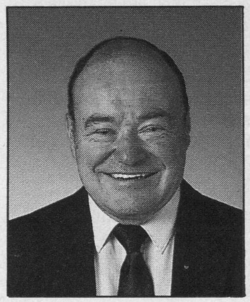
GPS RECEIVERS

System revolutionizes surveying and navigation

JOHN GALLANT, Technical Editor



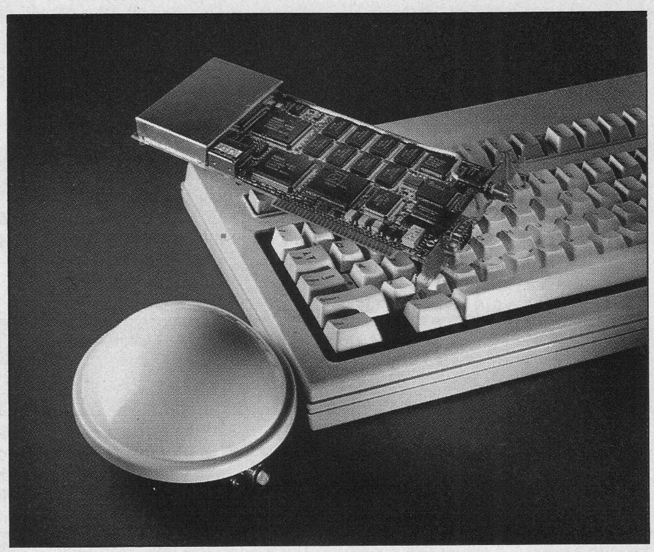
Science began when people looked to the skies to track the seasons and find their way. Today's engineers have achieved a satellite-based system that can determine your position to within a centimeter.

The Global Positioning System (GPS) is a radio-navigation system that employs RF transmitters in 24 satellites. GPS receivers decode the satellites' signals to calculate the latitude, longitude, and altitude of a position on earth. The positioning accuracy ranges from 40m to less than 1 cm. This description seems straightforward, but imagine the possibilities.

GPS applications appear limitless (see **Table 1**). You'll be designing them into surveying and navigational equipment, airplanes, boats, and trucks—and that's just for starters.

Already GPS receivers on airplanes and boats are providing accuracies 10 to 100 times better than those achieved by ground-based radio-navigation aids such as Loran, Omega, and VOR/VME Tacan. Geologists are using GPS to monitor fault lines. Oil companies are using GPS for offshore oil exploration. Because of their high-altitude orbit, GPS satellites can keep track of lower-orbit satellites such as weather satellites. Fleet vehicles are trading their squawking radios for GPS receivers so the home office can track vehicles in metropolitan areas.

Satlock Inc (Stanfield, AZ) is using the GPS to help crop sprayers spread fertilizer and pesticides more effectively. A GPS receiver monitors the sprayed area to prevent overspraying and overfertilization. As receiver costs plummet, there's no reason why every automobile shouldn't soon have a GPS receiver to determine an optimal route to a destination. An in-car computer would analyze the GPS data and present the route in color on a video screen. Information on popular tourist attractions and restaurants could be stored in CD-ROM. In fact, Etak (Sunnyvale, CA) already offers digital maps for automotive navigation.



