Chapter 16

Navstar Global Positioning System

Maj Jennifer Krolikowski, USAF

The global positioning system (GPS) is truly unique when compared to other Department of Defense space assets.[1] Although GPS was originally procured to aid in navigation, it has become a universal system used by both the civilian world and the military. GPS has become so integrated into our everyday lives that the Department of Homeland Security has declared it a part of the United States' critical infrastructure. Used by cell phones, computers, and cars, GPS can be found everywhere. This chapter will discuss the GPS missions; segments; limitations and vulnerabilities; tactics, techniques, and procedures; and modernization efforts.[2]

Missions

The GPS system is charged with three missions: navigation, time transfer, and nuclear detonation detection.

Navigation

The mission most commonly thought of is the navigation mission. GPS offers highly accurate position and velocity any time, any place. The required number of GPS signals needed for triangulation are guaranteed anywhere on the earth between the 70° north and 70° south latitudes—it is truly a global system. There is limited GPS capability at the poles due to poorer satellite visibility.

Another benefit of GPS is that it can perform in all weather conditions. The system is not affected by cloud cover. Unlike laser-guided munitions, GPS-aided bombs can be used at any time, 24/7. Some of the applications for navigation are determining position, targeting, and mapping.

Time Transfer

The second mission of GPS is time transfer. Ironically, this is probably the least-known mission, but it is now becoming the most used. The time standard used by DOD is Coordinated Universal Time, or UTC, which is the time maintained by the US Naval Observatory (USNO) and is considered the "world's time." Typically, it is not very practical to call the USNO every time a time hack is needed. Because GPS is widely available at all times and places, it has therefore become DOD's primary source for timing information. Since GPS time is within 20 nanoseconds (ns) of UTC time, GPS will likely be sufficient as a timing source for most purposes.

One of the applications of the time transfer mission is synchronizing digital communications. During frequency hopping, GPS timing is used to make sure each communication terminal moves to the new frequency at the same time. Another application is synching up networks, such as those used by computers, automated teller machines, or cell phones.

Nuclear Detonation Detection System

The GPS satellites carry an additional payload suite to support a Nuclear Detonation Detection System (NDS). The sensor array includes optical, x-ray, dosimeter, and electromagnetic pulse (EMP) sensors. The sensors detect and measure light, x-ray, subatomic particle, and EMP phenomenology to pinpoint the location and yield of a surface or airborne nuclear detonation. The information sensed on the GPS NDS system is relayed to the ground-based Integrated Correlation and Display System (ICADS) via a dedicated channel, L3 (1381.05 MHz). NDS supports several tasks, such as treaty monitoring and nuclear force management.

GPS Segments

The GPS system is made up of three parts: the space segment (or satellites), the control segment, and user equipment.

Space Segment

At a minimum, the GPS constellation needs 24 satellites in six orbital planes in order to ensure that at least four satellites are in view by the user at all times. The constellation flies in a semisynchronous orbit at approximately 20,000 km away from the earth. Another name for this orbit is middle Earth orbit (MEO). Although GPS has a semisynchronous orbit, its period is actually 11 hours and 58 minutes, vice 12 hours as the orbit implies. The two-minute differentiation is because the GPS period is based on a sidereal day and not the solar day.

The current constellation is around 30 satellites. The added redundancy offers improved accuracies and availability to users over the nominal 24-satellite constellation. Given how important GPS is to the world, constellation management is taken very seriously to avoid potential gaps in coverage or outages of service. Block IIR/IIR-M satellites are launched off of a Delta II rocket. The Block IIF will launch from the evolved expendable launch vehicle (EELV) boosters.

GPS offers two types of services to its user base—the standard positioning service (SPS) and the precise positioning service (PPS). The SPS is available for anyone's use—military or civil. SPS offers 3–5 meter accuracy. The PPS can only be accessed by authorized personnel—those with the correct decryption keys such as the US military or its allies. PPS accuracy is 2–4 meters. There are several signals and codes that make up each of the GPS services (fig. 16-1).

