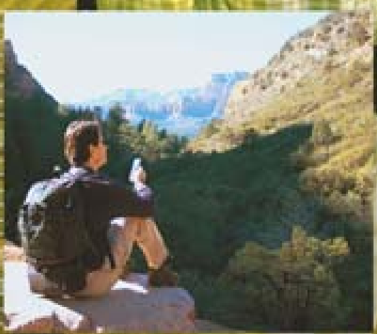
RETOOLING the Global Positioning System



From hikers navigating with handheld locators to pilots landing in zero-visibility conditions, the Global Positioning System now serves more than 30 million users. See what's coming next

By Per Enge

During the next decade, the capabilities of the Global Positioning System (GPS) will take off. Not only will advanced GPS technology ensure far greater reliability and safety than is possible today, it also will provide much more accurate geolocation services: to within a meter. Underlying the improved capabilities is a series of system upgrades that include additional satellite signals, increased broadcast power, performance monitoring, guaranteed error bounds, smart antennas that can selectively direct and receive signals, and integration with television and cellular-phone networks.

When next-generation GPS becomes available, it will enable a broad range of exciting new applications. Geolocation coverage will extend from hiking trails and sea-lanes all the way downtown, indoors and into areas that are currently plagued with weak reception, such as under tree limbs. Businesses operating in industries such as air, sea and land transport, electric power, telecommunications, construction, mining, mapping and farming are likely to profit from the augmented services. So will geographers and earth scientists. Military users should benefit the most, as was intended by the original builders. With its greater dependability, enhanced GPS could ensure that an airplane lands automatically in zero-visibility weather, for example, or that a U.S. naval aircraft lands safely on a pitching carrier deck in the dark. In years to come, it may even guarantee the security of passengers in cars and trucks riding down automated highways.

AS GPS GETS ever more pervasive, it will also become sufficiently dependable for safety-critical applications such as automated guidance for airplanes and cars.

Sky's the Limit

GPS GOT ITS START when the U.S. Department of Defense launched the first Navstar satellite in 1978. Although the designers expected that civil and commercial applications would develop, their prime goal at the time was to allow an estimated 40,000 military users to navigate the land, sea and sky with high precision. Civilians began taking advantage of the positioning system during the 1980s. As the orbital constellation of GPS satellites approached the minimum 24 needed for continuous service in the early 1990s, mass-market uses soon multiplied.

Today some 30 million people regularly track their whereabouts using GPS. The receiving units assist in guiding road vehicles, ships and boats, as well as in fleet management for rental cars and buses, and recreational uses [see "A Walk in the Woods," by Mark Clemens, Technicalities; SCIENTIFIC AMERICAN, February]. Every month vendors ship more than 200,000 civilian receivers. In 2003 GPS equipment sales reached nearly $3.5 billion worldwide, and that annual market could grow to $10 billion after 2010, according to a recent survey conducted by

Frost & Sullivan, a market research firm. Those figures do not count revenues from satellite construction, launch and control segments or from GPS-related enterprises such as delivery-truck fleet management. Consumers, the study says, now account for slightly more than half the equipment sales; commercial customers make up 40 percent, and the armed forces take up the remainder (8 percent).

The American GPS Navstar satellites are not alone in orbit, however. Russian GLONASS navigation satellites share that physical and functional space, and in a few years so will the European Galileo constellation. The Russians built GLONASS during the cold war to compete with the U.S. military. Of late, though, GLONASS has fallen into disuse because its operators cannot afford to replenish satellites. The European Community's system is expected to enter service later this decade. The attraction is an anticipated booming end-user market, which will only grow as GPS receivers are added to automobiles and cell phones. Both the Europeans and Russians believe that they need their own satellite navigation systems to participate. The GPS and the Galileo management teams have recently concluded agreements on how the systems will interact.

Each time a GPS receiver locates itself on the planet's surface, it trilaterates (a cousin of triangulation) its precise distance from at least four GPS satellites using ranging signals broadcast from overhead [*see illustration on opposite page*]. In essence, the specially coded radio signals serve as invisible rulers that measure the path from the satellites to the receiver.

