PDHonline Course L105F (12 PDH)

GPS Surveying (General)

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Module 4

The Design of NAVSTAR GPS

Back in 1973, the early GPS experiments were started. From the beginning of GPS, the plan included the best features and improved on the shortcomings of the previous work in the field of satellite navigational systems. For example, the GPS satellites were placed in nearly circular orbits over 20,000 km above the earth where the consequences of gravity and atmospheric drag are much less severe than those that affected some previous systems.

The genesis of GPS was military. It grew out of the congressional mandate issued to the Departments of Defense and Transportation to consolidate the myriad of navigation systems. Its application to civilian surveying was not part of the original design. In 1973 the DOD directed the Joint Program Office (*JPO)* in Los Angeles to establish the GPS system. Specifically, JPO was asked to create a system with high accuracy and continuous availability in real-time that could provide virtually instantaneous positions to both stationary and moving receivers.

Providing 24-hour real-time, high-accuracy navigation for moving vehicles in three dimensions was a tall order. Experience showed part of the answer was a signal that was capable of carrying a very large amount of information efficiently and that required a large bandwidth. So, the GPS signal was given a double-sided 10-MHz bandwidth. But that was still not enough, so the idea of simultaneous observation of several satellites was also incorporated into the GPS system to accommodate the requirement. That decision had far-reaching implications.

The GPS signal needed to be secure and resistant to both jamming and multipath. A spread spectrum, meaning spreading the frequency over a band wider than the minimum required for the information it carries, helped on all counts. This wider band also provided ample space for pseudorandom noise encoding, a fairly new development at the time. The PRN codes allowed the GPS receiver to acquire signals from several satellites simultaneously and still distinguish them from one another.

Unlike some of its predecessors, GPS needed to have not one, but at least four satellites above an observer's horizon for adequate positioning and even more if possible. The achievement of full-time worldwide GPS coverage required this condition be satisfied at all times, anywhere on or near the earth. Toward that end, several orbital arrangements of the satellites were tried. Today, the constellation consists of 32 usable satellites.

In summary then, the GPS constellation was designed to satisfy several critical concerns. Among them were the best possible coverage of the earth with the fewest number of satellites, the reduction of the effects of gravitational and atmospheric drag, sufficient upload and monitoring capability with all control stations located on American soil, and, finally, the achievement of maximum accuracy. And GPS does provide much more accurate positions in a much shorter time than any of its predecessors, but these improvements were only accomplished by standing on the shoulders of the technologies that went before.

GPS Segment Organization

The Space Segment

Though there has been some evolution in the arrangement, today's GPS constellation

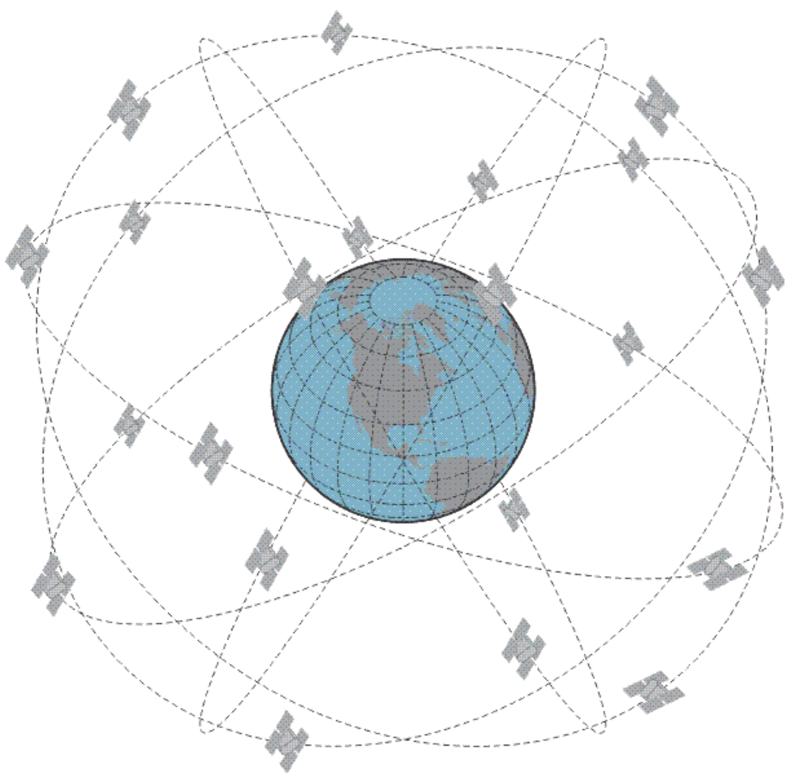

Figure 4.1

consists of 32 satellites, in six orbital planes (Figure 4.1). Each orbital plane is inclined to the equator by an angle of 55E and each of the six is rotated 60E from its neighbor.

