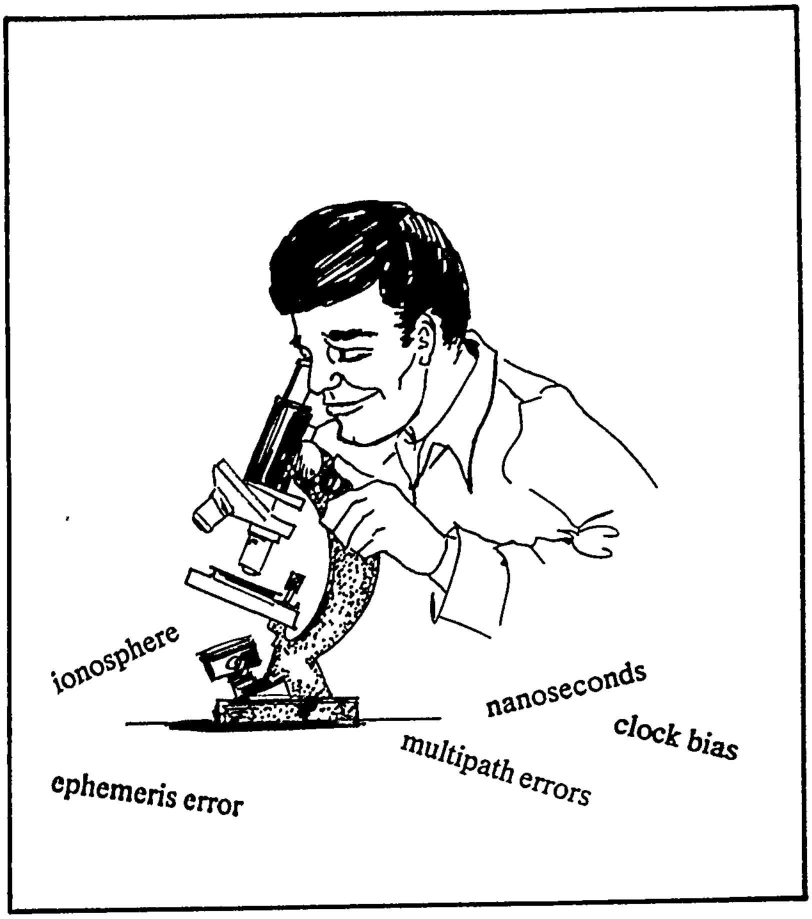


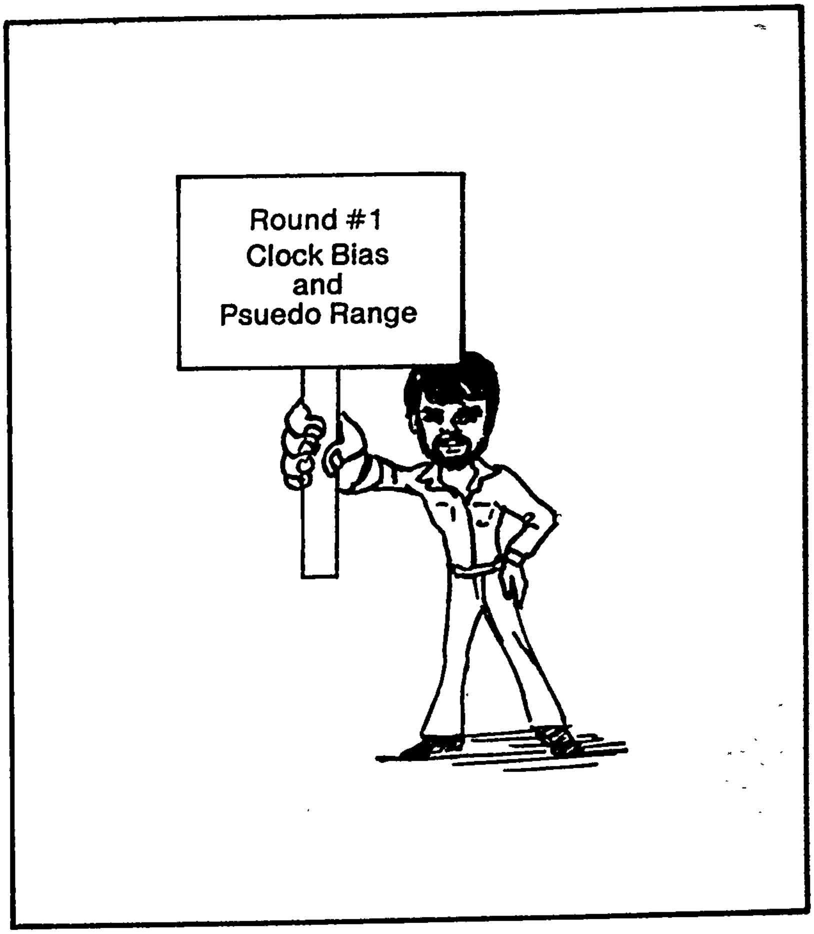
PART II

DETAILS, Details, details...

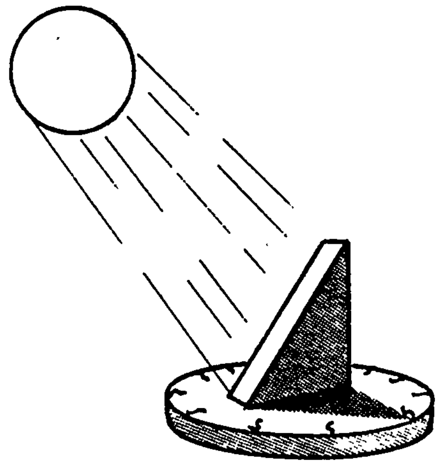
DON'T WORRY

(this stuff is easy)

...it only sounds hard because you haven't heard the words before. It's much easier than the concepts stuff.



This is an example of a real world problem. In the concept section, we just assumed that the receiver was generating the pseudo-random code simultaneously with the satellite.



