CHAPTER 2

VARIOUS NAVIGATIONAL AIDS FOR AVIATION

2.1 INTRODUCTION

Navigation is a process of directing a vehicle from one known point to other known point. Navigational aids are essential for the safe and smooth flow of air traffic. The pilot of an aircraft is provided with different types of navigational aids for positional guidance in space with reference to the ground references. Modern navigation systems are of two types. They are ground based and satellite based navigation systems. In this chapter, the salient features of various ground based navigational aids such as VOR, ILS, MLS, LORAN, OMEGA, DECCA etc. and the principle of operation of the modern satellite based navigation systems are presented. GPS is one modern satellite based navigation system designed and developed by Department of Defense (DoD), USA and available anywhere in the world with minimal 24 satellite constellation. GPS is an all weather, line of sight radio navigation and positioning system. The system became fully operational in 1994. Currently there are 32 operational satellites in the constellation.

2.2 MODERN GROUND BASED NAVIGATION SYSTEMS

Modern navigation systems use the transmission and reception of electromagnetic waves for position determination. The various ground based navigation systems are: VOR, ILS, MLS, LORAN C, DECCA and NDB. The navigational aids used in India are VOR and ILS (Kayton and Fried, 1997).
2.2.1 Very High Frequency Omnidirectional Range (VOR)

VOR provides azimuthal guidance to an aircraft. True bearing can be determined from comparison of the two signals (carrier mode signal and side band mode signal). It operates in the 108MHz-118MHz frequency range. VORs are of two types, namely conventional VOR (CVOR) and Doppler VOR (DVOR). Even though both VORs serve the same purpose as far as the aircraft is concerned, the selection of the CVOR and DVOR depends upon the various site conditions in an airfield. Presently DVORs are in use only in India.

2.2.2 Instrument Landing System (ILS)

ILS effectively guides the aircraft both in elevation and azimuth. Lobe switching is employed for both elevation and azimuthal guidance in a straight path. It operates in the frequency range of 110MHz-330MHz.

2.2.3 Microwave Landing System (MLS)

The MLS uses two narrow beams which are scanned to and from in the elevation and azimuth sectors. The elevation and azimuth scanning beam signals are time multiplexed into an allotted time frame. It operates in the 1GHz-5GHz frequency range. MLS was designated by ICAO (International Civil Aviation Organization) to be the new world standard for precision landing in 1998. But due to the reluctance of both service providers and aircraft operators to use MLS (due to its high cost) and the advent of satellite based guidance technology (i.e. GPS), ICAO recommended that ILS be
retained as an alternate until satellite based precision landing technology could be fully evaluated.

2.2.4 Long Range Navigation (LORAN C)

LORAN C is a medium to long-range low frequency time difference measurement system. A master and four secondary transmission stations transmit a set of radio pulses centered around 100KHz in precise time sequences. The receiver measures the difference in time interval between these transmissions from different stations. Then it produces a hyperbolic line position based on time difference.

2.2.5 OMEGA

OMEGA is a very long-range, very-low-frequency (VLF) radio navigation system operating in the internationally allocated navigation band between 10 KHz-14KHz. Omega is based on phase differencing techniques rather than time differences. A pair of transmitting stations provides the navigation with a family of hyperbolic lines of position. Eight transmitting stations with 5000-6000nmi baselines give global coverage. Omega is used primarily because as ‘Stringer’ observed at a meeting of the British Institute of Navigation, ‘It satisfies the three R’s – Reliability, Redundancy and Range’ (Kayton and Fried, 1997).

