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# The Global Positioning System

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## Introduction

The Global Positioning System (GPS) is quickly becoming part of the fabric of everyday life. Beyond recreational activities such as boating and backpacking, GPS receivers are becoming a very important tool to such industries as agriculture, transportation, and surveying. Very soon, every cell phone will incorporate GPS technology to aid first responders in answering emergency calls.

GPS is a satellite-based radio navigation system. Users anywhere on the surface of the earth (or in space around the earth) with a GPS receiver can determine their geographic position in latitude (north-south), longitude (east-west), and elevation. Latitude and longitude are usually given in units of degrees (sometimes delineated to degrees, minutes, and seconds); elevation is usually given in distance units above a reference such as mean sea level or the geoid, which is a model of the shape of the earth. Because these positions are based on an earth-referenced coordinate system, the positions are universal and repeatable, which means you can identify a location with latitude, longitude, and elevation, and anyone should be able to go to that location or find it on any map.

Even though GPS is becoming more and more common, the basis of the technology is still a mystery to most. The purpose of this publication is to explain in simplified terms how GPS works, the different kind of receivers that are available, some of the limitations of the technology, and some interesting activities that people can do with GPS receivers.

## GPS Basics

GPS was originally designed by the United States Department of Defense for military use. It was intended to help locate and identify troops and equipment as well as provide guidance signals for tactical weapons such as missiles and smart bombs.

The global positioning system is comprised of 24 satellites (plus a few spares) orbiting the earth. The satellites have an orbital period of about 12 hours. This means that each satellite will circle the earth about twice in a 24-hour period. The satellite orbits are about 12,500 miles above the earth's surface.

Each GPS satellite transmits radio signals that can be used to compute a position or location. These signals are currently transmitted on two different radio frequencies: L1 (1575.42 MHz) and L2 (1227.60 MHz). There are two basic codes or digital information streams that are transmitted on these frequencies. The civilian access (C/A) code is transmitted on L1 and is freely available to any user. The precise (P) code is transmitted on L1 and L2. This code is scrambled and can be used only by the U.S. military and other authorized users.

### *Using Triangulation*

To calculate a position, a GPS receiver uses a principle called triangulation. Triangulation is a method for determining a position based on the distance from other points or objects that have known locations. In the case of GPS, the location of each satellite is accurately known. A GPS receiver measures its distance from each satellite in view above the horizon.

To illustrate the concept of triangulation, consider one satellite that is at a precisely known location (Figure 1). If a GPS receiver can determine its distance from that satellite, it will have narrowed its location to somewhere on a sphere that distance from the satellite. To further narrow its position, the receiver will measure its distance from a second satellite. This second distance measurement will place the receiver somewhere on a circle that is the intersection of the two spheres (Figure 1). You can visualize this concept by picturing two pieces of string that are tied to two known fixed objects. If you hold the ends of those two strings together at one point, keeping both strings tight, you could swing the intersection of those strings through a circle.

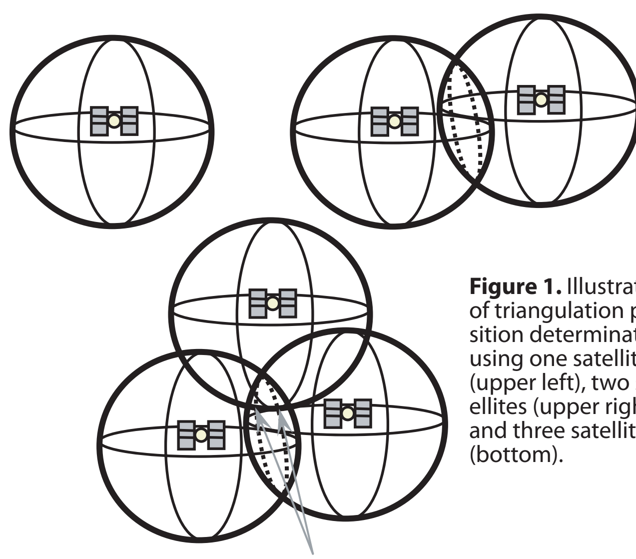

**Figure 1.** Illustration of triangulation position determination using one satellite (upper left), two satellites (upper right), and three satellites (bottom).