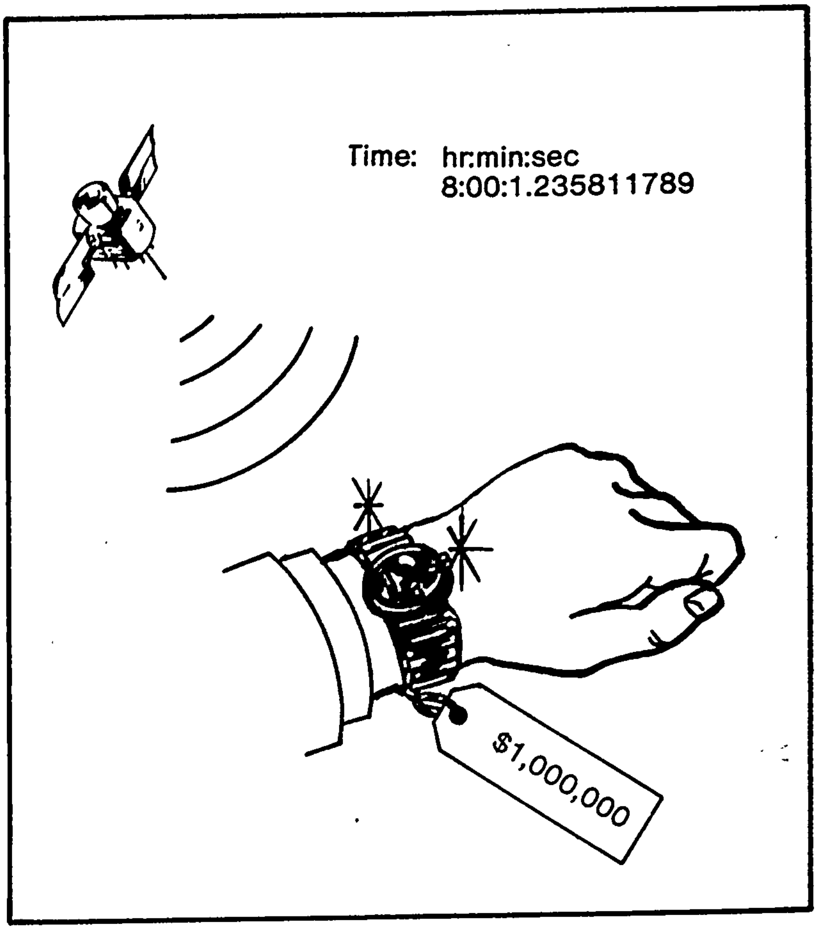
0.000000001 second

a nanosecond

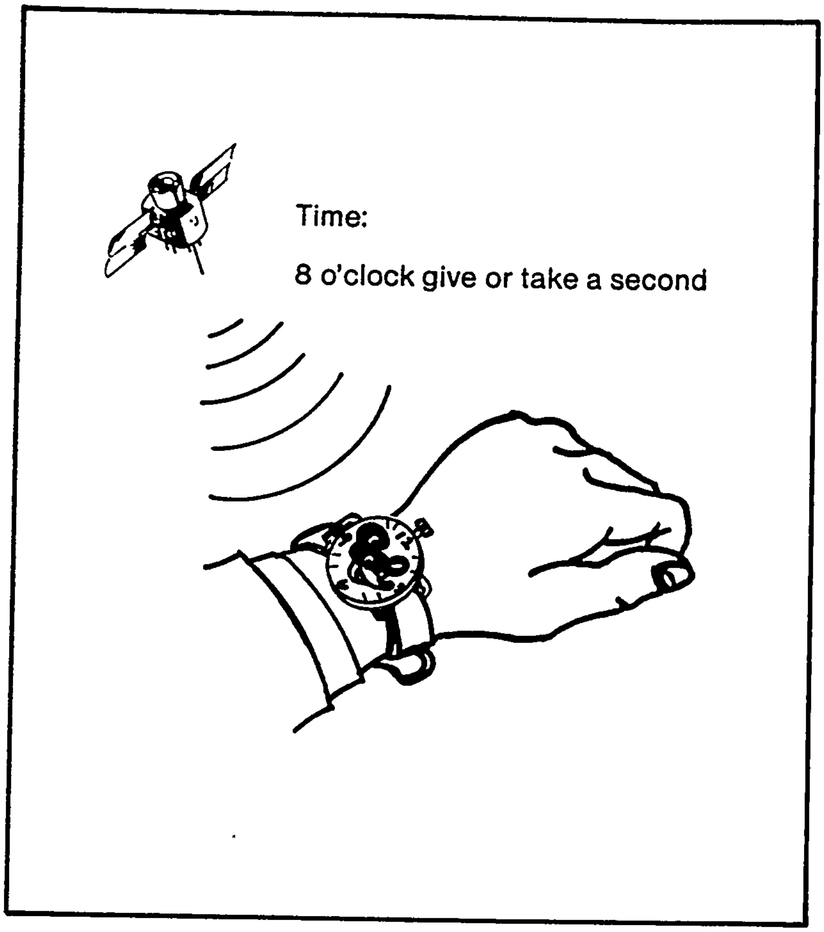
...not a lot of time

(It takes a billion of them to fill a second.)

In practice, doing this isn't so easy since the Δt's involved in the range calculations must be measured to within nanoseconds to produce the desired accuracy.

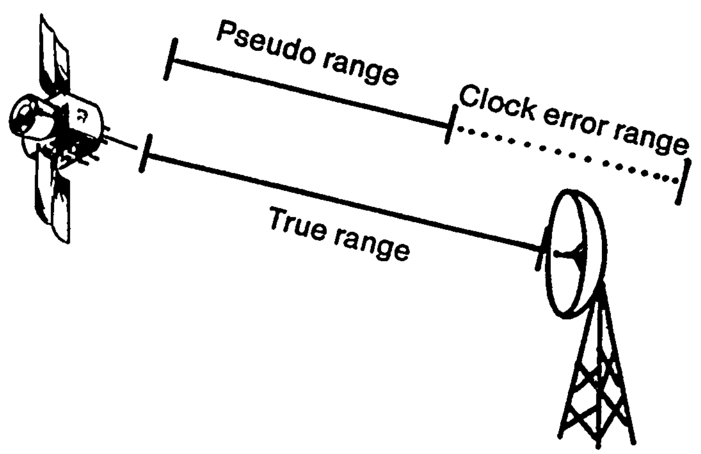


There are two ways around this. One is to put into all receivers very expensive atomic clocks that are as accurate as the four atomic clocks on each satellite.

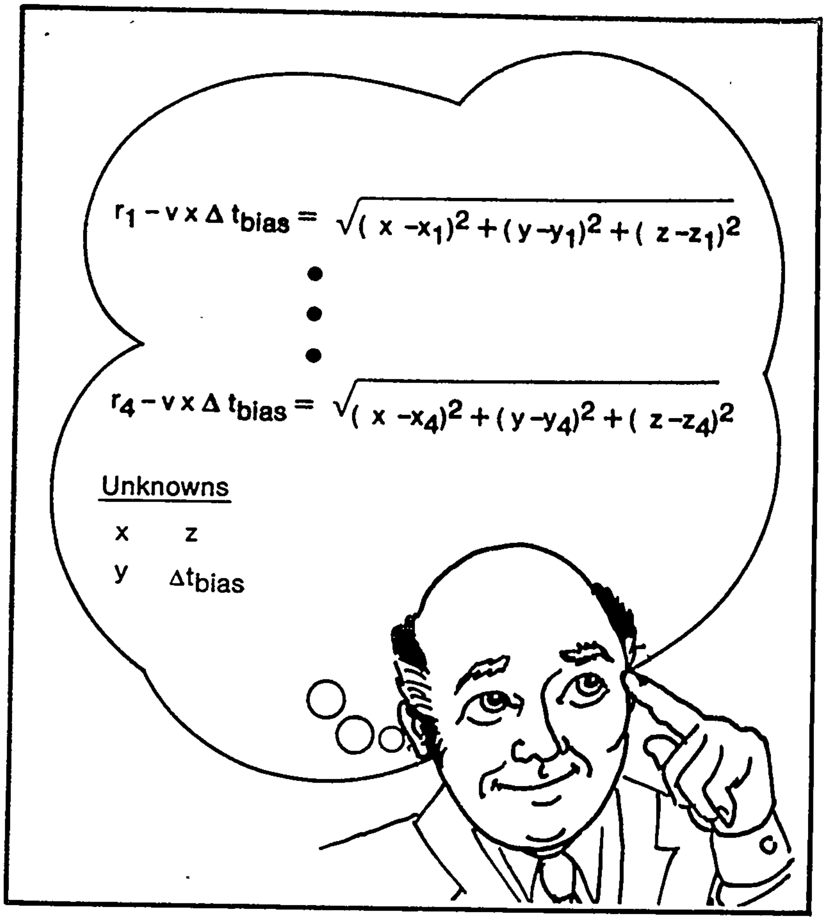


Or – we could just assume that our clock is "off" by some "clock bias." This may seem ludicrous but it is not. This error on our clock, or clock bias, Δt_{bias}, is just another unknown and can be included in our range equations.

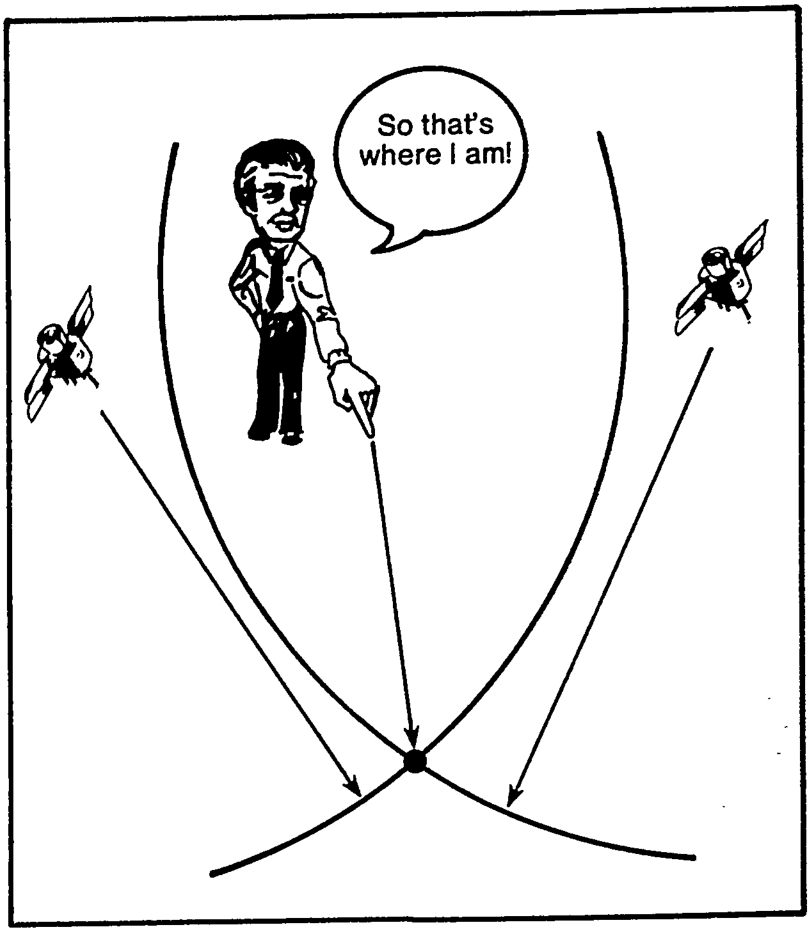
This bias represents the difference between our receiver's time and GPS time.



