Scanning the Issue/Technology

Special Issue on Global Positioning System

The Global Positioning System (GPS) is a great technological success story. It was developed by the Department of Defense (DoD) primarily for the U.S. military to provide precise estimates of position, velocity, and time. Civil use was a secondary objective. On the basis of national security considerations, the civil users of GPS have been limited to a purposefully degraded subset of the signals. Nevertheless, the civil applications of GPS have grown at an astonishing rate. Applications unforeseen by the designers of the system are thriving, and many more are on the way. GPS has found applications in land transportation, civil aviation, maritime commerce, surveying and mapping, construction, mining, agriculture, earth sciences, electric power systems, telecommunications, and outdoor recreational activities. The civil community has found ways to get around the purposeful degradation of the signal and to use the military signals, encryption notwithstanding. The system is being used to provide accuracy levels which would have been unthinkable 20 years ago. The commerce in GPS-related products and services has grown rapidly in the 1990's. The U.S. Department of Commerce estimates that the annual worldwide sales will reach $8 billion in the year 2000, and could exceed $16 billion by 2003. GPS is on its way to become a part of our daily lives as an essential element of the commercial and public infrastructure.

This Special Issue of this PROCEEDINGS offers a survey of the GPS technology and some of its civil applications. We begin this essay with a short introduction to GPS: the system, signals, and performance. The objective is to provide the necessary background and to introduce the basic concepts and vocabulary needed for the papers which follow.

GPS is not the first satellite navigation system. The first operational system was fielded by the U.S. Navy in 1964, and was named the Navy Navigation Satellite System [1]. This system, better known as Transit, was based on a novel concept discovered in the late 1950's following the launch of the Soviet Sputnik: measurements of Doppler shift in the signals broadcast by a satellite in a known, well-defined orbit could be used to estimate one's position. The system was realized with five satellites in low-altitude (1100-km), nearly circular, polar orbits. Each satellite broadcast narrowband signals at 150 MHz and 400 MHz. Only one satellite was in view at a time, and a user waited up to 100 min between successive satellite passes to determine position. After a satellite came in view, it took 10–15 min to compute two-dimensional position of a stationary or slow-moving user. The system was used by the U.S. submarine fleet to update a ship's position and reset the inertial navigation system. Transit saw a limited civil use in the maritime industry and geodesy starting in 1967, and it was decommissioned in 1996.

Unlike Transit, GPS is based on an idea that is both very simple and quite ancient: one's position, e.g., coordinates (x, y, z), can be determined given distances to objects whose positions are known. The situation can be modeled using high-school-level analytic geometry. Each measured distance can be related to the three unknown position coordinates by an equation. Given the distance measurements to three objects, there are three such equations which can usually be solved for the three unknowns. What is novel in GPS is the realization of this idea with the technology of the late twentieth century in a global navigation system with capability to provide estimates of position, velocity, and time to an unlimited number of concurrent users instantaneously, continuously, and inexpensively. The DoD approved the basic architecture of the system in 1973, and the first satellite was launched in 1978. The system was declared operational in 1995. The cost of development of GPS has been reported to be about $10 billion; the annual operation and maintenance cost is estimated to be between $250 million and $500 million. The history of development of GPS is recounted in [1] and [2]. A comprehensive treatment of the system, signals, performance, and applications can be found in [3].

In the realization of GPS based on the idea described above, the satellites, which broadcast their positions, are the objects at known locations. The distance between the user and a satellite is measured in terms of transit time of the signal from the satellite to the user. Indeed, the development of precise, ultrastable clocks and stable space platforms in predictable orbits are the two key technologies which have made GPS possible. The GPS satellites are moving in space at a speed of about 4 km/s, but the position of each at any instant can be estimated with an error no worse than a few meters based on predictions

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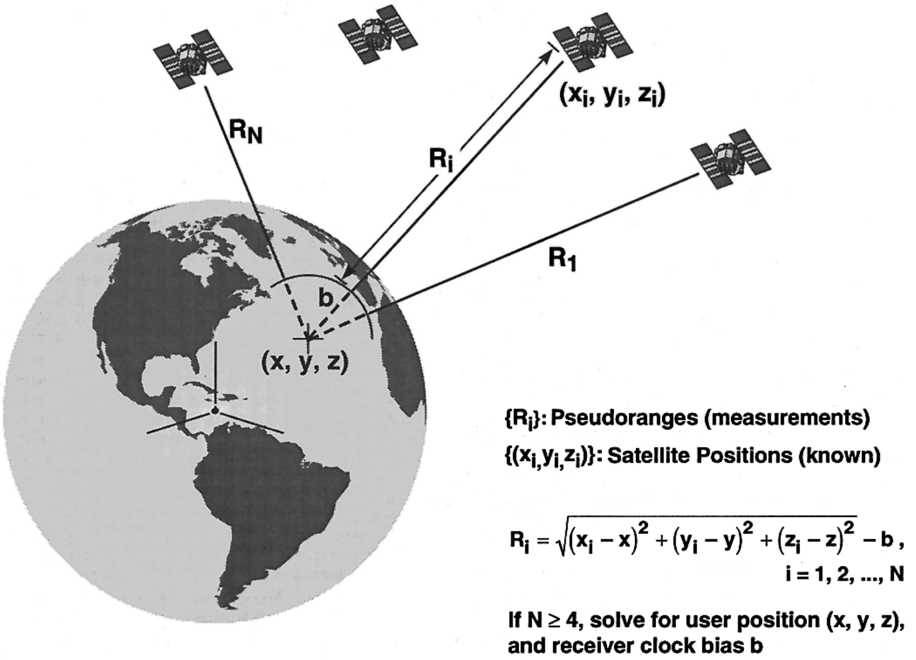


Fig. 1. The principle of satellite navigation. The user-satellite range measurements based on the times of transmission and receipt of the signals are biased by a common amount due to offset between the satellite and receiver clocks; they are called pseudoranges. Pseudorange measurements from four satellites are needed to estimate the user position and the corresponding receiver clock bias.

made 24–48 h earlier. The clocks, or more appropriately, frequency references, are carried aboard the satellites and used to generate signals with precise and synchronized timing marks. Each satellite typically carries a pair each of cesium and rubidium atomic standards. The frequency stability of these clocks over a day is about one part in 10^{14} and one part in 10^{13}, respectively. There are about 10^5 s in a day, and an error of 1–10 ns can accumulate over a day, if left uncorrected. Actually, the satellite clocks are maintained in synchronism by monitoring the signals from a network of tracking stations, estimating the correction parameters for each clock, and uploading new parameter values to update the navigation message broadcast by each satellite.

In order to measure the true transit time of a signal from a satellite to a receiver, clearly, the clocks in the satellite and the receiver must be maintained in synchronism. Fortunately, this onerous requirement is easily sidestepped, allowing use of inexpensive quartz oscillators in the receivers. The bias in the receiver clock at the instant of the measurements affects the observed transit times for all satellites equally. The corresponding measured ranges are thus all too short, or too long, by a common amount, and they are called pseudoranges. The receiver clock bias thus becomes the fourth unknown to be estimated, in addition to the three coordinates of position. A user, therefore, needs a minimum of four satellites in view to estimate his four-dimensional position: three coordinates of spatial position plus time. An idealized geometrical view of the pseudorange measurements and the resulting equations to be solved for the user position and receiver clock bias are given in Fig. 1.

