GPS

The First Global Navigation Satellite System

Accurate
LONGITUDE
GNSS
Satellite
Worldwide
TIME
MAP
DGPS
LATITUDE
Location
Information

Exact
RTK

Trimble

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Trimble®

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Welcome to GPS

GPS is a topic of worldwide interest. And we do mean worldwide. Bob Champoux, while using GPS technology to survey a construction site in Antarctica, noticed an emperor penguin watching from a hilltop some distance away. The curious penguin couldn’t quite figure out what Bob was doing, so it slid down the hill on its belly and waddled up to get a closer look.

It seems that everyone is interested in GPS—including you!

Unlike the penguin, you don’t have to stand in the freezing cold to learn about GPS. You can read this book in relative comfort, wherever you are. Enjoy!

Foreword

Mid-2008 will mark the 30th anniversary of the launch of the first Global Positioning System (GPS) satellite. That's roughly the time allotted to a human generation. But GPS is already well along in its second generation and is looking forward to the birth of the third, which is being called "the GPS for the next 30 years."

GPS is the first real Global Navigation Satellite System (GNSS). It has introduced and proven the advantages of worldwide, satellite-based navigation—and much more.

Since the early 1970s, the United States Government has spent tens of billions of dollars to develop, produce, and operate GPS as a dual-use (military and civilian) system. GPS is operated by the U.S. Department of Defense (DoD). But even before the system reached its full operational capability in 1995, the civilian user community had enthusiastically adopted GPS for its own applications. This civilian endorsement has profoundly influenced the Government's evolving vision of the system's future capabilities and direction.

Knowing your exact location can greatly improve how you work. GPS gives millions of people that knowledge on demand, around the clock and around the world, dramatically increasing their productivity and, in many cases, enabling them to do things they couldn't do before.

GPS has found its way into cars, boats, planes, surveying and construction equipment, cameras, farm machinery, laptop computers, cell phones, and virtually any other type of gear that can put knowledge of position to work for its users. As an added benefit, every GPS receiver also can provide near-atomic-clock-accurate time.

In the first 30 years, significant advances in technology have made GPS receivers far more capable, more accurate, and easier to use. The first GPS receivers were refrigerator-sized boxes costing hundreds of thousands of dollars that provided very rudimentary capabilities (rudimentary by today's standards; revolutionary then).

Today, basic GPS receivers have been condensed to just a few integrated circuits with very powerful software and are becoming ever more economical. This makes the technology accessible to and usable by virtually everyone. Public knowledge and acceptance of GPS have dramatically increased. GPS now is an integral part of the world's infrastructure and has literally become a new utility.

In the years ahead, GPS will be joined by other similar systems being developed in other parts of the world. Systems like GLONASS (Russia), Galileo (Europe), and Compass (China) either already exist or are being developed. Each is planned as a GNSS in its own right. But they also are expected to be mutually compatible. Receivers will be capable of using the signals from all the satellites to provide a virtually universal GNSS, providing far better, more robust performance and capabilities than any of the individual systems.

We're not there yet. We don't even really know where "there" ultimately will be. But we're well under way. And GPS will help us get there and tell us where we are, every step of the way. Exactly.

PART 1

GPS

What It Is and How It Works

What Is GPS?

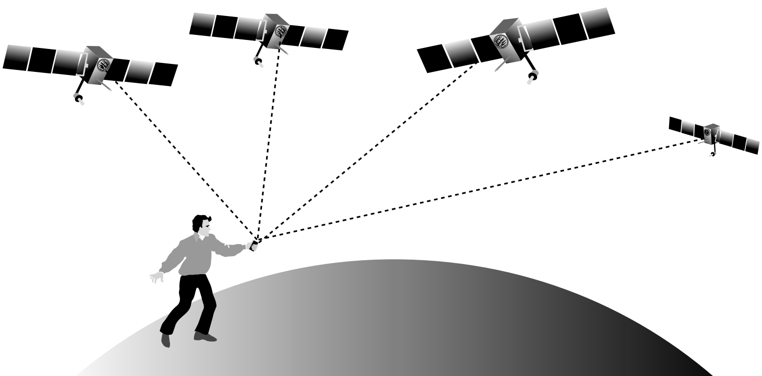
The NAVSTAR Global Positioning System (GPS) is a worldwide radio-navigation system formed by a constellation of 24 or more satellites, several ground stations, and millions of users like you. These system segments—space, ground, and user—work together to provide accurate positions any time, anywhere in the world, using the system's "man-made stars" as reference points.

It's like giving every point on the planet its own address.

Depending on your needs, you can use one of three common forms of GPS to tell you where you are to ever-increasing levels of accuracy:

- Even a modest, handheld GPS receiver, costing less than $100, can determine your location to within 15 meters (m). The rest of Part 1 explains the basic operation of this autonomous, or stand-alone, positioning.
- Slightly more expensive receivers, which use a second signal source for reference, can pinpoint your location to about 1 m. This form, called differential GPS (DGPS), is covered in Part 2.
- Surveyors and other professionals use advanced receivers and techniques to get precise measurements down to a centimeter (cm) or less. The Real-Time Kinematic (RTK) process is described in Part 3.

We'll begin by describing the segments of the Global Positioning System.



The Space Segment
The Satellites

The space segment is a constellation of 24 satellites in precise, nearly circular orbits about 20,200 kilometers (km) above the earth. Several additional satellites are also in orbit. They are designated as "spares" but are fully operational. So even if failure or planned maintenance takes one or more satellites out of service for some period, the constellation should always contain at least 24 operational satellites.

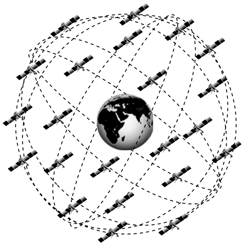
The satellites are arranged in six orbital planes. Each plane is tilted at 55 degrees relative to the equator, to provide polar coverage. Each satellite orbits the earth twice a day. As a result, at least four satellites are "in view" at any time, from any place on or near the earth's surface. This is significant because a GPS receiver requires signals from at least four satellites in order to determine its location in three dimensions (3D).

Each satellite is an autonomous navigation beacon in space. Each one continuously broadcasts low-power radio signals that identify it and provide information about its location in space, as well as system timing and other data. The signals are broadcast using two carrier frequencies in the "L" band of the ultrahigh frequency (UHF) range:

- L1 (1575.42 MHz)
- L2 (1227.60 MHz).

Rain, fog and snow have no effect on these signals, making GPS an all-weather system.

Image courtesy of Lockheed Martin Corporation.



THE GPS CONSTELLATION

The satellites continuously point their solar panels toward the sun and their transmitting and receiving antennas toward the earth. Each satellite contains several atomic clocks to keep very, very accurate time (to a *billionth* of a second). Each satellite also contains a computer, a radio transmission system, solar panels and batteries, and various other components.

Over time, the system and the satellites are being improved to provide ever-higher levels of capability: better accessibility for civilian users, improved security for military users, and increased reliability and accuracy for everybody.

Thus far, the major generations are Block I and Block II. Block III is currently being defined.

- Block I satellites were used for research and development and for gaining operational experience. No Block I satellites are still in use.
- Several versions of Block II satellites comprise today's operational system.
  - The first Block II satellite was launched in 1989. The system reached full capability with 24 active satellites in 1995.
  - As of early 2007, some 19 additional Block II GPS satellites have been launched to maintain the operational configuration and to introduce upgraded capabilities.
  - Seventeen more satellites are scheduled to be launched through 2012. For more information about Block II satellites, see Appendix A.
- Block III, the "GPS for the next three decades," is under development. The first Block III satellite is projected to be launched in 2013. The Block III planned capabilities are briefly described in Part 4.

GPS: BLOCK BY BLOCK

Generation	Block I	Block II	Block III
Function	Development	Operational	The Future
Satellites	11	60*	>30*
Launched	1978–1985	1989–2012*	2013* and beyond

**Projected*

The Control Segment

The Ground Stations

The Control Segment includes 12 ground stations; their locations and functions are listed in the table and shown on the map.

<table>
<tr><th colspan="3">GPS CONTROL SEGMENT GROUND STATIONS</th></tr>
<tr><th></th><th>Function</th><th>Location</th></tr>
<tr><td rowspan="3">Original Configuration</td><td>Master Control Station (MCS)*</td><td>Schriever Air Force Base (AFB), Colorado</td></tr>
<tr><td>Ground Antenna Station (uplink)</td><td>Ascension Island; Cape Canaveral, Florida; Diego Garcia; Kwajalein</td></tr>
<tr><td rowspan="2">Monitor Station (downlink)</td><td>Schriever AFB, Colorado; Ascension Island; Hawaii; Diego Garcia; Kwajalein</td></tr>
<tr><td>Added in 2005</td><td>Argentina; Bahrain; United Kingdom (UK); Ecuador; Washington, D.C.; Australia</td></tr>
<tr><td colspan="3">*An interim backup MCS is maintained near Washington, D.C. A permanent alternate MCS is under construction at Vandenberg AFB, California.</td></tr>
</table>

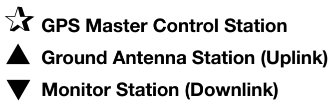
The monitor stations track the navigation signals from all the satellites and continuously send the data to the Master Control Station (MCS) for processing. The MCS computes orbit position projections for each satellite in the constellation, as well as corrections to the satellites' on-board clocks.

The MCS sends this updated orbit and clock data to the four ground antenna stations, from which it is uploaded to each satellite three times per day to maintain system accuracy. The ground stations also transmit commands to the satellites for routine maintenance, software updates, and orbit adjustments.

Every satellite is always in view of at least two ground stations and usually three.

For more information on planned Control Segment upgrades, see Part 4.

GPS GROUND STATIONS



The User Segment

You and Several Million Others

As far as you're concerned, the whole GPS system exists to tell you where you are right now. It does that very well—and for free!

But remember that it's a dual-use system, which means that it is intended for use by both military and civilian applications. So to be realistic about it, there are two distinct user segments:

- Military users can employ special system capabilities and have a very different list of applications than the rest of us.
- Civilians, like you and me, generally want to use the positioning and timing capabilities for everyday activities. This is the user segment for which this book is written.

How you use your GPS information is up to you, of course. Choose your receiver carefully for your specific application. Perhaps you want it to:

- help to keep you from getting lost in the wilderness,
- lead you to the nearest pizza restaurant in a strange town,
- pinpoint the position for a corner post of the building you're constructing,
- keep your fleet of service vehicles on schedule,
- steer your farm vehicle in a very straight line,
- help you to navigate your boat or airplane,
- or . . .

You get the idea. The civilian applications are virtually limitless; just a few are represented on the opposite page. The specialized types of receivers are legion. And the benefits to the user community are huge in terms of productivity, cost savings, safety, and even the ability to do things that couldn't be done before.

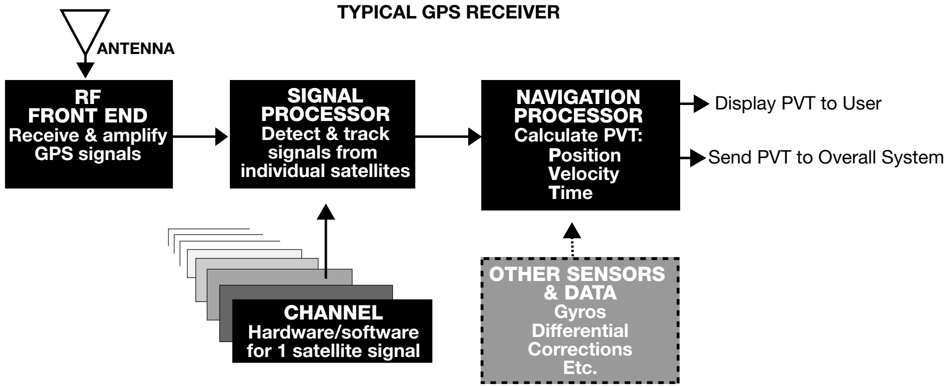
**TYPICAL GPS
CIVILIAN APPLICATIONS**

How Your GPS Receiver Works

Working Inside the Box

All GPS receivers have a similar core operation:

- collect the data broadcast by the satellites,
- measure the signals, and
- compute position, velocity, and time (PVT).



The antenna and a radio-frequency (RF) receiver (often called the RF front end) collect and amplify the incoming very low-power GPS radio signals.

The digital signal processor detects (acquires) and tracks the unique signals from multiple satellites. The signal processor also measures various parameters of each tracked signal. In most receivers, an individual "channel" is assigned for each satellite signal. Most modern GPS receivers have at least 12 channels; some have many more.

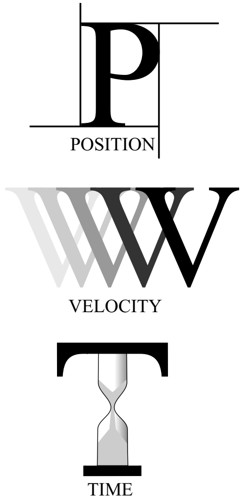
Using the measurements, the navigation processor calculates the PVT solution (often called a position "fix"). Once the solution is known, the receiver displays it in an appropriate form or sends it on to the rest of a larger system in which the receiver may be operating.

To further improve the final PVT solution, the receiver may also use data from other sensors (such as inertial gyros) or from differential GPS reference sources.

Now, about that PVT—how accurate is it?

The End Result

Accurate Position, Velocity, Time



Remember that we defined two user segments: military and civilian. Accordingly, there are two levels of accuracy standards:

- PPS: *Precise Positioning Service* provides special capabilities for users with military receivers; civilian receivers cannot access this service.
- SPS: *Standard Positioning Service* is the level of accuracy available with your civilian receiver.

Unless otherwise specified, all accuracy and other descriptions in this book refer to SPS operation.

Here are today's general rules of thumb for SPS accuracies:

TYPICAL GPS ACCURACIES			
PVT	**"Autonomous" GPS**	**Differential GPS (DGPS)**	**Real-Time Kinematic (RTK)**
***P*OSITION**	15 m or less (often much less)	1 m or less	2 cm or less
***V*ELOCITY**	0.5 km/hour or less		
***T*IME**	Within 100 nanoseconds of Universal Coordinated Time (UTC)		

The values above are very general. Naturally, with such a complex system, numerous specifications, definitions and caveats apply. Appendix D summarizes some of these details.

We'll explain DGPS and RTK—and why they offer much better accuracy than autonomous (standalone) GPS—in Parts 2 and 3 of this book. In the rest of Part 1, we'll discuss how autonomous GPS works, and why the position accuracy can vary.

How GPS Works

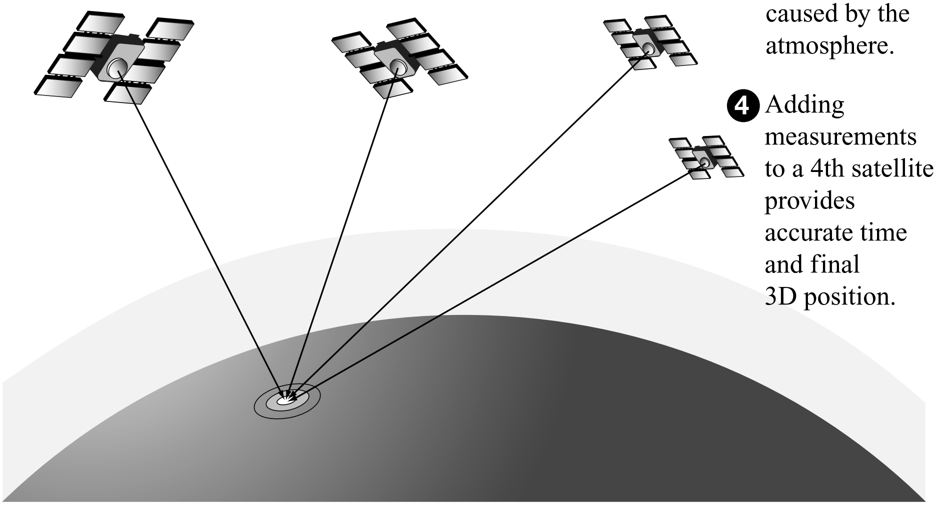
Improbable as it may seem, the whole idea behind GPS is to use rapidly moving satellites some 20,200 km out in space as reference points for locations here on earth. And this idea isn't limited to GPS alone. It is the fundamental concept for any GNSS.

To compute your exact position, your GPS receiver determines the distance to each of several satellites by:

- computing exactly where each satellite is in space,
- measuring the travel time from there to here of radio signals broadcast by the satellites, and
- accounting for delays the signals experience as they travel through the earth's atmosphere.

For right now, let's look at the "big picture" to see how this lets us figure out where we are. We'll fill in some details a little later.

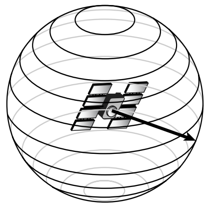
POSITIONING PROCESS



The Big Picture

Trilaterating from Satellites

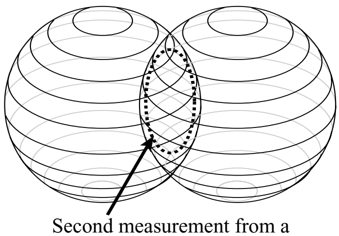
The process of determining where something is by measuring its distances from other objects is called trilateration; here's how it works in principle.



First measurement puts us somewhere on this sphere.

One Satellite

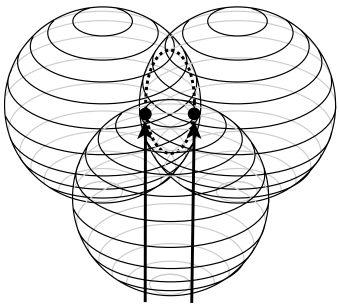
Suppose we measure our distance from a satellite and find it to be 20,200 km. This tells us we are located somewhere on the surface of a sphere with a radius of 20,200 km, centered on this satellite.



Second measurement from a second satellite shows we are somewhere on this circle.

Two Satellites

Next, we measure our distance from a second satellite and determine that it is 23,000 km away. So we're also on the surface of a sphere with a 23,000-km radius, centered on the second satellite. This limits our possible locations to somewhere on the circle where the first and second spheres intersect.



Third measurement from another satellite puts us at one of two points where all three spheres intersect.

Three Satellites

If we then measure to a third satellite and find that we're 25,800 km from that one, our position is one of the two points where the 25,800-km sphere cuts through the circle of intersection of the first two spheres.

Usually one of the two points is a ridiculous answer (either too far from earth or moving at an impossible velocity) and can be rejected. But we need an unambiguous answer: which one is the right one?

A fourth measurement will tell us, and has the additional important function of synchronizing your receiver's clock with the satellites' time. More about that later. Now that we've got the big picture, let's see how the system actually measures the distances.

First, Find the Satellites

Hey, Satellites, Where Are You?

OK, so we're going to use the GPS satellites as reference points. But how do we know where they are, other than they're way out in space and moving very fast?

It's easy: the satellites tell us. Each satellite knows where it is, based on a model of its orbit called an ephemeris. Each includes its ephemeris data as part of the information it broadcasts continuously.

The ephemeris for each satellite slowly changes. The medium-earth-orbit altitude of some 20,200 km is well above the earth's atmosphere, where there's almost no atmospheric drag. The orbits are very stable and precise—but not perfect.

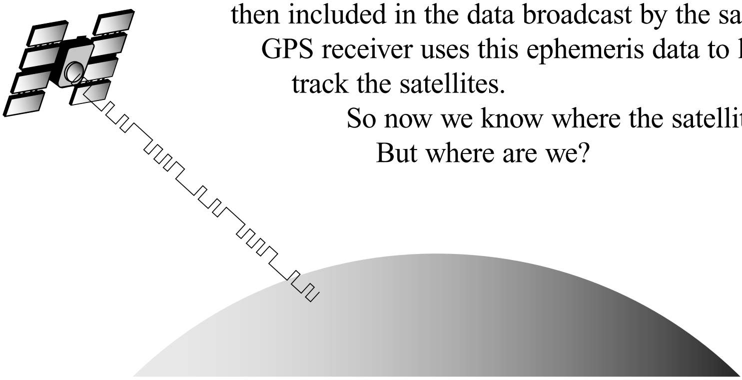
The satellites tend to "drift" from their planned orbits very slowly over time. The drift is caused by gravitational pulls from the moon and sun and by the pressure of solar radiation. The "ephemeris errors" caused by the drift are very slight, but they must be accounted for in order to maintain the precision of the system.

Each satellite is always in view of at least two ground stations. The ground stations continuously monitor the satellite's position, altitude, and speed with high precision and report the results to the master control station.

The MCS computes the ephemeris errors for each satellite and updates the ephemeris. The new ephemeris data is relayed back to the satellite by the uplink stations and is then included in the data broadcast by the satellite. Your GPS receiver uses this ephemeris data to locate and track the satellites.

So now we know where the satellites are.

But where are we?



Now, Find Yourself

Measuring Distance From a Satellite (Ranging)

Satellite ranging is the underlying principle of how GPS works. In a sense, the whole thing boils down to those math problems we did in school. Remember?

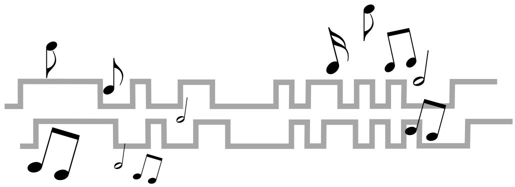
Q: IF A TRAIN GOES 80 KM PER HOUR, HOW FAR DOES IT TRAVEL IN 4 HOURS?

A: VELOCITY (80 KM) X TIME (4 HOURS) = DISTANCE (320 KM)

In the case of GPS, we're measuring a radio signal whose velocity is approximately the speed of light, or nearly 300,000 km per second. So if we can measure the travel time, then we can compute the distance.

Let's suppose we could get both the satellite and your receiver to start playing the same song at precisely 12:00:00 noon. (Of course, neither the satellite nor your receiver can play tunes, but let's pretend.)

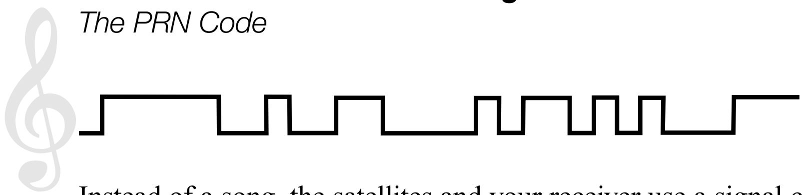
At the receiver, we'd hear two versions of the song: one from the receiver and one from the satellite. These two versions would be out of sync: the version from the satellite would be slightly delayed because it had to travel more than 20,000 km. The delay would be roughly 0.07 second (70 milliseconds).



To determine exactly how much the satellite's version was delayed, we start delaying the receiver's version until the two versions are exactly synchronized (in sync). The amount of time we have to shift the receiver's version is equal to the travel time of the satellite's version. So we just multiply that time by the speed of light and we have the distance.

Simple, right? But as always, there are a few details to work out.

What's the Name of That Song?
The PRN Code



Instead of a song, the satellites and your receiver use a signal called a pseudo-random number (PRN) code to determine travel time and, therefore, distance. The PRN code is one of the key elements of GPS.

The PRN code:

- uniquely identifies each satellite,
- provides the timing coordination for the system, and
- makes it possible to "amplify" the low-power GPS signal, so the receivers don't need big satellite dishes. For amplification of this subject, see Appendix B.

Each satellite generates its own, unique PRN code. The PRN code is a very complicated digital code—a sequence of "on" and "off" pulses as shown here. The sequence is not truly random; it repeats after a millisecond, hence the name "pseudo-random." It looks somewhat like random noise.

Even though each satellite's "song," or PRN code, is complicated, your receiver knows it too. Your receiver has been programmed with the PRN code of every satellite in the constellation. It's like there is a whole choir of at least 24 voices singing out there in space, and your receiver can pick out the individual voices—and sing right along with any one of them.

