Interference Mitigation Approaches for the Global Positioning System

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The satellite-based Global Positioning System (GPS) has evolved from its origins as a worldwide military navigation aid to a pervasive utility affecting all walks of life in the civil and military communities. As a result, the system must operate in a much wider range of environments than originally planned. Performance requirements have expanded, with a greater emphasis on substantially enhanced interference resistance and accuracy. This article focuses on these recent shifts and describes current efforts to address the updated requirements. First, we describe the GPS architecture and review its principles of operation. Then we outline the pressures in both the military and civil communities to upgrade performance. Next we cover some enhancements to GPS, and the program to implement them. We then examine efforts in the military community to address intentional interference, or jamming, with GPS operation. Mitigation of such jamming can be included in a user's equipment or in the signals transmitted to this equipment. Finally, we describe a GPS augmentation approach, known as a GPS military pseudolite, which was designed to substantially reduce interference susceptibility. Research on the technical challenges associated with such a pseudolite system is currently being conducted at Lincoln Laboratory.

The current design of the satellite-based Global Positioning System (GPS) evolved from competing candidate designs in the late 1960s [1, 2]. This design is based on a constellation of twenty-four man-made satellites (satellite lifetime and replenishment requirements cause the actual number of active spacecraft to fluctuate) orbiting the earth every twelve hours at an altitude of 20,000 km. Collectively, this baseline constellation makes up the Space Segment, as shown in Figure 1. Each satellite continuously transmits a position message, with precision timing among all system components and between satellites. Such timing is maintained by monitoring satellite transmissions at five ground stations that can send updates to the satellites when undesired deviations are detected. This set of ground stations makes up the Ground Segment.

The third segment—the User Equipment Segment—consists of what has become a wide variety of GPS receivers designed to utilize the space-based signals for accurate position and time determination. All such receivers operate on the same principle: estimate the arrival time of signals from at least four separate satellites and then use the known transmission times and the speed of light to estimate the ranges between the user and the satellites. The GPS receivers then use the ranges to calculate a user's position.

Each GPS signal is designed to carry a time stamp allowing the receiver to know when the signal left its GPS satellite. A properly equipped receiver can then

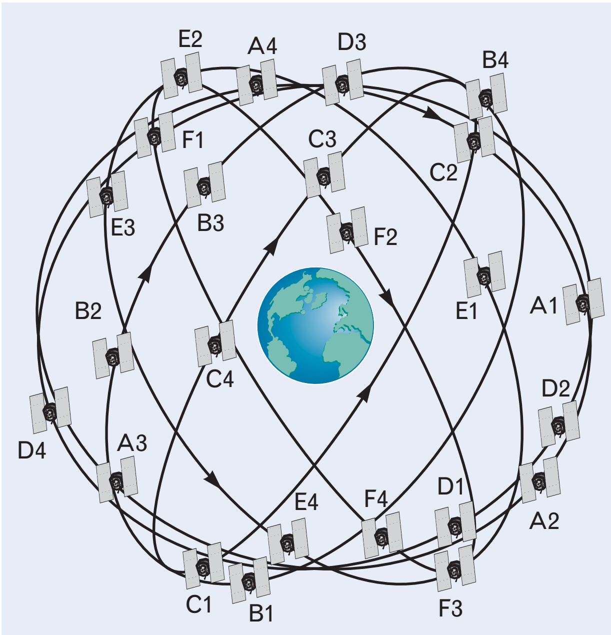

FIGURE 1. Constellation of twenty-four Global Positioning System (GPS) satellites in six orbital planes. This constellation is known as the Space Segment of the GPS system. The other segments are the Ground Segment, consisting of five ground stations that receive continuous position and time transmissions from the satellites, and the User Equipment Segment, consisting of individual GPS receivers that can accurately process position data from the satellites and calculate a user's location.

measure when the signal reaches the user. If the satellite clock and user clock are perfectly synchronized, the distance between them can be computed as the time delay multiplied by the speed of light. However, although the GPS clocks are all highly precise and synchronized with one another, the user clock may have an unknown bias relative to GPS system time. The term *pseudorange* is used to recognize that the user can only estimate each GPS signal arrival time relative to a biased clock.

Figure 2 illustrates how four range measurements can be used to produce estimates of user position and time bias. A single range measurement defines a sphere centered on the satellite; a second range measurement defines a second sphere, and the intersection of these two spheres defines a circle of position, as shown in Figure 2(a). A third range measurement defines an ambiguous pair of positions, as shown in Figure 2(b), and a fourth range resolves the ambiguity and determines the clock bias. The mathematical solution of the GPS equations is covered in many texts [3–5].

In many user applications, the GPS receiver is integrated with an inertial measurement unit (IMU) that can operate like a flywheel, smoothing the navigation solution provided by the GPS receiver and filling in short-term gaps in that solution, should the GPS receiver temporarily lose the GPS satellite signals. IMU quality and cost can vary over a wide range, and each application has a required navigation accuracy and a required immunity from interference. An appropriate navigation system design, intended to provide precise position, velocity, and time (PVT) to a user, involves a detailed analysis, usually resulting in a tradeoff between performance and cost. The IMU contributes to user independence from outside signals, and hence it enhances overall system immunity to interference. The GPS receiver, by frequently computing a fresh navigation solution, radically reduces the drift effects associated with all inertial systems.

Current Signal Characteristics

The navigation signals transmitted by GPS satellites have been almost unchanged since the first satellite was launched in 1978. Salient features of these signals include radio frequencies, modulation characteristics, signal power levels, and data content.

Transmission Frequencies

Each satellite transmits signals on two frequencies, both in the L-band. These are designated L1 (1575 MHz) and L2 (1227 MHz) [6]. As we discuss later, an additional frequency is in the planning stages.

Modulation

Each satellite transmits two types of modulation. A Coarse/Acquisition (C/A) signal, having a continuous, binary-phase, pseudonoise modulation format, is transmitted with a 1-MHz bandwidth. All characteristics of the C/A signal, including its modulation details, are known world wide and are fully predictable by anyone who has read (and understood) the open-signal specification. C/A is truly an open signal, used by all civil receivers to provide Standard Positioning Service (SPS).