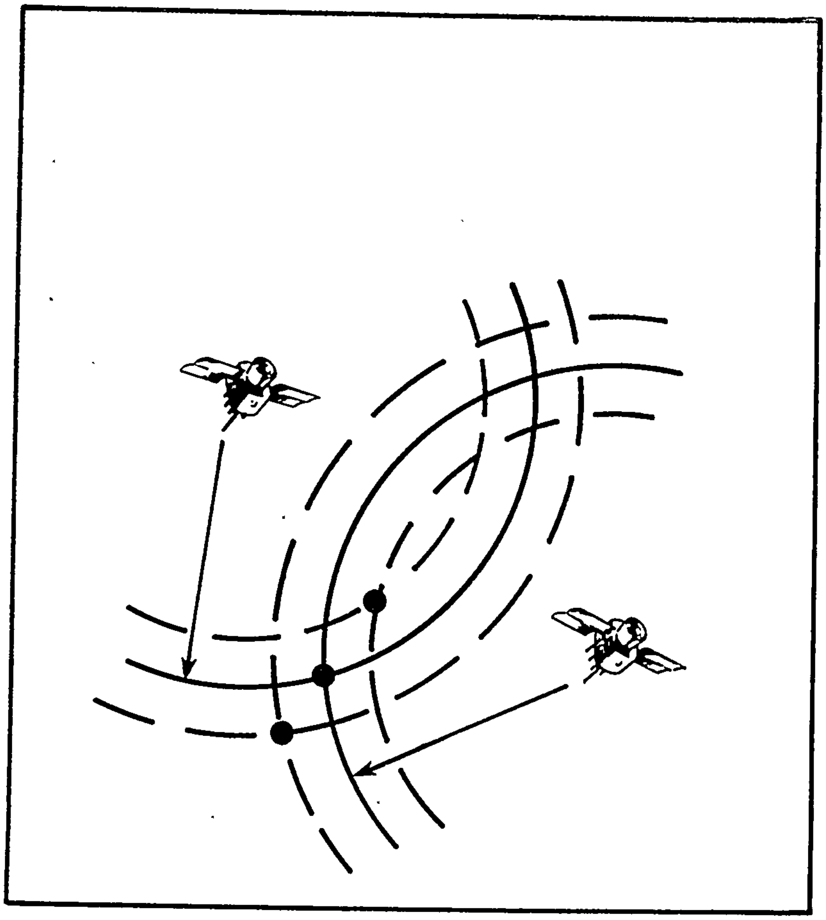
The Δt measured can be broken up into the "true" Δt and a "due-to-receiver clock error" Δt. Since range is calculated from the Δt, the measured range can be broken up into a "true" range part and a "range due to clock error" part. The range as measured is known as the "pseudo range" since it really isn't the true range.



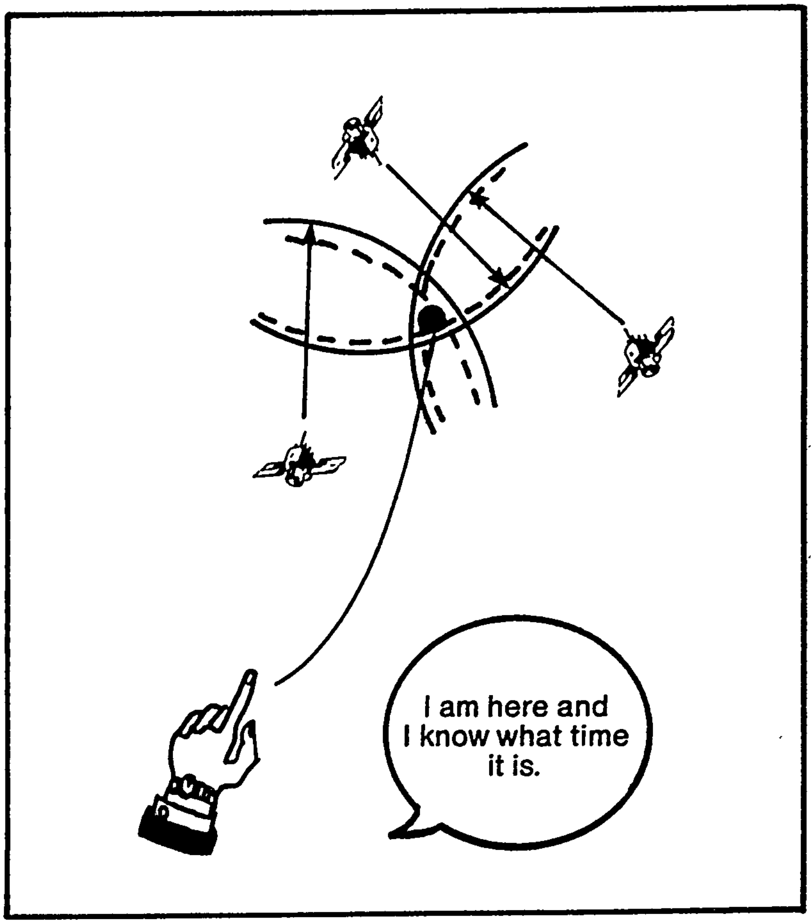
Now, when we measure the "pseudo range," we introduce another unknown, Δt_{bias}, so we need four satellites to give us four equations from which to fix our position (and accommodate our cheap clock).



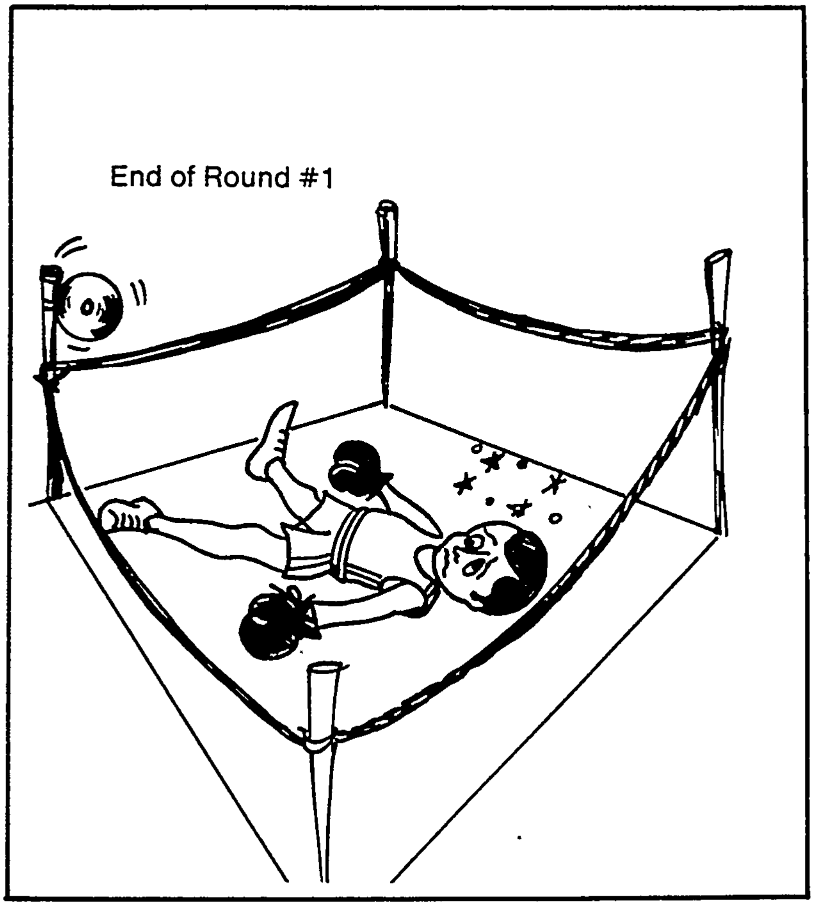
This is easier to visualize in two dimensions. Suppose there were no clock bias. We would need two satellites to fix our position.



Now, suppose we know we have a clock bias. It will affect all range measurements an equal amount. We just don't know how much clock bias we have. If we did, we would know which of the range intersections is right.



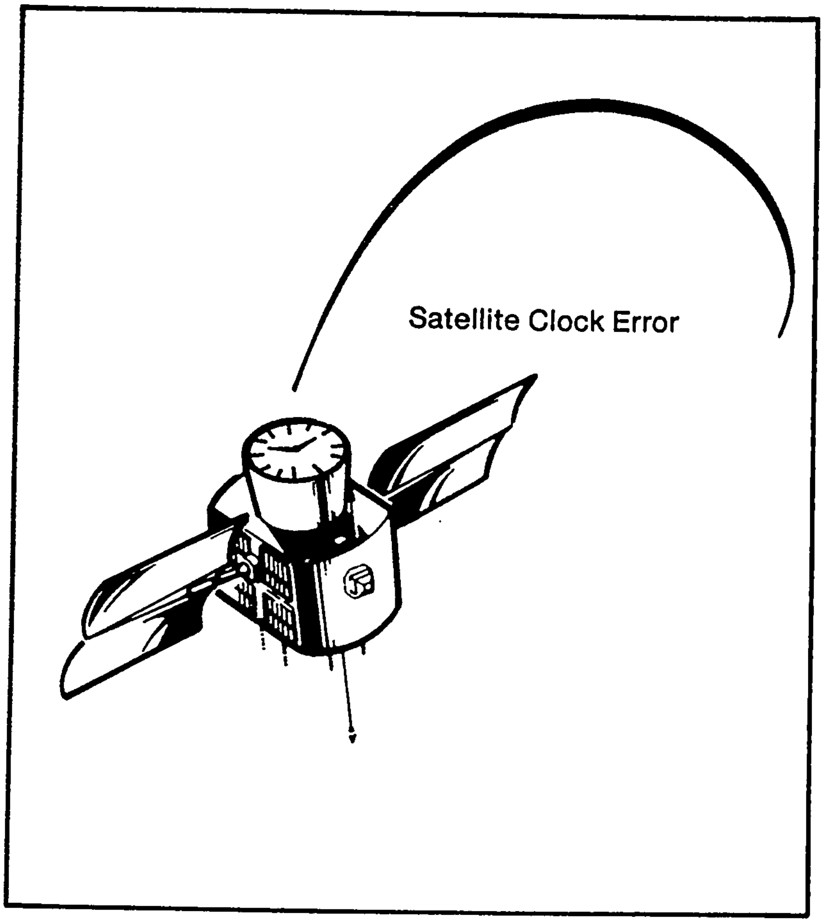
By adding a third satellite, we can determine what clock bias will make all three range measurements agree and thus fix our position. Obviously, the error of our clock is the same in relation to all the satellites. A fourth satellite allows for three-dimensional coverage.


