1.0 Introduction

OpenSource GPS is open source software that runs a GPS receiver based on the Zarlink GP2015 / GP2021 front end and digital processing chipset. It is a fully functional GPS receiver which acquires satellites, tracks satellites, makes ranging and carrier measurements and computes position and velocity fixes.

The purpose of this documentation is to provide someone with an interest in GPS the background knowledge of GPS and OpenSourceGPS software to understand the software and hopefully contribute to the community working on its debugging, extension and upgrading. This documentation describes an OpenSource approach to software for a civil GPS receiver using the Zarlink GP2015/GP2021 down converter/digital processing chipset. This chipset is ideal for learning about the inner workings of GPS receivers because the hardware data and manuals for them are freely and openly available over the internet. This chipset is essentially the minimum amount of hardware required to make a GPS receiver and is a good way to learn the basics of signal acquisition, tracking, data demodulation, and range and carrier frequency measurements. Since the focus of this documentation is on software the receiver hardware and software are described in detail along with listings of most of the code. Other parts of the system will be described only to the level of detail needed to understand and implement the software. In addition in chapter 5 a description of the expected positioning performance is discussed along with actual measurements made with the hardware and software described.

The need to know where we are and guidance to direct us to where we want to go is a basic human need going back to the beginnings of civilization. The history of navigation ranges from simple paths marked in the ground to navigating trajectories to the moon and other planets in our solar system. The most critical component for navigation is the accurate knowledge of time. The most recent developments in the measurement of time are the atomic clock and its use in radio navigation systems.

The NAVSTAR GPS and the Russian GLONASS provide unprecedented levels of global position, velocity and timing accuracy anywhere in the world at any time. It relies on the convergence of a number of technologies that came together in the 1970's and advanced dramatically in the 1980's, 1990's and continues to advance today. GPS would not be possible without RF integrated circuits, high speed base band signal processors and digital computers.

GPS uses one way ranging signals to determine position and time. In addition Doppler or carrier phase data is used to compute velocity and clock frequency errors. A simple schematic of this is shown in figure 1-1 for 2 dimensions. If we knew exactly when the signals arrived we could resolve our location to one point A. But, in order to do this it would require an extremely precise (and expensive) clock in our receiver. In this case we know precisely the difference in the arrival time and this creates a line of all possible positions that have the same difference in arrival. For this reason another ranging source is needed to resolve the time in addition to position

Thus, by knowing that all of the signals reached the receiver at the same time, precisely when the signals left each satellite and the precise location of the satellite when the signals left the satellite the receiver's position and clock offset can be computed. For the three components of position and time measurements from at least 4 satellites are required. In addition, in the same manner, by measuring the Doppler shift of the RF signals (or the number of carrier cycles over a short interval) the receiver velocity and clock frequency offset can be computed.

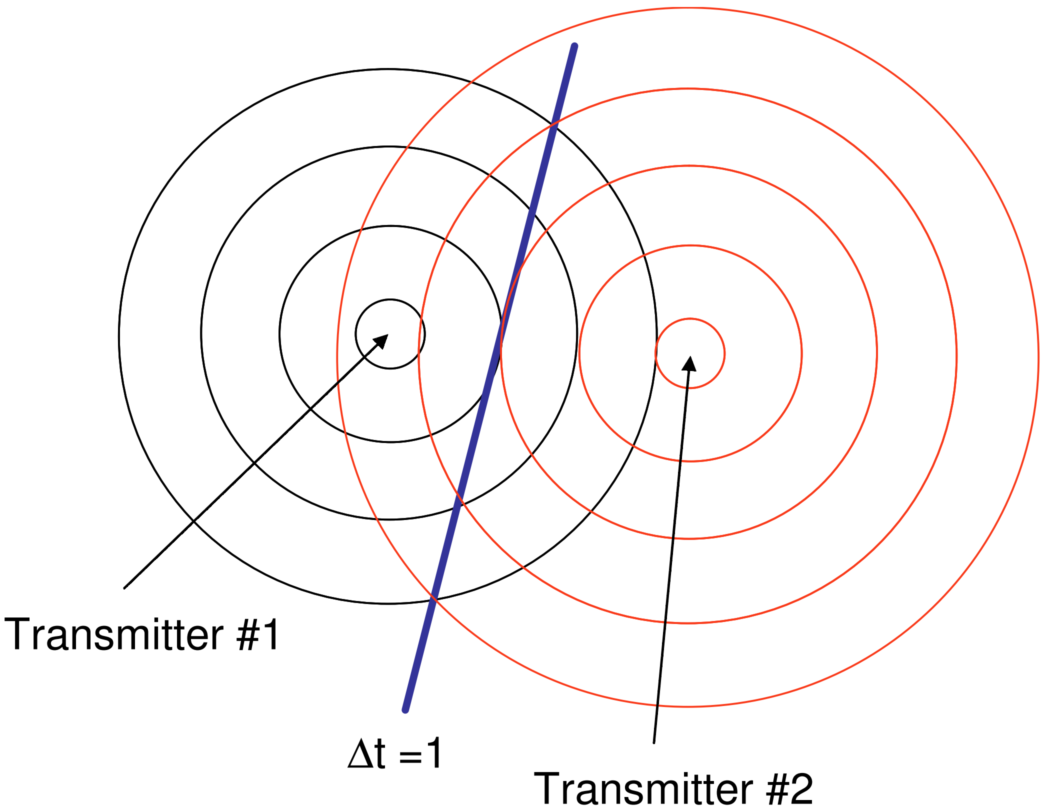


Figure 1-1
One Way Ranging Schematic

GPS is a complex system, studying it exposes one to real time software, rf hardware, statistics, control systems, estimation theory, relativity, orbital mechanics, and geodesy among others.

