CHAPTER EIGHT

GPS Modernization and GNSS

Part I

GPS MODERNIZATION

The configuration of the GPS Space Segment is well-known. A minimum of 24 GPS satellites ensure 24-hour worldwide coverage. But today there are more than that minimum on orbit. There are a few spares on hand in space. The redundancy is prudent. GPS, put in place with amazing speed considering the technological hurdles, is now critical to all sorts of positioning, navigation and timing around the world. It's that very criticality that requires the GPS modernization. The oldest satellites in the current constellation were launched in 1989. Imagine using a personal computer of that vintage today. It is not surprising that there are plans in place to alter the system substantially. What might be unexpected is many of those plans will be implemented entirely outside of the GPS system itself. This chapter is about some of those changes.

Block I, Block II and Block IIR Satellites

Currently, the GPS satellites in orbit around the Earth include none of the first launched GPS satellites, which were known as Block I (1978-1985). None of these are functional today. The last Block I was retired in late 1995. These satellites needed help from the Control Segment to do the momentum dumping necessary to maintain their attitude control. They carried two cesium and two rubidium frequency standards and had a design life of 5 years, though some operated for double that.

The oldest of the satellites operating on orbit today are those in the original Block II (1989-1997). Remarkably, a majority of them are still healthy. The Block II satellites are radiation hardened against cosmic rays. They were built to provide SA and AS capability and have on-board momentum dumping for the maintenance of velocity and attitude control. There are also upgraded Block II satellites known as Block IIA. The first of these was launched in 1990. Block IIA satellites can function continuously for six months without intervention from the Control Segment, but the broadcast ephemeris and clock correction would degrade if that were done. Like the Block I the Block II satellites are also equipped with rubidium and cesium frequency standards. They are expected to have a Mean Mission Duration (MMD) of 10.6 yrs. That has obviously been exceeded in most cases. But the Block II satellites do wear out and as they do, the next generation goes up.

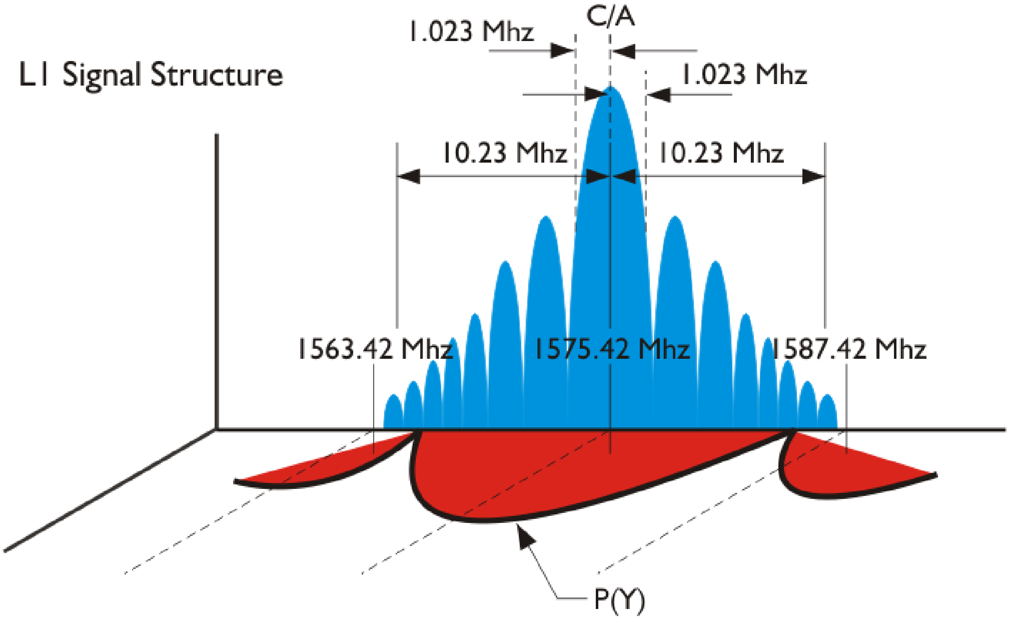
These are the Block IIR satellites, R is for replenishment. The first of these was launched in 1997. There are some significant differences between the Block II and the Block IIR satellites. Block IIR satellites can determine their own position using intersatellite crosslink ranging, called AutoNav. They have reprogrammable processors on-board to do their own fixes in flight. In other words, the Control Segment can change their flight software while the satellites orbit. Also, the Block IIR satellites can be moved into a new orbit with a 60-day advanced notice and they are more radiation hardened then their predecessors. In short they have more autonomy. On some of the Block IIR satellites there will be an improved antenna panel that will provide more signal power to GPS users on both L1 and L2. Eventually there will be approximately 21 Block IIR satellites launched.

