but 56% remained as a coherent carrier component which Transit receivers tracked with a simple phase locked loop.

Bi-phase data modulation, which has been the GPS practice, removes the carrier component, forcing the receiver to use a Costas loop to create a second harmonic of the carrier, which can be tracked. Although this may be ideal for data communication, it worsens the phase tracking threshold by 6 dB, i.e., four times more signal power is required to maintain phase lock than if there were no modulation.

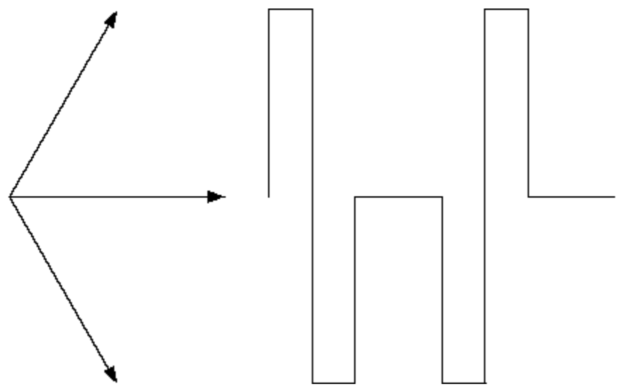

Fig. 16 – Transit Phase Modulation

Following the Transit precedent, L5 was designed with two equal power signal components, one with data and one without. Although each component has only half the total power (-3 dB), the 6 dB threshold advantage of tracking a data-less signal gives an overall +3 dB tracking improvement. With the resultant better phase reference and by using FEC, the data error rate is the same as if all the power were in just one data-modulated code. Since L5 is not shared with military signals, it achieves the power split by using two equal-length codes in phase quadrature, each of which is clocked at 10.23 MHz.

**Multiplexed Codes**

In contrast, L2 is shared between civil and military signals. Therefore, L2C is limited to a single bi-phase component in phase quadrature with the P/Y code, as shown in Fig. 3. Also, L2C is limited to a 1.023 MHz clock rate in order to maintain spectral separation from the new military M code, as shown in Fig. 1. Even so, it is clear that having two codes provides an important advantage. L2C achieves this by time multiplexing the CM and CL codes.

Two techniques were considered for code multiplexing: millisecond by millisecond and chip by chip. Although either will work, the first creates 500 Hz sidetones which the GPS receiver must avoid when acquiring a signal. Because there are no other advantages and because chip by chip is equally easy to implement and has no relative disadvantage, it was chosen.

**Code Lengths**

The key tradeoff in selecting code length is between correlation properties (which tend to be better with longer codes) and acquisition time (which is better with shorter codes). Although L5 was designed with two equal length codes, the L2C development team immediately saw benefit in having two different code lengths. The shorter of the two codes is used for initial acquisition and the longer code to achieve better correlation properties.

Many different codes were studied, including chip lengths of 10,230 (20 msec), 20,460 (40 msec), 204,600 (0.4 sec), 306,900 (0.6 sec), and 767,250 (1.5 sec). The multiplexed combinations had total chip lengths of 20,460 (20 msec), 40,920 (40 msec), 409,200 (0.4 sec), 613,800 (0.6 sec), and 1,534,500 (1.5 sec). (Recall that the individual codes are clocked at 511.5 kHz whereas the multiplexed combination is clocked at 1.023 MHz.)

CM was chosen to have 10,230 chips with a period of 20 msec. The key reasons were to minimize code length for acquisition while unambiguously resolving data symbols. (Bit synchronization is resolved as part of the Viterbi decoding process.) As a result, the problematic bit synchronization process now required with C/A code has been eliminated.

The CL code was chosen to have 767,250 chips with a period of 1.5 second. The key reason was to achieve excellent correlation properties. There was little reason to choose a shorter code, and the natural relationship with the 1.5 second GPS Z-count was a bonus. Fig. 17 shows the identical autocorrelation and crosscorrelation properties of the multiplexed CL code. The simulation assumed the alternate chips were not known but average to zero, as indeed they do with the perfectly balanced CM codes. The figure plots the probability that the peak correlation over the complete range of time shifts will exceed the corresponding value on the horizontal axis. It is evident that the probability of correlation greater than -45 dB is exceedingly small.

