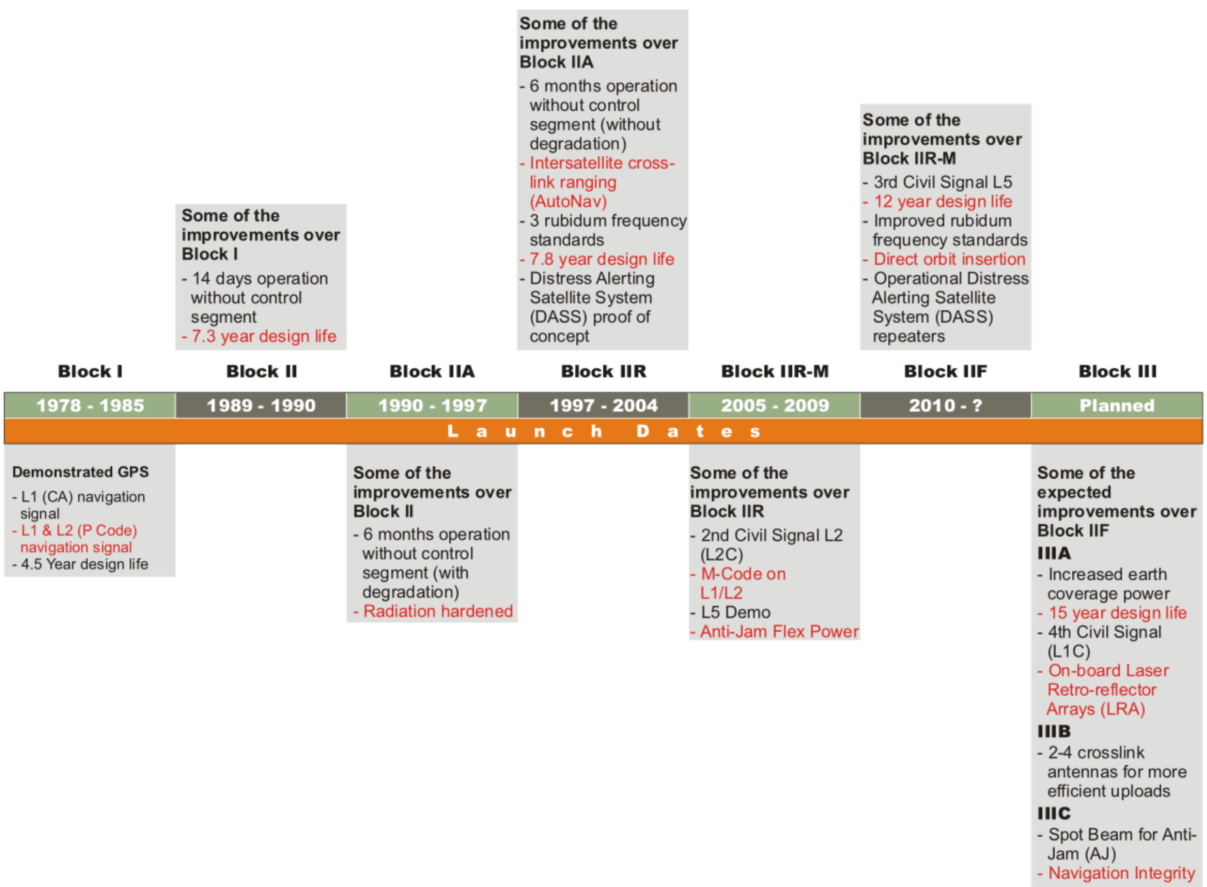
GPS Modernization

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 was put in place with amazing speed considering the technological hurdles. It reached its Fully Operational Capability (FOC) on July 17, 1995. Today GPS is critical to positioning, navigation and timing, of course. It is also critical to the smooth functioning of financial transactions, air traffic, ATMs, cell phones and modern life in general around the world. This very criticality requires continuous modernization.

The oldest satellites in the current constellation were launched in the early 1990s . If you imagine using a personal computer of that vintage today, it is not surprising that there are plans in place to alter the system substantially. In 2000, U.S. Congress authorized the GPS III effort. The project involves new ground stations and satellites, additional civilian and military navigation signals, and improved availability.

SATELLITE BLOCKS

BLOCK I, BLOCK II/IIA, BLOCK IIR and **BLOCK III SATELLITES**



BLOCK I

The GPS satellites on orbit around the earth include none of the first launched Block I satellites.

The first of them went up in1978 and 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 had a design life of 4.5 years, though some operated for double that. None of the Block I satellites are functional today. In subsequent blocks of satellites design lives increased and dependence on the Control Segment decreased. However, the equipment of the satellites with two cesium, two rubidium frequency standards and the onboard nuclear detonation detection sensors are features from Block I that has been carried forward into future blocks of satellites.

BLOCK II

The first of the Block II satellites was launched in 1989 and these satellites often exceeded their 7.3 design life too. The last of them was decommissioned in 2007 after 17 years of operation. They could be autonomous, without contact with the Control Segment, for up to 14 days. None of the Block II satellites are functioning today, but as of 2013 there are 8 of the next block, called Block IIA, operating in the GPS constellation.

