

Chapter 17: The Global Positioning System

Chapter 17 Objectives

At the conclusion of this chapter, the reader will be able to:

- ❑ Describe briefly the history of navigation.
- ❑ Explain the orbital parameters of satellites using Kepler's laws.
- ❑ List and explain the three segments of the current GPS system.
- ❑ Identify navigation signals.
- ❑ Define essential GPS terminology.
- ❑ Describe the operation of various types of GPS receivers.
- ❑ Explain how position is determined.
- ❑ Interpret correction methods as they relate to accuracy of position.
- ❑ Use simple handheld GPS navigational devices.
- ❑ Describe civilian applications for GPS.
- ❑ Troubleshoot civilian GPS installations

Since the beginning of recorded history, humans have been intensely interested in knowing where they are, and where they are going. The earliest people probably used stones, logs, or other objects as markers to guide people from place to place. Of course, these markers could be covered by snow, washed away by floods, or tampered with by enemies -- and at sea, you couldn't use these markers at all!

The position of the stars is relatively constant. For a long period of time the only way of navigating by sea was to use them. Navigating by stars required special skills, was only accurate within a mile or two, and only worked at night under a clear sky. This was hardly good enough when a ship was looking for a safe harbor on a stormy night! The use of lighted beacons and buoys certainly helped, but these devices required maintenance. Buoys could be washed out of position in storms.

The first electronic navigation systems were developed during World War II. Among these was the long-range navigation or *LORAN* system. LORAN transmitters were located along coastal areas, and each LORAN transmitter sent a special timing signal on a LF (below 300 kHz) frequency. A LORAN receiver tuned to three LORAN transmitters and by doing a little arithmetic, it computed its position. LORAN worked only in areas where transmitters have been set up, and was not very accurate, especially in a moving vehicle; errors of 10 miles were common. However, LORAN represented a great advance over previous navigation methods.

The United States has been studying space-based navigation since the 1960s. One of the early successful satellite positioning systems was *TRANSIT*, the Navy Navigation Satellite System, which was released for commercial use in 1967. Unfortunately, TRANSIT satellites are in a low earth orbit, and their transmission frequencies of 150 MHz and 400 MHz are fairly susceptible to ionospheric interference. TRANSIT satellites are visible for only about 20 minutes, and a position fix can be obtained once every 1 to 3 hours.

The *global positioning system*, or GPS, is the first system designed to provide world-wide, continuous, and highly accurate navigation coverage. It was developed by the US Department of Defense, and consists of a nominal array of 24 orbiting satellites. (There are actually more than 24 active satellites at present, but only 24 are required for a fully-functioning system.) Because of the large number of available satellites, a user can get a position reading at any time, in any location on the globe.

A GPS receiver gives the end user three important pieces of information. First, the receiver derives an accurate value for *time*, which is based upon the atomic clocks in the satellites. Second, the receiver gives the three-dimensional *position* (latitude, longitude, and altitude), which what most users desire. Finally, by doing a little arithmetic with subsequent position readings, a GPS receiver can report speed or *velocity*.

The possible applications of GPS are endless. Civilians have access to the *C/A (Coarse/Acquisition) code* channel, and use GPS during hiking, boating, and other outdoor activities. General Motors uses GPS as part of their OnStar system, which includes a GPS receiver in the automobile -- which is linked to a cellular phone. In the event of a serious accident (detected by in-car sensors), the OnStar system automatically dispatches help to the scene.

The military uses GPS for precise navigation and uses the *P (Precision) Code* channel. The P code channel operates at a much higher data rate than the civilian C/A channel, and in theory offers better accuracy than the C/A code. Advances in receiver design (such as differential GPS techniques) have diminished the accuracy difference between the C/A and P code channels. The *P* channel information can be encrypted (it is then referred to as the *Y* channel), and under this condition it cannot be demodulated by the general public. This would likely occur in a time of war (but could occur at any time), so that enemies would be denied access to precision navigation services.

GPS chipsets have fallen in price (they're now less than \$10 thanks to the cellular phone industry) are now incorporated into a wide variety of devices. In addition, the combination of GPS data received from satellites and information from mapping databases allows anyone to get real-time map and navigation instructions at the push of a button. This technology would have been considered either science fiction or magic a century ago!

17-1 Satellites and Orbits

All satellite communication systems rely upon one or more *space vehicles*, or *satellites* that are made to orbit the earth in predetermined way. With GPS satellites this is especially important, for it is important to be able to accurately calculate the position of each satellite. The motion of satellites, planets and other bodies in space can be described by Kepler's laws of planetary motion.

Kepler's Laws of Planetary Motion

Johannes Kepler published the first two of these laws in 1609, and the third nearly a decade later, in 1618. His laws are as follows:

1. A planet describes an ellipse in its orbit around the Sun, with the Sun at one focus.
2. A ray directed from the Sun to a planet sweeps out equal areas in equal times.
3. The square of the period of a planet's orbit p is proportional to the cube of its semimajor axis a ($p^2 \propto a^3$).
(Note that the symbol " \propto " means "is proportional to.")

Kepler's First Law

Kepler's first law is illustrated in Figure 17-1. What it tells us is that planetary orbits are *elliptical* or *oval* shapes. Most people think that orbits are perfectly round or circular, but that's only approximately true; for celestial objects, a circle does not adequately describe the positions of the orbiting masses.