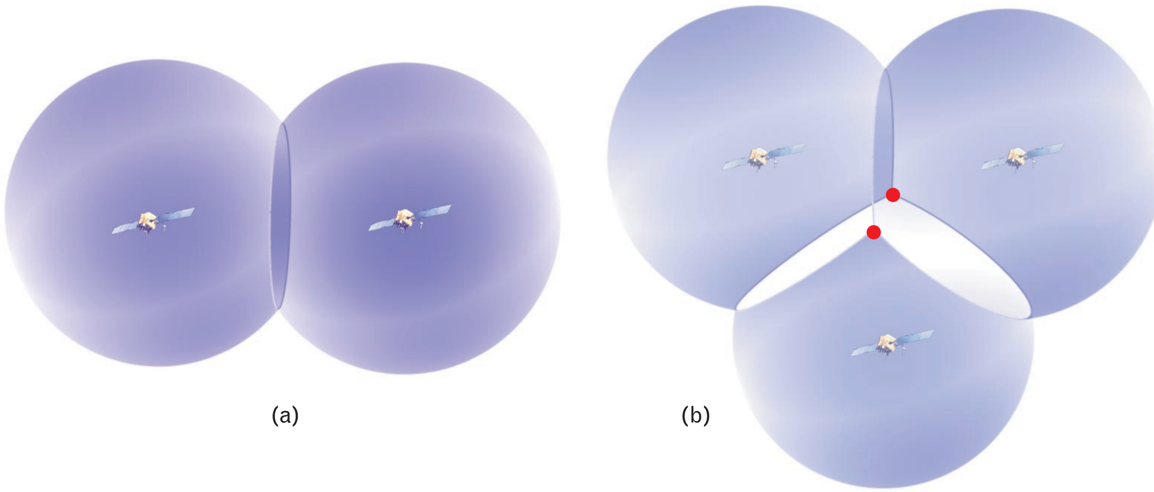

FIGURE 2. Navigation principles. (a) A range measurement from a single satellite defines a sphere centered on the satellite. A second range measurement defines a second sphere, and the intersection of these two spheres defines a circle of positions. (b) A third range measurement defines an ambiguous pair of positions, as indicated by the two red dots. A fourth range measurement resolves the ambiguity in position location.

C/A is also used by military receivers to acquire the more accurate and precise P(Y) signal with a 10-MHz bandwidth; the latter signal provides Precise Positioning Service (PPS). The C/A signal is currently transmitted only on L1; the P(Y) signal is transmitted on both L1 and L2. Both the C/A signal and the P(Y) signal are binary-phase, pseudonoise modulated signals. The P(Y) nomenclature is based on the process for generating this PPS signal. It is derived from a fully predictable open signal P and an encryption key stream, producing the actual transmitted signal Y.

Signal Power Level

The most salient feature of GPS signals is their low signal power level. Although each satellite bathes the entire earth below it with three continuous signals, the power of the signals received at a user receiver is approximately 10^{-16} watts, or one-billionth of a billionth of the power consumed by a single 100-watt light bulb. This level is less than one-thousandth of the noise generated in the user receiver covering the same bandwidth as the GPS signals. It is no wonder that interference degrades receiver performance!

Data

User equipment must have precise knowledge of the satellite position and signal transmission time. This information is encapsulated in data messages modulated onto the satellite signal transmissions. A low data rate is used (fifty bits per second) to make signal reception more robust. Details of the signal design and message structure are beyond the scope of this article. Suffice it to say, the signal structure imposes limitations on GPS performance and applications.

A Better GPS

Even though GPS has achieved success as a navigation aid and acquired a widespread user base, there is great demand for expanded capabilities and improved technology. Users continually envision new applications for GPS, especially in the civil user community, and many of these applications require more accuracy than the current system can deliver. These expanded interests have fostered several approaches to achieving greater accuracy. These approaches, however, have required new methods for processing the GPS signal, some of which would be enhanced with additional satellite transmissions.

Greater Accuracy

Accuracy has always been a key feature of GPS performance. Although the GPS system was designed for receivers to track the binary pseudonoise modulation (i.e., the pseudonoise code), this code has an inherent tracking accuracy determined by the code bandwidth. The C/A code accuracy is driven by a 1-MHz bandwidth due to the pseudonoise chip duration of one microsecond, for an inherent accuracy of three hundred meters. P(Y) accuracy is driven by a 10-MHz bandwidth, providing an inherent accuracy of thirty meters. By processing the GPS signal carefully, a receiver can track with an accuracy that is a small fraction of these values, perhaps to 1% of the inherent accuracy. However, once the receiver tracks a signal with an accuracy of less than one meter, other system limitations enter into the overall accuracy calculation.

Civil users, interested in greater accuracy than can be obtained by code tracking, devised schemes to track the GPS signal carrier [7]. These techniques exploit the wavelength of the carrier frequency, providing an inherent accuracy of 0.2 meters, with a subcentimeter final tracking accuracy, as long as the carrier cycle ambiguities can be resolved. Methods to accomplish this improvement in accuracy have been developed, and carrier-tracking kinematic GPS receivers have been used for a wide range of scientific purposes. Such receivers typically require reception of each GPS signal for an extended time before all carrier ambiguities can be resolved. Again, once the receiver tracking errors become very small, the final accuracy is affected by a host of other GPS system parameters.

Interference Susceptibility

The low level of the GPS signals makes them extremely susceptible to interference effects. A GPS receiver must lock onto (i.e., acquire) the signals from at least four satellites and then track them accurately. If there is excess interference, the receiver may be unable to lock onto the signals. The ability of a receiver to accomplish critical functions is characterized by its *antijam capability*, which is calculated as the ratio of interference power to GPS signal power, beyond which the specific function cannot be performed.

Figure 3 shows the jamming environment faced by a receiver as a function of the interferer transmitted power level and the distance of the interfering source, or *jammer*, from a hypothetical GPS receiver. The GPS receiver must be able to tolerate the jamming environment, but it has more tolerance in some modes than in others. The dashed horizontal lines in the figure indicate receiver tolerances for six important cases. Figure 3 can be used to predict receiver performance under various conditions. For example, a 1-W noise signal, transmitted from a distance of up to a hundred kilometers, is sufficient to prevent a typical GPS receiver from acquiring the C/A signal. A 1-kW interference signal, at the same range, will cause a receiver tracking the P(Y) signal to lose lock and stop providing its benefits to the military user. The reader can verify these and other examples by using the data shown in Figure 3.

A particularly important concern surrounds the signal acquisition or synchronization process in the GPS receiver. Although it is theoretically possible to acquire the P(Y) signal directly, the processing can be extremely slow if the user does not have an accurate estimate of GPS system time. In fact, even though a military receiver has been keyed to access the encrypted P(Y) signal, it will normally acquire C/A code first, obtain GPS system time through the C/A code track, and then make a transition to P(Y) code track. This process implies that even a military receiver will have difficulty acquiring a GPS signal in the face of a 1-W jammer at a distance of a hundred kilometers.

Clearly, as these examples show, GPS receivers are highly susceptible to interference. This operational shortcoming has inspired many efforts to mitigate the effects of interference and make GPS more robust. Some specific approaches are addressed later in this article.