2.2.6 Dedicated Englishmen Causing Chaos Abroad (DECCA)

DECCA works by taking observations to pairs of six transmission stations using phase differencing techniques. These give rise to hyperbolic lines of position. It operates in the 70KHz-130KHz frequency range.
2.2.7 Non-Directional Beacon (NDB)

NDB is an oldest form of radio navigation still in use. It transmits nondirectional signals in the low frequency (LF)/ medium frequency (MF) range (190KHz-535KHz). There are 4 types of NDB usages: i) Compass locators ii) Approach aids (25nmi), iii) Enroute beacon, iv) High power beacons- used in some coastal areas. NDB is used as an enroute navigational aid. When NDB is used in conjunction with the ILS markers, it is called a Compass Locator. The airborne equipment used for receiving the NDB signal is called Automatic Direction Finder (ADF). The ADF consists of Amplitude Modulation (AM) receiver, Sense Antenna, Loop Antenna (directional antenna) and Indicator (fixed or movable card). The magnetic bearing to the station is determined in the following way using the fixed card.

MB (to the station) = MH + RB

where, MH = aircraft magnetic heading, RB = Relative bearing and MB = Magnetic Bearing.

NDBs are subject to disturbances that may result in erroneous bearing information. The main limitations are: i) Fading, ii) Night effect, and iii) Shoreline effect. Fading usually occurs at night when the ground and sky waves interact and are going in and out of “phase” causing the signals to be either cancelled or reinforced as the atmosphere changes. During fading, pilots will notice a rhythmic swinging of the needle and a volume fluctuation of the identifier. Shoreline Effect: Ground waves change direction as they
pass from land to water and vice versa; they are bent slightly. Pilots should note potential bearing indication errors when flying in the vicinity of coastal areas (Kayton and Fried, 1997).

2.3 MODERN SATELLITE BASED NAVIGATION SYSTEMS

The ground based navigation systems have problems like ground reflections, electromagnetic interference and reflections from the physical systems. These problems are mostly avoided in satellite based navigation systems, due to the space constellation. Satellite navigation is based on a global network of satellites that transmit radio signals in the low/medium earth orbit. The satellite navigation system has the following advantages: (i) The satellite can transmit a radio frequency transmission and carry a transponder beacon which provides all weather service (ii) satellite navigation systems are capable of high accuracy. The modern satellite based navigation systems are: TRANSIT, GPS, GLONASS and GALILEO (Pratap and Per, 2006).

2.3.1 TRANSIT

Transit is the first satellite aided navigation system for civilian use from 1967. Transit works on the Doppler principle using seven low orbiting satellites. Each of these satellites transmits on two frequencies i.e., 150MHz and 400MHz. Position is calculated by measuring the change in frequency of the satellite transmissions as it speeds past in low orbit. Using the satellite’s position and velocity information, the user position is calculated by
measuring the change in frequency of the satellite transmissions. The TRANSIT satellites were orbiting in polar plane at an altitude of about 1100Km. The TRANSIT satellites were affected more by gravity field variations than the higher orbiting satellites like GPS. Since their number is limited, one does not get a ‘fix’ very often. Further, transmissions of TRANSIT satellites at 150 and 400MHz were more susceptible to ionospheric delays and disturbances than the higher GPS frequencies. Since GPS was fully operational, TRANSIT was discontinued on 31st December 1996 (Leick, 2004).

2.3.2 GPS

GPS is a satellite based radio navigation system designed and developed by the Department of Defense (DOD), U.S.A. The first GPS satellite was launched on February 22, 1978. GPS provides accurate three dimensional user position anywhere in the world and under all weather conditions (Kaplan 1996). The satellites transmit at frequencies L1 (1575.42MHz) and L2 (1227.6MHz) modulated by the two types of codes and the navigation message. At present the L1 carrier is modulated with C/A and P-codes, whereas L2 is modulated with P-code only. The advantages of GPS are: i) intentional interference like Jamming and unintentional interference will affect GPS least since spread spectrum techniques are used in it and ii) system accuracy can be improved to the order of centimeters using Differential techniques like DGPS, WAAS, GAGAN etc., Full operational capability of GPS was achieved on July 17, 1995.
2.3.3 GLONASS