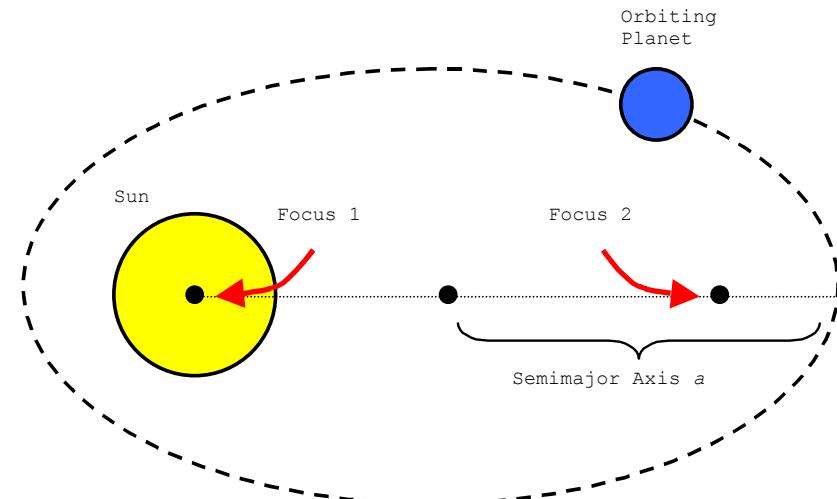


Figure 17-1: Kepler's First Law

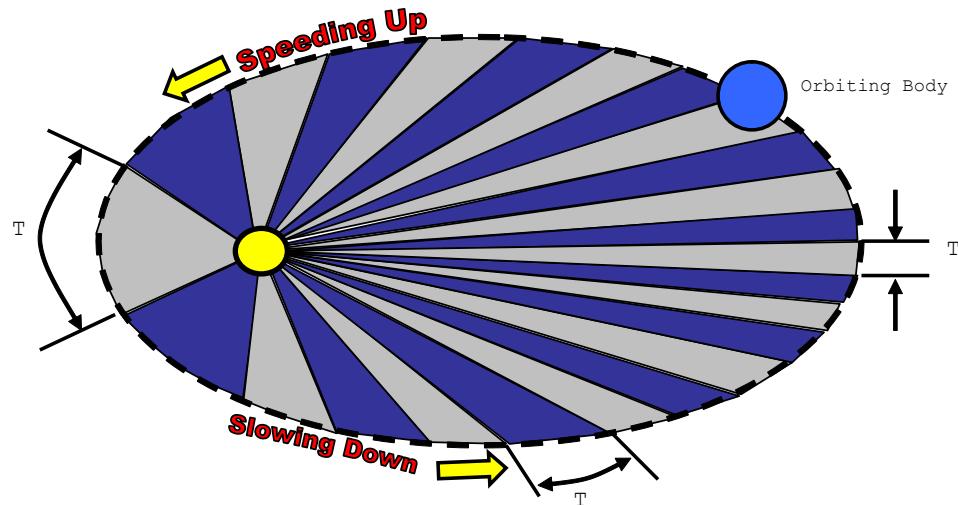
This first law applies to planets circling the sun, so what about satellites orbiting the earth? It still largely applies, because the mass of the earth is much larger than that of the orbiting satellite. *Our satellite orbits are elliptical, not circular.*

For bodies that are not so different in mass that appear to "orbit" each other, the motion is much more complicated, and the best analogy is to imagine two dance partners of slightly different weight spinning in a circle, holding onto each other with their arms outstretched on a dance floor. This dance floor has a hidden switch that can turn off the gravity - so once the couple begins spinning, we switch off the gravity and observe their motion. To our surprise, their motion appears "lumpy" -- the center of mass of the two dancers changes as they turn in free space, which constantly redefines the "orbit" of each person's orbit around the other. There is a big difference between this example and reality: The gravitational attracting force between two orbiting bodies is under constant change as they move closer and farther from each other, unlike the hand grasps of our surprised dancers!

This is important in GPS because for the system to work, we must be able to predict the orbital path of each satellite.

Kepler's Second Law

Figure 17-2 demonstrates Kepler's second law. Notice that the areas of each of the pie slices in this figure are equal.



All times T are equal, and the area of each slice is equal.

Figure 17-2: Kepler's Second Law

Kepler's second law can be condensed by stating that as an orbiting planet approaches the sun, it *speeds up*. An orbiting planet slows down as it moves away from the sun. You might wonder why this is so. The reason is that gravitational attraction builds up rapidly as two bodies approach each other. In order for the orbiting planet to not collide with the sun, it must speed along quickly enough to balance out the centripetal acceleration caused by the gravitational attraction of the sun.

Centripetal acceleration is the acceleration that tends to keep an object moving along a curved (usually circular) path. If you attach a weight to a rope and swing it in a circle, you will feel a force pulling outward on the rope. This is the reaction force to the centripetal accelerating force your muscles are providing in order to hold onto the rope as the weight attempts to fly off in a straight-line path. As a planet approaches the solar portion of its orbit, it experiences a greater gravitational pull from the sun, and moves closer to it. Conservation of momentum predicts that the planet will speed up, since its radius of motion has been reduced. This is why the pie slices above have constant area.

The second law tells us that satellites in low orbits must travel much faster than those in high orbits. There is a trade off here; satellites in low orbits are much less expensive to launch, can be seen from many places on the earth as they move in their path, and provide stronger signals on earth (because of their closer distances); but their orbits are more likely to be unstable. Low orbits plunge a satellite through part of the atmosphere, which creates drag. High orbits are more expensive, but generally more stable; but because of the increased distance to earth, the signals from satellites in high orbits are much weaker.

Kepler's Third Law

The third law predicts the orbital period of planets. If we take the square root of both sides of Kepler's relationship, we get the following equation:

$$(17-1) \quad p \propto a^{3/2}$$

Where p is the orbital period (in time units), and a is the distance of the semimajor axis of the planet's orbit as shown in Figure 17-1.