Today, GPS transmits on the frequencies L1 (1575.42 MHz) and L2 (1227.6 MHz), which are along the x-axis. The power levels for the signals are on the y-axis. The codes transmitted on these frequencies are the course acquisition (C/A) code (the green spike) and the pseudorandom (P[Y]) code (the yellow humps). Currently, the C/A code is transmitted on L1 and P(Y) is on both L1 and L2. The C/A code is what everyone receives—it is the code within the SPS. The P(Y) is an encrypted code and can only be

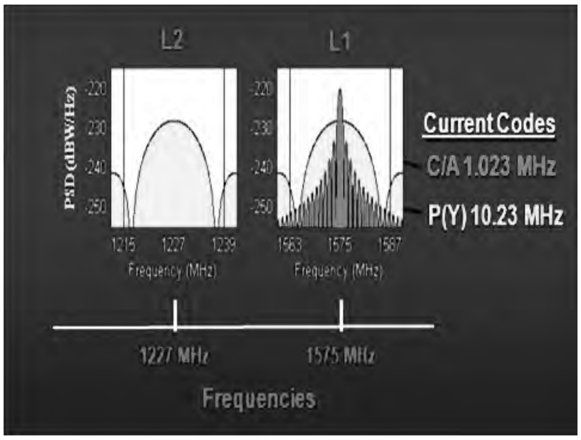

Figure 16-1. Signal/frequency/code relationship. (National Security Space Institute [NSSI] graphic prepared by the author)

received by those with the appropriate keys. This is the code that is obtained when a user is subscribed to the PPS.

Control Segment

While it is necessary to have satellites in the sky transmitting navigation signals, a control segment is needed to command them. This section discusses how that control segment works and what the GPS operations center (GPSOC) can provide the war fighter.

The headquarters for the control segment is the master control station (MCS) at Schriever AFB, operated by the 2nd Space Operations Squadron (2 SOPS). There is an unmanned backup master control station (BMCS) in Gaithersburg, Maryland, that is required to stand up within 24 hours in case something happens to the MCS. The alternate master control station (AMCS) is being built at Vandenberg AFB and is slated to replace the BMCS. The architecture evolution plan (AEP) must go online before the AMCS can go operational.

The GPSOC, part of the MCS team, is the one-stop shop for accuracy models, constellation health, and GPS service questions. It operates 24/7 and can provide assistance at any time. Not only does the GPSOC support the war fighter but also the civil community. The Federal Aviation Administration (FAA) or Coast Guard can use the GPSOC to answer civil-related GPS questions.

In addition to the master control station, there are six GPS monitoring stations and ground antennas, located at Colorado Springs, Kwajalein Atoll, Hawaii, Ascension Island, Diego Garcia, and Cape Canaveral. The Cape Canaveral site is primarily used for system checkout after launch, but it has transmit/receive capability that can act as a backup for the control segment, if necessary. Additionally, the Air Force Satellite Control Network has nondedicated resources that can provide ad hoc support to the GPS control segment. The National Geospatial-Intelligence Agency (NGA) also has a monitor station infrastructure used for its mapping missions. The Air Force is working with the NGA to incorporate the NGA's monitor stations with the GPS sites. This will allow 2 SOPS to observe the satellites more often and thus be able to discern more quickly if there is an issue or anomaly. As a result, the constellation accuracy performance will improve.

GPS satellites are commanded and controlled via the monitor stations, the MCS, and the ground antenna. Essentially, high-quality GPS receivers are placed at various precise locations throughout the world. These receivers track the satellites just like a normal receiver would—they obtain the satellites' ephemeris and any data. Information is then transferred to the MCS where it is put into the Kalman filter. The filter is an algorithm that can determine how the satellite has deviated from where it should actually be. The MCS takes that data and transmits back to the satellite via the ground antenna to update the satellite with its true location and time. For example, the monitor station is located at (0, 0), and the local time is 1700. This is known to be absolutely true. The GPS satellites are telling the monitor station it is at (1, 1), and the local time is 1705. The monitor station relays that information to the MCS. The MCS then builds an upload that will adjust the satellite transmissions. As a result, the monitor station's GPS-calculated position becomes more reflective of where the station truly is. These upload corrections occur at least once per day.