However, there is one significant way in which the Block II and the Block IIR satellites are very much the same. They both broadcast the same fundamental GPS signals that have been in place for a long time. Their frequencies are centered on L1 and L2. As mentioned before, the Coarse/Acquisition or C/A-code is carried on L1 and has a chipping rate of 1.023 million chips per second. It has a code length of 1023 chips over the course of a millisecond before it repeats itself. There are actually 32 different code sequences that can be used in the C/A code, more than enough for each satellite. The Precise code or P-code on L1 and L2 has a chipping rate that is ten times faster at 10.23 million chips per second. It has a code length of about a week, approximately 6 trillion chips, before it repeats. If this code is encrypted it is known as the P(Y) code, or simply the Y-code

Power Spectral Density Diagrams. A convenient way to visualize these signals is a diagram of the power spectral density function, PSD. In fact, a good deal of signal theory is expressed in PSDs. They are basically an expression of Watts per Hertz as a function of frequency. Another way of saying it is power per bandwidth. The actual definition of PSD is the Fourier transform of the autocorrelation function, but the idea behind them is to give you an idea of the power within a signal with regard to frequency. In GPS the diagram is usually represented with the frequency in MHz on the horizontal axis and the density, the power, represented on the perpendicular axes in decibels relative to one Hertz per Watt or dBW.

Perhaps a bit of explanation is in order for dBW. As mentioned in Chapter 4, the decibel unit was really begun in Bell Labs as a way to express power loss on telephone lines. It is logarithmic function, but can be thought of as a percentage or a ratio. In other words, a change of 1 decibel would be an increase or a decrease of 27 percent. A change of 3 decibels would be an increase or a decrease of 100 percent. Now a decibel per Watt or dbW indicates actual power of a signal compared to a reference of 1 Watt, *W*. For example the signal from a GPS satellite is about +13.4 dBW and the same signal as received is about -163 dBW. Actually the minimum level for power received from the C/A code is -158.5 dBW, for the P code it is -161.5 dBW and for L2 it is -164.5 dBW.

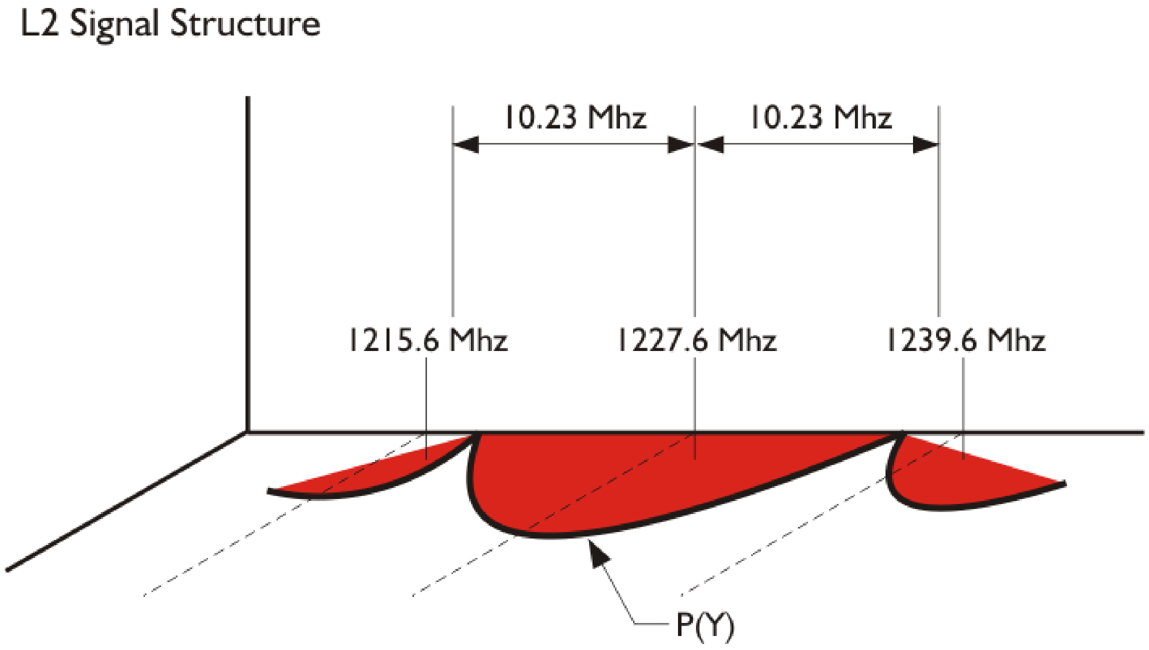
Therefore, these graphics show the increase or decrease, in decibels, of power, in Watts with respect to frequency in Hertz. Let's start with a couple of PSD diagrams of the well-known codes on L1 and L2.