As shown in figure 1-2 the system is divided up into 3 segments. The User segment is the receiver which computes its location and velocity by making one way distance measurements from a constellation of satellites. The second segment is the satellites themselves or the space segment. Using an atomic clock to maintain precise timing over many hours and days the satellites transmit radio signals with special coding which allows the receiver to determine the precise time the signal left the satellite. Data transmitted by the satellite provides precise time synchronized orbital data. The final segment is called the control segment. Its job is to create and maintain the precise orbital and clock data for the satellites and to transmit this data to the satellites for subsequent broadcast. It consists of reference receivers at precisely located sites around the world which transmit their measurements to a control center which uses a Kalman filter to estimate each satellites orbital and clock parameters. In addition it is their job to maintain the satellites and correct problems that occur from time to time on them.

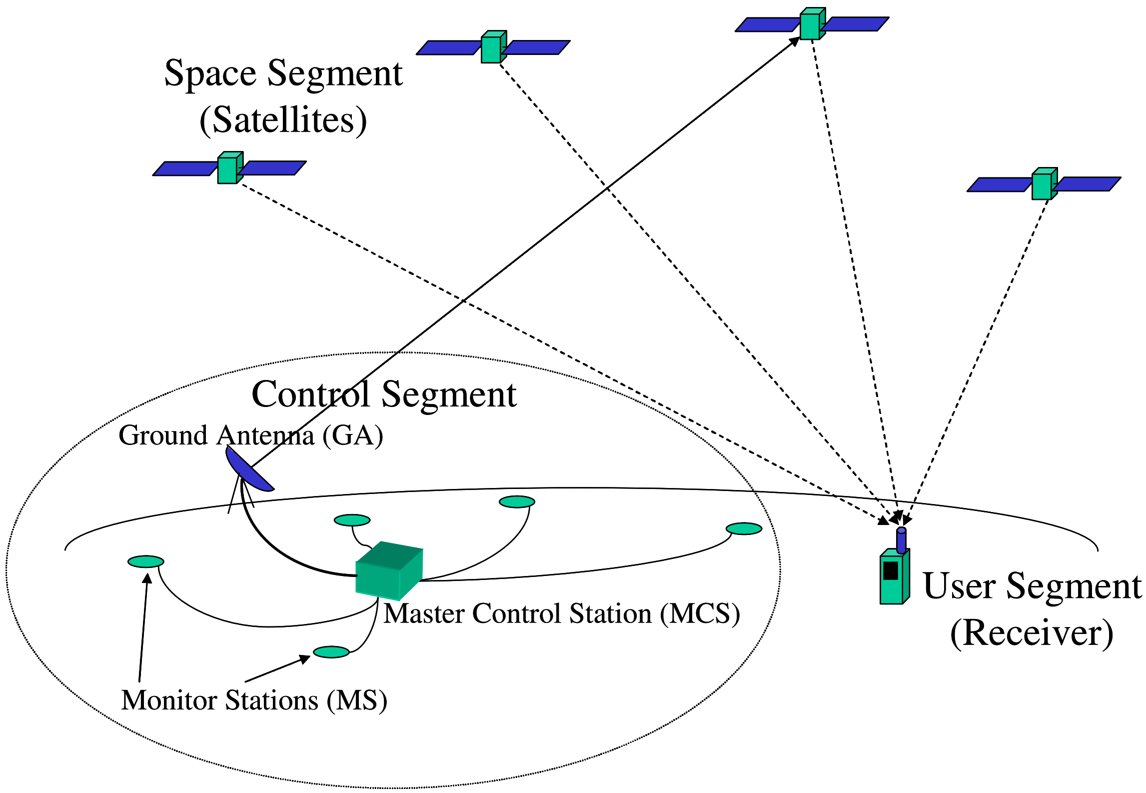
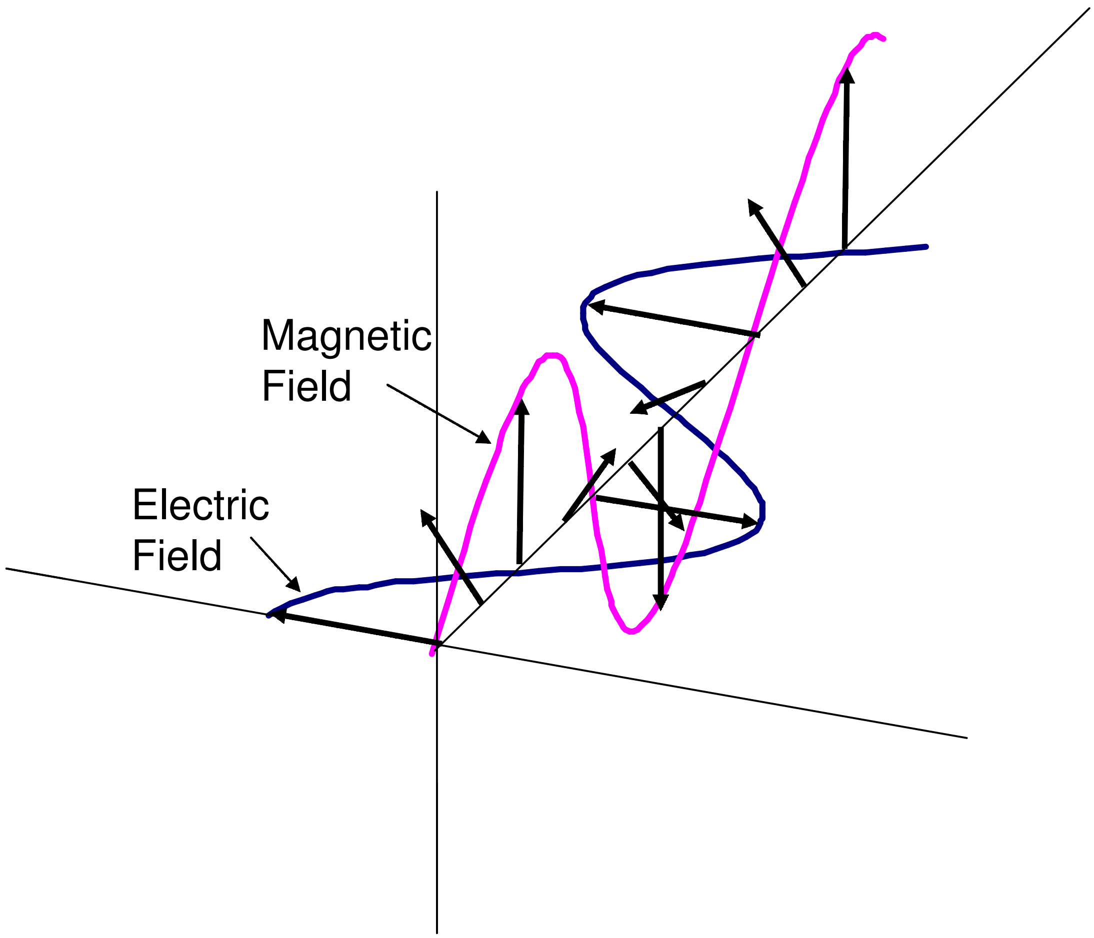