What Equation 17-1 tells us is that the orbital *period* of a satellite (the time that it takes to complete one orbital round-trip) increases as the height of a satellite is increased, but not in linear proportion (the exponent is 3/2 in Equation 17-1). We control the orbital period of a satellite by controlling the height of its orbit.

Types of Orbits

There are three primary types of satellite orbits, as shown below in Figure 17-3. These are *polar*, *inclined*, and *equatorial*.

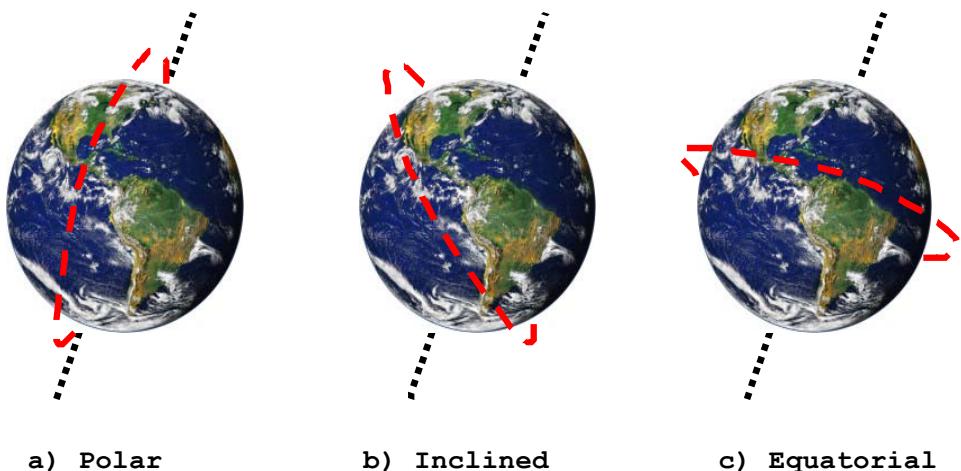


Figure 17-3: Types of Orbits

Polar orbits are used for low-flying satellite missions such as reconnaissance. In such an orbit, the satellite flies over both poles. The satellite path looks like a string that is being wrapped around a slowly-turning ball. The exact track (and thus the positions "seen" on earth by the satellite) depend on the orbital altitude.

Inclined orbits are used for communications work where coverage is needed mainly around the earth's middle regions, and continuous communication is not needed. GPS satellites use this type of orbit.

Equatorial orbits are used for *geostationary satellites*. You'll recall that Kepler's third law predicts the orbital period of a satellite in terms of the length of its semimajor axis. For earth satellites, an altitude of 22,300 miles leads to a geostationary orbit, where the satellite takes 24 hours to make one round trip. When placed over the equator in such an orbit, the satellite appears fixed at a point in space, which makes it immensely useful for long-distance communications. About 40% of the earth can be covered by one geostationary satellite; three such satellites can cover about 95% of the earth's surface (the polar regions are hard to reach).

The equatorial orbit locations are prime real estate. They were originally spaced every 4 degrees, for $(360/4)$ or 90 "parking spaces." Improvements in technology have resulted in a decrease to 2 degree spaces, and 1 degree spaces are not far off.

Orbits of GPS Satellites

GPS satellites are placed in orbits that are at 55 degrees inclination with respect to the equator. These satellites orbit within six equally-spaced planes (labeled A through F), which appear as overlapping rings circling the globe as shown below in Figure 17-4. There are nominally four satellites in each of these six planes, but they are not equally spaced in order to optimize world-wide visibility.⁵⁰

The semimajor axis of the GPS satellite orbits is approximately 16,156 miles (26,000 km), which is approximately 12,200 miles above the earth's surface. According to Kepler's third law, this leads to an orbital period of slightly less than 12 hours. This means that the satellites complete two round-trips every earth day, and because the orbital period is an exact multiple of the period of the earth's rotation, the satellite trajectories (the path of the satellite traced along the earth's surface) repeat daily, which simplifies the calculations needed to find their exact positions.

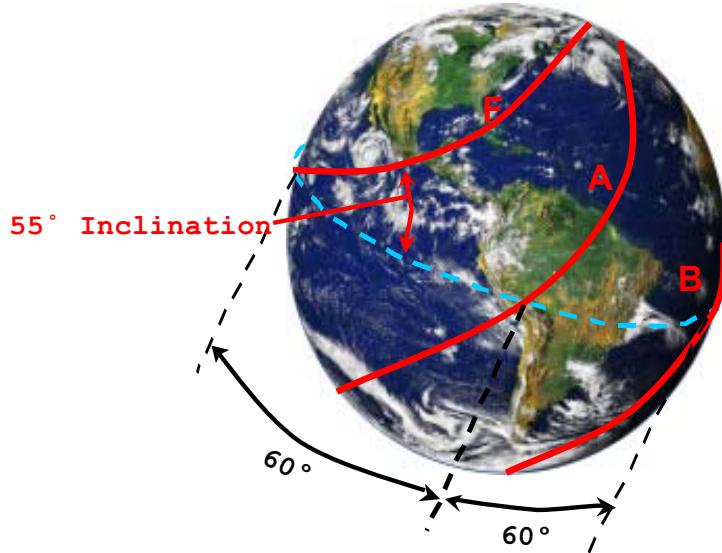


Figure 17-4: The Orbits of GPS Satellites

The height of the GPS satellite orbits gives excellent signal coverage as well, but leads to a path loss (signal loss between satellite and GPS receiver on the earth's surface) of around 186 dB; this causes the received GPS signals to be far below the terrestrial noise level on earth (they are approximately -160 dBm at the antenna input of a GPS receiver.) Special signal processing techniques are used to compensate for this loss, as we'll soon see.