L1 Signal

Figure 8.1

For example, in Figure 8.1 one can see the C/A code on the L1 signal, centered on the frequency 1575.42 MHz and spread over a bandwidth that is approximately 20.46 MHz, 10.23 MHz on each side of the center frequency. The P(Y) code is in quadrature that is 90 degrees from the C/A code. In both cases the majority of the power is close to the center frequency. The C/A code has many lobes but the P code with the same bandwidth but 10 times the clock rate has just the one main lobe.



L2 Signal

Figure 8.2

In Figure 8.2 the L2 signal diagram is centered on 1227.60 MHz . As you can see it is similar to the L1 diagram except for the absence of the C/A code which is, of course, not carried on the L2 frequency. As well-known as these are this state of affairs is changing.

New Signals

An important aspect of GPS modernization is the advent of some new and different signals that are augmenting the old reliable codes. In GPS a dramatic step was taken in this direction on September 21, 2005 when the first Block IIR-M satellite was launched. One of the significant improvements coming with the Block IIR-M satellites is increased L-band power on both L1 and L2 by virtue of the new antenna panel. The Block IIR-M satellites will also broadcast new signals, such as the M-code.

The M Code. Actually the M stands for modernized, but it is interesting to note that part of that modernization also includes a new M-code. Eight to twelve of these replenishment satellites are going to be modified to broadcast a new military code, the M-code. This code will be carried on both L1 and L2 and will probably replace the P(Y) code eventually and has the advantage of allowing the DoD to increase the power of the code to prevent jamming. There was consideration given to raising the power of the P(Y) code to accomplish the same end, but that strategy was discarded when it was shown to interfere with the C/A code.

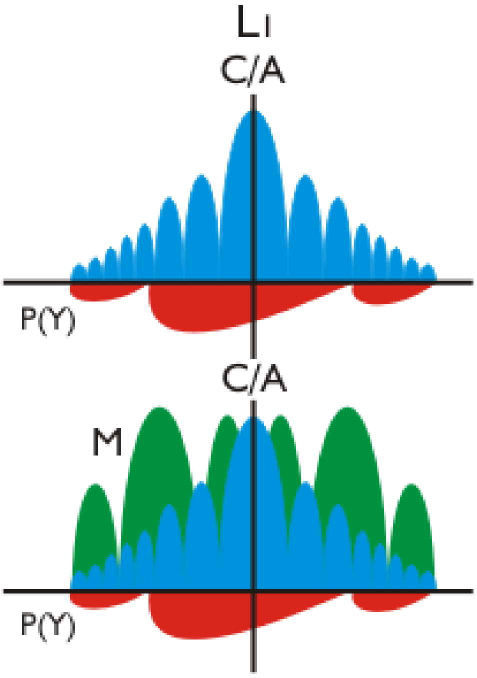


Figure 8.3

The M-code was designed to share the same bands with existing signals, on both L1 and L2, and still be separate from them. See those two peaks in the M-code in Figure 8.3? They represent a split-spectrum signal about the carrier. Among other things this allows minimum overlap with the maximum power densities of the P(Y) code and the C/A code, which occur near the center frequency. That is because the actual modulation of the M-code is done differently. It is accomplished with binary offset carrier (BOC) modulation which differs from the binary phase shift key (BPSK) used with the legacy C/A and P(Y) signals. An important characteristic of BOC modulation is the M-code has its greatest power density at the edges that is at the *nulls*, of the L1. This architecture both simplifies implementation at the satellites and receivers and also mitigates interference with the existing codes. Suffice it to say that this aspect and others of the BOC modulation strategy offer even better spectral separation between the M-code and the older legacy signals.

Perhaps it would also be useful here to mention the notation used to describe the particular implementations of the Binary Offset Carrier. It is characteristic for it to be written BOC(α,β). Here the α indicates the frequency of the square wave modulation of the carrier, also know as the sub-carrier frequency factor. The β describes the frequency of the pseudo-random noise modulation, also known as the spreading code factor. In the case of the M-code the notation is BOC(10,5) describes the modulation of the signal. Both here are multiples of 1.023 MHz. In other words their actual values are α = 10 x 1.023 MHz = 10.23 MHz and β = 5 x 1.023 MHz = 5.115 MHz (Betz).

The M-code is tracked by direct acquisition. This means that as mentioned in Chapter One the receiver correlates the signal coming in from the satellite with a replica of the code that it has generated itself.