Figure 1-2
The GPS System

1.1 The RF Signal

The RF signal transmitted by the satellites is a right hand circularly polarized Bi-phase modulated CDMA code with data impressed on it. The circular polarization is illustrated in figure 1-3. In this method the electric and magnetic fields instead of being in phase (linear polarization) are 90 degrees out of phase. This modulation allows the use of receiver antennas that are not very sensitive to orientation.



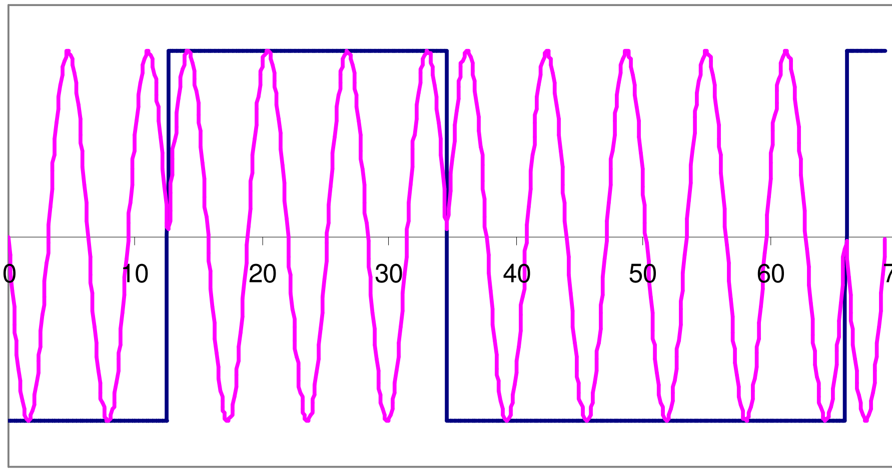
Circular polarization
Figure 1-3

The current system transmits at two frequencies, called L1 and L2 respectively. L1 is at 1575.42 MHz and L2 is at 1227.6 MHz. Two codes can be transmitted on these carriers, one called C/A (Coarse Acquisition) code and P (Y) or Precise code and its encrypted equivalent, Y code.

1.1.1 Bi-Phase Modulation

The RF signal is modulated as shown in figure 1-4 which changes the phase instantaneously by 180 degrees. The RF signal is modulated Bi-phase modulated CDMA code with data impressed on it. The signal can be defined by equation 1 and is illustrated in figure 1-2. The signal is modulated by changing the carrier phase 180 degrees. The signal is transmitted on both L1 and L2, the data message is transmitted at a rate of 50 bits per second.

$$v(t) = Data(\omega_D t)PRN(\omega_C t)\sin(\omega_{L1} t) \qquad \text{eqn \#1}$$



Bi-Phase Modulation
Figure 1-4

1.1.2 CDMA

CDMA stands for Code Division Multiple Access. This is a method of modulating a signal so that many transmitters can transmit signals at the same carrier frequency and a receiver can separate and track each signal. Each satellite is assigned a different PRN or Pseudo Random Noise sequence. This is a sequence of bits (+1, -1) generated by a pseudo random number generator. As shown in figure 1-5 while this algorithm appears to generate a random sequence it is deterministic, known and repeats, thus it is called a pseudo-random sequence. The C/A code is clocked at 1.023 MHz with a length of 1023 chips and thus repeats every millisecond. The P(Y) code is clocked at 10.23 MHz with a length of approximately 6.187x10^12 chips and it is reset every week. Because GPS is a dual civilian/military use system the C/A code is available for civilian use while the P(Y) code is reserved for military use. Although both C/A and P(Y) are transmitted on L1 only P(Y) code is transmitted on L2. The signal strength is very small, approximately -160 dBW which is below the noise level. The signal can be tracked only because it is amplified up out of the noise by correlation or integration over time.