A distance measurement from a third satellite will reduce the number of possible locations to one of two points (Figure 1). You can visualize this by considering how the circle we just described would intersect a sphere around the third point. The circle will go into the sphere, which gives one intersection point, then comes back out of the sphere at a second intersection point. In the case of the GPS system, if we know that we are operating somewhere on or near the surface of the earth, one of these two points can usually be eliminated because it is not near the earth's surface. Therefore, with some assumptions about elevation, a position can be triangulated using distance measurements from three satellites. A distance from a fourth satellite would allow complete three-dimensional triangulation of a position.

Many GPS receivers will actually compute a position with only three satellite signals available. Often they will display a message such as "2-D GPS Position." This means that the receiver is only calculating an actual horizontal position and is making an estimate of the elevation. The elevation estimation is usually based on a smoothed model of the earth called a geoid that predicts the approximate elevation of the surface of the earth at different locations. Position fixes based on this 2-D estimate are not as accurate as true 3-D positions and should be used with caution.

### *Measuring Distance*

How does a GPS receiver measure its distance from a satellite? The principle used is something that many people commonly do during a thunderstorm. If you can count the number of seconds between when you see a flash of lightning and when you hear a clap of thunder, you can determine how far away the lightning strike occurred. You see the flash of lightning almost immediately after it occurs, because light travels very fast. It takes longer for the sound to get to you because sound travels much more slowly than light. If you know the speed of sound, you can calculate how far away the lightning strike was by measuring the time it took for the sound to travel to you. For example, sound will travel one mile in approximately 4.5 seconds (depending on the air temperature and humidity). If you count approximately nine seconds between the flash of lightning and the sound of thunder, you know that the lightning strike was about two miles away.

GPS receivers use the same principle to measure their distance from a GPS satellite. The satellites send out radio signals that travel at the speed of light—approximately 186,000 miles per second. The radio signals carry two key pieces of information, which are part of the C/A and P codes. First, they transmit their ephemeris, which is a set of satellite orbit parameters used to calculate the position and velocity of the satellite. Ephemeris can be thought of simply as the location of the satellite and is used as the reference position for triangulation calculations. GPS satellites also transmit an accurate timing signal. Each GPS satellite contains a highly accurate atomic clock that generates a digital timing signal. GPS receivers compare the timing information transmitted by the satellite to timing information generated by a clock within the receiver itself to determine the time it took the radio signal to travel from the satellite to the receiver. Since radio waves travel at the speed of light, and the satellite orbits are about 12,500 miles above the earth, it takes the radio signal less than 0.07 seconds to travel from the satellite to the receiver. To put this in perspective, consider what would happen if the GPS receiver made an error in computing this transmission time. At the speed of light, an error of only 0.001 seconds would translate to a positional error of 186 miles. Even the least expensive GPS receivers that can be purchased today will give position accuracies to less than 30 feet. This level of precision requires time measurements to the tenth decimal place, or more.

## GPS Errors

Obviously with such a sophisticated system, many things can cause errors in the positional computation and limit the accuracy of measurement. These errors include clock errors, ephemeris errors, satellite configuration, atmospheric interference, and multipath.

### *Clock Errors*

One thing to realize about GPS receivers is that the internal clocks used to generate the timing information are not nearly as accurate as those used on the GPS satellites, nor are they absolutely synchronized with satellite clocks. This is part of the reason that four satellites are needed to achieve a three-dimensional fix. Even though signals from three satellites are all that would be necessary to compute a position on the earth's surface, receivers actually need a signal from a fourth satellite to resolve clock ambiguities.

### *Ephemeris Errors*

Because the satellites are orbiting in gravitational fields, their positions and movements can be known quite accurately. Nevertheless, there still could be some errors in the ephemeris information that is broadcast. There are base stations around the earth that are constantly monitoring the status of the GPS satellites and are updating ephemeris information. Nevertheless, ephemeris errors will contribute to inaccuracies in position measurement.