End of Round #1

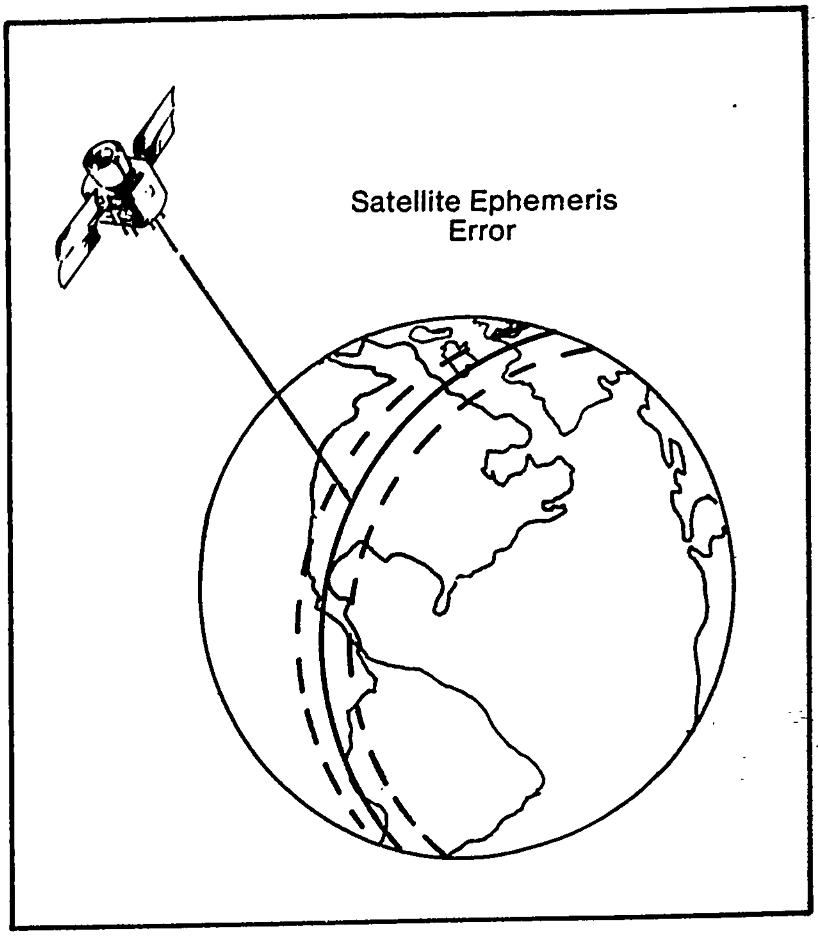
Typical Values For Range Errors

satellite clock error	2 feet
ephemeris error	2 feet
receiver errors	4 feet
atmospheric propagation error	12 feet

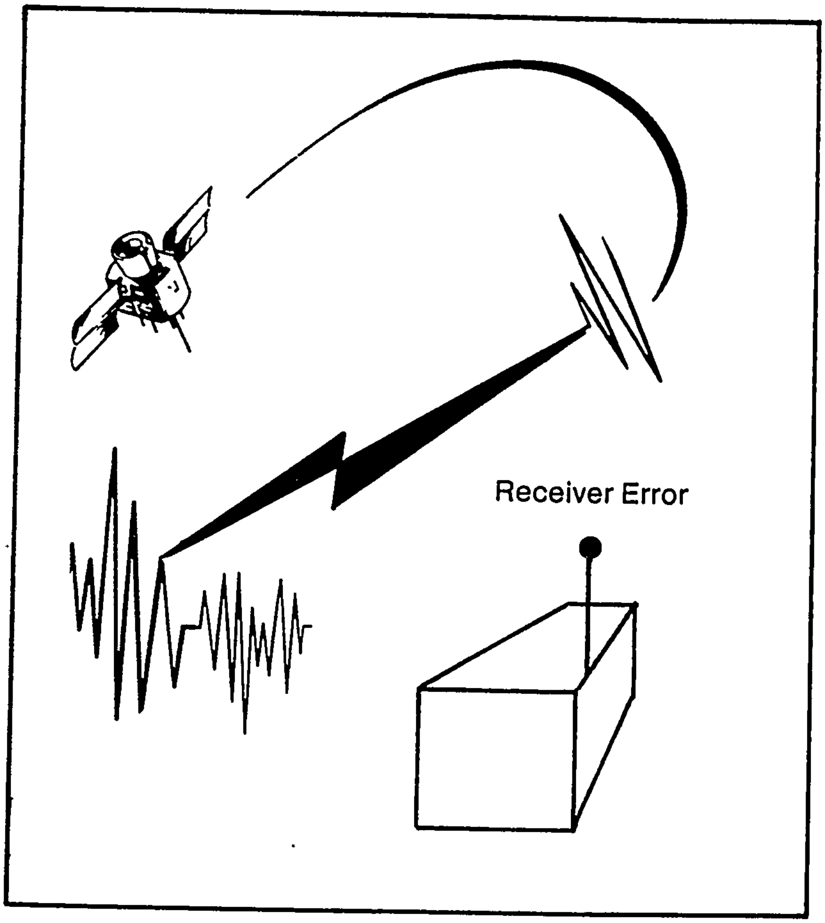
Despite our best efforts, there are still errors in our range measurements, other than the time bias. Typical errors in range measurements and their sources are shown above.



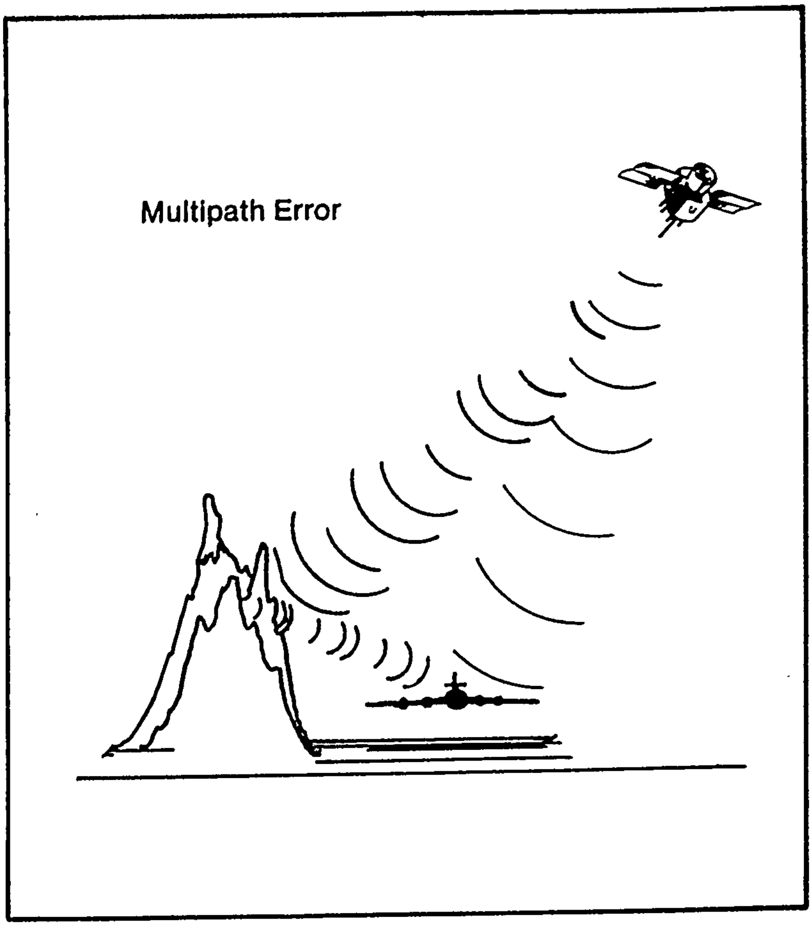
A satellite clock error means that, in spite of big bucks for four atomic clocks on each satellite, we still can't get the time just right. Fortunately we can reset the on-board clocks from the ground, if you can imagine adjusting a clock by a few nanoseconds. A slight error in the on-board clock means that the pseudo random radio code is being generated at a slightly "wrong" time. We can't solve for it like we did our receiver clock bias because the error will be different for each satellite.



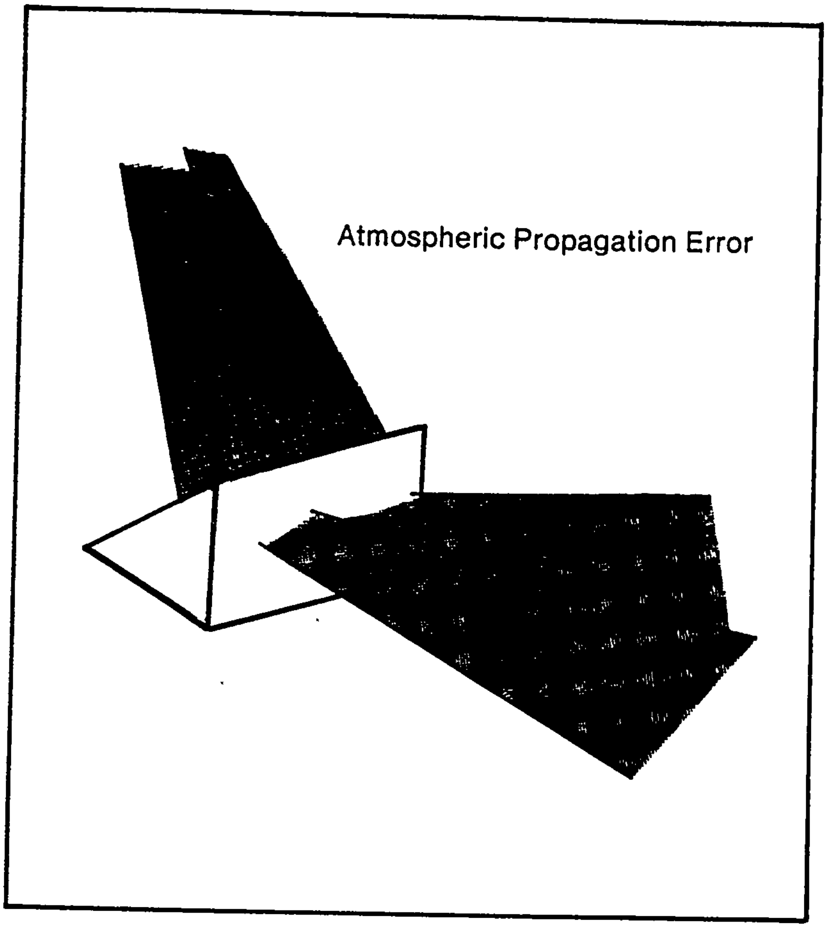
A satellite ephemeris error means that the satellite isn't where we thought it was. Since our position calculation depends on us ranging from known points, errors in satellite location show up as errors in our location. This could be serious if you were trying to use GPS to park in your driveway on a foggy night, but otherwise a couple of feet doesn't really matter. A small error in satellite ephemeris usually results in a very small error in calculating receiver position.