We should note that GPS is not the only system of its kind. A similar system, called GLONASS, was developed by the Soviet Union. GLONASS, like GPS, was designed primarily for the military, and a subset of its signals was offered for civil use apparently as an afterthought in the era of *perestroika*. Since the dissolution of the Soviet Union, the responsibility for GLONASS has been assumed by the Russian Federation. The system had a full constellation of 24 prototype satellites broadcasting briefly in early 1996, but it has since declined [4]. No satellites were launched between January 1996 and October 1998, and the constellation has been down to 14 working satellites since August 1997. The civil user community sees great benefits in having access to signals from two autonomous systems, and the absence of purposeful signal degradation in GLONASS is particularly appealing. However, general uncertainty about the future of the system appears to have limited the demand and discouraged the receiver manufacturers from producing GLONASS receivers. There is no basic challenge in design and manufacture of combined GPS–GLONASS receivers, and some models are now available.

GPS is the first passive, one-way ranging satellite system to become operational. GLONASS may follow in a few years. Other systems and satellite-based augmentations to be fielded by governments, international consortia, and commercial interests are expected to follow. The generic name given to these systems is Global Navigation Satellite System (GNSS). The European Commission, European Space Agency, and Eurocontrol are collaborating on studies to develop a system, named GNSS-2, which would be entirely under civil control. Commercial ventures would choose to exploit the full potential of a satellite system to provide communication, navigation, and surveillance services. Indeed, Boeing recently proposed a system of 16 satellites in medium-Earth-orbit to provide such service. There are other proposals for systems with low-Earth orbit (LEO) and geosynchronous satellites. For the next five years, however, GPS is expected to remain the only operational system of its kind. Changes, however, are coming to GPS. In about ten years, GPS is expected to have expanded considerably capabilities for both military and civil users, as discussed in Section VI.

I. GPS OBJECTIVES AND POLICIES

The principal objective of the DoD in developing GPS was to offer the U.S. military accurate estimates of position, velocity, and time (PVT). In quantitative terms, this statement was interpreted broadly as providing estimates with position error of 10 m, velocity error of 0.1 m/s, and time error of 100 ns, all in the root-mean-square (rms) sense. These estimates were to be available to an unlimited number of users all over the globe continuously and nearly instantaneously. The planned military use also required the system to be usable on high-dynamics platforms, and the signals to have a measure of resistance to jamming and interference. Finally, the adversaries of the United States were to be denied the full benefits of the system.

The civil users of GPS were to be provided with a "reasonable" accuracy consistent with the national security considerations. The initial view in the 1970's was to limit the accuracy of the position estimates to 500 m. Subsequent considerations allowed greater accuracy, with horizontal position error generally below 100 m. These considerations were formalized in a policy to offer two kinds of services: Standard Positioning Service (SPS) for open, unrestricted civil use, and Precision Positioning Service (PPS) for the DoD-authorized users.

Access to the full capability of the system (i.e., PPS) is restricted by encryption in two ways. First, the signals available for unrestricted use are purposefully degraded under a policy called Selective Availability (SA). The signals are generally degraded by "dithering" the satellite clock and, therefore, the timing marks on the ranging signals. Another mechanism to degrade the performance, though apparently it is not used often, is to broadcast erroneous or imprecise values of the satellite ephemeris parameters in the navigation message. Such degradation can be undone by the DoD-authorized users. Actually, SA can be undone by the civil users, too, but it requires additional expense, as discussed below. As might have been expected, SA made few friends among the civil users, and its scheduled departure in the next few years would be welcome. The second feature to limit access to signals is via encryption of the ranging code, referred to as anti-spoofing (A-S). The aim of A-S is to deny an adversary opportunity to generate and broadcast a GPS signal with the aim of spoofing the receiver. SA has been active nearly continuously since 1990, and A-S since 1994.

The policy for civil use of GPS was first announced by the DoD in the late 1970's with an assurance that the SPS signals will remain freely available. In 1983, Korean Airline Flight 007 went off course into the Soviet airspace, apparently due to navigation problems, and was shot down. This disaster drew attention to the potential benefits of GPS to civil aviation, and the U.S. policy on civil use of GPS was reaffirmed by President Reagan. At the time, the system was ten years away from being declared operational. Subsequently, the U.S. made a formal commitment in 1991 to the International Civil Aviation Organization (ICAO), a specialized agency of the United Nations, to make "GPS-SPS available for the foreseeable future on a continuous, worldwide basis, and free of direct user fees." While free signals and growing markets for GPS products and services created general enthusiasm in the civil sector worldwide, the governments, particularly in Europe, remained less sanguine about becoming dependent upon a system controlled by the military of a foreign government. There has been general reluctance to dismantle the existing terrestrial navaids and invest in the GPS-based infrastructure. There is a widely held view that technology as basic and vital as GPS requires an international institutional framework for development of policies, regulations, and standards.

The U.S. policy on GPS is based on balancing the basic requirement of retaining the military advantage of this technology with considerations of commercial and international policy. An interesting account of the issues and considerations is found in the report of a study conducted in 1994–1995 at the direction of the U.S. Congress by the National Academy of Public Administration (NAPA) and the National Research Council (NRC) of the National Academy of Sciences and Engineering [5]. This report has been influential in shaping the evolution of both GPS and the U.S. policy on its use. The report concluded that SA was not serving its intended purpose and recommended that it be discontinued immediately. The report also recommended several measures on governance of GPS to achieve the national goals and to promote its international acceptance. The Presidential Decision Directive (PDD) of 1996 on GPS appears to have adopted most of the recommendations of the NAPA–NRC report. According to the PDD, one of the U.S. policy objectives is to promote integration of GPS into peaceful civil, commercial, and scientific applications worldwide, and to advocate acceptance of GPS as an international standard. Accordingly, the Directive assigned to the DoD a softer role as "stewards" of the system, and included civil agencies in policy-making and management roles. The evolution of the U.S. policy on GPS is discussed by Shaw *et al.* in "The DoD: Stewards of a Global Information Resource, the Navstar Global Positioning System."

II. SYSTEM ARCHITECTURE

GPS consists of three segments: the space segment; the control segment; and the user segment. The space segment comprises the satellites and the control segment deals with

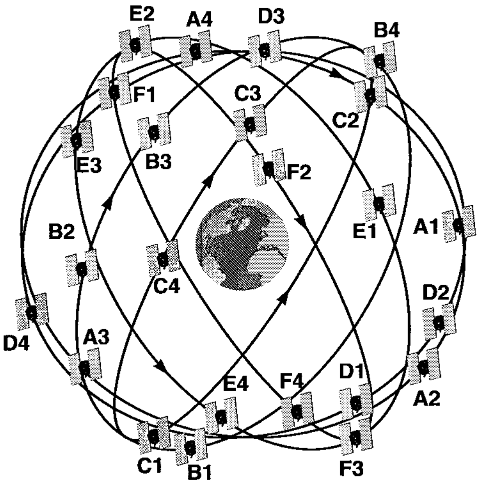


Fig. 2. The GPS constellation consists of six orbital planes with four satellites in each plane. Each satellite is identified with a two-character code: a letter identifies the orbital plane (A through F) and a number identifies the satellite number in the plane (1 through 4).

the management of their operations. The DoD is responsible for both the space and control segments. The user segment covers activities related to the development of GPS user equipment and services. The development of the receivers and services in the civil sector is essentially left to the market forces. The civil sector, however, clearly benefited from the investments by the DoD in the 1970's and 1980's in development of military receivers. This favor is now being returned as the design of a new generation of GPS military user equipment benefits from the extraordinary developments over the last ten years in civil receiver design and manufacturing.