The Russian GLONASS system launched its first navigation satellite in 1982. Like GPS, GLONASS was planned to contain at least 24 satellites. The nominal orbits of the satellites are in 3 orbital planes separated by 120°, with an inclination of 64.8°. The nominal orbits are circular with radius of 25,500Km. The major difference between GLONASS and GPS is that each GPS satellite transmits at its own carrier frequency. If p is the channel number that is specific to the satellite, then

\[ f_{1p} = 1602 + 0.5625p \text{ MHz} \quad (2.1) \]
\[ f_{2p} = 1602 + 0.437p \text{ MHz} \quad (2.2) \]

Similar to GPS, there are C/A codes on L1 and P-codes on L1 and L2. But the code structures are different. The GLONASS broadcasts navigation message that contains satellite positions and velocities in the PZ90 Earth Centered Earth Fixed geodetic system. Recently 3 GLONASS satellites are launched in 2002 and GLONASS program is undergoing modernization.

2.3.4 GALILEO

The European civil satellite navigation program is called Galileo. The Galileo space segment is expected to consist of a global constellation of about 30 satellites, distributed over 3 planes. The nominal orbits are expected to be circular, with semi major axes being close to GPS and GLONASS systems. Galileo satellites transmit on 3 frequency bands namely,
E1-L1-E2, E5A-E5B and E6. In order to make Galileo and GPS compatible, the carrier frequency for the Galileo E1-L1-E2 will be 1575.42MHz, which is the same as GPS L1. Similarly, E5A and L5 will use 1176.45MHz as the common carrier frequency. The carrier frequencies of GPS, GLONASS and Galileo are presented in Table 2.1 (Leick 2004).

Table 2.1 GPS, GLONASS and GALILEO carrier frequencies

<table>
<thead>
<tr>
<th>Carrier</th>
<th>Multiple of 10.23</th>
<th>Carrier frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L5 &amp; E5A</td>
<td>115</td>
<td>1176.45</td>
</tr>
<tr>
<td>E5B</td>
<td>117.5</td>
<td>1202.025</td>
</tr>
<tr>
<td>L2</td>
<td>120</td>
<td>1227.60</td>
</tr>
<tr>
<td>G2</td>
<td>See Eq.(2.1)</td>
<td>per satellite</td>
</tr>
<tr>
<td>E6</td>
<td>125</td>
<td>1278.750</td>
</tr>
<tr>
<td>L1, E1-L1-E2</td>
<td>154</td>
<td>1575.42</td>
</tr>
<tr>
<td>G1</td>
<td>See Eq.(2.2)</td>
<td>per satellite</td>
</tr>
</tbody>
</table>

Both VOR and GPS/GLONASS/GALILEO/WAAS can be used as a sole means of navigation for a transition period of 10 years (approximately). This period is a reasonable compromise between the ICAO's desire to minimize its cost for maintaining and replacing VOR and the aircraft operator's desire to get maximum utilization from their investment in conventional avionics. Present aircrafts have to be equipped with ILS receivers, until the GAGAN is certified as a sole means of approach aid, which will be meeting the requirements of CAT I PA.
2.4 GLOBAL NAVIGATION SATELLITE SYSTEM – GPS

At present, GPS is the only one GNSS because the GPS satellite constellation contains 32 satellites which are more than the nominal 24 satellites. All over the world, a minimum of 8 to 14 GPS satellite signals are available and are fully operational, providing services since 1995 to both civilians and military. This system is time-tested, reliable and available to all users independent of geography. After Soviet’s break-up, there were several setbacks in the GLONASS program. This limits its full scale deployment with only 9 satellites in the orbit, which are not able to provide the continuous coverage. At present, the Galileo system has only three satellites in the orbit which are not able to provide continuous coverage. Global Positioning System (GPS) is a satellite-based, worldwide, round-the-clock, all-weather navigation and timing system. The GPS is designed and developed to provide precise position, velocity and timing information on a global common grid system to an unlimited number of suitably equipped users. It is primarily designed as a land, marine, and aviation navigation system. GPS applications have expanded to include surveying, space navigation, automatic vehicle monitoring, emergency services dispatching, mapping, geographic information system etc. Because the dissemination of precise time is an integral part of GPS, a large community of precise time and frequency standard users has come to depend on GPS as a primary source of control to global time and frequency standards.
2.5 GPS ARCHITECTURE