The accuracy of a typical $100 handheld receiver places the user within about five to 10 meters of his or her actual location. A more costly military GPS unit can find itself within five meters. Tandem observations using a receiver that gets error adjustments from a nearby stationary receiving device at known coordinates can achieve accuracies of half a meter. These tandem operations are called differential GPS.

Geolocation coverage will extend all the way downtown, indoors and under tree limbs.

Data Stream from Space

TO APPRECIATE WHERE GPS is going, it helps to first review its current operations. The precipitation of transmitted data from GPS satellites is like a light sprinkle. One GPS satellite radiates signals at 500 watts, which is the power of five incandescent lightbulbs. After traveling the 20,000 kilometers from space, the radio-ranging signals arrive at the earth's surface with power densities of only 10^{-13} watt per meter squared. For comparison, the power of a television signal received by a home set is one billion times as strong.

GPS satellites shower down two varieties of information. One type, the navigation message, consists of data bits that identify the satellite's orbital location and the time the transmission was sent. These spatial and temporal coordinates are developed by GPS's ground-control segment, which employs a network of GPS receivers at known reference points to calculate them. These values are beamed up to the satellite and packed into the navigation message for subsequent transmission to all users.

The second type of information GPS satellites emit is a set of ranging codes, a unique patterned sequence of digital pulses. These transmissions do not carry data in the traditional sense. The codes are, in fact, designed to help the receiver measure the arrival time of the incoming signal, a key for precisely determining location. Engineers emphasize the distinct nature of these ranging signals by saying these so-called pseudo-random noise (PRN) codes are made up of a series of "chips" rather than bits.

Each PRN code sequence is like the musical notes in a song. Let's say a particular song was played by both the satellite and the receiver at exactly the same time. The user would hear both versions of the song (or PRN code), but the satellite's rendition would be delayed by the time it takes for sound to make its way from orbit to the earth's surface. If the user timed the delay between when each song version reached a specific note with a stopwatch, he or she could then tell how long it took for sound to traverse the distance from space. By multiplying the resulting number of seconds by the speed of sound, the user could calculate the range to the satellite.

GPS performs an analogous procedure when a receiver monitors a PRN code being broadcast from a satellite. By aligning the received ranging code sequence (the sequence of musical notes) with a replica of the unique PRN code sequence for that satellite stored in the receiver, the device can estimate the delay in the arrival time of that satellite's radio ranging signal. The receiver then multiplies the time delay by the speed of light and so can determine the distance to the satellite.

Overview/*Enhanced GPS*

- More than 30 million people rely on the Global Positioning System (GPS) regularly, and that number will soon multiply as receivers find their way into more cellular phones and automobiles.
- Enhanced geolocation accuracy will result when new signals become available for civilian and military uses. The first of these signals will appear when improved satellites are launched in 2005, and the second will come into operation a few years later.
- GPS integrity machines will guarantee GPS reliability by providing valid error bounds in real time. A range of institutional, operational and technical activities will harden GPS transmissions against radio-frequency interference.

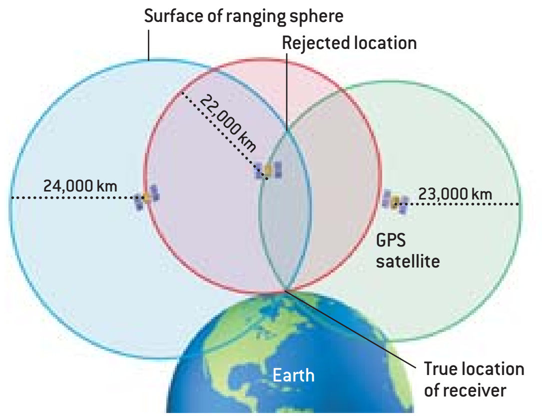
TOM DRAPER DESIGN (*preceding pages*); KEVIN MARTY *AP Photo/Imperial Valley Press* (*background*);
FROM LEFT TO RIGHT: CORBIS; LEIF SKOOGFORS *Corbis*; ALAN SCHEIN *Corbis*; CORBIS; RUSSELL MUNSON *Corbis*; PATRICK DURAND *Corbis Sygma*

HOW GPS WORKS

The Global Positioning System (GPS) is a radio-based worldwide navigation system comprising two dozen satellites and associated ground stations. Using a cousin of triangulation called trilateration, GPS calculates the coordinates of a terrestrial location by measuring the distance to at least four satellites. Several factors combine for accurate geolocation.