Your receiver identifies each satellite by its PRN code and generates the same PRN code itself. Then, using a process called correlation, it "slides" its own code in time until it is exactly synchronized (correlated) with the corresponding satellite's code.

But to determine the distance to each satellite, we need to know just when the satellite started transmitting the present "verse" of its code.

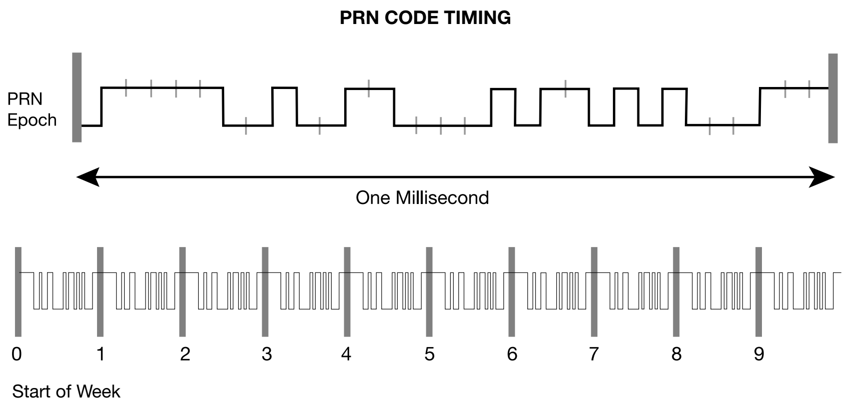
Timing is Everything (Almost)

Remember this: *GPS depends on time*. Without very, very accurate time, GPS is dead in the water (OK, in space).

The PRN code we use for ranging repeats every millisecond (msec), and each repeating cycle (or "verse") of the satellite's PRN code has a unique time tag. Effectively, GPS time starts with zero at the beginning of each week. Each msec thereafter has a unique, sequential identifier (from 0 up to 604,799,999 during the week).

This time-tagging provides an important capability. When your receiver examines a particular received epoch (start of the code), it can tell exactly when that epoch was sent from the satellite. It's as though the satellite sent out time packets that said, "At the epoch, the time will be 123,456,789, exactly…BEEP."

When the PRN code epoch arrives at the receiver, it has been delayed by an amount proportional to the distance of the satellite from the receiver. Now let's see how this is used in determining your position.



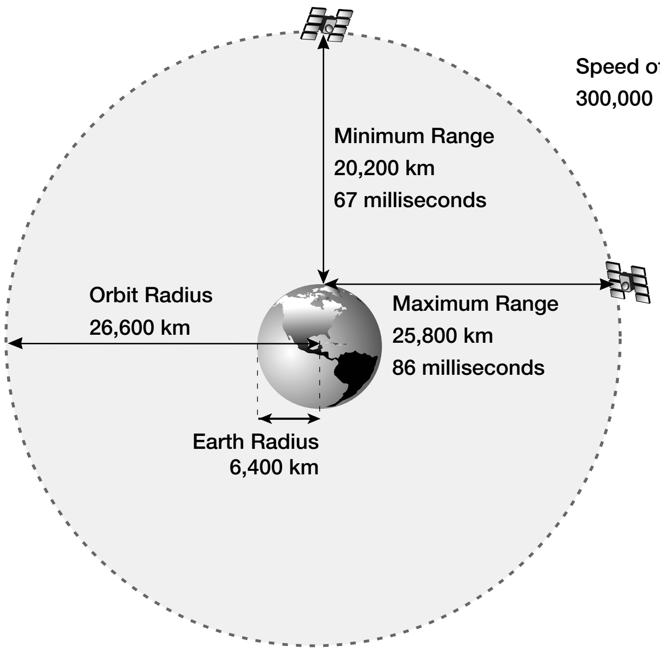
Range Geometry and Measurements

First, let's consider a bit of basic geometry involving the earth and the satellites. A satellite directly overhead is about 20,200 km above the earth's surface; a satellite at the horizon is 5,600 km farther away. All satellite distances vary between these two extremes when they're in view to your receiver.

The satellites' signals travel at roughly the speed of light and take between 67 and 86 msec to reach the earth. Signals arriving from different satellites will be delayed by various amounts between these values, depending primarily on where the satellites are in the sky.

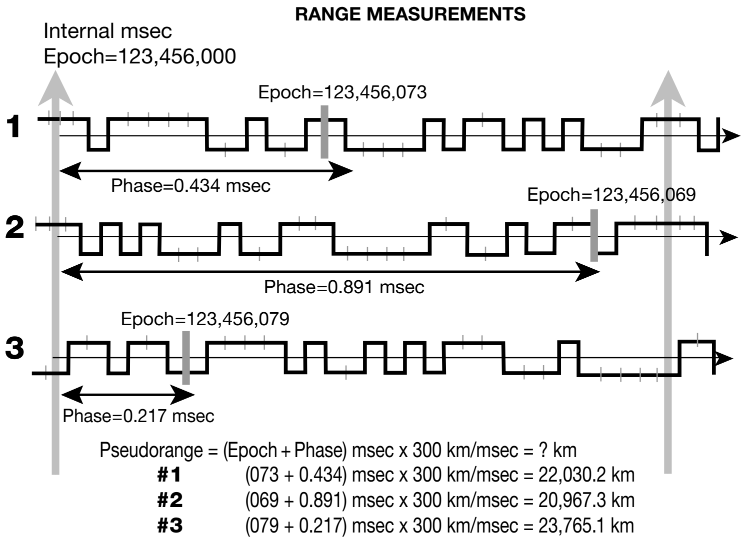
When we talk about making range measurements, what we really mean is the relative timing of the start of the received PRN code epochs. At some specific moment (usually aligned to the receiver's internal millisecond clock), we determine how far it is to the next PRN epoch on each received signal.

RANGE GEOMETRY



This gives us a partial range measurement between 0 and 1.0 msec. When we combine this value with the actual epoch count and multiply by the speed of light, we end up with the pseudorange (pseudo means false) to each satellite.

For example, in the illustration, pseudorange 1 is 22,030.2 km (73.434 msec x 300 km/msec); pseudorange 2 is 20,967.3 km; and pseudorange 3 is 23,765.1 km.



Because all the satellites are synchronized to each other (remember those atomic clocks and the ground control segment), they all launch matching epochs at the same time. Any differences we see between the received signals are due to differences in the distances the signals traveled to our antenna. The larger the pseudorange, the farther away that satellite is relative to the others.

It must be emphasized that we don't really know absolute timing here. We don't know our local clock error, so we can't determine the absolute delay—and therefore the accurate distance—to any satellite from the raw measurements. That's the reason for the term "pseudorange."

But a fourth measurement and some manipulation will give us our exact position and the exact time too.

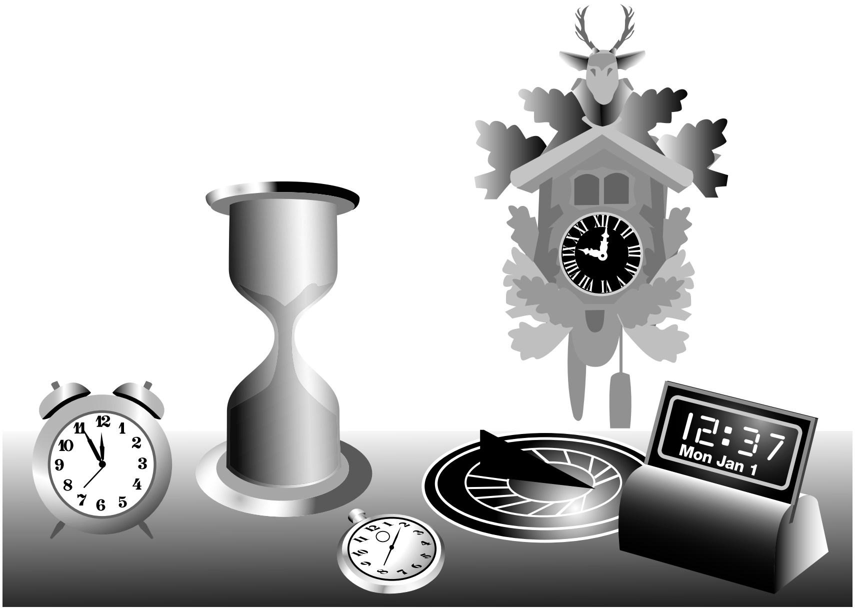
The Fourth Measurement is for Time

Time and Distance Go Together

If our receiver's clock were perfect, then all the satellite ranges would intersect at our exact position. But with our relatively crude clock, a measurement to a fourth satellite, done as a cross-check, will NOT intersect with the first three.

The receiver's computer recognizes the discrepancy and knows that it is not perfectly in sync with universal time. Any offset from universal time will be common to all our measurements. The receiver computes a single correction factor that it can apply to all its range measurements to cause them to intersect at a single point. That correction brings the receiver's clock into sync with the universal time broadcast by the satellites. Suddenly you have atomic-clock accuracy in the palm of your hand. And precise ranging too.

Or at least you're close.



What the Satellites Tell Us

I'm Here, All the Others Are There, the Time Is Exactly XXX, and I'm Feelin' Good!

Each satellite broadcasts two PRN codes that identify the specific satellite and provide a system time reference:

- A Coarse Acquisition (C/A) code for civilian users on the L1 carrier.
- A Precise (P) code for military users on both L1 and L2 carriers.

The satellites also continuously broadcast a Navigation (Nav) message (also called the Data message), superimposed on both the C/A code and the P code. The Nav message enables your receiver to determine the satellites' positions, their "health," the GPS time, and other factors; it includes the following information:

- Almanac: approximate orbit information for all satellites in the constellation. The receiver uses this data to determine which satellites it should track (which ones are "in view" and offer the best satellite geometry for the most accurate position fix).

  The almanac data is retained in your receiver's memory to enable rapid satellite signal acquisition, even if the receiver is turned off for several months. When you turn your receiver on again, it typically can recompute the satellite locations in less than a minute (a "warm" start).

  If, however, your receiver's memory has been erased and contains no almanac information when you turn it on, it may take a relatively long time (up to 15 minutes) to reacquire sufficient satellites for a position fix (a "cold" start).
- Ephemeris: predictions of the transmitting satellite's current position and velocity as determined by the Master Control Station and uploaded to the satellites. Your receiver uses this data to calculate the satellite's position at any point in time.
- Satellite clock correction parameters.
- Satellite health data that identifies if a satellite is operating properly or has been taken off-line.

The complete Nav message takes 12.5 minutes to transmit and then repeats. Within each repeat cycle, satellite clock and ephemeris data for the transmitting satellite repeat every 30 seconds.

Ranging Errors and How GPS Deals with Them

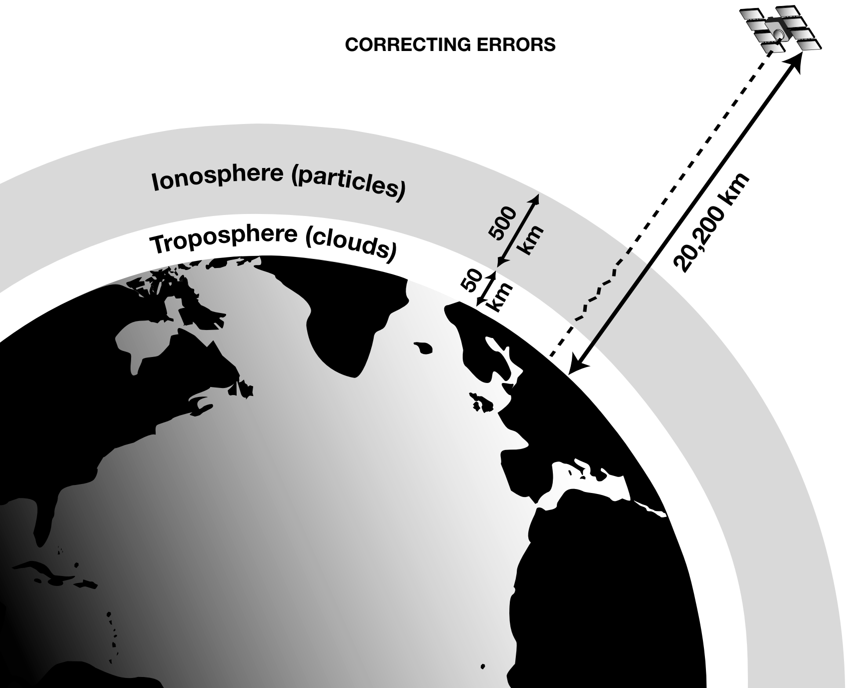
With a system this complex, operating in widely (sometimes wildly) varying conditions, there is plenty of potential for errors. Some of them can be predicted fairly accurately and factored out; others can't.

Ranging errors can be grouped into two general categories:

- User Range Errors (URE): these are errors due primarily to the space and ground control segments of the system, such as ephemeris and satellite clock errors, and atmospheric errors caused by signal delays in the ionosphere and troposphere.
- User Equipment Errors (UEE): these errors are due primarily to your equipment and local conditions. They include antenna orientation, receiver noise, and problems such as multipath reception and electromagnetic interference.

There are also just plain User Errors—mistakes—that you can make in using the equipment or interpreting the results. The system cannot predict them or factor them out. Only you can, by thinking through the process and not making the mistake in the first place.

CORRECTING ERRORS



User Range Errors

The combination of system errors and atmospheric errors constitutes URE. These errors can be significantly reduced through the use of DGPS or multiple-frequency techniques.

Through constant system improvements, the average URE has declined from more than 4 m in 1990 to just over 1 m in 2004. Note that this is a ranging error; the actual error in your position is always greater, as we will discuss shortly.

Ephemeris Errors

As described previously, the system monitors satellite drift and computes and broadcasts ephemeris corrections. However, even the updates are slightly off and slightly old, so errors in knowing the satellites' exact positions are inevitable. These ephemeris errors may add up to 2 m to your total range error.

Satellite Clock Errors

Although the atomic clocks on the satellites are excellent, they are not perfect and drift very slowly. This gradual drift, even though monitored and corrected by the ground segment, can account for up to 2 m of range error.

Ionospheric Delay

The ionosphere is the upper layer of the atmosphere, ranging in altitude from 50 to 500 km. It consists largely of ionized (charged) particles which can delay the GPS signals. The delay varies by location and time; the effects are most significant in the equatorial and polar regions. Ionospheric delay errors are typically in the range from 2 to 5 m in autonomous civilian receivers.

Ionospheric delay can be greatly affected by the 11-year sunspot cycle. Since its last peak in 2001, solar activity has been relatively low; as a result, even modest, autonomous GPS receivers often have provided good accuracies (down to a couple of meters). This may not be true when sunspot activity increases in the next few years. The next "up" cycle is expected to reach its peak around 2012.

Tropospheric Delay

The troposphere is the lower part of the earth's atmosphere where all our weather occurs. It's full of water vapor and varies in temperature and pressure, but actually causes relatively little error in the GPS signal transmission. Tropospheric delay errors are typically about 0.5 m.

Atmospheric Error Modeling

The "raw" errors caused by the ionosphere and troposphere are actually larger than described above. Mathematical models (predictions) of the atmosphere are built into most GPS receivers and take into account the charged particles in the ionosphere and the varying gaseous content of the troposphere. The satellites constantly transmit updates to the basic ionospheric model. The result is that most of the tropospheric error and some of the ionospheric error are removed through mathematical modeling in your receiver.

Other Ways Around Atmospheric Errors

Other techniques can remove most of the atmospheric error, reducing it to the range of 1 to 2 m. These include:

- ***Differential GPS***
  DGPS receivers, which receive corrections from a second receiver at a known location, are able to accurately account for the atmospheric delays.
- ***Dual-frequency, carrier-phase measurement***
  Lower-frequency signals are slowed more than higher-frequency signals as they travel through the ionosphere. Some advanced civilian receivers are able to compare both the L1 and L2 carriers to more accurately correct for the ionospheric delays.

DGPS and dual-frequency, carrier-phase measurements are described in Parts 2 and 3, respectively.

User Equipment Errors

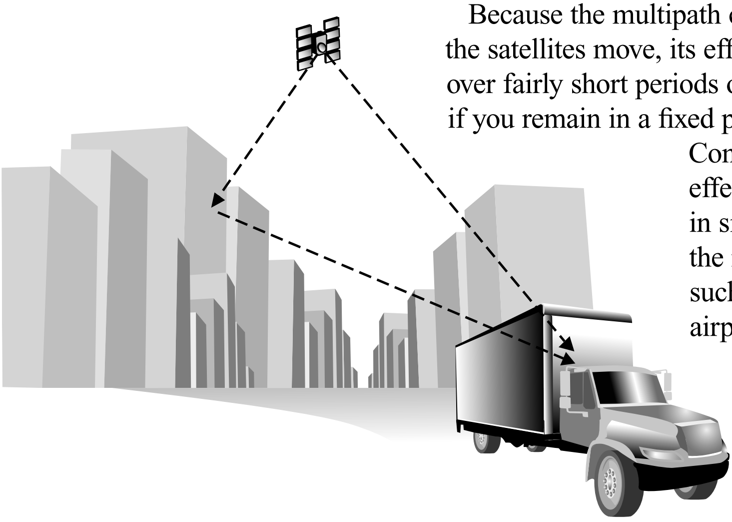
The other error sources—the receiver and antenna, interference from other signals, and multipath—are referred to as UEE.

Receiver Errors
GPS receivers can have minor errors in their ability to measure all signals equally. For example, the antenna may have different delays for signals at different elevations. Better receivers and antennas are capable of more accurate measurements to minimize such ranging errors, which can amount to up to 3 m.

Multipath Errors
All GPS ranging calculations assume the shortest possible direct path from the satellite to the receiver. Multipath errors occur when a signal reflects off nearby objects such as buildings before reaching the receiver. The result can be multiple signals arriving at the receiver: first the direct signal, then one or more delayed, reflected signals. If these "bounced" signals are strong enough, they can confuse the receiver and cause range measurement errors.

The potential ranging errors due to multipath can be as high as 10 m, but are usually much lower, on the order of 1 m. Sophisticated receivers use a variety of signal processing tricks to make sure that they only consider the earliest arriving (most direct) signals.

Because the multipath condition varies as the satellites move, its effects often change over fairly short periods of time, especially if you remain in a fixed position. Conversely, multipath effects are less severe in situations in which the receiver is moving, such as in cars or airplanes.



EMI/RFI

Because GPS uses very low-power signals that the receiver has to "dig out" of the background noise, the system is subject to degradation by electromagnetic or radio frequency interference (EMI/RFI).

- ***Jamming***

  GPS signals can be overwhelmed by other radio signals or electromagnetic radiation. Such "jamming" typically occurs as a side-effect of legitimate signals (such as general RFI) or intense solar sun-spot activity. It could also result from a hostile electronic attack, or from U.S. Government actions to deny access to GPS to hostile forces, although neither of these two situations has occurred.

  More advanced, higher-level receivers can minimize jamming. The addition of new frequencies and more powerful signals in later Block II satellites and the Block III system will reduce the likelihood of jamming.

- ***Spoofing***

  Spoofing is the transmission of a GPS-like signal intended to "fool" GPS receivers so they compute erroneous times or locations. The military signals are encrypted for anti-spoofing operations.

Selective Availability

In the early days of GPS, the U.S. Government used Selective Availability (S/A) to degrade system accuracy for civilian users. The idea was to prevent a hostile force from using GPS accurately for their own purposes. S/A caused continuously varying position errors that could reach as much as 100 meters.

S/A was turned off in 2000 by Presidential Decision Directive. This was done partly because of the system's rapidly increasing importance in business applications worldwide, and also because the growing use of DGPS essentially removed the S/A errors anyway. It appears that S/A is not likely to be turned on again in the future. However, the Government retains capabilities to deny civilian GPS service if deemed necessary.

Error Budget

The list of potential ranging error sources and their magnitudes is called the error budget and is shown in the following table for autonomous GPS.

TYPICAL GPS RANGING ERRORS	
Error Source	**Autonomous GPS**
User Range Errors (URE)	
SYSTEM ERRORS	
Ephemeris Data	0.4–0.5m
Satellite Clocks	1–1.2m
ATMOSPHERIC ERRORS	
Ionosphere	0.5–5m
Troposphere	0.2m–0.7m
Subtotals	**1.7–7.0m***
User Equipment Errors (UEE)	
Receiver	0.1–3m
Multipath (location dependent)	1–10m

**Ephemeris and clock errors are somewhat correlated and typically total less than the sum of the ranges for each.*

Our receiver has now done its job and calculated our position. Speaking autonomously, it appears that the solution is probably accurate to within 10 m unless we've got significant multipath problems. Not bad.

But not true. These ranging errors aren't the same as position errors, which are almost always larger. There are a few other considerations involved.

Other Considerations

Remember, the errors we've discussed are ranging errors, not position errors. The actual position errors encompass the ranging errors multiplied by a factor called the dilution of precision (DOP). And it's even possible that YOU have committed some kind of mistake, (not likely, of course, but possible) which might make the solution wrong by hundreds of meters!

Dilution of Precision

Different satellite geometries (the locations of the satellites in view relative to each other and to the receiver) affect the accuracy of your receiver's final position solution. The effect is quantified as the DOP value, which changes continuously as the satellites move across the sky.

There are several components of the overall DOP value, but we'll just deal with the big picture here, and talk primarily about Position DOP (PDOP).

Remember this important point: the satellite geometry can affect the vertical and horizontal components of position differently. The vertical component usually is worse than the horizontal, so GPS vertical accuracies aren't as good as horizontal accuracies.

The PDOP value is not used in the actual calculation of your position, but as a reference to evaluate the probable accuracy of the position. A PDOP of 2 (a typical number) means that, in the worst case, a 1-m URE will result in a 2-m positional error.

In general:

- Wider angles between the satellites lower the PDOP and provide a better measurement.
- Poor satellite geometry (all in a line or at small angles) yields a higher PDOP and poorer measurement accuracy.
- PDOP values range from 1 to infinity:
  - 1 to 4 results in accurate positions.
  - 6 or greater is poor.

Most GPS receivers can display the calculated PDOP for the current position. If the PVT data is being supplied for use by another system or for postprocessing, the PDOP data is usually recorded for reference along with the rest of the data.

Most modern GPS receivers can analyze the positions of the available satellites and use those that provide the best geometry and PDOP. Many receivers also can ignore or eliminate GPS readings with PDOP values that exceed user-defined limits.

Mask Angle

As we have seen previously, the distance a signal travels through the atmosphere is affected by the satellite's position (overhead, at the horizon, or somewhere in between). One way to minimize atmospheric errors is to set a mask angle that tells the receiver not to use satellites that are low on the horizon. A typical mask angle setting is 10 degrees to 15 degrees.

Number of Satellites in View

In the early days of GPS, before the full constellation of satellites was deployed, users needed to pay close attention to the times that at least four satellites would be visible in their locations. There often were days with only a few short windows of time during which operation was possible.

However, this has not been a problem since full operational capability was attained in 1995. The number of satellites your receiver can see at any time depends partly on your location and partly on the mask angle set into the receiver. Regardless, you should always have four or more satellites in view.

In the temperate regions of the world, typically about 1/3 of the constellation (some 8 to 9) satellites will be in view. But if your mask angle is set to 15 degrees, the number is reduced to about 1/4 of the constellation (about 6 or 7 satellites). You'll do a bit better in the tropics and worse in the polar regions.

Canopy, Canyons and Other Obstructions

The line-of-sight GPS signals can be obstructed by solid or semi-solid objects, such as mountains, buildings, or tree canopy, making GPS usage spotty or difficult in such surroundings.

There are various possibilities for achieving successful operation in such areas:

- GPS receivers vary in their abilities to function in obstructed areas; some are especially designed for maximum sensitivity to low-power signals.
- Other types of sensors or devices can aid your GPS receiver to maintain an accurate position. As one example, inertial navigation technology (based on gyros) can keep the receiver on track in areas where GPS is limited. GPS and inertial technologies are highly complementary. Inertial systems can be very accurate but tend to drift over time; GPS positions can be used to reset the inertial positions to minimize the drift.
- In some cases, surveyors and mappers can get around the problem by collecting an offset point in an area in which GPS signals are available and then recording the distance, bearing and slope to the obscured position of interest.