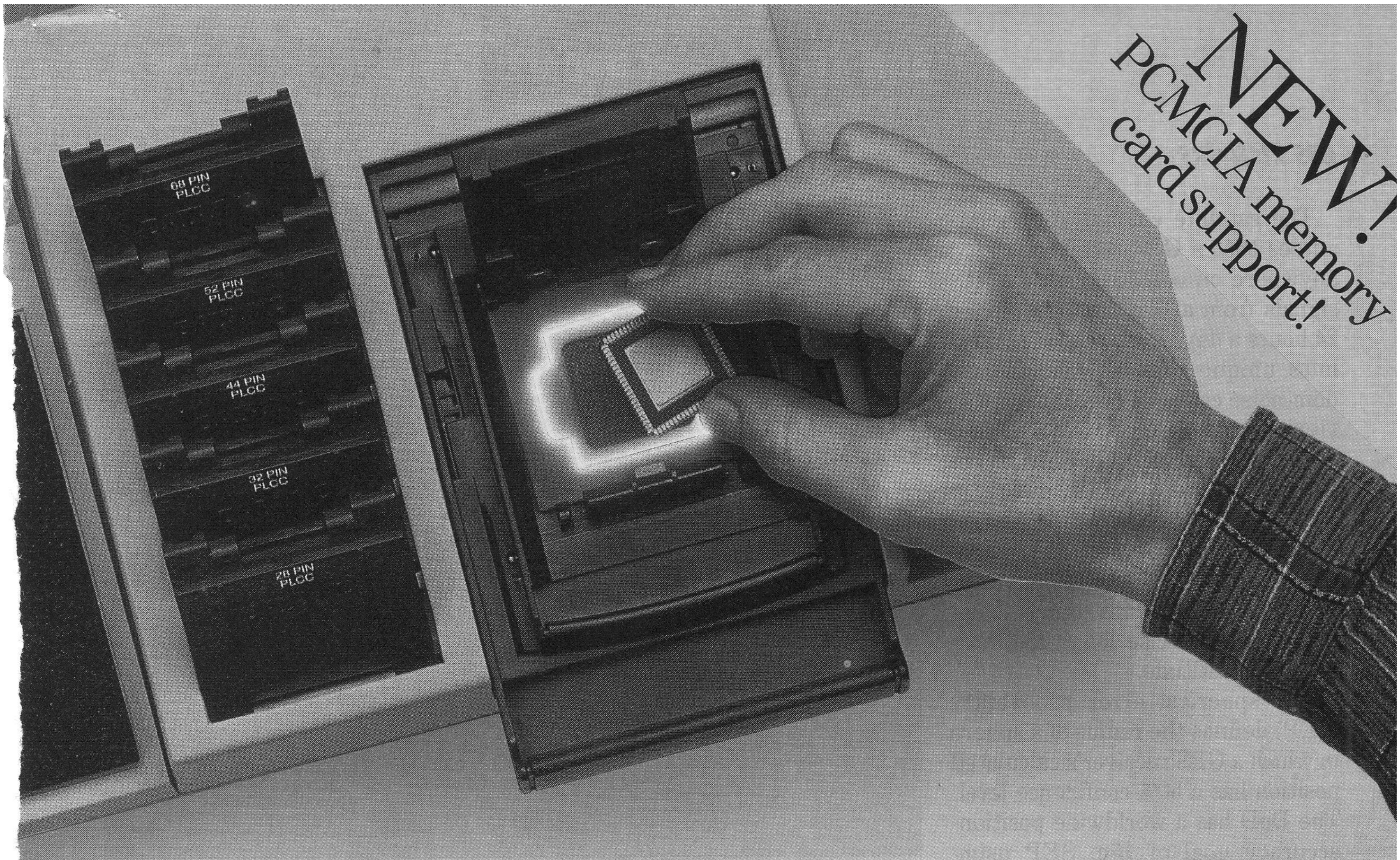
Tapping into the GPS can be as easy as plugging a GPSCard into your PC and connecting it to the Model 501 GPSAntenna and integrated low-noise amplifier. The Novatel card has 10 channels that track the C/A code and carrier signal's phase.

Taxpayers foot the bill

The GPS, officially known as the NAVSTAR GPS (NAVigation System with Timing And Ranging Global Positioning System), is nearing completion thanks to US taxpayers and the Department of Defense (DoD). For complete and continuous global coverage, the GPS requires 21 satellites and 3 spares circling the earth once every 12 hours. The orbits are 10,898 nautical miles above the earth and are arranged in six orbital planes (**Fig 1**). The planes are inclined 55° with respect to the earth's equatorial plane. At the date of this writing, 19 satellites are actively deployed. The launch schedule should complete the 24-satellite constellation in 1993.

