# GPS Tutorial

http://www.trimble.com/gps_tutorial/whygps.aspx
https://www.e-education.psu.edu/natureofgeoinfo/book/export/html/1620

*Here's how GPS works in five logical steps:*

*1.The basis of GPS is "triangulation" from satellites.*

*2.To "triangulate," a GPS receiver measures distance using the travel time of radio signals.*

*3.To measure travel time, GPS needs very accurate timing which it achieves with some tricks.*

*4.Along with distance, you need to know exactly where the satellites are in space. High orbits and careful monitoring are the secret.*

*5.Finally you must correct for any delays the signal experiences as it travels through the atmosphere.*

Trying to figure out where you are and where you're going is probably one of man's oldest pastimes.

Navigation and positioning are crucial to so many activities and yet the process has always been quite cumbersome.

Over the years all kinds of technologies have tried to simplify the task but every one has had some **disadvantage**.

Disadvantages of other navigation systems

Landmarks:
Only work in local area. Subject to movement or destruction by environmental factors.
Dead Reckoning:
Very complicated. Accuracy depends on measurement tools which are usually relatively crude. Errors accumulate quickly.
Celestial:
Complicated. Only works at night in good weather. Limited precision.
OMEGA:
Based on relatively few radio direction beacons. Accuracy limited and subject to radio interference.
LORAN:
Limited coverage (mostly coastal). Accuracy variable, affected by geographic situation. Easy to jam or disturb.
SatNav:
Based on low-frequency doppler measurements so it's sensitive to small movements at receiver. Few satellites so updates are infrequent.

Back to the tutorial...

Finally, the **U.S. Department of Defense** decided that the military had to have a super precise form of worldwide positioning. And fortunately they had the kind of money ($12 billion!) it took to build something really good.

The result is the Global Positioning System, a system that's changed navigation forever.

Why did the Department of Defense develop GPS?

In the latter days of the arms race the targeting of ICBMs became such a fine art that they could be expected to land right on an enemy's missile silos. Such a direct hit would destroy the silo and any missile in it. The ability to take out your opponent's missiles had a profound effect on the balance of power.

But you could only expect to hit a silo if you knew exactly where you were launching from. That's not hard if your missiles are on land, as most of them were in the Soviet Union. But most of the U.S. nuclear arsenal was at sea on subs. To maintain the balance of power the U.S. had to come up with a way to allow those subs to surface and fix their exact position in a matter of minutes anywhere in the world......Hello GPS!

The Global Positioning System (GPS) is a worldwide radio-navigation system formed from a constellation of 24 **satellites** and their **ground stations**.

GPS uses these "man-made stars" as reference points to calculate positions accurate to a matter of meters. In fact, with **advanced** forms of GPS you can make measurements to better than a centimeter!

In a sense it's like giving every square meter on the planet a unique address.

GPS receivers have been miniaturized to just a few integrated circuits and so are becoming very economical. And that makes the technology accessible to virtually everyone.

These days GPS is finding its way into cars, boats, planes, construction equipment, movie making gear, farm machinery, even laptop computers.

Soon GPS will become almost as basic as the telephone. Indeed, at Trimble, we think it just may become a universal utility.

GPS Satellites

Name: NAVSTAR

Manufacturer: Rockwell International

Altitude: 10,900 nautical miles

Weight:1900 lbs (in orbit)

Size:17 ft with solar panels extended

Orbital Period: 12 hours

Orbital Plane: 55 degrees to equitorial plane

Planned Lifespan: 7.5 years

Current constellation: 24 Block II production satellites

Future satellites: 21 Block IIrs developed by Martin Marietta.

## Ground Stations

(also known as the "Control Segment")

These stations monitor the GPS satellites, checking both their operational health and their exact position in space. The master ground station transmits corrections for the satellite's ephemeris constants and clock offsets back to the satellites themselves. The satellites can then incorporate these updates in the signals they send to GPS receivers.

There are five monitor stations: Hawaii, Ascension Island, Diego Garcia, Kwajalein, and Colorado Springs.