User Errors

User errors (blunders) aren't listed in the error budget, yet they can be the largest single flaw in the position solution. The most common type of user error—not carefully setting and recording the location format (coordinate system, map projection and map datum)—can result in errors of hundreds of meters.

- This is not really an issue if you are using a "closed system," such as a handheld receiver for personal navigation or an in-vehicle system while driving your car, in which the positions are presented in a standard, pre-determined form.
- But surveyors, map-makers, and many other specialized users who tie-in their GPS measurements with other systems and data, must be very sure to use the proper coordinate system, datum, and other factors to achieve proper information integration.

So make sure you do your job right, and your receiver will do its part.

PRACTICAL FACT

A GPS receiver calculates its position at its antenna, since this is where the satellite signals converge. This is fine for handheld and other types of receivers in which the antenna is built-in or attached to the receiver. However, in applications in which the antenna is offset from the receiver (such as on the top of a building), and/or may be far away from the position you really want to know, (such as the bow of a large ship), it is necessary to calibrate the installation to account for this difference.

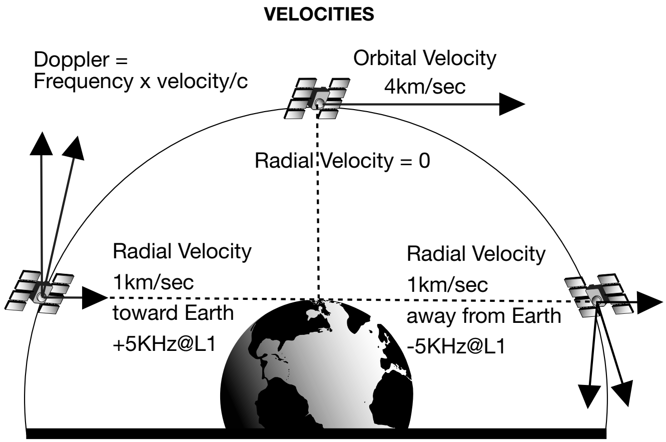
Velocity

Just How Fast Are We Moving, Anyway?

Most people assume (quite reasonably) that we calculate velocity by measuring positions at different times and then figuring out how far you moved in that time. This does work, but there's a better way.

Your receiver measures the Doppler frequency change or shift of the satellite signals (this effect is what makes the sound of a train or plane change as it goes by). The Doppler shift depends on where the satellite is in the sky, as shown in the diagram.

- Rising satellites are actually approaching the earth.
- Setting satellites are moving away from us.
- Satellites at their peak are only moving tangentially (momentarily parallel) to the earth's surface.



The Doppler frequency shifts are proportional to the velocity toward us or away from us.

Because we can predict exactly what the satellite Doppler ought to be and we can measure what it really is, we can compare the two values. Any differences are due to the motion of our receiver. Part of that motion comes from the rotation of the earth, but that is also predictable; removing that component gives us our velocity relative to our local coordinate system. This is an instantaneous measurement; that is, we can tell our motion from a single set of measurements.

And in conclusion . . .

So those are the basic concepts of autonomous (stand-alone) GPS. Let's review the key points:

- The Global Positioning System consists of a constellation of at least 24 satellites, synchronized and controlled by a network of ground control stations, to provide accurate position, velocity, and time solutions to millions of users—both military and civilian—worldwide.
- Autonomous GPS provides position accuracies of less than 15 m.
- Your receiver needs to have a clear view of at least 4 satellites to provide an accurate, 3D position.
- Your position is determined by trilateration—determining the pseudo-ranges to three satellites—and using a fourth satellite to compute a correction factor for precise time and accurate position.
- Pseudo-random number (PRN) codes identify each satellite and provide the timing references between the satellites and the users.
- Position errors are caused by drift of the satellite orbits and clocks, atmospheric factors, receiver errors, and multipath. And, possibly, by you.
- The positions of the satellites relative to each other also affect your position solution, as represented by the DOP factor.
- Obstructions such as terrain, buildings, and tree canopy can make GPS operation spotty or difficult. Rain has no effect.

PART 2

DGPS

What's the Difference?

The big difference between GPS and DGPS is accuracy. Differential GPS position accuracy is typically 1 to 2 m, sometimes less.

DGPS is much less affected by atmospheric conditions and system errors. DGPS has become the choice for all but the most casual GPS users and high-end users, like surveyors, who require even greater accuracy.

Remember the ranging errors budget we discussed in Part 1? Here's the table again, showing the difference that DGPS makes:

TYPICAL GPS RANGING ERRORS

Error Source	Autonomous GPS	Differential GPS
User Range Errors (URE)		
SYSTEM ERRORS		
Ephemeris Data	0.4–0.5m	Removed
Satellite Clocks	1–1.2m	Removed
ATMOSPHERIC ERRORS		
Ionosphere	0.5–5m	Mostly Removed
Troposphere	0.2–0.7m	Removed
Typical URE Ranges	**1.7–7.0m***	**0.2–2.0m**
User Equipment Errors (UEE)		
Receiver	0.1–3m	0.1–3m
Multipath	0–10m	0–10m

**Ephemeris and clock errors are somewhat correlated and typically total less than the sum of the ranges for each.*

As you can see, there is a significant difference in differential! Differential correction counteracts nearly all of the system and atmospheric errors that can be introduced into GPS signals. It does not help with local effects such as multipath and receiver errors.

How DGPS Works

Just as it takes two (dancers) to tango, it takes two (receivers) to gain the benefits of differential GPS. That's the basic meaning of "differential": comparing two different GPS signals to more accurately determine your location. Your DGPS receiver receives signals from the satellites and computes its pseudo-ranges, just as described in Part 1. But it also receives correction signals from a reference source or base station that already knows its exact location. Your receiver applies these corrections to its computed pseudo-ranges to produce a much more accurate position. This "real-time" DGPS is the predominant form of DGPS.

A second form, post-processed DGPS, uses a separate computer and specialized software to compute the position solution after the fact. The raw (uncorrected) data from your receiver is sent to the computer along with raw data from the reference source.

To begin, let's use your DGPS receiver and a generic GPS base station. We'll discuss various forms of reference sources later.

The Roving Receiver

Throughout this discussion, we'll call your receiver the roving receiver, or the rover. The rover determines your location as you move around, just as your basic GPS receiver did in Part 1. But now it's a DGPS receiver. The primary differences between the basic GPS receiver and your new DGPS rover receiver are:

- A radio receiver in the rover to acquire the differential corrections from the base station.
- Extra software to combine these corrections with the rover's computed pseudo-ranges.

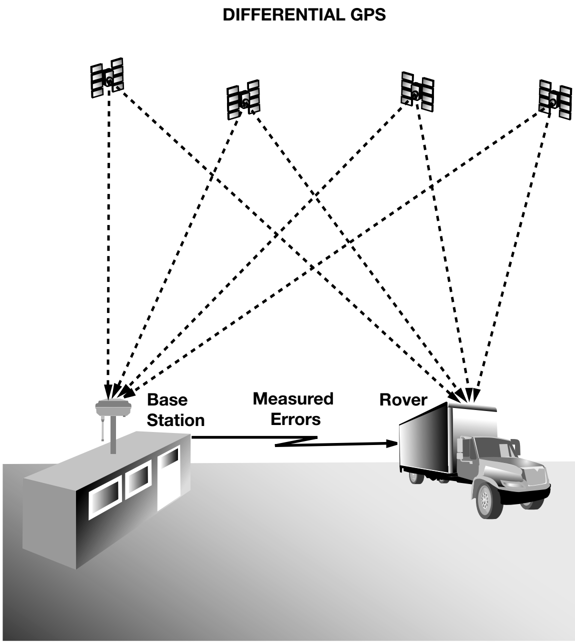
The Reference Receiver

The reference receiver (base station) is a GPS receiver located at a fixed position that has been surveyed or exactly determined by some other means. The base station:

- tracks all the satellites in view and measures their pseudoranges;
- solves the GPS problem in reverse to determine what the pseudoranges should be (remember: it already knows its exact position);
- generates a list of corrections needed to make the measured pseudorange values accurate for all visible satellites; and
- communicates the correction information to the rover(s).

One base station can support an unlimited number of rovers. The accuracy degrades gradually as the rover gets farther from the base station, primarily due to increasing differences in the atmospheric conditions affecting the URE. The typical practical limit for acceptable results is a few hundred kilometers.

Factors to consider in selecting the location for the base station include: clear view to the sky; proximity to your working areas; absence of RF interference; and minimal sources of multipath.



Real-Time DGPS

For real-time DGPS, the correction data usually is transmitted via a radio link from the base station to the rover. Radio provides the fastest path (and usually the most convenient) and minimizes solution "latency." Latency is the time lag between when the measurements are made and the resulting solution is generated by the rover; shorter is better. Mobile phone links also can be used, but generally are more limited in speed and connectivity.

Whatever the method, the data typically is transmitted in a format defined by RTCM-104, which is the standard for differential corrections and describes a set of message types and the way the data elements should be divided into streams of data bits. The structure is similar to that used for the data transmitted by the GPS satellites. (RTCM is the Radio Technical Commission for Maritime Services; it issues a variety of standards and specifications for marine navigation and communications equipment.)

Post-Processed DGPS

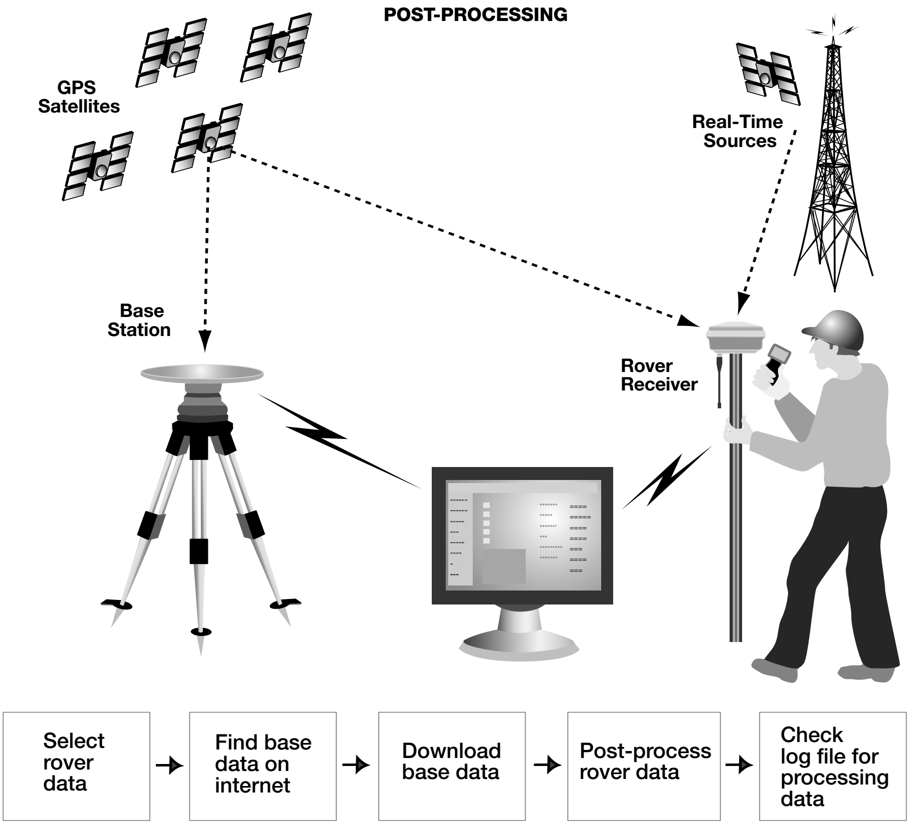
Because real-time DGPS corrections have latency in them, the corrections applied to a measurement are predictions based on the broadcast corrections for a few seconds beforehand. Post-processed DGPS can achieve better accuracy by using multiple base observations from before and after the measurement, as well as using more sophisticated algorithms.

The overall post-processing sequence is shown on the next page. Post-processing techniques require raw GPS base data to be stored in digital files that are later processed against raw GPS rover files by specialized software. The data from both the rover and the base station must contain simultaneous pseudo-range measurements to at least four satellites in common, as well as precise time stamps for each measurement.

The post-processing software calculates the error in each GPS pseudo-range measurement logged by the reference station receiver and applies the error corrections to the measurements in the rover data file. Accuracy can be submeter and better, but this depends on the capabilities of the rover receiver and the type of post-processing software used.

Post-processing was a more common practice in the early days of DGPS before adequate rover/base radio communication capabilities were developed. Today, post-processing primarily is used in certain surveying, mapping, or scientific applications. Extensive data is collected in the field, resolved to a high degree of accuracy, and further processed to meet the needs of the specific application. Most post-processing software packages are application-specific. They process the GPS position solutions and also manipulate the data as appropriate for the application.

For post-processed DGPS, data can be downloaded to the office computer from the instruments themselves, transferred via data card, or routed over the Internet. Increasingly, the data from both the rover and the base station are transmitted to the post-processing office over radio or mobile phone links.



Sources of DGPS Corrections

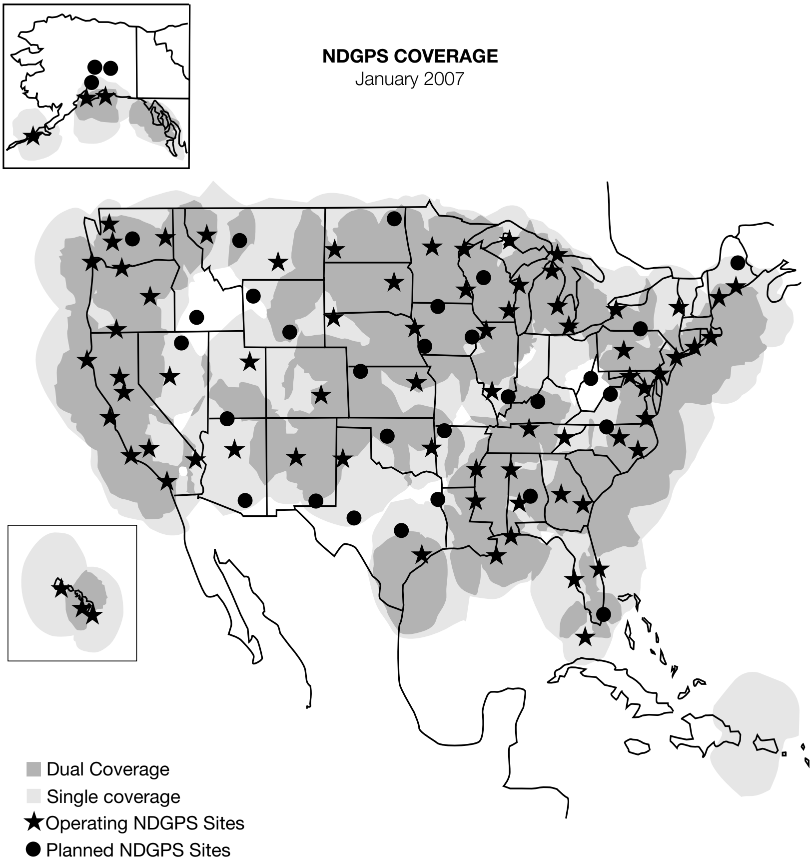
Setting up your own base station is just one of many potential sources of DGPS correction data. Numerous sources, both public (free) and commercial (paid subscription), are available throughout the U.S. and in a growing number of other countries. The sources can be broadly categorized as follows:

- Land-Based Beacons
- Satellite-Based Augmentation Systems (SBAS)
- Local Area Augmentation Systems (LAAS)
- Internet-Based Services

SUMMARY OF PUBLIC SOURCES FOR DGPS CORRECTIONS				
System	**Name**	**Areas Covered**	**Frequencies**	**Status**
Public Beacon Services				
NDGPS	Nationwide DGPS Service	Continental U.S., plus parts of Hawaii, Alaska, Puerto Rico	285–325 MHz	Operational
MDGPS	Maritime DGPS Service	Continental U.S. coastal areas, inland rivers, plus parts of Hawaii, Alaska, Puerto Rico	285–325 MHz	Operational
Satellite-Based Augmentation Systems				
WAAS	Wide Area Augmentation System	Continental U.S.	GPS L1	Operational
EGNOS	European Geo-Stationary Navigation Overlay Service	Europe	GPS L1	Partially Operational
MSAS	MTSAT Satellite-Based Augmentation System	Japan	GPS L1	Operational
QZSS	Quazi-Zenith Satellite System	Japan	GPS L1, L2, and L5	R&D
GAGAN	GPS-Aided Geo-Augmented Navigation	India	GPS L1	R&D
Local Area Augmentation Systems				
LAAS	Local Area Augmentation System	Local area around various airports in continental U.S.	108–117.975 KHz	R&D
Public Internet-Based Service				
CORS	National Continuously Operating Reference Station System	Continental U.S.	Internet Access	Operational
IGS	International GNSS Service	Worldwide	Internet Access	Operational

Public Beacons

As the agency responsible for GPS civilian operations, the U.S. Coast Guard (USCG) has developed and operates a network of reference beacon stations. These beacons provide real-time DGPS correction signals as a public service to support land and marine navigation applications throughout the U.S. The network began with the Maritime DGPS Service, which is being incorporated into the Nationwide DGPS Service. The NDGPS sites and coverage areas are shown below.



Maritime DGPS Service

The MDGPS Service is a medium-frequency, beacon-based augmentation system. It provides DGPS reference coverage (extending to at least 20 nautical miles offshore) for the continental U.S. coastline and parts of Hawaii, Alaska and Puerto Rico, as well as the Great Lakes and major inland rivers. Many of the reference stations are located at traditional marine navigation facilities, such as lighthouses.

The system's principal focus is to enhance harbor entrance and approach navigation, but the correction signals can be used for any surface DGPS application. Accuracy anywhere within the MDGPS coverage range is 10 m or better, and is typically within 1 to 3 m.

The MDGPS Service consists of more than 50 broadcast sites and 2 control stations. Each broadcast site receives GPS signals, computes real-time corrections, and continuously broadcasts correction signals on the marine radio beacon band between 285 and 325 kHz. The control centers remotely monitor and control the broadcast sites to ensure system integrity. Users are notified of an out-of-tolerance condition within a few seconds.

More than 40 other countries worldwide have developed similar systems for their own coastlines and waterways. Vessels can now take advantage of DGPS accuracy in coastal areas and ports around the world.

EXTRA POINT: ***GPS Signal Integrity***

The GPS system does not provide a warning if the signal(s) you're using become inaccurate. The "integrity" of your position solution (how much you can trust it) can be diminished if one or more of the satellites is unhealthy or out of service, or by other factors. GPS integrity is of significant concern in applications that affect user safety, such as aviation and marine port navigation. This is why most beacon and SBAS systems provide integrity checks and warnings to the user.

Nationwide DGPS Service

The NDGPS Service incorporates and adds to the existing Maritime DGPS Service. When complete, it will provide land-based differential GPS corrections and integrity data throughout the continental U.S. and portions of Alaska.

The NDGPS Service provides uniform DGPS coverage, even in areas with natural or man-made surface obstructions. The medium-frequency (285-325 kHz) radiobeacon is optimized for surface applications. Its ground-wave signals tend to hug the earth and wrap around objects.

Satellite-Based Augmentation Systems

Like the public beacons, SBAS collect data from numerous GPS reference stations. However, SBAS create and transmit correction messages to satellite(s), which broadcast the DGPS corrections to users over a wide area.

SBAS also can monitor GPS system integrity and notify users within seconds if GPS should not be used for navigation because of system errors or failures. This is a critical safety issue for civil aviation users and a principal reason for the development of SBAS. But they also work very well for land and maritime users as well as for aviators. With a suitable receiver, you can get DGPS accuracy without the need for a separate base station.

Satellite-based augmentation systems are being developed to support civil aviation needs in several regions of the world:

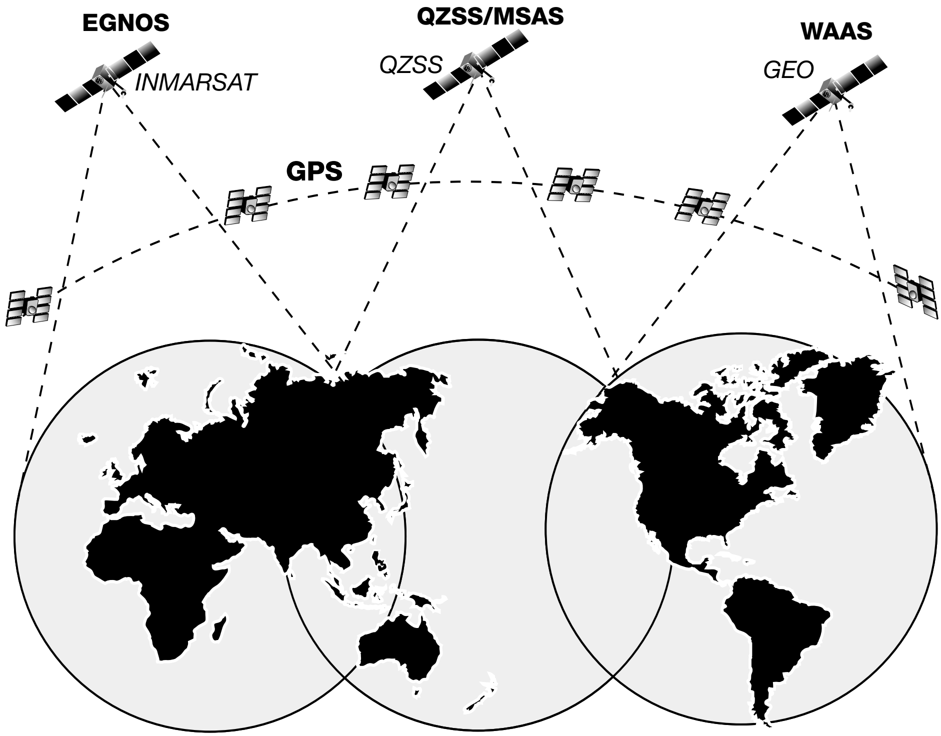
- WAAS in the U.S.,
- EGNOS in Europe,
- MSAS and QZSS in Japan, and
- GAGAN in India.

These regional systems are expected to be interoperable in the future to provide enhanced worldwide navigation.

The various SBAS are generally similar in concept. Each provides GPS look-alike signals and GPS corrections to improve positioning accuracies to about 1 to 2 m horizontally and 2 to 4 m vertically. Timing accuracy also is improved.

We'll go into a bit of detail about WAAS (it has been functional for land and maritime users for several years), and briefly describe EGNOS, MSAS, QZSS and GAGAN.

WORLDWIDE SBAS COVERAGE



Note*: The primary coverage areas for the SBAS are:*

EGNOS: Europe
MSAS/QZSS: Japan
WAAS: Continental U.S.

Possibilities exist to extend each coverage area to surrounding areas in the future.

WAAS

The Wide Area Augmentation System (WAAS) is operated by the U.S. Federal Aviation Administration (FAA) and is intended primarily to support aircraft navigation. It also provides DGPS accuracy for WAAS-enabled land and maritime GPS receivers in most of North America.

WAAS is designed to provide at least 7-m accuracy anywhere within its service area. Actual accuracies for WAAS-enabled GPS receivers are typically 1.5 to 3 m. The WAAS signal has been available since 2000 for non-aviation uses such as agriculture, surveying, recreation, and surface transportation. Millions of non-aviation, WAAS-enabled GPS receivers are in use today.

As shown on the next page, WAAS consists of:

- a network of some 25 GPS ground wide-area reference stations (throughout the continental U.S., plus Alaska, Hawaii and Puerto Rico),
- two wide-area master stations (one WMS at each end of the country), and
- several geosynchronous (GEO) satellites over the equator.