BLOCK IIA

Block IIA satellites are an improved version of the Block II. The first of them was launched in 1990 and they are now the oldest of the GPS satellites operating on orbit. Remarkably, about half of them are still healthy. There are 9 Block IIA satellites on orbit and operational. They are radiation hardened against cosmic rays, built to provide Selective Availability (SA), antispoofing (AS) capability and onboard momentum dumping. They can store more of the Navigation message than the Block II satellites and can, therefore operation without contact with the Control Segment for 6 months. However, if that were actually done their broadcast ephemeris and clock correction would degrade.

Two Block IIA satellites, SVN 35 (PRN 05) and SVN 36 (PRN 06), have been equipped with Laser Retro-reflector Arrays (LRA). The second of these was launched in 1994 and is still in service. The retro-reflectors facilitate satellite laser ranging (SLR). Such ranging can provide a valuable independent validation of GPS orbits.

Like the Block I and the Block II satellites, the Block IIA satellites are equipped with two rubidium and two cesium frequency standards. They are expected to have a design life of 7.3 years. While the design life has obviously been exceeded in most cases, Block IIA satellites do wear out.

BLOCK IIR

The first launch of the next Block, Block IIR satellites in 1997 was unsuccessful. The following launch succeeded. There are 12 Block IIR satellites on orbit and operational. There are some differences between the Block IIA and the Block IIR satellites. The Block IIR satellites have a design life of 7.8 years and can determine their own position using inter-satellite crosslink ranging, called AutoNav. This involves their use of reprogrammable processors onboard to do their own fixes in flight. They can operate in that mode for up to 6 months and still maintain full accuracy. The Control Segment can also change their software while the satellites are in flight and, with a 60-day notice, move them into a new orbit. Unlike their predecessors these satellites are equipped with three rubidium frequency standards. Some of the Block IIR satellites also have an improved antenna panel that provides more signal power.

Despite their differences Block IIA and the Block IIR satellites are very much the same in some ways. 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 code 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 in the constellation to have its own. The Precise code or P-code on L1 and L2 has a chipping rate that is ten times faster than the C/A code at 10.23 million chips per second. The P-code 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.

Nine of the Block IIR satellites carry Distress Alerting Satellite System (DASS) repeaters. These DASS repeaters are used to relay distress signals from emergency beacons and were part of a proof of the concept of satellite-supported search and rescue that was completed in 2009. Twelve additional IIR satellites will carry them too.

BLOCK IIR-M

In the current constellation (2013) there are 8 Block IIR-M satellites on orbit and operational. These are IIR satellites that were modified before they were launched. The modifications upgraded these satellites so that they radiate two new codes; a new military code, the M code, a new civilian code, the L2C code and demonstrate a new carrier, L5. The L2C code is broadcast on L2 only and the M code is on both L1 and L2. The L2C code helps in the correction of the ionospheric delay and the M code improves the military anti-jamming efforts through flexible power capability. One of the Block IIR-M satellites, SVN 49, transmits on L1, L2 and L5. L5 is a frequency intended for safety-of-life applications. The first of these Block IIR-M satellites was launched in the summer of 2005 and the last in the summer of 2009.

BLOCK IIF

The first Block IIF satellite was launched in the summer of 2010 as of 2013 there are 4 Block IIF satellites on orbit. Their design life is 12 years. They broadcast all of the previously mentioned signals, and one more, a new carrier known as L5. This signal that was demonstrated on the Block IIR-M. It will be available from all of the Block IIF satellites. The L5 signal is within the Aeronautical Radio Navigation Services (ARNS) frequency and can service aeronautical applications. The improved rubidium frequency standards on Block IIF satellites have a reduced white noise level. The Block IIF satellite's launch vehicles can place the satellites directly into their intended orbits so they do not need the apogee kick motors their predecessors required. All of the Block IIF satellites will carry DASS repeaters. The Block IIF satellites will replace the Block IIA satellites as they age.

BLOCK III

Block III satellites will replace the older Block IIR satellites as they are taken out of service. As yet (2013) there are no Block III satellites on orbit. This block will be deployed in three increments. The first of these is known as Block IIIA. It will be resistant to hostile jamming. The next two increments are Block IIIB and Block IIIC. Higher power is planned for the signals broadcast by the IIIB satellites. The IIIB and IIIC satellites will also carry Distress Alerting Satellite System (DASS) repeaters.

When the whole GPS constellation has DASS repeaters on board there will be global coverage for satellite-supported search and rescue and at least four DASS-equipped satellites will always be visible from anywhere on Earth. This system will enhance the international Cospas-Sarsat satellite-aided search and rescue (SAR) system and will be interoperable with the similar planned Russian (SAR/GLONASS) and European (SAR/GALILEO) systems.