User Equipment

Millions of users, both civil and military, are employing GPS in thousands of ways. This is possible through the third GPS segment—the user equipment. Given that the GPS industry is around $1 billion a year, receivers come in many shapes and forms and are easily obtained. However, they all work essentially the same way.

Each receiver contains an almanac that tells it which satellites to start looking for in order to acquire their signals. For instance, if the receiver is in Colorado Springs at 0800, the almanac tells it to find space vehicle (SV) 4, 17, 23, and so forth. The receiver acquires the signal from the satellites and compares the receiver's internally generated code (specific for each satellite) to the code it is obtaining from the satellites. It also starts to look at each satellite's navigation data to see where the satellite thinks its position is and how far the clock has drifted and get information about atmospheric-delay corrections.

It takes some amount of time for the signal from the satellite to reach the receiver. This is known as the time offset. The receiver then shifts its internally generated code to line up with the code received from the satellite and record that time offset. Based on the time offset, the distance between the satellite and the receiver can be determined.

This process is followed for at least four satellites. The cumulative information is entered into the position equations and calculated. As a result, the user then knows his or her position in the world and can navigate from there. If the receiver were turned off in Colorado Springs and turned back on in Hawaii, it would initially try to acquire the satellites from its last known position—Colorado Springs. As the receiver does not find the appropriate satellites, it will begin searching the entire almanac until it acquires the satellites overhead and can determine its new position.

Timing is very important when establishing an accurate position. Typically, the time it takes for a GPS signal to reach the receiver is 0.07 seconds. If the time offset is errant by 1 ns, it equates to a foot of error when calculating the distance to the satellite. This, in turn, decreases accuracy when the receiver calculates the position solution. Only atomic clocks give the level of fidelity required to provide highly accurate locations.

Four satellites are needed to solve for latitude, longitude, altitude, and receiver clock bias. It is impractical to have atomic clocks in a receiver—they are too large and expensive. Therefore, most receivers have the same kind of timing source that is in a watch. As a result, the receiver is not perfectly synched up with the satellites and has a bias. Fortunately, that receiver has the same clock error with each of the satellites it talks to. So while the position is being calculated, the bias is solved for as well.

Limitations and Vulnerabilities

Even though GPS is an awesome system, it does have some limitations and vulnerabilities, specifically in accuracy and low signal power.

Accuracy

It is impossible for GPS to be 100 percent accurate because there are several sources that introduce errors into the navigation solution. These contributing factors—troposphere, ionosphere, multipath, satellite clock, satellite ephemeris, wrong datums/grids, dilution of precision—are the most common, and largest, sources of error.

Most signals are degraded as they pass through the atmosphere. The same is true for GPS. When the GPS signal goes through the troposphere, 90 percent of the error induced by this part of the atmosphere comes from the "dry atmosphere." This part of the error is really easy to model and can be calculated and accounted for. The remaining 10 percent of the error comes from the "wet atmosphere." This part of the error is very difficult to model, so these inaccuracies must just be accepted. Fortunately, this is not a significant source of error.

On the other hand, the ionosphere can produce large sources of error. For example, the triangle in figure 16-2 represents the true position of the user. The perceived position calculated by a single-frequency receiver is seen in figure 16-3. If a dual-frequency receiver is used, the result from the second signal portrays the position in figure 16-4. The dual-frequency receiver subtracts the two values and can determine the true position that is in figure 16-2. Remember that the C/A code, the one used by civil receivers, is only transmitted on one frequency. Therefore, civil receivers cannot currently correct for ionosphere-induced errors. Some of the GPS modernization efforts address this issue for civil users by adding a second civil frequency.