GPS system architecture consists of three segments:

(i) Space segment
(ii) Control segment
(iii) User segment

2.5.1 Space Segment

The space segment consists of a constellation of 24 operational satellites, each of which continuously transmits a ranging signal that includes the navigation message giving the current position and time correction. Satellites are arranged in such a way that four satellites each are placed in the six orbital planes. The satellite orbits are nearly circular with a separation of 60°, an inclination of about 55° to the equator, with an altitude of 20,200Km above the earth and a period of approximately 11 hours 58 minutes. The satellites transmit two spread-spectrum pseudo-random noise (PRN) ranging codes along with the navigation data message at two frequencies, L1 (1575.42MHz) and L2 (1227.60MHz) which are derived from highly stable on-board atomic clocks.

2.5.2 Control Segment

The control segment comprises of three different physical components namely

(i) Master control station
(ii) Monitor stations and
(iii) Ground antennas
II. SPACE SEGMENT

4 selected satellites each with precision time standard pseudo-random data

Ephemeris

Clock Corrections

Pseudo-Range Data

(L1, L2)

III. CONTROL SEGMENT

Monitor stations
Hawaii, DiegoGarcia, Kwajalein, Colorado, Ascension Island

Master Control Station
Colorado Springs

Upload Stations
Ascension Island
Diego Garcia
Kwajalein

Receiver
Accurate
Position
Velocity
Time

Fig. 2.1 Basic elements of the GPS

Fig. 2.2 GPS satellite orbital planes

(i) Master control station: It is located near Colorado Springs and is responsible for data processing, maintenance of the worldwide network
of monitor stations and ground antennas. It processes the data received from monitor stations and estimates the satellite clock corrections, ephemeris and almanac data and other indicators in the navigation message such as satellite health status, for each satellite. This information is then uploaded to the GPS satellites by the ground antenna upload stations via S-band link.

(ii) **Monitor stations**: The monitor stations are located globally at Ascension Island, Diego Garcia, Kwajalein, Colorado Springs and Hawaii whose positions are precisely known. The monitor stations track GPS satellites by making pseudo range measurements to each satellite in view using both L1 and L2 GPS satellite down link frequencies. This information is transmitted to the master control station via a communication link for data processing.

(iii) **Ground Antennas**: It provides a means of commanding and controlling the satellites and uploading the predicted clock and ephemeris information in the form of navigation message and other data via S-band link.

The Control Segment consists of various facilities necessary for satellite health monitoring, telemetry, tracking, command and control, satellite orbit and clock data computations and data up linking. This information is then uploaded to the GPS satellites by the ground antenna upload stations through the S-band link. Every satellite can be given a fresh upload three times a day, approximately eight hours apart. The navigation
data uploaded is then fed to the GPS satellite processor. This processor reads out the appropriate set of navigation data for the specific time period appropriate to the time of transmission.

2.5.3 User Segment

The user segment includes both military and civilian users. User segment consists of GPS receivers which track the ranging signals of selected satellites and calculate three dimensional position and local time. The diversity of the GPS users depends on the type of receivers available today. Based on the type of observables (code pseudo ranges and carrier phases) and on the availability of codes (C/A code, P-code or Y-code), GPS receivers can be classified into four groups: C/A code pseudo range, C/A code carrier phase, P-code carrier phase and Y-code carrier phase measuring instruments. Every aircraft, ship, land vehicle incorporates GPS receivers to coordinate their military activities. Today, GPS receivers are routinely being used to conduct all types of land and geodetic surveys.