Receiver errors can be caused by electrical noise, computational errors, or errors in matching the pseudo random radio signals.

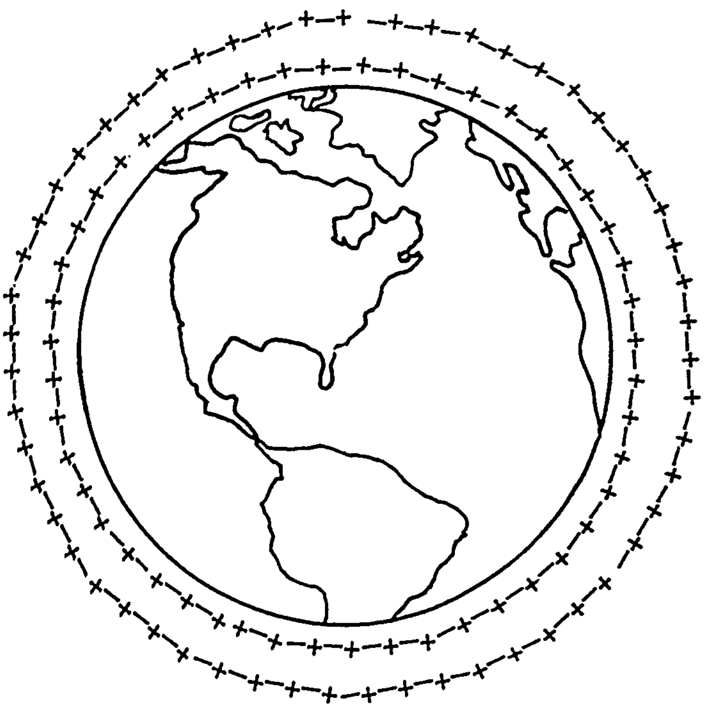


Although multipath errors are possible, to date they have caused no operational problems during testing.



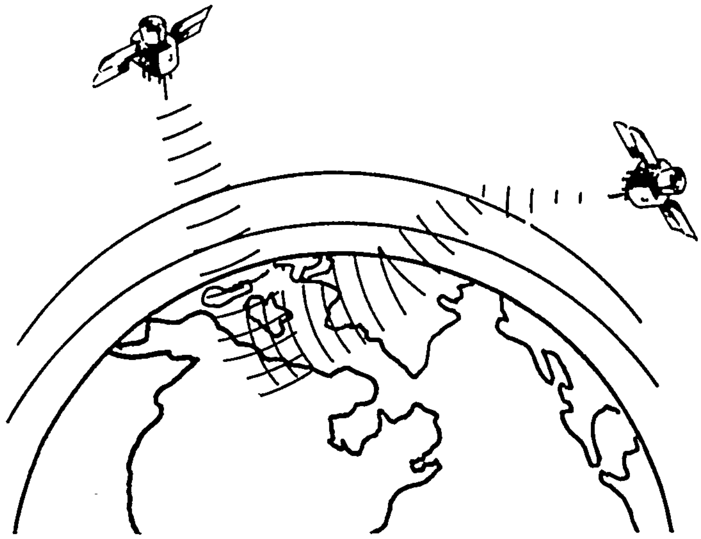
We assumed that our radio signal traveled at the speed of light, and it does in a vacuum, like space. But just as light is refracted through a prism because it travels at a different velocity in glass, our radio signal is bent and slowed down when it enters our atmosphere.

Atmospheric Propagation Error (continued)



This is primarily due to the ionosphere. The density of the charged particles (ions) in the ionosphere changes between day and night and also has a seasonal variation. Since the delay of the radio signal depends on the density of the ions, this delay error changes, but in a somewhat predictable way.

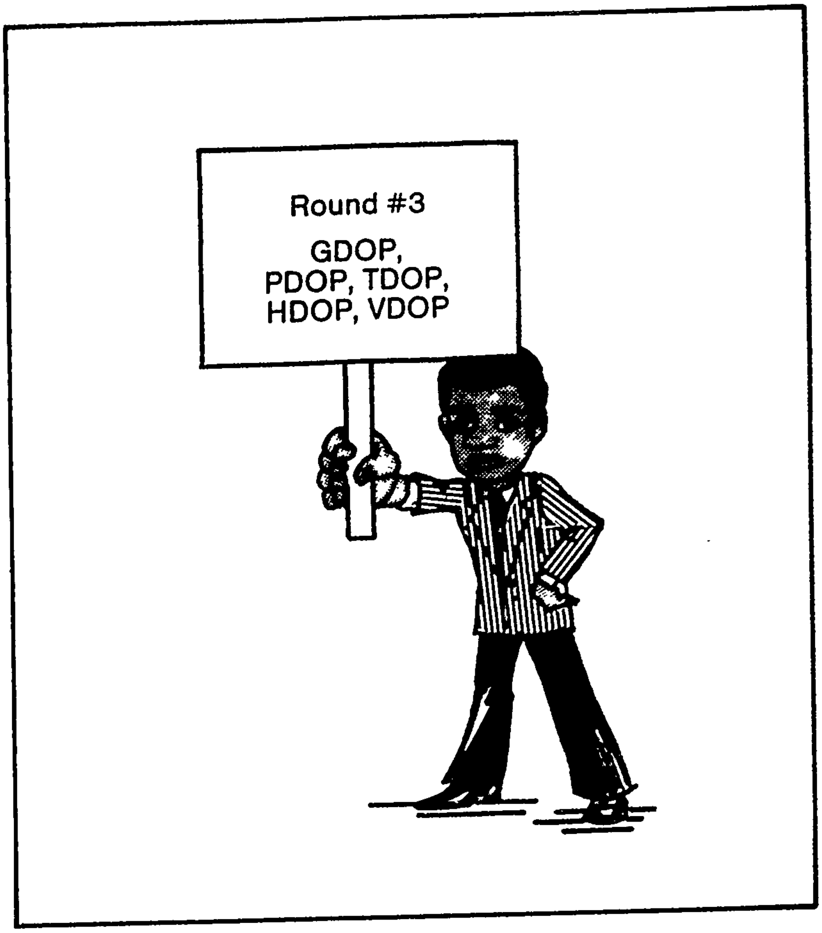
Atmospheric Propagation Error (continued)



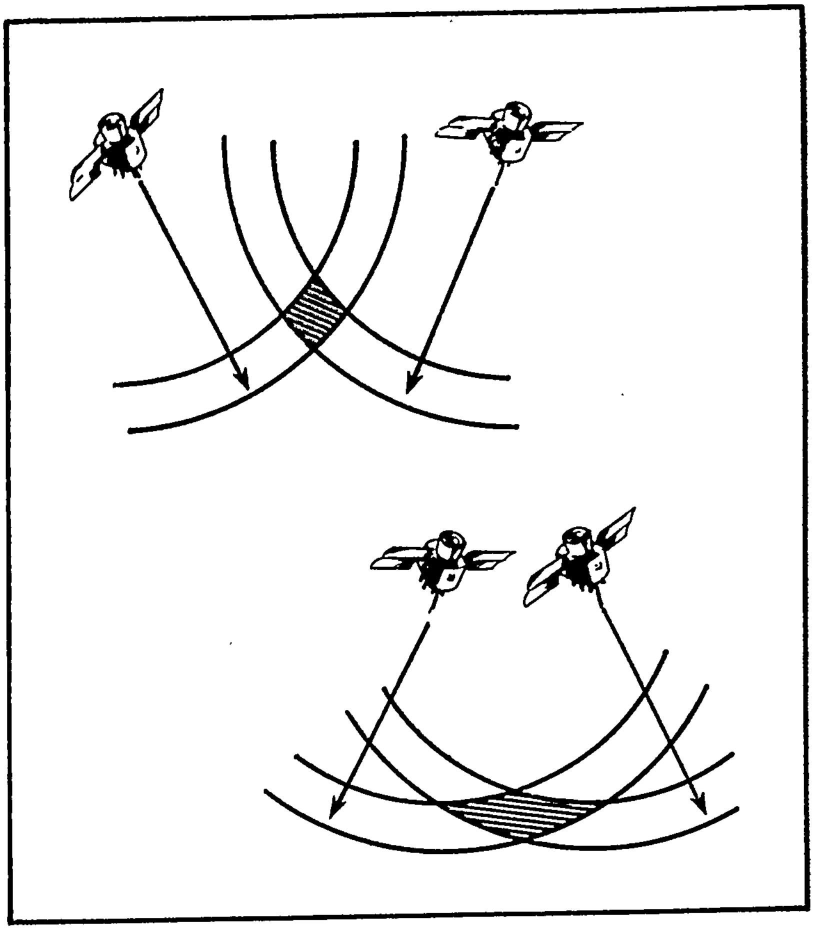
The degree to which the ionosphere affects the signal also depends on the angle of the signal as it passes through the ionosphere.