Section Checkpoint

- 17-1 What is the advantage of GPS over earlier systems such as LORAN?
- 17-2 What are the two code channels of GPS? What is each used for?
- 17-3 State Kepler's three laws of planetary motion.
- 17-4 Explain how each of Kepler's laws practically applies to satellites.
- 17-5 What are the three types of orbits? What is each used for?
- 17-6 Why are equatorial orbits valuable?
- 17-7 What is the type of orbit and orbital period of GPS satellites?
- 17-8 What is one bad effect of the high orbital height of GPS satellites?

17-2 How GPS Works

The principles behind the operation of GPS are fairly straightforward. In short, GPS operates by measuring the time that elapses between the transmission of special timing signals from the array of GPS satellites, and reception of those timing signals at a GPS receiver. Since these signals are carried by radio waves, which travel at an approximately constant speed, we can calculate the range (distance) to each satellite we have locked onto, and thus find our position in space. This involves nothing more complicated than that old standby formula from high school, "*distance is rate times time.*" Stated algebraically:

$$(17-2) \quad D \mid R \Delta T$$

Where D is the distance traveled, R is the rate at which radio wave energy travels (the speed of light, 3×10^8 m/s), and T is the elapsed time between transmission and reception.

In order to carry on a discussion about how this works, we'll need to assume that we know a few things beforehand. Later on we will see how these details are calculated.

Information Needed to Calculate a Position

In order for a GPS receiver to calculate its position in space, it needs to know the following information:

- ⌘ An accurate value for time. The receiver needs to know this so that it can calculate the time of travel for each signal it receives from a satellite. We will see that the receiver can get this from the satellites.
- ⌘ The position in space of each satellite it is measuring from. This is possible to know because the orbital characteristics of the satellites are known.

How Position is Calculated

Suppose that we turn on a GPS receiver, and it reads our distance from satellite *A* as 11,000 miles, as shown in Figure 17-5:

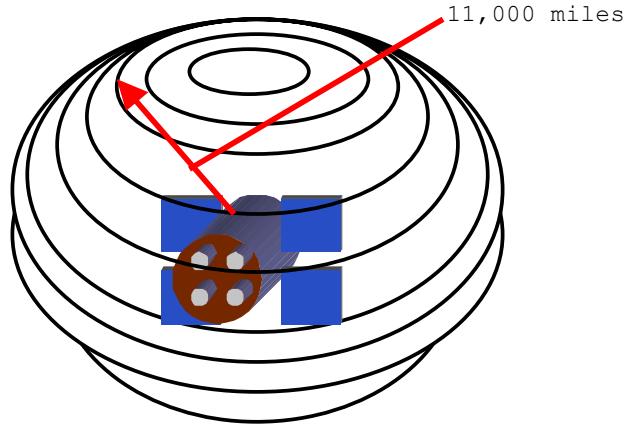


Figure 17-5: 11,000 Miles from Satellite *A*

With the measurement information above, we can be located at an infinite number of points on a sphere¹⁴ surrounding the satellite. Be careful; the sphere of Figure 17-5 doesn't represent the earth. It represents all points that are 11,000 miles away from the center, which is satellite *A*.

Suppose that we were able to get a fix on another satellite (call it satellite *B*) and find the distance between ourselves and this second satellite. We would now know that we are 11,000 miles from satellite *A* and 12,000 miles from satellite *B*. The picture now looks like Figure 17-6:

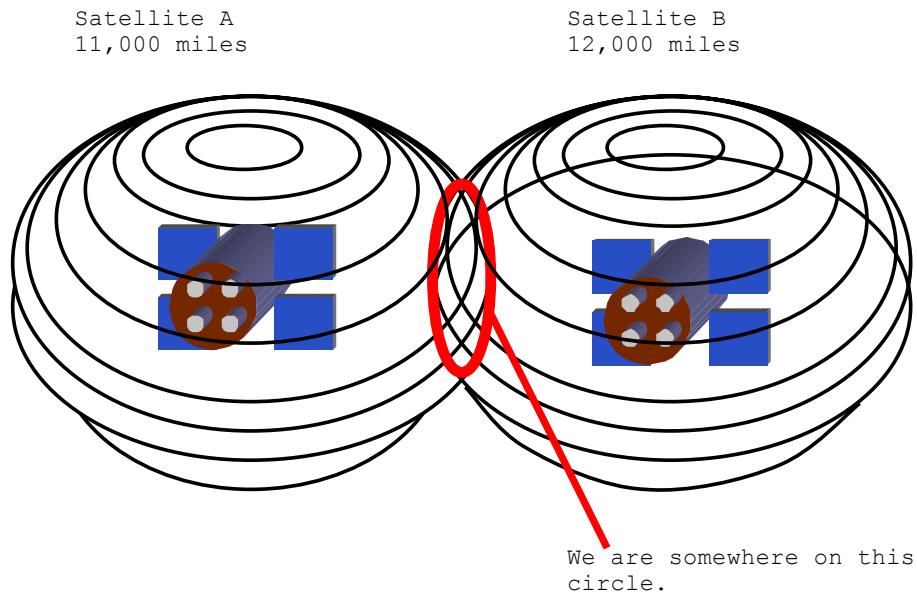


Figure 17-6: The Distances to Two Satellites are Known

¹⁴ Note that we employ spheres as an approximation. The actual geometry is more complicated due to multiple sources of timing error within GPS receivers.

