20.11. Review Questions

1. With the help of a sketch, describe the working of a VSAT/WLL network. Why such a system facilitates the use of very small antenna terminals?
2. Describe the operation of a typical VSAT user set-up giving details of the outdoor and indoor units.
3. With the help of a block diagram, describe how the sub stake in a VSAT system handles large inbound and outbound traffic.
4. Explain why FEC and Reed-solution interleavers are used coding and decoding of channels in a VSAT systems?
5. Describe how the TDM downlink outbound channels is linked to VSAT terminals how is the 64 kbts/sec equivalent voice channel is received?
6. What is the typical range, in metres, of the aperature diameter for a VSAT operating with a Ku-band satellite ?
7. Explain what Mesh and Star architectures are in a VSAT network. State two advantages and disadvantages of each.
8. Describe the three major types of multiple access schyemes that are used in satellite systems.
9. What are the advantages and disadvantages of an MF-TDMA access scheme in a VSAT system?
10. Why has a TDM approach been adopted for most downlink applications for digital VSAT and Internet applications to small terminals?
11. What do the symbols ACK and NAK mean when applied to a packet switched communications system?
12. What does the term spoofing mean when applied to the interface between dissimilar networks.

20.12. References

1. Timothy Pratt, Charles W. Bostian and J.E. Allnutt, *Satellite Communication*, John Wiley, NJ, 2003.
2. VSAT Systems and Earth Stations, *Handbook on Satellite Communications,* International Telecommunications Union, Geneva, 1994.

full 21

Global Positioning Satellite Systems

The Global Positioning Satellite Systems (GPSs) are used as means of navigation for ships and aircrafts and in surveying and many other applications.

21.1 The Technical Structure

The main features Global Positioning Satellite Systems (GPSs) are:

1. The GPS space segment consists of 24 satellites in medium earth orbit (MEO) at a nominal altitude of 20,200 km with an orbital inclination of 550.

2. The satellites are clustered in groups of four, called constellations, with each constellation separated by 600 in longitude.

3. The orbital period is approximately one-half a sidereal day (11 hours 58 minutes) so the same satellites appear in the same position in the sky twice each day.

4. The satellites carry station-keeping fuel and are maintained in the required orbits by occasional station keeping maneuvers, just like GEO satellites.

5. The orbits of the 24 GPS satellites ensure that at any time, anywhere in the world, a GPS receiver can pick up signals from at least four satellites. Upto 10 satellites may be visible at some times, and more than four satellites are visible nearly all of the time. They provide a direct readout the present position of a GPS receiver with a typical accuracy of 30 m.

6. A large number of GPS receivers can operate simultaneously because all that a GPS receiver has to do to locate itself is to receive signals from four GPS satellites.

Other position location systems, such as LORAN (long range navigation) that can also provide direct readout of position, but have far less accuracy and reliability.

21.2 Finding the Position of GPS Receiver: The Trilateration Method

One of the simplest and most accurate methods of locating an unknown position is the *trilateration method.* In this method, the distance of the unknown point from three known points is measured. The intersection of the arcs corresponding to three distances defines the unknown point relative to the known points, since three measurements can be used to solve three equations to give the latitude, longitude, and elevation for the receiver.

In the GPS systems, the trilateration method is used to locate a GPS receiver. Here the distance between a transmitter and a receiver is estimated by measuring the time taken by a pulse of RF energy to travel between the two. This distance is calculated using the velocity of electromagnetic waves in free space (the velocity of light of 299,972,458 m/s). Time is measured electronically more accurately by the use of atomic clocks so that the GPS position location system is able to achieve a measurement accuracy of 1 metre in a distance of 20,000 km. However, this position location accuracy can be obtained if timing measurements have an accuracy better than 3 ns. This is achieved as follows:

1. Each satellite carries several high accuracy atomic clocks and radiates a sequence of bits that starts at a precisely known time.

2. A GPS receiver contains a clock that is synchronized in turn to the clock on each satellite that it is receiving.

3. The receiver measures the time delay of the arrival of the bit sequence, which is proportional to the distance between the satellite and the GPS receiver.

4. After the distance of a GPS receiver from three satellites has been measured, it is now required to know the position of each satellite. This is calculated in the GPS receiver using the *ephemperis* for the satellite orbits that are broadcast by each satellite in its navigation message.

