



PDHonline Course L172J (1 PDH)

GPS Modernization

Instructor: Jan Van Sickle, P.L.S.

2020

PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

An Approved Continuing Education Provider

GPS MODERNIZATION

Jan Van Sickle, P.L.S.

THE SATELLITES

The basics of its configuration are well known. 24 GPS satellites needed for 24-hour worldwide coverage but there are actually more than 24 birds up at any one time to assure that the minimum will always be available. This constellation is the Space Segment. The satellites are in 6 Orbital Planes, 4 or more satellites per plane in orbit about 11,000 nautical miles above the Earth. Each completes an orbit every 12 hours sidereal time.

GPS reached its Fully Operational Capability (FOC) on July 17, 1995. 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. This course is about some of the changes in the modernized GPS.

Figure 1.1 is an illustration that summarizes the improvements made in the satellite blocks that have comprised the GPS constellation over the years. The text that follows gives some detail on these developments.

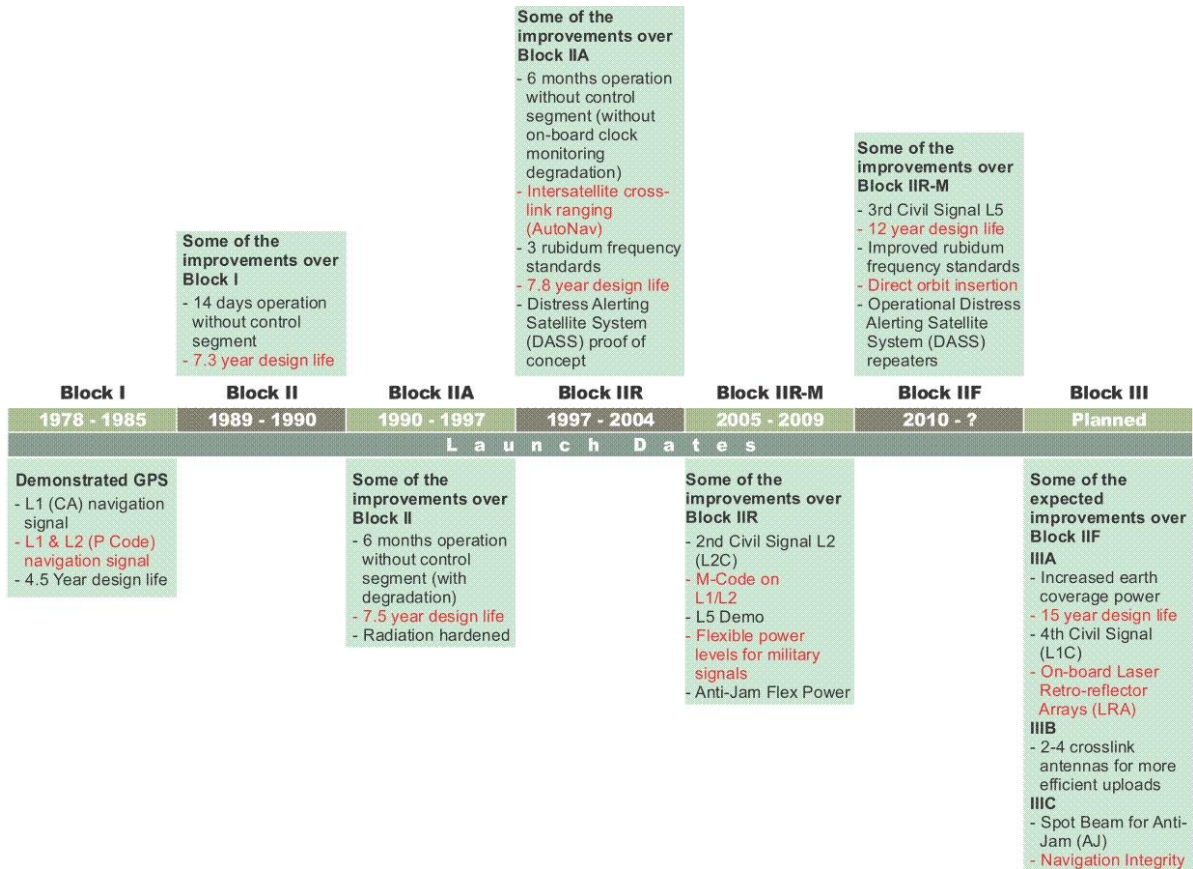


Figure 1.1

BLOCK I

The first of the 11 successful Block I satellites was launched in 1978 from Vandenberg Air Force Base. The last of them was launched in 1985. One launch failed, Navstar 7. They were all retired by late 1995. None of the Block I satellites are functional now. These satellites needed frequent help from the Control Segment, the tracking and upload systems on the ground. They could operate independently for only 3 1/2 days. They had a design life of 4.5 years, though some operated for double that. They were powered by 7.25 square meters of solar panels and they also had three rechargeable nickel-cadmium batteries. In subsequent blocks of satellites design lives increased and dependence on the Control Segment decreased. However, some of the features of Block I were carried forward into the subsequent blocks of GPS satellites. They carried onboard nuclear detonation detection sensors a feature which has continued in future GPS satellite blocks.