Table 1—Representative GPS receivers

Company	Model	Applications	Housing	Price	Features
Ashtech Inc	M-XII receiver	Surveying	3.9×8.5×8-in. case, 8.2 lbs	$16,800 Prism software, $8000	Receives L1, L2, C/A code, and P code; 12 Parallel channels; 2-minute cold start to first data; 8-line, 4-character display; 2 RS-232C ports; 12W from 10 to 36V dc supply; 1-PPS output; −20 to +55°C.
	OEM GPS receiver	OEM part	4.75×2.5x4-in. RF module, 2 lbs	$2500 to $5000, depending on options	Receives L1, C/A code; 12 parallel channels; 1-minute cold start to first data; 1-sec updates; NMEA 183 interface; 2 RS-232C ports; 4W.
Canadian Marconi Co	CMA 3012	Airborne navigation	2.6×8.5×9.5-in. RF module, 7 lbs	$17,250	Receives L1, C/A code; 12 parallel channels; 11 ARINC 429 ports; 2 RS-232C ports; conforms to MIL-STD-810; 20W from 18 to 36V dc supply; −55 to +70°C.
Garmin	GPS 75	Marine navigation	3.2×6.4×1.5-in. handheld unit with battery pack, 19 oz	$1419	Multitrac operating system tracks 8 satellites continuously; 250 waypoints, 101 map datums; NMEA 183 interface; 1.1W from battery pack; backlit dot-matrix LCD; 1-sec updates; waterproof; −15 to +70°C.
	GPS 100 MRN	Portable navigation	6.25×3.95×2-in. handheld unit, 25 oz	$1795	Multitrac operating system tracks 8 satellites continuously; 2 minutes to first fix; 1-sec updates; NMEA 183 interface; 250 waypoints; −15 to +70°C.
Magellan Systems Corp	NAV 5000D	Marine navigation	3.5×8.8×2.1-in. handheld unit	$1200	5 parallel channels; 55 sec from cold start to first fix; NMEA 183 interface; 100 waypoints, 12 map datums; 4-line, 16-character LCD; RTCM SC-104 differential corrections; −10 to +60°C.
Magnavox GPS	GPS Engine	OEM part	2.5×6.33-in. card	$500 to $1100	Receives L1, C/A code; 6 parallel channels; 1 minute to first fix; 1-sec updates; RTCM SC-104 differential corrections; 1.5W from 6.5V dc supply; 1W from 5V dc supply; −20 to +70°C.
Marcor	AVL-2	Vehicle location	6.91×6.38×3.05-in. waterproof enclosure, 1.6 lbs	$1399	2 parallel channels; tracks 8 satellites; Adaptive Kalman filter; 7 to 20 minutes from cold start to first fix; RS-232C port; NMEA 183 interface; 15W from 10 to 40V dc supply; −30 to +70°C.
Motorola	6-channel parallel receiver	OEM part	3.94×2.76-in. card, 4.5 oz	$500 (OEM)	Receives L1, C/A code; 6 parallel channels; RS-232C port; 1-sec updates; 49 datums; 1.3W from 5V supply; 1.8W from 12V supply; Microstrip antenna powered by receiver; −30 to +80°C.
Novatel Communications Ltd	GPScard Performance Series	OEM part	8-bit ISA bus card or Eurocard	$4390 (Model 911 with RTCM differential correction)	Receives L1, C/A code; 10 parallel channels; NMEA 183 interface; 1-PPS output; 68 datums; 2 RS-232C ports; 2-minutes from cold start to first fix; 200-msec updates; 6W.
Odetics	tSAT	Time synchro-nizations	ISA bus, VME bus, SBus, VAX-BI, and Nubus; Micro Channel Architecture board	$3995 to $13,995, depending on bus	5 parallel channels; generates IRIG A, IRIG B, XR3, NASA 36 and 2137 time codes; TTL outputs are 100k, 10k, 100, 10, IPPS; time accuracy ±1 μsec; receives Universal Coordinate Time (UTC) from GPS satellites.
Rockwell International Corp	Navcore V	OEM port	2.65×4-in. card, 4 oz	$395 (100)	Receives L1, C/A code; 5 parallel channels; 1-sec updates; 1.6W; −40 to +85°C (high-temp version).
Sercel Inc	NR 106	Surveying	10.83×5.31×10.83-in. waterproof case, 13.89 lbs	$12,600	Receives L1, C/A code; 10 parallel channels; 0.6-sec updates; RTCM SC104 differential correction; 2 minutes from cold start to first fix; 2 RS-232C ports; NMEA 183 interface; stores 10 stations in permanent memory; 12W from 10 to 36V dc supply; −10 to +55°C.
Trimble Navigation	System Surveyor 4000SE	Surveying	9.8×11×4-in. case, 6 lbs	$17,950; options ranging from $1250 to $2350	Receives L1, C/A code; 9 parallel channels; 2 RS-232C ports; RTCM SC104 differential corrections; 4-line, 40-character LCD; NMEA 183 interface; 1-PPS output; 5W from 10 to 35V dc supply; −20 to +55°C.
	TNL-3000	GPS and Loran navigation	6.25×10.8×2-in. unit, 2.75 lbs	$6795	Receives L1, C/A code; 6 parallel channels; 1-sec updates; RS-422 port; 2-line, 20-character LED display; Multichain Loran operation; All Loran chains available; 250 waypoints; 12W from 10 to 32V dc supply; −20 to +55°C.



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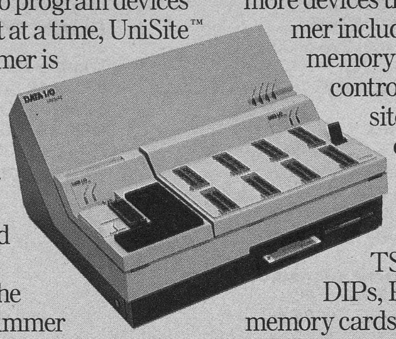

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GPS RECEIVERS

The satellite configuration guarantees that a GPS receiver located anywhere on earth can receive RF signals from at least four satellites 24 hours a day. Each satellite transmits unique biphase pseudo-random-noise codes on two L-band carrier frequencies—1575.42 and 1227.60 MHz. (For definitions of GPS terms, see **box,** "Glossary of GPS terms.") A GPS receiver decodes the spread-spectrum modulations and uses triangulation techniques on the satellite signals to determine its precise longitude, latitude, and altitude.