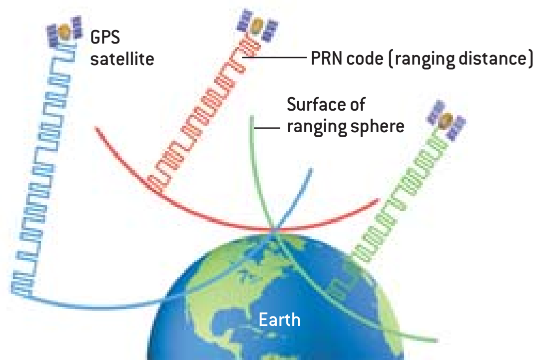
INTERSECTING SPHERES

Say that a GPS receiver measures the distance to one satellite as being 22,000 kilometers. The receiver must then sit on the surface of a ranging sphere centered on the satellite with a radius of 22,000 kilometers. Suppose the receiver also estimates the distance to two other satellites as being 23,000 and 24,000 kilometers, respectively. The receiver's location must therefore be at the intersection of those three ranging spheres. Geometry states that three spheres can mutually intersect at no more than two points. Only one of those positions will be close enough to the earth to be the receiver's position.



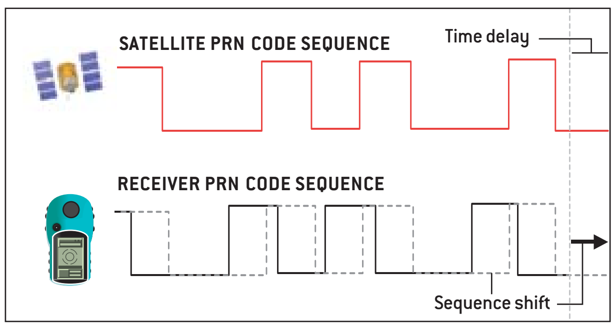
TIMING SIGNALS

Gauging the distance to a satellite requires timing how long it takes for a satellite signal to arrive at a receiver. Velocity multiplied by travel time equals the distance crossed. Radio signals move at the speed of light, or roughly 300,000 kilometers per second. The problem is measuring the travel time. The pseudo-random noise (PRN) code, a complicated sequence of digital data, helps to accomplish this task. Each code is unique to a satellite, which ensures that the receiver does not confuse the signals.



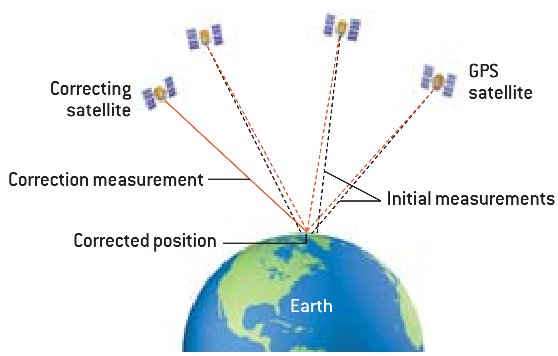
SHIFTING THE CODE

To understand how PRN codes aid in measuring distance, consider this analogy: suppose that both the satellite and the receiver started playing the same song—the PRN code—at the same time. The broadcast traveling from space would be slightly delayed compared with the receiver's reference song. By measuring how long it took for a given note in the song, or segment of the PRN code, from the satellite to arrive, the system could determine travel time. Multiply that time by the speed of light, and the result is the distance to the satellite.