5. As the time at which the transmitted bit sequence is started is known at the receiver, the position of the satellite at that time can be calculated from its orbital data.

6. Apart from the three satellites, a fourth satellite is also used because the clock in the receiver is not inherently accurate enough. The fourth distance measurement provides information from which clock errors in the receiver can be corrected and the receiver clock synchronised to GPS time with an accuracy better than 100 nsec.

21.3 Frequencies Used by GPS satellites

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GPS satellites transmit two signals at different frequencies, known at L1 and L2:

(*i*) The L2 signal is modulated with 10.23 Mbps pseudorandom (PN) bit sequence called the *P* code. This is used by military positioning systems. The *P* code is transmitted in an encrypted form known as the *Y* code, which restricts the use of is the *P* code to authorized users.

(*ii*) The L1 frequency carrier is modulated by a 1.023 Mbps PN sequence called the *Coarse Acquisition (C/A)* code that is available for public use, and also carries the *P* code as a quadrature modulation. The higher bit rate of the *P* code provides better measurement accuracy than the 1.023 Mbps *C/A* code.

L2 → Militar
L1 → Public

21.4 Types of GPS Services

The GPS system provides two types of service:

I. Precise positioning service (PPS): Here the receivers track both *P* code and *C/A* code on L1 and L2 frequencies. The PPS is used mainly by military users, since the *P* code is encrypted into the *Y* code before transmission and requires decryption equipment in the receiver. L2

II. Standard positioning service (SPS): Here the receivers track the *C/A* code on L1. This is the service that is used by the general public. The *P(Y)* and *C/A* code transmitted by each satellite create direct sequence spread spectrum signals which occupy the same frequency bands. Both the *C/A* code and the *P* code are publicly available.

DSSS

21.5 GPS Position Location Layout

Fig. 21.1 shows the schematic of position location with GPS. The principle is as follows:

1. The three satellites provide distance information when the GPS receiver makes three measurements of range, R_i, from the receiver to three known points.

2. Each distance R_i can be thought of as the radius of a sphere with a GPS satellite at its center. The receiver lies at the intersection of three such spheres, with a satellite at the center of each sphere. Locally, at the receiver, the spheres will appear to be planes since the radii of the spheres are very large.

3. Since the intersection of three planes completely defines a point, three satellites, through measurement of their distances to the receiver, define the receiver location close to the earth's surface.

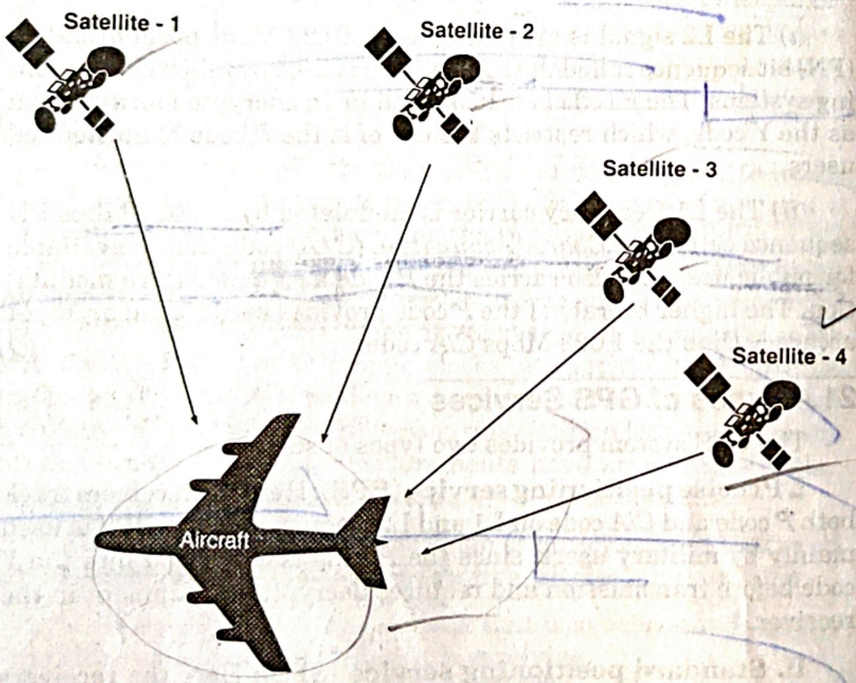

Fig. 21.1 GPS Position Location using Four Satellites.

