Unit VIII
Satellite Navigation and Global Positioning Systems

Radio and Satellite Navigation

- Prior to radio navigation
  - Compass,
  - Land Marks on land and
  - By the sun and stars at sea
- Neither technique provides high accuracy and shipwrecks caused by in-accurate navigation and foggy weather were a common occurrence.
- The development of bomber aircrafts that could fly above the clouds (1930), made radio navigation essential.
- GPS was preceded by an earlier satellite navigation system called **TRANSIT,**
  - Built for the U.S. Navy for ship navigation,
  - which achieved much lower accuracy and became obsolete when GPS was introduced
  - TRANSIT Satellites were in LEO
  - The system used the Doppler shift observed at the receiver when a beacon signal was transmitted by the satellite

- Because of the high velocity of LEO satellites (about 7.5 km/s),
  - Their signals are shifted up in frequency when the satellite appears over the horizon with a component of velocity toward the receiver
  - Doppler shift falls to zero as the satellite passes the observer, and then become negative as the satellite flies away
  - Observation of the Doppler shift with time, which may need to be as long as 10 min, and knowledge of the satellite orbit allows calculation of the receiver's position.
- Disadvantages
  - Sufficient number TRANSIT satellites were not there to provide continuous position data, and
  - The long time (10 min) required to obtain an accurate position fix.

- A similar system called **SARSAT (Search And Rescue Satellite)** is used to find Emergency Locator Transmitters (ELTs) on aircraft that have crashed.
  - Analysis of the Doppler shift over the observation period provides information about the location of the ELT, but with an accuracy of 1 or 2 kms.
  - Almost 97% of ELT locations turn out to be false alarms- the ELT was dropped or accidentally turned on.
- The Demand for accurate targeting of airborne weapons lead to the development of **GPS.**
- GPS can provide a single navigation system with better accuracy and reliability than all earlier radio navigation systems.
- It can provide navigation of aircraft directly between airports, instead of indirectly via airways, while providing absolute position read out of Latitude and Longitude.
- Differential GPS can be used instead of ILS (Instrument Landing System).
- Eventually, GPS will replace all other means of Navigation

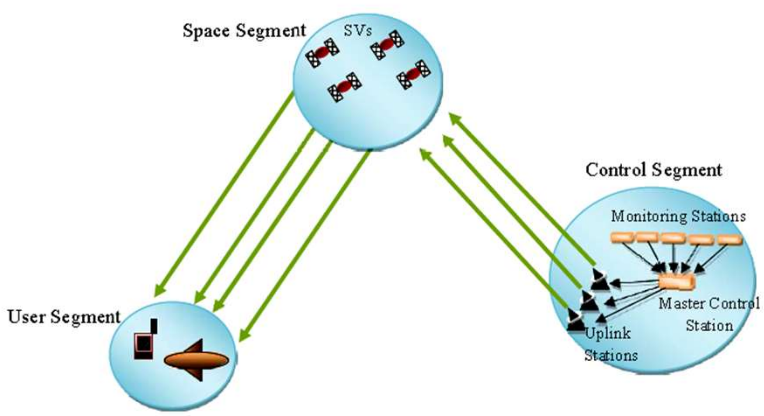
Introduction to GPS

The Global Positioning System (GPS) is a space-based navigation system that provides location and time information in all weather conditions, anywhere on or near the Earth where there is an unobstructed line of sight to four or more GPS satellites.

- Primary means of navigation for
  - Ships
  - Aircrafts
  - Surveying
- GPS also called as Navigation Satellite Timing And Ranging (NAVSTAR)
  - Developed as military Navigation system for guiding
    - Missiles
    - Ships, and
    - Aircrafts to their targets
- GPS satellite transmits L-band signals that are modulated by several codes
  - C/A code: Made available to public in mid 1980s
    - to achieve positioning accuracy of 30 m
  - P-code (secure and high accuracy): Authorized users (military)
    - to achieve positioning accuracy of 3 m

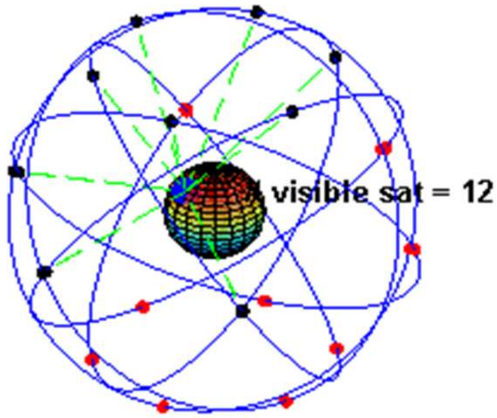
GPS architecture

- GPS architecture consists of three segments:
  -- space segment,
  -- control segment and
  -- user segment.