The spherical error probability (SEP) defines the radius of a sphere in which a GPS receiver's calculated position has a 50% confidence level. The DoD has a worldwide position-accuracy goal of 15m SEP using pseudorange measurements. (Because synchronization errors exist between the transmitter and re-

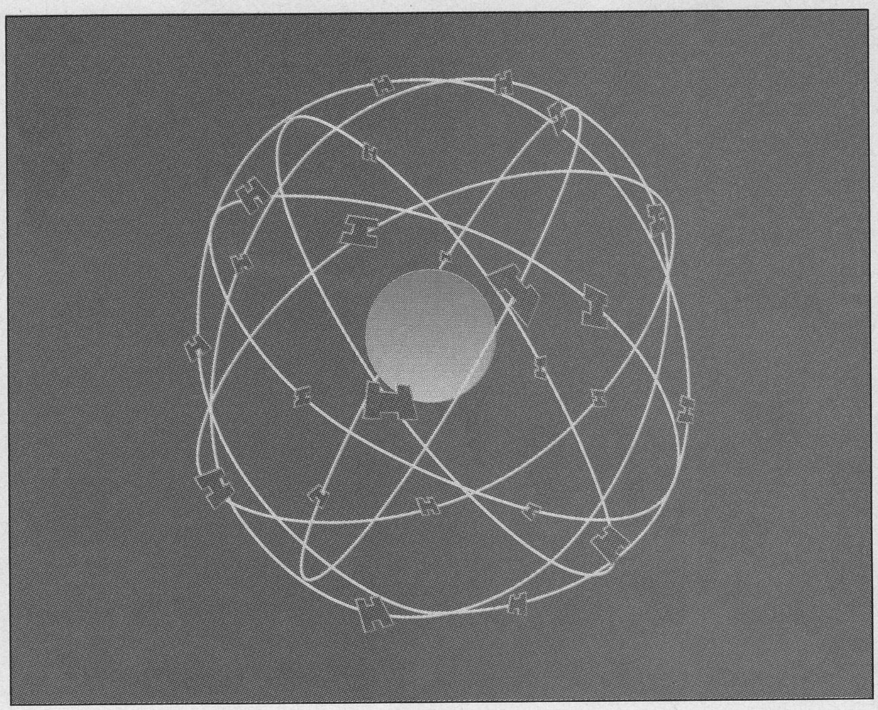

Fig 1—The complete Global Positioning System will include 21 satellites plus three spares traveling in 12-hour circular orbits 10,898 nautical miles above the earth's surface. There are six orbital planes, which are inclined 55° from the earth's equatorial plane.

For more information . . .

For more information on the GPS receivers discussed in this article, circle the appropriate numbers on the Information Retrieval Service card or use EDN's Express Request service. When you contact any of the following manufacturers directly, please let them know you read about their products in EDN.

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ceiver clocks, the pseudorange is not the true range. See **box,** "Finding your pseudoway," for how to convert the pseudorange to the true range.)

The GPS was conceived in the 1970s because of the insufficient coverage and inherent inaccuracies of the 1960's Transit system. This system—which is still operational—consists of five or six satellites in polar orbits 580 nautical miles above the earth. Transit is accurate to within 500m and does not include enough satellites to provide global coverage.

The DoD maintains the GPS via five monitor stations. The stations

Glossary of GPS terms

Biphase modulation—A phase-shift keying technique that changes the phase of the carrier frequency by 180° on each bit transition in a data sequence.

C/A code (Coarse/Acquisition code)—A sequence of pseudorandom binary bits that biphase-modulates the L1 satellite carrier frequency. The code has a switching rate of 1.023 MHz and repeats every 1023 bits.

Datum—A surveying term that describes how to position and orient a surveying matrix on the earth's surface.

Differential GPS—An accuracy-enhancing technique that employs two GPS receivers at two different locations. The receivers exchange data with each other in real time to eliminate ephemeris and clock errors.

Ephemeris—A set of parameters defining the orbit of a satellite. A GPS satellite broadcasts these parameters in a navigation message that modulates the two carrier signals. Six parameters define a smooth elliptical orbit in which a satellite's position is a function of time relative to a reference time. Additional parameters describe the deviation of the satellite's motion from the smooth ellipse. (The plural is "ephemerides.")

GDOP (Geometrical Dilution Of Precision)—A figure of merit for the range-measurement accuracy of a specific satellite configuration. The lower the GDOP, the greater the accuracy. The GDOP calculated by GPS receivers determines the optimal satellite selection, which changes with time.

NAVSTAR GPS (NAVigation System with Timing And Ranging Global Positioning System)—A satellite-based radio-navigation system financed by the US Department of Defense (DoD). The GPS consists of 21 satellites plus three spares arranged in six orbits 10,898 miles above the earth. Using the satellites' signals, a GPS receiver can calculate its longitude, latitude, and altitude. The system provides continuous global coverage to an unlimited number of users.

L band—The band of frequencies extending from 1 to 2 GHz. Both the L1 and L2 carrier frequencies GPS satellites transmit to receivers are in the L band. The frequencies are 1575.42 and 1227.60 MHz, respectively.

P code (Precision code)—A sequence of pseudorandom binary bits that biphase-modulates both satellite carrier frequencies. The frequency is 10.23 MHz, and the sequence repeats every 266.4 days. A unique segment of the code is assigned to each satellite and resets each week. The P code is primarily for military purposes.