21.5.1 GPS Satellite Clocks

Each GPS satellite has an atomic clock, which is calibrated against time standards in the GPS control stations around the world. This is called GPS time, a time standard that is available in every GPS satellite. The accuracy of an atomic clock is typically 1 part in 10^{11}

The time standard system in each GPS satellite consists of a set of four atomic clocks: two cesium clocks and two rubidium clocks. An atomic clock employs the fundamental resonance of the cesium or rubidium molecule as a frequency reference to lock a crystal oscillator.

In the GPS satellites, the master oscillator is at 10.23 MHz. All code rates, the L1, and L2 RF frequencies are multiples or sub-multiples of 10.23 MHz.

The atomic clocks are updated by the controlling ground stations to keep them within 1 μs of Universal Time Coordinated (UTC). The navigation message sent by each satellite contains information about its current clock error relative to GPS time. (UTC is a worldwide time standard, and equal to Greenwich Mean Time (GMT).

21.5.2 GPS Receiver Clock

An atomic clock very is expensive and therefore is not included in the GPS receivers. Instead, a standard crystal oscillator with an accuracy of 1 in 10^5 or 1 in 10^6 is used.

Since the receiver clock has an offset of 10 ms relative to GPS time, the distance measurements will have an error of 3000 km. Therefore, it is necessary to remove the time error from the receiver clock before to get position measurements. C/A code receivers synchronize their internal clocks to GPS time within 170 ns, corresponding to a distance measurement inaccuracy of 50 metres. A number of measurements and integration helps in improving the position location error to well below 50 metres.

As already discussed, a time measurement from a fourth satellite provides distance error corrections. Three time measurements are made to define the location of the receiver in the three unknown coordinates x, y, and z. When a fourth time measurement is added, we can solve the basic position location equations for a fourth unknown, the receiver clock offset error t_e. Thus the four unknowns in the calculation of the location of the receiver are x, y, z and t_e.

21.6 Calculation of Position Location in GPS Systems

In position location, first, the coordinates of the GPS receiver and the GPS satellites are defined in a rectangular coordinate system with its origin at the center of the earth. This is called the *earth centered earth fixed* (ECEF) coordinate system.

The ECEF coordinate system is part of the WGS-84 description of the earth. WGS-84 is an internationally agreed description of the earth's shape and parameters, derived from observations in many countries.

GPS receivers use the WGS-84 parameters to calculate the orbits of the GPS satellites with the accuracy required for precise measurement of the range to the satellites. Fig. 21.2 shows the geometry of a GPS measurement system:

1. The Z-axis of the coordinate system is directed through the earth's North Pole and the X- and Y-axes are in the equatorial plane.

2. The X-axis passes through the Greenwich meridian - the line of zero ECEF coordinate system rotates with the earth.

3. The receiver coordinates are (U_x, U_y, U_z), and the four satellites have coordinates (X_i, Y_i, Z_i), where $i = 1, 2, 3, 4$.

4. The measured distance to satellite i is called a psuedo-range, R_{Pi}, because it uses the internal clock of the receiver to make a timing measurement that includes errors caused by receiver clock offset.

Psuedo-range R_{Pi} is measured from the propagation time delay T_i between the satellite i and the GPS receiver. That is

$$R_{Pi} = T_i \times c \quad \text{... (21.1)}$$

We know from geometry that the distance R between two points A and B is a rectangular coordinate system will be