Space Segment

- GPS satellite constellation consists of a minimum of 24 satellites.
- Altitude of about 20,183 km and takes 11hr 58mins to orbit one time.
- There are 6 orbital planes, each consisting of a minimum of 4 satellites.
- The orbits are at an inclination of 55^{o} with respect to the equator.



Control Segment

- The GPS is controlled by the US Air Force from
  - The Master control Station (MCS), at Falcon Air force base in Colorado Springs, Colorado.
- These stations calculate ephemeris data for each satellite, atomic clock error, and numerous other parameters needed for the navigation message.
- The data are transmitted to satellite using a secure S-band link and used to update onboard data.
- There are 5 GPS monitoring stations located in
  1. Hawaii
  2. Colorado Springs,
  3. Ascension Island (in Atlantic Ocean)
  4. Diego Garcia (in Indian Ocean)
  5. Kwajalein (in Pacific Ocean)
- The monitor stations have precise Cesium standards and
  - Make continuous measurement of range to all visible satellites
  - These measurements are performed every 1.5 s, and
  - are used to provide updates for the navigation messages

User segment (Receiver)

- The position of a GPS Rx is found by Trilateration
  - The distance of the unknown point from the three known points is measured.
  - The intersection of 3 arcs corresponding to 3 distances defines the unknown point, relative to the known point.
    - 3 measurements are used to solve 3 equations to give Latitude, Longitude and Height of the Rx.
- The distance between a transmitter and receiver can be found by measuring the time it takes for a pulse of RF energy to travel between the two
  - The distance is calculated using the velocity of Electromagnetic waves in free space, assumed to be equal to velocity of Light v= 2,99, 792, 452 (~3×10^8) m/s.
- To achieve GPS location accuracy of 1 m, timing measurements must have an accuracy of better than 3ns

GPS satellite transmit two frequencies, L1 and L2

- The L2 signal (1227.60MHz) is modulated with a 10.23 Mbps pseudorandom (PN) bit sequence called the P (Precise)-code
  - Used by Military positioning systems
  - The P-code is transmitted in an encrypted form (known as Y-code), which restricts the use of P-code to unauthorized users.
- The L1 carrier frequency (1575.42MHz) is modulated by a 1.023Mbps PN sequence, called the C/A (Coarse/ Acquisition)-code (for public use) and the P-code as quadrature modulation
  - The higher bit rate for P code provides better measurement accuracy than the C/A code
- GPS systems using Y-code require the C/A code as an intermediate step in making distance measurements
- The accuracy of C/A code receivers was deliberately degraded some of the time (Selective availability (SA)).
  - SA causes variations in the C/A code satellite transmissions that result in less calculation of position.
  - SA was discontinued in May 2000, but can be reinstituted if President of US declares National Emergency.

The GPS system provides two categories of services:

The Precise Positioning Service (PPS)

PPS Receivers track both P-code and C/A code on L1 and L2 frequencies.

PPS is used mainly by military users

Since the P-code is encrypted as Y-code before transmission and requires decryption equipment in the receiver.

Standard Positioning Service (SPS)

SPS receivers track the C/A code on L1 only

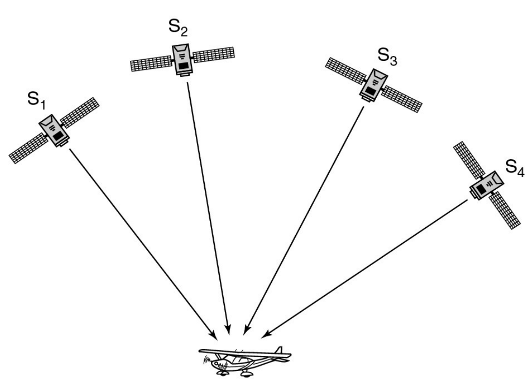
SPS is used by general public

- The P(Y) and C/A codes transmitted by each satellite create direct sequence Spread spectrum signals which occupy the same frequency bands.