The GPS baseline satellite constellation comprises 24 satellites fielded in nearly circular orbits with a radius of 26 560 km, period of nearly 12 h, and stationary ground tracks. The constellation is shown in Fig. 2. The satellites are arranged in six orbital planes inclined at 55° relative to the equatorial plane, with four satellites distributed somewhat unevenly in each orbit. With this constellation, almost all users with a clear view of the sky have a minimum of four satellites in view. It is more likely that a user would see six to eight satellites. The satellites broadcast ranging signals and a navigation message allowing the users to measure their pseudoranges and to estimate their positions in passive, listen-only mode.

An initial batch of ten prototype or developmental satellites, called Block I satellites, was launched between 1978 and 1985 and used to demonstrate the feasibility of GPS. The prototypes were followed by production models named Block II, Block IIA, and Block IIR, each successive batch designed with higher capabilities, longer service lives, and, it is worth noting, lower price tags. Fisher and Ghassemi survey the capabilities of these satellites and discuss Block IIF satellites, now being designed for launch starting in 2002, in their paper "GPS IIF—The Next Generation."

The U.S. Air Force (USAF) Space Command is responsible for planning, acquisition, and launch of the satellites, as well as general maintenance of the system. The USAF also manages the tracking of the satellites from five monitoring sites spread around the globe in longitude (Ascension Island, Diego Garcia, Kwajalein, Hawaii, and Colorado Springs) for orbital prediction and health indicators. Three of these monitoring stations, Ascension Island, Diego Garcia, and Kwajalein, also have the communication capability to upload (via S-band radio links) data to be broadcast by the satellites. The operations are managed by the Master Control Station located at the Schriever (formerly named Falcon) Air Force Base near Colorado Springs, CO.

GPS requires a precisely defined global terrestrial reference frame in which to express the positions. Clearly, this reference frame would have to be fixed to Earth so that coordinates of a stationary point would remain fixed. GPS uses an Earth-centered, Earth-fixed Cartesian coordinate frame defined as a part of the DoD's World Geodetic System 1984 (WGS 84), developed by the former Defense Mapping Agency (now a part of the National Imagery and Mapping Agency). The satellite positions and, therefore, the user positions are expressed in this coordinate frame. The Cartesian coordinates, though convenient for calculations, are not practical for representations on maps, which historically have used curvilinear coordinates: latitude; longitude; and height above a reference surface. Such coordinates are defined in WGS 84 relative to a reference ellipsoid. Before the advent of satellite navigation, many national and regional coordinate frames, called geodetic datums, had been defined using terrestrial surveying techniques. Maps based on these datums and various map projections remain in use worldwide, occasionally creating problems for an unsuspecting GPS user—the coordinates of a point in WGS 84 and a local datum can differ by hundreds of meters. Positions obtained from GPS can be converted into a local datum with an appropriate transformation, and the military receivers provide for over 100 such transformations. In time, these diverse national and regional datums would be abandoned in favor of WGS 84 and its refinements, and that in itself would be a great service of GPS.

Precise measurement of time and time interval is at the heart of GPS. GPS time is an atomic time, uniform and continuous, defined on the basis of a set of cesium atomic clocks included in the control segment. GPS time is similar to Coordinated Universal Time (UTC), but the discontinuities in the UTC time scale introduced by leap seconds are sidestepped for simplicity of operation. Between 1980 and 1998, 12 such leap seconds were introduced in UTC. The GPS time is specified to be maintained within 1 μs of UTC(USNO), the UTC as maintained by the U.S. Naval Observatory, not counting the leap seconds. In 1998, the GPS time differed from the UTC(USNO) by less than 10 ns. The clocks aboard the satellites are kept synchronized to GPS time. The synchronization is accomplished by estimating the time offset, drift, and drift rate of each satellite clock relative to GPS time, and transmitting the parameters of a model of this bias as a part of the satellite's navigation message.

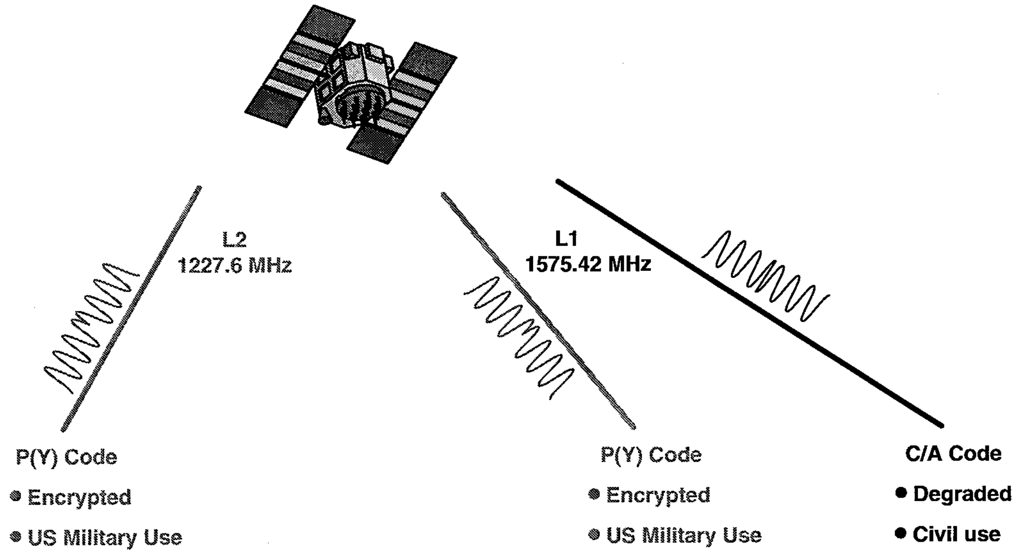


Fig. 3. Each GPS satellite transmits at two frequencies in the L band. The signal carrying C/A-code at L1 has been available for civil use in a degraded mode. Access to the P(Y)-code is limited to the DoD-authorized users via encryption. Civil users may use the P(Y)-code signals, but without the benefit of knowing these secure codes.

It is to the credit of the DoD that GPS has performed extremely well since it was declared operational, and glitches due to equipment malfunction or operational lapses have been rare.

III. SIGNALS AND MEASUREMENTS

Each GPS satellite transmits continuously at two frequencies in the L band: 1575.42 MHz (L1) and 1227.6 MHz (L2). The signal intended for unrestricted use is broadcast by each satellite at L1, and it is modulated by a pseudorandom noise (PRN) code called coarse/acquisition (C/A) code. Each C/A-code is a length-1.023 Gold code with a chipping rate of 1023 Mchips/s (Mcps), and null-to-null bandwidth of 2.046 MHz. Each satellite also broadcasts a pair of signals for the DoD-authorized users, one at L1 in phase quadrature with the civil signal, and the other at L2, as shown schematically in Fig. 3. Access to these signals is controlled by encrypting the PRN codes. When not encrypted (now rare), these signals are referred to as P codes; the encrypted codes are called Y-codes. In either case, the chipping rate is 10.23 Mcps, ten times that of the C/A-codes, and a period of one week. The null-to-null bandwidth of this signal is 20.46 MHz, ten times that for a C/A code. Altogether there are three signals: C/A code at L1 intended for the SPS users, and P(Y) codes at both L1 and L2 primarily for the PPS users.