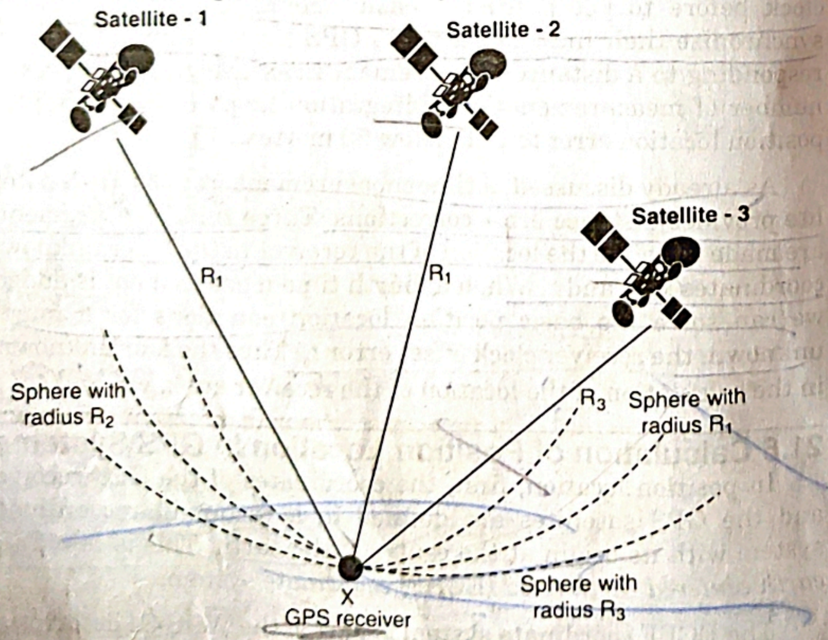

Fig. 21.2 GPS Position Location by measuring Distance from Three Satellites.

te = Rx clk offset error

$$R^2 = (x_A - x_B)^2 + (y_A - y_B)^2 + (z_A - z_B)^2$$

Using this above equation, the ranging equations which relate pseudo-range to time delay are will be

$$\begin{cases} (X_1 - U_x)^2 + (Y_1 - U_y)^2 + (Z_1 - U_z)^2 = (PR_1 - t_e^2) \\ (X_2 - U_x)^2 + (Y_2 - U_y)^2 + (Z_2 - U_z)^2 = (PR_2 - t_e^2) \\ (X_3 - U_x)^2 + (Y_3 - U_y)^2 + (Z_3 - U_z)^2 = (PR_3 - t_e^2) \\ (X_4 - U_x)^2 + (Y_4 - U_y)^2 + (Z_4 - U_z)^2 = (PR_4 - t_e^2) \end{cases} \quad \text{... (21.2)}$$

where t_e is receiver clock error (offset, or bias).

PR_i = exact distance of satellite

The process for position location is as follows:

1. The position of the satellite at the instant when sends the timing signal (that is, the start of a long sequence of bits) is obtained from ephemeris data transmitted along with the timing signals.

2. Each satellite sends out a data stream that includes its own ephemeris data and that of the adjacent satellites.

3. The receiver now calculates the coordinates of the satellite relative to the center of the earth, (X_i, Y_i, Z_i), and then its circuitry solves the four ranging equations using standard numerical techniques.

4. Solving of above equations leads to the values of the four unknowns - the location of the GPS receiver (U_x, U_y, U_z), relative to the center of the earth and the clock offset t - called *clock bias* in GPS terminology.

5. The receiver position is now referenced to the surface of the earth, and is displayed in latitude, longitude, and elevation.

21.6.2 2-DRMS error

This is the accuracy measurement for a low cost GPS receiver using the GPS C/A code is called 2-DRMS error, where DRMS is the distance root mean square error of the measured position relative to the true position of the receiver. Its typical value is 30 metres.

It has been found that since often the measurement errors are Gaussian distributed, 68% of the measured position results will be within a distance of 1 DRMS from the true location and 95% of the results will be within 2DRMS of the true location.

21.6.3 Standardisation of GPS Time

The clock bias value in the ranging equations for position location calculations is also added to the GPS receiver clock time to yield a time measurement that is synchronised to the GPS standard.

The crystal oscillator used in the GPS receiver is highly stable only over a period of a few seconds. Its frequency changes for longer periods are caused by:

(*i*) Temperature changes results in changes in the quartz crystal of crystal oscillator to expand or contract, and this changes the oscillator frequency.

(*ii*) Aging of crystals leads to the frequency to change with time. The changes are very small, but sufficient to cause errors in the clock time at the receiver when the clock is not synchronized to a satellite.

Thus, when the clock bias is calculated by solving ranging equations, it allows the receiver clock time to be updated every second or two with the result that the GPS receiver time- readout is identical to GPS time.

Every GPS receiver is automatically synchronized to every other GPS receiver anywhere in the world through GPS time. This makes every GPS receiver a super clock, which knows time more accurately than any other time standard.

21.7 GPS Codes

As already seen, the transmission by GPS satellites transmit is based on pseudo-random sequence (PN) codes. Fig. 21.3 shows the generation of L1 and L2 signals in a GPS satellite:

1. All satellites in the GPS system transmit a *C/A* code at the same carrier frequency, 1575.42 MHz, called L1, using BPSK modulation. The L1 frequency is 154 times the master clock frequency of 10.23 MHz.