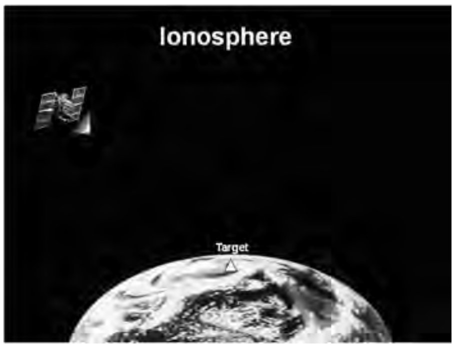

Figure 16-2. True position. (NSSI graphic prepared by the author)

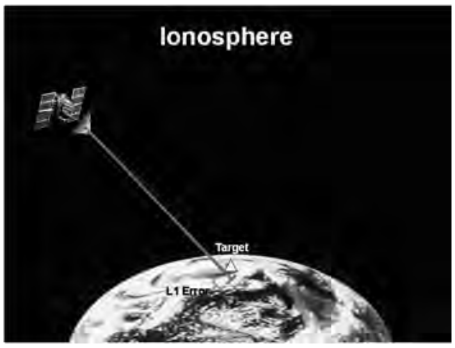

Figure 16-3. Error induced on L1 by the ionosphere. (NSSI graphic prepared by the author)

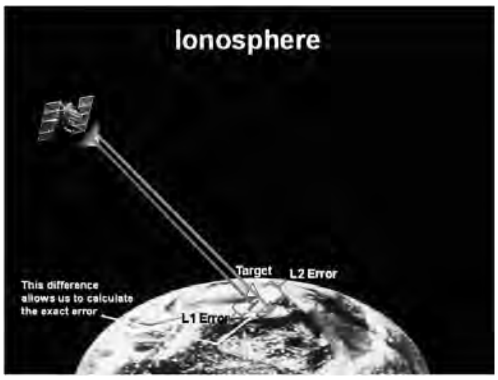

Figure 16-4. Error induced on L2 by the ionosphere. (NSSI graphic prepared by the author)

Multipath occurs when the signal bounces off objects before the user equipment receives it. This phenomenon is most prevalent in urban canyons. As the signal bounces around, it takes longer to reach the receiver, thereby increasing the time offset. As a result, the calculated distance to the satellite is longer, and the position is less accurate. There are a couple of ways to mitigate this. First, the signal structure is known as right-hand circularized. When it bounces off of a building, it becomes left-hand circularized. The receiver is programmed to disregard left-handed signals. Second, the receiver knows it should be obtaining the signal in a certain amount of time—around 0.07 seconds. If a signal breaks an established threshold, the receiver will disregard that signal.

One of the factors that 2 SOPS works to control is the errors generated by inaccurate satellite clocks and ephemeris data. Keeping the satellite information as precise as possible is done through the daily uploads discussed in the section on the control segment.

It should be noted that not all grids are the same. The difference between using a World Geodetic System (WGS) 84 or a Tokyo grid could lead to 1 km of error when talking about the same coordinate point. The best way to avoid this is by making sure everyone is using the same grid. While this may seem to be common sense, there are numerous cases in which a local population has used its mapping system, which was found to be incongruent with those used by standard GPS users.

The final source of error is generated through the geometry of the constellation with respect to the user. This is called the dilution of precision (DOP) (fig. 16-5). The solid line represents the actual ranging from the satellite to the receiver. The dashed line shows what the receiver thinks is the range to the satellite, or the pseudorange. Therefore, anywhere in the box is where the user could be.

If the geometry is a little more spread out, as in figure 16-6, the box becomes much smaller and provides much better accuracy. Therefore, the best configuration is one satellite overhead and the rest along the horizon.

Low Signal Strength

GPS is highly susceptible to jamming. Four parameters need to occur to be able to jam: a higher transmitted power, transmitting at the correct frequency, alignment with the antenna, and line of sight to the antenna.