Figure 1-5
CDMA PRN Code

The receiver detects the signal by correlating or integrating the signal over time by generating a replica of the same random number sequence used by the satellites. The integrated signal increases linearly the longer the integration interval while the noise increases as the square root of time the longer the integration interval. Thus the longer we integrate the higher the signal to noise ratio is. An important feature of the codes is the cross correlation characteristic. This is the ability to separate one code from another transmitted on the same carrier frequencies. As shown in figure 1-6 the square wave function correlation produces a sharp triangular function which is near zero everywhere more than +-1 chip away from the peak of the correlation. This is of course the idealized function. In reality with a limited bandwidth the peak of the function is rounded.

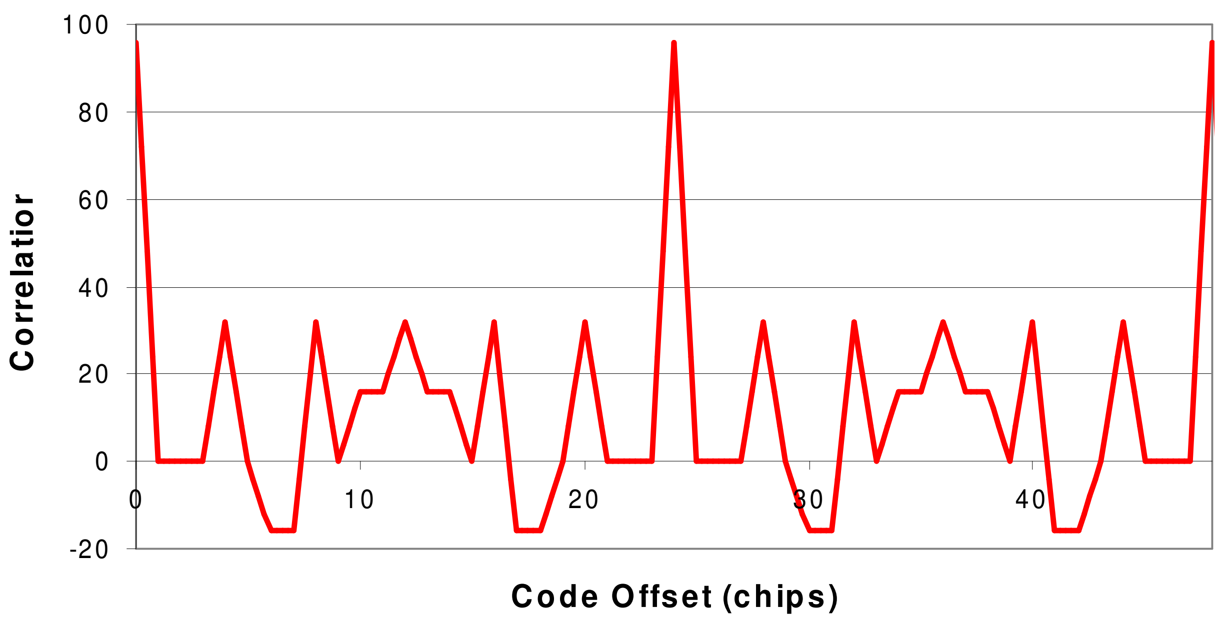


Figure 1-6
Correlation Function

The correlation peak is tracked by using 2 or more correlators separated in time. In the simplest case two correlators called the E or early and L or late are used as shown in figure 1-7 to produce an error function which is:

$$e = \frac{E - L}{E + L} \qquad \text{eqn \#2}$$

This function is illustrated in figure 1-7. This function allows the error function to be normalized with respect to signal strength.