Given this well-known susceptibility to interference, it is somewhat surprising that the use of GPS by the military is so widespread. However, most military platforms using GPS have inertial navigation systems that can help GPS receivers coast through periods of GPS signal outage. In fact, the two types of navigation systems (inertial and GPS) complement each other in several ways. For example, the inertial system provides a source of coasted track data when the GPS signal is interrupted, and the GPS receiver helps with inertial-system drift calibration when GPS signals are available. The result is reliable and accurate navigation data. Much research effort is currently under way to explore these closely coupled GPS/inertial navigation systems.

Other Issues

System security, or resistance to bogus satellite signals (called *spoofing*), is viewed with increased importance today. Current security measures, based on encryption of the military P(Y) signal, are effective for a receiver that has acquired the GPS signal and is tracking it. As noted above, however, unless a user has an accurate clock, the receiver must use the C/A signal to acquire the other GPS signals, and the C/A signal is transmitted entirely in the clear. The military is currently implementing a new signal called M-code to alleviate this dependence on the C/A signal.

Frequency spectrum allocations used by GPS are another concern. All segments of the electromagnetic spectrum are allocated to specific uses, and in today's environment several systems may be required to share the same band. Despite its large user base, GPS does not have sole use of the spectrum segment in which it operates. Many feel that GPS is so widely used that it has effectively become a utility, and deserves a sole-use international spectral allocation. The wireless cell-phone industry is fighting these interests with a major lobbying effort.

New frequencies are primarily demanded by the civil community. As indicated above, the signals used by the civil community are currently limited to the L1 frequency. Because of this limitation to a single frequency, corrections for ionospheric delay cannot be obtained directly by a civilian GPS receiver. A military receiver, however, can measure the time delay between the L1 and L2 signals from the same satellite and use this difference to compute an estimate of ionospheric delay.

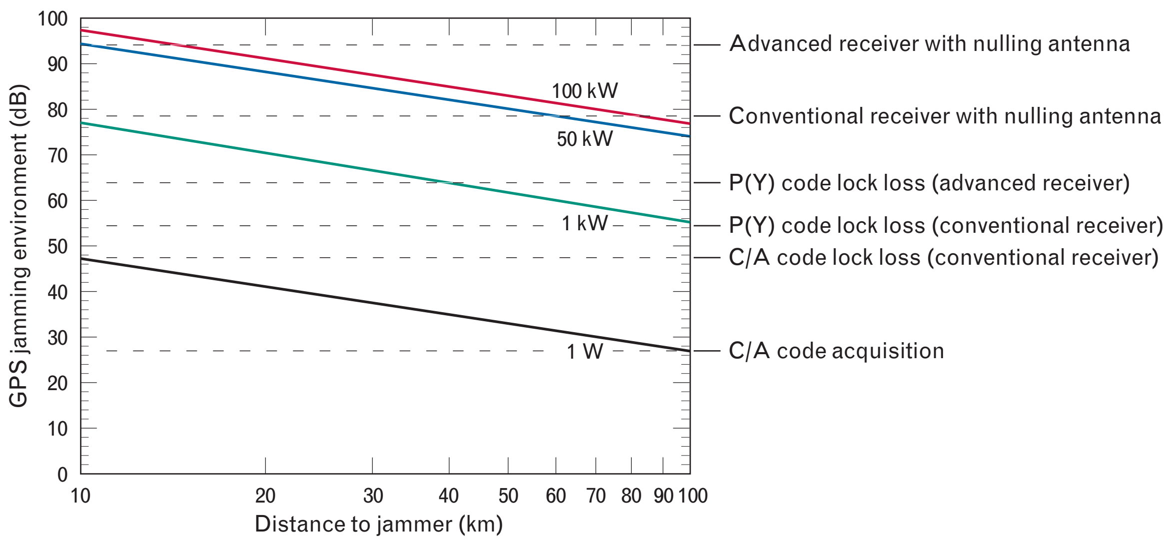

FIGURE 3. GPS jamming environment as a function of interferer power and distance from the interference source, or jammer, to a target GPS receiver. The environment is given for four levels of interference power from 1 W to 100 kW. The GPS receiver must be able to tolerate the jamming environment, but has more tolerance in some modes than in others. Advanced receivers are more tolerant than conventional designs; receivers equipped with nulling antennas are more resistant to jamming than receivers without them. The dashed horizontal lines indicate receiver tolerances for six important cases. The Coarse/Acquisition (C/A) signal is the worldwide standard recognized by all civil receivers; a civil receiver must first acquire (capture) the C/A signal and then track to provide navigation coordinates. The C/A code acquisition threshold of 27 dB indicates that acquisition will be successful as long as the jamming environment is below this level; the 47 dB C/A code lock loss threshold indicates the environment in which a conventional receiver can continue providing navigation results. The chart can be used to predict problem situations; for example, if a 1-W interference signal at a range of up to a hundred kilometers prevents a typical C/A receiver from acquiring the GPS signal. The C/A signal is also used by military receivers to acquire the broader-bandwidth encrypted P(Y) signal. Thus, when first turned on, a military receiver is subject to the C/A code acquisition threshold, but once it has acquired and tracked C/A code, its jamming tolerance increases to the P(Y) code level, and it can operate properly as long as the jamming environment is less than the P(Y) code lock loss threshold of 54 dB. Note that an advanced receiver with a nulling antenna can tolerate jamming environments as high as 95 dB.

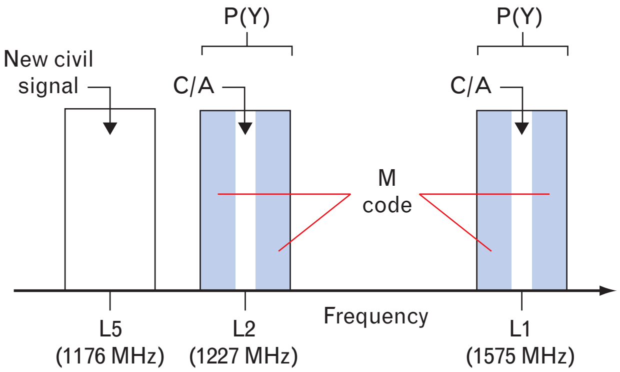

FIGURE 4. Enhanced GPS signal architecture. Civil receivers are currently limited to the L1 frequency, while military receivers use both the L1 and L2 frequencies. An expanded design for future GPS satellites adds a third frequency, known as L5, as well as an additional clear signal on frequency L2. The shaded areas around each frequency indicate the spectral distribution of each signal type. C/A code is concentrated in a 1-MHz band around its center frequency; P(Y) code is concentrated in a 10-MHz band around L1 and L2; M code will be concentrated in two pairs of 4-MHz bands with each pair centered on L1 and L2. The spectral distribution of the new signal around L5 is still under discussion, but it is likely to have a distribution similar to P(Y).