SYNCHRONIZING CLOCKS

Time is kept almost perfectly onboard GPS satellites, each of which carries an atomic clock, but GPS receivers must make do with a cheap, much less accurate quartz clock. The resulting timing flaws mean that the initial three ranging measurements do not intersect exactly (*black dashed lines*). To synchronize the clocks in orbit with those on the earth and thus compensate for the timing error, GPS must make a fourth satellite measurement. This reading determines a single correction factor that will bring the endpoints of the first three ranging measurements into coincidence at the true location of the receiver (*marked in red*).



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Thus, receivers measure range using a virtual ruler that each satellite extends to the earth. The codes provide tick marks on the radio ruler, whereas the navigation message describes the satellite's location, which is analogous to the end point of the ruler. If the GPS unit could incorporate a perfect clock, then three range measurements would allow the receiver to solve for its three-dimensional position—latitude, longitude and altitude. With perfect clocks, a single measurement would place it on the surface of a sphere with the prescribed radius from the satellite. Two GPS readings would locate the user on the intersection of two similar spheres, and three measurements would place the user at a unique point defined by the three spheres. Hence, the receiver would solve three equations for three unknowns: longitude, latitude and altitude.

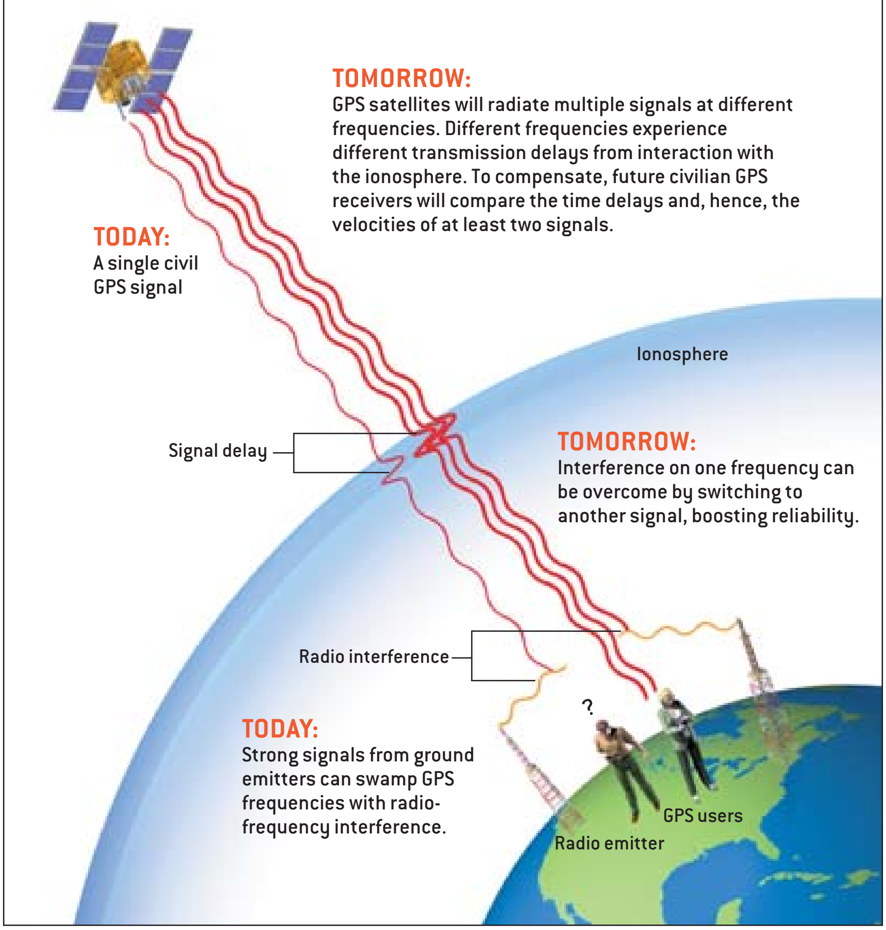
In fact, perfect clocks do not exist, so GPS receivers must also solve for a fourth unknown: the offset between the receiver's internal inexpensive clock and GPS network time. GPS time is controlled to within one billionth of a second by atomic clocks, but the receiver clock might be subject to an error of a second or more per day. One can convert time error to distance error by multiplying by the speed of light (300,000 kilometers per second). This offset adds an unknown number to the distance gauged to each satellite, explaining why the length measurements are called pseudo-range measurements. Fortunately, the time offset is the same for all satellites, so a fourth satellite reading allows the receiver to solve four equations for the four unknowns: longitude, latitude, altitude and time.