## Advanced Forms of GPS

The quest for greater and greater accuracy has spawned an assortment of variations on basic GPS technology. One technique, called "Differential GPS," involves the use of two ground-based receivers. One monitors variations in the GPS signal and communicates those variations to the other receiver. The second receiver can then correct its calculations for better accuracy.

Another technique called "Carrier-phase GPS" takes advantage of the GPS signal's carrier signal to improve accuracy. The carrier frequency is much higher than the GPS signal which means it can be used for more precise timing measurements.

The aviation industry is developing a type of GPS called "Augmented GPS" which involves the use of a geostationary satellite as a relay station for the transmission of differential corrections and GPS satellite status information. These corrections are necessary if GPS is to be used for instrument landings. The geostationary satellite would provide corrections across an entire continent.

All of these technologies are covered in more detail later in this tutorial.

Improbable as it may seem, the whole idea behind GPS is to use satellites in space as reference points for locations here on earth.

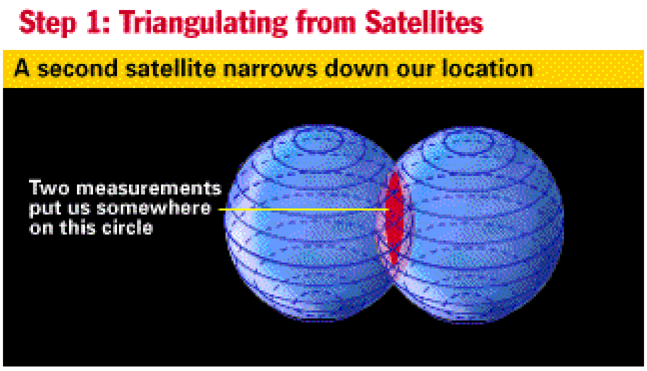
That's right, by very, very accurately measuring our distance from three satellites we can " triangulate " our position anywhere on earth.

Forget for a moment how our receiver measures this distance. We'll get to that later. First consider how distance measurements from three satellites can pinpoint you in space.

The Big Idea Geometrically:

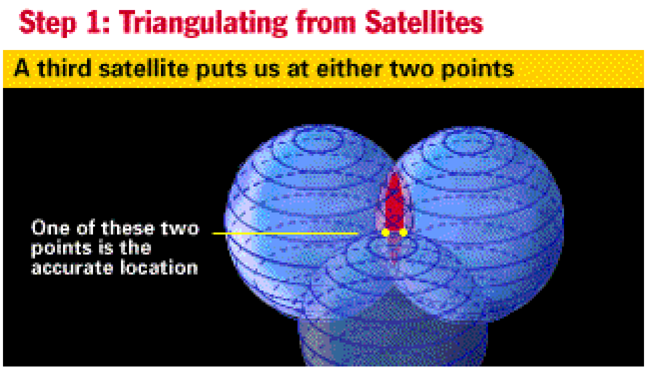
Suppose we measure our distance from a satellite and find it to be 11,000 miles.

Knowing that we're 11,000 miles from a particular satellite narrows down all the possible locations we could be in the whole universe to the surface of a sphere that is centered on this satellite and has a radius of 11,000 miles.