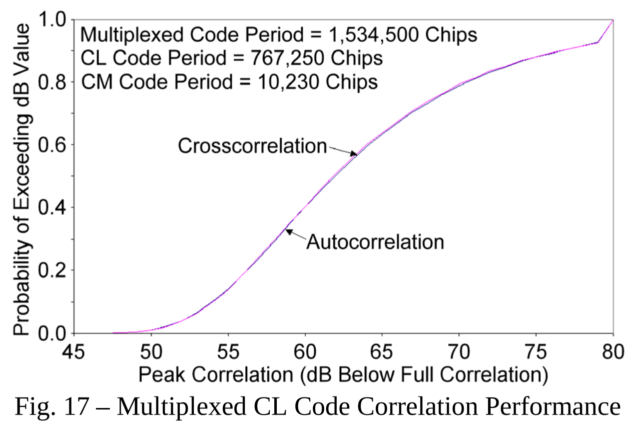


Fig. 17 – Multiplexed CL Code Correlation Performance

**Data and FEC Rates**

Tables VIII, IX, and X show some of the evaluations used to pick the message bit rate and the convolutional code rate. In each case the selected values are shaded. Table VIII compares the performance of several of these combinations with the assumption of perfect carrier phase tracking and no platform dynamics. The criterion was a

300 bit word error rate (WER) of 0.015. The center column lists the C/No (the ratio of total signal power to the noise power in a one Hz bandwidth) required to achieve this WER, considering only the signal power in the CM code. Lower C/No values are better. The third column includes the power in both the CM and CL codes, i.e., the total L2C signal power.

Table VIII – Optimizing Bit Rate and FEC Rate

| **Data rate & FEC rate** | **For WER = 0.015, $C/N_o$ in the data component =** | **For 50% power split, $C/N_o$ in the total signal =** |
|---|---|---|
| 50 bps, uncoded | 25.8 dB-Hz | 28.8 dB-Hz |
| 50 bps, rate-1/2 | 20.6 dB-Hz | 23.6 dB-Hz |
| 33.33 bps, rate-1/2 | 18.8 dB-Hz | 21.8 dB-Hz |
| **25 bps, rate-1/2** | **17.6 dB-Hz** | **20.6 dB-Hz** |
| 50 bps, rate-1/3 | 19.9 dB-Hz | 22.9 dB-Hz |
| 33.33 bps, rate-1/3 | 18.1 dB-Hz | 21.1 dB-Hz |
| 25 bps, rate-1/3 | 16.9 dB-Hz | 19.9 dB-Hz |

Table IX evaluates not only the data bit rate and FEC rate combinations but also four different power split ratios between CM and CL. These include CM power percentages of 100%, 75%, 50%, and 25%. Also, moderate platform dynamics appropriate for aviation applications are applied. With 29.8 Hz/sec maximum acceleration and 9.6 Hz/sec$^2$ jerk, the optimal one sided 3rd-order loop bandwidth, $B_L$, was set to 8 Hz. The third column lists the total (CM plus CL) signal C/No required to achieve a 0.015 WER, and the fourth column lists the equivalent C/No required to phase track the signal with a phase slip probability of 0.001 in 60 seconds. As before, lower numbers are better.

Table IX – Balanced Performance with Moderate Dynamics

| **Data rate (bps) & FEC rate** | **Carrier power percent** | **WER = 0.015 with total $C/N_o$ =** | **Phase slip = 0.001 with total $C/N_o$ =** |
|---|---|---|---|
| 50 & None | Costas | 26 dB-Hz | 25.5 dB-Hz |
| 50 & None | 50 | 29 dB-Hz | 23 dB-Hz |
| 25 & None | 50 | 26.5 dB-Hz | 23 dB-Hz |
| 50 & ½ | 50 | 24 dB-Hz | 23 dB-Hz |
| 33.3 & ½ | 50 | 22.5 dB-Hz | 23 dB-Hz |
| **25 & ½** | **50** | **22 dB-Hz** | **23 dB-Hz** |
| 25 & ½ | 25 | 24 dB-Hz | 26 dB-Hz |
| 25 & ½ | 75 | 24 dB-Hz | 21 dB-Hz |
| 33.3 & 1/3 | 50 | 22 dB-Hz | 23 dB-Hz |

Table X is the same as Table IX except that platform dynamics have been increased by an order of magnitude to 300 Hz/sec maximum acceleration and 100 Hz/sec$^2$ jerk. The 3rd-order loop bandwidth also is optimized for each set of conditions and shown in the third column.

