PDHonline Course L105 (12 PDH)

GPS Surveying

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

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

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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 28 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 consists of 28 satellites, in six orbital planes (Figure 4.1). Each orbital plane is inclined to the equator by an angle of 55° and each of the six is rotated 60° from its neighbor.

GPS satellites are in a *posigrade* orbit. A posigrade orbit is one that moves in the same direction as

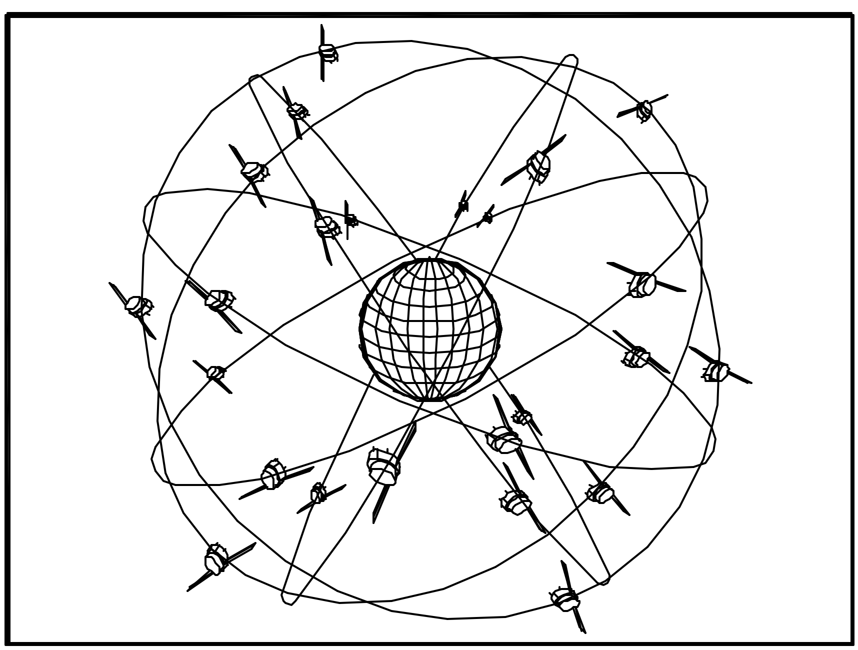

Figure 4.1

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 two rubidium and two cesium 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 and many of these birds are still flying. 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 7 2 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.

Today there are 7 Block II and 18 Block IIA usable GPS satellites in orbit. Two of the Block IIA satellites carry corner cube reflectors, Space Vehicles 35 and 36. These reflectors allow ground stations to measure satellite clock errors and broadcast ephemeris errors using satellite laser ranging (SLR).

Block IIR

The third generation of GPS satellites is known as *Block IIR* satellites; the R stands for *replenishment*. The first Block IIR satellite was launched on January 17, 1997 and failed to reach orbit because of a bad booster rocket

Significant advancements are built into these satellites. Instead of the cesium and rubidium clocks of the previous generations, these satellites will use hydrogen masers. Hydrogen masers are much more stable than earlier oscillators. The Block IIR satellites will have enhanced autonomous navigation capability because of its use of intersatellite linkage. These GPS satellites will not only be capable of self-navigation, they will also provide other spacecraft equipped with an onboard GPS receiver with the data it needs to define its own positions. Block IIR satellites will have the capability to operate for 6 months without uploads from ground stations. There are currently 3 usable Block IIR satellites in orbit. A total of 21 Block IIR satellites are expected to fly.

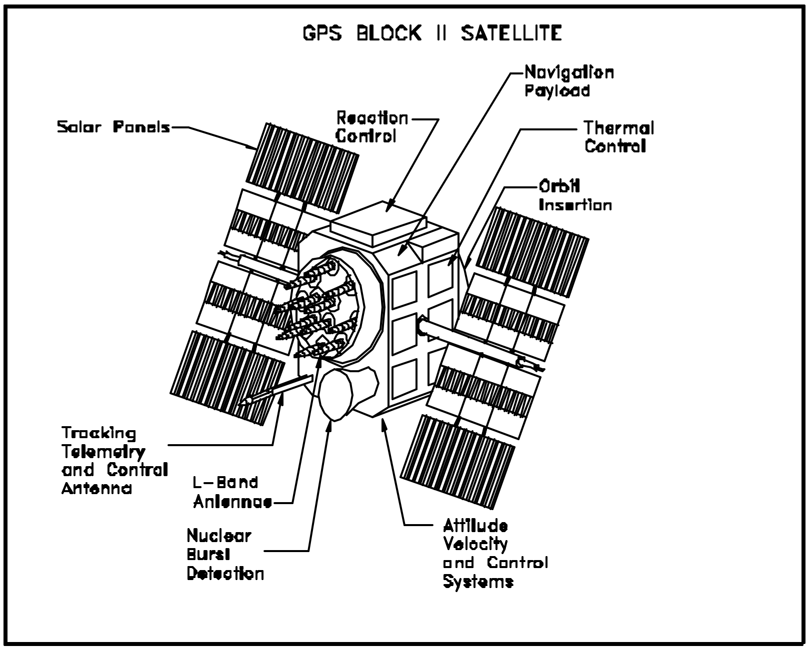

Figure 4.2

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 satellites (Figure 4.2). 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 on all Block II satellites 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.*

The Master Control Station

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 in Colorado Springs, Colorado. The U.S. Air Force's 2nd Satellite Operations squadron mans this station. There they compute updates for the Navigation message, including the broadcast ephemeris and satellite clock corrections derived from about 1 week of the tracking information it collects from five monitoring stations around the world.

The MCS controls the repositioning and replacement of satellites, but the GPS constellation requires lots of maintenance too. Regular data uploads orbital positioning adjustments and clock maintenance are vital. If the Control Segment stopped doing the work the system would be virtually uselessness in a couple of weeks. For example, a GPS satellite must have a *momentum dump* periodically. Each satellite uses gyroscopes for stabilization that are called *wheels*. These wheels accelerate as the satellite moves along its orbit. They would do accelerate without bound if the MCS didn't order them to dump the accumulated energy from time to time.

Other Stations

The monitoring stations located at Ascension Island, Colorado Springs, Diego Garcia, Hawaii and Kwajalein are each equipped with a dual-frequency GPS receiver and a cesium clock. They observe P code pseudoranges and integrated Doppler measurements from all available satellites. Their measurement of the satellites actual position is then compared with the latest reference ephemeris to discover the misclosures between the two.

Every GPS satellite is being tracked by at least one of the control segment's monitoring stations at all times. The MCS sends its updates around the world to four strategically located uploading stations. They in turn transmit the new Navigation messages to each satellite.

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.