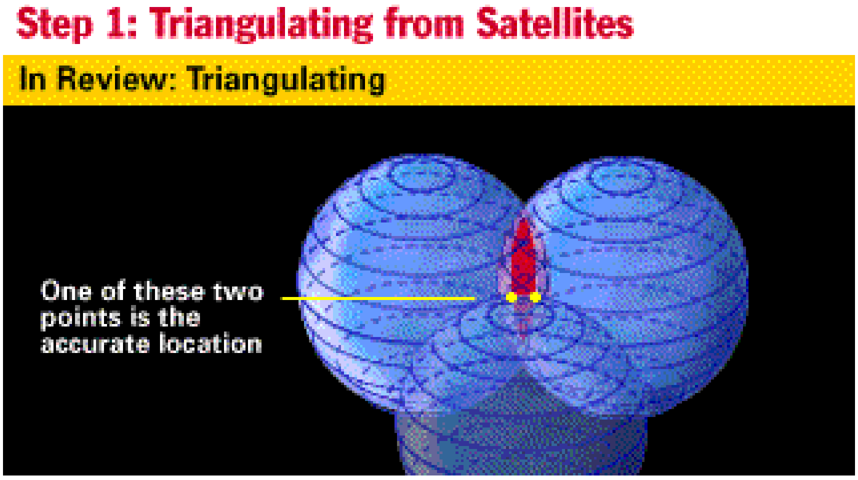

Next, say we measure our distance to a second satellite and find out that it's 12,000 miles away.

That tells us that we're not only on the first sphere but we're also on a sphere that's 12,000 miles from the second satellite. Or in other words, we're somewhere on the circle where these two spheres intersect.




If we then make a measurement from a third satellite and find that we're 13,000 miles from that one, that narrows our position down even further, to the two points where the 13,000 mile sphere cuts through the circle that's the intersection of the first two spheres.

So by ranging from three satellites we can narrow our position to just two points in space.




To decide which one is our true location we could make a fourth measurement. But 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 without a measurement.

A fourth measurement does come in very handy for another reason however, but we'll tell you about that later.

Next we'll see how the system measures distances to satellites

*In Review: Triangulating*

1. *Position is calculated from distance measurements (ranges) to satellites.*

2. *Mathematically we need four satellite ranges to determine exact position.*

3. *Three ranges are enough if we reject ridiculous answers or use other tricks.*

4. *Another range is required for technical reasons to be discussed later.*

We saw in the last section that a position is calculated from distance measurements to at least three satellites.

But how can you measure the distance to something that's floating around in space? We do it by timing how long it takes for a signal sent from the satellite to arrive at our receiver.

The Big Idea Mathematically

In a sense, the whole thing boils down to those “velocity times travel time” math problems we did in high school. Remember the old: “If a car goes 60 miles per hour for two hours, how far does it travel?”

Velocity (60 mph) x Time (2 hours) = Distance (120 miles)

In the case of GPS we're measuring a radio signal so the velocity is going to be the speed of light or roughly 186,000 miles per second.

The problem is measuring the travel time.

The timing problem is tricky. First, the times are going to be awfully short. If a satellite were right overhead the travel time would be something like 0.06 seconds. So we're going to need some really precise clocks. We'll talk about those soon.

But assuming we have precise clocks, how do we measure travel time? To explain it let's use a goofy analogy:

Suppose there was a way to get both the satellite and the receiver to start playing "The Star Spangled Banner" at precisely 12 noon. If sound could reach us from space (which, of course, is ridiculous) then standing at the receiver we'd hear two versions of the Star Spangled Banner, one from our receiver and one from the satellite.

These two versions would be out of sync. The version coming from the satellite would be a little delayed because it had to travel more than 11,000 miles.

If we wanted to see just how delayed the satellite's version was, we could start delaying the receiver's version until they fell into perfect sync.

The amount we have to shift back the receiver's version is equal to the travel time of the satellite's version. So we just multiply that time times the speed of light and BINGO! we've got our distance to the satellite.

That's basically how GPS works.

Only instead of the Star Spangled Banner the satellites and receivers use something called a "Pseudo Random Code" - which is probably easier to sing than the Star Spangled Banner.

A Random Code?

The Pseudo Random Code (PRC, shown above) is a fundamental part of GPS. Physically it's just a very complicated digital code, or in other words, a complicated sequence of "on" and "off" pulses as shown here:

The signal is so complicated that it almost looks like random electrical noise. Hence the name "Pseudo-Random."

There are several good reasons for that complexity: First, the complex pattern helps make sure that the receiver doesn't accidentally sync up to some other signal. The patterns are so complex that it's highly unlikely that a stray signal will have exactly the same shape.

Since each satellite has its own unique Pseudo-Random Code this complexity also guarantees that the receiver won't accidentally pick up another satellite's **signal**. So all the satellites can use the same frequency without jamming each other. And it makes it more difficult for a hostile force to jam the system. In fact the Pseudo Random Code gives the DoD a way to control access to the system.