As demand for accurate GPS positioning has grown in the civil community, networks of auxiliary systems have been developed to provide ionospheric corrections and other information necessary for increased accuracy. These auxiliary systems use separate local radio broadcasts to feed the requisite information to users. In the original GPS system design, this solution was acceptable, but today's demand for greater accuracy in the civil community, and a desire to avoid the costs associated with supporting the auxiliary signals, have increased pressure to add a second clear signal on the L2 frequency. Such a signal will be added to new satellites soon, and a third clear signal, on a new frequency (L5), will follow closely behind. These additional frequencies will increase navigation accuracy for the civil user, simplify the ambiguity resolution process for carrier tracking, and increase resistance to interference through diversity.

Figure 4 illustrates the enhanced GPS signal architecture, which incorporates these improvements. This design includes a second C/A code for L2, a new 10-MHz bandwidth signal on a third frequency (L5), and M-code signals on both L1 and L2. M code will be concentrated in a pair of 4-MHz bands, with one pair centered on L1 and the other pair centered on L2. These signals will be included on new GPS satellites beginning in 2004. At some time beyond 2010, enough satellites with the new signals will be in orbit and the new capabilities will be declared operational.

The Options for Robust Performance

Interference continues to be an issue for many users, and a vigorous program is under way to explore a variety of mitigation approaches. Figure 5 presents a taxonomy of alternatives. We can enhance performance by improving user equipment with jammer-rejection and/or gain-producing antennas, as well as more robust receiver signal processing with massive correlators. We can transmit a better signal, either a stronger signal or with features allowing more processing gain to give higher antijam performance. We can avoid jamming environments through operational workarounds or by using navigation systems that do not rely on GPS signal reception. Finally, we can knock out the interfering sources by attacking the jammers directly.

This article concentrates on those mitigation methods which improve user equipment and those methods which strengthen the transmitted signal. The improved equipment methods utilize currently available signals at their current power levels, while strengthened transmitted signals force an adversary to transmit more interference in order to compete with stronger GPS transmissions. Other mitigation approaches are either operational workarounds or provide an alternative to GPS.

Adaptive Antennas

All GPS receivers utilize an antenna to capture the signals transmitted by the GPS satellites. In many cases, it is a simple single-element antenna with a fixed pattern. Such an antenna may have some interference rejection capability, especially if its pattern has been designed to have low gain in some portion of its coverage. But there are feasibility limits to the benefits available with this approach. Multi-element antennas, equipped with antenna electronics that can adaptively shape a composite pattern in response to the signal environment, are substantially more effective in suppressing interference. Such adaptive antennas form deep nulls in their antenna patterns, with the nulls aimed in the direction of interference sources.

This general approach for canceling interfering signals is known as a *nulling* antenna system. A more aggressive approach, called a *beamformer*, not only causes the interfering signals to cancel but also causes the components of the satellite signals seen at each antenna element to combine coherently, providing useful antenna gain in the direction of the satellite. Figure 6 illustrates these two important antenna-based approaches to interference rejection.

Several important issues affect the choice of an antenna subsystem for GPS. The multi-element array required for an adaptive array is not only more costly than a single-element antenna but is also significantly larger. Thus the user platform requires more real estate for the antenna array and the associated electronics. On many platforms, real estate is a scarce resource, and the cabling from antenna to signal processing electronics is severely constrained. Although these implementation factors may preclude the use of an adaptive antenna system for many applications, such systems—when feasible—are capable of reducing interference by several orders of magnitude.

A further enhancement to adaptive antennas includes tapped delay lines behind each antenna element. Additional weights are applied to the delayed signals, and the results are included in the weighted sum. Such a space-time adaptive processor (STAP) provides immunity to multipath associated with the interference. Implementation of such nulling beamforming systems can take several forms. Figure 7 illustrates two important alternative architectures for an adaptive antenna system, a spatial-only adaptive processor and a space-time processor. In both of these architectures, each element of the antenna system is equipped with a signal processing capability that can collect samples of the signal environment seen by this element.

In the spatial-only processing shown in Figure 7(a), element-to-element correlations are computed and then used to derive phase and amplitude weights