Pseudorange—The distance between a transmitter and a receiver based on measuring the elapsed time for 1-way transmission and multiplying by the speed of light. Because synchronization errors exist between the transmitter and receiver clocks, the pseudorange is not the true range.

RTCM (Radio Technical Committee for Maritime Applications)—A Department of Transportation committee that defines data-exchange protocols and message formats for differential navigation corrections.

S band—The band of frequencies extending from 2 to 4 GHz. The GPS control station at Colorado Springs, CO, communicates with the satellites via an S-band uplink at 2227.50 MHz. The station sends tracking and telemetry data and command signals. The downlink from the satellites to the control station is at the ostensible S-band frequency of 1783.74 MHz.

SA (Selective Availability)—The DoD's method for denying civilian GPS receivers the same accuracy as military receivers. The DoD purposely degrades the resolution of the ephemerides data and dithers the C/A code's frequency to degrade a receiver's navigation accuracy from approximately 15m SEP without SA to approximately 40m SEP with SA.

SEP (Spherical Error Probability)—The radius of a sphere that defines a 50% confidence level in the accuracy of a position measurement in three dimensions—latitude, longitude, and altitude. The 2-dimensional analogue for latitude and longitude measurements is the CEP (circular error probability).

Waypoint—An intermediate latitude and longitude point on a navigated course. The navigator must pass the point to reach the final destination. A waypoint can be moving or stationary.

WGS-84 (World Geodetic System 1984)—The standard coordinate system adopted for the GPS. The system is a best-fit approximation of the earth's surface to an oblate spheroid. The latitudes and longitudes of the spheroid are used with local maps to determine the contours of a particular region.

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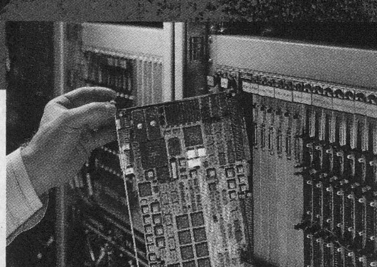

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are in Hawaii and Kwajalein in the Pacific ocean, the Ascension Islands in the Atlantic ocean, Diego Garcia in the Indian ocean, and Colorado Springs, CO. The Colorado Springs location is the master control station for the system. All of the monitor stations track the GPS satellites, and the master control station provides 24-hour updates to correct for satellites' ephemerides and clock errors. ("Ephemerides" is an astronomical term for tables of parameters defining the orbit of a satellite.) The master control station commu-

Finding your pseudoway

The Global Positioning System (GPS) calculates the latitude, longitude, and altitude of any point on earth using 1-way radio navigation. Conventional 2-way radionavigation systems determine distance by measuring the time of arrival or phase difference between a transmitted signal and a received echo signal. Because the signal traverses the distance twice, the range to the reflector is $c\Delta t/2$, where c is the speed of light and t is time.

Two-way radio navigation is impractical for a satellite-based system because of the potential interference when millions of user signals simultaneously try to use the satellites as reflectors or transponders. Therefore, the GPS determines position by transmitting information on two L-band carrier frequencies, L1 and L2. Transmission is in one direction only—from the satellite to a ground or airborne receiver. The accuracy of this 1-way scheme depends on the synchronization between the satellite and receiver clocks. These clocks, in turn, are synchronous with an atomic GPS time standard kept at the master control station.

The satellites modulate the carrier frequencies with two biphase pseudorandom-noise (PRN) waveforms and a biphase navigation message. The bit rates of the modulations are submultiples of the carrier frequencies and shift the carrier phase 180° on each bit transition.

Cross correlation measures time delay

One of the PRN waveforms is the Coarse/Acquisition (C/A) code. The C/A code, also known as the civilian code, modulates the L1 carrier at 1.023 MHz. The code comprises a sequence of 1023 pseudorandom bits, which repeat every millisecond. Each GSP satellite broadcasts a unique C/A code. The codes are orthogonal, so their cross correlations are nearly zero.

The other PRN waveform is the Precise, or Protected, code (P code), which the US military uses. The P code modulates both carrier frequencies at 10.23 MHz and repeats about every 266.4 days. Each GPS satellite has a unique 1-week segment of the P code, which resets each week.

The navigation message modulates both carrier frequencies at 50 bps and contains 1500 bits, which repeat every 30 seconds. Each satellite's navigation message contains information about the accuracy of the satellite's clock, the satellite's ephemeris, the condition of the satellite, and low-accuracy almanac data. By representing the C/A code as C(t), the P code as P(t), and the navigation message data as D(t), you can express the two L-band satellite signals as

$$L1(t) = P(t)D(t)\cos(f_{L1}t) + C(t)D(t)\sin(f_{L1}t)$$

$$L2(t) = P(t)D(t)\cos(f_{L2}t),$$

where f_{L1} is the L1 carrier frequency of 1575.42 MHz, and f_{L2} is the L2 carrier frequency of 1227.60 MHz. Actually, only the L1 carrier frequency is necessary to determine position. Dual-frequency receivers use the L2 carrier frequency primarily to compensate for atmospheric effects.