### *Satellite Configuration*

Because the satellites are moving relative to the earth, the configuration of the satellite constellation overhead at any point in time can vary significantly. The accuracy of a triangulation computation can be greatly affected by the positions of the satellites in the sky. If all the satellites happen to be clumped at one location (Figure 2a), the triangulation computation will not be as accurate as if the satellites are spread or distributed evenly around the sky (Figure 2b). The configuration of the satellites at any point in time is quantified by the Dilution of Precision (DOP). Smaller DOP values mean better accuracy. A good DOP value would be less than 2. More sophisticated GPS receivers will report DOP so that users can make some assessment of how well their position computations may be. Others receivers will combine DOP with other parameters to give an estimate of position accuracy. DOP can be predicted with orbital models, and some users needing utmost precision (survey crews, for example) will plan to do field work during the times of the day when the satellites will be in the best configuration.

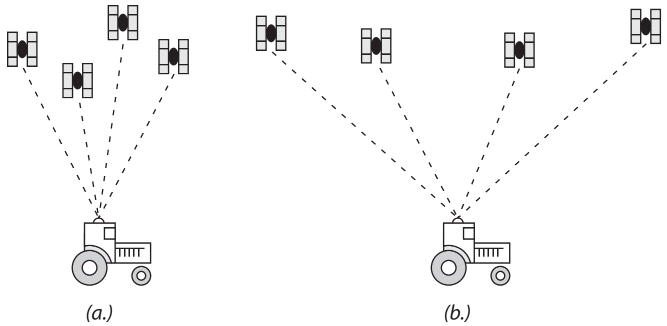


**Figure 2.** Satellite configurations showing poor (a) and good (b) DOP.

### *Atmospheric Interference*

As radio waves enter the earth's atmosphere, they can be bent or refracted much the same way light is refracted when it passes through a water surface (Figure 3). Their speed can also be altered by the ionosphere. If the radio waves are bent, they will have to travel a longer path to get from the satellite to the receiver. The atmosphere has a greater effect on satellites lower on the horizon. Because of this, many receivers will ignore or mask satellites that are located below a certain angle above the horizon. On more sophisticated GPS receivers, this mask angle can be selected by the user. Typical values for a mask angle may range from 8° to 14° above the horizon. The trade-off here is that eliminating satellites low on the horizon means that there are fewer satellite signals available, and that the ones that are available are bunched closer to the top of the sky, thereby increasing DOP.

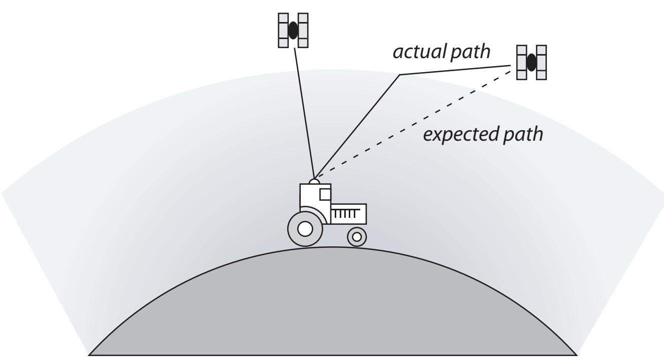


**Figure 3.** Atmospheric effects on radio signals.

### *Multipath Errors*

Multipath errors occur when the same radio signal is received at two different times. This will happen when the radio signal bounces off some object. For example, a GPS transmission could come straight to the receiver and also bounce off a building causing the same signal to arrive at the receiver a short time after the first (Figure 4). This multipath effect is the same thing that causes ghosting on television broadcasts. Multipath errors can cause significant problems with GPS receivers especially when operating around objects that reflect radio waves such as metal buildings and bodies of water. Placing the receiver antenna near any metallic objects could also increase the chances of multipath. The user should be careful to scrutinize GPS information when operating in places where multipath is a potential.