GPS satellites are in a *posigrade* orbit. A posigrade orbit is one that moves in the same direction as the earth's rotation. Since each satellite is nearly three times the earth's radius above the surface, its orbital period is 12 sidereal hours.

When an observer actually performs a GPS survey project, one of the most noticeable aspects of a satellite's motion is that it returns to the same position in the sky about 4 minutes earlier each day. This apparent regression is attributable to the difference between 24 solar hours and 24 sidereal hours. GPS satellites actually retrace the same orbital path twice each sidereal day, but since their observers measure time in solar units the orbits do not look quite so regular to them. The satellites lose 4 minutes with each successive solar day.

For example, if the satellites are in a particularly favorable configuration for measurement and the observer wishes to take advantage of the same arrangement the following day, he or she would be well advised to remember the same configuration will occur 4 minutes earlier on the solar time scale. Both Universal Time (UT) and GPS time are measured in solar, not sidereal units. It is possible that the satellites will be pushed 50 km higher in the future to remove their current 4-minute regression, but for now it remains.

The Blocks of Satellites

The first GPS satellite was launched February 22, 1978 and was known as *Navstar 1*. An unfortunate complication is that this satellite is also known as PRN 4 just as the second GPS satellite

Navstar 2 was known as PRN 7. The Navstar number is the order of launch and the PRN number refers to the weekly segment of the P code that has been assigned to the satellite, and there are still more identifiers. Each GPS satellite has an Inter Range Operation Number, a NASA catalog number, an orbital position number and a Space Vehicle Number. However, in most literature, and to the GPS receivers themselves, the PRN number is the most important.

Block I

The 11 GPS satellites launched from Feb. 22, 1978, to Oct. 9, 1985 from Vandenberg Air Force Base with refurbished Atlas F rockets were known as Block I satellites. The designation includes all of the prototype satellites built to validate the concept of GPS positioning.

The Block I satellites weighed 845 kg in final orbit. Three rechargeable nickel-cadmium batteries and 7.25 square meters of single-degree solar panels powered them. These experimental satellites served to point the way for some of the improvements found in subsequent generations.

For example, even with the back-up systems of atomic oscillators onboard each satellite, the clocks proved to be the weakest components. The satellites themselves could only store sufficient information for 32 days of independent operation and the uploads from the control segment were not secure; they were not encrypted. This test constellation was inclined by 63 degrees to the equator instead of the current 55 degrees. Still, except for Navstar 7, all 11 achieved orbit. But today, all the Block I satellites are out of service.

Block II and Block IIA

The next generation of GPS satellites is known as Block II satellites. While the McDonnell-Douglas Delta II rocket was set to launch the Block II satellites originally, it was the space shuttle that actually got the job. That is until the Challenger exploded in 1986. The launching of Block II satellites came to a halt. When it resumed all Block II satellites were, in fact, launched with the Delta II

The first left Cape Canaveral on February 14, 1989. It was about twice as heavy as the first Block I satellite and expected to have a design life of 72 years. The Block IIA satellites are modified Block II satellites. The Block II satellites can operate up to 14 days without a, now encrypted, upload from the control segment, but Block IIA satellites have the capacity to store 180 days worth of data. The satellites themselves are radiation hardened. It was during the launching of the Block II/IIA satellites, on Dec. 8, 1993, that the Defense Department announced the GPS constellation had achieved Initial Operation Capability. Two of the Block IIA satellites carry corner cube reflectors, Space Vehicles 35 and 36. These reflectors were included to allow ground stations to measure satellite clock errors and broadcast ephemeris errors using satellite laser ranging (SLR). Today, all the Block II and Block IIA satellites are out of service.

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 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 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. 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.

Some 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. Some additional IIR satellites will carry them too.

Block IIR-M

In the current constellation there are Block IIR-M satellites on orbit and operational (Figure 4.2). 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 2014 there are many Block IIF satellites on orbit. Their design life is 12 to 15 years. Block IIF satellites have faster processors and more memory onboard. They broadcast all of the previously mentioned signals, and one more, a new carrier known as L5. This is 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. 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.