There are still an infinite number of points where we could be located, but at least all of these points are now located on the edge of the circle common to satellites *A* and *B* in Figure 17-6. This circle is the intersection of the two spheres surrounding satellites *A* and *B*. This certainly narrows things down a bit. Perhaps we can look at a *third* satellite. If we do so, the result will look like Figure 17-7.

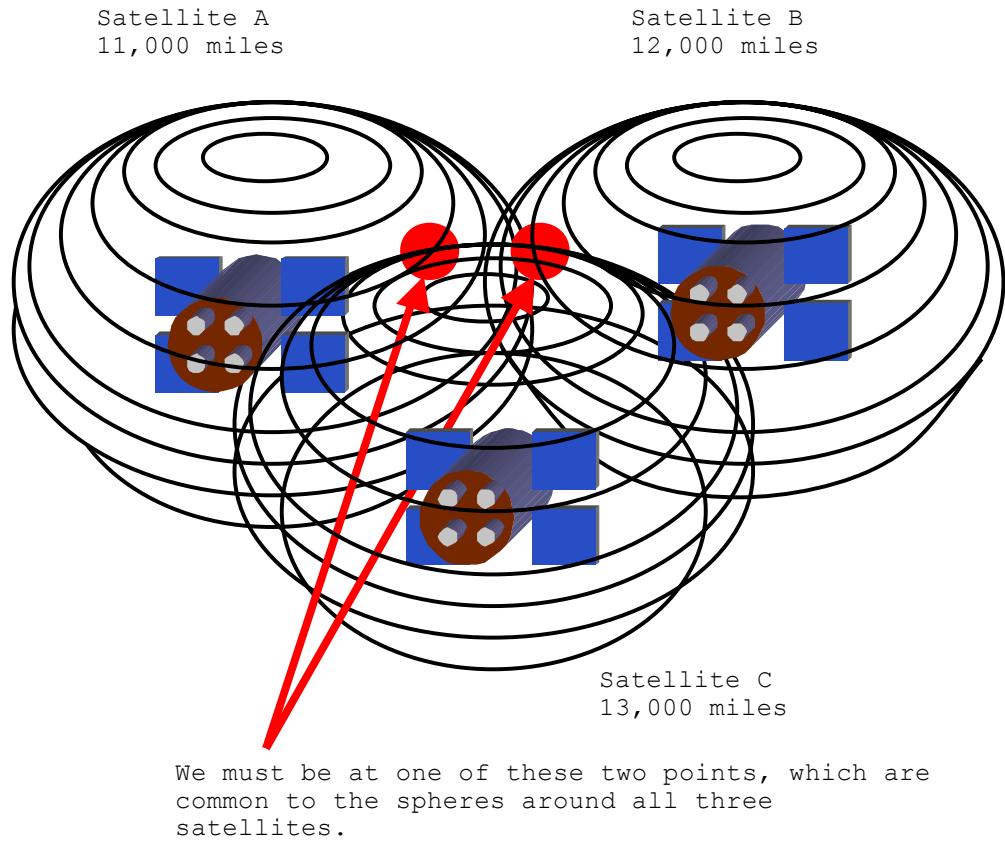


Figure 17-7: The position Fix with Three Satellites

By reading the distance to satellite *C*, we have now narrowed our position down to one of two possible points. That's much better. In fact, in some applications, this might actually be enough information to plot our position. One of the points might be a totally absurd answer -- such as a point 1,000 miles in the air -- in which case, we can reject it and use the other solution. Or we might know our altitude, and therefore choose the point that correctly corresponds with that bit of information. In early GPS receivers, these approaches were used. In the early days of GPS (late 1980s), all the planned satellites had not yet been launched, and receivers were slow to read data from multiple satellites. In those days, receivers had to work under less than optimal conditions -- so allowing a receiver to use this last simplification when only three satellites were in view could mean the difference between the user getting a GPS position fix, or not. Current receivers can get a 2-dimensional position (no altitude information) fix when only three satellites are readable.

To remove any ambiguity from the measurement of Figure 17-7, the distance to a fourth satellite must be measured. This is now quite feasible; modern GPS receivers can quickly read and process the data from multiple satellite channels at the same time. This measurement eliminates the incorrect point from Figure 17-7, providing an accurate measurement in all three dimensions. There's another reason why it is desirable to obtain measurements from four satellites, and that is the acquisition of the correct *time*, as we'll soon see.

What Data are Presented by a GPS Receiver?

A GPS receiver can give the end-user three important pieces of information. First, the user's position in three dimensions (altitude, longitude, and latitude) is reported by the calculation method above. Second, the *time* is available, as the receiver is able to receive the time information from the satellites themselves, which have extremely precise atomic clocks onboard. Finally, the speed or *velocity* of the receiver is available. The receiver calculates its speed by using equation 17-3 below. All the GPS receiver needs to do in order to calculate velocity is to take two successive distance measurements and divide them by the time interval between them.

$$(17-3) v \mid \frac{\div x}{\div t}$$

Where $\div x$ is the difference between two position readings, and $\div t$ is the difference between the two points in time where these positions were measured.

Getting Accurate Time

Accurate timing is essential to the operation of GPS, because radio waves travel at a very high speed (3×10^8 m/s, or 186,000 miles/sec). A timing error of just 10 μ s represents a distance measurement error of 3,000 meters (1.86 miles, or 9840 feet)!

Each of the satellites contains several *atomic clocks*. These are very accurate timekeeping devices that use the natural frequency of either cesium or rubidium atoms to control their oscillator circuit (much like using a quartz crystal in a conventional oscillator). Because each satellite has several of these clocks on board, their timing errors can be mathematically cancelled to provide superb accuracy (and extra reliability, in case one of them happens to fail). In addition, the satellite clocks are periodically corrected by the master control station located at Falcon Air Force base, near Colorado Springs, Colorado.