2.6 GPS PERFORMANCE REQUIREMENTS

Some of the performance requirements are listed below:

(i) The user position root mean square (rms) error should be 10–30m.

(ii) It should be applicable to real-time navigation for all users including the high-dynamics user, such as in a high-speed aircraft with flexible maneuverability.

(iii) It should have worldwide coverage. Thus, in order to cover the polar regions, the satellites must be in inclined orbits.
(iv) The transmitted signals should be tolerant to some degree of intentional and unintentional interferences. For example, the harmonics from some narrow band signals should not disturb its operation. Intentional jamming of GPS signals is a serious concern for military applications.

(v) It is not needed that every GPS receiver uses a highly accurate clock such as those based on atomic standards.

(vi) When the receiver is first switched on, it should take minutes rather than hours to find the user position.

(vii) The size of the receiving antenna should be small. The signal attenuation through space should be kept reasonably low.

These requirements combined with availability of frequency band allocation determine the carrier frequency of the GPS to be in the L band (1 to 2GHz) of microwave range.

2.6.1 Basic GPS Concept

The position of a certain point in space can be found from distance measured from this point to some known positions in space. A few examples illustrate this point. In Fig. 2.3, the user position is on the x-axis; this is a one dimensional case. If both the satellite position, S1 and the distance to the satellite, x1 are known, the user position can be at two places, either to the left or right of S1. In order to determine the user position, the distance to another satellite with known position should be measured. In this figure, the positions of S2 and x2 uniquely determine the position of the user, U.
Fig. 2.4 shows a two-dimensional case. In order to determine the position of the user, three satellites and three distances are required. The trace of a point with constant distance to a fixed point is a circle in the two-dimensional case. Two satellites and two distances give two possible solutions because two circles intersect at two points. A third circle is needed to uniquely determine the user position. In a three-dimensional case, four satellites and four distances are needed. The distance trace to a fixed point is a sphere in a three-dimensional case. Two spheres intersect to form a circle. This circle intersects with another sphere to produce two points. In order to determine which point is the user position, one more satellite is needed.

Fig. 2.3 One-dimensional user position

Fig. 2.4 Two-dimensional user position
In GPS, the satellite position is known from the ephemeris data transmitted by the satellite. The distance from the receiver to the satellite can be measured. Therefore, the position of the receiver can be determined. The distance measured from the user to the satellite is assumed to be very accurate and there is no bias error. However, the distance measured between the receiver and the satellite has a constant unknown bias, because the user clock is different from the GPS clock. In order to resolve this bias error, one more satellite is needed. Therefore, in order to find the user position five satellites are needed. If one uses four satellites and the measured distance with bias error to measure a user position, two possible solutions are obtained. Theoretically, the user position cannot be determined. However, one of the solutions is close to the surface of the earth and the other one is in space. Since the user position is usually close to the earth’s surface, it can be uniquely determined. Therefore, four satellites can be used to determine a user position, even though the distance measured has a bias error.

2.6.2 Basic Equations for finding User Position

In this section, the basic equations for determining the user position will be presented. Assume that the distance measured is accurate and under this condition, three satellites are sufficient. In Fig. 2.5, there are three known points at locations r1 or (x1, y1, z1), r2 or (x2, y2, z2), and r3 or (x3, y3, z3), and an unknown point at ru or (xu, yu, zu). If the distances between
the three known points to the unknown point can be measured as $\rho_1$, $\rho_2$, and $\rho_3$, these distances can be written as

$$
\rho_1 = \sqrt{(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2}
$$

$$
\rho_2 = \sqrt{(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2}
$$

$$
\rho_3 = \sqrt{(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2}
$$

Because there are three unknowns and three equations, the values of $x_u$, $y_u$, and $z_u$ can be obtained from these equations. Theoretically, there should be two sets of solutions as they are second-order equations. These equations can be solved easily with linearization and an iterative approach. In GPS operation, the satellite positions are given. This information can be obtained from the data transmitted from the satellites.