- Both C/A and P codes are publicly available, but P code can't be recovered in a GPS Rx without a knowledge of the Y-code decryption algorithm

GPS Position Location Principles

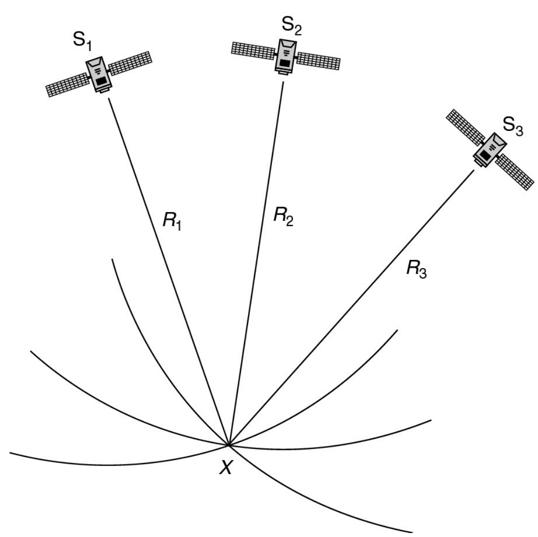
- Basic requirement of satellite navigation system → 4 satellites transmitting suitable coded signals from known positions.
- 3 satellites → provide 3 distance measurements
  1 satellite → to remove receiver clock error
- Ri (radius of sphere)→ range measurement from receiver to 3 known points.
- Receiver lies at the intersection of 3 spheres, with satellite at the center.



- Range is calculated from the time delay incurred by the satellite signal in traveling from the satellite to the GPS receiver, using known velocity of EM waves in free space.
- To measure the time delay we should know the precise instant at which the signal was transmitted.
- GPS satellite carry four atomic clocks → time standard → **GPS time.**
- Accuracy of atomic clock → 1 part in 10^11.
- Clock offset.
- C/A code receivers can synchronize their internal clocks to GPS time within 170 ns, corresponding to a distance measurement uncertainty of 50 m.
- It is easy to remove the clock error.
- 3 time measurements to define location (x, y, z)
- 4^{th} time measurement to remove receiver clock offset error *T* (x, y, z, *T*)

Position Location in GPS

Position location by measurement of the distance to three satellites. The GPS receiver is located at point *X*, where three spheres with radii R_1, R_2, and R_3 intersect. The centers of the spheres are the three GPS satellites S_1, S_2, and S_3. If the distances R_1, R_2, and R_3 are measured, the location of the point *X* can be uniquely defined.



- Earth Centered Earth Fixed (ECEF) coordinate system.
- WGS-84 → internationally agreed description of the earth's shape and parameters.
- GPS Rxs use WGS-84 parameters to calculate the orbits of GPS satellites with the accuracy required to precisely measure the range.
- Rx coordinates are (Ux, Uy, Uz)
- Satellite coordinates (Xi, Yi, Zi), where i=1,2,3,4.
- Pseudorange Pri
- Pri = T * c
- The distance R between two points A & B in rectangular coordinate system is

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

The equations which relate psuedorange to time delay → Ranging equations

$$(X_1 - U_x)^2 + (Y_1 - U_y)^2 + (Z_1 - U_z)^2 = (PR_1 - \tau c)^2$$
$$(X_2 - U_x)^2 + (Y_2 - U_y)^2 + (Z_2 - U_z)^2 = (PR_2 - \tau c)^2$$
$$(X_3 - U_x)^2 + (Y_3 - U_y)^2 + (Z_3 - U_z)^2 = (PR_3 - \tau c)^2$$
$$(X_4 - U_x)^2 + (Y_4 - U_y)^2 + (Z_4 - U_z)^2 = (PR_4 - \tau c)^2$$

- Accuracy for low cost GPS Rx using C/A code is 30 m defined as 2DRMS. (DRMS -> Distance Root Mean Square error of the measures position relative to the true position of Rx)
- If measurement errors are Gaussian distributed -> 68% of measured position results in 1DRMS from the true location.
- 95% of results in 2DRMS of the true location.
- Selective Availability (SA) -> Switched off on May 1, 2000 -> accuracy from 200 m to 10 m.