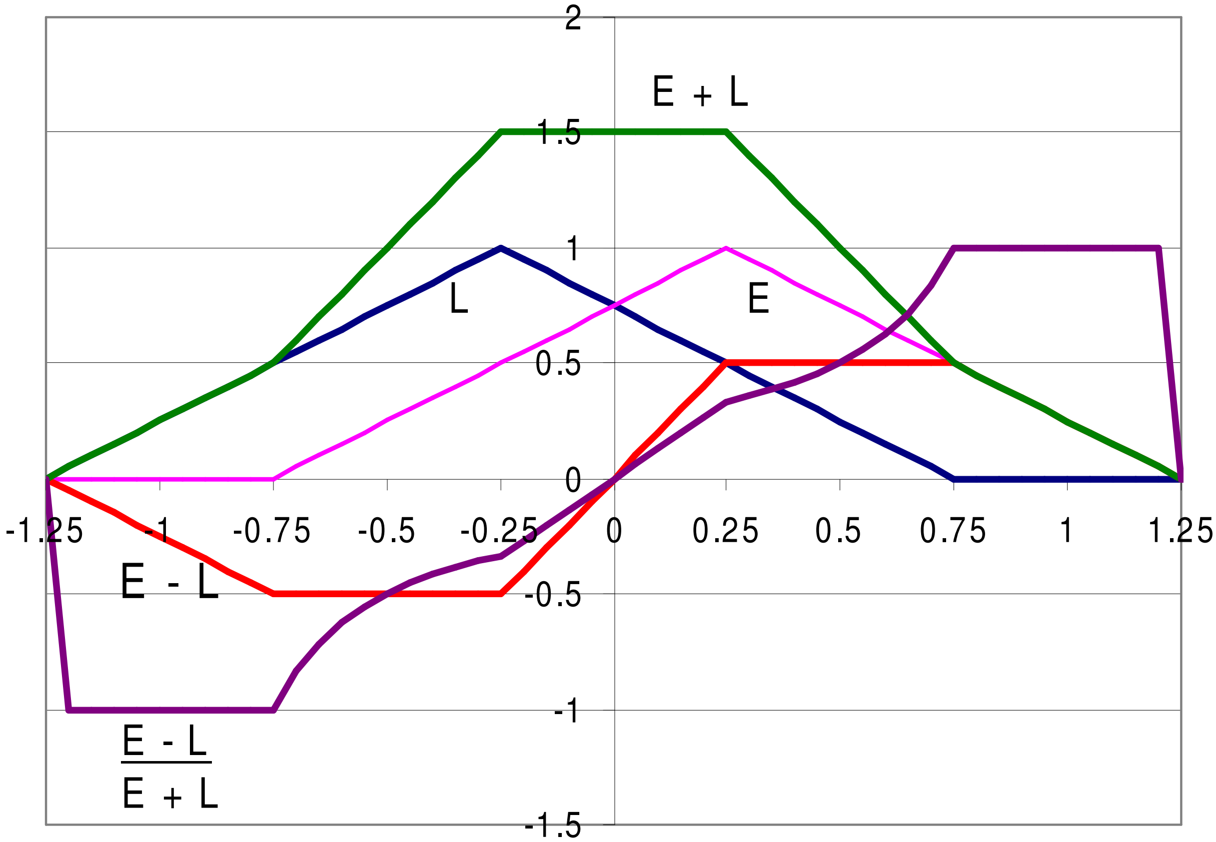


Figure 1-7
Error Function Components

In addition the phase of the signal must be tracked to maintain lock on the signal in the frequency domain. As also shown in figure 1-8 each correlator has an in-phase and quadrature correlator which are used to determine the phase of the signal. The philosophy of OpenSource GPS is to try to use all of the data available. By using both sets of correlators for phase information the fact that they are spaced by only ½ chip means there is a significant correlaton in the phase data between the early and late correlators.

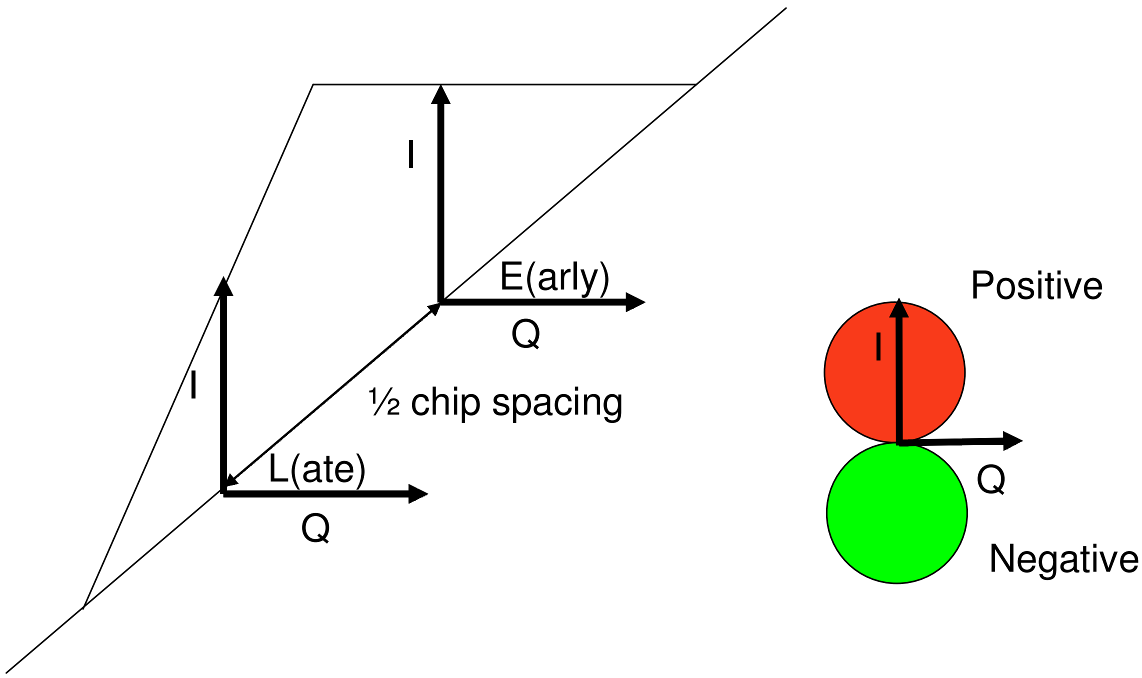


Figure 1-8
Correlator Relationships

1.1.3 Data Modulation

The data is also impressed upon the signal in the same Bi-Phase manner. As shown in Figure 1-9 the data bits are 180 degrees out of phase with each other. The data is transmitted at a rate of 50 bits per second and thus 20 ms or 20 complete C/A code PRN cycles are required per bit.