Atomic clocks are very expensive; the satellite clocks cost over \$50,000 apiece. If a receiver were required to have such a clock on board, only the very rich could afford to use GPS! However, by using a little algebra, and comparing the measurements from several satellites, a GPS receiver can correct its own internal clock to match that of the satellites. Figure 17-8 shows the effect of timing errors on position.

In the figure we have restricted the discussion to two dimensions, which makes it easier to draw the diagrams and understand the results. These results will also be valid in three dimensions. We have also shown distances in units of *time*, rather than distance. This makes it easier to see how the corrections can be applied (since we know that distance is obtained by multiplying time and velocity).

Our *actual* position is point *X*, which is one of the two points of intersection from the ranges derived from satellites *A* and *B*. Our receiver has reported that it took 50 ms for the signal to get to us from satellite *A* (a distance of 9300 miles), and 60 ms from satellite *B* (a distance of 11,160 miles). If all of our timing sources (both satellites and the receiver) agree, then this is the point that will be reported.

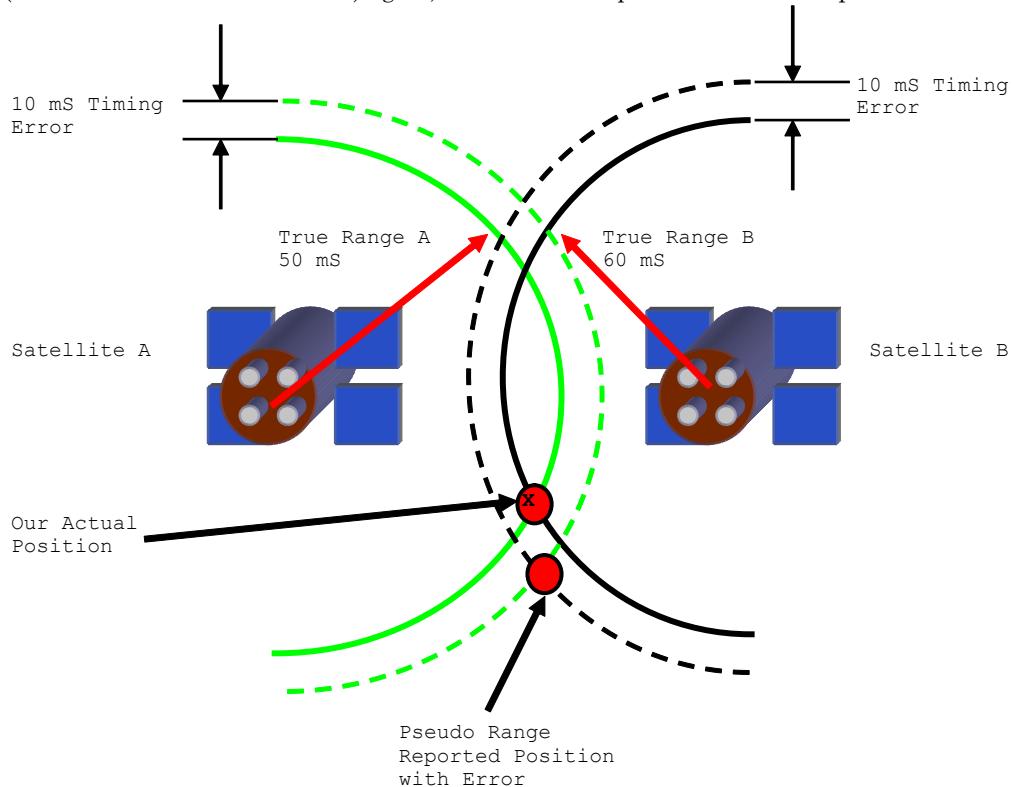


Figure 17-8: The Effect of Timing Errors

However, what happens if our receiver clock is 10 ms fast? It will report a *larger* distance to each of the satellites, which is represented by the dashed circles. The receiver now thinks that it is 60 ms (11,160 miles) to satellite *A*, and 70 ms (13,020 miles) to satellite *B*. In other words, the 10 ms of clock error caused the range to each satellite to be off by 1,860 miles! These ranges containing timing errors are sometimes

called *pseudo-ranges*, meaning that they are *false range measurements*. This problem can be resolved by taking a range measurement from a *third* satellite, as shown in Figure 17-9.