## GPS Signals in detail

### Carriers

The GPS satellites transmit signals on two carrier frequencies. The L1 carrier is 1575.42 MHz and carries both the status message and a pseudo-random code for timing.

The L2 carrier is 1227.60 MHz and is used for the more precise military pseudo-random code.

### Pseudo-Random Codes

There are two types of pseudo-random code (see tutorial for explanation of pseudo random codes in general). The first pseudo-random code is called the C/A (Coarse Acquisition) code. It modulates the L1 carrier. It repeats every 1023 bits and modulates at a 1MHz rate. Each satellite has a unique pseudo-random code. The C/A code is the basis for civilian GPS use.

The second pseudo-random code is called the P (Precise) code. It repeats on a seven day cycle and modulates both the L1 and L2 carriers at a 10MHz rate. This code is intended for military users and can be encrypted. When it's encrypted it's called "Y" code. Since P code is more complicated than C/A it's more difficult for receivers to acquire. That's why many military receivers start by acquiring the C/A code first and then move on to P code.

### Navigation Message

There is a low frequency signal added to the L1 codes that gives information about the satellite's orbits, their clock corrections and other system status.
But there's another reason for the complexity of the Pseudo Random Code, a reason that's crucial to making GPS economical. The codes make it possible to use "information theory" to " amplify " the GPS signal. And that's why GPS receivers don't need big satellite dishes to receive the GPS signals.

We glossed over one point in our goofy Star-Spangled Banner analogy. It assumes that we can guarantee that both the satellite and the receiver start generating their codes at exactly the same time. But how do we make sure everybody is perfectly synced? Stay tuned and see.

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Encrypted GPS

GPS was developed by the Defense Department primarily for military purposes. And even though it's been estimated that there are ten times as many civilian receivers as military ones the system still has considerable military significance.

To that end the military maintains exclusive access to the more accurate "P-code" pseudo random code. It's ten times the frequency of the civilian C/A code (and so potentially much more accurate) and much harder to jam. When it's encrypted it's called "Y-code" and only military receivers with the encryption key can receive it. Because this code is modulated on two carriers, sophisticated games can be played with the frequencies to help eliminate errors caused by the atmosphere.

It almost makes you want to enlist, doesn't it?

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Expanded Topic:
Using the Pseudo Random Code as an amplifier.

The pseudo random code is one of the brilliant ideas behind GPS. It not only acts as a great timing signal but it also gives us a way to "amplify" the very weak satellite signals.

Here's how that amplification process works:

The world is awash in random electrical noise. If we tuned our receivers to the GPS frequency and graphed what we picked up, we'd just see a randomly varying line --- the earth's background noise. The GPS signal would be buried in that noise.

The pseudo random code looks a lot like the background noise but with one important difference: we know the pattern of its fluctuations.

What if we compare a section of our PRC with the background noise and look for areas where they're both doing the same thing?

We can divide the signal up into time periods (called "chipping the signal") and then mark all the periods where they match (i.e. where the background is high when the PRC is high).

Since both signals are basically random patterns, probability says that about half the time they'll match and half the time they won't.

If we set up a scoring system and give ourselves a point when they match and take away a point when they don't, over the long run we'll end up with a score of zero because the -1's will cancel out the 1's.

But now if a GPS satellite starts transmitting pulses in the same pattern as our pseudo random code, those signals, even though they're weak, will tend to boost the random background noise in the same pattern we're using for our comparison.

Background signals that were right on the border of being a "1" will get boosted over the border and we'll start to see more matches. And our "score" will start to go up.

Even if that tiny boost only puts one in a hundred background pulses over the line, we can make our score as high as we want by comparing over a longer time. If we use the 1 in 100 figure, we could run our score up to ten by comparing over a thousand time periods.

If we compared the PRC to pure random noise over a thousand time periods our score would still be zero, so this represents a ten times amplification.

This explanation is a greatly simplified but the basic concept is significant. It means that the system can get away with less powerful satellites and our receivers don't need big antennas like satellite TV.