Because mobile users change position rapidly, current GPS receivers also monitor the Doppler shift of the incoming signals—that is, motion-caused shifts of the signal's wavelengths. If the user is traveling away from the satellite, the wavelength appears longer. If the user is moving toward the satellite, the arriving wave gets shorter. Each satellite is analogous to a train passing a person (the receiver). As the train approaches, its whistle rises in pitch, but as the train moves away, the pitch becomes lower. Monitoring these wave shifts allows these devices to estimate the user's velocity directly and more accurately.

It is notable that GPS receivers accomplish the complex geolocation task without transmitting any signals. Nevertheless, those receivers destined for installation in future cell phones will be quite cheap, costing less than $5 apiece.

MULTIPLE SIGNALS FOR BETTER RELIABILITY

Finding GPS coordinates requires precise estimation of the distances from geolocation satellites to a receiver—a calculation that depends on the time it takes the signal to travel from orbit [*see box on preceding page*]. Charged particles in the ever changing ionosphere, however, slow the signals, which creates a timing error. Advanced GPS will correct for ionospheric effects and signal disruption from competing broadcasts.



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To Pierce the Ionosphere

TRANSMITTERS ONBOARD GPS satellites broadcast their information through standard radio-frequency (RF) waves. The RF carrier is the classic sinusoid; its frequency counts the number of cycles (each peak and valley) per second. Current GPS technology employs two frequency bands—L1 and L2—that fall in the microwave portion of the radio spectrum. L1 is commonly referred to as the civil signal, even though the armed forces also share this resource. It is available to everyone and supports the vast majority of today's civilian applications. L2 serves the military primarily. The public is permitted to use the L2 signal, but without knowledge of the military PRN codes. This knowledge gap makes civilian application of L2 fragile. Civilian receivers, for example, have difficulty using the L2 signal from satellites that are sitting low in the sky or are obscured by even minor obstructions, such as trees. Moreover, L2 receivers are expensive because they require special signal-processing techniques to access the L2 signal when the PRN codes are not known.

For these reasons, the vast majority of civilian units use only the L1 signal. By so doing, they typically achieve an accuracy of five to 10 meters, an error range largely caused by charged particles in the earth's ionosphere, which extends from about 70 kilometers above the ground out to 1,300 kilometers or more. This conductive shell slows the transmission of radio waves from the GPS satellites much as water in a glass bends or diffracts the view of an immersed pencil. Depending on conditions, it can delay the arrival of transmission from one to 10 meters or more.

To compensate, some users employ differential GPS, or D-GPS. The technique involves two GPS receivers: a roving unit and a reference unit that is placed at a known location. The reference device transmits the differences between its measurements and the computed ranges to the roving receiver, which then uses the data to correct its reported location. D-GPS works best when the mobile receiver stays relatively close to the reference receiver. At ranges of less than 100 kilometers, the ionospheric errors cancel out almost completely because the radio beam from the satellite to the reference receiver passes through the same atmospheric obstacles that the signal from the satellite to the mobile receiver did.

Overcoming GPS Signal Interference

GPS radio emissions are very weak, so users depend on a quiet radio spectrum; even low-power radio-frequency sources can interfere with GPS operations. The U.S. Federal Communications Commission has mandated that the GPS bands must be kept quiet—only nature's radio noise is present.