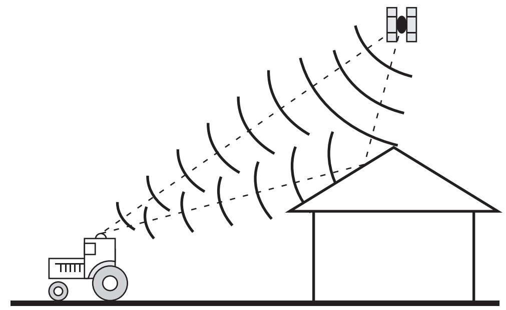

**Figure 4.** Multipath errors in GPS transmissions.

## GPS Accuracy

Just how accurate are GPS positions? The GPS system was designed so that users anywhere on the earth's surface would always be able to see at least four satellites and be able to compute their position to within about 100 feet. Most GPS receivers will track up to 12 satellite signals at the same time if that many are visible above the horizon. Using multiple satellite signals, most GPS receivers can compute a position to within at worst about 30 feet of the absolute known location.

Most manufacturers will report at least basic accuracy specifications for their GPS receivers. Users should be aware of several general issues regarding GPS accuracy. For one, GPS positions tend to drift with time, which means that the accuracy is better in the short term than in the long term. In other words, if a user marks a location with a GPS receiver, leaves that location and then returns to it within approximately 15 minutes, they should be fairly close to the original point. If they try to return to the same point a day later, they may not be as close.

Another key point to realize is that while most GPS receivers report elevation information, errors in vertical measurements are two to three times greater than horizontal. Although not always stated explicitly, the accuracy specifications given by manufacturers are usually based on horizontal accuracy only.

One final minor note on accuracy is that, because of GPS satellite orbit patterns, GPS receivers in general are slightly more accurate in east-west measurements than in north-south measurements.

### *Differential GPS*

To achieve higher position accuracy, most GPS receivers utilize what is called Differential GPS (DGPS). A DGPS receiver utilizes information from one or more stationary base-station GPS receivers at accurately known locations (Figure 5). The base-station GPS receiver calculates a position from the satellite signals. This position will not be the same as the known location, but since the absolute location is known, the error from the GPS satellite signals can be computed. This error information is transmitted to the rover GPS receiver. The rover receiver computes positions from the GPS satellites and then improves the accuracy using the error or differential correction information.

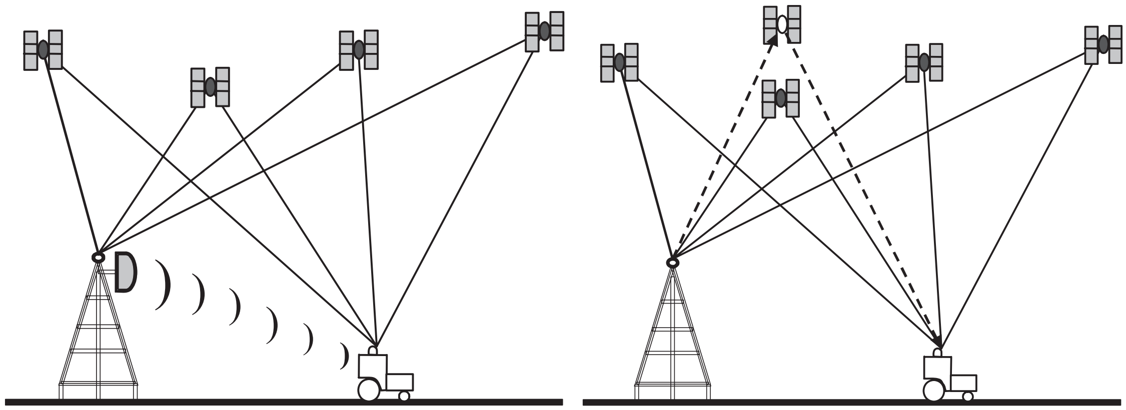

**Figure 5.** Local area (left) and wide area (right) DGPS systems.

### *Differential Correction Sources*

Although they could, most GPS users do not set up their own differential correction base station. They usually receive the differential correction information from another source. Differential correction sources can be classified as either local area or wide area broadcasts (Figure 5). Local area differential corrections are usually broadcast from land-based radio towers and are calculated from information collected by a single base station. The most common local area differential correction source is a free service maintained by the United States Coast Guard. These Coast Guard beacons are generally located near major navigable bodies of water. In Kentucky, there are Coast Guard beacons located along the Ohio and the Mississippi rivers giving good coverage in the western and north central parts of the state (Figure 6).