The ground network collects dual-frequency (L1 and L2) measurements of pseudorange and pseudorange rate for all GPS satellites in view, as well as local meteorological conditions.

Each WMS collects data from the reference stations and creates a GPS correction message. Unlike a standard DGPS correction message, this message does not provide composite pseudorange corrections. Rather, it provides separate ephemeris, clock, and ionospheric corrections. Tropospheric corrections are not included, because tropo errors are highly localized and the WAAS covers a very wide area. The correction message also includes GPS system integrity data and GEO satellite orbital parameters.

The correction messages are uplinked to the GEO satellites, combined with other data by the satellites, and broadcast back to the ground on the GPS L1 frequency. The signals are modulated with a PRN code similar to the signals from GPS satellites.

WAAS signals can be received in much of South America. However, there are currently no WAAS reference stations generating appropriate corrections in that continent, so the WAAS signals do not provide accuracy improvement over autonomous GPS in South America.

WIDE AREA AUGMENTATION SYSTEM

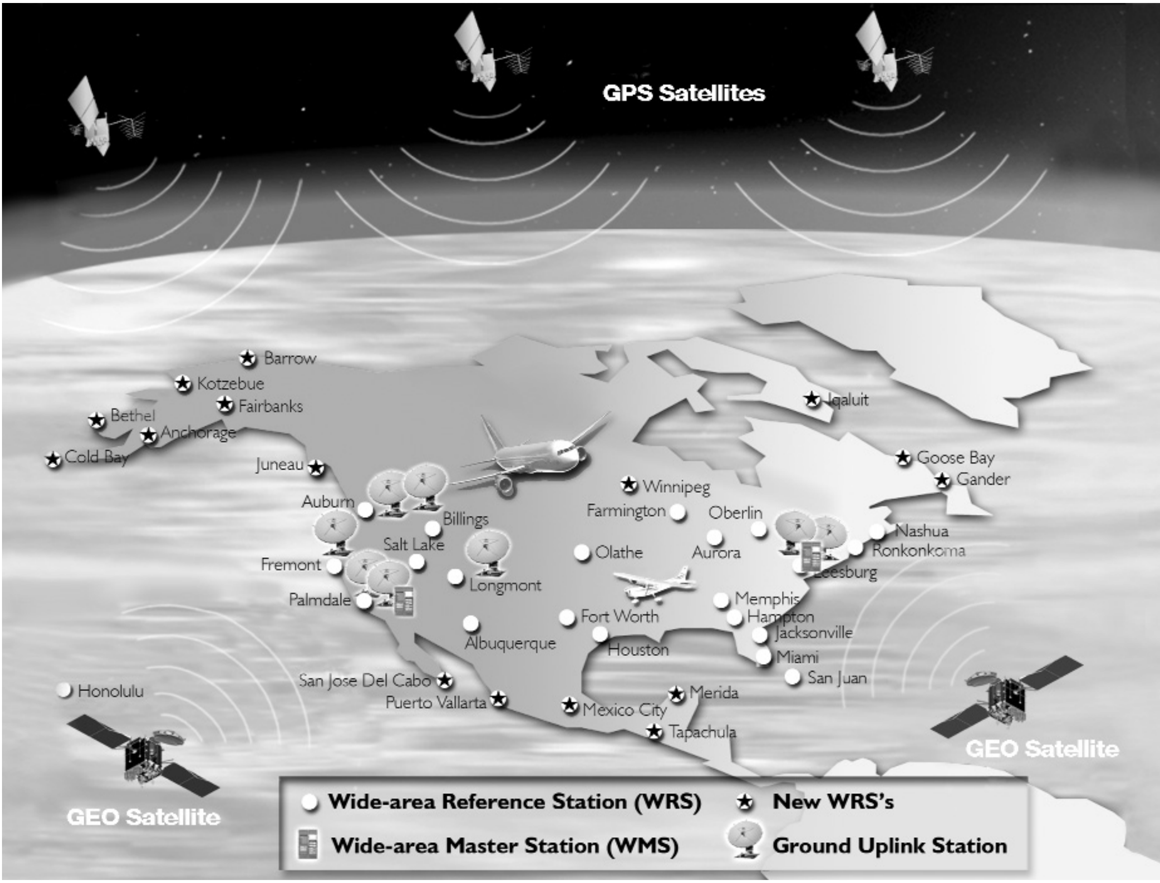


Image courtesy of U.S. Federal Aviation Administration.

EGNOS

The European Geostationary Navigation Overlay Service (EGNOS) is a satellite augmentation system generally similar to WAAS, serving aviation, maritime and land-based users in Europe. The system is being developed and will be operated by a group of European government agencies, headed by the European Space Agency.

EGNOS is the first step in the European Satellite Navigation strategy leading to the Galileo satellite navigation system that is expected to complement GPS in the future (see Part 4 for Galileo information). The system includes 34 reference stations and 4 mission control centers located throughout Europe. EGNOS is usable now for non-aviation applications.

MSAS and QZSS

The Japanese Civil Aviation Bureau has developed the MTSAT Satellite-Based Augmentation System (MSAS), which covers the Flight Information Region of Japan. The system relays GPS and GLONASS augmentation information to aircraft via Japan's existing two Multifunctional Transport Satellite (MTSAT) geostationary satellites. In addition, the system communicates with air traffic control stations to enable display of aircraft positions, identification, and other information.

The Quasi-Zenith Satellite System (QZSS) is projected to begin operation sometime after 2010 to further augment GPS and GLONASS over Japan. The system will enhance high-speed, broadband mobile communications and other applications in addition to navigation capabilities. Its three satellites will be placed in an orbit that will maximize their time directly overhead (more than 70 degrees) for greatest visibility in the country's deep urban canyons and mountainous landscape. The QZSS project is managed by a partnership between the government and an industry consortium.

GAGAN

The Indian Space Research Organization and the Airport Authority of India are planning and jointly developing a satellite-based augmentation system using GPS/GLONASS over Indian airspace. Named GAGAN (GPS Aided Geo-Augmented Navigation), the system is planned to be compatible and interoperable with other SBAS including WAAS, EGNOS and MSAS.

Local Area Augmentation Systems

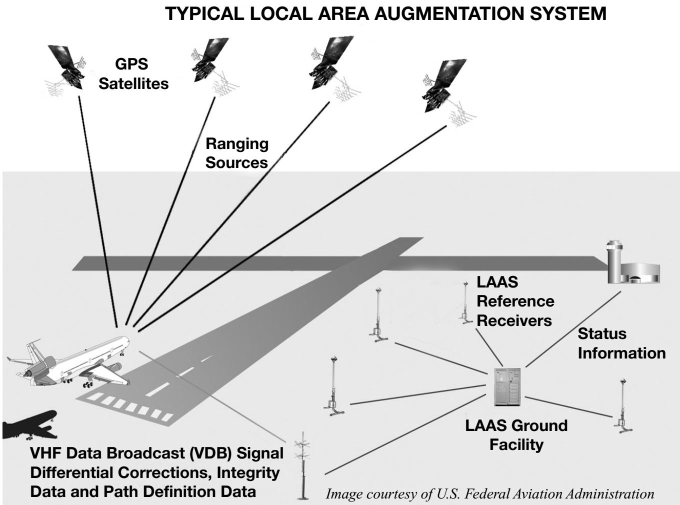


Image courtesy of U.S. Federal Aviation Administration

A LAAS is a reference and correction service provided for a specific local area, such as an airport. Typically, a LAAS comprises a group of GPS reference receivers, combined with a central processing and transmitting station, all usually within the boundaries of an airport, to provide terminal-area navigation.

The FAA is planning LAAS capability at major airports throughout the U.S.; the effort is currently in the research and development phase. The combined benefits of WAAS and LAAS eventually will provide accurate, all-weather GPS navigation capability for civil aircraft throughout the U.S., from takeoff through landing, including precision approach operations.

As shown here, the LAAS at each airport will use multiple GPS reference receivers to receive GPS and WAAS range measurements and navigation data. Data from the individual reference receivers are processed and averaged by specialized software to provide highly accurate differential range corrections, as well as integrity and availability parameters. The LAAS correction data are then broadcast to each aircraft operating in the local terminal area (nominally within 35 to 40 km) via the LAAS transmitter.

Because the LAAS reference stations are close to the approaching airplane, the tropospheric errors are common to both and are included in the correction message. Also, because multiple reference receivers are used, LAAS is able to correct for multipath effects.

Internet-Based Services

Internet-based corrections services are used primarily to provide corrections information for DGPS post-processing operations.

CORS System
The Continuously Operating Reference Stations (CORS) System supports non-navigation post-processing applications of GPS. Established by the National Geodetic Survey (NGS), the CORS System provides code-range and carrier-phase data from a growing nationwide network of more than 800 GPS reference stations.

The CORS system primarily serves two types of users:

- For post-processing applications using C/A code range data, users receive actual observations from a reference station (rather than corrections), and then compute the corrections in their post-processing software.
- Surveyors and others, who need post-processing positioning accuracies from sub-centimeter to a few centimeters, use dual-frequency (L1 and L2) carrier-phase observations from reference stations, rather than range data.

Rather than building an independent network of reference stations, the system uses data from stations operated by a wide variety of government, university and commercial entities. Stations from the Nationwide DGPS and Maritime DGPS services are included, as are stations operated separately by NOAA and NASA and by state and local governments.

The data from these sources is sent to the CORS Central Data Facility (CDF) via either the Internet or mobile phone packet service. The CDF converts the data to a common format, provides quality control, and places the final data in files on the Internet for access by users. The CDF also provides software to help you extract, manipulate, and interpolate the data.

International GNSS Service (IGS)

The IGS is a voluntary federation of many worldwide agencies that pool resources to provide high-accuracy data from GNSS satellites to users via the Internet. At present, data is derived from GPS and GLONASS satellites. The organization plans to also include Galileo data when that system begins service. All of the present suite of IGS data "products" is provided without charge to the user.

The IGS collects, archives and distributes GNSS observational data sets for post-processing use in a wide range of scientific applications and experimentation. Some of the applications include: monitoring deformation of the earth's crust and variations in the hydrosphere (sea level, ice sheets, etc.); monitoring the earth's rotation; ionospheric monitoring; climatological research; and time and frequency transfer.

The IGS comprises networks of tracking stations, a number of data centers, and several analysis centers.

- The tracking stations continuously track GNSS satellites and transmit the received data to the data centers.
- The data centers collect, validate, and permanently archive the data, and make it available over the Internet to IGS participants and external users.
- The analysis centers receive and process tracking data from one or more data centers to provide ephemerides, earth rotation parameters, ionospheric information, tropospheric parameters, station coordinates and clock information.

Named the International GPS Service when it began operation in 1994, the federation changed its name to the International GNSS Service in 2005 to reflect its expansion beyond GPS.

Commercial Services

Numerous firms offer DGPS correction services, generally on a paid subscription basis. Typically, for an annual fee, you can connect the appropriate receiver for the correction signals to your DGPS receiver and go on your merry way, realizing accuracies of 1–2 m. Some services transmit their signals on the FM radio band; others utilize their own satellites for broadcast. The commercial services are typically highly specialized for a particular application or locale.

PART 3

RTK

An Even Bigger Difference

As we've seen, the big difference between GPS and DGPS is accuracy. And the big difference between DGPS and Real-Time Kinematic (RTK) is even better accuracy—all the way down to the centimeter level!

Here's that error budget table again, with yet another column added to highlight the differences that RTK makes.

TYPICAL GPS RANGING ERRORS			
Error Source	**Autonomous GPS**	**Differential GPS**	**RTK**
User Range Errors (URE)			
SYSTEM ERRORS			
Ephemeris Data	0.4 – 0.5m	Removed	Removed
Satellite Clocks	1–1.2m	Removed	Removed
ATMOSPHERIC ERRORS			
Ionosphere	0.5 – 5m	Mostly Removed	***Almost All Removed***
Troposphere	0.2m – 0.7m	Removed	Removed
Subtotals	***1.7–7.0m****	***0.2–2.0m***	***0.005–0.01m***
User Equipment Errors (UEE)			
Receiver	0.1–3m	0.1–3m	***Almost All Removed***
Multipath	0–10m	0–10m	***Greatly Reduced***

* *Ephemeris and clock errors are somewhat correlated and typically total less than the sum of the errors for each.*

The term "kinematic" is derived from a Greek word meaning "to move." So using RTK measurement techniques means you can get super accuracy, right now, while moving. Pretty impressive! And very productive!

RTK isn't for everybody. The equipment is more expensive and its use is more technically demanding than standard DGPS. But for surveyors and other users who require the best accuracies they can get, RTK is an essential tool in their arsenal—even if they don't speak Greek.

How RTK Works

It's All Relative

To the average person, GPS is a navigation resource. It locates you somewhere on the planet in terms of latitude and longitude.

But, in many surveying and other scientific applications, the job isn't to locate a point according to latitude and longitude, but rather to fix the positions of a group of points in relation to each other. These points are often tied into a "control" point that locates them with respect to the rest of the world, but the important relationship is really the position of each point relative to the others.

This distinction is important when it comes to accuracy. Relative positions can be measured much more accurately than stand-alone, absolute positions. And that's where RTK shines!

Like basic DGPS, RTK uses a rover receiver and a reference (base) station. The base station sends real-time corrections to the rover over a communications link. The two receivers should be within approximately 20 km of each other. The increase in accuracy comes from the "ruler" that is used as the basis for the measurements. RTK uses a better ruler.

Carrier-Phase Positioning

RTK determines locations relative to the reference station by measuring the phase of the carrier wave rather than the PRN code. The carrier signal has a much shorter wavelength than the PRN code cycle width—a hundred to a thousand times shorter—so our ability to measure distance should improve proportionally. In effect, we're using a ruler with a much finer graduation. We'll spare you the gory details here; but if you must know, you'll find some of them in Appendix E. We'll try to keep it simple at this point.

Using the carrier phase gives us some advantages, as well as a problem:

- *Advantage: receiver errors are minimized.*
  With DGPS, we minimized the satellite errors and some of the atmospheric errors by measuring the PRN code at a reference point and sending the results to the rover. The rover subtracted the errors from its own range measurements to get a better result. This can be thought of as "differencing." This process leaves receiver errors as a significant

limitation to accuracy. By using the carrier phase and much more elaborate mathematical techniques, we can also difference away the receiver errors.

- *Advantage: atmospheric errors are minimized.*
  Ionospheric errors vary quite a bit from place to place and are very hard to model (predict) for single-frequency receivers. However, the ionospheric delay induced in the signal is a very predictable function of frequency. By measuring the delays in both the L1 and L2 carrier frequencies, the ionospheric error can be very accurately determined and significantly reduced. For this reason, centimeter-level equipment typically measures both the L1 and L2 carriers and is able to work at greater distances from the base station.
- *Problem: we must solve carrier-phase ambiguity by trial and error.*
  While the carrier phase gives us a "ruler" with much finer graduations, those graduations aren't marked. Unlike the PRN code, the carrier phase is not time stamped; it's just one wave after another, all alike. We can measure the phase of an individual carrier cycle very accurately, but we have no idea how many carrier cycles there are between us and the satellite.

  However, in this case we don't really care about the distance to the satellite; we only care about the distance and bearing from the reference receiver to our rover. This distance is much shorter and allows us to use some high-powered mathematical guesswork. We start by trying one solution and then another until we find one that best fits (satisfies) all the measurements. This process is known as "RTK initialization" or sometimes as "finding integers."

Obviously, all of this involves math—a lot of math. When carrier-phase positioning was first adopted in the late 1980s, it could only be done by post-processing on a computer after all the measurements were taken and collected together. The results could take hours to compute. With advances in techniques and technology, it is now possible to do this in real-time at the rover. Hence the name RTK.

Post-processing, rather than real-time, is still used for applications that demand ultimate accuracy (down to the millimeter). But RTK has become by far the method of choice for most surveyors and other GPS power users.

Differences Between DGPS and RTK

Here's a quick summary of the major differences between RTK and autonomous GPS and DGPS:

DIFFERENCES BETWEEN DGPS AND RKT			
CHARACTERISTIC	**AUTONOMOUS GPS**	**DGPS**	**RTK**
Satellites needed for operation	4		4 (after initialization)
Satellites needed for initializing	Initialization not applicable		5 minimum
Time required for accurate positioning	Instant		Less than 1 minute
Receiver	Single frequency sufficient		Dual frequency optimal
Measurements base	PRN code phase		Carrier phase
Accuracy	10–15 m	~ 1 m	~ 1 cm horizontal ~ 2 cm vertical
Base station requirement	None	■ Operator-owned; or ■ Fee-based correction service provider; or ■ Free government broadcasts (e.g., Coast Guard or WAAS)	■ Operator-owned; or ■ Fee-based correction network, with station or repeater not more than about 20 km from rover(s); or ■ Public or private "infrastructure" RTK reference network

RTK Reference Sources

So far, we have assumed the source of RTK correction information to be a single reference receiver. This carries with it a significant limitation: distance. The farther the rover gets from the reference receiver, the more the signal paths from the receivers to the satellites diverge through different parts of the atmosphere. This creates greater atmospheric (primarily ionospheric) variances, increasing the error in the resulting position.

This distance-related error is a more significant problem for carrier-phase processing than it is for the regular PRN code processing. There are two reasons for this:

- The basic accuracy of carrier phase is much better; therefore atmospheric errors will first be noticeable in carrier-phase results.
- As the rover gets farther away from the reference, eventually the errors will make the fitting of the correct number of carrier waves into the solution uncertain, causing an abrupt increase in the position error.

How far away the rover can be from the reference without guessing wrong on the carrier-wave integers depends primarily on the ionospheric activity:

- With a benign ionosphere, good results may be had at more than 20 km from the reference.
- Under a more active ionosphere or in the tropics, you can't get much farther than 5 km from the reference without risking abrupt accuracy degradation.

RTK Networks and GPS Infrastructure

We can improve this situation by using several reference receivers, configured as a network. A network of reference receivers is more than the sum of its parts. By sharing information from multiple sites, a network can make better error estimates for the spaces in between the reference receivers than could be provided by any single receiver. Thus, a network can use fewer reference receivers across a broader area than would ordinarily be expected.

RTK networks provide several common advantages to users.
For example, an RTK network:

- enables fast, centimeter-level positioning anywhere over a large area;
- provides a common coordinate reference frame; and
- eliminates the need to set up a private base station for each job.

Your RTK network choice depends on your requirements and the coverage area needed.

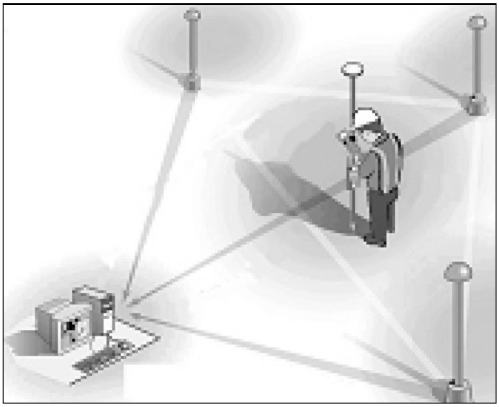
Single Reference Station

The first infrastructure level is an independently operated community reference station providing data for multiple applications. Private firms, municipalities and larger agencies all find single reference stations a good starting point. Generally, a single reference station can support a variety of applications, including:

- post-processed file logging for static surveying; and
- single-base RTK positioning for precision applications within a 20-kilometer radius.

Multiple Reference Stations

The next GPS infrastructure level is a multi-station network covering a larger area but still controlled from one central site. Each station offers single-base RTK positioning but all stations are managed centrally. The advantages of these networks include increased quality control and enhanced coordinate/data monitoring. Network managers can control who has access to the systems for RTK broadcasts.



Wide Area RTK Network

The third GPS infrastructure level is the wide area RTK network. Network software—offered in various forms by several vendors—processes data from a network of three or more reference stations simultaneously and provides a fully modeled solution which factors in potential errors. Users access the network using a wireless connection such as radio or mobile phone. The network software receives the rover's approximate position and generates RTK corrections that the rover applies to significantly reduce errors due to atmospheric disturbances. This type of network provides the largest ratio of coverage area per reference station of any network, enabling surveyors to work at long distances from the physical reference stations.

Infrastructure is Growing

As time goes on, more and more GPS reference sources are covering more and more ground, both in the U.S. and in other countries worldwide. These sources include some of those described in Part 2 for DGPS, as well as specialized reference networks just for RTK users. Collectively, such sources (both private and public) are creating a growing GPS infrastructure in many areas of the globe.

Japan has built the world's most dense nationwide GPS network. Its GPS Earth Observation Network (GEONET) System comprises more than 1,200 reference stations throughout the country and an extensive data analysis system. Created and maintained by the Geographical Survey Institute of Japan, GEONET is used to monitor and study geodetic/geophysical phenomena in this seismically active area of the world.

In the U.S., the Ohio Department of Transportation has created a statewide RTK network consisting of some 52 reference station sites. This network is expected to be incorporated into the NGS CORS System described in Part 2. The department built the network for its own use, but allows other surveyors and construction workers to access the network for a small fee.

PART 4

Today and Tomorrow

GPS and GNSS

Making GPS Even Better

The Global Positioning System is a huge success in its impact on civilian uses, far exceeding most projections made during its development. However, in the world of high tech (and GPS is one of the highest of high-tech environments), what's good today won't be good enough tomorrow.

So, way back in 1998, the U.S. Government announced a long-range program to extend the capabilities of the GPS system. The GPS Modernization Program (projected for completion in 2012), will improve the accuracy of the system, as well as increase its usability and reliability for all users. Military users also will benefit from a number of advanced features along with increased security and resistance to jamming.

And the next GPS generation, Block III, is now being planned to provide a whole new level of system performance extending to well beyond 2030!

GPS Modernization

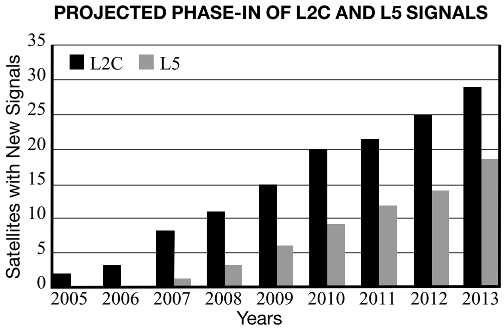
The GPS Modernization Program primarily involves the addition of new codes and signaling channels to the Block II satellites over a time period that started in 2005 and extends to 2012. In addition, the Control Segment is being improved to take full advantage of the new capabilities.

Satellites and Signals

Two new versions of Block II satellites constitute the GPS Modernization Program: Block IIR-M and Block IIF.

- Block IIR-M satellites, which began launching in 2005, introduce a new civilian code (L2C) and a new military code (M).
- Block IIF satellites, which are projected to begin launching in 2008, introduce another new civilian code and carrier (L5C).

The legacy codes (C/A and P) will still be used in all satellites. At the current satellite replenishment rate, the two new civilian signals (L2C and L5) will be available from every satellite in the constellation by approximately 2015. However, civilian users should be able to make practical use of them long before that time.



For example, the first L2C-capable satellite was launched in 2005 and three were in orbit by the end of 2006. Some equipment vendors introduced L2C-capable receivers even before the first Block IIR-M launch.

An L2C-capable receiver can use the signal in conjunction with the existing L1 signal to more accurately correct ionospheric time-delay errors in dual-frequency applications. Therefore, L2C signals contribute to improved performance in such receivers whenever even a single L2C satellite is in view. As the number of satellites broadcasting this signal increases, the available in-view times and coverage areas also will increase, resulting in a corresponding performance improvement.

On the other hand, the L5 signal from the Block IIF satellites is an entirely new capability. Its benefits will not be fully usable until sufficient satellites are in orbit for L5-capable receivers to acquire the signal consistently from at least four satellites. For more details on the evolution of the satellite constellation and the signals, see Appendix A.