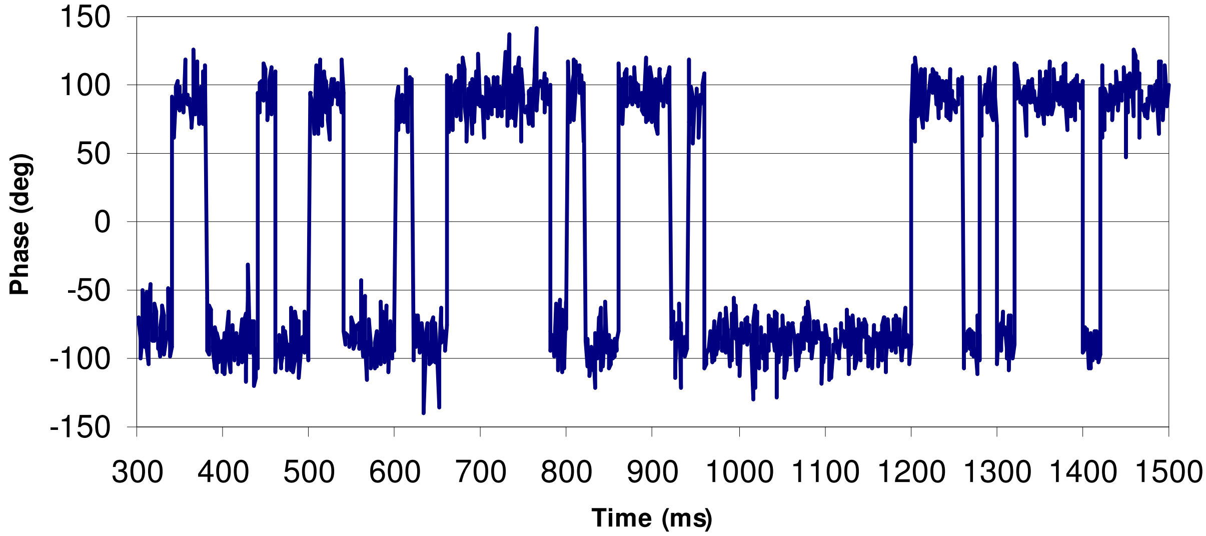


Figure 1-9
Data Bits on the Signal

1.2 Satellite Orbits

The GPS satellites are in a MEO or medium earth orbit with a period of approximately 12 hours. The ground track is designed to repeat daily. This means that the same set of satellites with the same geometry will appear to a geographic location every day but shifted in time a few minutes earlier each day. This group of satellites or constellation is at an orbital radius or semi-major axis of 26,560 km. The constellation was designed with 24 satellites to provide at least 4 satellites in view everywhere on earth at all times. In practice though more satellites have been added to the constellation and when they are all working 6 or more are in view everywhere in the world. On average about 8 satellites are in view at any time anywhere in the world. As shown in figure 1-10 the constellation has at least 24 satellites and with spares generally more. The orbits are nearly circular with an inclination of 55 degrees with respect to the equator. The fact that the gravitational field of the earth is well known as well as solar pressure and other perturbing effects allows a small network of receivers at precisely surveyed locations to accurately estimate the satellite orbital parameters and atomic clock parameters.