Civilian receivers use the C/A code. To determine the distance between the receiver and a particular satellite, the receiver generates a replica of the satellite's C/A code using its onboard synchronized clock. A cross-correlator delays the receiver-generated code to align it in time with the C/A code from the satellite. When the codes align, a peak in the correlator's output lets the receiver determine how long ago the code was sent, or the time delay. The receiver and satellite clocks are synchronous, so the receiver can deduce the distance from the time delay: Distance = speed of light × time delay.

Pseudorange contains clock errors

This distance is called the pseudorange because it contains clock-synchronization errors. Incorporating the clock-error term (t_{ERROR}), the pseudorange is given by

$$\text{Pseudorange} = \rho + c\Delta t_{ERROR},$$

where ρ is the true range, which equals the speed of light times the change in the GPS master-control-station clock.

The clock-error term is the difference between the satellite-clock error (δt_S) and the receiver clock error (δt_R):

$$\Delta t_{ERROR} = \Delta t_S - \Delta t_R.$$

The satellites use rubidium and cesium atomic clocks that have long-term frequency stabilities of 10^{-13}/day;

nicates with the satellites via an S-band uplink and downlink.

Civilian GPS receivers decode one of the satellites' two biphase spread-spectrum codes to determine position. The code called the Coarse/Acquisition code (C/A code), is a pseudorandom-noise (PRN) modulation at 1.023 MHz on the L1 carrier frequency. The other PRN code, called the Precise code (P code), modulates both the L1 and L2 carrier frequencies at 10.23 MHz to provide better position accuracy. The P Code is intended for military

the receivers generally use crystal clocks having long-term frequency stabilities of 10^{-7}/day. The receiver-clock error dominates, so

$$\text{Pseudorange} = \rho - c\Delta t_R, \text{ and}$$

$$\rho = \text{pseudorange} + c\Delta t_R.$$

The fundamental frequency of the satellite clock is 10.23 MHz. Actually, the satellite-clock error is so small that the GPS must take into account the clock offset caused by relativity effects.

You are here

To locate a point P on the earth's surface relative to a satellite located at point S_1 **(Fig A)**, a receiver must calculate the following vector relationships:

$$\left|\overrightarrow{\rho - c\Delta t_R}\right| = \left|\vec{S}\right| - \left|\vec{P}\right|$$

$$(\rho - c\Delta t_R)^2 = (X_1 - X_0)^2 + (Y_1 - Y_0)^2 + (Z_1 - Z_0)^2.$$

The satellite's navigation message contains accurate ephemeris data, which determine X_1, Y_1, and Z_1—the satellite's coordinates from the earth's geocenter. The message also contains correction factors for the satellite's clock error.

The pseudorange equation for one satellite has four unknowns—P's coordinates X_0, Y_0, Z_0 and the receiver's clock error t_R. The receiver's clock error is the same for all the satellites. Thus, the receiver can simultaneously obtain pseudorange data from four different satellites to generate four equations with four unknowns. The receiver's software iteratively solves these equations to determine P's coordinates. The software then translates the geocentric coordinate data to longitude, latitude, and altitude.

With the Selective Availability (SA) feature turned off, GPS receivers typically achieve 15m SEP (spherical error probability) accuracy when tracking the C/A code. When SA is on, the accuracy degrades to 40m SEP. (SA is the DoD's attempt to doctor the GPS signals so that civilian users cannot achieve military accuracy. See **box,** "Glossary," for complete definitions of GPS terms.)

GPS receivers achieve greater accuracy by comparing the satellite information from multiple receivers over long baselines. The technique, called differential GPS, achieves position accuracy of less than 5m SEP on the C/A code and can effectively cancel the effects of SA. By using differencing techniques, differential GPS can track the carrier phase of the L1 frequency and achieve position accuracy to a fraction of the carrier wavelength. This wavelength is approximately 19 cm.

The references give much more detail on the GPS than space allows here. They are arranged in order of complexity ranging from the layman's tutorial in **Ref 1** to the complex analytical treatment of **Ref 4**. You can obtain all of the books from