Each signal is made up of three elements: a carrier; a unique PRN spread spectrum code; and a binary data message. Each element of the signal is derived coherently from a single clock aboard the satellite. The structure of the signal available for civil use is shown in Fig. 4. It consists of the L1 carrier; a unique 1023-bit-long C/A code, which repeats each millisecond; and a 50 bits/s navigation message organized in frames and subframes and containing data on the satellite orbit, clock, health, and other parameters. The carrier is modulated by the code and the navigation message using binary phase shift keying (BPSK).

The codes (C/A and P) transmitted by the GPS satellites were chosen for their auto- and cross-correlation properties. The autocorrelation function in each case has a sharp peak for zero shift. For a C/A code, for example, the autocorrelation function is more than 24-dB lower for all shifts greater than one chip width. A GPS receiver can measure the code phase with submeter precision by tracking the peak of the autocorrelation function. The various codes used are also nearly uncorrelated: cross correlation between two C/A-codes for any time shift is at least 24 dB lower than the peak of the autocorrelation function of each. This near-orthogonality of the codes allows all satellites to broadcast at the same two frequencies via code division multiple access (CDMA) without interfering with each other. This signal design also offers a measure of protection against multipath for the reflected signals which are delayed by more than 1.5 chip width. Finally, the spread-spectrum nature of the signals provides a processing gain against interference of about 43 dB for a C/A code and 53 dB for a P/Y-code.

The GPS signals received on Earth are extremely weak. The RF power at the antenna input port of a satellite is about 50 W, of which about half is allocated to the civil signal. The satellite antenna is designed to spread the RF signal roughly evenly over the surface of Earth below. The specifications on the minimum received power level for the users on Earth are −160 dBW for the C/A-code, −163 dBW for P(Y)-code at L1, and −166 dBW for P(Y)-code at L2. These signal powers are well below the receiver noise level. The low signal power is widely seen as the Achilles' heel of GPS, especially in military use. Even in civil use, there is concern about the vulnerability of the signals as the national commercial and public infrastruc-

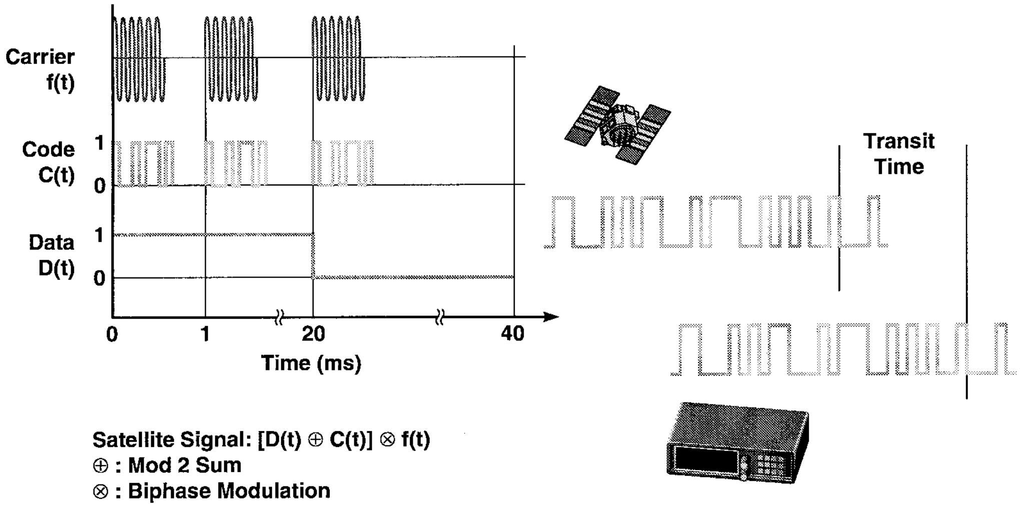


Fig. 4. The structure of the signal available for civil use and estimation of its transit time from the satellite to a user via correlation with a receiver-generated signal. Each GPS signal comprises three components: an RF carrier; a unique binary PRN; and a binary navigation message.

ture comes to rely more and more on GPS. Frequency diversity and increased signal power are being considered under modernization plans to make the GPS service more robust.

The signal acquisition process essentially consists of “tuning” to each satellite in view. The receiver attempts to acquire the known C/A-code with an initial time uncertainty of 1023 code chips and frequency uncertainty of up to 5 KHz due to Doppler shift. Acquisition of P(Y)-code, if the user is authorized, is based on the coherence of the C/A- and P(Y)-codes at the satellite in two steps: the receiver first acquires the C/A-code and then acquires the P(Y)-code with the aid of the timing information in the data message. Direct acquisition of a P(Y)-code is difficult by design due to the length of the code and would require an ultra-precise clock and/or thousands of parallel correlators in a receiver. A receiver makes the following measurements: pseudorange based on code phase measurements; Doppler shift in carrier frequency characterizing the rate of change in pseudorange; and carrier phase measured relative to the phase of the signal generated by the receiver clock, also used to measure change in pseudorange.

The measurement of a pseudorange is conceptually quite simple, as shown in Fig. 4, and it is based on tracking the sharp peak of the autocorrelation function. The PRN code transmitted by each satellite is known to the receiver, which generates a replica of it. The delay between this code replica and the signal received from the satellite is the apparent transit time of the signal. Basically, the receiver slides the code replica in time until it matches the code received from the satellite. This process of correlating the received signal with the receiver-generated replica gives the apparent transit time of the signal modulo 1 ms. Multiplying the apparent transit time by the speed of light gives pseudorange. Pseudoranges measured from four (or preferably more) satellites are used to compute position. A GPS receiver does this automatically, continuously, and virtually instantaneously.

Doppler shift and carrier phase measurements are formed in the carrier tracking loop. The Doppler shift, caused by the relative motion of a satellite and the user, is the projection of the relative velocity on the line of sight and can be converted into pseudorange rate. Given the pseudorange rates corresponding to four satellites and the satellite velocity vectors (transmitted in the navigation message), a user can compute his velocity. Braasch and Van Dierendonck discuss the formation of these measurements in their paper “GPS Receiver Architectures and Measurements.” How these measurements are used in estimation of position and velocity is discussed by Misra *et al.* in “GPS Performance in Navigation.”

IV. ESTIMATES OF PVT

The quality of PVT estimates obtained by a user from GPS depends basically upon two factors. The first is the number of satellites in view and their spatial distribution relative to the user, referred to as satellite geometry. The satellite geometry changes with time as the satellites rise, move across the sky, and set. Roughly speaking, the geometry is good if the satellites are on all sides of the user and offer good coverage in azimuth and elevation. If a significant part of the sky is somehow blocked, the user may still be able to compute PVT estimates if four or more satellites are in view, but there would be an accuracy penalty for the poor geometry.

The second factor determining the quality of the PVT estimates is the quality of the measurements obtained from GPS. There are several sources of random and systematic errors which affect the measurements from GPS: uncompensated error in the clocks in the satellites; accuracy of the predicted satellite positions; unmodeled propagation delays in the ionosphere and the troposphere; multipath; and receiver noise. For the SPS users, currently the largest source of measurement error is due to the purposeful degradation of the signal in accordance with SA. The

Table 1
GPS Performance Specifications for Global Positioning and Time Dissemination Expressed as Ninety-Fifth Percentiles of the Error Distributions

Error	PPS	SPS
Horizontal position	21 m	100 m
Vertical position	28 m	156 m
Time	200 ns	340 ns

rms error in the pseudorange measurements due to SA is estimated to be about 25 m. Ionospheric propagation delay can be large too, ranging from several meters to several tens of meters, depending upon the state of the ionosphere and the elevation of the satellite. This error, however, can be removed substantially by a user equipped with a dual-frequency receiver.