It was clear from the beginning that atomic frequency standards, clocks, were necessary for the proper functioning of the system. Therefore the Block I satellites had cesium and rubidium

frequency standards on-board, a feature that future GPS satellites share. Unfortunately some of the frequency standards stopped working after about a year in space. The rubidium standards were improved and equipment was added to keep the frequency standards at a constant temperature during flight.



Block II Satellite 1989-1997

Figure 1.2

BLOCK II

The Block II satellites were about twice as heavy as the Block I satellites. The first of them was launched in 1989. The Block II satellites often exceeded their 7.3 design life. The last was decommissioned in 2007 after 17 years of operation. They could be autonomous, without contact with the Control Segment, for up to 14 days. The uploads from the Control Segment to the Block II satellites were encrypted unlike uploads during the Block I. The signals from the Block II satellites were periodically and purposely disrupted. Specifically the on-board clocks were intentionally dithered in a procedure known as Selective Availability (SA).

BLOCK IIA

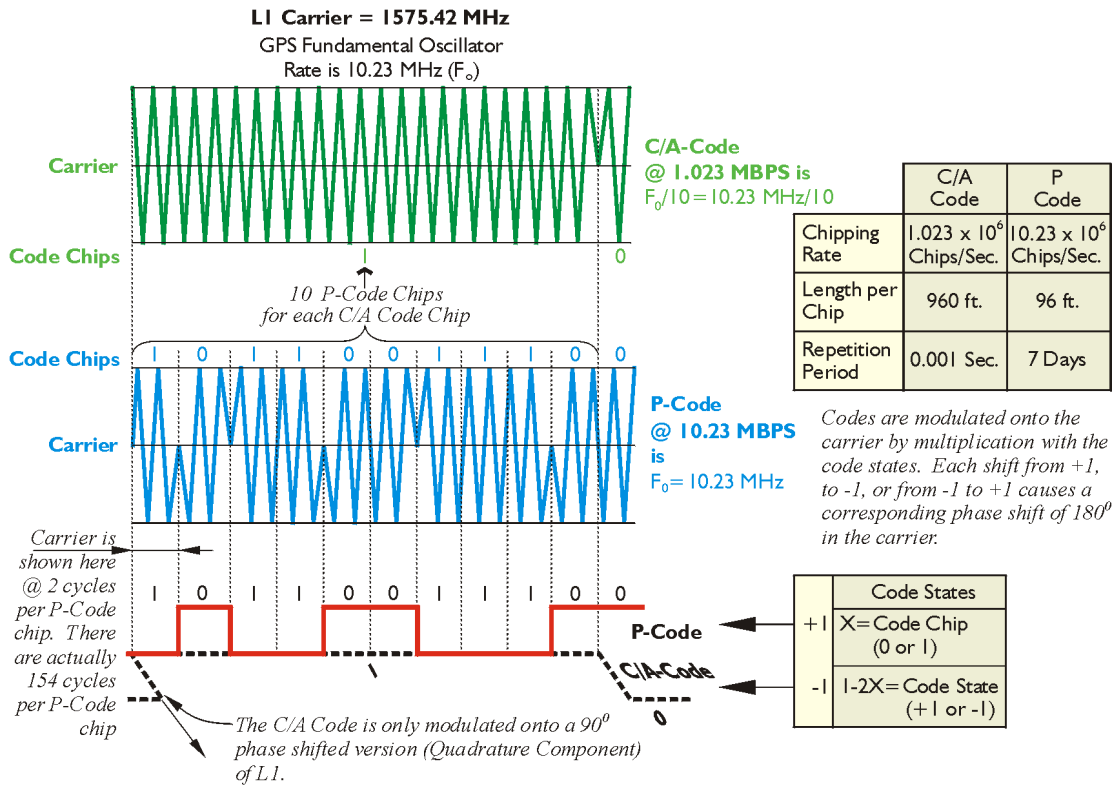
Block IIA satellites were an improved version of the Block II. The first of 19 Block IIA satellites was launched in 1990. They were radiation hardened against cosmic rays, built to provide Selective Availability (SA), antispoofing (AS) capability and onboard momentum dumping. This SA was discontinued on May 2, 2000. Block IIA satellites stored more of the

Navigation message than the Block II satellites and could operate without contact with the Control Segment for 6 months. Two Block IIA satellites, SVN 35 (PRN 05) and SVN 36 (PRN 06), were equipped with Laser Retro-reflector Arrays (LRA). The second of these was launched in 1994. The retro-reflectors facilitated satellite laser ranging (SLR). Such ranging provided a valuable independent validation of GPS orbits. Like the Block II satellites, the Block IIA satellites were equipped with two rubidium and two cesium frequency standards. They were expected to have a design life of 7.3 years. While the design life was obviously exceeded in most cases none of the Block IIA satellites are in service today.