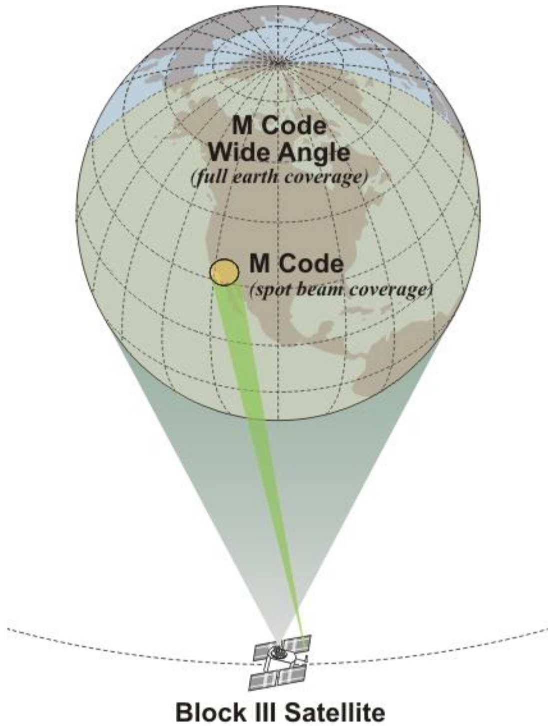
Block III satellites will have cross-link capability to support inter-satellite ranging and transfer; telemetry, tracking and control (TT&C) capability. Block IIIB satellites will have from two to four directional crosslink antennas. This means they can be updated from a single ground station instead of requiring each satellite to be in the range of a ground antenna to be updated. This and their high speed upload and download antennas could help increase the upload frequency from once every 12 hours to once every 15 minutes.

Each Block III satellites will have three enhanced rubidium frequency standards (clocks) and a fourth slot will be available for a new clock, i.e. a hydrogen maser.

It was established in 2010 that all Block III satellites will have on-board Laser Retroreflector Arrays (LRA) (*aka retro-reflectors*). The satellite laser tracking available with this payload will provide data from which it will be possible to distinguish between clock error and ephemeris error Similar LRA are planned for the Russian (GLONASS) and European (GALILEO) systems

There is a plan for these satellites that includes the broadcast of a new civil signal, known as L1C, on the L1 carrier. This signal was designed with international cooperation to maximize interoperability with Galileo's Open Service Signal and Japan's Quazi-Zenith Satellite System (QZSS)

Codes available from earlier blocks, i.e. the M code, L5, the P code and the C/A code will be broadcast with increased power from the Block III satellites. The broadcast of the M code will change in an interesting way. It will continue to be radiated with a *wide angle* to cover the full earth just as in the Block IIR-M satellites, but the Block IIIC M code will also have a rather large deployable high-gain antenna to produce a directional *spot beam*. The spot beam will have approximately 100 times more power (-138 dBW) compared with (-158dBW) the wide angle M-code broadcast. It will have the anti-jam (AJ) capability to be aimed to a region several hundreds of kilometers in diameter.



POWER SPECTRAL DENSITY DIAGRAMS

To better illustrate the differences in the new signals let's look at a convenient way to visualize all the GPS and GNSS signals. It is a diagram of the power spectral density function (PSD). In fact, a good deal of signal theory can be visualized in PSDs. They illustrate power per bandwidth. They are a graphical representation of Watts per Hertz as a function of frequency. The actual definition of PSD is the Fourier transform of the autocorrelation function. In GPS and GNSS literature the diagram is often 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/Hz.

A bel unit originated at Bell Labs to quantify power loss on telephone lines. A decibel is a tenth of a bel. A decibel, dB, is a dimensionless number. In other words it's a ratio that can acquire dimension by being associated with measured units. Here are some of the quantities with which it is sometimes associated: seconds of time, symbolized dBs, and bandwidth measured in Hertz, symbolized dBHz and temperature measured in Kelvins, symbolized dBK. Since signal power is of interest here dB will be described with respect to 1Watt, dBW.

DBW is used because it provides a short concise number that can conveniently express the wide variation in GPS signal power levels. In other words, dBW can represent quite large and quite small amounts of power more handily than other notations. For example, consider a value of interest in the realm of GPS signals, one tenth of a millionth billionth of a watt. Expressing it as 0.0000000000000001 W is a bit exhausting. It would be more convenient expressed in dBW, a value that can be derived using the formula

$$P_{dBW} = 10\log_{10}\frac{P_W}{1W}$$

where P_W is the power of the signal.

$$P_{dBW} = 10\log_{10}\frac{10^{-16}\,W}{1W}$$
$$P_{dBW} = 10\log_{10}10^{-16}\ \mathrm{W}$$
$$-160dBW = 10\log_{10}10^{-16}\,W$$