First, the GPS signal is very weak and operates below the noise threshold. Basically, the GPS signal is equivalent to shining a 25-watt light bulb from 20,000 km away. In

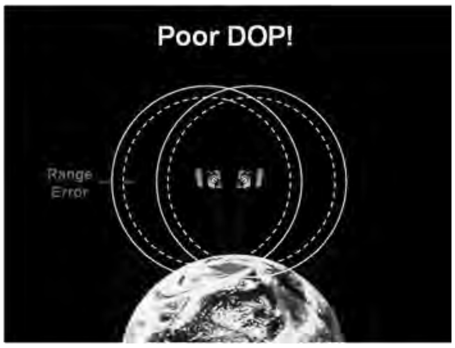

Figure 16-5. Poor constellation geometry or DOP. (NSSI graphic prepared by the author)

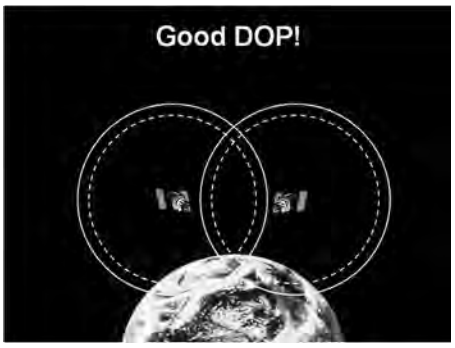

Figure 16-6. Good constellation geometry or DOP. (NSSI graphic prepared by the author)

terms of power, the GPS signal is 10–16 watts. Because the signal does not have a lot of power and is traveling a long distance, it is remarkably easy to make a jammer that transmits higher power levels. Second, because the frequencies on which GPS transmits are common knowledge—L1 and L2—it is not hard to program a jammer to hone in on those frequencies. Third, since most receiver antennas are omnidirectional, alignment is not an issue for a jammer. Finally, the only thing that is mostly variable to a jammer is its line of sight. If a jammer cannot see the receiver, it will not be able to jam it.

Tactics, Techniques, and Procedures

There are a number of tactics, techniques, and procedures (TTP) that are used to overcome the limitations and vulnerabilities of GPS. The most common TTPs deal with accuracy prediction and jamming mitigation.

Accuracy Prediction

The GPS Interference and Navigation Tool (GIANT) is used to generate a variety of products. It can predict the accuracy for a given region over a 24-hour period. It can also provide a chart that depicts the DOP for an area of interest. This is useful when trying to determine if a GPS-aided munition will be effective or if mission planners should strike a target at another time or use a different platform if it is a time-sensitive target. It should be noted that DOP is unit-less and *not* the accuracy for that area. A DOP of two does not mean that the accuracy is two meters. It means that the constellation geometry is favorable. Typically, if the DOP is greater than six, the accuracies will not be good enough for most military missions.

GIANT can also map out what the jamming environment looks like. By inserting a known jammer location and the power it is emitting, GIANT relays how effective the jammer is to various platforms. It lets the user know where to acquire the C/A code and hand off to P(Y) before being adversely affected by the jammer. In addition, GIANT can aid in developing a flight plan that would avoid the jammers all together.

Jamming Mitigation

While GPS is relatively easy to jam, the GPS signal structure itself offers some antijam capability (fig. 16-7).

We can think of jamming these signals as trying to block a bridge. If the bridge is narrow, few rocks are needed to block it. If it is a fairly wide bridge, a lot of rocks are required. The same is true of signals. If the bandwidth of the signal is small (like C/A), the signal can be jammed by relatively low power. If it has a large bandwidth (like P[Y]), more power is needed. The more power that is used to jam a signal, the easier it is to locate the jammer. Also, if an adversary jams P(Y) on L1, the user could switch to L2 and still get GPS. Therefore, even more power is necessary to jam both frequencies. Unfortunately, most military receivers must acquire C/A first before getting handed off to P(Y). Given this requirement and the fact that it does not take a lot of power to jam C/A, it is very appealing to attack the C/A code.