You may wonder why satellite TV doesn't use the same concept and eliminate those big dishes. The reason is speed.

> The GPS signal has very little information in it. It's basically just a timing pulse, so we can afford to compare the signal over many time periods. A TV signal carries a lot of information and changes rapidly. The comparison system would be too slow and cumbersome.

We glossed over one point in our goofy Star-Spangled Banner analogy. It assumes that we can guarantee that both the satellite and the receiver start generating their codes at exactly the same time. But how do we make sure everybody is perfectly synced? Stay tuned and see.

*In Review: Measuring Distance*

1. *Distance to a satellite is determined by measuring how long a radio signal takes to reach us from that satellite.*

2. *To make the measurement we assume that both the satellite and our receiver are generating the same pseudo-random codes at exactly the same time.*

3. *By comparing how late the satellite's pseudo-random code appears compared to our receiver's code, we determine how long it took to reach us.*

4. *Multiply that travel time by the speed of light and you've got distance.*

If measuring the travel time of a radio signal is the key to GPS, then our stop watches had better be darn good, because if their timing is off by just a thousandth of a second, at the speed of light, that translates into almost 200 miles of error!

On the satellite side, timing is almost perfect because they have incredibly precise **atomic clocks** on board.

> Atomic Clocks
>
> Atomic clocks don't run on atomic energy. They get the name because they use the oscillations of a particular atom as their "metronome." This form of timing is the most stable and accurate reference man has ever developed.

But what about our receivers here on the ground?

Remember that both the satellite and the receiver need to be able to precisely synchronize their pseudo-random codes to make the system work. ( to review this point click here )

If our receivers needed atomic clocks (which cost upwards of $50K to $100K)

GPS would be a lame duck technology. Nobody could afford it.

Luckily the designers of GPS came up with a brilliant little trick that lets us get by with much less accurate clocks in our receivers. This trick is one of the key elements of GPS and as an added side benefit it means that every GPS receiver is essentially an **atomic-accuracy clock**.

Using GPS for Timing

We generally think of GPS as a navigation or positioning resource but the fact that every GPS receiver is synchronized to universal time makes it the most widely available source of precise time.

This opens up a wide range of applications beyond positioning. GPS is being used to synchronize computer networks, calibrate other navigation systems, synchronize motion picture equipment and much more.

And it's a great resource at 11:59 on New Year's Eve!

The secret to perfect timing is to make an extra satellite measurement.

That's right, if three perfect measurements can locate a point in 3-dimensional space, then four imperfect measurements can do the same thing.

This idea is so fundamental to the working of GPS that we have a separate illustrated section that shows how it works. If you have time, cruise through that.

If you don't have time here's a quick summary:

Extra Measurement Cures Timing Offset

If our receiver's clocks were perfect, then all our satellite ranges would intersect at a single point (which is our position). But with imperfect clocks, a fourth measurement, done as a cross-check, will NOT intersect with the first three.

So the receiver's computer says "Uh-oh! there is a discrepancy in my measurements. I must not be perfectly synced with universal time."

Since any offset from universal time will affect all of our measurements, the receiver looks for a single correction factor that it can subtract from all its timing measurements that would cause them all to intersect at a single point.

That correction brings the receiver's clock back into sync with universal time, and bingo! - you've got atomic accuracy time right in the palm of your hand.

Once it has that correction it applies to all the rest of its measurements and now we've got precise positioning.

One consequence of this principle is that any decent GPS receiver will need to have at least four channels so that it can make the four measurements simultaneously.

With the pseudo-random code as a rock solid timing sync pulse, and this extra measurement trick to get us perfectly synced to universal time, we have got everything we need to measure our distance to a satellite in space.

But for the triangulation to work we not only need to know distance, we also need to know exactly where the satellites are.

*In Review: Getting Perfect Timing*

1. *Accurate timing is the key to measuring distance to satellites.*

2. *Satellites are accurate because they have atomic clocks on board.*

3. *Receiver clocks don't have to be too accurate because an extra satellite range measurement can remove errors.*

In this tutorial we've been assuming that we know where the GPS satellites are so we can use them as reference points.