The performance achievable from GPS is dynamic, changing both with time and place as the satellite geometry and measurement errors change. A global characterization of the performance is given in statistical terms, e.g., as rms error or various percentiles of the error distribution. The GPS performance specifications for positioning and time are given in Table 1 as ninety-fifth percentiles of errors for users worldwide [5], [6]. There are no specifications for velocity estimates. The PPS performance specifications essentially show the limits of the current system due to the size of the GPS satellite constellation and its deployment, and the error sources inherent to the measurements. The difference between the PPS and SPS specifications is mostly due to SA. The actual SPS performance in recent years has consistently exceeded these specifications.

Accuracy is the simplest and most commonly used performance measure of a navigation system, but not the only one. In safety-critical applications, it is essential that a user be assured that the system is operating within design tolerances and that the position estimates derived from it can be trusted to be within specifications. This is the so-called integrity requirement. Civil aviation, for example, requires that a pilot be warned in a timely manner of a navigation system anomaly which may create a hazard. Such "time to alarm" varies with the phase of flight, and ranges from 30 s for an aircraft in en route phase to 2 s for precision landing. At present GPS does not have the capability to detect a system anomaly and reset the appropriate parameters in the navigation message of a satellite quickly enough to meet such requirements, and the responsibility for integrity monitoring is left to the user. Such integrity monitoring is usually based on redundant measurements, or system augmentations, which are discussed later.

Availability and continuity of service are also important performance measures of a GPS-based service. Consider, for example, a hypothetical application with accuracy and integrity requirements which are met only when eight or more satellites are in view. Such service would be available from GPS less than one-third of the time. The continuity of service is vital in civil aviation which requires that once an airplane embarks upon a precision approach, the service must remain available for the duration of the approach, typically about 1-min long.

V. GPS AUGMENTATIONS AND DIFFERENTIAL GPS

As noted previously, the quality of the position estimates from GPS depends upon the geometry of the satellite constellation and the error sources inherent to the measurements. It turns out that the errors can be mitigated simply. It was recognized early that the errors associated with the GPS measurements are similar for users located "not far" from each other, and they change "slowly" in time. In other words, the errors are correlated both spatially and temporally. The errors in the measurements of two users separated by tens of kilometers are generally similar. The errors also change slowly over time: the error due to SA, the largest source of error in SPS, is highly correlated over 5–10 s; the error due to atmospheric propagation delays changes more slowly over minutes and tens of minutes. Clearly, error in a measurement can be estimated if the receiver location is known. These error estimates computed at a reference receiver, if made available to other GPS users in the area, would allow them to mitigate errors in their measurements. Of course, to be usable for navigation, such "differential corrections" have to be transmitted in real time over a radio link. That is differential GPS, generally abbreviated as dGPS or DGPS.

DGPS can provide meter-level and even submeter-level position estimates depending upon the closeness of the user to a reference station and the latency of the corrections transmitted over the radio link. Such performance can meet the requirements of much of land transportation and maritime traffic; dGPS services, both commercial and federally provided, are now widely available. The commercial services provide differential corrections via communication satellites and FM subcarrier, and use of such services is now common for offshore oil exploration and fleet management. The U.S. Coast Guard (USCG) provides the differential corrections for free on marine radiobeacon frequencies (285–325 KHz) from about 50 broadcast sites in the coastal areas and around Great Lakes and inland waterways in the conterminous United States (CONUS), and in parts of Hawaii, Alaska, and Puerto Rico. This service, called Maritime dGPS, provides accuracy of several meters at a distance of 100 km or more from a reference station. Several countries are now implementing similar systems to enhance maritime safety in their waterways. The success of Maritime dGPS service has led to a plan in the United States for Nationwide dGPS to be completed in the next few years. This service would essentially extend the network of maritime radiobeacons nationwide, benefiting operations of railroads, agriculture, environment, forestry, and emergency response.

The Federal Aviation Administration (FAA) is developing GPS augmentations to meet the needs of civil aviation. The first such initiative, the Wide Area Augmentation System (WAAS), currently is being implemented and would be used operationally starting in 1999. WAAS would augment

GPS with GPS-like signals transmitted from geostationary satellites. These signals would be modulated with data messages so that a user in the U.S. airspace would have additional ranging signals and would also receive satellite integrity data and differential corrections to the measurements. WAAS is planned to meet the accuracy, integrity, and continuity requirements of en route and terminal phases of flight and nonprecision and Category I precision approaches. Europe and Japan are developing similar geostationary augmentations of GPS signals. Another FAA initiative called the Local Area Augmentation System (LAAS) would soon offer capability for Category I precision approaches at airports not served by WAAS. LAAS is being designed to support Category III precision approaches, including autolandings.

DGPS compensates for errors that are common to the measurements at the reference and user stations. One source of error that is unique to each antenna/receiver and its environment is multipath: interference due to reception at the antenna of a direct signal from the satellite, and one or more reflections from the ground or structures in the area. Multipath cannot be mitigated in differential mode and can be a significant source of error in applications requiring precise positioning. An approach being examined is to use antennas that exhibit a measure of immunity against multipath. Counselman discusses the design of such an antenna in his paper "Multipath-Rejecting GPS Antennas."

VI. CIVIL APPLICATIONS

The success of GPS in large-scale civil use is attributable almost entirely to the revolution in integrated circuits, which has made the receivers compact, light, and an order of magnitude less expensive than thought possible 20 years ago. The first geodetic-quality receivers, introduced in the mid-1980's, provided code and carrier phase measurements from four to six satellites and were priced at over \$100 000. Receivers with much higher capabilities are now available for less than \$10 000. As late as 1980, it had only been hoped that the receiver manufacturers would be able to produce a basic GPS receiver for the mass market for about \$2000. Price barriers, however, fell quickly. An important industry milestone was reached in 1992 with the introduction of the first hand-held receiver priced below \$1000. In 1997, the industry breached the \$100 barrier with a pocket-size receiver running on two AA batteries. There are now hundreds of GPS receiver models on the market.

Knowledge of one's precise three-dimensional position by itself is only of academic interest for most users. But the position information can be invaluable if given in relation to the intended path, showing points of interest and potential hazards: a hiker's position in relation to a trail; a car on a moving street map; or a boat in relation to islands and obstacles. Combined with communication technology, say, a cellular phone, the knowledge of position can be life saving, reducing search and rescue to simply rescue. The full power of GPS would be realized in civil applications in combination with other technologies, especially communication systems and geographic data bases.

The civil applications of GPS may be divided roughly into: 1) high-precision (millimeter-to-centimeter level) positioning; 2) specialized applications such as aviation and space; 3) land transportation and maritime uses; and 4) consumer products. While the positioning capability of GPS receives most attention among the civil users, GPS is also a global source of precise time. The use of GPS as a timing service is growing rapidly in the electric power and telecommunication industries. We review these applications briefly below and introduce the remaining papers in this issue, which offer detailed treatments of five application areas.