2. The clock rate of the *C/A* code is 1.023 MHz and the *C/A* code sequence has 1023 bits, so that the PN sequence lasts exactly 1.0 msec. The exact values of the frequencies are about 0.005 Hz lower than stated here to allow for relativistic effects caused by the high velocity of the satellites in their orbits (3.865 km/sec).

3. The transmission of the *P* code is by using BPSK modulation at the L2 carrier frequency of 1227.6 MHz (120 x 10.23 MHz), and it is also transmitted with BPSK modulation on the L1 carrier frequency, in phase quadrature with the *C/A* code BPSK modulation.

4. The *C/A* and *P* code transmissions from all GPS satellites are overlaid in the L1 and L2 frequency bands, making GPS a direct sequence spread spectrum (DSSS) system.

5. At the receiver, the signals from individual GPS satellites are separated using knowledge of the unique *C/A* code that is allocated to each satellite.

21.7.1 The C/A Code

Figure 21.5 shows the schematic of a *C/A* code generator :

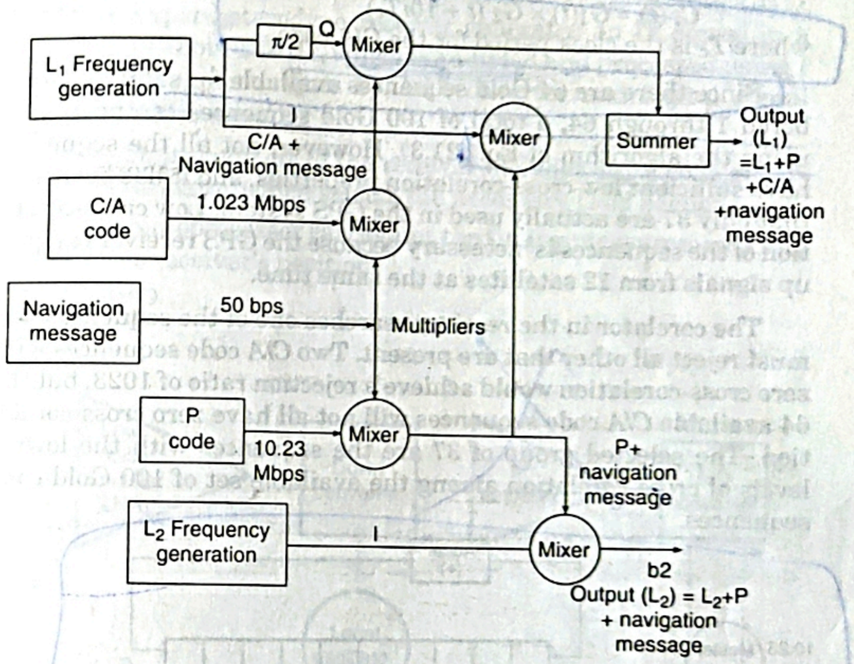

Fig. 21.3 Generation of L1 and L2 Signals in a GPS Satellite.

1. The *C/A* codes transmitted by GPS satellites are all 1023 bit Gold codes. The GPS *C/A* Gold codes are created from two 1023 bit m-sequences, called G1 and G2, by multiplying together the G1 and G2 sequences with different time offsets.

2. An *m*-sequence is a maximum length pseudo-random (PN) sequence, which is easy to generate with a shift register and feedback taps.

3. As a shift register with *n* stages can generate a PN sequence $2^n - 1$ bits in length, the bit pattern is set by its feedback taps and combining logic. The PN sequences G1 and G2 are both generated by 10-bit shift registers and are therefore both 1023 bits long.

4. The clock rate for the *C/A* code is 1.023 MHz, so each sequence lasts 1.0 ms.

For a particular satellite in the GPS system, the C/A code is created with an algorithm that includes the identification number (ID) of the GPS satellite, thus creating a unique code for each satellite. For the satellite with ID number i, a C/A code sequence $C_i(t)$ given by

$$C_i(t) = G_1(t) \times G_2(t + 10iT_c) \qquad \ldots (21.3)$$

where T_c is the clock period for the C/A code.