As part of the modernization effort, one antijam capability being fielded is the M-code. The M-code is spread across two frequencies, has a large bandwidth, and is split. The

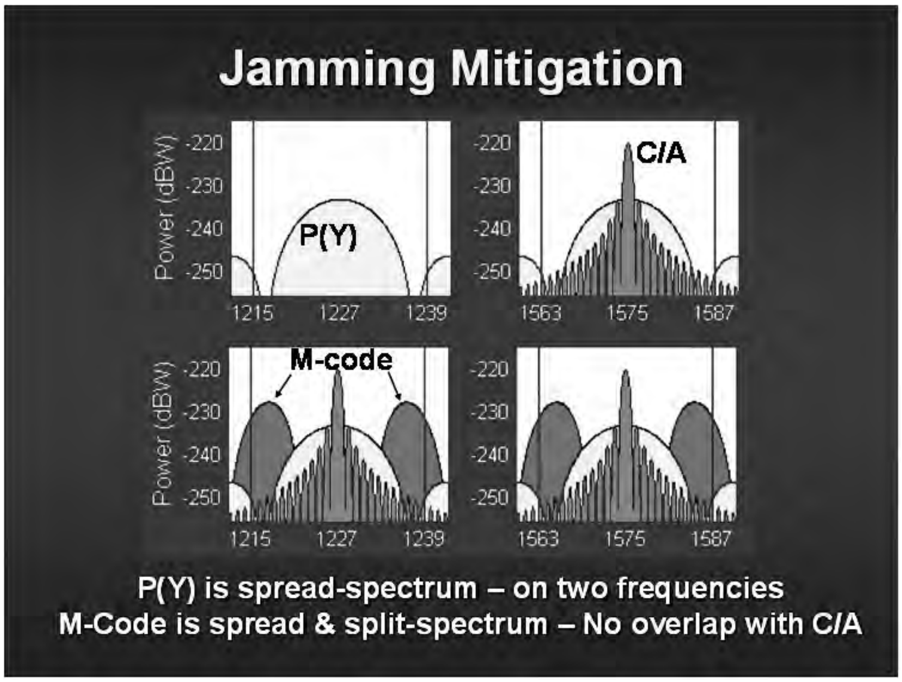

Figure 16-7. GPS signal structure. (NSSI graphic prepared by the author)

M-code also has a little more power associated with it. As a result, an inordinate amount of power will be needed to jam the entire M-code. Also, it will no longer be essential to acquire C/A before acquiring the M-code—the M-code will be direct access. Another benefit is that the M-code is spectrally separated from the C/A code, thereby reducing potential interference issues.

In addition to the signal structure, there are other ways to mitigate a jammer's effectiveness. By using directional antennas, the receiver will look only for satellites above the horizon, usually 10° or higher. This nullifies the jammers that are transmitting on the earth's surface. Another technique is antenna nulling. In this case, an antenna is made up of a number of elements. If one of the elements detects a jamming signal, that element is shut off, leaving the rest of the antenna to function normally to receive the GPS signal without interference. To prevent a jammer from having line of sight to the receiver, the user could go behind a mountain, dig a hole, or use his or her body to block the jamming signal.

Modernization

There are a number of efforts underway in each of the GPS segments to improve the system and address additional user needs. This section describes modernization efforts in the space, control, and user segments.

Satellite Evolution

The current GPS constellation contains Block IIA and IIR satellites. Both of these transmit only two signals and codes—C/A on L1 and P(Y) on both L1 and L2. Within the Block IIR-M, the M-code, a second civil signal (L2C), and flex power are added. L2C enables civil receivers to correct for the ionosphere. Flex power allows power to be transferred from one signal to another, thus providing some additional antijam capability. Block IIF will have everything that IIR-M offers but will add a third civil signal on L5. That signal will be used during "safety of life" applications. The final block being developed is GPS III. It will have all the same capabilities as IIF and many added capabilities. It will have increased power in the form of a spot beam. It will have slightly better accuracy, mostly due to crosslinks that will greatly reduce the age of data. Assured integrity is a major requirement desired by the civil community. With this precision, approach landings are possible with confidence that the GPS is available and working. Finally, as part of the negotiations with Galileo, GPS III will have a fourth civil signal on L1 (L1C) that will be compatible with the signals transmitted on Galileo. Table 16-1 summarizes the capabilities of each GPS block.

