SATELLITE COMMUNICATIONS AND GPS

MODULE 4

Module 4

Module 4:

Introduction and Fundamentals of Satellite Navigation:

Introduction, Condensed GPS Program History, GPS Overview, PPS, SPS, Concept of Ranging Using TOA Measurements, Reference Coordinate Systems: Earth-Centered Earth-Fixed Coordinate System, Position Determination Using PRN Code, GPS Satellite Constellation Description, User Receiver, Navigation Message Format, Modernized GPS Signals.

(Text Book 2)

Contd.

Navigation: Defined as art or science of plotting , ascertaining, or directing the course of movements. Knowing where the satellite is and being able to find the way around. Common saying wandering.

*Wandering at college in the initial days.

*Celestial navigation – direction and distance determined from precisely timed sighting of celestial bodies (satellite) including stars, moon. Primitive technique used over several thousands of years. Disadvantage is it works best during nights in clear sky.

Piloting- another term for navigation. Fixing a position and direction wrt familiar significant landmarks- word derived from early aircraft pilots using this navigation.

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Approximately over 100 domestic radio navigation systems currently in use. Some using terrestrial (land based), some use satellite based (space) broadcast transmitters. Most useful and accurate systems:

Decca (terrestrial surface broadcast)

Omega (terrestrial surface broadcast providing global coverage)

Loran (terrestrial surface broadcasting)- most used today

Navy Transit GPS (low- orbit satellite broadcast providing global coverage)

Navstar GPS (medium- orbit satellite broadcast providing global coverage)- most used today.

Contd.

Long Range Navigation- Loran- most effective , reliable, and accurate radio navigation technique. Developed during world war II. Most recent version Loran C, currently for recreational aircraft and ships.

PPS(Precise Positioning Signal)

The PPS is specified to provide a predictable accuracy of

- at least 22m (2 drms, 95%) in the horizontal plane
- 27.7m (95%) in the vertical plane. Accurate military positioning, velocity and timing service available on a continuous worldwide basis to users authorized by DoD.

The distance root mean square (drms) is a common measure used in navigation.

Twice the drms value, or 2 drms, is the radius of a circle that contains at least 95% of all possible fixes that can be obtained with a system (in this case, the PPS) at any one place.

The PPS also provides

- a UTC time transfer accuracy within 200 ns (95%) referenced to the time kept at the U.S. Naval Observatory (USNO) and is denoted as UTC (USNO) .For authorized users only with cryptography.
- Velocity measurement accuracy is specified as 0.2 m/s (95%)

Contd.

SPS (Standard Positioning Service)

The SPS is available to all GPS users worldwide free of direct charges. There are no restrictions on SPS usage. This service is specified to provide accuracies of better than 13m (95%) in the horizontal plane and 22m (95%) in the vertical plane (global average; signal-in-space errors only). Precise positioning and timing. For military, private and commercial

UTC Universal Transverse Mercator Grid (USNO) time dissemination accuracy is specified to be better than 40 ns (95%). For security reasons, accuracy of SPS service is intentionally degraded during national emergencies using selective availability technique, manipulating navigation message orbit data (epsilon) and /or satellite frequency (dither).

SPS measured performance is typically much better than specification.

At the time of this writing, the SPS was the predominant satellite navigation service in use by millions throughout the world.

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Antispoofing (AS) and Selective availability (SA)

The PPS is primarily intended for military and selected government agency users.

Civilian use is permitted, but only with special U.S. DOD approval.

Access to the aforementioned PPS position accuracies is controlled through two cryptographic features denoted as

Antispoofing (AS) and Selective availability (SA).

Antispoofing (AS)

AS is a mechanism intended to defeat deception jamming through encryption of the military signals. Deception jamming is a technique in which an adversary would replicate one or more of the satellite ranging codes, navigation data signal(s), and carrier frequency Doppler effects with the intent of deceiving a victim receiver.

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Selective availability (SA)

SA had intentionally degraded SPS user accuracy by *dithering* the satellite's clock, thereby corrupting TOA measurement accuracy. Furthermore, SA could have introduced errors into the broadcast navigation data parameters. SA was discontinued on May 1, 2000 and per current U.S. government policy is to remain off. When it was activated, PPS users removed SA effects through cryptography

In terrestrial surveying only 3 such markers are needed to determine 3 unknowns latitude, longitude and altitude by means of triangulation. With GPS system time co-ordinator is also needed, necessitating getting simultaneous measurements from four satellites.