The expression −160 dBW is immediately useful. Here's an example. A change in 3 decibels is always an increase or a decrease of 100% in power level. Stated another way a 3 decibel increase indicates a doubling of signal strength and a 3 decibel decrease indicates a halving of signal strength. Therefore, it is easy to see that a signal of -163 dBW has half the power of a signal of -160dBW. Considering the broadcasts from the current constellation of satellites, the minimum power received from the P code on L1 by a GPS receiver on the Earth's surface is about -163 dBW and the minimum power received from the C/A code on L1 is about -160dBW. This difference between the two received signals is not surprising since at the start of their trip to Earth they are transmitted by the satellite at power levels that are also 3 decibels apart. The P code on L1is transmitted at a nominal +23.8 dBW (240 W) whereas the nominal transmitted power of the C/A code on L1 is +26.8 dBW (479 W). It is interesting to note that the minimum received power of the P code on L2 is even less at -166 dBW and its nominal transmitted power is +19.7 dBW (93 W).

$$P_{dBW} = 10\log_{10}\frac{P_W}{1W}$$
$$P_{dBW} = 10\log_{10}\frac{93W}{1W}$$
$$+19.7dBW = 10\log_{10}93W$$

One might wonder why there are such differences between the power of the transmitted GPS signal, called the Effective Isotropic Radiated Power (EIRP), and the power of the received signal. The difference is large. It is 186 - 187 dB, nearly 10 quintillion decibels. The loss is mostly because is the 20,000 km distance from the satellite to a GPS receiver on the Earth. There is also an atmospheric loss and a polarization mismatch loss, but the biggest loss by far, about 184 dB, is along the path in free space. By the time the signal makes that trip and reaches the GPS receiver it is pretty weak. It follows that GPS signals are easily degraded by vegetation canopy, urban canyons and other interference.

A GPS signal has power, of course, but it also has bandwidth. Power spectral density (PSD) is a measure of how much power a modulated carrier contains within a specified bandwidth. Using the following formula and allowing that there is an even distribution of 10^{-16} W over the 2.046 MHz C/A bandwidth of the C/A code:

$$Power\ density\left(\frac{dBW}{Hz}\right) = 10\log_{10}\left[\frac{power\ (W)}{bandwidth\ (Hz)}\right]$$

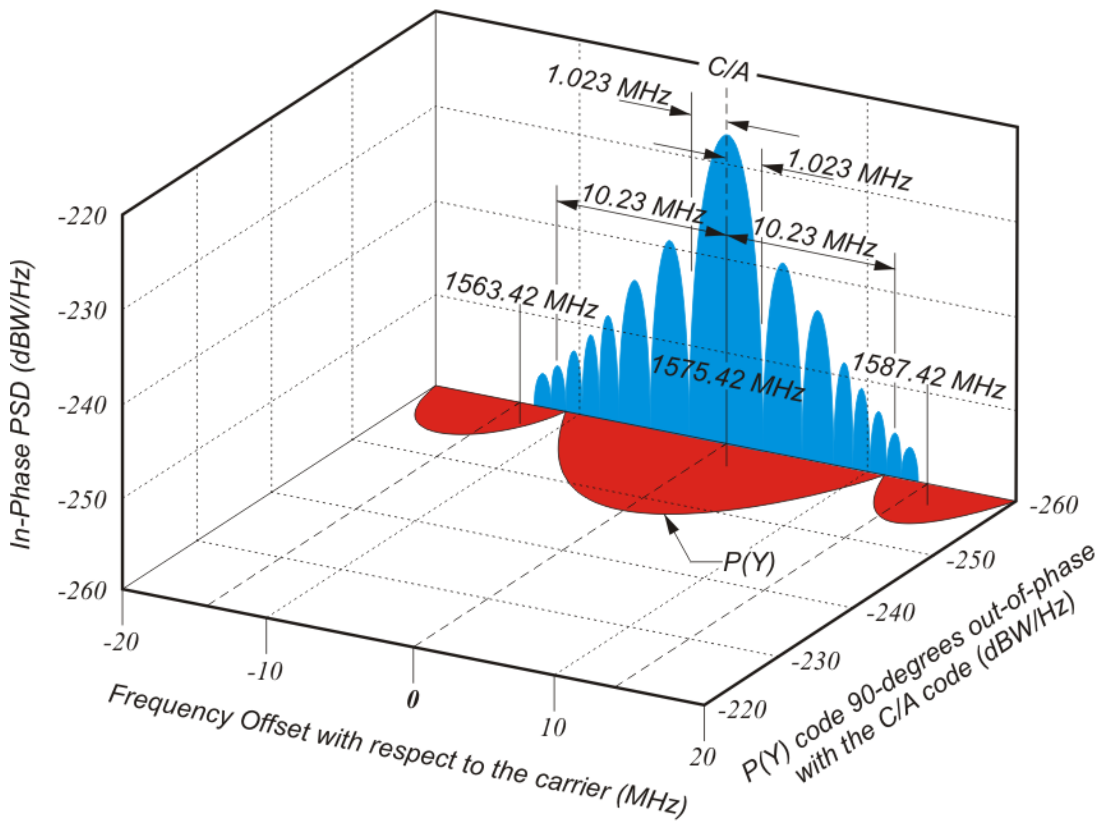
$$Power\ density\left(\frac{dBW}{Hz}\right) = 10\log_{10}\left[\frac{10^{-16}\ W}{2.046x10^{6}\ Hz}\right]$$
$$Power\ density\left(\frac{dBW}{Hz}\right) = 10\log_{10}[\ 4.888^{-23}]$$
$$Power\ density\left(\frac{dBW}{Hz}\right) = 10(-22.3)$$
$$Power\ density = -223\ dBW/Hz$$