But how do we know exactly where they are? After all they're floating around 11,000 miles up in space.

A high satellite gathers no moss

That 11,000 mile altitude is actually a benefit in this case, because something that high is well clear of the atmosphere. And that means it will orbit according to very simple mathematics.

The Air Force has injected each GPS satellite into a very precise orbit, according to the **GPS master plan**.

GPS Master Plan

> The launch of the 24th block II satellite in March of 1994 completed the GPS constellation.
>
> Four additional satellites are in reserve to be launched "on need."
>
> The spacings of the satellites are arranged so that a minimum of five satellites are in view from every point on the globe.

On the ground all GPS receivers have an almanac programmed into their computers that tells them where in the sky each satellite is, moment by moment.

The basic orbits are quite exact but just to make things perfect the GPS satellites are constantly **monitored** by the Department of Defense.

Ground Stations

(also known as the "Control Segment")

These stations monitor the GPS satellites, checking both their operational health and their exact position in space. The master ground station transmits corrections for the satellite's ephemeris constants and clock offsets back to the satellites themselves. The satellites can then incorporate these updates in the signals they send to GPS receivers.

There are five monitor stations: Hawaii, Ascension Island, Diego Garcia, Kwajalein, and Colorado Springs.

They use very precise radar to check each satellite's exact altitude, position and speed.

The errors they're checking for are called "ephemeris errors" because they affect the satellite's orbit or "ephemeris." These errors are caused by gravitational pulls from the moon and sun and by the pressure of solar radiation on the satellites.

The errors are usually very slight but if you want great accuracy they must be taken into account.

Once the DoD has measured a satellite's exact position, they relay that information back up to the satellite itself. The satellite then includes this new corrected position information in the timing signals it's broadcasting.

So a GPS signal is more than just pseudo-random code for timing purposes. It also contains a navigation message with ephemeris information as well.

With perfect timing and the satellite's exact position you'd think we'd be ready to make perfect position calculations. But there's trouble afoot. Check out the next section to see what's up.

*In Review: Satellite Positions*

1. *To use the satellites as references for range measurementswe need to know exactly where they are.*

2. *GPS satellites are so high up their orbits are very predictable.*

3. *Minor variations in their orbits are measured by the Department of Defense.*

4. *The error information is sent to the satellites, to be transmitted along*

*with the timing signals.*

Up to now we've been treating the calculations that go into GPS very abstractly, as if the whole thing were happening in a vacuum. But in the real world there are lots of things that can happen to a GPS signal that will make its life less than mathematically perfect.

To get the most out of the system, a good GPS receiver needs to take a wide variety of possible errors into account. Here's what they've got to deal with.

First, one of the basic assumptions we've been using throughout this tutorial is not exactly true. We've been saying that you calculate distance to a satellite by multiplying a signal's travel time by the speed of light. But the speed of light is only constant in a vacuum.

As a GPS signal passes through the charged particles of the **ionosphere** and then through the water vapor in the **troposphere** it gets slowed down a bit, and this creates the same kind of error as bad clocks.

Ionosphere

The ionosphere is the layer of the atmosphere ranging in altitude from 50 to 500 km.

It consists largely of ionized particles which can exert a perturbing effect on GPS signals.

While much of the error induced by the ionosphere can be removed through mathematical modeling, it is still one of the most significant error sources.

Troposphere

The troposphere is the lower part of the earth's atmosphere that encompasses our weather.

It's full of water vapor and varies in temperature and pressure.

But as messy as it is, it causes relatively little error.

There are a couple of ways to minimize this kind of error. For one thing we can predict what a typical delay might be on a typical day. This is called **modeling** and it helps but, of course, atmospheric conditions are rarely exactly typical.

Error Modeling

Much of the delay caused by a signal's trip through our atmosphere can be predicted.

Mathematical models of the atmosphere take into account the charged particles in the ionosphere and the varying gaseous content of the troposphere.

On top of that, the satellites constantly transmit updates to the basic ionospheric model.