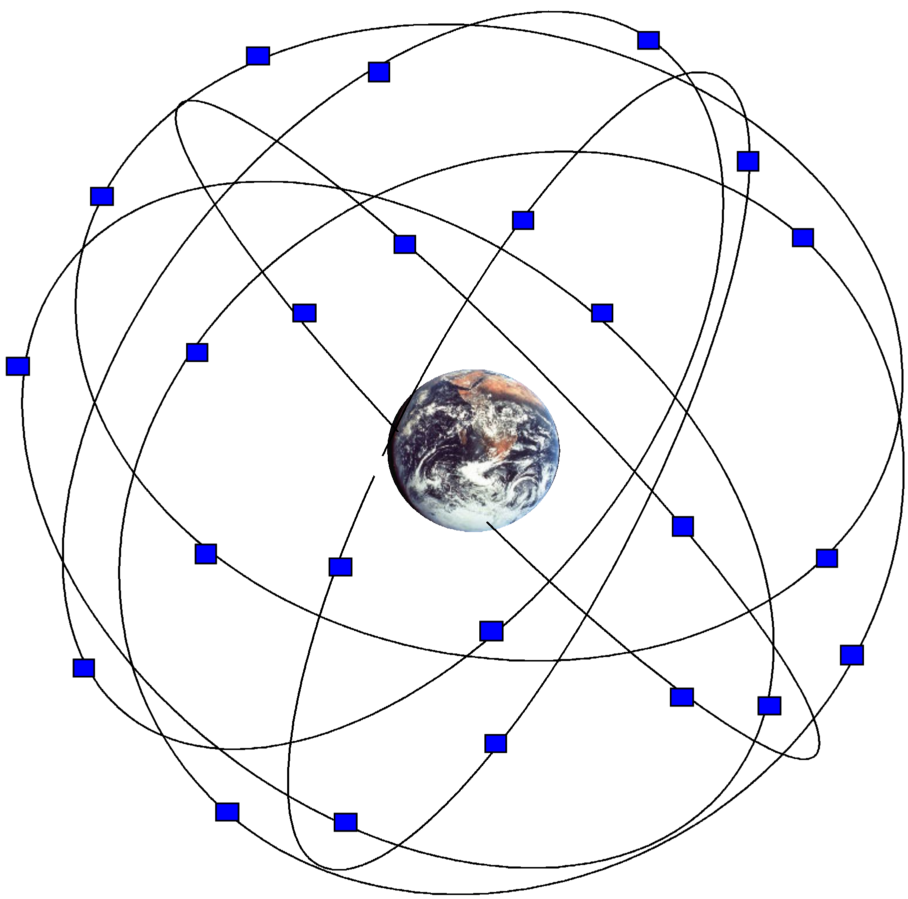


Figure 1-10
GPS Satellite Constellation

1.3 Coordinate Systems

There are two coordinate systems used in GPS. The first is ECEF or Earth Centered Earth Fixed. This is a Cartesian coordinate system with its origin at the center of the Earth. It rotates with the earth and thus is fixed to it. As shown in figure 1-11 the positive Z axis points to the North Pole. The positive X axis points to the equator at the prime meridian. The positive Y axis points to equator 90 degrees east of the prime meridian. The second coordinate system is shown in figure 1-12 and is known as WGS-84 or World Geodetic Service 1984. This is a spherical coordinate system with latitude, longitude and height above an ellipsoid. Since the earth "bulges" at the equator about 21 km the surface of the earth is modeled as an ellipsoid that is symmetric about the polar axis.

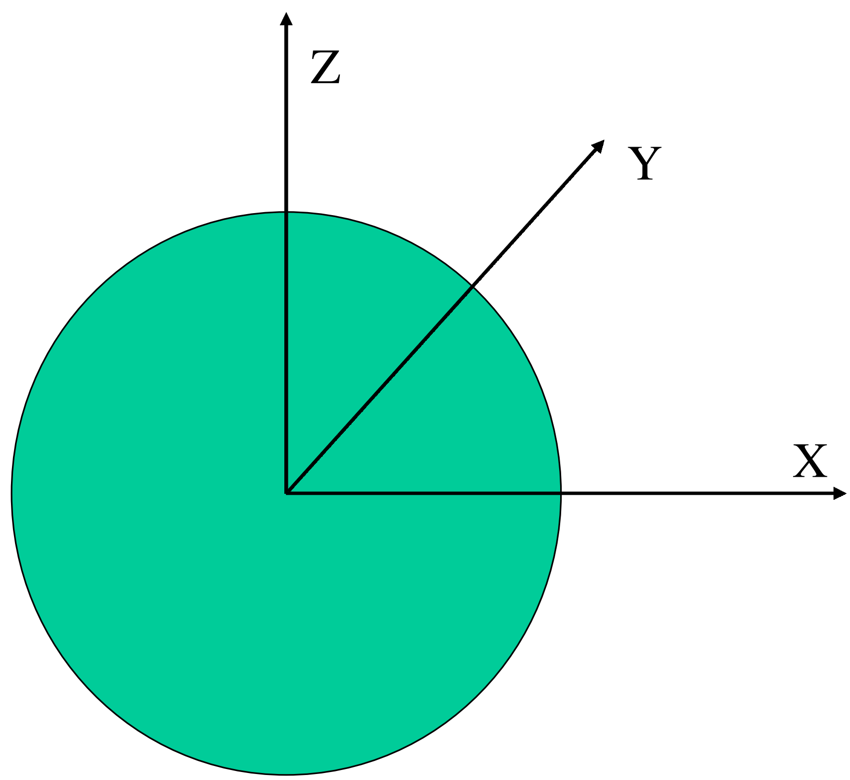


Figure 1-11
The ECEF Coordinate System

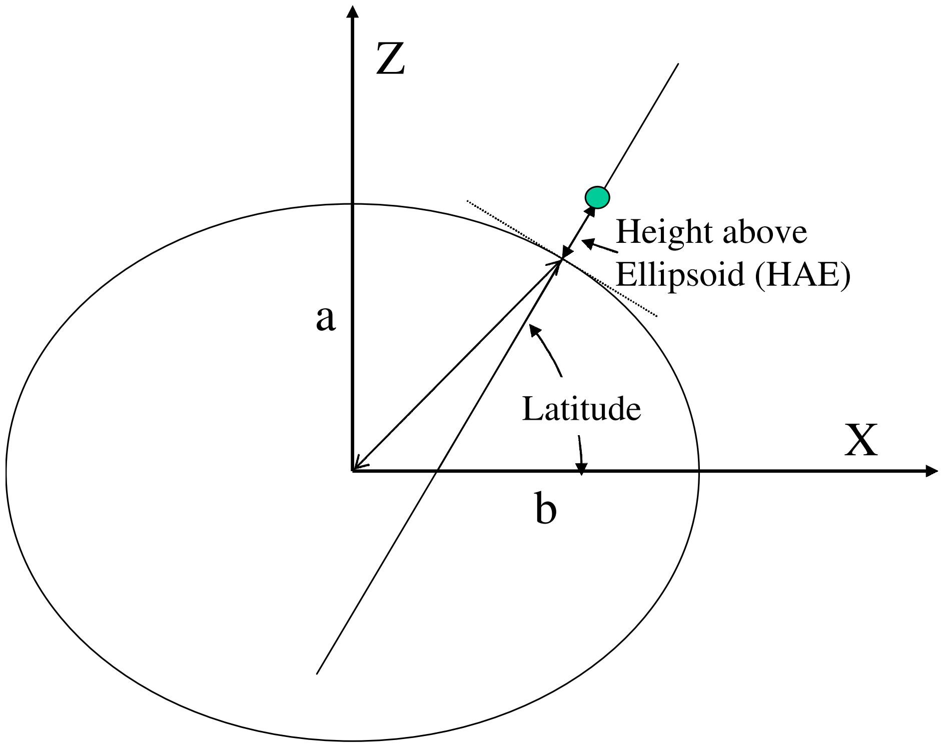


Figure 1-12
The WGS-84 GEOID

The geoid will be will be handled in detail in chapter 4 where the routines to convert from ECEF to WGS-84 and back are described.