GPS Control Segment

The GPS Control Segment is also being modernized. The principal upgrades include:

- equipping dedicated monitor stations and ground antennas with new receivers and computers;
- replacing the existing master control station mainframe computer with a distributed architecture;
- adding capabilities to match the evolving technology of the satellite constellation; and
- building an alternate master control station at Vandenberg Tracking Station in California.

Once the control segment modernization is complete, improved system performance with more precise clock and ephemeris information will be available.

And Then Comes Block III . . .

GPS Block III is described as the GPS system of the next three decades. The goal of the GPS Block III program is to satisfy the evolving user needs for a space-based positioning, navigation and timing system through 2030. More than one hundred million dollars already have been spent on conceptual studies, research, and planning for the new system.

In general, Block III will provide more power and improved accuracy, as well as increased civilian navigation safety. In addition to the improved signals, the accuracy and reliability of the GPS navigation message will be improved by adding more monitor stations to ensure that each satellite is simultaneously monitored by at least three monitor stations.

Block III satellites will broadcast another new signal, L1C, for civilian use in local, regional and national safety-of-life applications. L1C will be broadcast at a higher power level and include advanced design for enhanced performance. The L1C signal also is intended to be compatible and interoperable with the planned European Galileo system.

The first of the new Block III satellites is projected to be launched in 2013, with the entire Block III constellation expected to remain operational through at least 2030.

The Evolution in Accuracy

The accuracy provided by an autonomous GPS receiver will continue to improve in the coming years, as shown in the following table.

EVOLUTION OF GPS AUTONOMOUS ACCURACY (CIVILIAN)		
TIME FRAME	**ACCURACY**	**BASIS**
Before May, 2000	20–100 m	C/A code; Selective Availability (S/A) on
May 2000–2005	10–20 m	C/A code; SA off
Starting in 2005	5–10 m	C/A code + L2C code
Starting in 2008	~5 m	C/A code + L2C code + L5 civil code
Starting in 2013 (Block III)	~5 m	C/A code + L2C code + L5 civil code + L1C code

Note that the autonomous accuracy, even with Block III, is not as precise as the typical 1- or 2-meter accuracy available today with DGPS.

Other Global Navigation Satellite Systems

GPS is Not Alone

GPS is the first global navigation satellite system (GNSS). More are on the way.

Several other GNSS systems, which will provide satellite navigation services similar to GPS, are either in development or partially deployed. Since these systems are very much like GPS, we'll describe them primarily by their differences from GPS.

GLONASS

The Russians launched their first **GLO**bal **NA**vigation **S**atellite **S**ystem (GLONASS) satellite in 1982. Like GPS, a full GLONASS constellation is 24 satellites, but GLONASS only attained as many as 23 operating satellites during the first half of 1996. In the ensuing ten years, significantly fewer satellites were available in orbit due to budget constraints. Russia now has renewed efforts to improve the system and is launching new satellites with the goal of filling out the system in the next few years.

Where GPS has satellites in six orbital planes, GLONASS uses only three orbital planes. Since three satellites are launched at a time, and all satellites in a single launch must use the same orbital plane, this configuration optimizes the ability to place new satellites efficiently.

Many GPS receivers today can use signals from both GPS and GLONASS satellites. This can provide better performance with more satellites in view and improved DOP.

Galileo

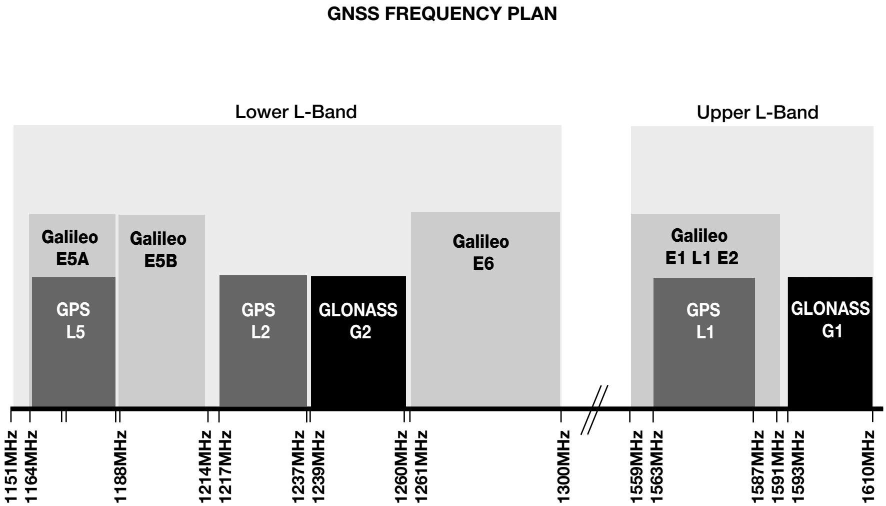
The European Union and the European Space Agency are developing a satellite navigation system named Galileo. The first Galileo test satellite was launched in 2005.

In contrast to both GPS and GLONASS, Galileo is planned to be run by a commercial concessionaire rather than directly by government agencies. Although all the development and most of the startup costs will be publicly borne, the original plan calls for operational costs to be recovered in the marketplace. Therefore, Galileo has multiple frequency bands and services, including an open service, a commercial service, a public regulated service (governmental and military), a safety-of-life service, and a search and rescue communication service.

Galileo uses three orbital planes for launch efficiency, similar to GLONASS. Galileo satellites are expected to be light enough to allow as many as eight to be launched at a time. The full Galileo constellation is 30 satellites, compared to 24 for both GPS and GLONASS, and the orbits are about 10 percent higher. Both factors improve high-latitude visibility to provide optimum coverage in northern Europe.

GPS, GLONASS, and Galileo Frequency Plan

To illustrate the potential interrelationships of GPS, GLONASS, and Galileo, the frequency allocations of the three systems are shown in the following chart.



As you can see, the frequencies used by each of the systems are the same or very close to each other. As long as the respective controlling agencies continue their cooperation and commitment to interoperability, producing GNSS receivers that can utilize the satellites of all three systems is quite feasible.

And More ???

Beidou/Compass

After launching Beidou geostationary satellites to provide positioning in the coastal regions of China, the Chinese government announced a plan to expand the system to cover global navigation as well. The future Compass system is projected to add as many as 30 medium-earth-orbit satellites (similar to GLONASS and Galileo) to several Beidou geostationary satellites already maintained over China. Positioning accuracy to 10 meters is projected. China launched the first Beidou satellite in 2000. Projected in-service dates are 2009 for coverage of the Asian region, and 2012 for worldwide service.

GNSS Today and Tomorrow

With the first GPS satellite launch in 1978, GPS established the possibility of worldwide satellite navigation. As the GPS constellation filled out, the reality of a GNSS made navigation easier for cars, planes, and ships around the world and transformed the way agriculture, surveying, construction, mapmaking, and other activities are done.

Each of the systems we've described—GPS, GLONASS, Galileo, Compass—is (or is projected to be) in itself a GNSS. As such, each has the potential—already realized by GPS—to provide worldwide navigation support to its users and, to some degree, to enhance the capabilities of the other systems and their users.

For example, receivers are available today that can utilize signals from both GPS and GLONASS. The addition of the GLONASS satellites to the 24 GPS satellites (plus the operational spares in each system) almost doubles the number of satellites that are in view at any time. This can provide better PDOP values for greater accuracy, improved coverage throughout the world, lower susceptibility to interference, and many other distinct performance and reliability improvements.

And, as Galileo, Compass, and others reach operational status, their interoperability with GPS will provide even better coverage and results for users with appropriate receivers. The combined coverage of these systems should enhance the universal performance of GPS to commercial customers and consumers throughout the world.

But is there more?

To be continued in the near future . . .

PART 5

Applications

How GPS is Used

Perhaps the most common image people have when they think of GPS is that of a hiker somewhere out of doors using a handheld receiver. Or perhaps it's of a navigation unit sitting on the dashboard of a car. Those are indeed popular applications of this worldwide utility. But they are by no means the only ones. GPS has become essential to a very large number of users in many different applications, and is responsible for huge gains in productivity and capability in many professions.

We'll briefly describe some of the major civilian applications in the following pages. We can't possibly cover them all, because new uses are being developed practically every day. Maybe the next discovery will be yours!

GPS for Everybody

Ever been lost? On the road? On a backwoods trail? In your boat? In your plane? Anywhere?

Almost everybody has; many of us more than once. At such time(s), we wished we had a magic box that would tell us where we were and how to get where we wanted to be. Today that magic box is a GPS receiver.

We're speaking here of the small, handheld GPS receivers you can buy in most consumer electronics stores, sporting goods stores, or over the Internet. They range in price from less than $100 to several hundred dollars, depending primarily on their features and performance. There's sure to be a GPS receiver out there that's just right for your needs.

Common Characteristics

All consumer-level GPS receivers share a number of basic features. They have map displays and databases that contain a variety of information about the displays. And all will tell you the precise time.

All provide basic navigation functions. They show you where you are now (point A) and how to get from point A to some other location (point B) by indicating the bearing (direction) and the range (distance) to go. You can create waypoints (any location of interest) and navigate to any of them. You also can create routes: a series of waypoints on the map that are to be followed in sequence to reach your desired destination.

You can enter a variety of data manually in the field, or you can use computer mapping software to plan waypoints or routes at home. Most units are prepackaged with a database for a large region; many can be customized by downloading data for other regions or special purposes.

Beyond these basic navigation capabilities, the more-advanced units generally add more features and capabilities tailored to a specific application, such has hiking/outdoors activities, or navigating your car, boat, or airplane.

Applications

Personal Navigation

Hikers, bikers, hunters, fishermen and other outdoorsmen and women are usually interested in their position, the range and bearing to a particular waypoint, the distance traveled, and perhaps their average and instantaneous speed. They may also be interested in precisely how they have gotten to where they are and how far it still is to where they're going. Most GPS units allow you to record a track, or "breadcrumb" trail, of your path, which is very helpful if you need to return on the same path to camp, where you parked your car, or to another landmark of interest. Increasingly, computer programs like Google Earth allow consumers to view paths between points complete with terrain features in three dimensions.

Aviation Navigation

GPS has become the preferred method of navigation for all types of civilian aircraft, from crop dusters to jumbo jets and from business helicopters to recreational airplanes. It provides accurate position fixes and velocity readings anywhere in the world for less cost than inertial navigation systems. And, unlike previous radio navigation systems (such as VOR, LORAN, and others), GPS doesn't require ground equipment infrastructure and maintenance for use in a region.

Aircraft owners can choose from numerous types of panel-mounted or portable GPS receivers. Panel-mount units are often coupled into the aircraft's autopilot and approved for instrument approaches in poor weather.

Extensive aviation databases can be loaded into the receiver, providing complete information on all airports and other relevant navigation information in a region for use in flight planning, en-route navigation, or dealing with emergencies. The pilot can enter a flight plan directly into the GPS receiver, or into a laptop computer and then download it into the GPS receiver in the plane. En-route changes—such as identifying the nearest airport that sells hamburgers and plotting a course change to get there—can easily be entered directly into the receiver at any time.

Techniques such as Receiver Autonomous Integrity Monitoring (RAIM) and Fault Detection and Exclusion (FDE) allow airborne, FAA-certified GPS receivers to detect errors in the satellite signals or within the receivers themselves. Often, the unit can be allowed to continue to operate without the faulty signals, ensuring the reliability required for safety-of-life applications in aviation.

Several GPS augmentation systems are being deployed to improve accuracy, availability, and signal error detection for aviation applications. WAAS and LAAS are the two principal systems in the United States.

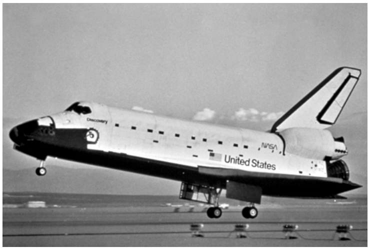
- WAAS-capable receivers can use the reference data to enhance GPS integrity and accuracy, enabling precision landing approaches to many airports that do not have instrument landing equipment on the ground.
- LAAS provides differential corrections for very high accuracy in a local region such as an airport. One LAAS ground station can support instrument landing on several runways at local airports in extremely limited visibility and very low cloud ceilings. Fully automated, hands-off landings have been successfully demonstrated with properly equipped aircraft.

See Part 2 for more information on WAAS and LAAS.

The Automatic Dependent Surveillance-Broadcast (ADS-B) system is the core of the Next Generation Air Traffic Control System for the U.S. ADS-B will be critical in changing air traffic control systems from reliance on radar technology to use of precise location data from global navigation satellite systems. Each aircraft periodically transmits GPS-derived position, altitude, speed, direction of travel and other identifying information. Other aircraft and air traffic controllers receive these broadcasts and provide information to pilots about potential conflicts between aircraft.

GPS even is critical for flying out of this world:

- The Space Shuttle uses GPS receivers for guidance as it glides back to earth to land on a runway.
- The International Space Station uses GPS receivers to help provide precise orbit information. Two of its GPS receivers are equipped with multiple antennas and special software to determine the station's attitude (its physical orientation in space—not its mood).



Vehicle Navigation

When you're trying to find the nearest coffee house that has a WiFi connection or want to find your way out of the maze of downtown streets in a strange city, there's nothing quite like a friendly voice telling you exactly how to get there, turn by turn. And it's especially nice that, unlike most human navigators, the voice doesn't get impatient as it redirects you to get back on track after you miss a turn or otherwise don't follow the directions.

Car navigation systems are a very rapidly growing GPS application. Such systems first became popular in the mid 1990's in Japan and then Europe, where complex road systems and traffic congestion proved their value.

The first systems were expensive after-market units that provided only basic navigation. They quickly evolved as the navigation system was integrated into audio systems. Today most high-end cars offer entertainment systems with built-in navigation and the popularity of car navigation continues to grow worldwide.

Car navigation systems use GPS to determine the vehicle's location. Navigation software then uses a map database to calculate a route to the destination. A display shows progress along the route and indicates when to turn, with time and distance to the destination. Many units provide voice guidance for safety, eliminating the need to watch the display while driving. Map databases are normally distributed on a CD or DVD and typically include information about road classification, road names and numbers, intersection details, one-way streets, tolls, addresses, and points of interest.

Navigation systems are available today as in-car systems or portable devices:

- Portable devices are quite compact and can be easily moved from one vehicle to another. There are a wide variety of software packages and compact GPS receivers designed to work with phones, notebook computers, and PDA's.
- The in-car systems may be either factory-installed, dealer-installed or after-market systems. These systems are generally more costly than the portable devices but usually provide more advanced features such as voice recognition, voice guidance and dead reckoning.

Dead reckoning is a means of generating position data when the primary navigation sensor is unavailable. When GPS satellite signals are blocked, the navigation system may use a built-in gyroscope or similar sensor, along with the vehicle's speed and reversing sensors, to temporarily calculate the vehicle's position until the GPS signals are again available. These systems can perform very well in dense urban areas.

Some car navigation systems can automatically communicate with other vehicles and special highway infrastructure. Such communications can provide up-to-date, location-sensitive traffic, weather, and other information to the driver and can assist with traffic management.

Various agencies—especially in Europe—are experimenting with "smart highway" systems that may take advantage of these capabilities in the future. Smart highways are seen as a way to reduce traffic congestion (and its resulting air pollution), save fuel, and, most importantly, save lives by reducing accidents. GPS positioning and navigation will almost certainly be an integral part of such future safety and driver-assist systems.

Marine Navigation

For centuries, man sailed the seven seas guided by the sun and stars. He determined his position by using a quadrant and compass and plotted his course using paper charts, drafting instruments and pencils. Today a new kind of star—NAVSTAR—guides his journey much more accurately, day or night, rain or shine.

Small-Boat Navigation

Consumer-level GPS navigation receivers are well suited to small-boat marine navigation. Many models are designed for that specific use. Additionally, GPS capability is commonly integrated with other marine instruments such as chart plotters, fish-finders, and depth sounders.

Extensive databases of navigation details are available for most of the world's waters, large and small. Getting from point A to point B is easier and safer when you can see your present location on the chart at any time, along with the locations of buoys, channels, rocks, shallow areas, marinas, and many other items of interest. You also can create waypoints for any locations of significance to you—such as where you caught the "big one"—and easily navigate to them again.

Large-Ship Navigation

Cruise ships, oil tankers, container freighters, and virtually every other type of commercial vessel use GPS as an adjunct to their other navigation equipment. Extensive navigation and route-planning capabilities, the ability to devise efficient alternate routes around storms, visualize tidal currents versus time, and estimated time of arrival (ETA) are powerful tools for the ship's master. All help him to get the vessel to its destination in the shortest time, or by using the minimum amount of fuel, or in the safest manner possible under virtually any conditions.

Knowing your precise location is important in mid-ocean. It's even more important in the crowded approaches to harbor entrances and within harbor channels. As described in Part 2, numerous countries worldwide have developed DGPS augmentation systems for coastal and harbor areas to provide maximum positional accuracy in these congested areas.

Also, a ship's GPS position is embedded in automatic ship-to-ship and ship-to-shore transmissions of the Automatic Identification System (AIS), which is required for installation on all passenger ships and other ships of over 300 tons. AIS transmissions, which also include ship identification and type and cargo information, are used to help control ship traffic in major shipping lanes and increasingly to enhance port security.

Replacing Paper Nautical Charts

GPS is also a prime force in the development of Electronic Chart Display and Information Systems (ECDIS), which are revolutionizing marine navigation and which will eventually replace paper nautical charts. More and more ships are being equipped with Integrated Bridge Systems, which combine data from GPS, radar, fathometers, AIS, and other sensors in an ECDIS for continuous position and navigational safety information.

Other Maritime Uses

GPS is a principal tool of oceanographers, marine surveyors, and seismic researchers. It provides new capabilities and accuracy levels for: underwater surveying; placement of buoys and other navigation markers; offshore oil and gas exploration and oil rig placement; the laying of marine communications cables and seabed pipelines; and dredging operations. Its accuracy, worldwide availability 24/7, and low cost make it the method of choice for virtually any maritime navigation or positioning application.

Agriculture

Farming will never be easy. But today GPS is changing the way farming practices have been done for hundreds of years, and is making the farmer's work just a bit easier in the process.

GPS Guidance and Steering Systems
The most widespread use of GPS in agriculture is GPS guidance and steering systems for farm vehicles such as tractors, sprayers, spreaders and harvesters.

- GPS manual guidance systems typically use a display to show the driver where to steer and by how much in order to accurately cover the field from one pass to the next.
- GPS automated steering systems take this a step further by controlling the vehicle's steering automatically.

Such systems let the operator focus primarily on the field operation rather than on trying to drive in a straight line for long distances over varying terrain. This increases safety and reduces operator fatigue, enabling longer operating hours—even at night—when needed to beat the weather. GPS guidance and steering systems can save fuel and improve in-field productivity as much as 20 to 30 percent, depending on the type of operation and the accuracy of the GPS being used.

Both approaches—manual and automated—compare the vehicle's real-time position in the field (measured by the GPS receiver on the vehicle) with a previously defined guidance pattern or method to cover the field. Some systems provide repeatable accuracies all the way down to one inch. (See Appendix D for accuracy definitions.)

Consistent accuracies such as these enable farmers to:

- Get better yields by planting more rows more closely together.
- Use less water by laying irrigation drip tape precisely and then planting seeds near the tape.
- Use less fertilizer and crop-control products by spreading them exactly where they are needed (strip tillage).
- Minimize soil compaction and crop damage by following the same tracks, pass after pass and even year after year.

GPS Field Management Systems

GPS can also help to develop field-specific data that describes how soil or crop yields vary throughout a field. The farmer can then manage the application of seed, fertilizer, and crop protection products. The goal is to increase farm profitability by increasing yield and lowering the costs of the input materials.

A field map typically is developed during harvest by using a GPS receiver and a crop yield monitor. The map shows how the crop yield varies within the field. From this, the farmer can create a prescription map, which is then loaded into a field computer on board the tractor or application equipment. The computer, combined with a GPS receiver, controls the application of seed, fertilizer or chemicals across the field, so that just enough material is applied precisely where it is needed.

Field management systems can also help the farmer to automate the record-keeping of what practices and products are applied to each field. Such records may be useful for traceability of produce to secure higher prices or for environmental application records required by government agencies such as the Environmental Protection Agency (EPA).

Mother Nature is still the biggest factor in farming. But with GPS, the farmer now has a little more help in making the most of what nature allows.

Construction

In perhaps no other field does GPS play as many roles in so many phases of a project than in the heavy- and highway-construction business. GPS technology, coupled with computer and communications capabilities, makes the work go faster and much more efficiently than conventional practices throughout the jobsite life cycle, from surveying and initial design through earth moving to final checking and documentation. Actual results vary from project to project, but productivity improvements of up to 30 percent are often realized. On big projects, that’s a lot of money!

Design and Data Preparation

In planning and preparing for construction work, extensive measurements of the work site are required, including details of the amount of material to be moved or removed. The use of GPS surveying methods and site preparation systems speeds the initial measurements. The data collected can be transferred electronically to the designer’s computer and integrated directly into the design software.

Grading and Excavation

GPS-based machine control systems are available on dozers, motor graders, scrapers, excavators and compactors. These systems enable operators to load the digital site design data into an in-cab computer and use the information to precisely position the blade or bucket in three dimensions as the machine does its work.

The blade's position is measured many times per second by the GPS receiver. The computer compares this data with the design plan for that location and determines the necessary change in blade lift and tilt. The system displays the lift/tilt information to guide the operator in controlling the blade or, in a fully automatic system, directly controls the blade position.

Use of these systems significantly reduces, and in some cases completely eliminates, the need for the tedious and repetitive use of stakes and string lines to guide the machine operators.

- In the "old days," a surveyor would measure the necessary "cut and fill" depths at many locations and a stakeout person would position a marked stake at each one. When ready, a dozer would do the cutting and filling, with a second person (gradechecker) walking beside it shouting guidance instructions to the operator. These tedious—and dangerous—operations were repeated, perhaps several times each, until the final grading matched the site plan.
- Today, with GPS, rework is minimized. Dirt-moving is often completed in just one or two passes, with only the machine operator involved. GPS grade control systems can be accurate to as little as an inch. Adding an advanced tracking sensor (such as a laser) to the system can provide accuracy down to a fraction of an inch to provide precise finished grade work.

Final Checking and As-Builts

Once the dirt is moved, GPS measurements are made to ensure that the completed grade work is correct by comparing the actual grades against the design information. Again, using GPS makes the process faster and more efficient than traditional methods. And the electronic files from the final measurements serve as the "as-built" records for the project.

From start to finish, GPS technology is fundamental to successful, modern construction projects.

Mapping and GIS

Since the late 1960s, government agencies, scientific organizations and commercial operations have increasingly adopted Geographic Information Systems (GIS) to record and map a huge variety of data. The advent of GIS has revolutionized cartography by converting ordinary paper maps into digital, "intelligent" maps.

Viewed on computer screens, these GIS digital maps accurately depict the locations of natural and man-made features. The features are contained in separate layers of related elements, (e.g., transportation routes, political boundaries, land parcels, building footprints, etc.). A database of attributes and geometry relating to specific features can be accessed simply by clicking on one feature or performing a spatial query of the entire GIS map or a subset of it.

GPS technology provides the fastest, easiest and most productive method of mapping the locations and geometries of ground features for a GIS database. For example, GPS can rapidly and inexpensively pinpoint precise locations of street signs as well as the perimeters of land parcels. These data points can be easily downloaded into a GIS to build a new feature layer or update an existing one.

Special-purpose portable GPS receivers, integrated with a handheld computer and data collection software, enable one person to collect attribute details that are linked simultaneously to their GPS coordinates. GPS/GIS data collection software allows the user to take digital GIS maps into the field in the handheld GPS/GIS device for real-time creation or updating of feature layers and attribute tables.

With its ease-of-use and relatively low operating costs, mobile GIS enables users to accurately map the locations of features and quickly enter a breadth of attribute details that was previously impractical, if not impossible.