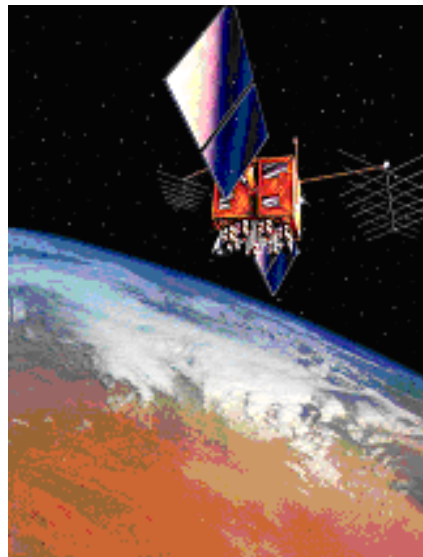
BLOCK IIR

The first launch of the next Block, Block IIR satellites in January of 1997 was unsuccessful. The following launch in July of 1997 succeeded. 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 some of their direct 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. They are more radiation hardened than their predecessors and they cost about a third less than the Block II satellites did. 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. 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, 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.

Code Modulation of the L1 Carrier



Code Modulation of the L1 Carrier
Figure 1.3



Block IIR Satellite

Figure 1.4

Nine of the Block IIR satellites also 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.

BLOCK IIR-M

The first Block IIR-M satellite was launched in the summer of 2005 and the last in the summer of 2009. 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. This code is carried on both L1 and L2 and probably will replace the P(Y) code. It has the advantage of allowing the DoD to increase the power of the code to prevent jamming. They also broadcast 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. While a new military code may not be terribly exciting to civilian users the new civilian code is interesting. This is a code that was announced way back in March of 1998. We have been using the L2 carrier since the beginning of GPS of course, but now there is a new code broadcast on what was an exclusively military signal carrying the P(Y) code. And this new code is not a merely a copy of the C/A-code. L2C is a bit more sophisticated. 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.



Block IIF Satellite

Figure 1.5

BLOCK IIF

After multiple delays, the first IIF was launched successfully on May 28, 2010 and placed directly into orbit. Block IIF satellites have faster processors and more memory onboard. They broadcast all of the previously mentioned signals including the new carrier known as L5. This is the signal that was demonstrated on the Block IIR-M. It is 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 carry DASS repeaters. Their onboard *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 reprogrammed on orbit.

SOME NEW SIGNALS

In fact a good deal of the agenda for GPS modernization is related to the GPS signal itself. As you know there are two legacy carrier frequencies assigned to GPS, L1 at 1575.42 MHz and L2 at 1227.60 MHz. The rate of these two are multiples of the fundamental clock rate of the oscillators in the satellites, that is 10.23 MHz. This frequency is multiplied 154 times for L1

and 120 times for L2. From the very beginning of GPS surveyors have been deriving positions from tracking both carriers. That strategy is the source of the extraordinary accuracy available to us using GPS. In fact, the first civilian receiver, the Macrometer, was completely codeless. It did not track any codes at all and was delivering centimeter-level positions in the early 1980's. So why should we care about a new civilian code on L2?

L2C

There are a couple of reasons. First, 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, but still 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 with two civilian signals, one on L1 and one on L2, the pseudorange from that handheld can model the ionospheric delay. It seems feasible then that an autonomous code-phase receiver may be able to achieve positions with a 5-10m positional accuracy. And there are developments coming. Developments that just might increase that accuracy to a sub-meter range.

Second, there are no completely codeless receivers today. Our survey-grade receivers have code tracking capabilities. Even if it is the carrier-phase that ultimately delivers the wonderful positional accuracy we all depend on, it is the code-based pseudoranges that gets us in the game and keep us out of trouble every time we turn on the receiver – from locking on the first satellite to cross-correlation techniques. 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. And while this method works ok, the results are noisy, especially over long baselines. It is cleaner to get the signal directly once there are two clear codes, one on each carrier.

Civil-Moderate (CM) and Civil-Long (CL)

L2C is actually composed of two pseudorandom noise signals the civil-moderate length code, CM, and the civil long code, CL. They both utilize the same modulation scheme, binary phase shift key (BPSK), as the legacy signals and both signals are broadcast at 511.5 kilobits per

second (Kbps). This means that CM repeats its 10230 chips every 20 milliseconds and CL repeats its 767250 chips every 1.5 seconds.