The amount of delay caused by the ionosphere is inversely proportional to the frequency of the radio signal. By using two signals of different frequency and noting the difference in the delay times, we can remove much of the effect of the ionospheric delay. As an alternative, a receiver can be programmed with a computer model to predict the delay.

Atmospheric propagation errors can cause position uncertainties of up to 12 feet, so this range error has attracted the most attention.

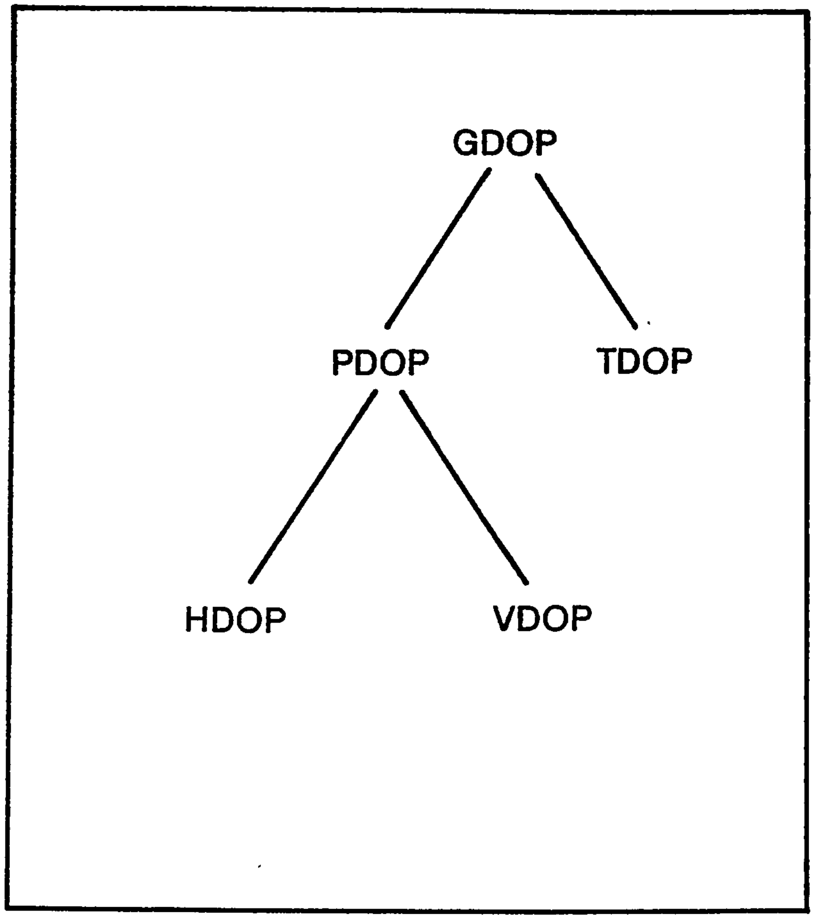

Round #3
GDOP,
PDOP, TDOP,
HDOP, VDOP

GDOP stands for "geometric dilution of precision." Translated into English, it means, "In practice, the system isn't quite as accurate as it is in theory." Just how imprecise the calculation is may depend on the relative positions of the satellites involved.



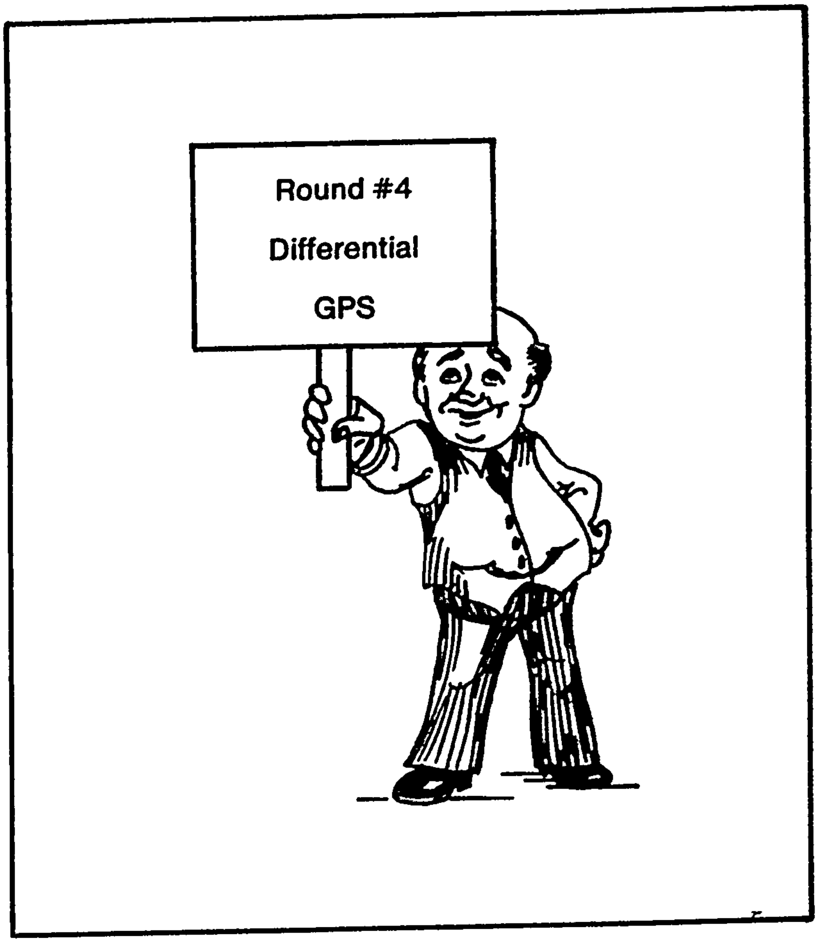
To see why, let's again return to two dimensions. From the illustrations above, we can see that the area of uncertainty in position, the shaded area, depends greatly on the relative positions of the satellites, so that for the same uncertainty in range, we can have different uncertainties in our position. Generally, the closer together (in angle) two satellites are from us, the greater the GDOP.

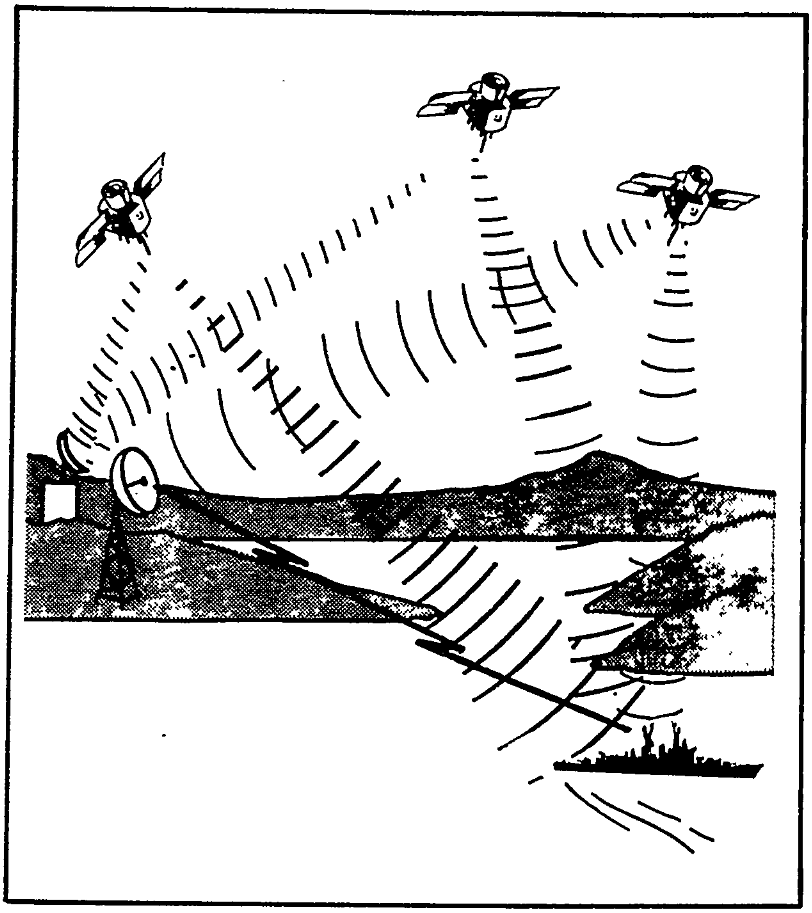
The relationship between the uncertainty in range and uncertainty in position is called the GDOP. The GDOP is a function of the relative geometry of the satellites and the user. A large GDOP is bad.