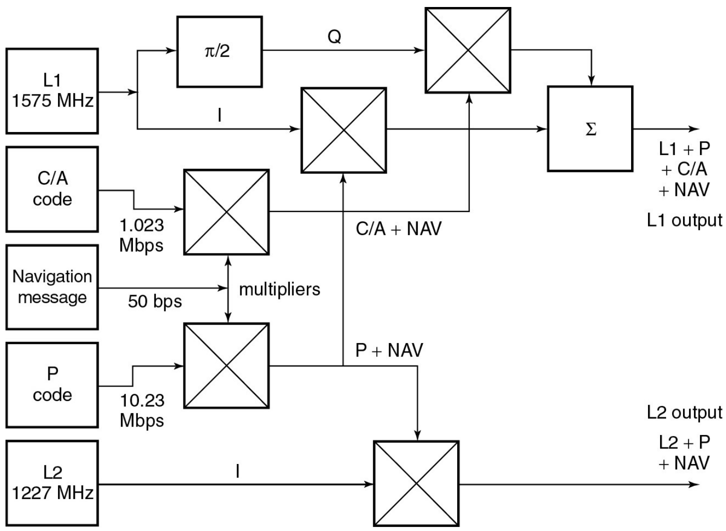
GPS Time

- GPS Rx use highly stable crystal oscillators
- GPS satellite consists of two cesium clocks plus two rubidium clocks (atomic clocks).
- An atomic clock uses the fundamental resonance of the cesium or rubidium molecule as a frequency reference to lock a crystal oscillator.
- In GPS satellites -> master oscillator is at 10.23 MHz
- The atomic clocks are updated by controlling ground stations to keep them within 1 us of Universal Time Coordinated (UTC) (UTC = GMT)

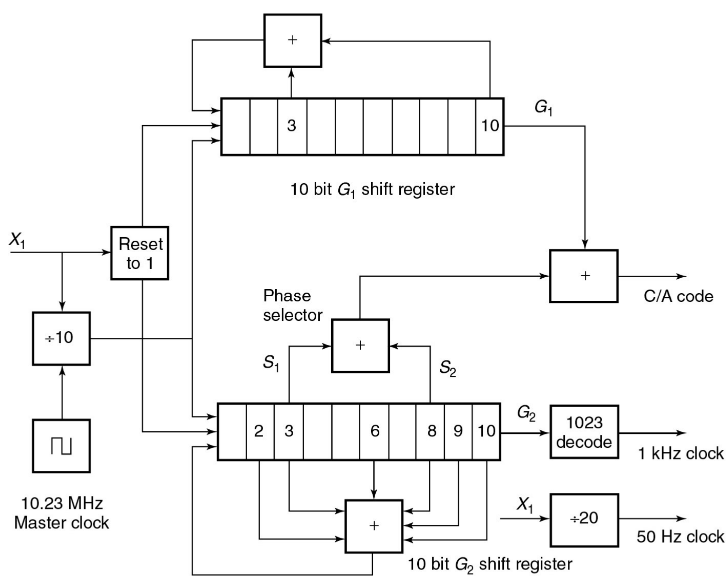
GPS Receivers and Codes

- GPS satellite transmit using pseudorandom sequence (PN) codes.
- All satellite Tx **C/A code** at same frequency -> 1575.42 MHz (L1) (154*10.23 MHz)
- Modulation used is BPSK.
- L1 frequency is 154 times the master clock frequency of 10.23 MHz.
- C/A code has clock rate of 1.023 MHz and has 1023 bits so the PN sequence lasts for 1 ms.
- **P Code** Tx using BPSK modulation at L2carrier frequency 1227.6 MHz (120*10.23 MHz) and is also Tx with BPSK modulation on L1 carrier frequency, in phase quadrature with C/A code BPSK modulation.