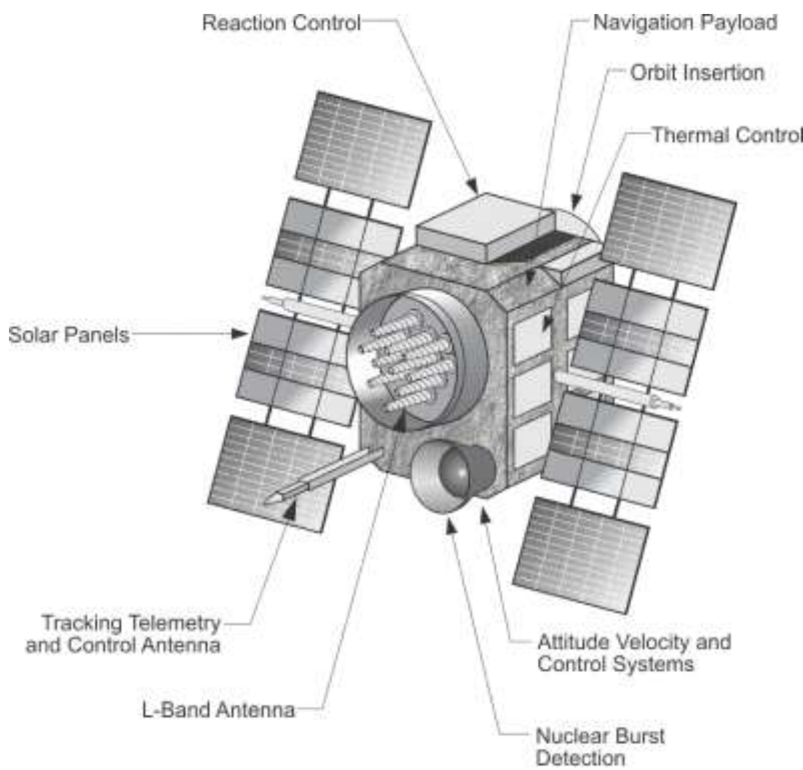

Figure 4.2

Intentional Signal Degradation

While the signals from Block I satellites were not subject to any officially sanctioned deterioration, the same cannot be said of the Block II/IIA/IIR satellites. In the interest of national security the signals from the operational constellation of GPS satellites, including the Block II/IIA and IIR satellites were and still are intentionally degraded periodically. The dithering began shortly after the launch of the first Block II satellite. The selective availability (SA) of the C/A code was implemented by disrupting the satellite clock frequency from time to time since April 1990. Well, it lasted just a bit more than a decade, but was finally switched off on May 2, 2000 by presidential order.

However, the P code is still intermittently replaced by the encrypted Y code in a procedure known as *anti-spoofing (AS)*. Since December of 1993, P codes have been encrypted from time to time. But from the beginning receiver manufacturers had software that got around AS. In other words, there are GPS receivers available that do make observations on the Y-code.

It is important to note that neither of these procedures ever affected relative positioning methods that rely on the carrier phase observable. But when the original plans for the GPS constellation were under development, it was thought that Anti-spoof (AS), by itself, would be sufficient to degrade the accuracy level to the ±100 m intended by the design. However, after the first group of Block I GPS satellites were launched, it turned out that C/A-code point positioning was much better than expected and SA was incorporated into Block II satellites. Code tracking, also known as code phase, receivers used in point positioning were affected by SA, but even that is moot now that SA is turned off.

GPS Satellite Characteristics

All GPS satellites have some common characteristics. They weigh about a ton and with solar panels extended are about 27 feet long. They all have three-dimensional stabilization to ensure that their solar arrays are perpendicular to the sun and their antennae are pointed at the earth. GPS satellites move at a speed of about 8,700 miles per hour. Even so, the satellites must pass through the shadow of the earth from time to time. During an eclipse the absence of the pressure of solar radiation is over in less than an hour, but it must be taken into account. Onboard batteries provide power, but of more concern is the prediction of precise ephemeris information at such times. In a related issue, all satellites are equipped with thermostatically controlled heaters and reflective insulation to maintain the optimum temperature for the oscillator's operation.

The Control Segment

As mentioned in previous modules, there are government tracking and uploading facilities distributed around the world. Taken together these facilities are known as the *Control Segment.*

There are government tracking and uploading facilities distributed around the world. These facilities not only monitor the L-band signals from the GPS satellites and update their Navigation Messages but also track the satellite's health, their maneuvers, and many other things, even battery recharging. Taken together these facilities are known as *the Control Segment*.

Figure 4.3

The Master Control Station (MCS), once located at Vandenberg Air Force Base in California, now resides at the Consolidated Space Operations Center (CSOC) at Schriever (formerly Falcon) Air Force Base near Colorado Springs, Colorado, and has been manned by the 2nd Space Operations Squadron, *2SOPS*, since 1992. There is an alternate MCS in at Vandenberg Tracking Station in California.