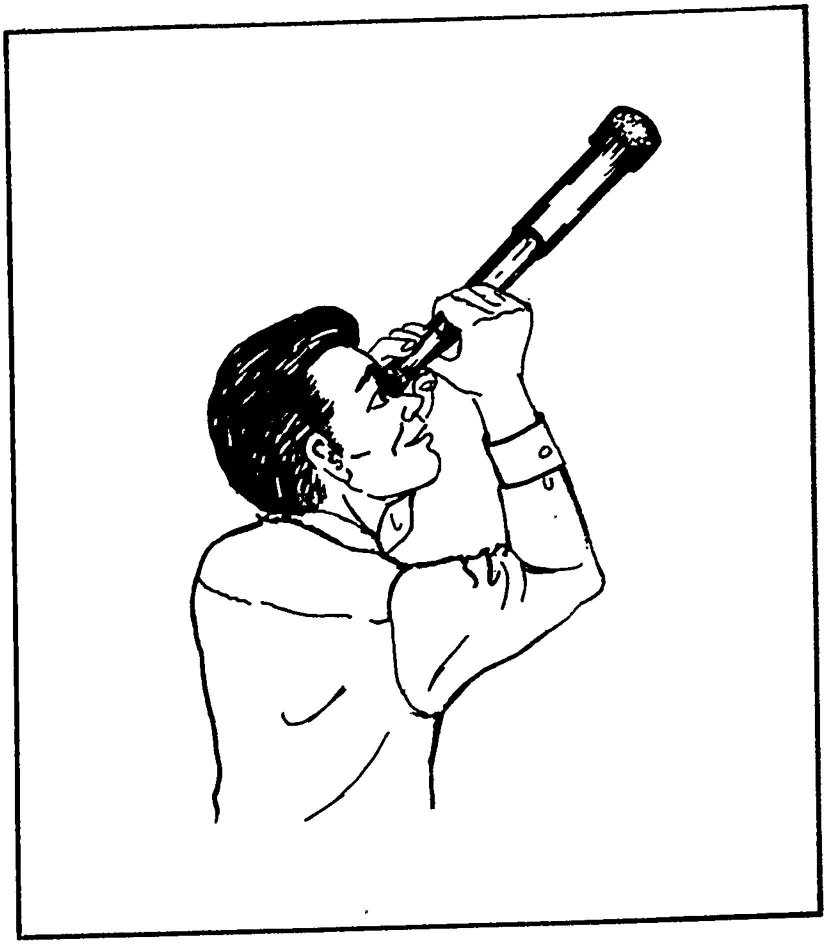
GDOP can be broken up into components. TDOP is the range equivalent of the clock bias. PDOP is the position dilution based only on the geometry of the satellites (not counting the uncertainty in the clock bias). And VDOP and HDOP are the vertical and horizontal shares of the PDOP. For what it's worth,

$$GDOP = \sqrt{(PDOP)^2 + (TDOP)^2}$$


Round #4
Differential
GPS



Differential GPS uses a ground receiver at a known location to check the GPS signals and measure range errors. These corrections are broadcast from a local transmitter and allow GPS users in the vicinity to include the corrections in their calculations.

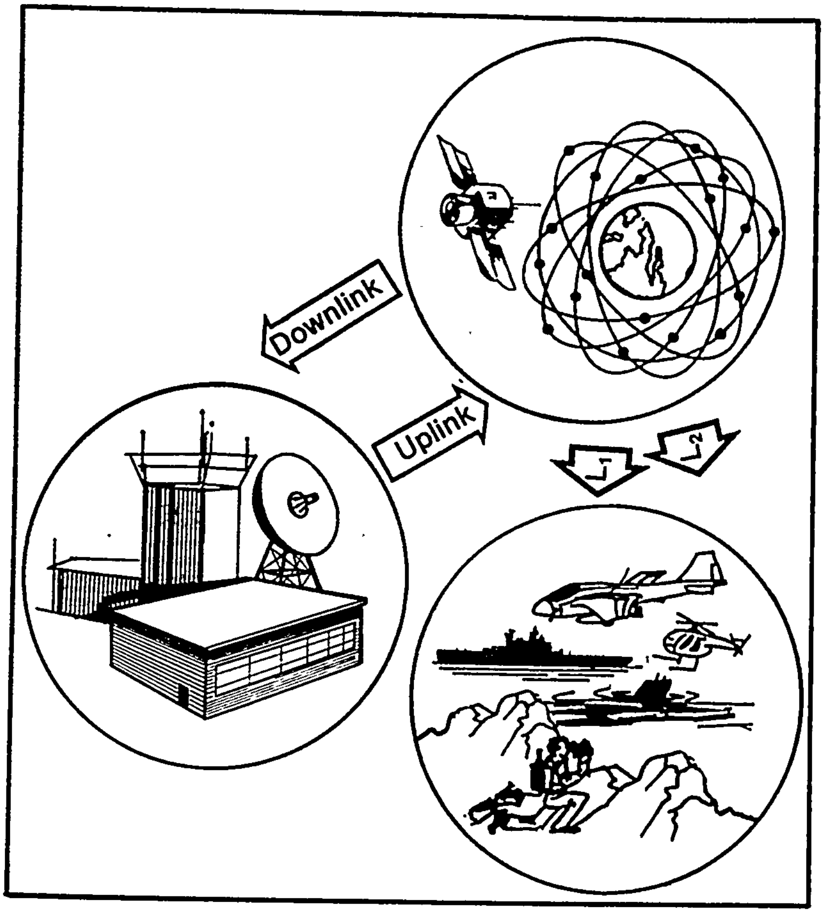


PART III

THE SYSTEM

...the system is the solution

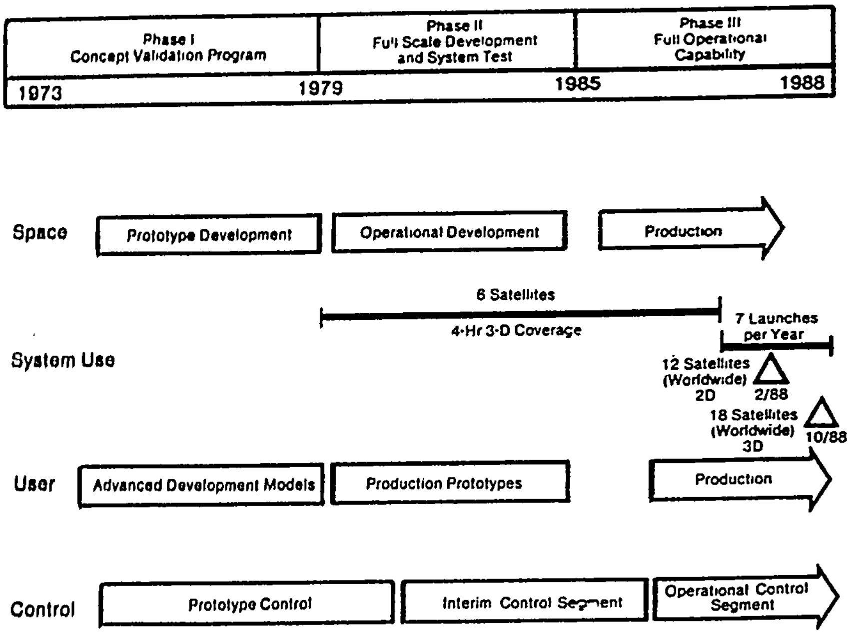
– Ma Bell



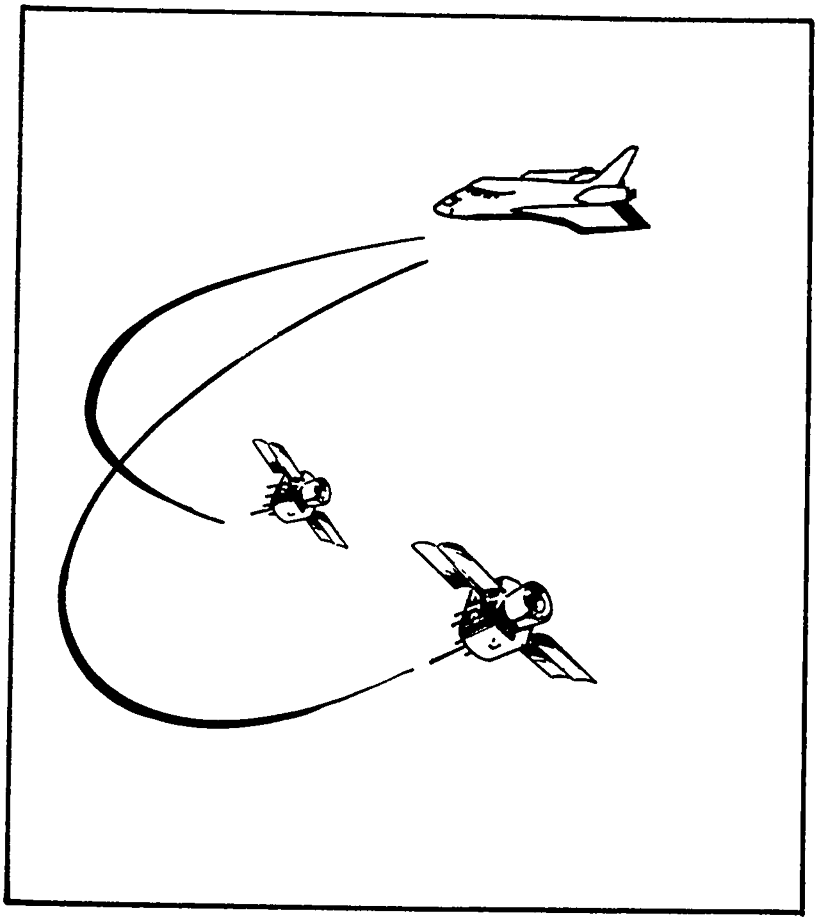
The GPS System has three parts:

- The space segment consists of 18 satellites plus three spares sending out radio signals.
- The control segment tracks the satellites and uploads satellite ephemerides and clock characteristics. There are five monitor stations, three uplink stations, and one master control station.
- The user segment tracks and receives the satellite radio signal and computes user position.