The community of geodesists and geophysicists appears to have been the most surprising and unintended beneficiary of GPS. The geodesists have adopted techniques developed previously for radio astronomy to achieve millimeter-level accuracy in relative positioning with GPS carrier phase measurements. These techniques are now being used widely to study tectonic plate motion and crustal deformation, earthquakes, volcanic processes, ice sheet processes and postglacial rebound, and variations in Earth's rotation. In these studies, the answers generally are not needed in real time, and data collected over hours and days at different locations are postprocessed to obtain estimates of relative position vectors good to millimeters. The value of GPS in studies of the dynamics of Earth has been enhanced greatly by the establishment of the International GPS Service for Geodynamics (IGS), which coordinates collection and analysis of GPS measurements recorded continuously at sites around the world. Herring surveys the role of GPS high-precision positioning in "Geodetic Applications of GPS."

The high-precision positioning capability of GPS is also being used to monitor deformations of large engineering structures in real time under actual loads, e.g., bridges and towers under actual traffic and wind-loading conditions. Such real-time estimates typically are good to centimeter level. GPS-based precise estimates of position and attitude of an aircraft are proving invaluable in airborne surveys and photogrammetry. Atmospheric scientists are using GPS measurements for precise, real-time characterization of electron densities in the ionosphere and water vapor content of the troposphere.

Actually, the market for high-precision GPS receivers for scientific studies is rather small. The techniques developed in these studies, however, have become indispensable tools of the surveyors and mapmakers, creating a large market for high-end GPS receivers and services. Indeed, the field of surveying has been revolutionized by GPS with vast improvements in accuracy, speed, and economy. The convergence of GPS and personal computer technologies has made it possible to collect vast amounts of positional data and to organize them into geographic databases. A number of positioning and attribute collection systems are on the market. At its simplest, such a system typically consists of a backpack containing a battery-powered personal computer with a GPS card (and perhaps radio modem to receive differential corrections for real-time dGPS) and a handheld keyboard and display unit. A user thus equipped can walk around gathering information and entering it through the keyboard to create or update a spatial database showing, e.g., the location and status of every utility pole or manhole in a town, or a map showing concentrations of toxic or radioactive wastes. Such geographic databases are becoming invaluable tools for monitoring and management of forests and coastlines.

Until a few years ago, civil aviation relied entirely on ground-based radionavigation aids. Such aids are expensive to operate and maintain, and large parts of the world lack even the basic radionavigation infrastructure. GPS is widely seen as the most important advance in civil aviation since the advent of radionavigation, with a potential to enhance greatly both the economy and safety of air operations. Civil aviation is a demanding application with stringent requirements on accuracy, integrity, and continuity of navigation service. In order to ensure that these requirements would be met by a navigation system, the regulatory authorities adopt and promulgate avionics standards and certification criteria. GPS has been certified for use in the U.S. airspace as a supplemental system for en route, terminal, and nonprecision approach phases of flight, and as a primary system for oceanic and remote area operations. A GPS augmentation to support instrument approach and landing under poor visibility conditions is described by Enge in “Local Area Augmentation of GPS for the Precision Approach of Aircraft.”

GPS receivers aboard satellites in LEO’s would become the primary source for position, velocity, attitude, attitude rate, and time, replacing an array of sensors and reducing the cost and complexity of spacecraft. A number of successful experiments and demonstrations have been carried out in various space missions in the last ten years, and a few spacecraft have actually integrated GPS measurements into their operational control systems. The International Space Station is designed to use GPS for navigation, attitude determination, tracking of vehicles approaching the station, and as a source of time for scheduling vehicle operations. GPS measurements have been used extensively for orbit determination, both in real time and postprocessing mode, and GPS has been shown to perform much better than any ground-based tracking system in use today. On-orbit attitude determination based on GPS has been demonstrated but not used routinely yet. This would change with the introduction of a new generation of GPS receivers designed with hardware and software capabilities for orbital applications. One such application is considered by Axelrad and Behre, who focus on a technique for using GPS for coarse attitude determination in “Satellite Attitude Determination Based on GPS Signal-to-Noise Ratio.”

The largest current application of GPS is in land transportation, especially vehicle navigation and tracking. GPS-based systems and services for motorists, commercial fleets, public transit, and emergency response agencies are in great demand, and a vast majority of the GPS receivers manufactured in 1998 were intended for this market. Rental-car companies now routinely offer GPS-based navigation and route-guidance systems. High-end cars have incorporated GPS-based roadside assistance systems and automatic vehicle location systems as standard features. Railroad companies are considering GPS for positive train control. In time, GPS-based services would offer the motorists the best route to office, given the traffic and road conditions of that day.

At least four satellites are required to be in view for three-dimensional navigation with GPS, as noted previously. Terrain, foliage, and buildings, however, can obstruct parts of the sky, and maintaining four or more satellites in track continuously is often impractical for land vehicles. A land-vehicle navigation system must, therefore, supplement GPS with dead-reckoning sensors, e.g., gyroscopes, compasses, odometer, inclinometer, and accelerometers. These sensors cannot provide the absolute position, but they can measure change in position accurately over a short period. DGPS can provide absolute position, but only intermittently. The complementary nature of GPS and the dead-reckoning sensors is analyzed by Abbott and Powell in “Land-Vehicle Navigation Using GPS.” The authors discuss the impact of the individual navigation sensors on the performance of a land-vehicle navigation system.

There are millions of pleasure boats, fishing boats, ferries, cruise lines, cargo lines, and oil tankers in the world. All would benefit from GPS. Since the oil spill caused by the grounding of Exxon *Valdez*, the harbors are exploring active monitoring of the oil tankers. A promising approach is to transmit dGPS-derived tanker positions via radio link to a control station monitored by the harbor authorities. Such automatic dependent surveillance (ADS) would make the harbor operations safer and more efficient. A similar concept has been proposed for the surveillance of air traffic.

The consumer market for GPS products is believed to be vast and is expected to see an explosive growth in the next five to ten years. At present, this market consists basically of inexpensive hand-held receivers for hikers, backpackers, and fishermen. The convergence of wireless communications, Internet, and GPS technologies is seen as the key to the consumer market. Two-way messaging devices incorporating GPS technology are on the market now with which a user can navigate and communicate his or her position, course, or any other information, to anyone on Earth who has an e-mail address. When combined with access to databases for services, this would lead to development and growth of “location-aware” services directing a user in an unfamiliar place to a gas station, Indian restaurant, or a tourist attraction. The consumer market would be fueled by single-chip GPS receivers costing $10 or less. Such receivers would be integrated into an array of consumer products: personal digital assistants, personal communicators, and security devices for personal possessions ranging from cars to computers.

GPS is a worldwide resource of unprecedented accuracy and precision for time and frequency. The national and international laboratories which serve as standards for time and frequency rely on GPS as a source of time and for time transfer. An inexpensive GPS receiver can provide estimates of time with an accuracy heretofore offered only by atomic standards, and GPS-derived time, therefore, is a logical choice for recording times of events for scientific purposes and correlating events recorded at different geographic locations. GPS has also become an essential element of the commercial and industrial infrastructure as a source of precise time. The electric utilities are using GPS to analyze the state of a power grid via precisely synchronized measurements of the voltage phasor at different substations. In the future, GPS-synchronized measurements are expected to become an essential element of power system control. GPS is also being used increasingly to synchronize the elements of telecommunications networks, both wireline and wireless. In fact, GPS is now used to set the clocks at the major Internet nodes, and the time is passed down to the local-area networks. Lewandowski *et al.* survey the revolution in time transfer technology in "GPS: Primary Tool of Time Transfer."