Wide area differential corrections are broadcast from geostationary satellites and are based on a network of GPS base stations spread throughout the intended coverage area. A common source for different corrections used by many low-cost GPS receivers is the Wide Area Augmentation System (WAAS). WAAS is a satellite-based differential correction system that was maintained by the Federal Aviation Administration. There are other satellite-based differential correction systems available in the United States. Many of these services charge an annual fee to receive the differential correction information. Examples of the systems include Omnistar, Racal, and Starfire.

Another option for obtaining differentially corrected positions is to post-process the data. Instead of receiving the differential correction information in real time, users will collect only GPS information in the field. Then they obtain the differential correction data from a base station and combine it with their field data using proper software to correct the positions. While the obvious disadvantage of post-processed DGPS data is that the user cannot perform real-time tasks in the field with the receiver, the corrections can be more accurate than real-time systems. Post-processing is commonly used for data collection and mapping functions.


**Figure 6.** United States Coast Guard DGPS correction coverage in Kentucky.

## Receiver Classifications

GPS receiver technology can be divided into four broad classifications (Table 1). Low-cost GPS receivers include receivers that are commonly purchased at department stores or sporting goods stores or through many Internet suppliers for recreational use. They could also include some dedicated receivers that are intended to be connected to a laptop computer or handheld computers called Personal Digital Assistants (PDAs). These receivers typically cost less than $500 and will give position accuracies somewhere between 3 and 15 feet. They almost exclusively use the WAAS differential correction service. This is because the WAAS differential correction signal is broadcast on the same radio frequency as the GPS signals; therefore, the receivers do not need a separate antenna tuned to a different frequency to receive the correction signals.

Sub-meter GPS receivers will give reliable position accuracies to within 3 feet. They could use a variety of local area or wide area differential correction services. Naturally, they are more expensive, but the increased accuracy lends them to more applications.

**Table 1.** Classification of GPS receivers.

| | Low-Cost | Sub-Meter | Decimeter | RTK* |
|---|---|---|---|---|
| Cost | $100-300 | $1K – 4K | $5K-10K | > $25K |
| Accuracy | 3-15 ft. | < 3 ft. | < 6 in. | < 1 in. |
| Diff. correction | WAAS | Various | Omistar HP, Starfire II | Your Own |

* RTK = Real time kinematic (RTK) receivers.

A relatively new class of receivers provides position accuracies to the "decimeter" (4-inch) level. These receivers must make use of select subscription-based wide area differential correction services such as Omnistar HP and Starfire II. The hardware will obviously be more expensive than sub-meter receivers, and annual subscription fees for the differential corrections typically range between $800 and $1,500 per annual license.

Real time kinematic (RTK) GPS receivers are the most expensive and most accurate class of GPS receivers. Some RTK receivers can give position accuracies to within 1/2 inch, making them useful even for surveying. To achieve that accuracy, users must create their own differential correction signal with a base-station receiver and radio link. In general, the user cannot be more than a couple of miles from the base station to achieve the highest accuracy levels. There are efforts under way to create local area RTK networks, but these are currently confined to a few select states and are generally focused toward metropolitan areas.

## GPS Interfacing

One of the useful things about GPS receivers is that many can be connected to other electronic devices. For example, many low-cost GPS receivers with mapping capabilities can be connected to a computer to transfer maps, routes, and waypoints to and from the receiver. They can also be connected to portable computers or PDAs with specialized software to do real-time navigation and data collection. Different receivers may have different communication ports available including serial ports, USB, CAN (Controller Area Network common on new agricultural machinery), and Bluetooth wireless. Others can be connected directly to a Compact Flash, PCMCIA, or SDRAM slot in a laptop or a PDA.