Signal generation in GPS satellite



C/A Code Generator

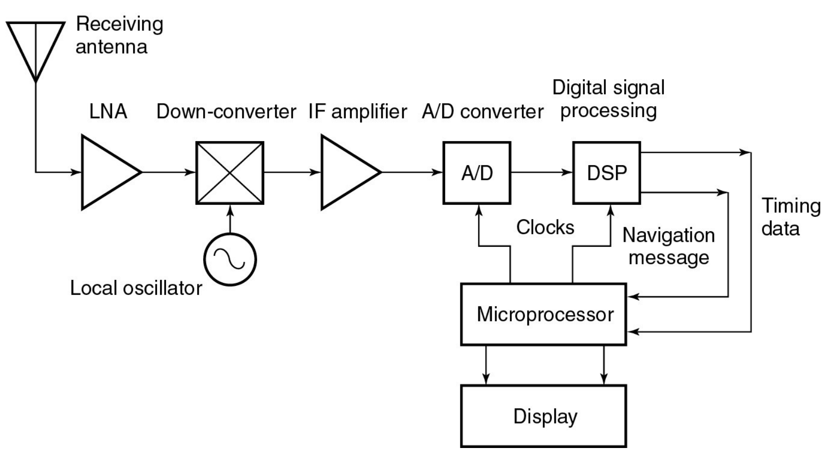


Satellite ID Number	GPS PRN Signal Number	Code Phase Selection	Code Delay Chips	First 10 Chips C/A Octal
1	1	$2 \oplus 6$	5	1440
2	2	$3 \oplus 7$	6	1620
3	3	$4 \oplus 8$	7	1710
4	4	$5 \oplus 9$	8	1744
5	5	$1 \oplus 9$	17	1133
6	6	$2 \oplus 10$	18	1455
7	7	$1 \oplus 8$	139	1131
8	8	$2 \oplus 9$	140	1454
9	9	$3 \oplus 10$	141	1626
10	10	$2 \oplus 3$	251	1504
11	11	$3 \oplus 4$	252	1642
12	12	$5 \oplus 6$	254	1750
13	13	$6 \oplus 7$	255	1764
14	14	$7 \oplus 8$	256	1772
15	15	$8 \oplus 9$	257	1775
16	16	$9 \oplus 10$	258	1776
17	17	$1 \oplus 4$	469	1156
18	18	$2 \oplus 5$	470	1467
19	19	$3 \oplus 6$	471	1633
20	20	$4 \oplus 7$	472	1715
21	21	$5 \oplus 8$	473	1746
22	22	$6 \oplus 9$	474	1763
23	23	$1 \oplus 3$	509	1063
24	24	$4 \oplus 6$	512	1706
25	25	$5 \oplus 7$	513	1743
26	26	$6 \oplus 8$	514	1761
27	27	$7 \oplus 9$	515	1770
28	28	$8 \oplus 10$	516	1774
29	29	$1 \oplus 6$	859	1127
30	30	$2 \oplus 7$	860	1453
31	31	$3 \oplus 8$	861	1625
32	32	$4 \oplus 9$	862	1712
**	33	$5 \oplus 10$	863	1745
**	34*	$4 \oplus 10$	950	1713
**	35	$1 \oplus 7$	947	1134
**	36	$2 \oplus 8$	948	1456
**	37*	$4 \oplus 10$	950	1713

*34 and 37 have the same C/A code.

**GPS satellites do not transmit these codes; they are reserved for other uses.

Simplified GPS Receiver



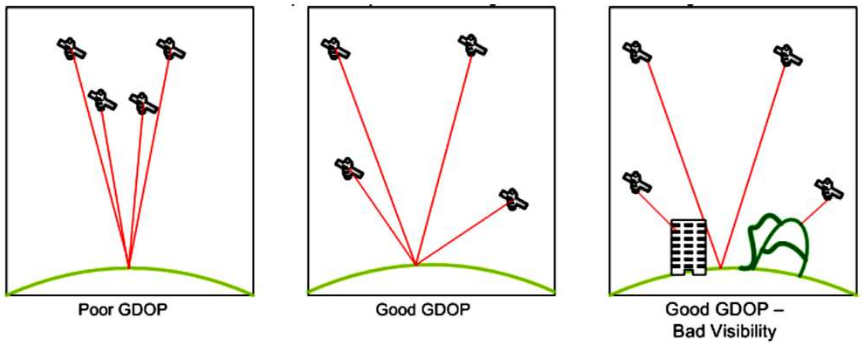
GPS C/A Code Accuracy

Range error for C/A code measurements (m)