Table X – Balanced Performance with High Dynamics

| **Data & FEC rates** | **Carrier Power percent** | **Optimum $B_L$** | **WER = 0.015 with total $C/N_o$ =** | **Phase slip = 0.001 with total $C/N_o$ =** |
|---|---|---|---|---|
| 50 & none | Costas | 15 Hz | 27 dB-Hz | 29 dB-Hz |
| 50 & ½ | 50% | 15 Hz | 25 dB-Hz | 25.5 dB-Hz |
| **25 & ½** | **50%** | **15 Hz** | **24.5 dB-Hz** | **25.5 dB-Hz** |
| 25 & ½ | 66.7% | 15 Hz | 24 dB-Hz | 24.5 dB-Hz |
| 25 & ½ | 75% | 13 Hz | 24 dB-Hz | 24 dB-Hz |
| 33.3 & 1/3 | 50% | 13 Hz | 24.5 dB-Hz | 25.5 dB-Hz |
| 33.3 & 1/3 | 66.7% | 15 Hz | 24 dB-Hz | 24.5 dB-Hz |
| 33.3 & 1/3 | 75% | 13 Hz | 25 dB-Hz | 24 dB-Hz |

In all three tables the selected values of 25 bps with rate-1/2 FEC and a 50/50 power split between CM and CL have been highlighted. Even though 25 bps with rate-1/3 FEC gives slightly better WER results, the fact that a rate-1/2 FEC is used both on WAAS and L5 weighed heavily in the selection. Also, 75 symbols per second and the corresponding symbol period of 13-1/3 msec were not numerically convenient.

Perhaps the most important aspect of the chosen values is the excellent balance between carrier tracking threshold and data demodulation threshold. Not only are these values much lower than they would be with C/A code, but L2C makes it possible to demodulate the data message with very weak signals, right at the tracking threshold. This is an important capability for navigation in forests or inside buildings.

## CONCLUSIONS

### Future Choice of Signals

In the future, civil GPS receiver manufacturers will be able to choose from three rather different signals to serve the full range of applications. Because there are so many different GPS requirements for, e.g., aviation, wireless E911, hiking and camping, automobile navigation, marine navigation, vehicle tracking, GIS, survey, machine control, etc., no one signal will be best for every one. Having signal choices also will introduce another dimension into product competition. Company A will claim certain advantages because of the signal it chose, company B will argue that their choice was better, and company C will explain that using two (or three) signals was the right choice. Furthermore, the choices won't be static, because GPS III ought to introduce new variables, e.g., more power for the L1 and L2 civil signals and very likely a new civil signal on L1 in addition to C/A.

**Signal Characteristics Summary**

The next three tables and Table VII compare the three civil signals. Table XI lists the frequencies, the code lengths, and the code clock rates. Table XII shows whether the signal is bi-phase or quad-phase, the data bit rate, and whether FEC is used. Clearly, the signals have rather different characteristics.

Table XI – Civil Signal Characteristics

| Civil Signal | Carrier Frequency (MHz) | Code Length (chips) | Code Clock (MHz) |
|---|---|---|---|
| L1 | 1,575.42 | 1,023 | 1.023 |
| L2 | 1,227.60 | 10,230<br>767,250 | 1.023 |
| L5 | 1,176.45 | 10,230<br>10,230 | 10.23 |

Table XII - Civil Signal Characteristics (cont'd)

| Civil Signal | Phases | Bit Rate (BPS) | Forward Error Correction |
|---|---|---|---|
| L1 | Bi-Phase | 50 | No |
| L2 | Bi-Phase | 25 | Yes |
| L5 | Quad-Phase | 50 | Yes |