L2C. A new military code on L1 and L2 may not be terribly exciting to civilian users, but these IIR-M satellites have something else going for them. They are outfitted with new hardware that will allow them to broadcast a new civilian code. This is a code that was first announced back in March of 1998. It will be on L2 and will be known as L2C. The "C" is for civil.

We have been using the L2 carrier since the beginning of GPS of course, but now there will be two new codes broadcast on the carrier, L2, that previously only carried one military signal exclusively, the P(Y) code. Now L2 will carry a new military signal, the M-code, and a new civil signal as well, L2C.

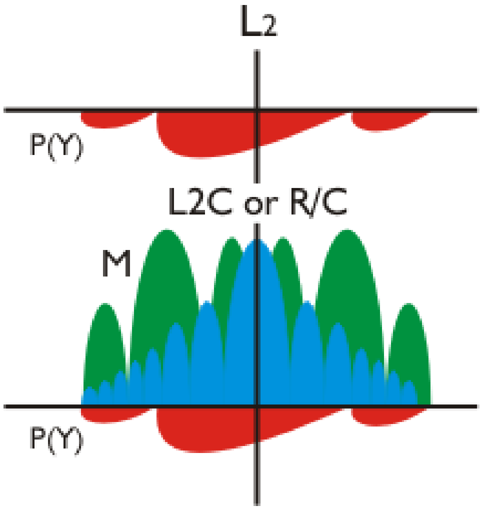


Figure 8.4

Even though its 2.046 MHz from null-to-null gives it a very similar power spectrum to the C/A code, it is important to note that L2C is not merely a copy of the C/A-code. Still that was in fact the initial idea. The original plan was that it would be a replication of the venerable C/A code, but carried on L2 instead of L1. This concept changed when

Colonel Douglas L. Loverro, Program Director for the GPS Joint Program Office (JPO) was asked if perhaps it was time for some improvement of C/A. The answer was yes. The C/A code is somewhat susceptible to both waveform distortion and narrow-band interference and its cross-correlation properties are marginal at best. So the new code on L2, known as L2 civil, or L2C was announced.

CM and CL. L2C will be a bit more sophisticated that C/A. L2C is actually composed of two codes, L2CM and L2CL. The CM designation stands for the civil-moderate length code. This signal carries data. The message that it carries is an improved Navigation code. You may recall that the legacy Navigation message was mentioned in Chapter One. It also known by the acronym NAV, and is broadcast at 50 bps. The new Navigation message is known by the acronym CNAV. It is broadcast at 25 bps. Like the original NAV message it has 300 bit subframes, but given the lower broadcast rate CNAV takes 12 seconds to transmit each of its subframes whereas NAV requires only 6 seconds. Nevertheless because CNAV is a bit more flexible and compact than the original NAV it has the very desirable effect of allowing a receiver to get to its first fix on a satellite much faster than before.

CNAV. While the information in CNAV is fundamentally the same as that in the original Navigation message; including almanac, ephermides, time and satellite health; the data is more accurate and provides higher precision. Also, instead of using the same frame-subframe format of the Navigation message illustrated in Chapter One, CNAV uses 12-second 300-bit message packets. One of every four of these packets includes clock data;

two of every four contains ephemeris data and so on. CNAV can accommodate the transmission of the information in support of 32 satellites using 75% or less of its bandwidth and a fraction of the available packet types.

There could be a packet that would contain differential correction like that available from satellite based augmentation systems, SBAS. This could be used to improve the L1 NAV clock data. As it stands a packet is assigned to the time offset between GPS and GNSS which is a boon for interoperability between GPS, GALILEO and GLONASS. Also each packet contains a flag that can be toggled on within a few seconds of when a satellite is known to be unhealthy and should not be used. This is exactly the sort of quick access to information necessary to support safety-of-life applications. In other words, CNAV is designed to grow up to accommodate 63 satellites and change as the system requires.

There is also a very interesting aspect to the data broadcast on CM known as Forward Error Correction, FEC. An illustration of this technique is to imagine that every individual piece of data is sent to the receiver twice. If the receiver knows the details of the protocol to which the data ought to conform it can compare each of the two instances it has received to that protocol. If they both conform, there is no problem. If one does and one does not, the piece of data that conforms to the protocol is accepted and the other is rejected. If neither conforms then both are rejected. Using FEC allows the receiver to correct transmission errors itself, on the fly. The CL for civil-long on the other hand is a pilot signal and it carries no message. They utilize the same modulation scheme, binary phase shift key (BPSK), as the legacy signals

Multiplexing. But wait a minute, how can you do that? How can you have two codes in one? L2C achieves this by multiplexing. Since the two codes have different lengths L2C alternates between chips of the CM code and chips of the CL code. It's called chip-by-chip time multiplexing. So even though the actual chipping rate is 511.5 KHz, half the chipping rate of the C/A code, with the time multiplexing it still works out that taken together L2C ends up having the same overall chip rate as L1 C/A code, 1.023 MHz .