Satellite clock error	3.5
Ephemeris errors	4.3
Selective availability	32.0
Ionospheric delay	6.4
Tropospheric delay	2.0
Receiver noise	2.4
Multipath	3.0
RMS range error	33.4 m with SA
[RMS range error	9.5 m without SA]

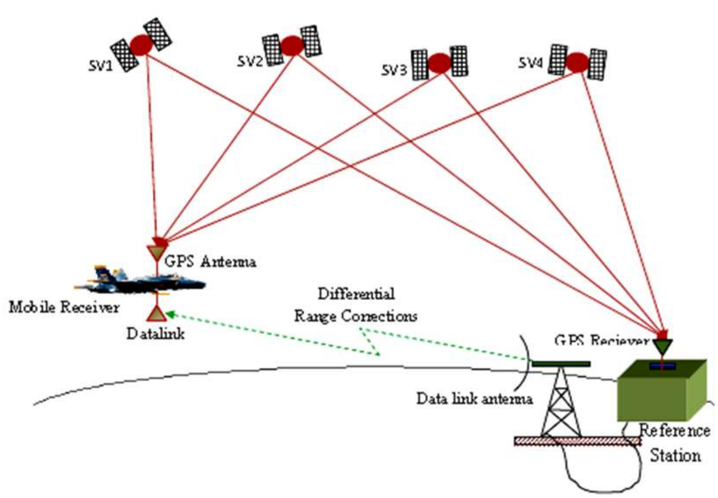
Dilution of Precision (DOP)

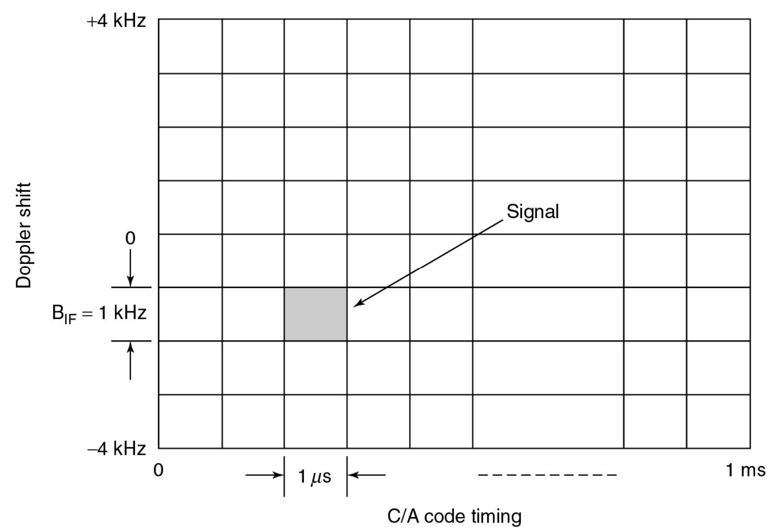
- Horizontal DOP (HDOP) -> most important DOP factors. It provides error metric in x and y directions.
- HDOP -> 1.5 (typical value)
- Horizontal measurement error for a C/A code Rx -> 14.3 m with SA off. 50 m with SA on. (Both values are in 1DRMS)
- 2DRMS accuracy of 28.6 m with SA off.



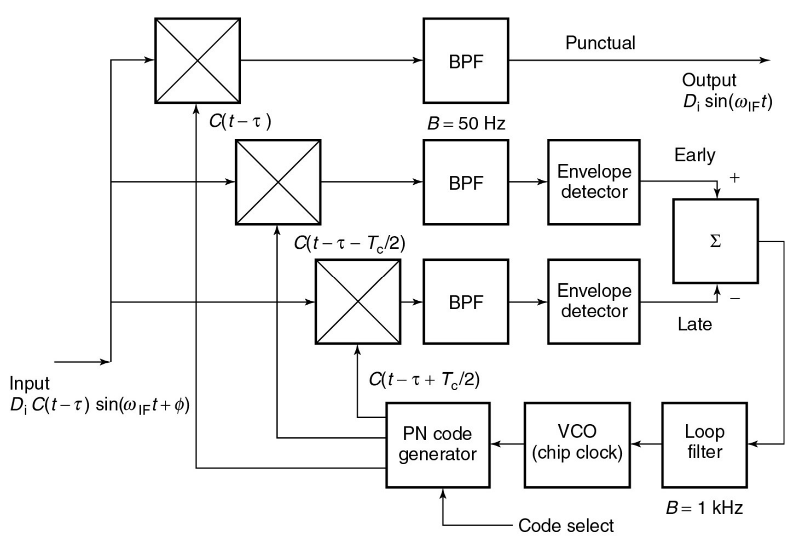
GDOP : Geometrical Dilution of Precision, (measure of accuracy in 3-D position and time)
PDOP : Position Dilution of Precision (measure of accuracy in 3-D position), also called spherical DOP
HDOP : Horizontal Dilution of Precision (measure of accuracy in 2D position, for example Latitude and Longitude)
VDOP : Vertical Dilution of Precision (measure of accuracy in 1D position, Height)
TDOP : Time Dilution of Precision (measure of accuracy in Time)