A GPS receiver must factor in the angle each signal is taking as it enters the atmosphere because that angle determines the length of the trip through the perturbing medium.

Hey, THIS IS ROCKET SCIENCE!

Another way to get a handle on these atmosphere-induced errors is to compare the relative speeds of two different signals. This " **dual frequency**" measurement is very sophisticated and is only possible with advanced receivers.

Dual Frequency Measurements

Physics says that as light moves through a given medium, low-frequency signals get "refracted" or slowed more than high-frequency signals.

By comparing the delays of the two different carrier frequencies of the GPS signal, L1 and L2, we can deduce what the medium (i.e. atmosphere) is, and we can correct for it.

Unfortunately this requires a very sophisticated receiver since only the military has access to the signals on the L2 carrier.

Civilian companies have worked around this problem with some tricky strategies.

Unfortunately they're so secret if we told you how they work we'd have to kill you.

Trouble for the GPS signal doesn't end when it gets down to the ground. The signal may bounce off various local obstructions before it gets to our receiver.

This is called **multipath error** and is similar to the ghosting you might see on a TV. Good receivers use sophisticated signal rejection techniques to minimize this problem.

Multipath error

The whole concept of GPS relies on the idea that a GPS signal flies straight from the satellite to the receiver.

Unfortunately, in the real world the signal will also bounce around on just about everything in the local environment and get to the receiver that way too.

The result is a barrage of signals arriving at the receiver: first the direct one, then a bunch of delayed reflected ones. This creates a messy signal.

If the bounced signals are strong enough they can confuse the receiver and cause erroneous measurements.

Sophisticated receivers use a variety of signal processing tricks to make sure that they only consider the earliest arriving signals (which are the direct ones).

Problems at the satellite

Even though the satellites are very sophisticated they do account for some tiny errors in the system.

The atomic clocks they use are very, very precise but they're not perfect. Minute discrepancies can occur, and these translate into travel time measurement errors.

And even though the satellites positions are constantly monitored, they can't be watched every second. So slight position or " **ephemeris**" errors can sneak in between monitoring times.

Ephemeris errors

Ephemeris (or orbital) data is constantly being transmitted by the satellites.

Receivers maintain an "almanac" of this data for all satellites and they update these almanacs as new data comes in.

Typically, ephemeris data is updated hourly.

Basic geometry itself can magnify these other errors with a principle called "Geometric Dilution of Precision" or GDOP.

It sounds complicated but the principle is quite simple.

There are usually more satellites available than a receiver needs to fix a position, so the receiver picks a few and ignores the rest.

If it picks satellites that are close together in the sky the intersecting circles that define a position will cross at very shallow angles. That increases the gray area or error margin around a position.

If it picks satellites that are widely separated the circles intersect at almost right angles and that minimizes the error region.

Good receivers determine which satellites will give the lowest GDOP.

The bottom line

Fortunately all of these inaccuracies still don't add up to much of an error. And a form of GPS called "Differential GPS" can significantly reduce these problems. We'll cover this type of GPS later.

To get an idea of the impact of these errors click here for a typical **error budget**:

Summary of GPS Error Sources

| Typical Error in Meters (per satellite) | Standard GPS | Differential GPS |
|---|---|---|
| Satellite Clocks | 1.5 | 0 |
| Orbit Errors | 2.5 | 0 |
| Ionosphere | 5.0 | 0.4 |
| Troposphere | 0.5 | 0.2 |
| Receiver Noise | 0.3 | 0.3 |
| Multipath | 0.6 | 0.6 |
| SA | 30 | 0 |
| Typical Position Accuracy | | |
| Horizontal | 50 | 1.3 |
| Vertical | 78 | 2.0 |
| 3-D | 93 | 2.8 |

In Review: Correcting Errors

1. The earth's ionosphere and atmosphere cause delays in the GPS signal that translate into position errors.

2.Some errors can be factored out using mathematics and modeling.

3.The configuration of the satellites in the sky can magnify other errors.

4.Differential GPS can eliminate almost all error