## GPS Modernization

GPS is a very active and dynamic system. Over the next several years, the system will undergo a series of updates and improvements called GPS modernization. These improvements will include the addition of a new C/A code broadcast on L2 and the addition of third broadcast frequency (L5) at 1176.45 MHz, which will also carry a C/A code. Many of these improvements are intended to add robustness and redundancy to the system so it can be used for commercial aircraft navigation, but it will likely mean increased accuracy and functionality to receivers available to the general public.

## Suggested GPS Activities

Given the range of GPS equipment that is available, the uses for the technology are limited only by the user's imagination. Here are some ideas of simple things you can do with a handheld GPS receiver.

One of the most basic things that a GPS receiver can do is to record specific locations, which are often called waypoints. Waypoints are latitude, longitude, and possibly elevation coordinates of points of interest. Boaters and anglers often use waypoints to record the location of fishing hotspots or their origin slip or launch ramp. Hikers and backpackers often record trailhead or base camp locations so they can always find their starting location. Amateur and professional photographers use GPS technology to record the location of individual or groups of pictures that they have taken. Waypoints can be transferred to and from GPS receivers either manually or electronically.

Most handheld GPS receivers will help you navigate to waypoints by telling you what direction to travel and how far it is to the destination. Many will also estimate your time of arrival based on your travel speed. Handheld GPS receivers with more sophisticated mapping data will even route to destinations by roads and trails, telling you when and where to turn. As you travel, most receivers will record your trip statistics such as distance traveled, travel time, average speed, etc.

GPS receivers can give a new twist to an old game. For example, GPS technology has revolutionized the game of scavenger hunts. Again, we use the basic concept of latitude and longitude locating points and then turn it into a game. The game master will set out the objects to be found or formulate questions to be answered at certain locations. Many scavenger hunts that use GPS technology will use a theme of the event such as popular movie titles or even a school sports or class activity. Those looking for the objects will be given the latitude and longitude along with any additional clues needed to find the object. After setting the correct latitude and longitude coordinates into their individual GPS units, they are off on the hunt.

There is an official and very popular GPS scavenger hunt established on the Internet called "geocaching" (www.geocaching.com). "Cache" refers to hidden items, and "geo" refers to the geography involved in their locations. The Web site lists locations of geocaches that anyone can search for. Only a few years after the Internet site was established, thousands upon thousands of geocaches have been registered in more than 200 countries. There are many different types of geocaches, but the most popular is a container filled with trinkets and a log sheet. Finders will typically sign the sheet, take something from the cache, and leave something else in it. Once you have become a master at locating these sites, you can become registered and then set up hidden caches for others to find.

Many receivers will also perform distance and area computations. If you record two waypoints, your GPS unit will calculate the straight line distance between those two points. By setting a series of waypoints, you can determine the total or segmented distances of a complex path such as a race course that was run on a series of streets or a sailboat race that passed around several buoys or floating markers. Some receivers will even compute areas within boundaries created either by connecting waypoints around the boundary or by traversing the boundary with the receiver. This feature is particularly useful to farmers for measuring the acreage in their fields.

Teachers in middle and high schools are finding new ways to incorporate handheld GPS technologies into educational activities. Now math can be taught with a practical hands-on approach. Using the tracking and waypoint options of GPS, students can calculate and verify measurements of distance, direction, and area. This is a great way to learn the old fundamentals of trigonometry and geometry with exciting new technologies.

This list of ideas only begins to scratch the surface of the potential for GPS technologies. In fact, there are entire publications dedicated to GPS information and innovative uses of all levels of GPS technology (gpsworld.com, for example).

Like many other new technologies, GPS is continually changing with upgrades to the satellite infrastructure as well as improved receiver devices. The fundamental concepts of how GPS works have not changed, but new technologies will allow users to utilize GPS for many innovative applications. Using GPS, we have the ability to improve safety and security, develop more efficient transportation systems, improve agricultural production, and impact many other areas that affect our everyday lives.


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