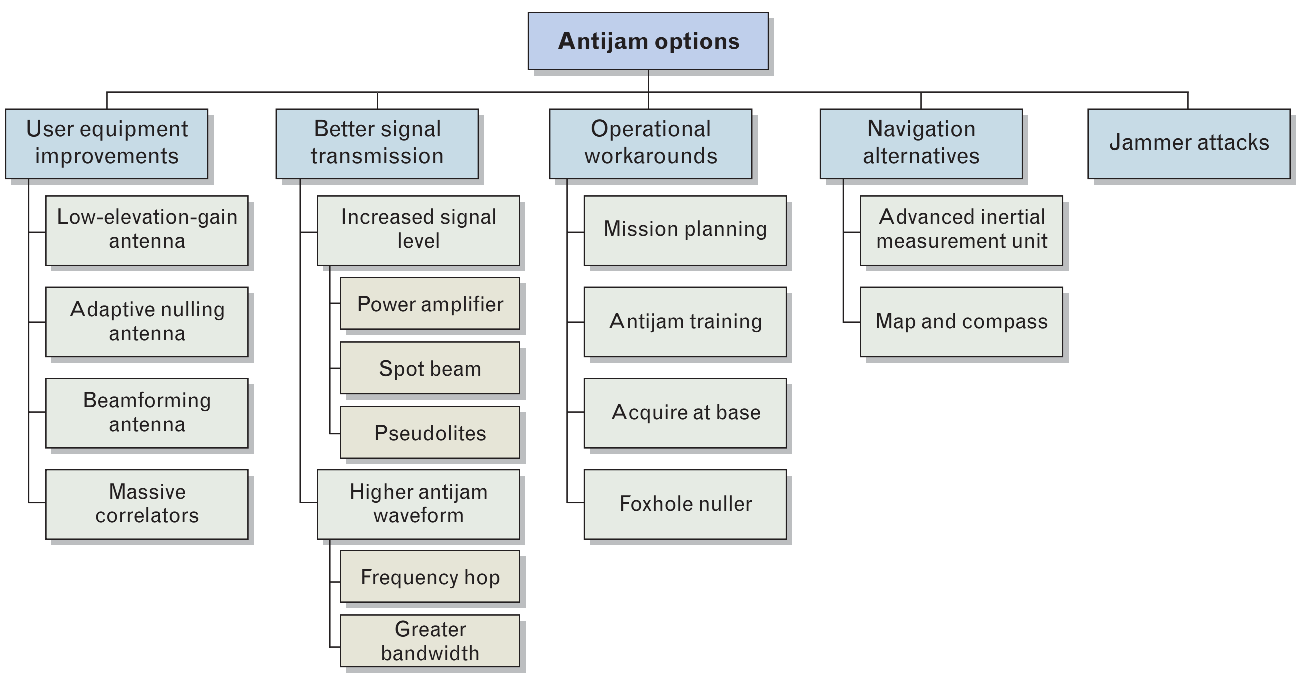

FIGURE 5. Taxonomy of interference mitigation alternatives. This article focuses on those methods which enhance performance through improvements to user equipment and those methods which use better signal transmission. Operational workarounds use tactics that avoid putting the user equipment into an environment with intolerable interference. Users employing navigation alternatives use systems other than GPS for location information. Jammer attacks are active approaches that force the jammer to turn off, thereby improving the jamming environment.

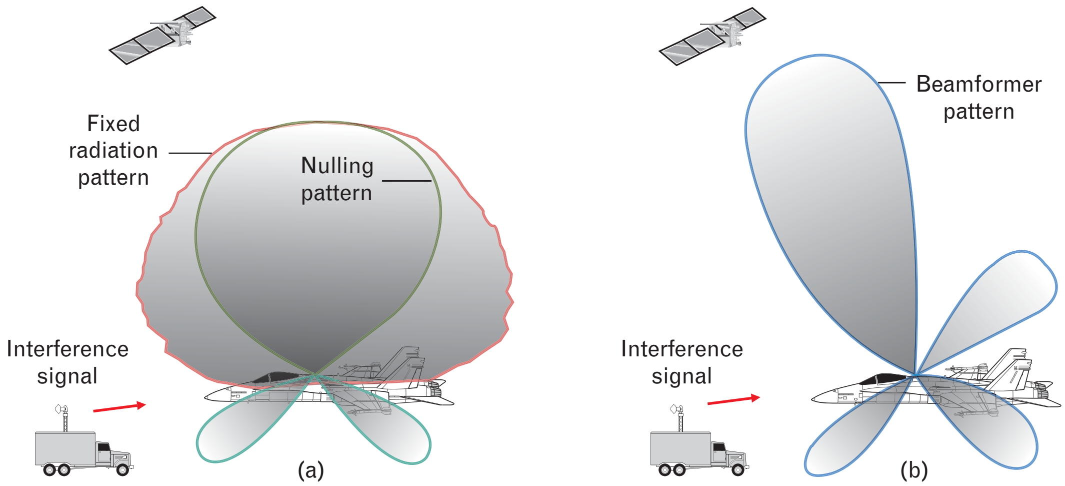

FIGURE 6. Antenna-based approaches to interference control. Multi-element antennas can adaptively shape a composite pattern in response to the environment, and form nulls in the direction of interference sources. (a) A nulling antenna system reduces gain in the direction of a jamming signal, but with no additional gain on the GPS satellite signal. (b) A beamformer antenna system reduces gain in the direction of the jamming signal *and* increases gain on the GPS satellite signal.

for each element of the antenna array. The weighted signals are combined in a summing network to form a single composite signal that is passed along to a conventional GPS receiver. The element weights are carefully constructed to make the components of the interfering signals, as seen by the individual array elements, cancel each other at the output. When the direction of the desired signal is known, antenna gain can be provided at that angle. The GPS signals, arriving from a different direction, will not cancel and will be available to the receiver for user navigation. When the signal environment seen by the GPS multi-element antenna varies with frequency, a STAP processor is necessary to obtain deep interference nulls. This nulling is realized by a set of tapped delay lines, as shown in the processing architecture in Figure 7(b).

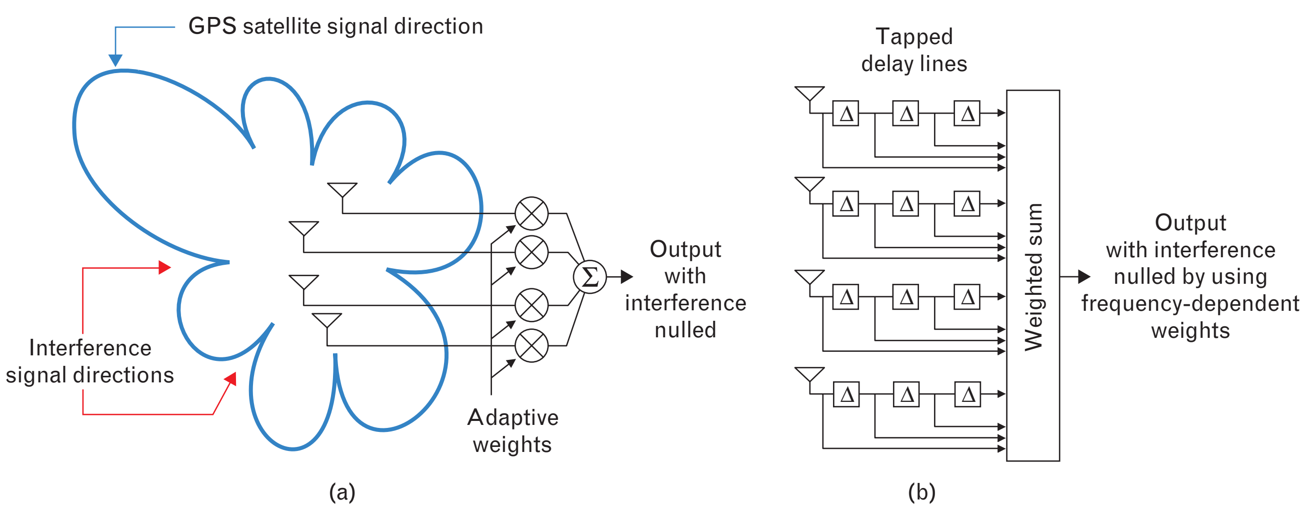

FIGURE 7. Adaptive antenna array architectures for interference suppression; (a) spatial-only adaptive processing. Such structures shape a response pattern that adapts to the signal environment. Nulling systems attempt to cancel interference, and beamformers provide additional gain in specific directions. Spatial-only processors weight the signals seen by each element. (b) Space-time adaptive processing permits a response pattern that varies with frequency.

Adaptive antenna systems of both classes—nulling and beamformer—have been built for GPS applications. A typical high-performance nulling system can suppress interference by more than a factor of 10^5. A beamformer can increase the satellite signal level by about a factor of three. The result is an improvement of 3×10^5 (55 dB) in jammer rejection over a GPS receiver with a single-element antenna. Such adaptive antenna systems make it difficult for an intentional interferer to generate strong bothersome signals.