The calculation is also frequently normalized and done presuming an even distribution of 1W over the 2.046 MHz C/A bandwidth of the C/A code:

$$Power\ density\left(\frac{dBW}{Hz}\right) = 10\log_{10}\left[\frac{power\ (W)}{bandwidth\ (Hz)}\right]$$
$$Power\ density\left(\frac{dBW}{Hz}\right) = 10\log_{10}\left[\frac{1W}{2.046x10^{6}\ Hz}\right]$$
$$Power\ density\left(\frac{dBW}{Hz}\right) = 10\log_{10}[\ 4.888^{-7}]$$
$$Power\ density\left(\frac{dBW}{Hz}\right) = 10(-6.31)$$
$$Power\ density = -63\ dBW/Hz$$

Increased signal power at the Earth's surface in Block III

- M-code: –158 dBW / –138 dBW.
- L1 and L2: –157 dBW for the C/A code signal and –160 dBW for the P(Y) code signal.
- L5 will be –154 dBW.



The minimum received signal level of the GPS signal under open-sky conditions is defined as -160 dBW for the L1 coarse/acquisition (C/A) code, assuming a receiver antenna with hemispherical gain pattern (ICD200C, 2000). This power is spread over a large bandwidth by a code division multiple access (CDMA) technique, leading to a peak power spectral density (PSD) near -220 dBW/Hz, which is significantly lower than average radio frequency (RF) noise levels of about -204–208 dBW/Hz. 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.

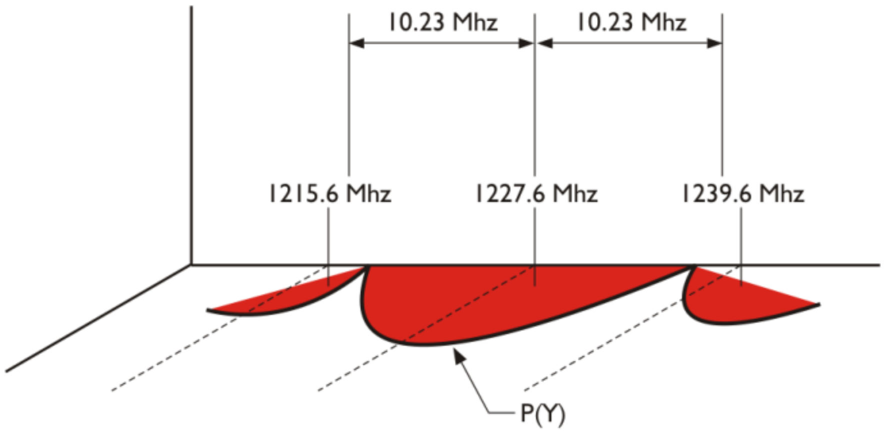
L1 SIGNAL

For example, the C/A code on the L1 signal, centered on the frequency 1575.42 MHz and a portion of the bandwidth over which it is spread, approximately 20.46 MHz, 10.23 MHz on each side of the center frequency. The horizontal scale shows the offset in MHz from 1575.42 center frequency. Other scales show the decibels relative to 1 Watt per Hertz (dbW/Hz)

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

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 IIRM 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.

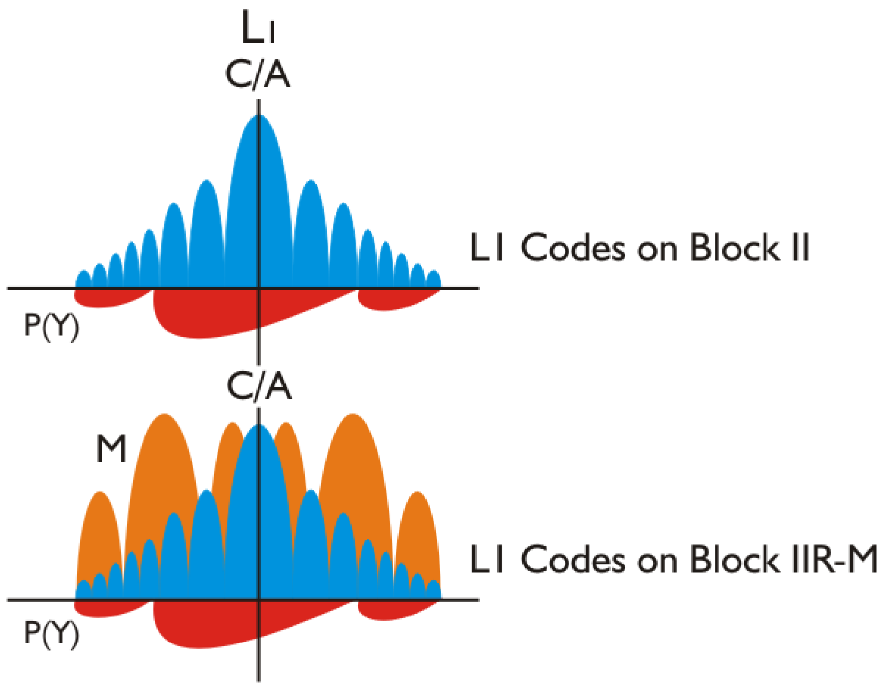
THE M CODE

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 Department of Defense (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.