Since there are 64 Gold sequences available for satellites numbered 1 through 64, a total of 100 Gold sequences can be created using the algorithm of Eq. (21.3). However, not all the sequences have sufficient low cross-corelation properties, and it has been seen that only 37 are actually used in the GPS system. Low cross-corelation of the sequences is necessary because the GPS receiver can pick up signals from 12 satellites at the same time.

The corelator in the receiver searches one of the sequences and must reject all other that are present. Two C/A code sequences with zero cross-corelation would achieve a rejection ratio of 1023, but the 64 available C/A code sequences will not all have zero cross-corelation. The selected group of 37 are the sequences with the lowest levels of cross-corelation among the available set of 100 Gold code sequences.

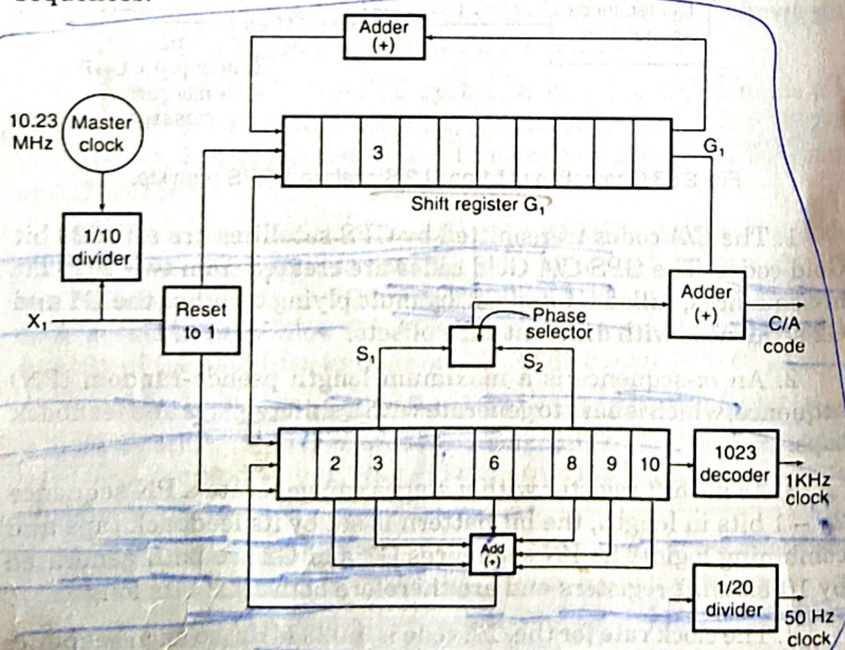

Fig. 21.4 Generation of C/A Code in a GPS System.

21.8 GPS Receiver

Figure 21.5 shows a schematic of a C/A code GPS receiver:

1. The antenna is a circularly polarized patch antenna with an LNA mounted on it.

2. The super-heterodyne receiver generates an IF signal in a bandwidth of about 2 MHz, which is sampled and processed using I and Q sampling techniques by A/D converter and digital signal processing (DSP) circuit.

3. The digital portion of the receiver includes a C/A code generator and a corelator which selects the necessary Gold sequences.