Lincoln Laboratory has been working to develop a high-performance adaptive antenna array processing system for use with GPS signals [8] as a component of the military pseudolite system described in the next section. This system is based on a seven-element antenna array, and utilizes tapped delay lines behind each antenna element to implement a STAP processor. Tapped delay lines are motivated by the reflections of interfering signals from metallic surfaces located near the antenna array. These surfaces make each antenna array element electromagnetically different from the others; the differences are a function of frequency. The tapped delay lines allow the array structure to become a frequency-dependent spatial filter. As a result, the multipath reflections associated with many complicated military platforms (especially aircraft) can be compensated effectively.

One of the challenges associated with the desired high level of adaptive array performance involves achieving array gain on each of the GPS satellites needed for a navigation solution. Because each of the satellites is in a different direction from a user, this goal implies that a different set of phase and amplitude weights are required to steer a beam to each satellite. This capability is included in the Lincoln Laboratory adaptive array development system, known as the Multi-Antenna Multi-Beam Array (MAMBA), which is shown in Figure 8. MAMBA is a STAP pro-

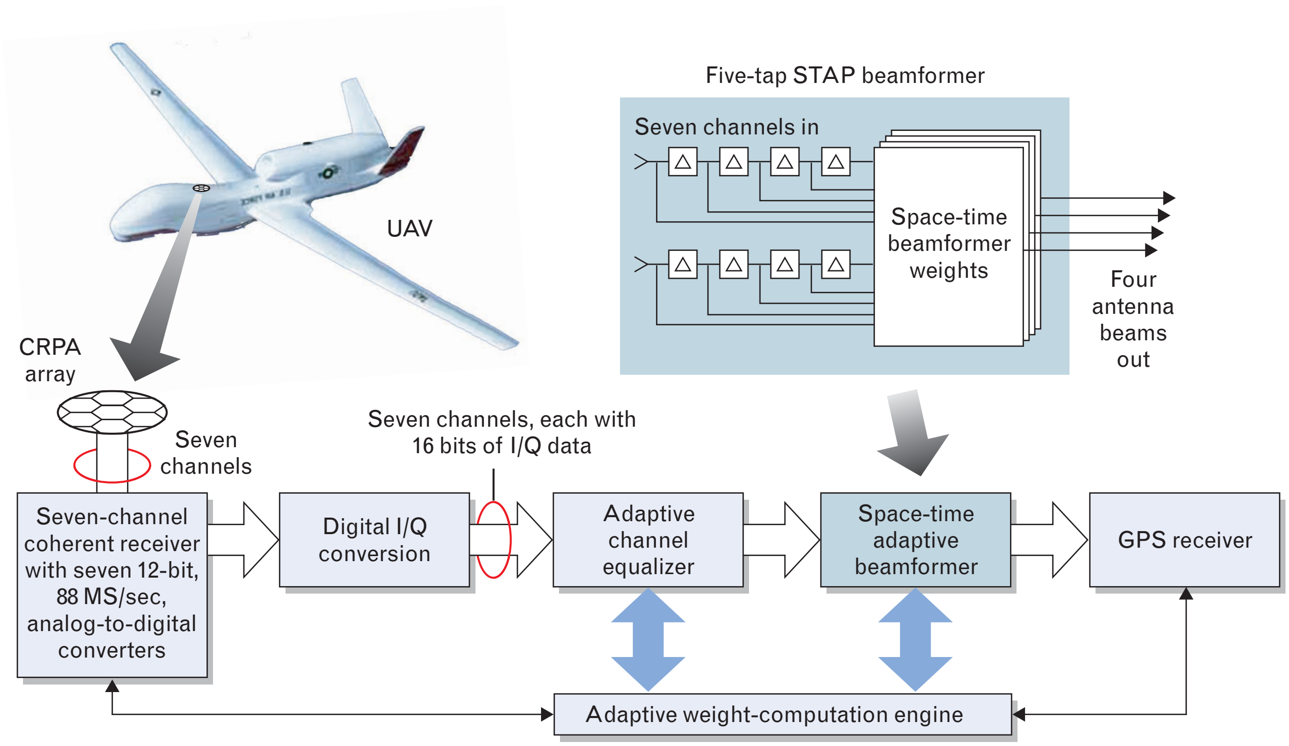

FIGURE 8. Multi-Antenna Multi-Beam Array (MAMBA) multipath adaptive processor for GPS receiver systems, mounted on an unmanned air vehicle (UAV). Signals captured by each element of the seven-element controlled reception-pattern antenna (CRPA) array are amplified, digitized, and converted to in-phase and quadrature (I/Q) data streams. The space-time adaptive processor (STAP) adaptive weight-computation engine computes space-time beamformer weights for each set of thirty-five taps (seven antenna elements and five taps per element). Four GPS antenna beams are formed simultaneously. The STAP beamformer constraints eliminate multipath dispersion effects on primary GPS satellite signals, which avoids introducing bias to GPS position calculations.

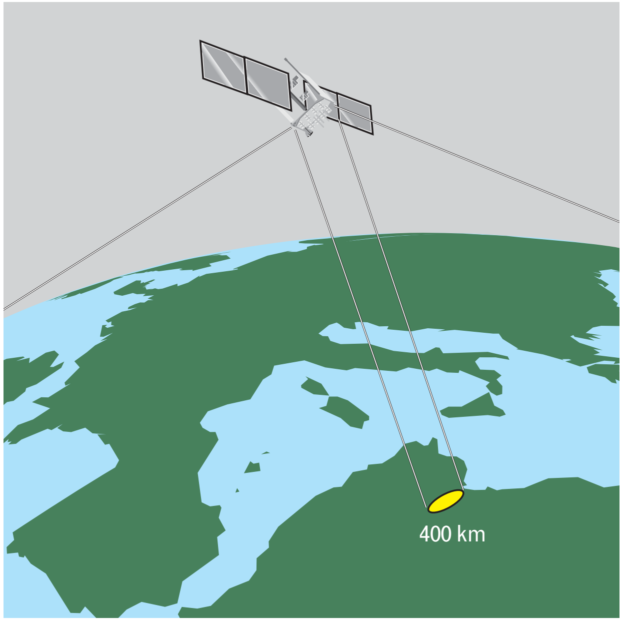

FIGURE 9. The concept of a spot-beam antenna, which is being considered for a new class of GPS satellites. A high-gain narrowbeam antenna would significantly enhance immunity to interference because of the gain in GPS signal power. This antenna would be particularly useful in a specific small area, such as a region of military conflict.

cessor for a seven-element GPS antenna that forms four separate beams, each steered to a different GPS satellite. It employs five time taps behind each antenna element and computes the required processor weights by using a Lincoln Laboratory–developed algorithm that constrains the output signal in order to manifest a common time bias among the four beams. This system has been extensively tested in the laboratory and, after installation on a Lincoln Laboratory Falcon-20 test aircraft, in a large anechoic chamber. Two weeks of field tests were also conducted at White Sands Missile Range, New Mexico. Test results have shown outstanding performance.