1.4 Time Systems

The GPS has its own time reference (called GPS time) based on a number of atomic clocks separate from any other timing system. UTC is based on sidereal time, or the time needed for the earth to rotate and point to the same spot in the sky. Unfortunately, due to the wobble of the earth and varying angular momentum of the earth it is not accurate enough to make measurements in the meter level. Occasionally there is the need to add a leap second when the difference between UTC and the atomic standards is large enough. The offset from international atomic time or UTC (Universal Time Coordinated) is monitored and translations from GPS time are available in the navigation message. The translation between GPS time and UTC is covered in more detail in chapter 4.

More Stuff Needed

1.5 Navigation Data

In order to compute position and velocity fixes the receiver needs precise data on the location of the satellite and what time it is transimitting the signal. GPS accomplishes this by broadcasting a navation message from each satellite. In addition other data on the accuracy of the orbit and clock data, satellite health, and rough orbital information are transmitted. The GPS satellite transmits data on its signal to give the receiver enough data to compute the price location of the satellite. A number of possible methods are available. GPS chose a form of Keplerian orbital elements with a number of second harmonic perturbation terms. The lower fidelity orbital parameters are also Keplerian orbital elements with a smaller number of perturbation terms. The atomic clocks are very stable and are modeled as a bias and constant drift rate.

Table 1-I

Orbital Parameter	Almanac	Ephemeris
Inclination	X (delta from 55 deg)	X
Inclination rate		X
Delta mean motion		X
Rate of right ascension	X	X
Right ascension at epoch	X	X
Argument of perigee	X	X
Argument of latitude second harmonic sine term		X
Argument of latitude second harmonic cosine term		X
Radius second harmonic sine term		X
Radius second harmonic cosine term		X
Inclination second harmonic sine term		X
Inclination second harmonic cosine term		X
Square root of semi-major axis	X	X
Eccentricity	X	X

The navigation message is organized into 25 pages of 5 sub frames. Table 1-II shows the allocation. An entire frame consists of 1500 bits. Transmitted at a rate of 50 bits per second it takes 30 seconds to receive a frame. It takes 12 ½ minutes to download all 25 pages of data. The navigation data will be discussed in more detail in chapter 4 where the routines to decode the message are given. The satellite clock and ephemeris data is repeated every frame. Subframes 4 and 5 provide almanac data for the whole constellation as well as some special messages such as the ionospheric delay model and the conversion of GPS time to UTC. Many of the subframe 4 messages are reserved for the military and are unavailable to civilian users.

Table 1-II
Navigation Data Allocation

Page	SubFrame 1	SubFrame 2	SubFrame 3	SubFrame 4	SubFrame 5
1	Clock	Ephem 1	Ephem 2	57	PRN 1 Alm
2	Clock	Ephem 1	Ephem 2	PRN 25 Alm	PRN 2 Alm
3	Clock	Ephem 1	Ephem 2	PRN 26 Alm	PRN 3 Alm
4	Clock	Ephem 1	Ephem 2	PRN 27 Alm	PRN 4 Alm
5	Clock	Ephem 1	Ephem 2	PRN 28 Alm	PRN 5 Alm
6	Clock	Ephem 1	Ephem 2	57	PRN 6 Alm
7	Clock	Ephem 1	Ephem 2	PRN 29 Alm	PRN 7 Alm
8	Clock	Ephem 1	Ephem 2	PRN 30 Alm	PRN 8 Alm
9	Clock	Ephem 1	Ephem 2	PRN 31 Alm	PRN 9 Alm
10	Clock	Ephem 1	Ephem 2	PRN 32 Alm	PRN 10 Alm
11	Clock	Ephem 1	Ephem 2	57	PRN 11 Alm
12	Clock	Ephem 1	Ephem 2	62	PRN 12 Alm
13	Clock	Ephem 1	Ephem 2	52	PRN 13 Alm
14	Clock	Ephem 1	Ephem 2	53	PRN 14 Alm
15	Clock	Ephem 1	Ephem 2	54	PRN 15 Alm
16	Clock	Ephem 1	Ephem 2	57	PRN 16 Alm
17	Clock	Ephem 1	Ephem 2	55	PRN 17 Alm
18	Clock	Ephem 1	Ephem 2	56 Iono	PRN 18 Alm
19	Clock	Ephem 1	Ephem 2	58	PRN 19 Alm
20	Clock	Ephem 1	Ephem 2	59	PRN 20 Alm
21	Clock	Ephem 1	Ephem 2	57	PRN 21 Alm
22	Clock	Ephem 1	Ephem 2	60	PRN 22 Alm
23	Clock	Ephem 1	Ephem 2	61	PRN 23 Alm
24	Clock	Ephem 1	Ephem 2	62	PRN 24 Alm
25	Clock	Ephem 1	Ephem 2	63	51 Status

1.6 The future of OpenSource GPS

OpenSource GPS has matured quite a bit since 1996. Most of the functionality and (hopefully) most of the bugs have been fixed.

Near term plans include:

Improved acquisition algorithms
Improved tracking loop algorithms
Use of a Kalman filter
Increasing the number of compilers supported (beyond Borland and Microsoft)
Increasing the number of operating systems supported
Increasing the number of computer interfaces supported
Add WAAS capability

In the far term it is hoped that we can:

Add dual frequency hardware and software
Use Galileo signals
Expand to other baseband chipsets and hardware implementations