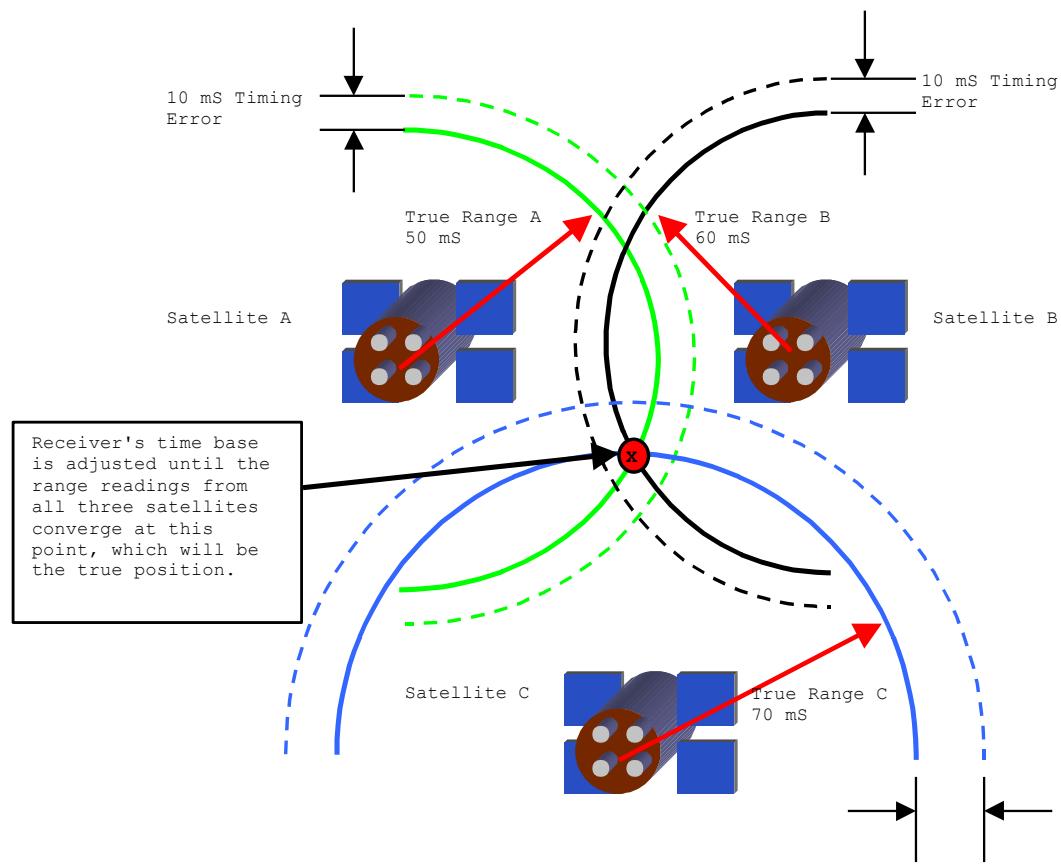


Figure 17-9: Correcting the Time

If our receiver measures from a third satellite, it will find a similar timing error (10 ms) in the range measurement. A little geometry will also reveal that the receiver will "discover" that the three pseudo-range circles do not coincide at our actual position. The receiver then knows that its internal clock is off, and can then make an adjustment to correct itself.

This adjustment is not made by trial and error. Because four satellites are actually used in three dimensions, a system of four equations in four unknowns must be solved to determine the nature of the timing error. These calculations are carried out by the microprocessor in the GPS receiver and are of little consequence to the technician. Once the receiver has corrected its time clock, it can calculate its position with high accuracy.

GPS receivers use a precision crystal oscillator as their internal clock source, and constantly perform this correction as they receive data from the satellites. This is one reason that you can really trust the time given on the display of a GPS receiver, as long as the GPS unit has recently locked onto at least four satellites, and has been set for the correct time zone. The GPS system uses coordinated universal time (UTC) as its standard, not the regional time of any particular location.

Finding the Satellite Positions

In order to calculate position from the satellite timing signals, the positions of the satellites must be known. Each satellite has a specific and precise *orbit* and *orbital position* that is predictable, and this information is programmed into a lookup table called an *almanac* that is contained within the software in the GPS receiver. The almanac of a GPS receiver contains the planned orbital patterns of all GPS satellites in the receiver's memory.

GPS satellites travel in orbits that are 12,200 miles above the earth's surface, and are designed to orbit the earth once every 12 hours. This is part of the GPS master plan, and it allows all the satellites to periodically pass over the Colorado Springs master control station for maintenance and updating.

At an altitude of 12,200 miles, a satellite must travel at an average speed of 8,500 mph in order to have a stable orbit. If the satellite moves too fast or slow, it will leave the intended orbit with disastrous results. Fortunately, at this height, there is no significant atmosphere to interfere with the motion of the satellite, and the primary forces acting on the satellite are the gravitational pulls of the earth, sun, and moon.

Each satellite has a specific identification code, and these codes are programmed into the receiver's almanac. Therefore, when a GPS receiver receives a message from a satellite, it can determine the satellite's position in space by looking up its ID code in the almanac, and then applying the almanac information into the satellite's orbital equations.

Ephemeris Information

In spite of the extreme precision involved in planning the orbits of GPS satellites, orbital changes do occur. Errors build up in the orbital position of a satellite, and are caused by the gravitational pulls of the sun and moon, and the changing effect of *solar radiation*.

Solar radiation tends to exert a push on satellites, but because the earth, sun, and the satellite are in an ever-changing arrangement, this extra push can cause very complicated changes in the orbit, especially when the earth passes between the satellite and the sun (where the solar push temporarily disappears).

Since a GPS satellite passes by one of the Department of Defense monitoring stations twice a day, its altitude, position, and speed can be accurately measured, and this information can be relayed back up to the satellite. The satellite then retransmits this data, called the *ephemeris data*, along with its timing message. The word "ephemeris" means short-lived -- the ephemeris data provide essentially short-term, fine-tuning adjustments to the orbital information in the GPS almanac.

The almanac in a receiver gives the *planned* orbital data for each GPS satellite, while the *ephemeris* provides the same information that has been "fine-tuned" by the master control station to reflect the actual orbital conditions of the satellite. By using the ephemeris data, GPS receivers always know the most up-to-date and exact orbital information for each satellite. This is important, for to calculate position accurately, the receiver must be able to calculate the position of each satellite with precision.

Selective Availability

GPS has the potential to be useful to enemies of the United States, and because of that, the Department of Defense has implemented *selective availability*, or SA. When selective availability is enabled, errors are deliberately introduced into the system. For example, random errors can be introduced into the ephemeris and timing messages on the C/A (civilian) channel, which directly degrades the accuracy of GPS measurements. Even with selective ability enabled, innovative GPS receiver manufacturers have found ways of coping with these errors, as we'll see in a later section.