One adaptive antenna design issue concerns the number of interference sources that can be effectively eliminated by nulling. This number depends on several factors, but the number of elements in the antenna array is the most significant factor. It can be shown theoretically that $(N - 1)$ independent sources can be nulled with an N-element array. When a STAP structure is included in the array processor, more than $(N - 1)$ narrowband sources can be nulled. The precise number is not well defined because it depends on the multipath environment and interfering signal characteristics.

Therefore, an adaptive antenna array is a powerful tool for the military user interested in interference immunity. However, there are costs associated with this capability, and it may not always be appropriate to incur them. The following sections describe some alternatives to equipping all interference-sensitive users with costly interference suppression equipment.

Spot-Beam Space Vehicles

The previous description of the current GPS system emphasized the low power level of the GPS satellites impinging on near-earth users. As a result, relatively low levels of interference can cause GPS receiver problems. One potential solution to the interference susceptibility problem is to increase the level of the GPS signals significantly.

Although this approach would quantitatively improve interference immunity by the ratio of the power increase, there are many potential objections because the increased GPS signal level would itself become a source of interference to other systems. To circumvent such problems, a high-gain narrowbeam antenna is being considered for a new class of GPS satellites. This *spot beam* would impinge on a relatively small area, presumably one associated with a military conflict. Figure 9 illustrates the spot-beam concept.

It is too early to know whether the cost and complexity of such narrowbeam satellite antennas will be declared worthwhile, especially when other alternatives are considered. A second approach to a local increase in GPS signal power is described next.

Military Pseudolites

As noted above, adaptive antenna systems add substantial costs to a GPS receiving system, and all users must be equipped with this costly equipment. This section describes an alternative approach—a military pseudolite system—that provides a stronger navigation signal to all users in the operating theatre, allowing those with pseudolite signal processing capabilities the ability to operate in a stronger interference environment. Although each pseudolite transmitting platform is much more costly than each adaptive an-

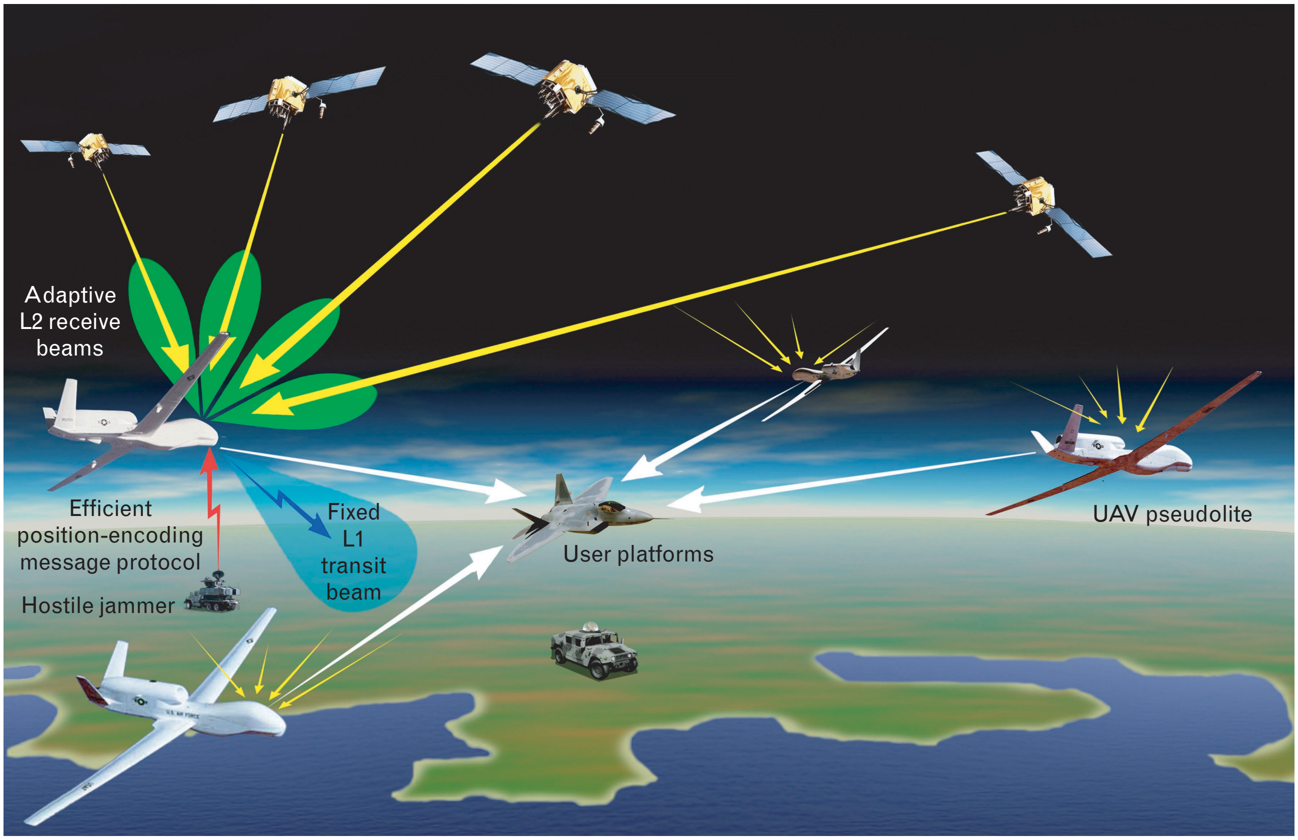

FIGURE 10. Architecture of the GPS pseudolite system. Four airborne UAV pseudolite platforms, each equipped with STAP beamformers, track GPS satellites for self-navigation. Each of the four pseudolites transmits a strong encoded signal to a user platform, which decodes the pseudolite positional data and estimates the range to each pseudolite. Equipment on the user platform accepts these data as surrogate for similar data normally derived from GPS satellites tracks. The result is significantly reduced GPS signal interference and a more robust navigation capability for the user.

tenna system, a set of four such pseudolite systems would serve many users, who could operate with only minor upgrades to their current GPS receivers. As a result, the overall total cost would be lower than the cost of widely deployed adaptive antennas.