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 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.

New Navigation Signals
Military (M-code)
A major component of the modernization process, a new military signal called M-code was designed to further improve the anti-jamming and secure access of the military GPS signals. The M-code is transmitted in the same L1 and L2 frequencies already in use by the previous military code, the P(Y) code. The new signal is shaped to place most of its energy at the edges (away from the existing P(Y) and C/A carriers).

Unlike the P(Y) code, the M-code is designed to be autonomous meaning that a user can calculate their position using only the M-code signal. P(Y) code receivers must typically first lock onto the C/A code and then transfer to lock onto the P(Y)-code.



In a major departure from previous GPS designs, the M-code is intended to be broadcast from a high-gain directional antenna, in addition to a wide angle (full Earth) antenna. The directional antenna's signal, termed a spot beam, is intended to be aimed at a specific region (i.e. several hundred kilometers in diameter) and increase the local signal strength by 20 dB, or approximately 100 times stronger. A side effect of having two antennas is that the GPS satellite will appear to be two GPS satellites occupying the same position to those inside the spot beam. While the full Earth M-code signal is available on the Block IIR-M satellites, the spot beam antennas will not be available until the Block III satellites are deployed, tentatively in 2013.

- Satellites will transmit two distinct signals from two antennas: one for whole Earth coverage, one in a spot beam.
- Modulation is binary offset carrier
- Occupies 24 MHz of bandwidth

- It uses a new MNAV navigational message, which is packetized instead of framed, allowing for flexible data payloads
- There are four effective data channels; different data can be sent on each frequency and on each antenna.
- It can include FEC and error detection
- The spot beam is ~20 db more powerful than the whole Earth coverage beam
- M-code signal at Earth's surface: -158 dBW for whole Earth antenna, -138 dBW for spot beam antennas.

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 known as the subcarrier frequency factor. The β describes the frequency of the pseudorandom noise modulation, also known as the spreading code factor. In the case of the M-code the notation BOC (10, 5) describes the modulation of the signal. Both here are multiples of 1.023 MHz. In other words their actual values are $\alpha = 10 \times 1.023$ MHz = 10.23 MHz and $\beta = 5 \times 1.023$ MHz = 5.115 MHz (Betz).

The M-code is tracked by direct acquisition. This means that 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.

One of the first announcements was the addition of a new civilian-use signal to be transmitted on a frequency other than the L1 frequency used for the existing GPS Coarse Acquisition (C/A) signal. Ultimately, this became known as the L2C signal because it is broadcast on the L2 frequency (1227.6 MHz). It is transmitted by all block IIR-M and later design satellites.

The L2C signal is tasked with providing improved accuracy of navigation, providing an easy-to-track signal, and acting as a redundant signal in case of localized interference.
The immediate effect of having two civilian frequencies being transmitted from one satellite is the ability to directly measure, and therefore remove, the ionospheric delay error for that satellite. Without such a measurement, a GPS receiver must use a generic model or receive ionospheric corrections from another source (such as a Satellite Based Augmentation System). Advances in technology for both the GPS satellites and the GPS receivers have made ionospheric delay the largest source of error in the C/A signal. A receiver capable of performing this measurement is referred to as a dual frequency receiver.

Civilian L2 (L2C)
Technical Details

- L2C contains two distinct PRN sequences:

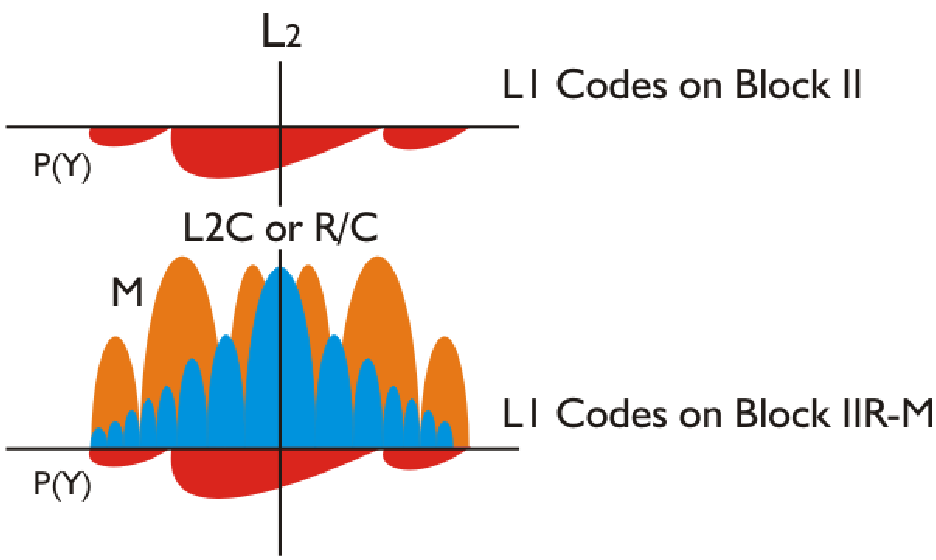
    - CM (for Civilian Moderate length code) is 10,230 bits in length, repeating every 20 milliseconds.
    - CL (for Civilian Long length code) is 767,250 bits, repeating every 1500 milliseconds.
    - Each signal is transmitted at 511,500 bits per second (bit/s); however they are multiplexed to form a 1,023,000 bit/s signal.
- CM is modulated with a 25 bit/s navigation message with forward error correction; whereas CL is a non-data sequence (it does not contain additional modulated data).
- The long, non-data CL sequence provides for approximately 24 dB greater correlation protection (~250 times stronger) than L1 C/A.
- L2C signal characteristics provide 2.7 dB greater data recovery and 0.7 dB greater carrier tracking than L1 C/A
- The L2C signals' transmission power is 2.3 dB weaker than the L1 C/A signal.
- In a single frequency application, L2C has 65% more ionospheric error than L1.

It is defined in IS-GPS-200D.

Block III satellite improvements
Increased signal power at the Earth's surface

- M-code: -158 dBW / -138 dBW.
- L1 and L2: -157 dBW for the C/A code signal and -160 dBW for the P(Y) code signal.
- L5 will be -154 dBW.

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,



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.

Civil-Moderate (CM) and Civil-Long (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 is also known by the acronym NAY, and is broadcast at 50 bits per second (bps). The new Navigation message is known as CNAV. It is broadcast at 25 bps. Like the original NAY message, it has 300 bit subframes, but given the lower broadcast rate CNAV takes 12 seconds to transmit each of its subframes, whereas NAY requires only 6 seconds. Nevertheless because CNAV is a bit more flexible and compact than the original NAY 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 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 NAY 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.

“Compatible” refers to the ability of U.S. and foreign space-based positioning, navigation, and timing services to be used separately or together without interfering with use of each individual service or signal,

Interoperability provides users a better PNT solution using signals from multiple GNSSs rather than from one GNSS Ideally, interoperability involves no additional receiver cost or complexity

- U.S. suggests that compatibility and interoperability are beneficial to both GPS and other systems
- Compatibility protects full utility of each system
- For example, spectral separation from M code not only protects utility of M code, but also protects other systems signals
- Avoids interference to other systems from higher power M code and large GPS constellation
- Interoperability benefits users and receiver manufacturers
- Lower cost and better performance for receivers that use GPS and other systems signals together
- More users benefit from both systems’ signals
- More rapid and extensive adoption of highly interoperable signals
- Interoperable and compatible signals simplify international acceptance of other systems in ITU and other forums

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 is 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 longer than the C/A code and present a subsequent improvement in autocorrelation, as well as cross-correlation. This is because the 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 that 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 data-less 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

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 under very good conditions. 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 submeter range.

So, even if it is the carrier-phase that ultimately delivers the wonderful positional accuracy we all depend on, the codes get 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 wide laning, and so forth. 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.

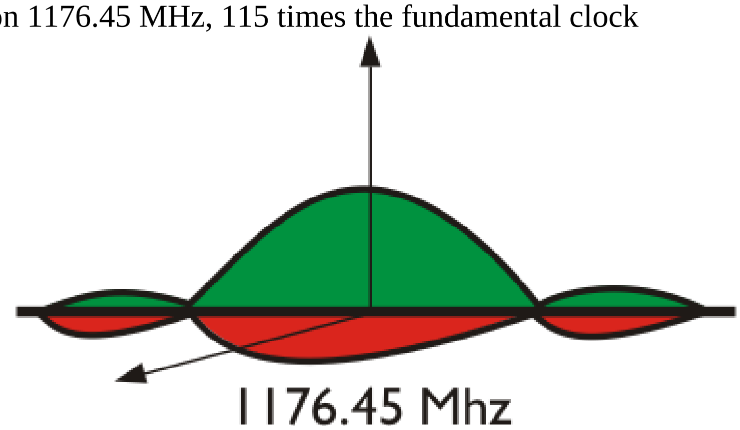
Along that line, it is worthwhile to recall that the L2C has an overall chip rate of 1.023 MHz, just like L1 C/A. Such a slow chip rate can seem to be a drawback until you consider that that rate affects the GPS chipset power consumption. In general, the slower the rate the longer the battery life and 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 is 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

Alright, 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. 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 with one of the signals, E5, from an entirely separate satellite system, GALILEO, a very good idea

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 signal-to-noise ratio (SNR) conditions.

The fast chipping rate is also good news. a rule of thumb is the maximum resolution available in a pseudorange is about 1% of the chipping rate of the code used. The faster the chipping rate the better the resolution, and it also improves multipath protection. L5 will also have higher power than L1, about four times more power. The increased 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).