Anti-Spoofing

Anti-spoofing or AS is an additional mode that can be selectively turned on or off by the government. The purpose of anti-spoofing is to prevent an enemy from transmitting false navigation codes on top of the authentic satellite data. When AS is enabled, the *P code* is further encrypted to form the *Y code*.

Section Checkpoint

17-9 What two pieces of information must a GPS receiver possess in order to find its position in space?

17-10 Explain how a position "fix" can be obtained from three and four satellites.

17-11 List the three types of information a GPS receiver can provide for the user.

17-12 What type of clocks are used in GPS satellites? Why are these practical for receivers?

17-13 Explain how a GPS receiver finds the correct time.

17-14 How does a GPS receiver know the exact position of each satellite?

17-15 What forces can move a satellite from its planned orbit?

17-15 Explain what the purpose of ephemeris data is. What is the difference between almanac and ephemeris data?

17-16 What is selective availability? How is it implemented?

17-3 GPS Segments and Navigation Signal Processing

The GPS system contains an impressive array of technologies. Because of this, understanding how all the pieces of the system fit together can be a little intimidating at first. GPS can be best understood if it is analyzed in pieces or *segments*. The GPS system is divided into three parts. These are the *space segment*, the *control segment*, and the *user segment*.

The GPS satellites make up the *space segment*. The satellites transmit the navigation messages on two different phase-modulated frequencies (we will see why two frequencies are used later).

The *control segment* runs the entire GPS system. It consists of a *master control station* or MCS which is located at Falcon Air Force base near Colorado Springs, CO, and a number of monitoring stations distributed around the globe. The primary mission of the control segment is to track the position and health of all GPS satellites, and update the navigation messages transmitted by each satellite. Part of the navigation message includes the *ephemeris data*. The ephemeris is the set of recently-computed (and short-lived) information about the GPS satellite's orbit. The ephemeris data is transmitted periodically to each GPS satellites by the master control station, which has received data about each "bird" from the various tracking stations around the world. The satellite then retransmits this information along with the

navigation message. In this way, all GPS receivers have exact and up-to-date information about the orbital position of each satellite, which compensates for errors that accumulate in the satellite orbits.

The *user segment* consists of all receivers in use on and near the earth. A GPS receiver has a tremendous computational task; it must lock onto at least four different satellites, and compute its position from the received timing signals. Most GPS end-users are intimately familiar with their own equipment (the receivers), but have no real idea of the complex network of resources that supports the receiver's operation.

Space Segment

The GPS satellites have been released in *blocks* (groups) since the system's inception in 1978. There are currently 31 active satellites in this segment, divided into *blocks*. Ten Block I satellites were launched between February 1978 and October 1985. These were used as a test bed to demonstrate the capabilities of the system, and all of them have long since been turned off, or have failed. The current satellites are in Blocks II, IIR, and III. Block III satellites incorporate new additional features including a new military signal called the M-code, which is transmitted by a directional "spot" antenna providing 20 dB additional field strength in a limited geographic area, additional of new civilian frequencies (L1C, 1575.42 MHz and L2C, 1227.6 MHz), and a civilian safety of life signal (L5, 1176.45 MHz). The active satellites are listed in Figure 17-10.

Satellite ID	Service Vehicle Number (SVN)	Launch Date	Orbital Plane	GPS Block
USA-132	43	July 23, 1997	F6	IIR
USA-150	51	May 11, 2000	E4	IIR
USA-154	41	November 10, 2000	F5	IIR
USA-166	56	January 29, 2003	B1	IIR
USA-168	45	March 31, 2003	D3	IIR
USA-177	59	March 20, 2004	C5	IIR
USA-180	61	November 6, 2004	D1	IIR
USA-183	53	September 26, 2005	C4	IIRM
USA-190	52	September 25, 2006	A2	IIRM
USA-192	58	November 17, 2006	B4	IIRM
USA-196	55	October 17, 2007	F2	IIRM
USA-199	57	December 20, 2007	C1	IIRM
USA-201	48	March 15, 2008	A4	IIRM
USA-206	50	August 17, 2009	E3	IIRM
USA-213	62	May 28, 2010	B2	IIF
USA-232	63	July 16, 2011	D2	IIF
USA-239	65	October 4, 2012	A1	IIF
USA-242	66	May 15, 2013	C2	IIF
USA-248	64	February 21, 2014	A3	IIF
USA-251	67	May 17, 2014	D4	IIF
USA-256	68	August 2, 2014	F3	IIF
USA-258	69	October 29, 2014	E1	IIF
USA-260	71	March 25, 2015	B5	IIF
USA-262	72	July 15, 2015	C3	IIF
USA-265	73	October 31, 2015	E2	IIF
USA-266	70	February 5, 2016	F1	IIF
USA-289	74	December 23, 2018	F4	III
USA-293	75	August 22, 2019	D6	III
USA-304	76	June 30, 2020	E5	III
USA-309	77	November 5, 2020	B6	III
USA-319	78	June 17, 2021	D5	III

Figure 17-10: GPS Active Satellite Status

Navigation Messages

The satellites repeatedly transmit a *navigation message* that is sent at a data rate of 50 BPS. The complete navigation message consists of 25 *frames* (data blocks), each containing 1500 bits. Each frame is divided into five 300-bit subframes, which are 10 *words* of 30 bits each. At the 50 bps data rate, it takes 6 seconds to send a subframe, 30 seconds for a frame, and 12.5 minutes for the entire navigation message. Figure 17-11 illustrates the basic structure of the navigation message frames.