Figure 10 illustrates the basic pseudolite concept [9]. At least four pseudolite platforms are required, each of them receiving the GPS satellite signals for self-navigation. Because all pseudolites must be able to receive these signals if the pseudolite construct is to be effective, an extremely robust adaptive array antenna system is necessary on each platform.

The GPS receivers on the pseudolite platforms are tightly coupled to the platform inertial measurement unit, providing even more robust reception. This coupled navigation system provides the pseudolite platform with highly accurate data on its position. But these positional data must be transmitted to a user receiver if that user is to utilize the pseudolite signals for navigation in the same way that GPS satellite signals are used when no jamming interference is present. This transfer of positional data has been one of the critical challenges in making a pseudolite system successful. Needless to say, this challenge has been met; an efficient position-encoding message protocol has been developed and proven in field tests.

The pseudolites each transmit an encoded signal similar to those transmitted by the GPS satellites. In fact, the signals are similar enough that modest software modifications can enable typical GPS receivers to receive and process the pseudolite signals. Users equipped with these modified receivers can obtain navigation solutions with about the same accuracy as can be obtained from GPS satellite signals.

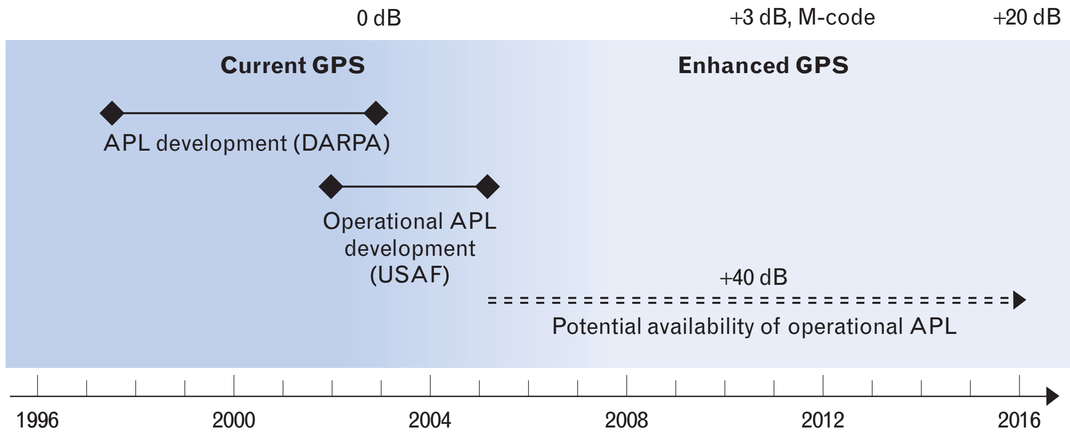

FIGURE 11. GPS interference mitigation time line. Development of an airborne pseudolite (APL) system is currently under way, and an operational APL system could be available as soon as 2005. A spot-beam capability could be available in 2016.

Care must be taken in transmitting the pseudolite signals. When a GPS receiver processes GPS satellite signals, it does not have to deal with multiple signals at different power levels. Because the GPS satellites are all at approximately the same range from a user receiver, their signals reach it at almost the same power level. In a pseudolite system, however, the user might be far from some of the pseudolites and close to others. As a result, the receiver might have a near-far problem, demanding an unusual degree of receiver dynamic range. This problem is important enough to motivate a special transmit antenna on the pseudolite platform, an antenna that shapes its beam to reduce the signal power variation over the operating area.

Another key element of the pseudolite construct is the frequency plan. As indicated above, the GPS satellite signals are transmitted at two frequencies, L1 and L2; many military GPS receivers can operate on either or both of these frequencies. However, many handheld receivers in use by the Army operate only on L1. Because these receivers are prime candidate users for the pseudolite signals, the pseudolite must also transmit on L1. However, to avoid the co-site problem, which occurs when continuous signals are transmitted and received on the same platform, the pseudolite can receive only the other frequency (L2) if it is to transmit continuously on L1. This means the pseudolite must navigate on a single frequency (L2). As a result, ionospheric corrections must be made available to the pseudolite from an external source.

Another issue concerns the effects of the strong pseudolite L1 broadcast on users in the operating theatre who are not pseudolite-ready. Since this transmitted signal is substantially stronger than the GPS satellite signals, it will interfere with the operation of these receivers to some degree. The extent of this problem will depend on the details of the pseudolite transmitted power, whether the transmissions are continuous or pulsed, and the deployed pseudolite constellation.

The technology for a military pseudolite system has been under development at Lincoln Laboratory for several years. Rockwell-Collins has been an industrial partner in this effort funded by the Defense Advanced Research Projects Agency (DARPA). At this point, most of the technology has been proven in field tests; message protocol, user equipment software changes, and the high-performance beamformer have been shown to meet requirements. The shaped-beam pseudolite antenna will be tested in the near future. Finally, system-level tests are in the planning stage.

A Future Path

With the wide range of GPS users, their different operating environments, and the variety of interference countermeasures available, it is difficult to predict how GPS interference issues will be addressed in all cases. Analysis of alternatives for many specific users is under way. To put this problem in perspective, it is useful to think about the timeline shown in Figure 11. This timeline depicts a window of opportunity for an operational airborne pseudolite system (APL) starting in 2005, when the development efforts could be largely complete. This window extends until 2016, when a spot-beam capability may become available.

A decision to deploy an APL system involves a complex set of tradeoffs. Such a system would provide substantially more interference resistance than a spot-beam satellite-based system, and as noted above, it would be available sooner. However, it could be operationally more constraining and technically more challenging to develop. Also, APLs could be costly to maintain if the platforms are dedicated entirely to the pseudolite role. An interesting possible approach involves APLs as tenant payloads on surveillance platforms; in this way much of the infrastructure cost would be shared with the primary surveillance mission.

Summary

In the years since the first GPS satellite launch in the 1978, GPS has become an important system for military and civil users. Many applications of GPS demand enhanced system accuracy. Other applications bring the user into environments where interference—either intentional or otherwise—compromises performance. This article addresses the extent of this interference, and discusses technical approaches to its mitigation. Although this article focuses on technology included in current Lincoln Laboratory programs, adaptive antenna arrays, and airborne pseudolite systems, it puts these technologies in context with other options. Within the next few years, we can expect to see the legacy of this research included in high-performance operational GPS user systems of the future.

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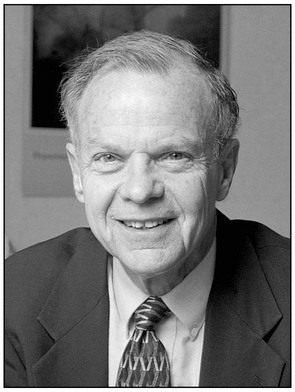

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