Safety of Life (L5)

Safety of Life is a civilian-use signal, broadcast on the L5 frequency (1176.45 MHz), planned to be implemented with first GPS IIF launch (2008).

- Improves signal structure for enhanced performance
- Higher transmission power than L1 or L2C signal (~3db, or twice as powerful)
- Wider bandwidth, yielding a 10-times processing gain
- Longer spreading codes (10 times longer than used on the C/A code)
- Located in the Aeronautical Radionavigation Services band, a frequency band that is available worldwide.

SUMMARY OF COARSE ACQUISITION (C/A), L2C, AND L5

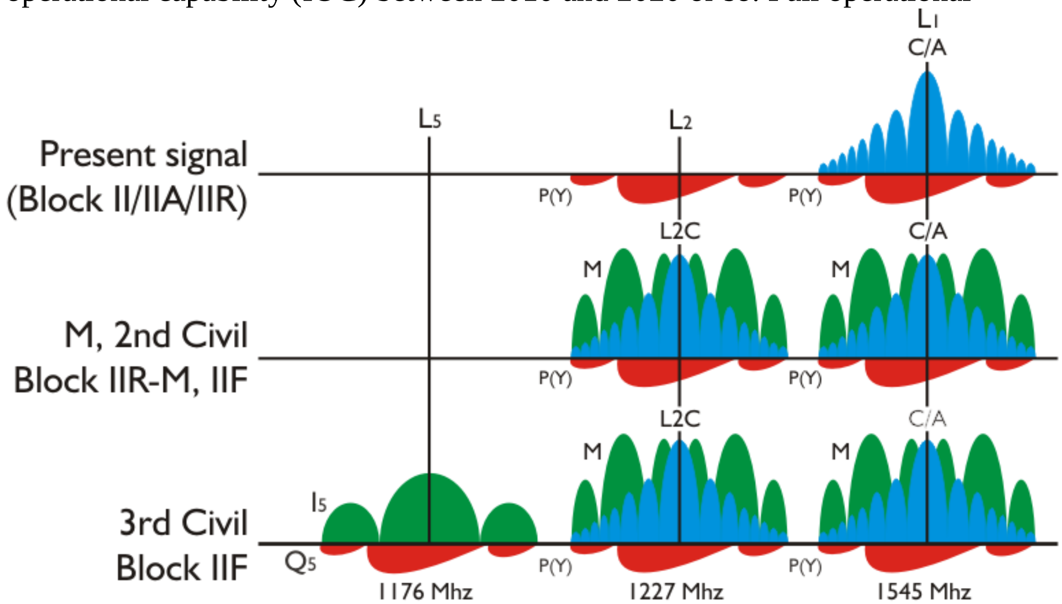
GPS modernization is no longer a future development, it is underway. New spacecraft with better electronics, better navigation messages, newer and better clocks are just part of the story. Beginning with the launch of the first IIR-M satellite new civil signals began to appear, starting with L2C. It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

NEW SIGNAL AVAILABILITY

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 to 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.

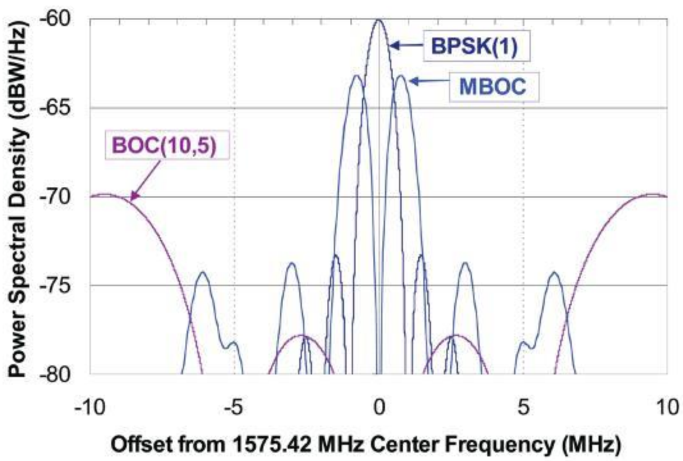
Correlation Protection

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 United States and the European Union (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 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 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 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 as complete as other aspects of this signal. Also, as in L2C, L1C will likely incorporate FEC.

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% BOC (1, 1) and 9.1% 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. It also has a good tracking threshold. Please recall that this also allows tracking with the superior phase-locked loop as opposed to the Costas loop.

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.

New Civilian L1 (L1C)

L1C is a civilian-use signal, to be broadcast on the same L1 frequency (1575.42 MHz) that currently contains the C/A signal used by all current GPS users. The L1C will be available with first Block III launch, currently scheduled for 2013.

- Implementation will provide C/A code to ensure backward compatibility
- Assured of 1.5 dB increase in minimum C/A code power to mitigate any noise floor increase
- Non-data signal component contains a pilot carrier to improve tracking
- Enables greater civil interoperability with Galileo L1