Fig. 2.5 Use of three known positions to find one unknown position

The distances from the user (the unknown position) to the satellites must be measured simultaneously at a certain time instant. Each satellite
transmits a signal with a time reference associated with it. By measuring the
time of the signal traveling from the satellite to the user, the distance
between the user and the satellite can be found.

**2.6.3 GPS Signal Structure**

A GPS satellite transmits continuously using two radio frequencies in
the L-band referred to as link 1 (L1) and link 2 (L2). Two signals are
transmitted on L1, one for civil users and the other used for military
purposes. Thus L2 is a classified link and is restricted for use by civilians.
Only one signal is transmitted on L2 for authorized users. Satellites transmit
additional RF signals at frequencies L3 and L4. L3 is associated with the
Nuclear Detonation Detection system and L4 is reserved for other military
purposes.

**2.6.4 GPS Signal Components**

Each GPS satellite transmitted signal consists of three components:

(i) Carrier

(ii) Ranging code

(iii) Navigation data

(a) **Carrier**

The GPS signal contains two frequency components: link 1 (L1) and
link 2 (L2). The center frequency of L1 is at 1575.42MHz and L2 is at
1227.6MHz. These frequencies are coherent with a 10.23MHz clock and can
be related to the clock frequency as

\[ L1 = 154 \times 10.23 = 1575.42\text{MHz} \]
L2 = 120 \times 10.23 =1227.60MHz

These frequencies are very accurate as their reference is an atomic frequency standard.

(b) Ranging code

Each satellite is assigned a unique sequence of 0’s and 1’s which allow the receiver to determine the signal transmission time instantaneously. These sequences are randomly generated. The sequences called pseudo-random noise (PRN) sequences or PRN codes have special properties which allow all satellites to transmit at the same frequency without interfering with each other. These sequences also allow precise range measurements and reduce the deleterious effects of reflected and interfering signals received by a GPS antenna.

Each satellite transmits two different codes:

(i) Coarse/acquisition (C/A) code

(ii) Precision (encrypted) [P(Y)] code

C/A-code

The C/A code is a bi-phase modulated signal. Each C/A code is a unique sequence of 1023 bits, called chips, which is repeated for every millisecond. The duration of each C/A code chip is about 1\mu sec i.e. the chip width or wavelength is about 300m. The rate of the C/A code chips, called chipping rate, is 1.023MHz (Mega chips/sec). Therefore, the null-to-null bandwidth of the main lobe of the spectrum is 2.046MHz. Each chip is about 977.5nsec (1/1.023MHz) long. The transmitting bandwidth of the GPS
satellite in the L1 frequency is approximately 20MHz to accommodate the P-code signal; therefore, the C/A code contains the main lobe and several side-lobes. With a chip rate of 1.023MHz, 1,023 chips last 1msec; therefore, the C/A code is 1msec long. This code repeats itself every millisecond.

**P-code**

A P-code is a unique segment of a long (approximately $10^{14}$/chips) PRN sequence with a chipping rate of 10.23Mbps i.e., ten times that for a C/A code and the chip width is about 30m. The smallest wavelength results in greater precision in the range measurements than that for the C/A codes. The P-codes repeat for one week. Encrypted P-codes called Y-codes are also being transmitted to limit accessibility to the authorized users only.

The P-code is bi-phase modulated at 10.23MHz. Therefore, the null-to-null bandwidth of the main lobe of the spectrum is 20.46MHz. The chip length is about 97.8nsec (1/10.23MHz). The code is generated from two pseudorandom noise (PRN) codes with the same chip rate. One PRN sequence has 15,345,000 chips, which has a period of 1.5sec, the other one has 15,345,037 chips, and the difference is 37 chips. The two numbers, 15,345,000 and 15,345,037 are relative prime. Therefore, the code length generated by these two codes is 23,017,555.5 (1.5/15,345,037) sec, which is slightly longer than 38 weeks. However, the length of the P-code is 1 week as the code is reset every week. This 38-week long code is divided into 37 different P-codes and each satellite uses a different portion of the code. There are a total of 32 satellite identification numbers but only 24 of them are in
orbit. Five of the P-code signals (33–37) are reserved for other uses such as ground transmission. If acquisition is to be carried out on the signal, the time of the week must be known very accurately. Usually this time is found from the C/A code signal. The navigation data rate carried by the P-code through phase modulation is at 50Hz.