GPS system uses one way transmissions- satellite to users. User has no transmitter but only receiver, the only quantity it measures is time, propagation delay from this and hence range to each satellite can be determined.

Each satellite broadcasts its ephemeris (table of orbital elements) from this position can be calculated. Knowing the range to 3 of these satellites, and their positions, position of observer (user) can be found. GPS system uses geocentric equatorial co-ordinate system.

Contd.

Here it is called earth centered- earth fixed co-ordinate system (ECEF) co-ordinate system.

Let for a satellite n co-ordinates are (x_n, y_n, z_n) and for the observer (x_o,y_o,z_o), the range from observer to satellite ρ_{on} is

ρ_{on}^2= (xn-xo)^2 + (yn-yo)^2 + (zn-zo)^2

The three unknowns are (x_o,y_o,z_o), only 3 equations (for n=1,2and 3) are needed in theory. Knowing positions of 3 satellites and measured range to each, position of observer relative to the co-ordinate system can be measured.

Satellites are moving, their positions must be accurately tracked.

In practice measurements for 4 satellites must be made (n from 1 to 4).

Contd.

By measuring propagation times and knowing speed of propagation, second needed time markers indicate when transmissions leave satellite. User stations do not have no direct knowledge of when transmissions started from satellite.

A continuous wave carrier is transmitted by satellite modulated by pseudo random code, timing for carrier and pseudo code being derived from atomic clock on satellite.

At user station receiver generates a replica of modulated signal from its own (non atomic) clock and this is correlated with the received signal in a correlator. A delay is introduced into the replica signal path and is adjusted until the two signals show maximum correlation If the receiver clock started exactly when satellite clock started delay in replica path= propagation delay. But there is a unknown delay between starting of two clocks . Let tn is true propagation time from satellite n to observer and tdn correlator measured delay, Δt is unknown delay between start of two clocks , tn= tdn-Δt, (Δt can be + or -) .

Contd.

Satellite clock is synchronized to master atomic clock, so that Δt is same for all satellites. Range to satellite n is

$\rho on = ctn = c(tdn - \Delta t)$,   c is speed of light

$\rho on\text{^}2 = (xn-xo)\text{^}2 + (yn-yo)\text{^}2 + (zn-zo)\text{^}2 - c\text{^}2\ (tdn-\Delta t)\text{^}2$

Here, location coordinates (xo, yo, zo) and Δt are unknown.

Contd.

Satellite orbits are predicted from orbital parameters and are continually updated by a master control station that transmits them upto the satellites. They are broadcast as part of navigational message from each satellite.

Using reference points well separated in space better accuracy results. Ex: range measured to three reference points clustered together will yield almost equal values.

GPS constellation has 24 satellites in 6 near circular orbits at a heght of ~ 20000km. Ascending nodes of orbits are separated by 60deg and inclination of each orbit is 55deg. As position calculation involves range differences, and when ranges are nearly equal any error is greatly magnified in the difference.

Contd.

This effect due to satellite geometry called *dilution of precision (DOP).* Other causes such as timing errors are magnified by geometric effect.

In GPS a factor *position dilution of precision (PDOP) factor* takes into account dilution of position . By this factor range errors are multiplied to get position error. GPS system is designed to keep PDOP factor <6 most of the time.

Four satellites in each orbit are irregularly spaced to keep PDOP factor within limits <6.