Despite these efforts, safety-critical users, such as air traffic controllers, are still subject to signal loss from accidental interruption or malevolent jamming of GPS broadcasts. Thankfully, these users have access to a growing number of defenses against interference. Airborne users, for example, can rely on backup navigation systems based on inertial measurements, Loran-C, or distance-measuring equipment. Military GPS applications frequently make use of "smart," beam-steering antennas that selectively null out interfering signals (by suppressing reception from certain directions) without appreciably degrading GPS signal strength. In the not too distant future, consumer applications may well augment GPS reliability with range measurements to the antennas of nearby television stations or cellular-phone base stations. *—P.E.*

Sharper, Stronger Signals

STARTING IN 2005, GPS satellites will begin to broadcast new signals that will boost the robustness of services and help fine-tune their positioning accuracy by eliminating the ionospheric errors [*see illustration on opposite page*]. Two military signals will be added to the L1 and L2 bands, and another civilian signal will supplement the L2 band. The current signals will continue to operate to ensure that existing receivers will work well into the future. By around 2008, a further round of improved GPS satellites will begin to emit even more civil signals in a third frequency band called L5. (L3 and L4 carry nonnavigation information for the military.) The new L5 signals will be four times as powerful as today's.

The extra signals will enable a single receiver to calculate the transmission delay caused by the ionosphere, reducing errors. L1 signals traveling through the uneven ionospheric layer would show a delay different from that seen in signals sent through L5, for example. Future receivers could thus first compare the delay in the signals received from L1 and L5. They could then use this calculation to estimate the electron density of the ionosphere and compensate for its effects. This is the calculation that some costly civilian GPS receivers try to make using the current civil signal at L1 and the military signal at L2. Because the civil signals will employ publicly known codes, the operational frailties currently associated with dual-frequency signal processing will disappear. This means that dual- or even triple-frequency receivers will be the rule for consumer and commercial users.

Operators of D-GPS units will also benefit from the new signals. Remember that D-GPS accuracy degrades as the user moves away from the reference receiver, because the radio beam from the satellite to the user pierces the ionosphere at a point that is increasingly distant from where the reference beam traversed the plasma layer. With multiple frequencies, the roving receiver would be able to evaluate the ionosphere autonomously and the D-GPS corrections could be used to mitigate the other (smaller) errors. Future D-GPS users will be able to achieve accuracies of 30 to 50 centimeters.

The most demanding users of today's GPS, including surveyors, scientists and farmers, need centimeter- and even millimeter-level accuracy. Such accuracy requires an advanced form of D-GPS that goes beyond the application of PRN codes, a technique that digs under these codes and measures the arrival time of the carrier waves that transport GPS signals from orbit.

The radio-frequency waves that carry the GPS signals are sinusoidal microwaves. An individual cycle has a wavelength—the distance from one peak to the next—of 19 centimeters. A receiver can measure this arrival time with a precision of about 1 percent. This resolution corresponds to a travel distance of one or

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two millimeters. This is the level of accuracy high-end users need, yet the carrier-wave measurements are ambiguous—that is, the receiver cannot tell which cycle is which. Unless it can uniquely identify which individual cycle it is tracking, the measurement can contain an error equal to any number of whole wavelengths.

This difficulty resembles measuring distance using the fine tick marks on a ruler. Unlike the coarse tick marks, the fine marks are very close together and therefore precise, but because they are not individually marked, they are ambiguous. Fortunately, a special procedure unambiguously links the rough, 30-centimeter-scale resolution of standard D-GPS to the desired fine, two-millimeter-scale resolution of the carrier wavelengths. This process generates an intermediate-length measurement scale with the right-size resolution to connect them. The computational bridge that spans the measurements is built on this intermediate scale, as I will explain.