(c) Navigation data

Navigation data is defined as a binary coded message consisting of data on the satellite health status, ephemeris, clock bias parameters, and an almanac giving reduced-precision ephemeris data on all satellites in the constellation. The navigation message is usually transmitted at 50 bits per second (bps), with bit duration of 20msec. It takes 12.5 minutes for the entire message to be received. The essential satellite ephemeris and clock parameters are repeated every thirty seconds. The GPS navigation message consists of time-tagged data bits marking the time of transmission of each sub frame at the time they are transmitted by the SV. A data bit frame consists of 1500 bits divided into five 300 bit sub frames. A data frame is transmitted for every thirty seconds. Three six second sub frames contain orbital and clock data. SV clock corrections are sent in sub frame one and SV orbital data sets (ephemeris data parameters) for the transmitting SV are sent in sub frames two and three. Sub frames four and five are used for transmitting different pages of system data.

An entire set of twenty-five frames (125 sub frames) makes up the complete navigation message that is sent over a 12.5 minute period. Data
frames (1500 bits) are sent every thirty seconds. Each frame consists of five sub frames. Data bit sub frames (300 bits transmitted over six seconds) contain parity bits that allow for data checking and limited error correction. These three components of a signal (namely carrier, code, and navigation data) are derived coherently from one of the atomic standards on board the satellite. The frequency of the atomic standards on board a satellite is 10.23MHz.

2.6.5 Desired GPS Navigation Signal Properties

To achieve user position, velocity and time, the GPS signal should posses the following properties:

i) Tolerance to signals from other GPS satellites sharing the same frequency band i.e., multiple access capability.

ii) Tolerance to some level of multipath interference. There are many potential sources of multipath reflection. For example man-made or natural objects, atmospheric interferences etc.

iii) Tolerance to reasonable level of unintentional or intentional interference, jamming or spoofing by signal designed to mimic a GPS signal.

iv) Ability to provide ionospheric delay measurements- dual frequency measurements made at L1, L2 frequency must permit accurate estimation of the slowly changing ionosphere.
GPS signal received on the earth should be sufficiently low in power spectral density so as to avoid interference with terrestrial microwave line-of-sight communication.

GPS uses spread spectrum technique to achieve these goals. The signal spectra are spread out over a much wider bandwidth than their information content in order to permit use of higher power levels and also to achieve sufficiently precise ranging accuracy.

### 2.6.6 GPS Signal Characteristics

Thus, the GPS signal consists of two components, link1 or L1 at a center frequency of 1575.42MHz and link2 or L2 at a center frequency of 1227.6MHz. Each of the center frequencies is a coherently selected multiple of 10.23MHz frequency master clock. In particular the link frequencies are the following:

\[
\begin{align*}
L1 &= 154 \times 10.23 = 1575.42\text{MHz} \\
L2 &= 120 \times 10.23 = 1227.60\text{MHz}
\end{align*}
\]