Mapping Property in Peru
The government of Peru is conducting a massive land-titling program aimed at mapping and collecting property ownership information on some four million parcels across the entire nation. Field crews use GPS/GIS data collection equipment to quickly map parcels and to record a basic property description. Submeter GPS data accuracy is consistently achieved, even in the dense tropical jungles of the Amazon region and the deep valleys of the Andes Mountains.

Stopping Spills in San Francisco
The San Francisco Public Utilities Commission (SFPUC) uses mobile GIS to map the locations of the catch basins (curb drainage inlets) in its storm water run-off network. The GIS links these basins to their proper positions within the city-wide underground pipe system. When hazardous material from a vehicle accident or other incident spills into a catch basin, SFPUC can use the GIS to instantly trace the pipeline network to determine which downstream water treatment plant or watershed may be impacted. The SFPUC can then take appropriate action to contain the spill.

Staying on Top of Tough Situations
The combination of GPS, GIS, and mobile communications helps people stay in control of rapidly changing situations too. Field crews can use mobile GIS to map and wirelessly transmit the locations and conditions of dynamic events, such as wildfires or floods. The data can be instantly displayed on a GIS miles from the scene, where public safety commanders, the media and citizens can access it via the Internet to make well-informed decisions.

Mobile Resource Management

Managing a mobile workforce can present many challenges:

- Service technicians arriving late—or not at all—for scheduled appointments with customers.
- Ambulances driving long distances through heavy traffic to reach the scene of an accident.
- Trucks waiting in line to deliver materials at a construction site.

These problems and many more can cost a company money, delay projects, and alienate the customers. All can be solved by a GPS-enabled Mobile Resource Management (MRM) system designed to maximize the productivity of mobile workers. And that means more jobs completed per day, with less overtime and fuel expense, safer driving, and less frustration for both the mobile worker and the customer. MRM systems are used in transportation, construction, utilities, telecommunications, public safety and any other industry with fleets of mobile workers.

How MRM Works

A "black box" containing a GPS receiver, a computer and wireless communications is installed in a vehicle. The black box also can collect data from on-vehicle sensors to detect ignition on/off, door open/close, load/unload, load temperature, vehicle maintenance needs, and many other events and conditions. Throughout the work day, vehicle data is automatically sent to a hosted data center via the cellular or satellite communications network.

At the office, a dispatcher or fleet manager can view the data on maps or reports via a secure link to the data center. All the data the dispatcher needs to effectively manage the fleet can be provided in real-time. He or she can determine the closest vehicle to a new job, know when a truck enters and leaves the customer site, see who is en route or on break, and many other relevant factors. In addition, management reports help to identify productive technicians, driver safety issues, proper use of company equipment, and more.

Managing Mobile Businesses

MRM systems can be generic, such as simple vehicle tracking, or highly tailored to a specific application.

- A building solutions company produces over 90 million cubic yards of ready-mix concrete per year. A team of dispatchers must constantly check incoming customer orders against concrete production and delivery capabilities.

  A specialized MRM system provides the dispatcher with real-time vehicle location and status of all key operational steps, including the loading process, arrival, concrete pour start and end, exit, and arrival back at the plant to complete the delivery cycle. The dispatchers can confidently commit to incoming orders and schedule and route the trucks for maximum efficiency. The system also provides the fleet manager with extensive data (which drivers have unsafe driving habits such as speeding, who makes unscheduled stops for snacks, and many other factors) that can be corrected or improved for safer, more efficient and cost-effective fleet operation.
- A large bottling company, with a fleet of hundreds of vehicles, electronically transmits service call assignments with customer contact, service history, and equipment data to the field service representatives. The service reps are able to more efficiently do their work with less administration and improved reporting of time, mileage, parts usage and service-call disposition. The reps can also track the location and status of company-owned assets, such as coolers and vending machines, and develop more accurate and timely demographic and competitive data for their business.

Public Safety

The public safety arena is a virtually unlimited storehouse of potential applications for GPS. Since public safety is concerned with getting emergency personnel to the right place as quickly as possible and with following the movement of critical people or items, there's a natural fit between the public safety sector and GPS capabilities.

Emergency Dispatch
An emergency dispatcher takes a call about a car accident and determines an immediate need for an ambulance. Via GPS locators installed in the emergency vehicle fleet, the dispatcher quickly sees that there's an ambulance within two blocks of the scene, returning from a simple patient transport. The dispatcher contacts the ambulance and it is on-scene in moments.

Law Enforcement.
A state game warden comes across hunters on private property that is posted *No Trespassing*. The warden logs in the coordinates of the exact location with a GPS device, and issues the citation. In court, the hunters claim that they were on public land and had a permit. With the GPS data, the warden proves that they were, indeed, on private land and that they broke the law. Case closed.

Crime Tracking

A bank robber in Spokane, Washington herds employees and customers into a back room and demands money. Taking advantage of the tension and confusion, quick-thinking bank employees hurriedly dump cash and a tiny GPS tracking device into the robber's duffle bag. Police, homing in on the tracking device's signal, apprehend the robber not long after he leaves the bank.

Natural Disasters

When a wildfire threatens a residential neighborhood, an engine crew may be dispatched with the GPS coordinates not just of the fire but also of homes in the locale. Without GPS capabilities, a crew would only be able to guess where homes *might* be, particularly in rural areas where mailboxes are centrally located and homes are hidden up long driveways. The advent of GPS on mobile devices enables emergency crews to go directly to at-risk locations, to know which routes to take and to send back current information.

Tracking People

Tracking individuals is yet another public-safety related application of GPS. There are now children's wrist watches that contain a GPS locator chip. If a child becomes at-risk for abduction—possibly in a parental custody battle—it would be a relatively simple matter for police to locate the child wearing such a watch. And, because a watch is a normal item worn by children, it would be unlikely that it would be noticed or identified as a threat by the abductor.

GPS clearly has a variety of realistic and potentially life-saving applications in the public safety sector. Whether saving time in getting to the scene of an accident or finding a lost child, GPS capabilities can go a long way towards saving precious time and lives.

Survey and Infrastructure

Surveyors measure distances, directions and elevation differences of points relative to the earth's surface. This enables them to:

- locate or establish legal boundaries of land,
- install control networks to support large land development projects or municipal land planning,
- collect precise feature data to provide an accurate "as-built" representation of a particular area.

GPS has revolutionized the land survey industry over the past 20 years by dramatically increasing the accuracy, precision and efficiency with which many survey tasks are accomplished. Some tasks that used to take teams of surveyors days or even weeks of field work to complete can now often be performed by one person in just a few hours.

Formerly, using optical instruments and basic techniques like traverse, triangulation or trilateration, the surveyors took a series of angular and distance measurements between points to establish coordinates and determine relative positions. Each point had to be within line of sight from at least one other point.

These techniques are still used today for some survey operations, but most surveyors prefer to use GPS technology whenever possible for its relative ease and efficiency. No longer is line-of-sight needed between points. Each point only needs a clear view of the GPS satellites. And, with the use of a base station positioned at an accurately known control point, a single surveyor can use a rover receiver to establish multiple relative positions very quickly.

The development of RTK surveying enables instantaneous, centimeter-level solutions in the field, even while the surveyor is in motion, and brings the advantages of GPS to the average surveyor. RTK techniques are described in Part 3.

Single baseline RTK is a GPS solution used by surveyors to establish very precise 3-dimensional position on control points over long distances up to 20 km or even more. A precise position can be established in a matter of minutes.

RTK also fits very well when surveyors need to collect large amounts of location data, like sidewalks, roadways, and landscaped features to support mapping projects. Imagine the surveyor as a pencil just drawing the lines of the feature on the ground so it can be viewed later on a map.

Geodetic Surveying

GPS technology also enables the continuous monitoring of multiple sensors embedded in, for example, a dam or along an earthquake fault. Movement of any of the sensors by as little as a centimeter is detected instantly and the data is relayed to a central control station to alert personnel of the changing situation.

GPS Infrastructure

GPS networks are being installed throughout much of the world today to support surveyors and survey activities. This means that an individual surveyor can connect directly to the Internet and receive corrections from an RTK network without ever setting up a base receiver. Tasks that used to require weeks or months of effort can now be accomplished as easily as turning on a receiver and tapping the Measure key.

For more information on GPS networks and infrastructure, see Part 3.

Timing & Synchronization

GPS is known for location, location, location. Used primarily as a positioning technology, a lesser-known benefit of GPS is its ability to provide precise time. In fact, time is the factor that puts the P in GPS.

GPS receivers calculate their position using the precise timing signals that originate from the atomic clocks in each satellite. And that makes the simple quartz clock in a GPS receiver as accurate as an atomic clock—down to the nanosecond. With that kind of accuracy readily and economically available anywhere in the world, GPS has become a primary source of timing for business transactions and synchronization of a wide variety of networks.

Prior to GPS, precise timing was available only with expensive atomic clocks. With GPS, small, inexpensive circuit boards, or even just individual semiconductor chips, can be built into virtually any device to harness the power of the atomic clocks on the GPS satellites, making precise timing available to anyone.

Transaction Timing

GPS is used by companies to time-stamp business transactions to provide a consistent and accurate way to maintain records and ensure their traceability. Banks and businesses use automated systems with GPS timing to track, update, and manage multiple transactions made by customers around the world.

Process Control

Supervisory Control and Data Acquisition (SCADA) systems monitor and control processes in large-scale systems. Applications include pipelines, oil and gas metering, mass transit and traffic systems, and water and power utilities. These systems comprise a main central processor with remote sensors that send data back to the central unit. Precise timing enables the system to identify points of failure based on information time-stamps and ensures quick response and recovery in case of problems.

Wireless Communications

Wireless communications systems often depend on GPS for both precise timing and a frequency standard. For example, every code division multiple access (CDMA) base station includes a GPS clock to enable the network to "hand off" calls as you leave one base-station area and go into another. Paging and radio networks also use GPS timing to synchronize their towers.

Emergency Response

When the U.S. required cellular network providers to locate cell phones calling the E911 emergency response number, they turned to GPS. Adding GPS to a base station enables carriers to locate cell phone callers within hundreds of feet by triangulating between several towers, using the time difference of arrival of the signals.

And Many Others

- Tracing blackouts—electrical power grids require good timing synchronization. GPS-based timing equipment in power plants and substations can provide a precise trail for engineers to determine the exact location of a power line break.
- Coordinating the weather—GPS timing synchronizes hazardous weather reporting from the FAA's 45-terminal Doppler weather radars throughout the United States.
- GPS goes to the movies—rather, you'll benefit from it when you go to the movies. Used to synchronize multi-camera sequencing and control video and audio data, GPS timing helps studios put a better product on the screen.

Just remember—you'll always have a good time with GPS!

Appendices

GPS. The First GNSS.

Appendix A: The Satellites and Their Signals

Today's Block II GPS satellites are considerably more advanced in capability, accuracy, and reliability than their Block I predecessors. Tomorrow's planned Block III successors will take GPS to yet another level. This appendix provides some details about the evolving satellites and the signals they broadcast to the user communities.

Evolution of the Constellation

In Part 1, we showed the progress of the system from Block I to the future Block III levels.

GPS: BLOCK BY BLOCK			
Generation	**Block I**	**Block II**	**Block III**
Function	Development	Operational	The Future
Satellites	11	60*	>30*
Launched	1978–1985	1989–2012*	2013* and beyond

**Projected*

Here we will focus on the satellites themselves and especially on the Block II satellites, since they will continue to comprise the operating constellation for the next several years.

Block I

The eleven Block I satellites were developmental prototypes and were used to test the principles of space-based navigation. No Block I satellites are still in use.

Block II

As of the end of 2006, the GPS constellation consists of 29 Block II satellites: 1 Block II, 14 Block IIA, 12 Block IIR, and 2 Block IIR-M satellites. Six Block IIR-Ms remain to be launched, plus a projected 12 Block IIFs through 2012.

Block II satellite details are listed in the following table.

BLOCK II GPS SATELLITE DETAILS			
	Block II/IIA	**Block IIR/IIR-M**	**Block IIF**
Manufacturer	Rockwell International (now Boeing)	Lockheed-Martin	Boeing
Quantity Launched	9 (II) 19 (IIA)	13 (IIR) 8 (IIR-M) (projected)	12 (projected)
SVN #	13–21 (II) 22–40 (IIA)	41–62	63–TBD*
First/Last Launched	1989/1995	1997/2004 (IIR) 2005/TBD (IIR–M)	2008 (projected) / TBD
Design Life	7.5 years	10 years	12 years
Improvements Over Previous Versions	Can operate up to 14 days (II) or 180 days (IIA) without contact from control segment; Increased storage capacity Anti-spoof capabilities Improved reliability Reduced error probability	IIR: Capable of automated operation independent of ground control segment Improved accuracy IIR-M: 2 new military signals (L1M & L2M) New civil signal (L2C) Increased signal power Enhanced encryption & anti-jamming	Extended design life Improved accuracy Options for L5 civil signals Increased autonomy from ground segment Rapid on-orbit re-programmability
Weight	2,176 lbs.	2,370 lbs.	3,439 lbs.
Wingspan	17.5 ft.	38 ft.	43 ft.
Orbital Height	20,200 km		
Orbital Period	12 hours (sidereal time)		
Orbital Planes	55 degrees from equatorial plane		
Broadcast Carriers and Codes	L1 C/A (civilian) L1 & L2 P(Y) (military)	(IIR): same as IIA (IIR-M): same as IIR, plus L2C (civilian) L1 & L2M (military)	Same as IIR-M, plus: L5 (civilian)

**TBD = To Be Determined*

Block III

GPS Block III, currently in the concept development phase, is intended to provide satellite-based navigation and timing capabilities for the next three decades. Initial launch of a Block III satellite is projected for fiscal year 2013.

All the Satellites' Signals

We've learned that the satellites transmit a great deal of information to the users. This information is contained in several signals that modulate the two carrier frequencies (L1 and L2). A third carrier (L5) and a new civilian signal (L5C) will be added in 2008.

The carrier frequencies, the codes that modulate each, and the applicable user segment are summarized below.

GPS CARRIER SIGNALS AND CODES				
Users	**Carrier**	**Code**	**Satellites**	**First Used**
Civilian	L1	C/A	All	1978
	L2	L2C	Block IIR-M and later	2005
	L5	L5C	Block IIF and later	2008*
Military	L1 & L2	P or P(Y)	All	1978
	L1 & L2	M	Block IIR-M and later	2005

**Projected*

The Carriers

A carrier signal is a single frequency that is transmitted continuously. In general, the carrier frequency itself provides little or no information. The information it carries is contained in one or more additional signals which are impressed, or modulated, onto it.

For example, the frequency to which you tune your AM or FM radio is the carrier frequency for the station you're listening to. The information content (music, news, etc.) is impressed onto the carrier by modulating its amplitude (AM) or frequency (FM).

Downlink

Since the beginning, every GPS satellite has transmitted information on two carrier frequencies in the "L" band:

- L1 (1575.42 MHz)
- L2 (1227.60 MHz).

The first Block IIF satellite will add a third carrier:

- L5 (1176.45 MHz)

The L band is the segment of 390-1550 MHz in the ultrahigh frequency (UHF) range; some of the band is reserved for a variety of satellite communication purposes, such as GPS.

Uplink
All transmissions from the ground stations to the satellites use an S-band signal.

The Information

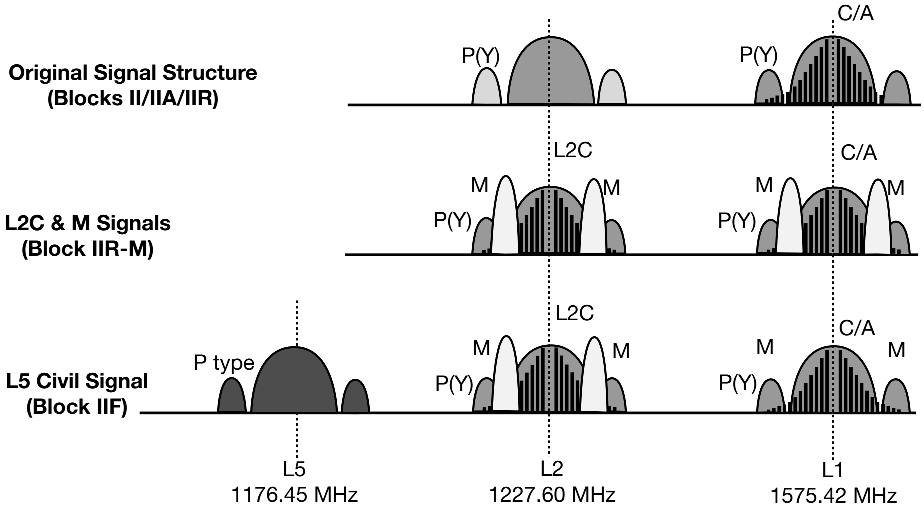
Each satellite transmits three spread-spectrum signals on two of the L-band carriers:

- a Coarse Acquisition (C/A) PRN code on L1;
- a precise (P or P(Y)) PRN code on both L1 and L2; and
- a 50-Hz navigation data message (Nav message).

Both PRN codes are phase-synchronized to the satellite clock and modulated with the common 50-Hz Nav message.

The graphic illustrates the general relationships between the various signals, including the signals to be added in the future.

GPS CARRIER SIGNALS AND CODES VS. FREQUENCY



Coarse Acquisition (C/A) Code

The C/A code has been the basis for civilian GPS use from day one, and is the basic PRN code that we discussed in Part 1. It identifies the satellite and carries the system timing signal (a new epoch every millisecond). The C/A code is a 1023-bit PRN code that repeats each millisecond and modulates the L1 carrier frequency at 1.023 MHz.

Navigation Message

The Nav message (also called the Data message) is a low-frequency (50 bits/second) signal that is superimposed on both the civilian C/A code and the military P code and takes 12.5 minutes to transmit on the L1 carrier. The entire Nav message repeats every 12.5 minutes; within each repeat cycle, satellite clock and ephemeris data for the transmitting satellite are sent 25 separate times so they repeat every 30 seconds.

The information contents of the Nav message are described in Part 1, in *What the Satellites Tell Us*.

L2 Civilian Signal (L2C)

This civilian code—called the Civilian Signal or CS—was added to the L2 carrier with the first Block IIR-M satellite. The L2C signal is broadcast at a higher power level than the original L2 signal. This provides a higher signal-to-noise ratio (SNR) and enables better tracking by the receiver.

The L2C signal consists of two codes:

- CM—a moderate-length code that repeats every 20 milliseconds and is modulated with message data.
- CL—the L2C long code repeats every 1.5 seconds and has no data modulation.

Availability of the L2C signal enables the use of dual-frequency (L1 and L2C) civilian GPS receivers that provide more accurate correction of ionospheric time delay errors. Some L2C-capable receivers were available even before the first Block IIR-M satellite was launched.

The L2C signal is slated for general use in non-safety critical applications. Its value to civilian users will steadily increase as additional Block IIR-M and Block IIF satellites are introduced into the constellation.

L5 Civilian Code

Beginning with the launch of the first Block IIF satellite, a second new civilian code will be broadcast on the new L5 carrier (1176.45 MHz). The L5 frequency is in the Aeronautical Radio Navigation Service (ARNS) band, which is specially designed for aviation applications and provides additional protection from interference.

The L5 signal will be broadcast at a higher power level and have a larger bandwidth (enabling longer codes) than other signals. This will make it easier to acquire and track weak signals. The lower L5 frequency may also enhance reception for indoor users. Additionally, the availability of three civilian signals (L1, L2C, and L5) also will speed RTK initialization.

The new signal will support aviation safety-of-life applications. Its addition will make GPS a more robust radio-navigation service for many aviation applications, as well as all ground-based users (maritime, railways, surface, shipping, agriculture, recreation, etc.). Many expect that the L5 signal will become the most popular GPS signal.

L1C Civilian Code

The L1C signal will be added to the GPS system with the advent of Block III. A GPS/Galileo agreement between the U.S. and the European Union provides for a compatible and interoperable signal on the L1 frequency.

The L1C signal will be far more robust than the existing L1 C/A. It will provide better signal reception and be less susceptible to interference, thereby improving GPS usability in tough signal-tracking environments, such as inside buildings, in urban canyons, and under tree canopy. Users will not have to choose between L1 C/A and L1C; receivers will be able to use both for a stronger overall signal.

Precise (P) or P(Y) Code

The P code is a PRN code for military users of GPS. The P code modulates both L1 and L2 at 10.23 MHz and repeats on a 7-day cycle. (The full code is actually 267 days long, but each satellite broadcasts only a 7-day segment.)

The P code can be encrypted for additional security. When encrypted it's called the "Y" code, or P(Y), and can only be deciphered by authorized military and government users having a valid decryption key.

At 10 times the bit rate of the civilian C/A code, the P code is potentially much more accurate and harder to jam. Because this code modulates both the L1 and L2 carriers, some advanced civilian receivers can play sophisticated games with the two frequencies to help eliminate errors caused by the atmosphere, as described in Part 3.

M (Military) Code

A new military (M-Code) signal is broadcast on both the L1 and L2 carriers, beginning with the Block IIR-M satellites. The M-code is a more robust and capable signal architecture than the P(Y) and will have increased power and reduced vulnerability to signal jamming when fully implemented.

Your Receiver is Still OK

The new signals coming on line in the near future are in addition to the existing signals. So your present receiver will continue to operate at its current level of performance, or maybe even a little better. But of course it won't be able to reap all the benefits of the new signals—for that you *will* need the "latest and greatest."

GPS and GLONASS: A Key Difference

Every GPS satellite broadcasts its data on the same frequencies (L1 and L2). Each satellite uses a unique PRN code to identify itself.

All GLONASS satellites use the same frequency-spreading code. Satellite identity is maintained by slightly different broadcast frequencies. To minimize the number of frequencies used, the satellites at opposite sides of the same orbital plane (antipodal) use the same frequency. Only one of the antipodal satellites can be seen from any point on earth.

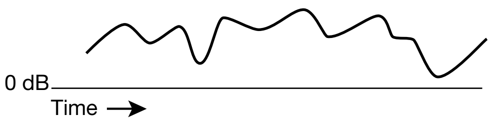
Many GPS receivers today can use signals from both GPS and GLONASS satellites to provide better performance.

Appendix B: PRN Codes

The pseudo-random number (PRN) code is one of the brilliant ideas behind GPS. It not only provides a great timing reference but it also gives us a way to find and “amplify” the very weak satellite signals.

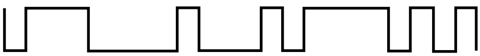
Separating Noise from Noise

It’s a noisy world we live in. Radio, TV, radar, cell phone and other electronic emissions are constantly bombarding us. Beyond that, the earth and space have a natural background radiation of electronic “noise.” A graph of the background noise level might look something like the one shown here.



BACKGROUND NOISE LEVEL

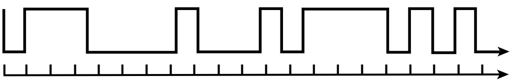
Somewhere in all that random clutter is our tiny, low-power GPS signal. You might think finding it is like trying to find the proverbial needle in a constantly changing haystack. And you’d be right, except that we have a very effective weapon on our side: the PRN code. It’s sort of a magnet for that needle.



BASIC PRN CODE

PRN codes are streams of ones and zeros that approximate a random sequence of bits. Although the code appears to vary randomly like the background noise, there’s one important difference: noise is truly random; the code is pseudo-random. We know the pattern of its fluctuations between 0 (low) and 1 (high).

In the case of the C/A code, the pattern repeats every millisecond. Each repetition is divided into 1,023 “chips.” Therefore the “chipping rate” of the C/A code is 1.023 MHz. (A chip is the same as a bit, but is named differently because no information is carried.)