Concept of Ranging By TOA Measurement

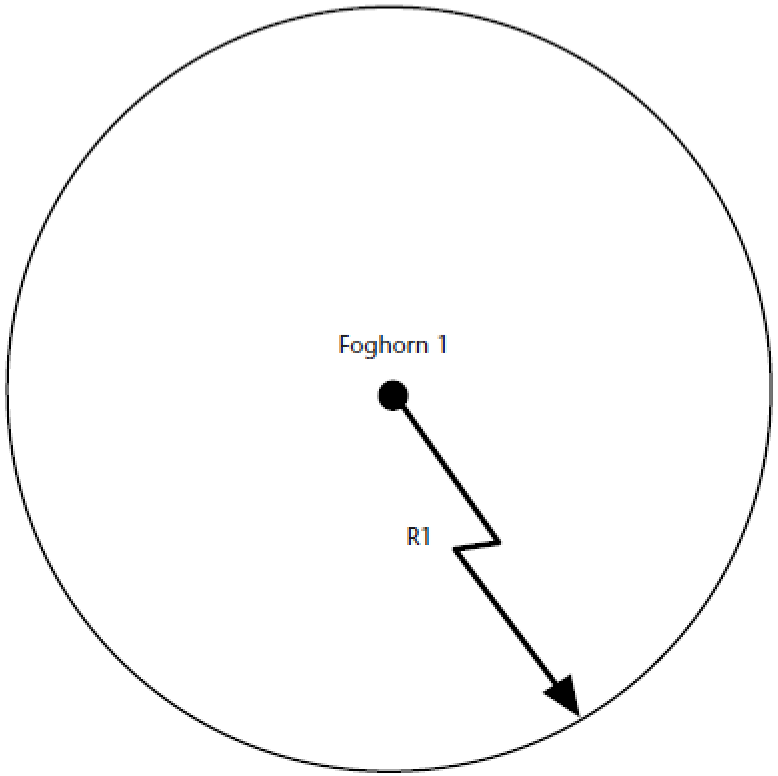

Figure 2.1 Range determination from a single source. (*After:* [1].)

Contd.

In TOA , time of arrival measurement time taken by transmitted signal by an emitter (eg. Foghorn, radio beacon , satellite) at a known location to reach a user receiver- signal propagation time Δt is measured.

This multiplied by speed of signal, sound or electromagnetic wave gives the distance between emitter and receiver. If signal is broadcast from multiple emitters (navigation aids) at known location, receiver can determine its position.

Two Dimensional Position Determination

A mariner in sea determines his vessel's position from a foghorn. Foghorn whistle is given exactly at one minute interval. Vessel's clock is synchronized with foghorn clock. Mariner notes the elapsed time from the minute mark until the foghorn whistle is heard.

Contd.

Propagation time is difference between the time whistle left foghorn to and the time it is heard by mariner. This time is multiplied by speed of sound (335m/s) to get distance from foghorn to mariner. From fig.2.1, if R1 is the distance , with only one measurement, the mariner finds the distance.

By using second foghorn and simultaneous measurement of range from it the same way, R1 is range from first foghorn and R2 is the range from second foghorn as in fig.2.2. Foghorns are synchronized to a common time base, mariner has knowledge of both foghorn whistles transmission times.

R1 and R2 are ranges causing ambiguity in range circles. Using 3rd foghorn, the ambiguity can be removed fig.2.3.

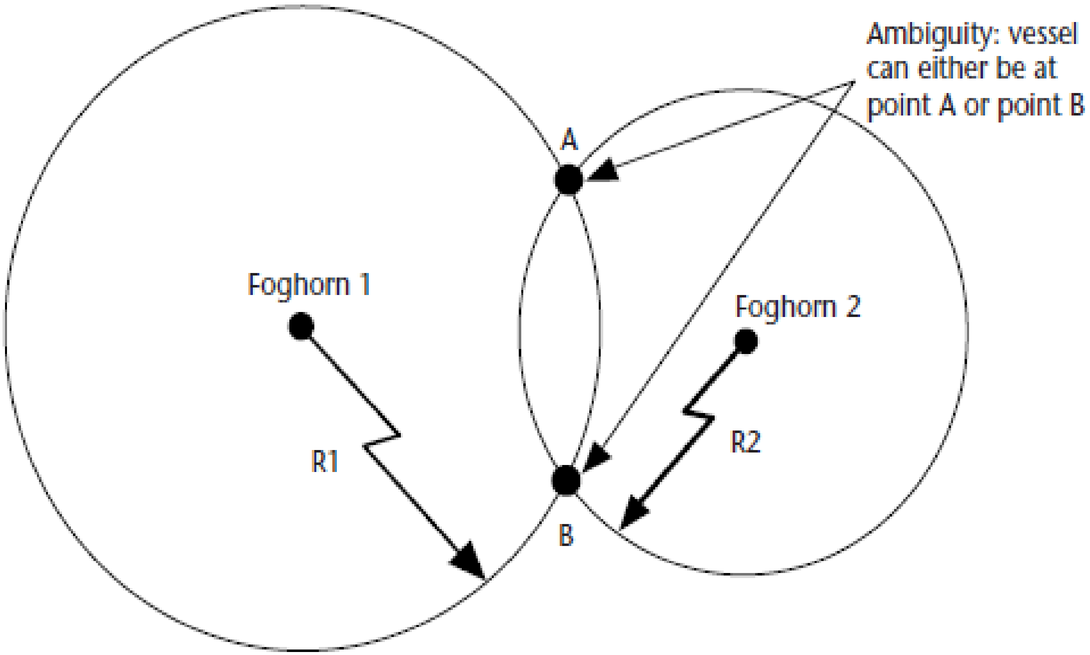

Figure 2.2 Ambiguity resulting from measurements to two sources. (*After:* [1].)