Availability – Tables VII and XIII highlight key functional differences between the signals. Table XIII notes that L1 is fully available now but that L2C will not be fully available for many years. The term "fully available", of course, is in the eye of the beholder. It is likely that many dual-frequency applications will take advantage of L2C one satellite at a time, as they are launched. However, even these receivers will not be able to abandon semi-codeless tracking for L2 measurements until almost all the present generation of satellites have been replaced. Single frequency L2C applications will not be practical until there are enough satellites with the new signal. Fig. 7 suggests there may be 18 early in 2008, 21 in 2009, and 24 by 2010. Whether any of these coverage levels is sufficient depends on performance and on competition. If a very significant performance advantage can be demonstrated, products will come sooner. However, it is very difficult to overcome the advantage of a robust satellite constellation. If one product uses 24 satellites with L2C in 2010 but another offers a 30+ satellite constellation with L1 C/A, which product will customers judge better? Table XIII suggests 2011 is the year of "fully available" L2C, meaning nearly every satellite will have the new signal. Fig. 7 also makes clear that L5 availability lags L2C by four or more years. (Fig. 7 is based on the assumption that 12 IIR satellites will be modified and launched, although this is not yet certain.)

Table XIII – Civil Signal Functional Differences

| Civil Signal | Fully Available | Ionospheric Error Ratio | Correlation Protection (dB) |
|---|---|---|---|
| L1 | Now | 1.00 | > 21 |
| L2 | ~ 2011 | 1.65 | > 45 |
| L5 | ~ 2015 | 1.79 | > 30 |

Ionospheric Error – The third column of Table XIII shows an important effect of the frequency differences. Ionospheric refraction error is inversely proportional to frequency squared, so ionospheric error at L2 is 65% larger than at L1, and at L5 it's 79% larger. Because the largest source of single frequency navigation error is due to the ionosphere, this is a significant issue, not only when differential GPS (DGPS) is not used but also for users of wide area DGPS, e.g., WAAS, EGNOS(2), MSAS(3), etc., because high integrity correction of ionospheric error already is a major challenge at L1, and it becomes more difficult at lower frequencies. Wherever a truly local DGPS correction signal is available, e.g., LAAS(4), E911, and to a lesser extent NDGPS(5), the increased ionospheric error at L2 should not be much of a problem. It is likely, however, that L1 C/A will continue to be the preferred civil signal for all applications where single-frequency, non-local-DGPS accuracy is the primary concern. If GPS III eventually provides a better and stronger L1 signal, then the advantages of a modern signal structure and lower ionospheric error will be combined.

Correlation Protection – The fourth column of Table XIII shows the correlation protection characteristics for each signal. Because L2 has the longest code, it gives the best correlation protection. L1, with the shortest code, has the worst. This is very important for situations where some satellite signals are strong and others are very weak, like wireless E911 inside buildings or for navigation in or along heavily wooded areas.

A significant problem with L1 C/A is that a strong signal from one satellite can crosscorrelate with the codes a receiver uses to track other satellites. A strong signal thus can block reception of weak signals. Also, to track very weak signals the receiver must test every signal so it doesn't falsely track a strong signal instead of a weak signal. With more than 45 dB of crosscorrelation protection, L2C completely eliminates this problem. Also, better crosscorrelation performance provides headroom for future increases in L2 power, e.g., from GPS III satellites, and it helps L2C receivers reject narrowband interference signals.

Tracking Threshold and Data Recovery – Table VII summarized the threshold tracking and data recovery performance of the three civil signals, using L1 C/A as the reference. The bottom line is that in spite of having 2.3 dB less power, L2C is better in both respects than L1 C/A because of the signal design. The table also shows that when L5 is available it will have even better tracking and data recovery performance. The key difference between L2C and L5 is that L5 has four times more power.

**L2C Advantages**

Each of the three civil GPS signals has one or more key advantages. For example, L1 has the lowest ionospheric refraction error, L5 has the highest power and also is in an Aeronautical Radio Navigation Service (ARNS) band, and L2C has the best crosscorrelation performance. As a result, each one is important to one or more segments of the user community. The following paragraphs highlight L2C advantages which make it an attractive choice for a wide variety of applications.

L2C is superior to L1 in terms of crosscorrelation, threshold tracking, and data recovery performance. It also has a better message structure. It will be fully available years earlier than L5, and because of its lower code clock rate it will be better than L5 for many consumer applications, even after there are enough L5 signals.