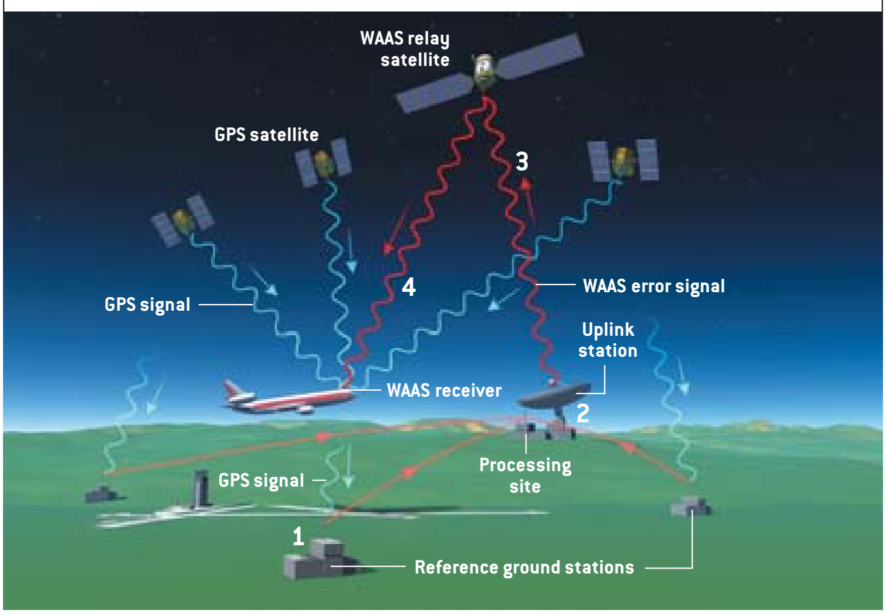
The challenge is best understood by analogy. As noted previously, PRN codes can be likened to a song's musical note sequence, where every note is distinct and identifiable. The carrier-wave measurements are akin to the song's drumbeat, which encompasses many beats per note. If one listens to the drumbeat alone, it is hard to say what part of the song one is hearing. The key is to use the song's notes to identify which drumbeat is which. For GPS, this is a tough task: the starting time of each note (or PRN code chip) can be determined with an accuracy of just 30 centimeters. Each drumbeat (the carrier wavelength) lasts for just 19 centimeters. Separated by only 19 centimeters, these beats are too close together to discern—one cannot tell them apart with the 30-centimeter accuracy of the PRN codes.

To identify an individual beat, one needs an additional drummer, one that beats at a slower rate. Advanced GPS receivers create this slower beat by multiplying the L1 carrier and the L2 carrier to produce what is known as a beat frequency. This operation also has a musical analogy. When two tones are played simultaneously on an instrument, the listener hears the original tones but also perceives a new tone corresponding to the difference in the two original frequencies—the beat frequency. Because the new frequency equals the difference frequency, it is necessarily lower in pitch than either of the two original tones. Lower frequencies mean longer wavelengths. In GPS the wavelength of the difference frequency is 85 centimeters, and the system can measure that with a resolution of about eight millimeters. This wavelength is sufficiently long to be resolved to the 30-centimeter acuracy of the receiver's code measurements. Thus, expensive receivers that employ this technique can meet the requirements of top-end users.

With the soon-to-be-added GPS signals, this computational bridge from the PRN code chips to the underlying carrier cycles will get even stronger: Civilian receivers will have access to public codes on the L2 signal as well as on the brand-new L5 signal. Receivers will be able to process a trio of beat notes (L1 minus L2, L1 minus L5, and L2 minus L5), which will provide several paths from the PRN code chips to the carrier cycles and, thus, ultrahigh geopositioning accuracies.

FLYING ON A WING AND A WAAS

Flying safety is greatly improved when pilots know their airplane's position precisely. The wide-area augmentation system (WAAS), designed by the U.S. Federal Aviation Administration, improves the accuracy and integrity of safety-critical GPS signals. WAAS offers accuracy of one to two meters in the horizontal axis and two to three meters in the vertical throughout most of the U.S. The system starts with a network of 25 reference ground stations that are placed at known locations (*1*). Each station compares its GPS satellite reading with its confirmed map coordinates and develops corrections for all the satellites in view, which are then transferred to one of two master processing sites (*2*). From there, correction data are uplinked to geostationary relay satellites (*3*), which in turn broadcast to WAAS receivers (*4*) that decode the geopositioning corrections in real time.