The CM code, the moderate length code goes through 10,230 chips before it repeats. It does that every 20 milliseconds. But the CL code, the long code repeats after 767,250 chips every 1.5 seconds and that length gives you very good cross-correlation protection. In fact, both are a longer than the C/A code and present a subsequent improvement in auto-correlation, as well as cross-correlation. This is because longer the code the easier it is to keep the desired signals separate from the background. In practice this means these signals can be acquired with more certainty by a receiver which can maintain lock on them more surely in marginal situations where the sky is obstructed.

Phase-Locked Loop. It is also important to note that L2C overall is approximately 2.3 dB weaker than is C/A on L1. Surprisingly that is not a disadvantage due to the structure of the L2C signal. The receiver can track the long data-less CL with a phase-locked loop instead of a squaring Costas loop that is necessary to maintain lock on CM, C/A and

P(Y). This allows for improved tracking from what is, in fact, a weaker signal and a subsequent improvement in protection against continuous wave interference. As a way to illustrate how this would work in practice, here is one normal sequence by which a receiver would lock onto L2C. First there would be acquisition of the CM code with a frequency locked or Costas loop, next there would be testing of the 75 possible phases of CL and finally acquisition of CL. The CL as mentioned can be then tracked with a basic phase-locked loop. Using this strategy, even though L2C is weaker than C/A there is actually an improvement in the threshold of nearly 6 dB by tracking the CL with the phase-locked loop.

In other words the long dataless sequence of the CL provides for a correlation about 250 times stronger than the C/A code. So despite the fact that its transmission power is 2.3 dB weaker, compared to the C/A code L2C has 2.7 dB greater data recovery and 0.7 dB greater carrier-tracking.

Practical Advantages. OK. Great so what does all that mean in English? It means that L2C has better tolerance to interference. It also means increased stability. It means improved tracking in obstructed areas like woods, near buildings and urban canyons It means fewer cycle slips.

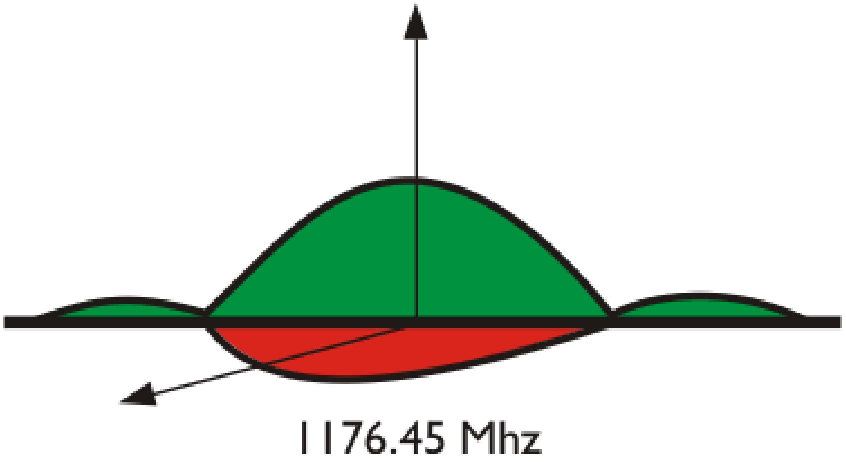
There are more solid practical advantages to the introduction of L2C. Before May 2, 2000 with Selective Availability on, a little handheld code-based receiver could get you within 30 to 100 meters of your true position. When SA was turned off that was whittled down to 15 to 20 meters or so. But with just one civilian code C/A on L1 there was no way to remove the second largest source of error in that position, the ionospheric delay. But now with two civilian signals, one on L1 (C/A) and one on L2 (L2C) it becomes possible to effectively model the ionosphere using code phase. In other words, it may become possible for an autonomous code-phase receiver to achieve positions with a 5-10m positional accuracy with some consistency. And there are more developments coming. Developments that just might increase that accuracy to a sub-meter range.

So, even if it is the carrier-phase that ultimately delivers the wonderful positional accuracy we all depend on, the codes gets us in the game and keep us out of trouble every time we turn on the receiver. The codes have helped us to lock on to the first satellite in a session and allowed us to get the advantage of cross-correlation techniques almost since the beginning of GPS. In other words, our receivers have been combining pseudorange and carrier phase observables in innovative ways for some time now to measure the ionospheric delay, detect multipath, do widelaning, etc. But those techniques can be improved, because while the current methods work, the results can be noisy and not quite as stable as they might be, especially over long baselines. It will be cleaner to get the signal directly once there are two clear civilian codes, one on each carrier. It may also help reduce the complexity of the chipsets inside our receivers, and might just reduce their cost as well.