Novel applications of GPS include automatic tracking of oil spills and flooding with especially fitted buoys, sounding of the upper atmosphere with radiosondes equipped with GPS receivers, and tracking of wild animals with special GPS collars for research on habits and habitats. GPS-guided construction, agriculture, and mining machinery are on their way. Indeed, the applications appear limitless.

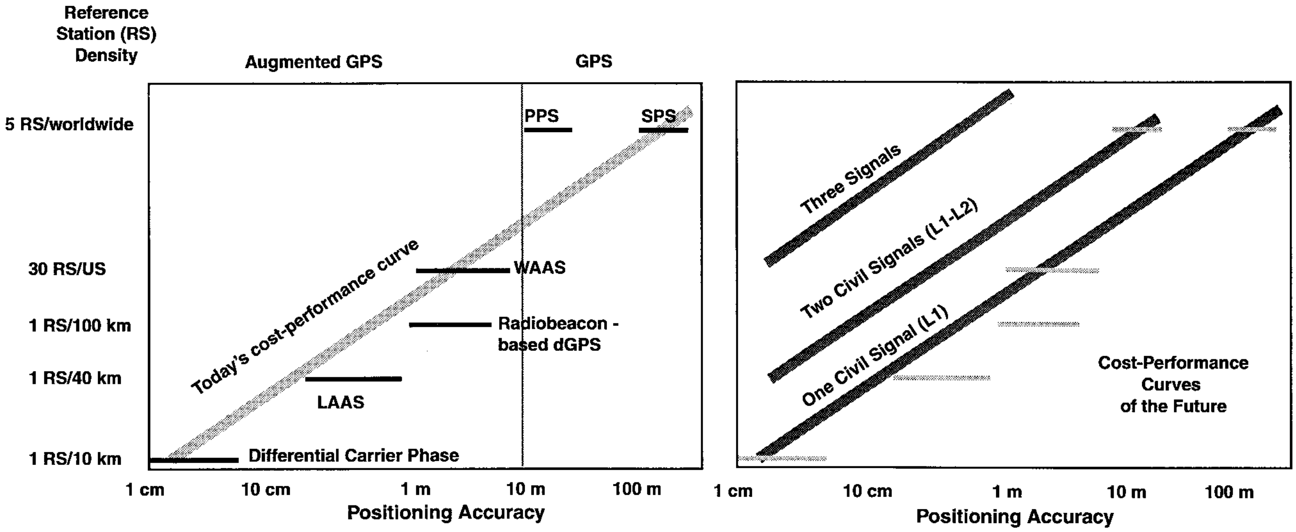
VII. GPS MODERNIZATION

The world has changed since the time GPS was designed and the policies on its use by the military and civil users were adopted by the U.S. Government. Changes in the world political order and emergence of commerce as a national priority has given the civil users and the GPS industry in the United States a new clout, which they have used to push for changes in GPS design and policies. The discontinuation of SA (the policy of purposeful degradation of the signals available for civil use) which is scheduled to occur before 2006 in accordance with the PDD of 1996 would mark an important change in direction for the U.S. policy. With our growing dependence on GPS, some other concerns have emerged, too. Several well-publicized cases recently of inadvertent signal interference and loss of GPS service have brought attention to the vulnerability of the signals. Indeed, the signals are extremely weak, and the spread-spectrum processing gain against interference is modest. RF interference (RFI) constitutes a single point of failure for the civil users and is a hurdle in the use of GPS for safety-of-life applications. In recent years, pressures have also grown for commercial exploitation of the electromagnetic spectrum, especially for mobile satellite communication. The GPS community was jolted recently when a satellite communication provider nearly succeeded in winning approval at the ITU World Radio Conference (WRC) of a proposal to share a portion of the frequency allocation for GPS at L1.

It is a measure of success of GPS and its importance to national security and domestic and foreign policy issues that an ambitious program of modernization is underway for this system which has been operational for barely three years. All through 1997 and 1998, the DoD, DOT (and other civil agencies of the United States), and the civil user community have conducted intensive discussions and negotiations on additional capabilities to be built into the future GPS satellites to serve the civil community better. Of course, the military has also learned from their experiences with GPS and would make some changes in the military signals as well. The challenge is to accommodate the expanding civil use, and its demands for greater accuracy and robustness, with the military mission of GPS.

Before discussing the planned changes and their implications for accuracy and robustness of service, let us review the current capabilities of GPS. As discussed earlier, and as shown in Fig. 5(a), the accuracy of GPS position estimates can range from tens of meters to centimeters depending upon the augmentation. With code measurements, real-time position estimates within tens of meters of the true location are obtained from SPS. The military users, unencumbered with SA and capable of estimating the ionospheric effect with dual-frequency measurements, obtain substantially improved accuracy. To obtain even better performance, additional investment is required in the form of augmentation to the GPS signals. With about 30 reference stations distributed over CONUS, GPS/WAAS would provide meter-level accuracy. Submeter accuracy would be available locally from GPS/LAAS with a reference station at an airport. The position of a user relative to a local reference station may be determined with centimeter-level accuracy in real time using carrier phase measurements. Using the density of the required network of reference stations as a simple, qualitative measure of the cost of service, the diagonal line across Fig. 5(a) can be interpreted as the cost-performance curve for today's GPS.

Befitting its importance, the announcement on the plans for GPS modernization was made by Vice President Gore on 30 March 1998. It is planned to provide two new signals for civil use in addition to the one available today. The structure of the additional signals is yet to be decided. The future GPS satellites will transmit a civil code at L2, in addition to the C/A-code at L1. A third civil signal will also be added at as yet unspecified frequency. A decision on the placement and structure of the third civil signal will be made late in 1998, or early 1999. The frequency diversity would alleviate concerns over accidental interference and would constitute the key step toward achieving robustness of service. The civil signal at L1 will remain unchanged, thereby ensuring that all of the fielded GPS receivers will continue to operate. Two-



(a) (b)

Fig. 5. GPS cost-performance curves. (a) The accuracy of position estimates currently available from GPS can range from tens of meters to centimeters depending upon system augmentation in the form of reference stations. Using the reference station density as a measure of cost provides a simple, qualitative cost-performance curve. (b) Cost-performance curves for GPS of the future. Availability of three-frequency signals for civil use would offer submeter accuracy without any user-provided augmentation. The service would also be robust in the face of RFI and would degrade in stages as one or two frequencies are affected by interference.

frequency signaling would allow civil users to estimate the ionospheric propagation effect and, in the post-SA era, would offer positioning accuracy of better than 10 m without any augmentation.

While two frequencies would improve accuracy for the civil users significantly, the third frequency would bring about an improvement of an order of magnitude. With three frequencies, the user equipment can multiply and filter the individual signals to create two beat frequency signals. The L1 and L2 measurements can be processed to create a beat frequency signal with a wavelength of approximately 86 cm. Since this wavelength is significantly greater than the wavelength for either L1 or L2, the corresponding measurement is called a wide-lane observable. A second wide lane would be generated by multiplying the third signal with either the L1 or L2 signal. This pair of wide-lane measurements can be used to solve for the pseudorange and the ionospheric delay from user to satellite. Unlike the two-frequency case, these estimates would be accurate to within a fraction of the wide-lane wavelength, or a few centimeters. Taken together with the planned improvements in the GPS ephemeris, this three-frequency technique would yield submeter positioning accuracy for GPS in real time with a relatively sparse ground infrastructure.