Table 16-1. Evolution of GPS capabilities

Block IIA/IIR	*Block IR-M, IIF*	*Block III*
• Basic GPS • Standard service (16–24 M SEP) – Single frequency (L1) – C/A code navigation • Precise service (16 M SEP) – Two frequencies (L1 & L2) – P-code navigation	IIR-M: IIA/IIR capabilities plus: • 2nd civil signal (L2C) • Earth-coverage military code IIF: IIR-M capability plus: • 3rd civil signal on L5 Flex-power upgrade adds ability to increase power on either P- or M-code signals to defeat low-level enemy jamming	Incremental acquisition: • Increased AJ power • Assured integrity • Increased security • System survivability • Increased accuracy • 4th civil signal on L1C for Galileo compatibility

Control Segment Upgrades

A lot of work is being done to update the control segment as well. That effort is called the architecture evolution plan (AEP). AEP is required to command and control the Block IIF satellites and to operate the M-code signals in a test mode. By implementing AEP, the backup master control station can be replaced by the alternate master control station.

Recently deployed was the Launch, Anomaly Resolution, and Disposal Operations (LADO) software. LADO replaced the command and control structure used by the Air Force Satellite Control Network (AFSCN).

The final control segment upgrade is the Operational Control Segment of the Future (OCX). OCX will incorporate some of the functionality that was originally allocated to AEP and add GPS III–unique functions, like commanding the spot beam. In addition, the OCX architecture is designed to be very flexible so future upgrades will be easier to accomplish.

Receiver Modernization

On the user equipment side, the Defense Advanced GPS Receiver (DAGR) is being fielded to replace the existing precision lightweight GPS receivers (PLGR). The DAGR will be a dual-frequency receiver, unlike the PLGR, which can obtain only L1. Therefore, the DAGR will be able to correct for the ionosphere whereas the PLGR cannot. The DAGR will have a graphical display versus the numerical latitude/longitude the PLGR shows today. Although DAGR cannot receive the M-code, it is much better than the handhelds currently in the field.

The next generation of user equipment is called the Modernized User Equipment (MUE). Essentially, MUE will be a "common card" for all systems—like aircraft, handhelds, ships, and so forth—that can be easily integrated into the platform. These cards will be able to acquire all of the GPS codes—P(Y), M, and C/A codes (YMCA).

In the area of security, the Selective Availability Anti-Spoofing Module (SAASM) was developed. SAASM will allow compromised receivers to be "shut off" by denying the receiver new crypto keys. Key updates over the horizon will be possible so receivers will not have to be taken back to the depot for new keys. This greatly reduces logistics footprints. Also, SAASM chips have a special antitamper coating on them to prevent people from reverse engineering the processor.

Notes

1. This chapter is adapted from a lesson written by Maj Jennifer Krolikowski for the National Security Space Institute.

2. For additional reading on GPS and related topics, see Ahmed El-Rabbany, *Introduction to GPS: The Global Positioning System* (Norwood, MA: Artech House, 2002); Joint Requirements Oversight Council, *Joint Capabilities Document for Positioning, Navigation and Timing*, Version 7.1 Draft, April 2006; Steven Lazar, "Modernization and Move to GPS III," *Crosslink*, Summer 2002, http://www.aero.org/publications/crosslink/summer2002/07.html (accessed 12 March 2008); Keith D. McDonald, "The Modernization of GPS: Plans, New Capabilities and Future Relationship to Galileo," *Journal of Global Positioning System* 1, no. 1 (2002): 1–17; Michael Russell Rip and James M. Hasik, *The Precision Revolution* (Annapolis, MD: Naval Institute Press, 2002); and GPS Operations Center, *NAVSTAR GPS User Equipment Introduction: Public Release Version*, September 1996, http://gps.afspc.af.mil/gpsoc/gps_documentation.aspx (accessed 7 May 2009).