Along that line it is worthwhile to recall that the L2C has an overall chip rate of 1.023 MHz, just like L1 C/A. Such a slow chip rate can seem to be a drawback until you consider that that rate affects the GPS chipset power consumption. In general, the slower the rate the longer the battery life and the improvement in receiver battery life could be very helpful. And not only that, the slower the chip rate, the smaller the chipset. That could mean more miniaturization of receiver components.

L2C is clearly going to be good for the GPS consumer market, but it also holds promise for surveyors. Nevertheless, there are a few obstacles to full utilization of the L2C signal. As mentioned earlier the first Block IIR-M, namely SVN53/PRN17, was launched on September 21, 2005. It will be some time before the constellation of Block IIR-M necessary to provide L2C at an operational level are up and functioning. Additionally aviation authorities do not support L2C. It is not in an *Aeronautical Radionavigation Service, ARNS,* protected band. It happens that L2 itself occupies a radiolocation band that includes ground-based radars.

L5



The L5 Carrier

Figure 8.5

Ok, L2C is fine, but what about the new carrier everybody has been talking about, L5? It will be centered on 1176.45 MHz, 115 times the fundamental clock rate. As you see from Figure 8.5 the basic structure of L5 looks similar to that of L1. There are two codes on this carrier in quadrature to each other. They have separate pseudorandom noise (PRN) codes two codes per satellite, which are modulated using Quad Phase Shift Key (QPSK). However, borrowing a page from the newer developments the in-phase (I) signal carries a data message and the other; the quadraphase signal (Q) is data-less. Both have equal power. The data that is carried on L5 is a compact flexible message similar to that carried by L2C CM. L5 will also utilize time multiplexing in broadcasting its two codes as does L2C in broadcasting CM and CL.

Unlike L2C, L5 will have the benefits of its place in a band designated by the International Telecommunication Union for the Aeronautical Radionavigation Navigation

Services (ARNS). Therefore, it will not be prone to interference with ground based navigation aids and will be available for aviation applications. It is also quite helpful that no other GPS signal occupies this band. However, L5 will share space one of the signals, E5a-I from an entirely separate satellite system, GALILEO, a very good idea, more about that later.

As mentioned, L5 will have one signal modulated with data and one without. And since L5 does not carry military signals, it achieves the power split by using two long equal-length codes in phase quadrature on each satellite. Both have a 10.23 MHz chipping rate, the same as the fundamental clock rate. It is worth noting that this is the same rate that has been available on the P(Y) code from the beginning of the system. However, as you know the P(Y) code is unavailable for civilian use. So this will be the fastest chipping rate available in a civilian code, it will have the same overall length as CM on L2C and L1C, 10,230 chips. But L5 will have the only civilian codes that are both ten times longer and ten times faster than the C/A code so the risk of interference is very low and, good news, the data-less signal will be much easier to acquire in unfavorable SNR conditions.

The fast chipping rate is also good news. As mentioned in Chapter One a rule of thumb is the maximum resolution available in a pseudorange is about 1 percent of the chipping rate of the code used. The faster the chipping rate the better the resolution, it also improves multipath protection. L5 will also have higher power than L1, about 4 times more power. The increase power is also good news because the legacy signals from GPS satellites are weak. L5 will also have a wide bandwidth, about 20 MHz. L5 will also incorporate Forward Error Correction, FEC.

The Block IIF Satellites L5 will be first introduced on the fourth generation GPS satellites, Block IIF, the F is for follow-on. These satellites have a somewhat longer expected lifetime of 12-15 years with faster processors and more memory on-board. They carry two rubidium atomic frequency standards and one cesium. Their on-board *navigation data units, NDU,* support the creation of new navigation messages with improved broadcast ephemeris and clock corrections. Like the Block IIR satellites the Block IIF can be re-programmed on orbit. But we are going to have to be a little patient. The IIR and IIR-M satellites are in line in front of the IIF satellites. The dozen or so IIR's will be launched, orbit and reach the end of their functional lives before L5 will be on all the satellites. And the satellites already in orbit have performed well beyond their design life.

As a matter of fact that development is somewhat responsible for the delay in implementing GPS III. GPS III is the effort to take a new look at the entire GPS architecture to ensure the best service for the next 30 years. We may have to wait a while before L5 and the L2C on L2 are fully operational. It is unfortunate that L5 cannot be built into the IIR's, the satellites that are going up now.