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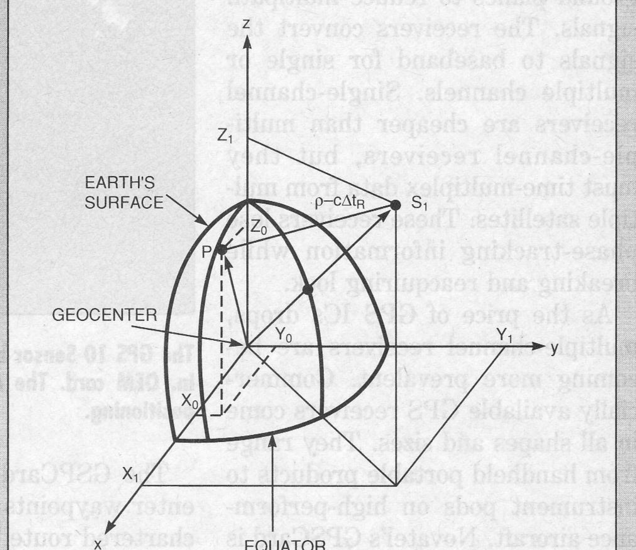
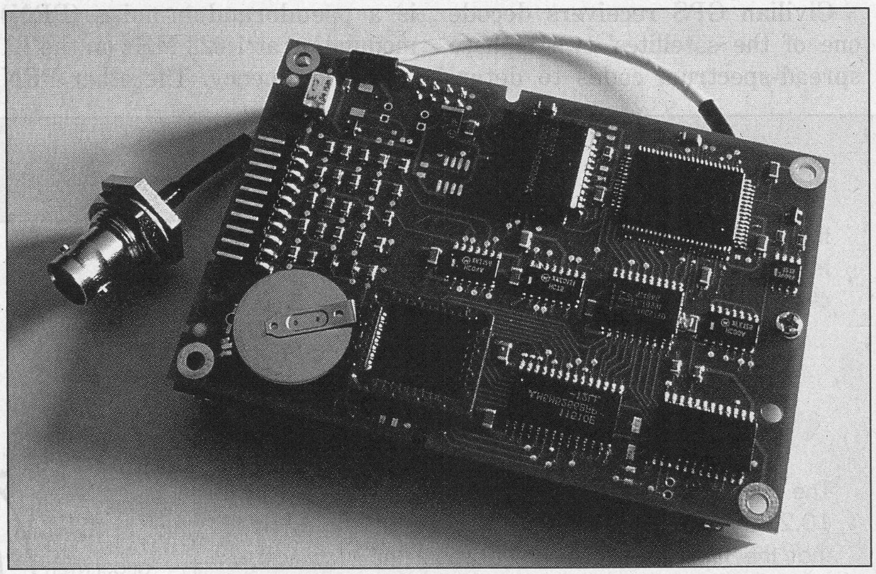


Fig A—A GPS receiver locates a position, P, on the earth's surface by measuring the time of arrival of a pseudorandom-noise code on a satellite signal. The satellite is in orbit at point S. The system makes simultaneous measurements from four satellites (only one shown here) to determine X_0, Y_0, Z_0, and the receiver's clock error (t_R).

use. The DoD plans to encrypt the code in the near future.

The receivers have omnidirectional antennas for receiving the L1 and L2 signals from several satellites simultaneously. The antennas have low-noise amplifiers and ground planes to reduce multipath signals. The receivers convert the signals to baseband for single or multiple channels. Single-channel receivers are cheaper than multiple-channel receivers, but they must time-multiplex data from multiple satellites. These receivers lose phase-tracking information while breaking and reacquiring lock.

As the price of GPS ICs drops, multiple-channel receivers are becoming more prevalent. Commercially available GPS receivers come in all shapes and sizes. They range from handheld portable products to instrument pods on high-performance aircraft. Novatel's GPSCard is a representative multiple-channel GPS receiver for OEM applications.



The GPS 10 Sensor board implements Garmin's Multitrac technology on a 4×2.65×0.75-in. OEM card. The receiver can track and use as many as eight satellites for accurate positioning.

Simply plug in a card

The GPSCard is available with an 8-bit ISA bus or Eurocard connector. The card accepts signals from an external GPS antenna and feeds them to 10 parallel tracking channels. High-speed samplers convert each channel's analog data to digital data. Proprietary ASICs digitally process the data to calculate the receiver's position.

The GPSCard specifies a time to the first satellite fix of 2 minutes from a cold start. A cold start means that the receiver's memory has no ephemeris data from any satellite. A GPS satellite broadcasts its ephemeris data in a navigation message that modulates the L1 and L2 carrier signals. The receiver must decode the navigation message to store the ephemeris in memory. The card can reacquire a signal within 5 seconds once the memory contains recent satellite ephemeris data via the navigation message.

The GSPCard software lets you enter waypoints to mark off an unchartered route. The software contains a global map based on WGS-84 (Worldwide Geodetic System 1984) coordinates. These coordinates are a best-fit spheroid approximation of the earth's surface. Using a built-in or user-defined survey datum, you can refine your location on the global map.