Similarly, all the signal clock rates for the codes, radio frequency carriers, and a 50bps-navigation data stream are coherently related. The frequency separation between L1 and L2 is 347.82MHz or 28.3% and is sufficient to permit accurate dual frequency estimation of the ionosphere delay (The ratio of L1/L2=77/60 =1.2833). The L1 signal is modulated by both 10.23MHz precision P-code signal and 1.023MHz civil C/A signal to be used by the field user. The transmitted signal spectra for both L1 and L2 are shown in Fig. 2.6.
The binary modulating signals are formed by P-code or C/A code that is modulo-2 added to the 50bps binary data, D to form P⊕D and C/A⊕D respectively. The P-code can be converted to a secure anti spoof Y-code at the same clock rate and is labeled as P(Y) code. The L1 signal has an in-phase component of its carrier that is modulated by the P-code, P⊕D, and a quadrature carrier component that is modulated by C/A code, C/A⊕D. The peak power spectral density of the C/A code exceeds that of the P-code at L1.
by approximately 13dB because it is nominally 3dB stronger and has 1/10 the chip rate and bandwidth. L2 signal is bi-phasic modulated by the P-code. Data modulation on L2 depends on the ground command.

The signal leaving the antenna of the \(k\)th satellite can be modeled as
\[
S[k](t) = \sqrt{2P_c} x(t) D[k](t) \sin(2\pi f_{L1} + \Theta_{L1}) + \sqrt{2P_{Y.L1}} y[k](t) D[k](t) \cos(2\pi f_{L1} t + \Theta_{L1}) + \sqrt{2P_{Y.L2}} y[k](t) D[k](t) \cos(2\pi f_{L2} t + \Theta_{L2})
\]

where, \(P_c\), \(P_{Y.L1}\) and \(P_{Y.L2}\) are the signal powers for signals carrying C/A code on L1 and P(Y)-codes on L1 and L2 respectively; \(x[k]\) and \(y[k]\) are the P(Y) and C/A code sequences assigned to satellite number \(k\); \(D[k]\) denotes the navigation data bit stream; \(f_{L1}\) and \(f_{L2}\) are the carrier frequencies corresponding to L1 and L2 respectively; and \(\Theta_{L1}\) and \(\Theta_{L2}\) are phase offsets.

At the receiver end, the navigation data has to be tracked from the acquired GPS signal to calculate the satellite position and there by the user position. The GPS system provides each authorized user with at most 10m rms position error, which translates to a required accuracy of pseudo range measurement of the order of 11ns. We choose to accomplish this required accuracy with a 10.23Mcps precision P-code. Two other GPS objectives i.e., rapid acquisition of the P-code and providing a lesser accuracy for the civil user are achieved by the use of civil C/A code, which has a 1.023Mcps chip rate and a code period of 1023 chips. Civil users do not have access to the P(Y) code when it is in the anti spoof (AS) Y-code mode. The unusual code rates of 1.023Mcps and 10.23Mcps are selected so that the period of the C/A code corresponds exactly to 1ms for time keeping purposes.
The GPS L1 signal has two spread spectrum signals i.e., civil C/A and precision P, multiplexed on to a single radio frequency carrier. In addition to this, the signals from multiple satellites must share the same frequency channel. The GPS multiplexes the civil C/A code and the P-code on a single carrier in phase quadrature and then employs CDMA so that the different satellite signals can share the identical frequency band. C/A signal is modulated in phase onto the L1 carrier and P-code on a quadrature phase (90° rotated) thus providing a constant envelope modulated carrier even if the two signals have different power levels. The GPS signals then have the form (neglecting the data modulation) $X_{P_i}(t)\cos(\omega_f t) + X_{C/A}(t)\sin(\omega_f t)$ where $X_{P_i}$ represents the P-code and $X_{C/A}$ represents the C/A code (Parkinson and Spilker 1996).

Fig. 2.7 GPS signal structure
2.7 CONCLUSIONS

Ground based navigational aids provide the navigational signals for an aircraft receiver which allow the pilot to determine bearing of the aircraft in case of terrestrial navigation and precise geographic location coordinates in latitude/longitude in case of global navigation satellite systems. Various Global Navigation Satellite Systems (GNSS) existing in the world (USA’s GPS, Russia’s GLONASS, and European Union’s GALILEO) have been described. The GPS system architecture, L1 and L2 signal structure, frequency assignment and the GPS performance requirements are presented.