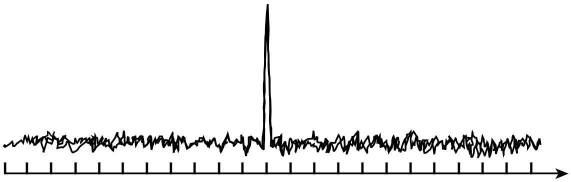
Chipping Rate=1.023 MHz; 1.023 chips/millisecond; Each chip ”~1µ sec

PRN CODE WITH CHIPS

So all we need to do is find that pattern among all the background noise and we'll be on the right track.

Because the received signal is buried in noise, you can't just look at it or measure it. Instead, your receiver creates a replica of the signal's carrier and PRN code. (It knows and can generate replicas of all 32 PRN codes used by the system, as well as the carriers.) Each replica is a clean digital signal and can be measured easily.

Correlating the Codes

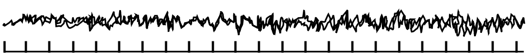

AUTOCORRELATION BETWEEN SAME PRNs

The process of matching the satellite's PRN code with a PRN code generated by your receiver is called correlation. The PRN codes used in the GPS system are very carefully selected for certain correlation characteristics. Considerable number theory is involved, but the important message is this:

- *Autocorrelation* is the correspondence between two samples of the same code. The PRN from a satellite and the same code generated by your receiver will show a low autocorrelation value except when very closely aligned. As your receiver slides its code, it will locate the autocorrelation "spike" and lock onto this phase alignment.
- *Cross-correlation* is the correspondence between samples of two different codes. The satellite's PRN code and another PRN code generated by your receiver don't cross-correlate very much at all, regardless of how your receiver tries to align them.

Each satellite uses a different PRN code to modulate the L1 carrier. The signals from different satellites don't interfere with each other because the PRN codes don't cross-correlate.

So as your receiver "slides" its codes to align them with the codes being received from the satellites, each will "hit" only when almost precisely aligned with its corresponding code. The process is repeated over many epochs of the


CROSS-CORRELATION BETWEEN DIFFERENT PRNs

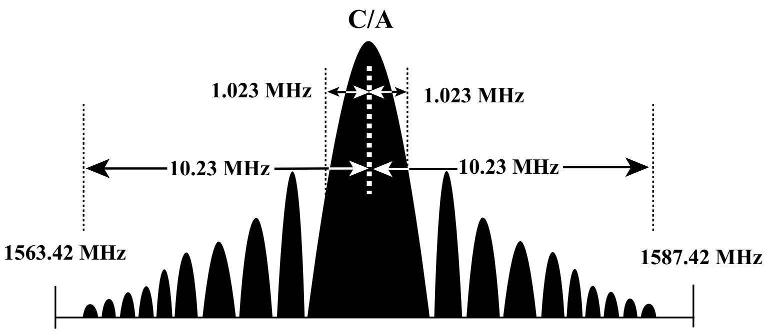
C/A code and the results averaged to fine-tune the alignment and maintain lock on the signal.

The correlation properties of PRN codes allow us to detect the presence of the desired codes and to accurately lock on to them, even when the signals are buried in noise. With the 1,023-chip C/A code, the noise can be almost 1,000 times more powerful than the signal and we can still locate and lock onto the signal.

Spreading the Spectrum

Each satellite uses its distinct PRN code to modulate the carrier signal. This technique is called spread spectrum, because instead of a narrow, single-frequency carrier, the PRN modulation spreads a signal out into multiple smaller signals with different frequencies over a wide bandwidth. This provides the ability to recover tiny signals that are buried in noise, and also resists interference from other signals.

SPREAD SPECTRUM



The Military Codes

The military P and M codes, which modulate both the L1 and L2 carriers, are much longer and more complex than the C/A code. For example, the P code would actually be 266 days long before naturally repeating, but only 7 days are used. The net effect of the longer length and a higher chipping rate is to provide better rejection of both interference and multipath effects, as well as increased security when the codes are encrypted.

For maximum security, the P code can be (and usually is) transmitted in encrypted form (the P(Y) code). The M code is always encrypted. Reception of either encrypted code requires a military receiver with a special module. Only authorized personnel in possession of a classified electronic "key" are able to decrypt the signal.

In Case You Were Wondering . . .

Since the PRN codes let us use very low-power transmissions and pick them up with very small antennas, why doesn't satellite TV do the same? Then we could get rid of those big dishes on the roof.

The reason is the need for speed. Remember that the PRN code itself carries very little information: it merely identifies the satellite and provides a timing reference for the system. And the same signal repeats every millisecond.

On the other hand, a TV signal carries an immense amount of information and changes rapidly and continuously. The PRN comparison system would be much too slow and cumbersome.

Appendix C: It's About Time

What Time is It?

If you really want to know the *exact* time, check your GPS receiver. It bears repeating: GPS is all about time. And GPS time is based on some very exact, international time standards.

International Atomic Time (TAI)
TAI is the time baseline for the world. TAI is kept by the International Bureau of Weights and Measures (BIPM) in Paris, France. It's derived from the inputs of many atomic clocks around the world, each of which is corrected for environmental and relativistic effects. Other time standards, such as UTC, are calculated from TAI.

Coordinated Universal Time (UTC)
UTC has been the basis for the worldwide civil time system since January 1, 1972. The military refers to UTC as Zulu time.

UTC is a high-precision atomic time standard, accurate to approximately one nanosecond (one billionth of a second), whose uniform seconds are defined by TAI. The rate of UTC is exactly that of TAI. However, a "leap" second is added periodically to UTC to compensate for the earth's slowing rotation and other factors.

The U.S. Naval Observatory is the source of the exact UTC time basis (often referred to as UTC (USNO)) for GPS.

The world's time zones are defined as positive or negative offsets from UTC. For example, Pacific Standard Time in the U.S. is 8 hours behind UTC.

GPS Time
The atomic clocks on the GPS satellites are set to GPS time. GPS time was set to read the same as UTC in 1980 and has counted days, hours, minutes and seconds ever since. It gradually diverges from UTC because it ignores the leap seconds that are added to UTC.

The GPS navigation message specifies the difference between GPS time and UTC, which is 14 seconds currently (in 2007). Receivers display UTC by subtracting this offset from GPS time and may make an additional adjustment to reflect local time.

GPS time is automatically steered to UTC (USNO) on a daily basis to keep the system time within one microsecond of UTC (USNO) (ignoring the leap seconds). During the last several years, GPS time has been within a few hundred nanoseconds of UTC.

GPS Week Number Rollover

Due to the original GPS coding structure, which limited the number of GPS weeks to 1,024, the GPS week number reset to zero at precisely 13 seconds before midnight UTC on Aug. 21, 1999. The event was known as GPS Week Number Rollover (WNRO) and caused considerable advance concern about its possible effects on GPS solutions following rollover. However, the rollover event did not cause significant problems. Many receiver models required no change; for most others, users were able to update their receiver's software or firmware with support from the manufacturer.

A WNRO event will occur again in 2019. However, changes made to the coding structure in the later Block II satellites should restrict any difficulties to older, C/A-code only receivers. In general, well-designed GPS receivers should have no WNRO problems for 19 years after manufacture; any problems suffered will usually be unimportant to the positioning solutions.

Got the Time?

Although better known for its uses in positioning and navigation, GPS is a very important source of time synchronization for large telecommunications and computer networks. With its ability to produce atomic-clock accuracy with a relatively inexpensive receiver anywhere in the world, GPS is the most practical—and accurate—means available for time transfer.

Check Part 5 for more information on timing applications.

Appendix D: Accuracy Definitions

How Do We Define "Pinpoint"?

Well, that depends partly on the size of the pin and partly on who's doing the defining.

We've used terms like 15-meter, 2-meter, and even centimeter-level accuracy throughout this book to generally describe what you can expect in "normal" operation. But you know that when the Government spends billions of dollars and more than 30 years on a system, incredibly many specifications, definitions, what-ifs, and wherefores will be involved.

This appendix discusses a few of these issues and what they might mean to your GPS usage. We've tried to keep it brief and fairly simple.

But if you really want details, check out the SPS Performance Standard (SPSPS) at www.navcen.uscg.gov/gps/geninfo/. It gets very specific and, for some things, very mathematical. But that's what accuracy specs are all about, isn't it?

What the Government Says About GPS Accuracy, Reliability and Availability

To highlight the consistently strong performance expected of the Global Positioning System, we've paraphrased just a few items from the 2001

STANDARD
Service Availability ≥ 99% horizontal and vertical service availability at average location for accuracy thresholds of: 36 meters horizontal: 77 meters vertical (signal-in-space (SIS) only)
Service Reliability ≥ 99.94% global average
PDOP Availability ≥ 98% global PDOP of 6 or less
SPS Signal in Space User Range Error ≤6 meters RMS across entire constellation
Accuracy (SIS Only) *Global Average Positioning Domain Accuracy* ≤13 meters 95% all-in-view horizontal error *Time Transfer Accuracy* ≤40 nanoseconds time transfer error 95% of time

SPSPS. (There is a 2005 version of the SPSPS in the works, but as of our publication date in 2007, it was not yet released.)

Note that these standards are based on signal-in-space (SIS) performance. The variable effects of the ionosphere, troposphere, receiver, multipath, or interference are not included. (In other words, the Government is not responsible for what might happen to the signals after they are broadcast by the satellites.)

What the Receiver Manufacturers Say and What You Need to Know About It

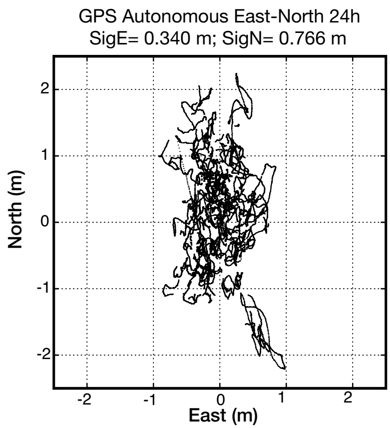
If a particular receiver is specified with accuracy to within, say, 10 meters, just what does that mean? That depends on several things.

A Moving Experience While Standing Still

A typical GPS receiver calculates its position once every second. Each measurement is subject to a variety of errors. Therefore each position is slightly different from the previous one, even if the receiver is stationary at one location.

If you set up a GPS receiver over a point and record its computed positions over a period of time, you'll get a scatter plot of the positions something like the one shown here. Most of the positions fall within a couple of meters of the center point (that's where the receiver antenna is). But a number of them wander several meters farther away. How do we quantify what the accuracy actually is?

SCATTER PLOT OF GPS DATA OVER 24 HOURS



Statistical Accuracy vs. Fixed Bias

Any measure of GPS accuracy is statistical in nature. We can't guarantee it will always be better than a certain value, say 10 meters, for all measurements. But we can say it will be better than that for a certain percentage of measurements. This way of specifying accuracy is much different from what we think of as "fixed error" (a bias in which a device always gives the same answer for the same measurement, even though the answer may be wrong).

With GPS measurements, the statistical part of accuracy is usually much larger than the bias error. So we can ignore the bias when thinking about specifications. But statistical measures can be misleading. The same GPS receiver can have different accuracies depending on:

- what percentage of the measurements is specified, and
- whether you're talking about horizontal, vertical or 3-dimensional accuracy.

Horizontal Accuracy

Most terrestrial users of GPS care more about horizontal accuracy than vertical accuracy. They want to know where they are on a map or in a field or on the ocean. Vertical accuracy is less important in these applications. That's a good thing, because GPS gives better horizontal accuracy than vertical accuracy.

Most manufacturers specify horizontal accuracy separately from vertical accuracy (which sometimes is not mentioned at all). Terrestrial receivers rarely give a 3-dimensional accuracy specification, since that would make the receiver look less accurate than it actually is for horizontal measurements.

Common horizontal specifications are horizontal rms (also called drms), 2drms, and circular error probable (CEP). These are two-dimensional measurements. The following definitions assume that the north-south and the east-west statistics are similar.

- CEP—The radius of the circle (centered on the antenna) in which half of the measurements occur.
- rms—The radius of the circle in which 63 percent of the measurements occur.
- 2drms—The radius of the circle twice that of rms, in which 98 percent of the measurements occur.

So be careful when you compare accuracy claims of GPS receivers. An accuracy claim of 10 meters can mean different things depending on its basis. As an example, the table lists the various approximate horizontal accuracies for receivers rated at 10 meters for each definition.

COMPARING THE SPECS			
STATED ACCURACY	**CEP**	**rms**	**2drms**
10 meters (CEP)	10m	12m	24m
10 meters (rms)	8.3m	10m	20m
10 meters (2drms)	4.2m	5m	10m

Vertical Accuracy

Vertical accuracy is typically given as rms, which is the distance from the center of the distribution in which 68 percent of the distribution occurs. Twice rms (2drms) encompasses 95 percent of the distribution. These percentages differ from their horizontal cousins simply because they are one-dimensional distributions.

3D Accuracy

There are applications where a three-dimensional specification is important, often in military and aviation uses. In these cases, the specification is typically Spherical Error Probable (SEP), the radius of a sphere in which half of the measurements occur.

Most of the time, vertical measurements are half as accurate as a measurement in a horizontal direction. Given this rule of thumb, a receiver with a 20 m SEP should have horizontal performance similar to a receiver with a 10 m CEP specification.

But With Respect to What?

To have any true relevance, measurements must always be determined with respect to some kind of reference system. In the case of position measurements, the reference system can be one of many datums.

Datums

A datum is a reference system that mathematically defines the size and shape of the earth (or a specific portion of it) for computing positions. Hundreds, perhaps thousands, of local reference datums have been developed throughout the world, usually referenced to some convenient local reference point. There also are numerous worldwide referencing systems in use today. The WGS84 (World Geodetic System of 1984) datum is the default standard for all GPS measurements.

As mentioned in the *User Errors* section of Part 1, worrying about the datum is not an issue for most people who use GPS as a "closed system," such as a mobile phone or personal navigator. In such applications, the positions are computed in WGS84 form and do not need to be translated to some other datum.

However, surveyors, map-makers, and other specialized users who need to tie in their measurements with other systems and data must be sure to convert their results to the proper local datum. If they forget, or make a mistake, it can result in errors of hundreds of feet.

Time
Time measurements also must be related to a standard reference system. For GPS, that system is UTC (USNO). Refer to Appendix C for timely information.

A Special Case for Agriculture
Accuracies for agricultural applications are often specified as pass-to-pass or year-to-year.

- *Pass-to-Pass accuracy* measures the relative accuracy over a 15-minute interval—usually thought of as guess-row error when driving rows, or skip/overlap from one pass to the next when driving swaths. A GPS receiver with pass-to-pass accuracy of ±4 inches means you get less than 4 inches skip or overlap 95 percent of the time.
- *Year-to-year accuracy* is the measure of repeatable accuracy attainable when you drive the same rows any time up to a year later. A ±1-inch year-to-year accuracy means you can drive the same rows next year within 1 inch of this year's rows, 95 percent of the time.

Appendix E: Carrier-Phase Positioning

A Different Form of Differential

Like DGPS, carrier-phase positioning requires both a reference receiver and a rover receiver. Unlike DGPS, each receiver tracks phases of the L1 and/or L2 carriers as well as the C/A code. Comparison of the carrier-phase measurements between the two receivers provides centimeter-level—or even millimeter-level—accuracy in the rover's position, relative to the reference receiver.

This "carrier-phase GPS" can be orders of magnitude more accurate than the "code-phase GPS" that most mortals use. Carrier-phase GPS, and the Real-Time Kinematic (RTK) process that uses it, have revolutionized surveying. The surveyor no longer needs line-of-sight (LOS) visibility from one point to the next—just LOS to the satellites, which lets him (or her) cover much more ground much more quickly and still get excellent accuracy.

Recall that the C/A code cycle width, or epoch, of 1 msec represents a distance of 300,000 m at the speed of light. The carrier wavelengths are much shorter distances: L1 is 0.19 m and L2 is 0.24 m. So if we can measure the difference between the reception times of the same carrier phase at two different receivers, and measure them to about 1 percent of a cycle, we can resolve their relative positions to within 0.001 m.

The concept is simple, but to understand it let's review a few basic principles of GPS.

Code Phase vs. Carrier Phase

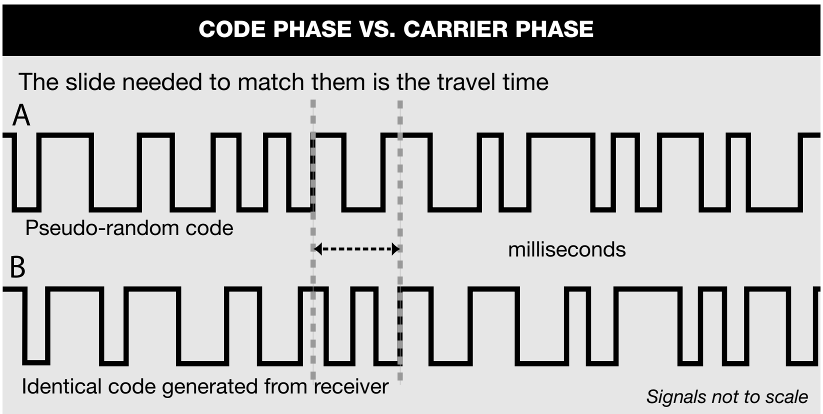
Remember that your basic GPS receiver determines the travel time of a signal from a satellite by comparing the PRN code it's generating with an identical code from the satellite. The receiver "slides" its own code in time until it is synchronized (correlated) with the satellite's code. The amount of slide indicates the travel time of the signal from the satellite to the receiver.

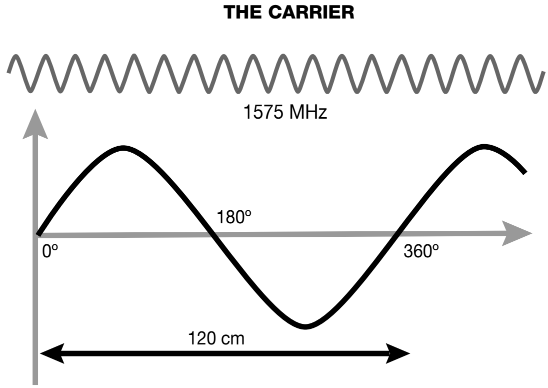
Just How Exact Is Exact, Exactly?

Consider the two PRN-code signals in the illustration. If you compared them logically, you'd say they matched. When signal A is a one, signal B is a one; and when signal A is a zero, signal B is a zero. But, as you can see, they're not exactly aligned. Even though they are the same most of the time, signal A may change state a little before signal B.

That's the problem with code-phase GPS. It's comparing PRN codes that have a cycle width of almost a microsecond which, at the speed of light, is almost 300 m of error!

Code-phase GPS receivers get you a lot closer than 300 m because designers have come up with ways to make sure that the signals are almost perfectly in phase; good units get within a percent. But that's still as much as 3 m of error.





The Carrier

The L1 carrier frequency is ~1575 MHz, which corresponds to a wavelength of about 20 cm. As with any sinusoidal waveform, each cycle is identical; it sweeps through phases from 0 to 360 degrees and then repeats. The phase at any time is proportional to the amount of time since the last positive-going zero crossing.

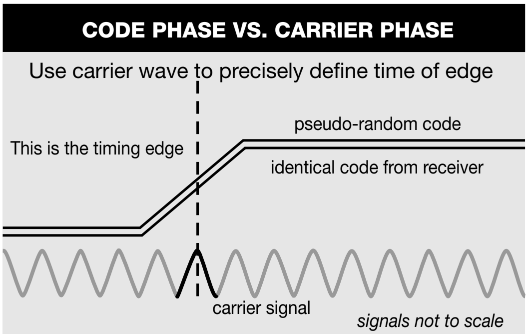
If we can get the same one percent of accuracy as we do with the code phase, the error reduces to 0.002 m, or 2 mm.

Counting Carrier Cycles

In essence, carrier-phase GPS tries to count the exact number of carrier cycles between the satellite and the receiver. The problem is that the carrier frequency is hard to count because it's so uniform. Every cycle looks like every other. The PRN code, on the other hand, is intentionally complex to make it easier to know which cycle you're looking at.

So the trick with carrier-phase GPS is to use code-phase techniques to get a fairly accurate position—to about a meter. Then we only have a few wavelengths of carrier to consider as we try to determine which cycle really marks the edge of our timing pulse. Resolving this "carrier-phase ambiguity" for just a few cycles is much more feasible.

Unfortunately, turning carrier-phase measurements into positions isn't nearly as easy as it is for code-phase measurements.



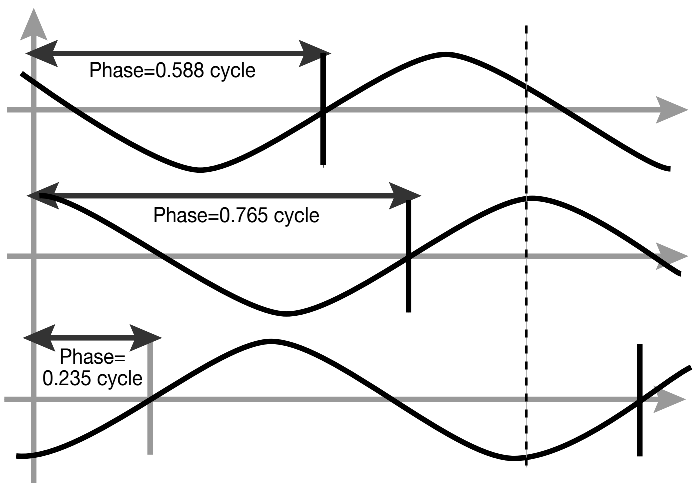
Phase Measurements

Carrier-phase measurements are made by accurately determining the delay since the last positive-going zero crossing on each of the carrier replicas. As with code-phase measurements, your receiver makes a matched set of measurements on signals from multiple satellites at a specific time. At that time, it measures the carrier-phase delay on each of the carrier replicas.

The actual mechanisms to do this are quite different from those of the code-phase technique, but the idea is the same. For instance, your receiver doesn't actually generate a signal replica of the real carrier wave. Instead, the incoming signal frequency is down-converted to a much lower frequency (on the order of 100 kHz), and the replica is generated at this same lower frequency. All of the phase information is preserved in the down-conversion, and it's a lot easier working with the lower frequencies than with microwave frequencies.

After measuring, the receiver knows the relative phases of the carriers with respect to each other at some time. These phases are related to the relative positions of the satellites. But, just as with the code-phase measurements, there is still an inherent ambiguity as to the absolute ranges to the satellites.