The first six Block IIF satellites are expected to have a Mean Mission Duration (MMD) of 9.9 yrs. Block IIF will have all the codes discussed earlier, including L2C on L2 and it will broadcast the new L5 carrier. L5 will not cause any interference to existing systems nor require their modification.

Summary of C/A, L2C and L5

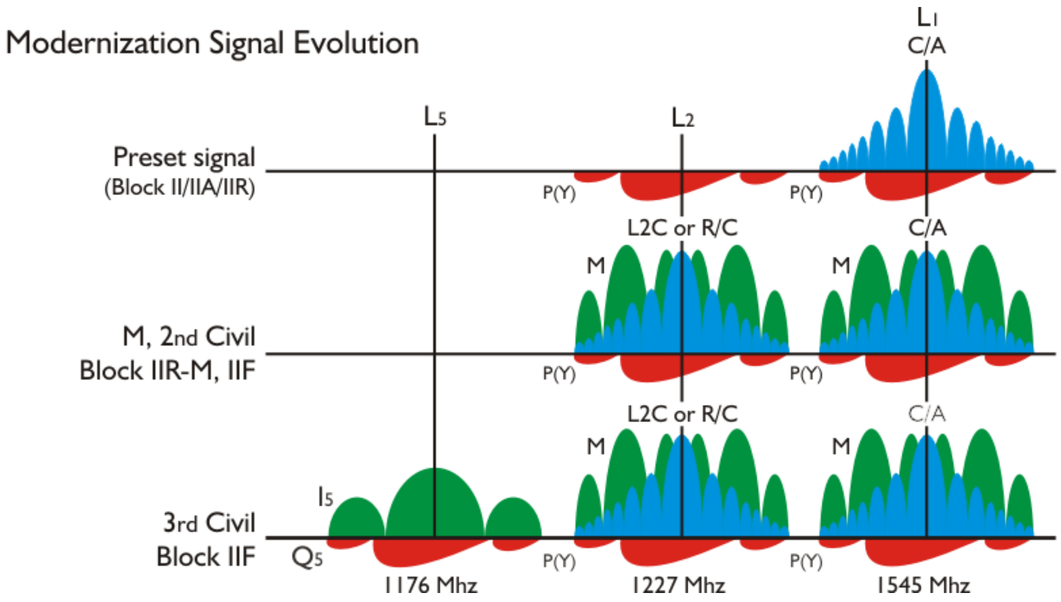


Figure 8.6

(Adapted from Steve Lazar, Crosslink (Summer 2002), Aerospace Corporation, http://www.aero.org/publications/crosslink/summer2002/07.html)

GPS modernization is no longer a future development, it is underway. New spacecraft with better electronics, better navigation messages, newer and better clocks are just part of the story. Beginning with the launch of the first IIR-M satellite new civil signals began to appear, starting with L2C. It will be followed by others, including L5.

These signals tend to have longer codes, faster chipping rates and more power than the C/A and P(Y) codes have. In practical terms these developments lead to faster first acquisition, better separation between codes, reduced multipath and better cross-correlation properties.

Signal/SV	**IIR**	**IIR-M**	**IIF**
L1 C/A	●	●	●
L1 P/Y	●	●	●
L1 M		●	●
L2 L2C		●	●
L2 P/Y	●	●	●
L2 M		●	●
L5 Civil			●

New Signal Availability

Figure 8.7

Table 8.7 provides a general outline of all of the signals that are or will be available on the upcoming satellite blocks.

Availability. Given the current projected launch schedules it looks like the three new civil signals: L1-C/A, L2-L2C, and the in-phase and quadraphase signals on L5 will attain initial operational capability, IOC between 2010 and 2020 or so. Full operational capability, FOC will follow IOC within 5 -10 years. These years are, of course, impossible to predict with accuracy. Aviation, in particular, is looking forward to L5 for its promise of precision approach capability.

Ionospheric Bias. Concerning the effect of the ionosphere- as you know ionospheric delay is inversely proportional to frequency of the signal squared. So it is that L2's atmospheric bias is about 65% larger than L1, and it follows that the bias for L5 is the worst of the three at 79% larger than L1. L1 exhibits the least delay as it has the highest frequency of the three.

Correlation Protection. Where a receiver is in an environment where it collects some satellite signals that are quite strong and others that are weak, such as inside buildings or places where the sky is obstructed, correlation protection is vital. The slow chipping rate, short code length and low power of L1 C/A means it has the lowest correlation protection of the three frequencies; L1, L2 and L5. That means that a strong signal from one satellite can cross correlate with the codes a receiver uses to track other satellites. In other words the strong signal will actually block collection of the weak signals. To avoid this the receiver is forced to test every single signal so to avoid incorrectly tracking the strong signal it does not want instead of a weak signal that it does. This problem is much reduced with L2. It has a longer code length and higher power than L1. It is also reduced with L5 as compared to L1. L5 has a longer code length, much higher power and a much faster chipping rate than L1. In short, both of the civilian codes on L2 and

L5 have much better cross correlation protection and better narrowband interference protection than L1, but L5 is best of them all.