Like L1 C/A, the L2C codes have an overall 1.023 MHz chip rate, ten times slower than L5. This might seem like a disadvantage, but for many low-power applications it's a significant advantage. The power consumed by a GPS chipset is a strong function of the code clock rate. This is not a problem for vehicle mounted equipment with adequate power, but for wristwatch and cell phone navigation, battery drain is a major issue. Equally important, chip size often is driven more by thermal dissipation than by the number of gates, so a slower clock helps with miniaturization.

Another very important advantage of a lower clock rate is the flexibility it offers in design of radio frequency (RF) filter(s). Whereas the 10.23 MHz L5 code clock forces use of a wide bandwidth filter with sharp cutoff characteristics to avoid out-of-band interference, L2C provides at least three design choices. For example, a sharp cutoff 1 MHz filter can be used for very difficult RF interference (RFI) environments. For minimum cost applications, a simple 1 MHz filter with gentle bandpass slopes is ideal. For high performance applications, a wide bandwidth filter with sharp cutoff characteristics in conjunction with multipath mitigation correlators in the chipset will achieve the same accuracy as L5. Thus, in addition to the maximum accuracy option, L2C receivers can be designed for minimum cost or best RFI protection.

In summary, with the exception of ionospheric refraction error, L2C is superior to L1 C/A in all other respects. Although L5 is a 6 dB stronger signal, L2C offers more design flexibility, with particular advantages for low power, very small, and low cost consumer applications. Because these characteristics make it likely that L2C will become the signal of choice for battery operated consumer products, eventually it is likely there will be more users of L2C than any other GPS signal.

**ACKNOWLEDGMENTS**

Without being able to acknowledge all who participated in the L2C design, definition, and implementation, the following individuals made particularly key contributions:

L2C development occurred because Col. Douglas L. Loverro, Program Director of the GPS JPO, questioned the wisdom of installing the old C/A code on modernized GPS satellites.

Steve Lazar of The Aerospace Corporation prepared a white paper, "Replacement Civil (R/C) Code for L2", 22 November 2000, which explained the issue, evaluated one alternative, and was the basis for initial discussions.

LCDR Richard D. Fontana (USCG), DoT Liaison and JPO Deputy Program Manager, led the JPO design and acquisition effort, including interagency and industry coordination.

At SAIC, Wai Cheung, senior systems engineer, helped organize the process, hosted team meetings, and managed the system integration process.

**The core signal structure technical team consisted of:**

Dr. Charles R. Cahn selected the codes, proposed chip-by-chip multiplexing, performed most of the signal analyses and tradeoff studies, and added indispensable insight.

Dr. Philip A. Dafesh of the Aerospace Corporation proposed lowering the message bit rate to balance the data recovery and carrier tracking thresholds and provided an initial hardware proof of concept demonstration.

Richard G. Keegan of RP Wireless LLC validated receiver implementation of the proposed signals.

Thomas A. Stansell, Jr. of Stansell Consulting, who originally proposed having a GPS coherent carrier signal component, guided the technical meetings and presented the results.

Dr. A. J. Van Dierendonck of AJ Systems offered alternate signal suggestions, performed analyses, and added L5 perspective.

Subsequent to the basic signal definition, Karl Kovach, Soon Yi, and Dr. Rhonda Slattery of ARINC documented L2C in the proposed revision of ICD-GPS-200.

**NOTES**

(1) "The Modernized L2 Civil Signal", *GPS World*, September 2001

(2) EGNOS is the European Geostationary Navigation Overlay Service, similar to WAAS in the U.S. (http://www.esa.int/EGNOS/)

(3) MSAS is the MTSAT Satellite-based Augmentation System, similar to WAAS in the U.S. (http://www.mlit.go.jp/koku/ats/e/serv/next/01.html)

(4) LAAS is the Local Area Augmentation System being designed to support high precision landings and airport surface navigation. (http://gps.faa.gov/Programs/LAAS/laas.htm)

(5) NDGPS is the Nationwide DGPS extension of the Coast Guard Beacon DGPS service throughout the U.S. (http://www.navcen.uscg.gov/dgps/ndgps/)