But wait a minute, how can you do that? How can you have two codes in one? L2C achieves this by time multiplexing. Since the two codes have different lengths L2C alternates between chips of the CM code and chips of the CL code as shown in Figure 1.6. 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 . This provides separation from the M code.

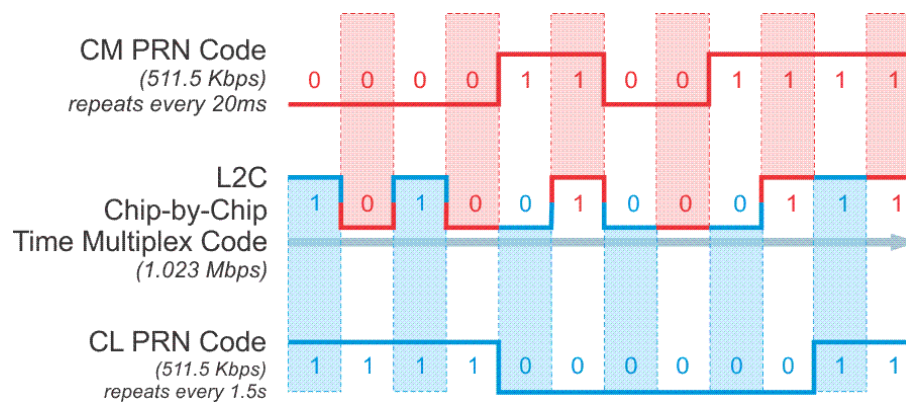


Figure 1.6

L2C has better autocorrelation and cross-correlation protection than the C/A code because both of the CM and CL codes are longer than the C/A code. Longer codes are easier to keep separate from the background noise. 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. There is also another characteristic of L2C that pays dividends when the signal is weak. While CM carries newly formatted navigation data and is, therefore, known as the *data channel*, CL does not. It is dataless and known as a *pilot channel*. A pilot channel can support longer integration when the signal received from the satellite is weak. This is an idea that harks all the way back Project 621B at the very beginnings of GPS. The benefits of a pilot channel distinct from the data components carried by a signal was known in the 1960s

and 1970s but was not implemented in GPS until recently. Even though the L2C signals' transmission power is 2.3 dB weaker than is C/A on L1 and even though it is subject to more ionospheric delay than the L1 signal, L2C is still much more user friendly. The long data-less CL pilot signal has 250 times (24dB) better correlation protection than C/A. This is due in large part to the fact that 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. 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? Having two civilian frequencies being transmitted from one satellite affords the ability to model and lessen the ionospheric delay error for that satellite while relying on code phase pseudorange measurements alone. In the past ionospheric modeling was only available to multi carrier frequency observations, or by reliance on the atmospheric correction in the Navigation message.

The L2C signal also ameliorates the effect of local interference. This increased stability means improved tracking in obstructed areas like woods, near buildings, and urban canyons. It also means fewer cycle slips.

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.

THE L5 CARRIER

Alright, L2C is fine, but what about L5, the new carrier being broadcast on the Block IIF satellites? It is centered on 1176.45 MHz, 115 times the fundamental clock rate. The basic structure of L5 is similar to that of L1. It has higher power than L1, about 6 dB higher. There are two pseudorandom noise (PRN) codes on this 20 MHz carrier. The two codes are modulated using Quad Phase Shift Key (QPSK) and they are broadcast in quadrature to each other. However, borrowing a few pages from other recent developments the in-phase (I) signal carries a data message that is virtually identical to the CNAV on L2. The other, the quadrature signal (Q), is data-less and L5 utilizes chip-by-chip time multiplexing in broadcasting its two codes as does L2C in broadcasting CM and CL. Both L5 codes have a 10.23 MHz chipping rate, the same as the fundamental clock rate. This is the same rate that has been available on the P(Y) code from the beginning of the system. However, this is the fastest chipping rate available in any civilian code. L5 has the only civilian codes that are longer and faster than the C/A code. Since the maximum resolution available in a pseudorange is typically about 1% of the chipping rate of the code used, the faster the chipping rate the better the resolution.

L5 has more power as L1 and since L5 does not carry military signals, it achieves an equal power split between its two signals. In this way L5 lowers the risk of interference and improves multipath protection. It also makes the data-less signal easier to acquire in unfavorable and obstructed conditions.

Unlike L2C, L5 users benefit from its place in a band designated by the International Telecommunication Union (ITU) for the Aeronautical Radionavigation Navigation Services (ARNS) worldwide. Therefore, it is not prone to interference with ground based navigation aids and is available for aviation applications. While no other GPS signal occupies this band L5 does share space with one of the Galileo signals, E5. L5 does also incorporate Forward Error Correction (FEC).

GPS MODERNIZATION IS UNDERWAY

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 which was followed by L5 on the Block IIF satellites. 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.