PHASE MEASUREMENTS

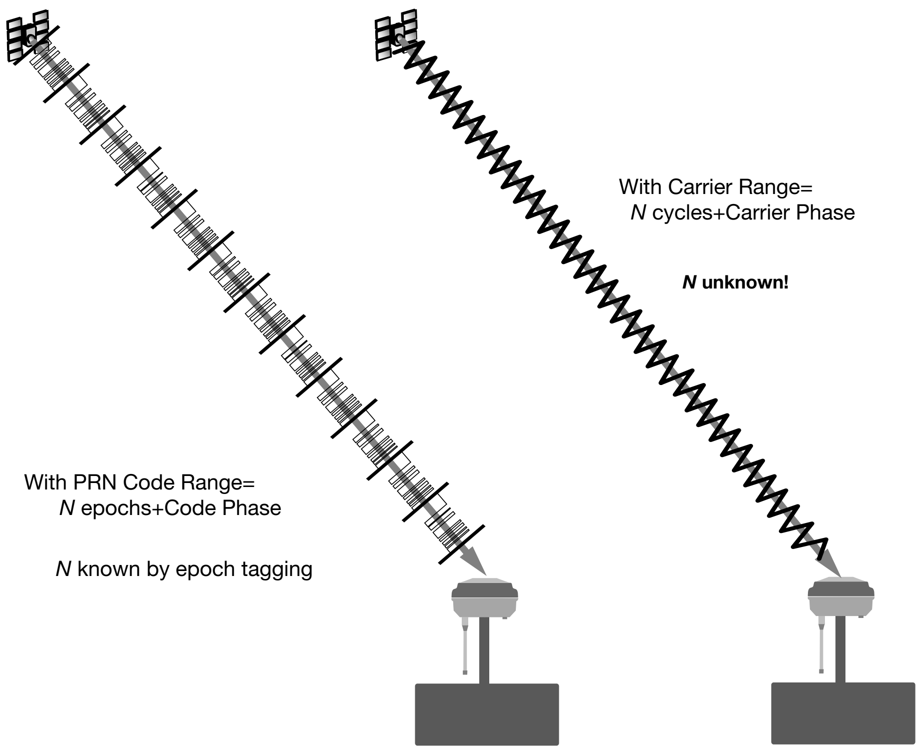


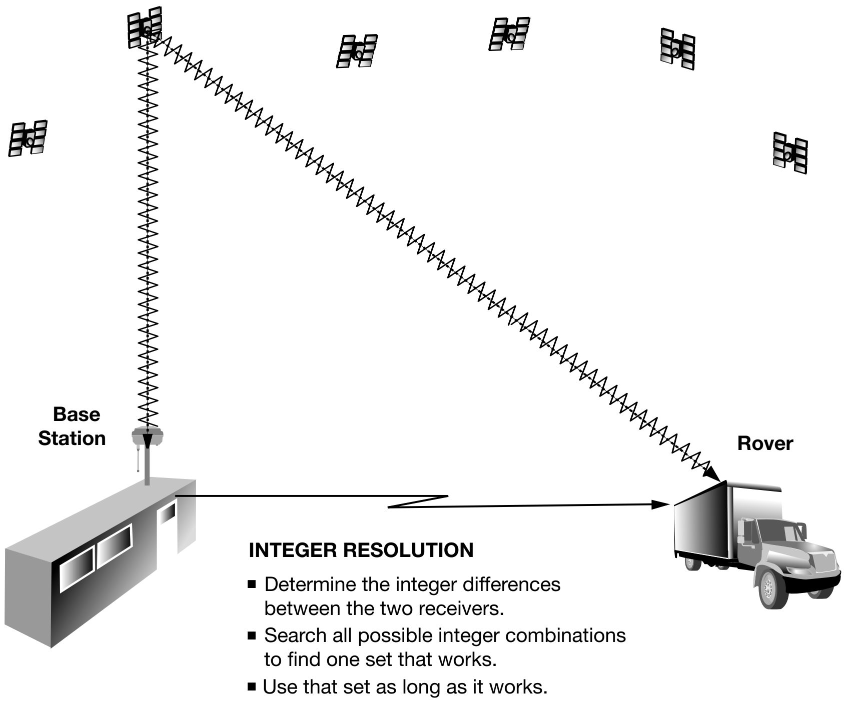
The Integers

Just as with the PRN code-phase measurement, the carrier-phase measurement (partial cycle) must be combined with an integer (whole) number of cycles to create a full pseudorange. That value can then be combined with those from the other satellites to produce a position fix.

Determining these integers is perhaps the trickiest part of using carrier-phase measurements. So tricky, in fact, that we don't even do it. Instead, we figure out (note that we didn't say count) the number of integers of difference between the signals at the rover and at the base station. And that gives us the rover's position relative to the base station position.

THE INTEGERS





Resolving Integers

The complex algorithms that resolve the integers basically boil down to searching all possible combinations of integers over a limited range, on all available satellites and frequencies, until a set is found that works for all measurements.

In essence, we attempt a position fix assuming each possible set of integers, and look at how well all of the measurements agree. When a single set is found that clearly matches reality, that set of integers are locked in place and we're in business.

In the early days of carrier-phase GPS, if one or more of the satellite signals were interrupted or lost (loss of lock), it often was necessary to go back to the previous position and re-initialize the receiver—a process that could take up to an hour. But with today's advanced technology and much higher computing power in the receiver, we're usually back in business in less than a second after reacquisition, with no real interruption. Life is good!

The History of GPS

In Three Pages

Prelude To GPS

1957 Russia launches Sputnik 1 satellite.
In the U.S., Johns Hopkins Applied Physics Laboratory (APL) researchers find that a satellite orbit and the location of a fixed point can be predicted from each other using the satellite's Doppler frequency shift.

1959 The first Transit satellite is launched. A forerunner to GPS, Transit was developed by the Johns Hopkins APL to enable satellite navigation for marine applications. Position fixes take hours.

1967 The first U.S. Timation satellite is launched. Timation was another forerunner to GPS that proved the atomic frequency standards onboard satellites as well as other concepts for practical satellite navigation more.
The same year, the Transit system is made available to the civilian community.

1968 The Department of Defense (DoD) establishes a Navigation Satellite Executive Steering Group (NAVSEG) to coordinate the efforts of several satellite navigation groups.

GPS Conceived and Born

1973 U.S. Air Force (USAF) designates a program manager to consolidate multiple satellite navigation concepts for all U.S. military services into a single system known as the Defense Navigation Satellite System. A GPS Joint Program Office (JPO) was established to lead this effort. The U.S. Government approves NAVSTAR GPS for development.

1978 First GPS satellite launched.
So is Trimble.

1983 Korean Airlines flight 007 strays over the Soviet Union and is shot down. President Reagan declares GPS will be available and free to all when operational to help prevent future navigation tragedies.

***198*4** The U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) published the first geodetic standards that allow use of GPS data for mapping.
Surveyors become early civilian GPS users due to dramatic productivity gains, despite limited satellite "in view" times.
Differential GPS and carrier-phase tracking capabilities are developed.

1986 Space Shuttle Challenger tragedy. Future GPS satellite launches delayed by 2 years. The Space Shuttle was the planned launch vehicle for GPS and satellites are moved to the Delta II rocket.

1987 DoD formally requests the Department of Transportation (DoT) to establish an office to respond to civil users' needs and to work closely with DoD to ensure proper implementation of GPS for civil use.

1988 GPS commercial dual-frequency user equipment introduced to the market.
The Secretary of the Air Force announces the expansion of the GPS constellation to 21 satellites and 3 spares.

1989 First GPS Block II satellite launched.
U.S. Coast Guard (USCG) becomes lead agency for interfacing with growing civilian GPS user communities.

1990 DoD activates Selective Availability (S/A).

1991 U.S. offer to make the GPS Standard Positioning Service (SPS) available beginning in 1993 to the international community on a continuous, worldwide basis free of direct user fees at the International Civil Aviation Organization's (ICAO) conference.

GPS Reaches Maturity

1990-91 Operation Desert Storm, the first major test of GPS in combat, creates unprecedented demand for GPS equipment.
Real-time kinematic (RTK) technology developed.

1991 U.S. GPS manufacturers establish the U.S. GPS Industry Council (USGIC) as a technical information resource to governments, the public and media.

1992 FAA issues performance standards for GPS receivers (TSO C129).

1993 GPS achieves Initial Operational Capacity (IOC) with full constellation of 24 GPS satellites providing continuous worldwide coverage.

1994 FAA recognizes GPS as operational for civil aviation use and is an integrated part of the U.S. air traffic control system. GPS is approved for use as a stand-alone navigation aid for all phases of flight through non-precision approach provided the GPS equipment meets TCO C129 criteria and is capable of Receiver Autonomous Integrity Monitoring (RAIM).
Development and installation of the Wide Area Augmentation System (WAAS) begins.
USCG's Navigation Center (NAVCEN) is commissioned.

1995 USAF Space Command announces the GPS system has met Full Operational Capability (FOC).

1996 Presidential Decision Directive (PDD) provides a comprehensive national policy on joint civil/military GPS management. S/A to be turned off by 2006.

1997 Congress embeds the policy principles of the GPS PDD into legislation that becomes public law signed by the President.
First Block IIR satellite launched.

1998 WAAS begins service; improves DGPS accuracy to 2 meters.

2000 S/A turned off. Autonomous accuracy improves from 100 meters to 12 meters.

2003 FAA commissions WAAS for aviation use.

2004 The President issues U.S. policy on Space-based Positioning Navigation and Timing (PNT).
Joint U.S.-E.U. Agreement on GPS-Galileo Cooperation signed.

2005 First Block IIR-M satellite launched introduces a new L2C civilian signal and two new military signals.

GPS In The Future

2009 First Block IIF satellite projected for launch.

2013 First Block III satellite projected for launch.

About Trimble

Enabling Productivity Through Innovation

Trimble was founded in 1978, the same year in which the first GPS satellite was launched. Today (2007), Trimble is a billion-dollar company whose products are used in over 100 countries around the world. More than 3,400 employees in over 18 countries, coupled with a highly capable network of dealers and distribution partners, serve and support Trimble customers.

For nearly 30 years, Trimble has created unique positioning products that help customers grow their businesses. Trimble technology can be found in consumer and commercial vehicles, construction equipment, farm machinery, computers, personal digital assistants (PDAs) and more. Innovative applications include dispatching and managing fleets, surveying and building roads, monitoring and mapping earthquake damage, recording and synchronizing international financial transactions, and improving the efficiency of wireless communications networks. Trimble's portfolio includes over 700 patents and serves as the basis for the broadest positioning offerings in the industry.

Trimble and GPS Grew Together

From the start, Trimble focused on developing innovative positioning and navigation products, based primarily on GPS technology. Trimble spearheaded the rapid development of commercial and consumer applications, as well as military use of the new technology. Many major commercial advances, including RTK surveying and Wide Area RTK networks (see Part 3), were originated by Trimble.

More than GPS

Though best known for its GPS technology, Trimble today integrates a wide range of positioning technologies, including GPS, laser, optical and inertial technologies, with application software, wireless communications, information technology and services to provide complete commercial solutions. Integrated solutions allow customers to collect, manage and analyze complex information faster and easier, making them more productive, efficient and profitable.

Glossary

2drms	One of several standards for defining the two-dimensional accuracy of a position; the radius of a circle (twice that of rms) in which 98 percent of the measurements occur.
Acquisition time	Time required for a GPS receiver to lock onto enough satellites to compute a position fix.
Algorithm	A list of mathematical instructions for accomplishing some task that, given an initial state, will end in a defined state.
Almanac	Approximate orbit information for all satellites in the constellation. Almanac data is included in the Nav message broadcast by each satellite.
Ambiguous	Capable of being understood in two or more possible senses or ways.
Atomic clock	A clock that uses resonance frequencies of atoms (usually cesium or rubidium) to keep time with extreme accuracy.
Autocorrelation	Correspondence between two samples of the same PRN code.
Autonomous	Self-sufficient; stand-alone, with no reference source (as in autonomous GPS).
Bandwidth	The range of frequencies in a signal.
Base station	A reference GPS receiver located on a precisely known point; used in DGPS and RTK to provide reference/correction signals to a roving receiver.
Beacon	In general, a continuously broadcast signal for use as a navigation aid (such as a light beam from a lighthouse). In GPS, a radio transmitter that continuously broadcasts a DGPS correction signal.

Bearing A compass direction from one position to another.

C/A code Coarse/Acquisition code. The standard GPS civilian code. A sequence of 1,023 pseudo-random, binary, biphase modulations on the GPS carrier at a chipping rate of 1.023 MHz.

Canopy Vegetation (such as tree cover) that can obstruct GPS signals.

Carrier A signal that can be varied from a known reference by modulation.

Carrier frequency The frequency of the unmodulated fundamental output of a radio transmitter.

Carrier-phase positioning A signal processing technique that measures the phase of the GPS carrier signal to achieve better accuracy than by using the PRN code.

CDMA See Code Division Multiple Access

CEP See Circular Error Probable

Cesium clock A type of atomic clock based on the vibrations of cesium atoms.

Channel A channel of a GPS receiver consists of the hardware and software necessary to receive the signal from a single GPS satellite.

Chip An individual bit in the pseudo-random number code sequence.

Chipping rate The frequency of a pseudo-random number code.

Circular Error Probable (CEP) One of several standards for defining the accuracy of a position; radius of a circle in which half of the measurements occur.

Code Division Multiple Access (CDMA)
A form of multiplexing in which many radios use the same frequency but each has a unique code. In GPS, each satellite broadcasts on the same frequency but has its unique PRN code.

Cold start The first start of a GPS receiver after its almanac memory has been erased. It may take up to 15 minutes to download almanac data and determine a position fix from a cold start.

Continuously Operating Reference Station (CORS)
A permanently installed reference station that provides continuous DGPS corrections.

Control segment A worldwide network of GPS monitor and control stations that ensures the accuracy of the satellites' positions and their clocks.

Coordinated Universal Time (UTC)
A high-precision time standard accurate to approximately 1 billionth of a second; the basis for the worldwide civil time system.

Coordinates Mathematical definition of a location; usually based on latitude/longitude or on a specified datum.

Correlation The process of matching a GPS receiver's PRN code with a satellite's PRN code.

CORS See Continuously Operating Reference Station

Cross-correlation Correspondence between samples of two different PRN codes.

Data message See Navigation message

Datum A mathematical model of a part of the earth's surface.

Dead reckoning Determining your position from a record of the directions taken, the distance made, and the known or estimated drift.

DGPS See Differential GPS

Differential GPS (DGPS)
A form of GPS using two receivers: a reference station at a known location calculates the errors in the received GPS signals and sends corrections to a rover receiver to improve the accuracy of the rover's position fixes.

Dilution of Precision (DOP)
The multiplier factor that modifies ranging error. It is based on the geometry between the user and the satellites being received.

DoD U.S. Department of Defense

DOP See Dilution of Precision

Doppler shift The apparent change in the frequency of a signal caused by the relative motion of the transmitter and receiver.

DoT U.S. Department of Transportation

Downlink Communications path from the GPS satellites to the ground and user segments.

EGNOS The European Geostationary Navigation Overlay Service. A satellite-based augmentation system being developed by the European Union. EGNOS is the first step towards the Galileo satellite navigation system.

Electromagnetic Interference (EMI)
An unwanted disturbance (interference) in a receiver caused by electromagnetic radiation from an outside source; may also be called radio frequency interference (RFI).

Elevation The altitude (height) component of a position.

EMI See Electromagnetic Interference

Ephemeris The predictions of current satellite position that are transmitted to the user in the Navigation message.

Epoch In GPS, the duration of one repetition of the PRN code.

Error budget The total amount of potential ranging errors from each type of error source, including User Range Errors and User Equipment Errors.

FAA U.S. Federal Aviation Administration

Frequency band A particular range of frequencies.

GAGAN The GPS-Aided Geo-Augmented Navigation System. A satellite-based augmentation system being planned by the Government of India.

Galileo A GNSS being developed by the European Union.

Geographic Information System (GIS)
A combination of computer hardware, software, and geographic data used to capture, manage, analyze, and display all forms of geographically referenced information.

Geosynchronous satellite
A satellite in an orbit that keeps the satellite "stationary" over a specific portion of the earth.

GIS See Geographic Information System

Global Navigation Satellite System (GNSS)
A system of satellites and control stations that provides accurate positioning information to users worldwide. GPS and GLONASS are operational; others such as Galileo are being developed.

Global Positioning System (GPS)
A GNSS developed and operated by the U.S. Government.

GLONASS A GNSS developed and operated by the Russian government.

GNSS See Global Navigation Satellite System

GPS See Global Positioning System

Inertial guidance A type of guidance system based on the use of gyros to detect and measure changes in direction and acceleration.

Initialization The process of getting a first position fix using RTK.

Integer A whole number (1, 2, 3, etc,). In carrier-phase processing, determining the integer number of cycles of the carrier waves is the key to the process.

Integrity The integrity, or reliability, of the GPS system, and therefore the position solutions obtained from it, is crucial to safety-of-life applications, such as aviation.

Ionosphere The upper part of the atmosphere (from 50 to 500 km above the earth's surface), containing numerous charged particles (ions).

LAAS See Local Area Augmentation System

Latency In GPS, refers to the time lag between when the measurements are made and the resulting solution is generated by the rover receiver.

Latitude/Longitude (Lat/Long)
Latitude describes the location of a place on earth, expressed as degrees north or south of the equator. Lines of latitude are the horizontal lines shown running east-to-west on maps. Longitude describes the location of a place on earth, expressed as degrees east or west of a north-south line called the prime meridian. The Greenwich meridian is the universal prime meridian or zero point of longitude.

L band The group of radio frequencies extending from 390 MHz to 1550 MHz. The GPS downlink carrier frequencies all are in the L band: 1575.42 MHz (L1), 1227.6 MHz (L2), and 1176.45 MHz (L5).

Line-Of-Sight propagation (LOS)
High-frequency radio waves (generally above 2 MHz) travel in a straight line from the transmitter to the receiver. The radio waves can be blocked by obstructions and cannot travel over the horizon. In general, for links on the earth's surface, the receiving antenna must be visible from the transmitter. For links to and from satellites, the line-of-sight requirement still holds, even though the satellites are too far away to be visible to the naked eye (which is why your GPS receiver must have a "clear view of the sky").

Local Area Augmentation System (LAAS)
A differential GPS reference and correction source provided for a specific local area, such as an airport.

Maritime DGPS Service (MDGPS)
A beacon-based augmentation system, administered by the U.S. Coast Guard, that provides differential GPS corrections to the continental US coastal areas, parts of Alaska and Puerto Rico, as well as the Great Lakes and major inland rivers.

Mask angle A setting, adjustable in most GPS receivers, that prevents the receiver from using satellites that are low to the horizon. Mask angles are generally set to 10 to 15 degrees.

Master Control Station (MCS)
A principle component of the GPS Control Segment, located at Schriever AFB, Colorado.

MCS See Master Control Station

MDGPS See Maritime DGPS Service

MHz Megahertz. One million hertz (cycles per second).

Modulation The process of varying a periodic waveform (a carrier signal) in order to use that signal to convey a message. In GPS, the carrier signals (L1, L2) are modulated by the C/A code.

MSAS A satellite-based augmentation system being developed by Japan.

Multipath error Errors caused by the interference of a signal that has reached the receiver antenna by two or more different paths; usually caused by one or more paths being bounced or reflected.

Nanosecond One billionth of a second.

Nationwide DGPS Service (NDGPS)
A beacon-based augmentation system, administered by the U.S. Coast Guard, that provides differential GPS corrections throughout the continental U.S. and parts of Alaska.

Navigation message
A message transmitted continuously by each GPS satellite containing almanac and ephemeris data as well as satellite time and health information. Often referred to as the Nav message or the Data message.

NAVSTAR The official name of the GPS system, standing for NAVigation Satellite Timing And Ranging.

NDGPS See Nationwide DGPS Service

P-code The Precise code. A very long sequence of pseudo-random binary biphase modulations on the GPS carrier at a chip rate of 10.23 MHz which repeats about every 267 days. Each one-week segment of this code is unique to one GPS satellite and is reset each week.

PPS See Precise Positioning Service

Position fix The determination of the receiver's location. Most GPS receivers compute a position fix every second.

Post-processing The processing of data from the rover and reference receivers in a computer at some time after the measurements are taken, as opposed to real-time processing.

Precise Positioning Service (PPS)
The most accurate dynamic positioning possible with standard GPS, based on the dual-frequency P-code. Available only to authorized users.

PRN Code See Pseudo-Random Number code

Pseudolite A “pseudo-satellite,” or simulated satellite. In GPS, a ground-based GPS transceiver which transmits a signal like that of an actual GPS satellite and can be used for ranging.

Pseudo-Random Number code (PRN code)
A signal with random-noise-like properties. It is a very complicated but repeating pattern of 1’s and 0’s.

Pseudorange A distance measurement, based on the correlation of a satellite’s transmitted code and the local receiver’s reference code before correction for errors in synchronization between the respective clocks.

PVT Position, Velocity, and Time; the essential elements of a GPS position fix.

P(Y) code The encrypted P code. Only authorized personnel with a classified electronic “key” are able to decrypt the signal.

QZSS The Quasi-Zenith Satellite System being planned by Japan.

Radio-Frequency Interference (RFI)
An unwanted disturbance (interference) in a receiver caused by electromagnetic radiation from an outside source; may also be called electromagnetic interference (EMI).

Real time Performed "in the moment;" in GPS, real-time position fixes are computed within a fraction of a second from the time the signals are received, as opposed to post-processing, in which they are computed at another, later time.

Real-Time Kinematic (RTK)
A specialized form of GPS that uses carrier-phase positioning and a reference station to attain centimeter-level accuracies, even while moving.

RFI See Radio-Frequency Interference

rms One of several standards for defining the two-dimensional accuracy of a position; the radius of a circle in which 63 percent of the measurements occur.

Rover receiver In DGPS or RTK, the rover receiver is moved to the position to be determined; the accuracy of its position fix is enhanced by corrections broadcast by a reference receiver.

RTK See Real-Time Kinematic

Rubidium clock A type of atomic clock based on the vibrations of rubidium atoms.

S/A See Selective Availability

Satellite-Based Augmentation Systems (SBAS)
Systems (e.g., WAAS, EGNOS, MSAS, QZSS, GAGAN) that use numerous GPS reference stations and broadcast DGPS correction messages from satellites to users over a wide area.

SBAS See Satellite-Based Augmentation Systems

Selective Availability (S/A)
A policy adopted by the DoD in 1990 to introduce intentional, varying clock noise into the GPS satellite signals, thereby degrading their accuracy for civilian users. S/A was turned off in 2000 by Presidential Decision Directive.

SEP See Spherical Error Probable

Signal In Space (SIS)
The GPS signals as they are transmitted by the satellites, before being affected by ionospheric delays or other variable factors.

SIS See Signal In Space

Space segment The part of the GPS system that is in space, i.e., the satellites.

Spherical Error Probable (SEP)
A standard for defining the 3D accuracy of a position; the radius of a sphere in which half of the measurements occur.

Spoofing Transmission of a GPS-like signal intended to "fool" GPS receivers so they compute erroneous times or locations.

Spread spectrum A system in which the transmitted signal is spread over a frequency band much wider than the minimum bandwidth needed to transmit the information being sent. In the GPS, this is done by modulating the carrier with a pseudorandom number (PRN) code.

SPS See Standard Positioning Service

Standard Positioning Service (SPS)
The normal civilian positioning accuracy obtained by using the single-frequency C/A code.

Static positioning Location determination when the receiver's antenna is presumed to be stationary. This allows the use of various averaging techniques that significantly improve accuracy.

SV Space vehicle, or satellite.

Time To First Fix (TTFF)
The time required for a GPS receiver to locate the satellites and compute the first position fix after power-on.

Trilateration The process of determining a location by measuring its distance from other objects.

Troposphere The lower part (about 50 km) of the earth's atmosphere, where all of the weather occurs.

TTFF See Time To First Fix

UEE See User Equipment Error

UHF See Ultrahigh Frequency

Ultrahigh Frequency (UHF)
The portion of the radio frequency spectrum between 300 and 3000 MHz. All GPS uplink and downlink communications frequencies are within the UHF band.

Uplink A communications link from the ground stations to the satellites.

URE See User Range Error

USCG U.S. Coast Guard

User Equipment Error (UEE)
The portion of the GPS ranging errors budget consisting of user errors such as receiver errors and multipath errors.

User interface The way(s) in which a receiver conveys information to the user or in which the user controls the receiver.

User Range Error (URE)
The portion of the GPS ranging errors budget consisting of system errors (ephemeris data and clock errors) and atmospheric errors (ionospheric and tropospheric).

User segment The part of the GPS system that includes the receivers.

USNO U.S. Naval Observatory

UTC See Coordinated Universal Time

WAAS See Wide Area Augmentation System

Wavelength The distance between the same points in two successive phases of an electromagnetic (radio) wave.

Waypoint A location of interest to the user in navigation. A waypoint can be your campsite, a scenic view, a favorite fishing spot, or any other location you determine.

WGS84 The World Geodetic System of 1984 (WGS84) datum is the default datum for all GPS measurements.

Wide Area Augmentation System (WAAS)
A satellite-based augmentation system that acts as a DGPS reference source throughout the continental United States. WAAS-enabled GPS receivers are typically capable of accuracy to approximately 2 meters.

WNRO Week Number Rollover. An event, occurring approximately every 19 years, in which the GPS week number reaches its maximum and resets to zero.

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