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Flight-Ready GPS

TO SEE SOME of the real-world implications of improved GPS, consider the Federal Aviation Administration's new flight guidance technology, a function in which reliability is clearly critical. The innovative systems, parts of which are already online, will allow pilots to employ GPS to guide aircraft right down to the runway even when severe weather creates conditions of zero visibility. Completing this task safely and surely entails more than mere navigation accuracy. It also requires two guarantees. First, pilots must know the maximum size of their possible positioning error (that is, an error bar) for all circumstances. When maneuvering for final approach, for example, a pilot can tolerate location errors that are no larger than 10 meters. Second, users need a guarantee that their navigation system will suffer no breaks in service.

The FAA has developed two D-GPS-based systems to provide these real-time error bounds for location data. These systems include networks of reference receivers that monitor GPS measurements continuously but operate independently from the ground-control segment.

The wide-area augmentation system (WAAS), which began operating in 2003, relies on a nationwide network of sensor stations to measure GPS performance [*see illustration on opposite page*]. These monitors resemble the reference stations for D-GPS, and indeed, WAAS does produce corrections to improve accuracy. In addition, however, it compares positioning corrections from multiple stations to generate the error bounds that are crucial for guiding aircraft. It then employs geostationary satellites to relay its performance guarantees to pilots. If needed, WAAS can adjust the transmitted error range within seven seconds. The system pinpoints the location of aircraft flying at altitude and helps to steer aircraft that are descending toward airports down to an altitude of 300 feet. Engineers in Europe, China, Japan, India, Australia and Brazil are working on similar systems.

Where WAAS leaves off, local systems take over to shepherd aircraft on the lower segments of their landing paths. In time, the local-area augmentation system (LAAS) will enable completely automatic landings in zero visibility. Because the system serves only aircraft near an airport, it uses a short-range radio system to send its corrections and error bounds. LAAS is closely related to the Joint Precision Approach and Landing System (JPALS), a developmental system that will guide aircraft onto the pitching and rolling decks of aircraft carriers. During final approach, naval aviators must control the altitude of their aircraft relative to a moving deck to within a single meter to make sure that the drag hook hanging off the rear fuselage catches the capture cable.

Navy engineers are attempting to make carrier landings easier and safer through JPALS, which places the D-GPS reference receiver on the aircraft carrier. It should enter trials later this year. Both LAAS and JPALS are dual-frequency systems—two GPS frequencies are required to ensure accuracy during these most demanding of aircraft operations. JPALS will be able to use the military signals that are available on L1 and L2 today.

Even though the aforementioned improvements will make GPS all but ubiquitous, the U.S. government has begun planning the next round of further improvements to satellite navigation technology, known as GPS III. The driving forces behind the upgrade are to gain even better reliability and accuracy, to ensure more resistance to interference and jamming, and to foster the adoption of alternative geolocation services as well as new, more sophisticated GPS-enabled applications such as intelligent highway and traffic safety systems. As a result, industrial competitors for the eventual multibillion-dollar program—Boeing and the partnership of Lockheed Martin and Spectrum Astro—have announced that they will vie for the contracts. Initial launch of a GPS III satellite may occur early next decade. SA

GPS during Wartime

In recent years, civilian GPS users have begun to vastly outnumber the military users for whom the system was originally developed. The civil signal is available free to anyone with a GPS receiver. But because the U.S. armed forces and its allies rely on GPS for navigation and weapons targeting, military use takes priority when martial conflict threatens. In regions of the world where warfare is occurring, the U.S. could jam local GPS operations by transmitting strong radio signals with frequencies that lie right in the center of the bands, swamping the weak GPS signals. Sanctioned military use, however, continues because the military signal broadcasts are far enough offset from the center of the civil bands to be unaffected. Under these circumstances, any adversary's utilization of the military signals is impossible, because the military codes are secret. Enemy jamming of the military GPS signals is likely to be short-lived, given that allied armed forces can rapidly detect and destroy such systems, as was demonstrated in the recent war in Iraq. Civilian GPS use would continue outside the conflict area because any jamming signal would lose power far away from the jamming emitter. *—P.E.*

GPS will guide aircraft right down to the runway, even in conditions of zero visibility.

MORE TO EXPLORE

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