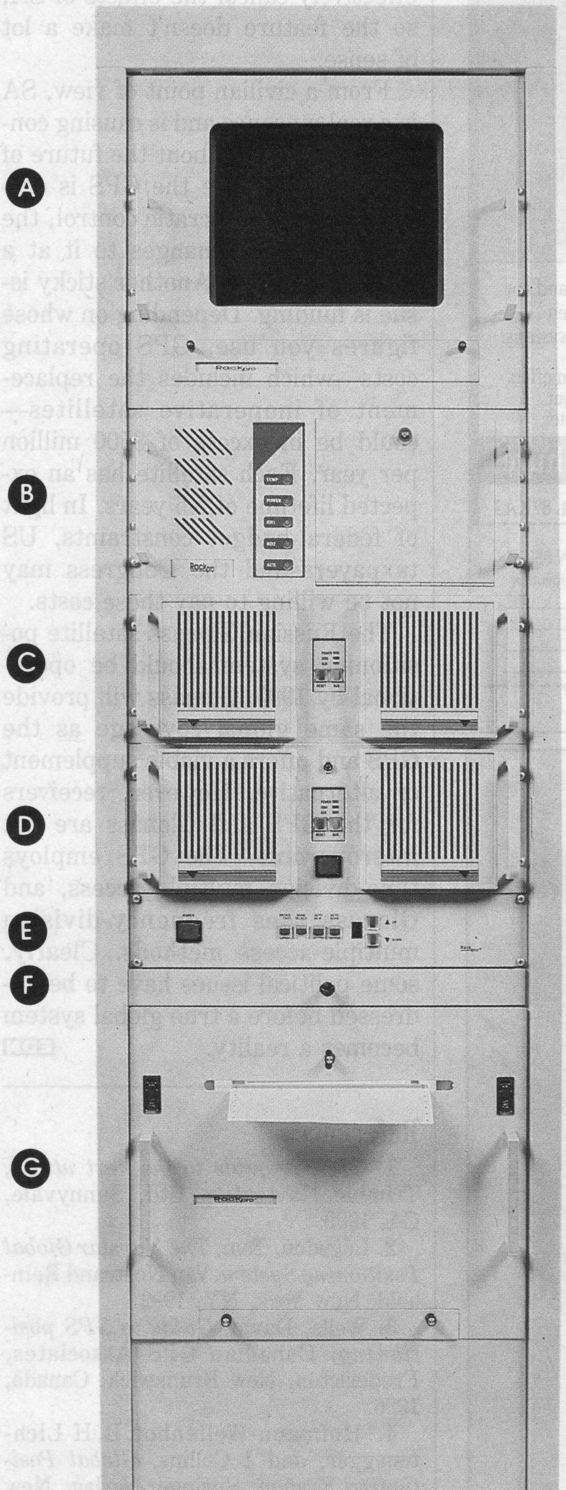
All GPS receivers specify a zero-baseline measurement accuracy. The zero-baseline specifications are the receiver's accuracy limits taken when using one antenna and two of the receivers in one location. Manufacturers also provide accuracy data for GPS receivers under an assumed operating condition. This condition assumes a certain geometrical dilution of precision (GDOP) for the arrangement of the satellites. The receiver's software calculates the GDOP using a matrix of data from four satellites.

You obtain a receiver's position accuracy by multiplying the GDOP value by the zero-baseline measurement accuracy. GDOP values usually range from 2 to 6. A high GDOP value occurs when the four satellites are bunched close together, which results in poor position accuracy. The lowest GDOP occurs when one satellite is directly overhead and the other three are equally spaced on the horizon. If more than four satellites are in view, a GPS receiver can calculate the various GDOPs to select the four satellites that have the minimum GDOP value.

Civilian surveying, exploration, and navigation equipment use differential GPS to improve position accuracy. The mobile GPS receivers receive the satellite signals in tandem with signals from a reference receiver at a known fixed position on earth. This technique can result in a measuring accuracy of within a centimeter.

GPS receivers specify accuracy with the Selective Availability (SA) feature turned on or off. SA lets the DoD decrease a receiver's position accuracy. When on, SA degrades the C/A code's frequency and the resolution of ephemeris data for civilian use. The intent is to provide more resolution for a military receiver than for a potential adversary receiver using the

ONE-STOP INDUSTRIAL COMPUTER SHOP



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CIRCLE NO. 36

GPS RECEIVERS

same satellite signals. However, the differential GPS technique can effectively cancel the effects of SA, so the feature doesn't make a lot of sense.

From a civilian point of view, SA is a real nuisance and is causing considerable unrest about the future of the GPS. Because the GPS is currently under autocratic control, the DoD can make changes to it at a moment's notice. Another sticky issue is funding. Depending on whose figures you use, GPS operating costs—which includes the replacement of inoperative satellites—could be in excess of $500 million per year. Each satellite has an expected lifetime of 7.5 years. In light of federal-budget constraints, US taxpayers and the Congress may not be willing to pay these costs.

The Russian Glonass satellite positioning system should be operational by 1995. Glonass will provide the same global coverage as the GPS and offers a viable supplement or alternative. However, receivers for the GPS and Glonass are not interoperable. The GPS employs time-division multiple access, and Glonass uses frequency-division multiple-access methods. Clearly, some political issues have to be addressed before a true global system becomes a reality. EDN

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