The benefits to the civil users from these changes in the form of improved accuracy and robustness of service would come slowly over the next 10-20 years as new satellites with expanded capabilities are produced and launched to replace the current satellites. A simple, qualitative view of the benefits is provided in Fig. 5(b) as cost-performance curves akin to Fig. 5(a) for GPS of today. Fig. 5(b) shows a dramatic reduction in cost for the nominal service with three-frequency signals: submeter accuracy from the basic satellite system without any augmentation. Secondly, it envisions a system which degrades gracefully in stages when faced with RFI. The service degrades when access to one of the signals is lost. When two of the signals become unavailable, the cost-performance curve reduces to that for GPS of today in Fig. 5(a).

The civil users, especially the civil aviation community, would prefer the third signal in the 960–1215-MHz band currently allocated for Aeronautical Radio Navigation Service (ARNS) on a primary basis and protected for safety-of-life applications. Given the pressures on the electromagnetic spectrum, agreement on frequency allocation for the new signal would not be easy. The hardest of all, given the budgetary pressures, would be an agreement on sharing the costs for these additional capabilities to be built into the new satellites.

VIII. SUMMARY

GPS is widely seen as the most important gift of the DoD to the civil world, perhaps with the exception of the Internet. (A GPS system summary is included in Table 2.) Civil applications unforeseen by the developers of the system are thriving and many more are on the away. Commerce in GPS equipment and services continues to grow rapidly. This success has also created expectations, indeed demands, which the system was not designed to meet. It is expected that the planned GPS modernization, when complete, would make determining position as easy as determining precise time is today. This knowledge of position would come to

Table 2
A System Summary of GPS

- *Basic Description*

  Space-based radionavigation system broadcasting precise, synchronized timing signals to provide estimates of position, velocity, and time based on passive, one-way ranging to satellites.

- *Milestones*

  1973: Architecture approved
  1978: First satellite launched
  1995: System declared operational

- *Satellite Constellation*

  24 satellites in 6 orbital planes inclined at 55°; near-circular orbits with radius 26,560 km;
  orbital period: 11h 58m; ground track repeat each sidereal day

- *Reference Standards*

  Coordinate frame: WGS 84

  Time: UTC(USNO)

- *Signals*

Carrier signals (MHz)	L1: 1575.42
	L2: 1227.6
Multiple Access Scheme	CDMA
PRN Codes	C/A-code on L1; P(Y)-code on L1 and L2
Code frequency (Mcps)	C/A-code: 1.023; P(Y)-code: 10.23

- *Performance Specifications*

  Standard Positioning Service (civil users)

    Horizontal position error (95th percentile): 100 m

  Precise Positioning Service (U.S. military)

    3-D position error (50th percentile): 16 m

- *Performance Achievable*

  Real-time: Typically, absolute positioning accuracy of tens of meters with a single receiver, decimeters in differential mode

  Batch processing: millimeter-level relative positioning

- *Receiver Bazaar*

  Chip sets (L1): \$ 25 - \$ 50 (in volume)

  OEM boards (L1): \$ 50 - \$ 1000 (large orders)

  Pocket-size receivers for hikers and backpackers: \$ 100 - \$ 250

  USCG dGPS-capable receivers for boats: \$ 1000 - \$ 2500

  Receivers certified for non-precision approaches under IFR: \$ 2000 - \$ 5000

  Geodetic-quality, dual-frequency (L1-L2) receivers: \$ 10k - \$ 30k

occupy the same important place in our daily lives as time does today.

We have assembled ten papers in this Special Issue to introduce the various aspects of GPS: the satellites; receivers; positioning algorithms; and several important civil applications. We hope that the reader will find them useful for understanding the technology and applications of this new global resource.

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PER ENGE, *Guest Editor*
Stanford University
Stanford, CA 94305-4035 USA

PRATAP MISRA, *Guest Editor*
Massachusetts Institute of Technology
Lexington, MA 02420-9185 USA

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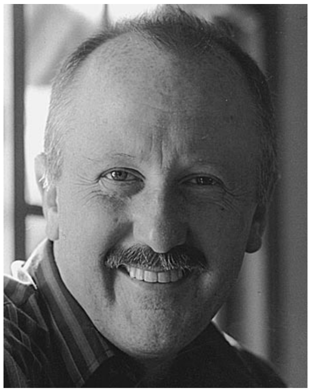
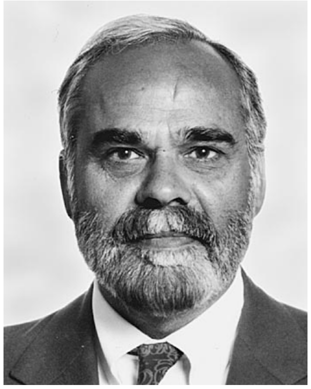


Per Enge *received the B.S. degree in electrical engineering from the University of Massachusetts, Amherst, in 1975. He received the M.S. and Ph.D. degrees from the University of Illinois, Urbana-Champaign, in 1979 and 1983, both in electrical engineering. His Ph.D. dissertation was in the area of spread spectrum multiple-access communications.*

Since 1992, he has been at Stanford University, Stanford, CA, where he currently is an Associate Professor in the Department of Aeronautics and Astronautics. At Stanford University he teaches courses in satellite navigation and control theory. He is also responsible for the Federal Aviation Administration's program to use differential operation of the Global Positioning System (GPS) for navigation during aircraft approach and landing. Specifically, he investigates and flight tests wide-area differential GPS for Category I precision approach, and local area differential GPS for Category I, II, and III precision approach. Currently, both systems are being deployed for operational use. From 1986 to 1992, he was with Worcester Polytechnic Institute (WPI), Worcester, MA, where he achieved the rank of Associate Professor of Electrical Engineering. At WPI, he taught and directed research for the U.S. Coast Guard. The research included the design of a medium-frequency (MF) radio system to broadcast differential GPS corrections to marine users. Today, this system covers much of the world's coastline and provides positioning accuracy of one or two meters to hundreds of thousands of marine users.

Dr. Enge is the recipient of the 1996 Thurlow Award from the Insitute of Navigation, and he is Executive Vice President of the same institute.



Pratap Misra *(Senior Member, IEEE) received the B.S. degree from Indian Institute of Technology, Kanpur, in 1965 and the M.S. degree from Lehigh University, Bethlehem, PA, in 1967, both in mechanical engineering. He received the Ph.D. degree in engineering sciences in 1973 from the University of California, San Diego.*

Since 1983, he has been with Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA, where he is now a Senior Staff Member. Since 1989, he has been Program Manager for FAA-sponsored studies related to application of global navigation satellite systems to civil aviation. During 1983–1989, he was engaged in developing algorithms for adaptive array processing and high-resolution spectral analysis. From 1974 to 1983, he was with IBM Federal Systems Division (FSD), where he worked on NASA-sponsored studies of pattern recognition techniques to identify crops in Landsat images and performance modeling of computer systems.

Dr. Misra is a member of the Institute of Navigation. In 1980 he received an IBM/FSD Outstanding Achievement Award for developing a mathematical model of the IBM 3850 Mass Storage System.