4. The microprocessor carries out the timing measurements and calculate the receiver's position.

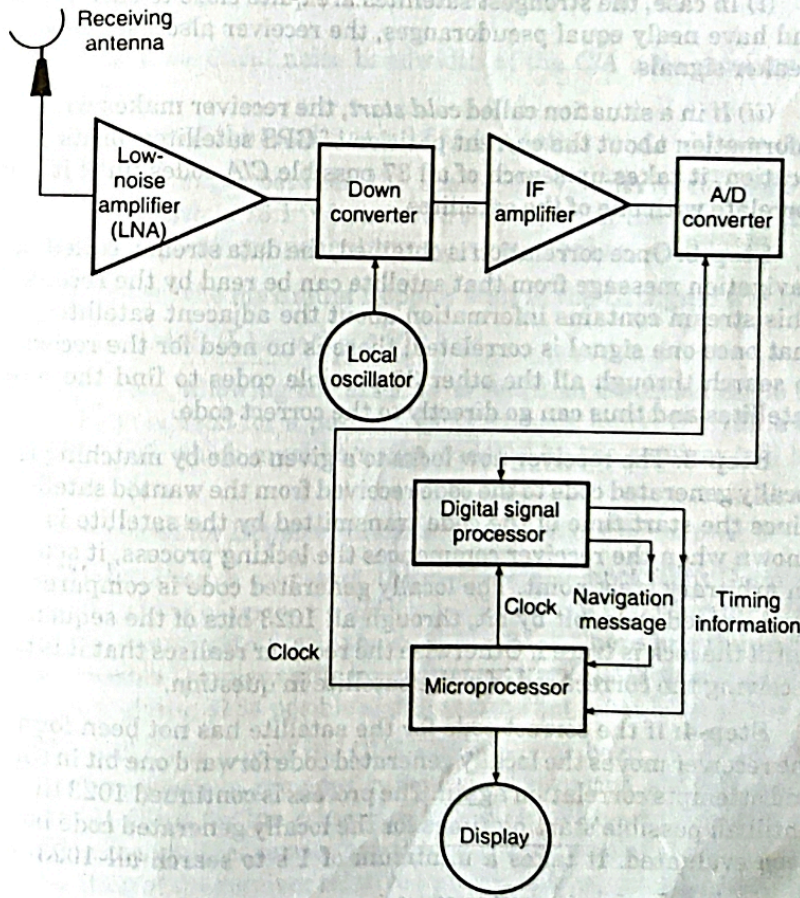

Fig. 21.5 Block Diagram of a GPS Receiver.

21.9. Method of Satellite Signal Acquisition by GPS Receiver

This is carried out by the GPS receiver by two corelation processes: (*a*) code synchronisation with the satellites; and (*b*) Doppler frequency offset measurements.

21.9.1. Code Synchronisation

Step-1: The GPS receiver first determines the starting time of the unique *C/A* code for each of four satellites. This it does by corelating the received signal with stored *C/A* codes, as in any direct sequence spread spectrum system. In practice, the receiver automatically selects the four strongest signals and corelate to those. However, it faces two problems:

(*i*) In case, the strongest satellites are quite close to each other, and have nealy equal pseudoranges, the receiver also uses several weaker signals.

(*ii*) If in a situation called *cold start*, the receiver makes with no information about the current position of GPS satellites, or its own location, it takes up search of all 37 possible *C/A* codes until it can correlate with one of the satellites.

Step-2: Once correlation is obtained, the data stream, called the navigation message from that satellite can be read by the receiver. This stream contains information about the adjacent satellites, so that once one signal is correlated, there is no need for the receiver to search through all the other 36 possible codes to find the next satellites and thus can go directly to the correct code.

Step-3: The receiver now locks to a given code by matching the locally generated code to the code received from the wanted satellite. Since the start time of the code transmitted by the satellite is not known when the receiver commences the locking process, it selects an arbitrary start point. The locally generated code is compared to the received code, bit by bit, through all 1023 bits of the sequence, untill the lock is traced. Otherwise the receiver realises that it is not receiving the correct code for the satellite in question.

Step-4: If the correct code for the satellite has not been found, the receiver moves the locally generated code forward one bit in time and attempts correlation again. The process is continued 1023 times untill all possible starting times for the locally generated code have been evaluated. It takes a minimum of 1 s to search all 1023 bit

positions of a 1023 bit *C/A* code, so in a typical case, it will take at least 15 sec to acquire the first satellite.

Step-5: Once one *C/A* code is found, the remaining satellites can then be acquired in a few seconds because their IDs are known from the data transmitted in the navigation message of each satellite.

21.9.2. Tracking Doppler frequency offset

Apart from locking to the *C/A* code of one satellite, the GPS receiver has to simutanously estimate the Doppler frequency offset for at least one satellite before final correlation can occur. To understand this process, we first carry out an estimate of the Doppler shift than must be accommodated by the receiver. The facts of the situation are:

1. The receiver bandwidth is matched to the bandwidth of the *C/A* code.

2. The theoretical noise bandwidth of the *C/A* code receiver = 1.023 MHz.

3. Velocity of the satellites = 3.865 km/sec.

Since the angle between the spacecraft velocity vector and a receiver on earth is 76.1° when a GPS satellite is at the horizon, the maximum velocity component toward a receiver is v_r = 928 m/s.

Therefore, the maximum Doppler shift in the L1 signal will be

Doppler shift (L1)= v_r/λ = 4.872 kHz

Therefore, allowing the satellite to reach an elevation angle of 5° before it is used for a position measurement limits the value of Doppler shift which must be accommodated by the receiver will be upto ± 4 kHz.