GPS MASTER PROGRAM SCHEDULE



The current schedule calls for full operational capabilities by the late 1980s.



The majority of the satellites will go up with the space shuttle in the late 1980s.

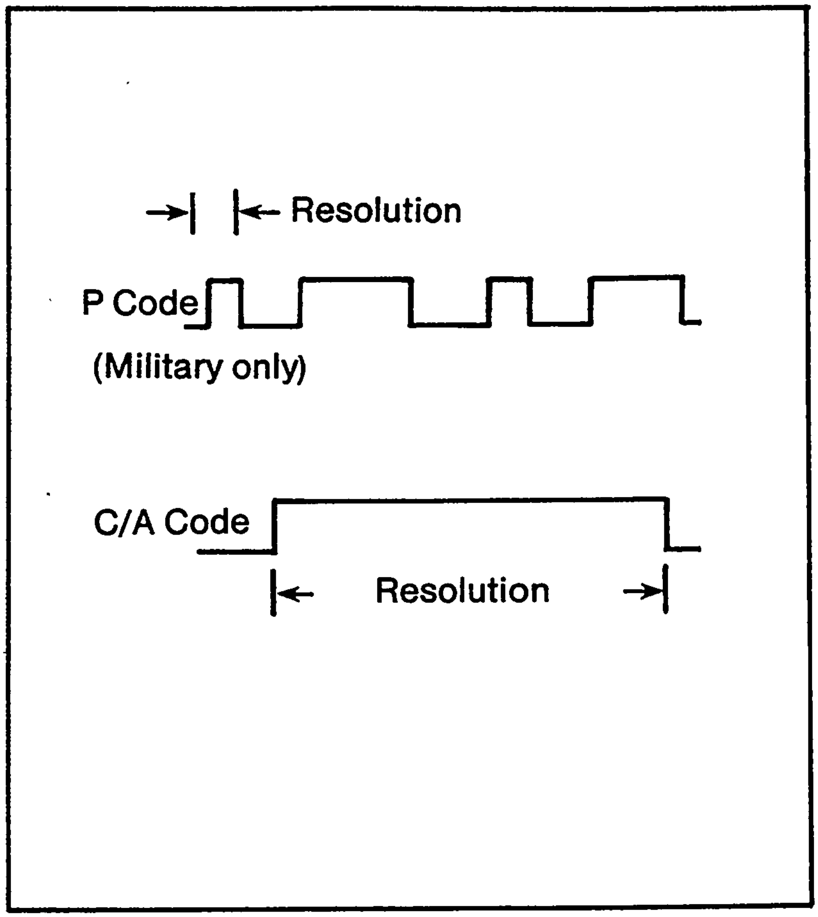
$L_1 = 1575.42$ MHz

$L_2 = 1227.6$ MHz

uplink = 2227.5 MHz

downlink = 1783.74 MHz

The satellite transmits on two "L" band frequencies to allow for ionospheric delay calculations. The uplink and downlink frequencies, used for satellite control, are higher, in the S band.

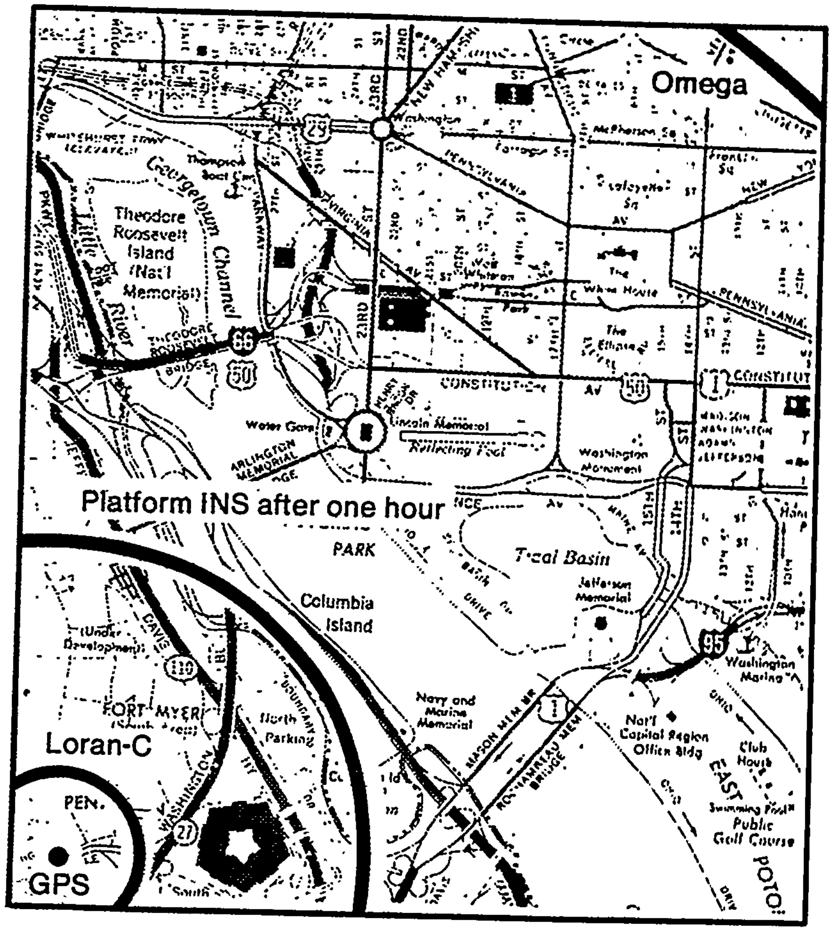


The L_1 signal is modulated with both the P and C/A pseudo-random code and the L_2 signal is modulated with the P code. The P code operates at 10.23 million bits per second and offers high accuracy range measurements but is difficult to acquire. The C/A code, operating at only 1.023 million bits per second is less accurate but easier to acquire. Only the C/A code will be available to civilian users. The radio signals can also be used to carry messages or data for uses other than navigation. Information can be modulated a lot of different ways on the same carrier signal.

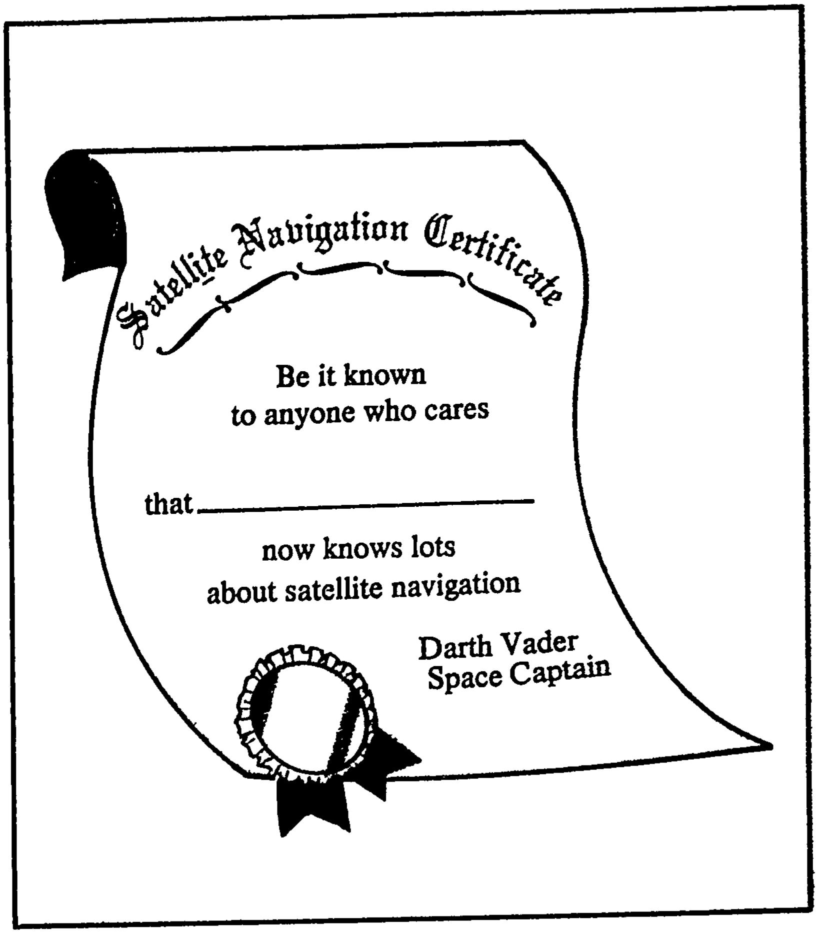
P Code Accuracy
~ 16 meters

C/A Code Accuracy
~ 100 meters

Actually, the C/A code is used by military receivers too. It gives a "ball park" figure for position and helps the receiver acquire the P code. Its inherent accuracy is close to 30 meters, but it is deliberately degraded to approximately 100 meters.



The GPS seems complicated, perhaps, but its high degree of accuracy and world-wide coverage provide a major breakthrough in navigation technology.



Congratulations