Differential GPS

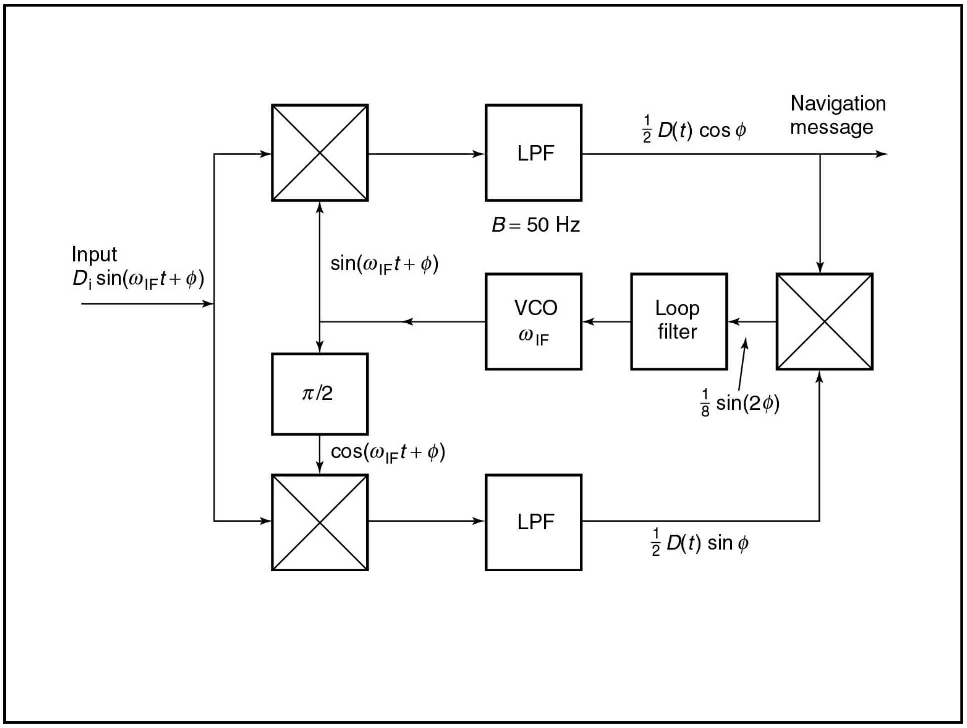




+4 kHz
Doppler shift
0
B_{IF} = 1 kHz
–4 kHz
Signal
0
1 μs
1 ms
C/A code timing



BPF
Punctual
Output
$D_i \sin(\omega_{IF} t)$
$C(t-\tau)$
$B = 50$ Hz
BPF
Envelope detector
Early
+
Σ
$C(t-\tau-T_c/2)$
BPF
Envelope detector
–
Late
Input
$D_i C(t-\tau) \sin(\omega_{IF} t+\phi)$
$C(t-\tau+T_c/2)$
PN code generator
VCO (chip clock)
Loop filter
$B = 1$ kHz
Code select


Input
$D_i \sin(\omega_{IF} t + \phi)$
LPF
$B = 50$ Hz
$\frac{1}{2} D(t) \cos\phi$
Navigation message
$\sin(\omega_{IF} t + \phi)$
VCO
ω_{IF}
Loop filter
$\frac{1}{8} \sin(2\phi)$
$\pi/2$
$\cos(\omega_{IF} t + \phi)$
LPF
$\frac{1}{2} D(t) \sin\phi$