The search for Doppler shift is now carried out as follows:

Step-1: From a cold start, the receiver attempts eight Doppler frequency shifts of up to ± 4 kHz in 1-kHz steps when searching for the signal from a satellite as shown in Fig. 21.6. Therefore, there are eight possible Doppler shifts for each signal, and 1023 possible code positions, giving 8184 posible signal states that must be searched.

Step-2: Once any of the GPS satellites has been acquired, the navigation message provides sufficient information about the adjacent satellites for the remaining visible satellites to be acquired quickly. The receiver carries out the search in Doppler shift because the position of the receiver relative to the satellites is not known, but their C/A codes are.

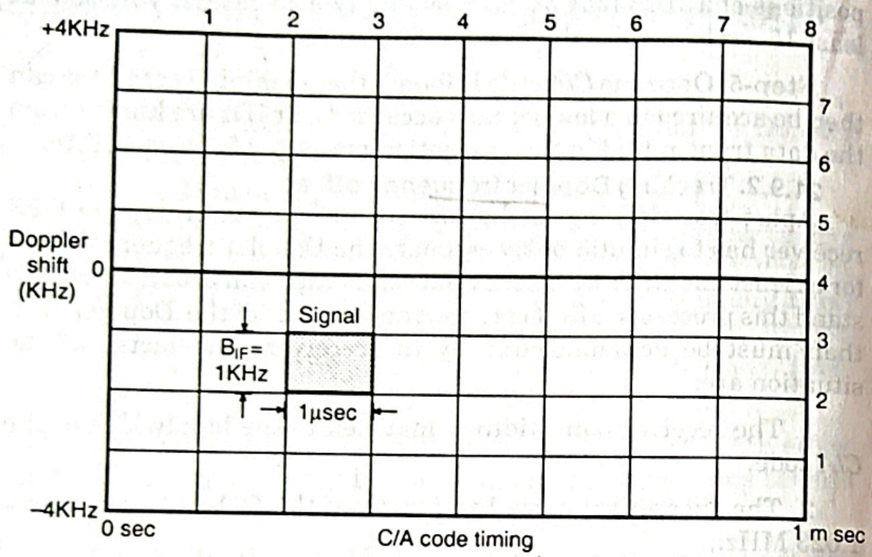

Fig. 21.6 Syncronisation between C/A Code Timing and Doppler Shift for a GPS Satellite Search.

Step-3: The receiver stores the information from the navigation message when switched off, and starts running its internal clock. When it is switched on again, it assumes that its position is close to its last known position when it was switched off. It, therefore, calculates which satellite should be visible, and search for those first. This greatly speeds up the acquisition process.

In the correlation process described above, it is assumed that each satellite is acquired sequentially, one at a time, as in the case of lower cost GPS receivers. However, sophisticated receivers are designed to have parallel correlators which can search for and acquire satellites in parallel. It has been found that 12 parallel correlators allows acquiring of all visible GPS satellites. As a result, the start-up time is much shorter than with sequential acquisition. Parallel processing of the signals also leads to better accuracy.

The *P* code for GPS satellites is typically of long sequences because the long length of the *P* code sequene makes the distance measurements unambiguous. It repeats after 266.4 days, but is changed every *7* days for security reasons. Therefore, the *P* code sequences cannot be acquired easily because they do not repeat, and thus their unauthorized use is prevented.

21.10. References

1. B.H. Hofman-Wellwenhof, H. Lichtenegger and J. Collins, *GPS Theory and Practice*, Springer Verlag, New York, NY, 1992.
2. B. Clarke, *Aviation Application of GPS*, McGraw-Hill, New York, NY, 1996.
3. Timothy Pratt, Charles W. Bostian and J.E. Allnutt, *Satellite Communication*, John Wiley, NJ, 2003.

21.11. Review Questions

1. Describe The main features of the technical Structure of a Global Positioning Satellite System.
2. Explain the trilateration method used in GPS systems to locate a receiver.
3. Derive the four ranging equations used in locating the position of a receiver in a global positioning satellite system.
4. Describe the method of satellite signal acquisition by GPS Receiver by code synchronisation
5. Describe how the Doppler frequency offset is tracked in a GPS system and taking an example explain how it is synchronised with C/A coding timing.