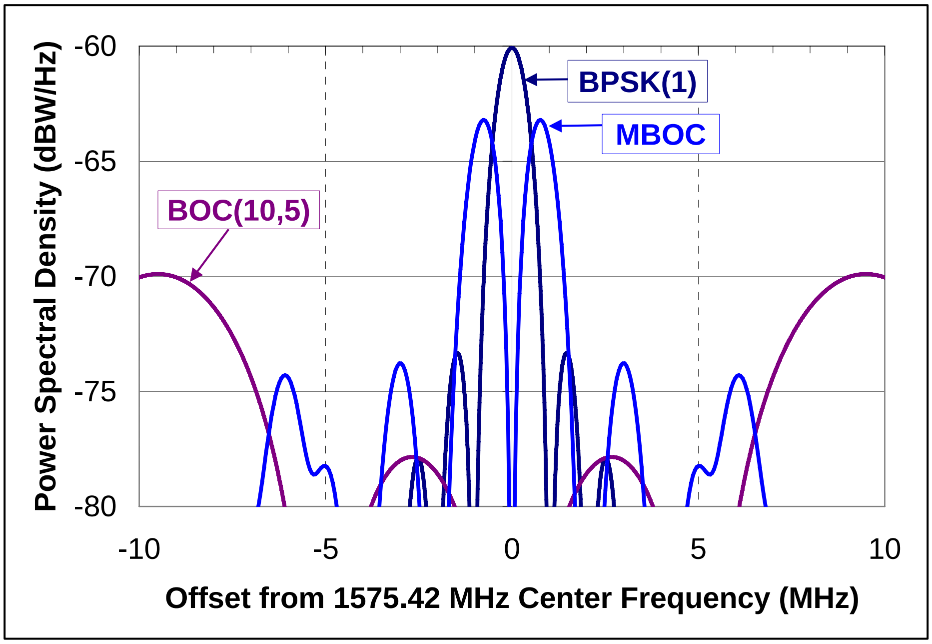
Another Civil Signal - L1C

As the result of an agreement reached between the US and the EU in June of 2004 yet another civil signal is in the beginning stages of development. Part of that deal involved the creation of an interoperable GPS/GALILEO signal on L1. This signal, known as L1C and will be only one of two common interoperable signals shared by both GPS and GALILEO's L1 Open Service signal. Work is also underway to allow L1C to be interoperable with QZSS, the Japanese Quasi-Zenith Satellite System, as well. These developments open extraordinary possibilities of improved accuracy and efficiency when one considers there may eventually be a combined constellation of 50 or more satellites all broadcasting this same civilian signal. All this is made possible by the fact that each of these different satellite systems utilizes carrier frequencies centered on the L1, 1575.42 MHz frequency.

While the details of L1C's design are somewhat provisional it is intended to provide a performance improvement over the C/A code and will have some similarities with L2C. L1C will have double the power of the C/A signal and a code of the same length as CM on L2C 10,230 chips. Like L2C it will have a pilot signal that does not carry a message, and will also have a one signal with a data message with exactly the same code length on both components. This approach means that all of the signal power can be used for acquisition of the signal. In other words, this strategy offers equal power splitting between the data and a data-less portions.

The data portion of L1C will carry a Navigation message known as CNAV-2 just like L2C. Among other things this feature will allow the receiver to reach its first fix to the satellite faster. The details of this Navigation message are not yet complete as other aspects of this signal. Also, as in L2C, L1C will likely incorporate FEC, Forward Error Correction.

The L1C provisional design also shares some design similarities with the M code, Binary Offset Carrier, BOC modulation. L1C will use MBOC, which is 90.9 percent BOC(1,1) and 9.1 percent BOC(6,1), and as with the M code it will have good separation from the other signals on L1 and a good tracking threshold as well. Please recall that this also allows tracking with the superior phase-locked loop as opposed to the Costas loop.



(Mr. Tom Stansell of Stansell Consulting)

Figure 8.8

There are many signals on L1. Perhaps that has something to do with the fact that L1 having the highest frequency experiences the least ionospheric delay of the carrier frequencies. There is the C/A code, the P(Y) code, the M code and now perhaps the L1C code. It is a challenge to introduce yet another code on the crowded L1 frequency and still maintain separability.