The 2SOPS squadron controls the satellites orbits. For example, they maneuver the satellites from the highly eccentric orbits into which they are originally launched to the desired mission orbit and spacecraft orientation. They monitor the state of each satellite's onboard battery, solar and propellant systems. They resolve satellite anomalies, activate spare satellites and control Selective Availability (SA) and Anti-Spoofing (A/S). They dump the excess momentum from the *wheels,* the series of gyroscopic devices that stabilize each satellite. With the continuous constellation tracking data available and aided by Kalman filter estimation to manage the noise in the data, they calculate and update the parameters in the Navigation message (ephemeris, almanac and clock corrections) to keep the information within limits because the older it gets, the more its veracity deteriorates. This process is made possible by a persistent two-way communication with the constellation managed by the control segment that includes both monitoring and uploading accomplished through a network of ground antennas and monitoring stations.

The data that feeds the MCS comes from monitoring stations. These stations track the entire GPS constellation. In the past there were limitations. There were only six tracking stations. It was possible for a satellite to go unmonitored for up to two hours each day. It was clear that the calculation of the ephemerides and the precise orbits of the constellation could be improved with more monitoring stations in a wider geographical distribution. It was also clear that if one of the six stations went down the effectiveness of the Control Segment could be considerably hampered. These ideas, and others, led to a program of improvements known as *the Legacy Accuracy Improvement Initiative, L-AII*. During this initiative from August 18 to September 7 of 2005, six *National Geospatial Intelligence Agency, NGA*, stations were added to the Control Segment. This augmented the information forwarded to the MCS with data from Washington, D.C., England, Argentina, Ecuador, Bahrain, and Australia. With this 12-station network in place every satellite in the GPS constellation was monitored almost continuously from at least two stations when it reached at least 5º above the horizon.

Today there are 6 Air Force and the 11 National Geospatial-Intelligence Agency (NGA) monitoring stations. The monitoring stations track all the satellites, in fact every GPS satellite is tracked by at least 3 of these stations all the time. The monitoring stations collect range measurements, atmospheric information, satellite's orbital information, clock errors, velocity, right ascension and declination and send them to the MCS. They also provide pseudorange and carrier phase data to the MCS. The MCS needs this constant flow of information. It provides the basis for the computation of the almanacs, clock corrections, ephemerides and other components that make up the Navigation message. The new stations also improve the geographical diversity of the Control Segment and that helps with the MCS isolation of errors, for example, making the distinction between the effects of the clock error from ephemeris errors. In other words, the diagnosis and solution of problems in the system are more reliable now because the MCS has redundant observations of satellite anomalies with which to work. Testing has shown that the augmented Control Segment and subsequent improved modeling has improved the accuracy of clock corrections and ephemerides in the Navigation Message substantially and may contribute to an increase in the accuracy of real-time GPS of 15% or more.

However, once the message is calculated it needs to be sent back up to the satellites. Some of the stations have ground antennas for uploading. Four monitoring stations are collocated with such antennas. The stations at Ascension Island, Cape Canaveral, Diego Garcia, and Kwajalein upload navigation and program information to the satellites via S-band transmissions. The station at Cape Canaveral also has the capability to check satellites before launch.

The modernization of the Control Segment has been underway for some time and it continues. In 2007 the Launch/Early Orbit, Anomaly Resolution and Disposal Operations mission (LADO) PC-based ground system replaced the mainframe based Command-and-Control System (CCS). Since then LADO has been upgraded several times. It uses Air Force Satellite Control Network (AFSCN) remote tracking stations only, not the dedicated GPS ground antennas to support the satellites from spacecraft separation through, checkout, anomaly resolution and all the way to end of life disposal. It also helps in the performance of satellite movements and the presentation of telemetry simulations to GPS payloads and subsystems. Air Force Space Command (AFSPC) accepted the LADO capability to handle the most modern GPS satellites at the time, the Block IIF, in October 2010.

Another modernization program is known as the Next Generation Operational Control System or OCX. OCX will facilitate the full control of the new GPS signals like L5, as well as L2C and L1C and the coming GPS III program. These improvements will be discussed more in Chapter 8.

The User Segment

The military plans to build a GPS receiver into virtually all of its ships, aircraft, and terrestrial vehicles. In fact, the Block IIR satellites may be harbingers of the incorporation of more and more receivers into extraterrestrial vehicles as well. But even with such widespread use in the military, civilian GPS will be still more extensive.

The uses the general public finds for GPS will undoubtedly continue to grow as the cost and size of the receivers continues to shrink.   The number of users in surveying will be small when compared with the large numbers of trains, cars, boats, and airplanes with GPS receivers. GPS will be used to position all categories of civilian transportation, as well as law enforcement, and emergency vehicles. Nevertheless, surveying and geodesy have the distinction of being the first practical application of GPS and the most sophisticated uses and users are still under its purview. That situation will likely continue for some time.