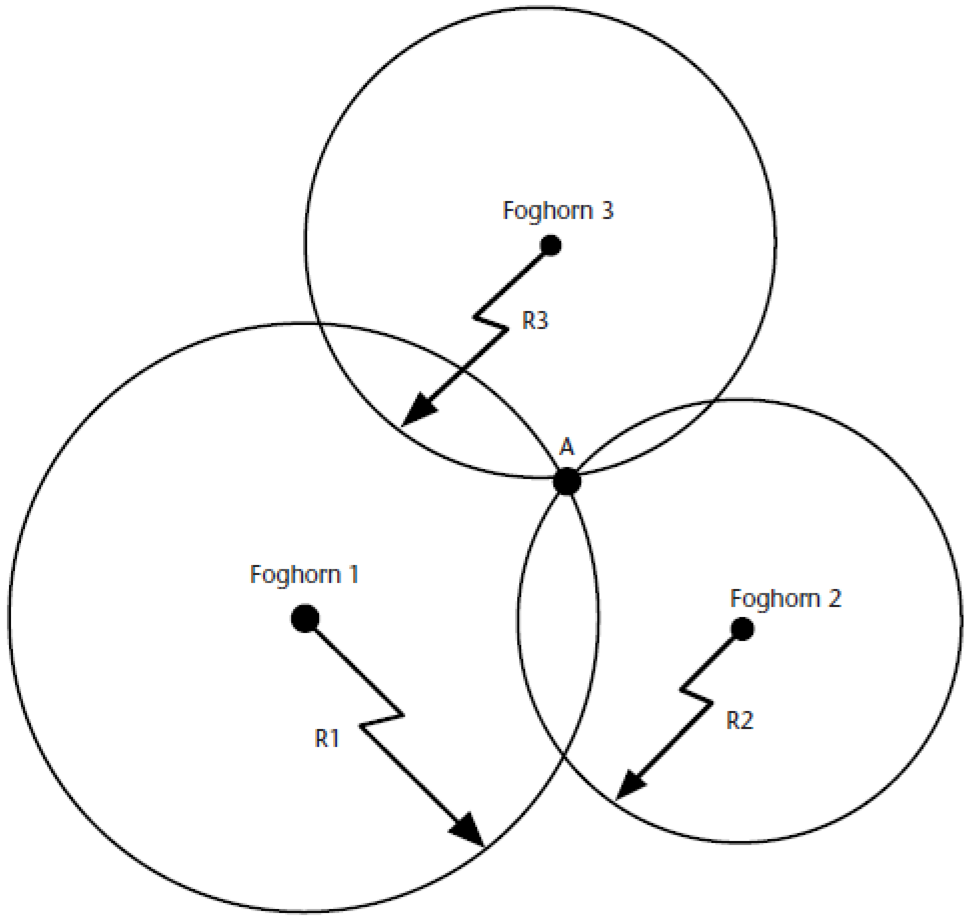

Figure 2.3 Position ambiguity removal by additional measurement. (*After:* [1].)

Contd.

Common Clock Offset Compensation:

The above assumes that vessel's clock is precisely synchronized with foghorn time base. Not the case always. If vessel's clock is advanced wrt foghorn time base by 1s. Vessel's clock believes that minute mark occurs 1s earlier. Propagation intervals measured by mariner by 1s larger due to offset. Timing offsets are same for each measurement. Timing error equates to range error of 335m (ε), fig.2.4.

C,D and E are offset from true position of vessel at A due to clock offset. If offset is removed then position A can be located.

Due to atmospheric effects TOA measurements cannot be accurate. Clock offset is common to all measurements but these errors are independent. Inaccurate distance computations each time.

Fig.2.5 shows this effect. Errors are $\varepsilon 1, \varepsilon 2, \varepsilon 3$ in the range measurement, even with foghorn time base and mariner clock are synchronized. Error is within a triangular error space.

Principle of Position Determination via Satellite- Generated Ranging Signals:

GPS employs TOA ranging for user position determination. Making TOA measurement to multiple satellites 3D positioning is achieved. Similar to foghorn example but the speed of light is that of light ~3x10^8m/s. Assumes satellite ephemerides are accurate (satellite positions are accurately known).

If a single satellite is transmitting ranging signals, with clock onboard.

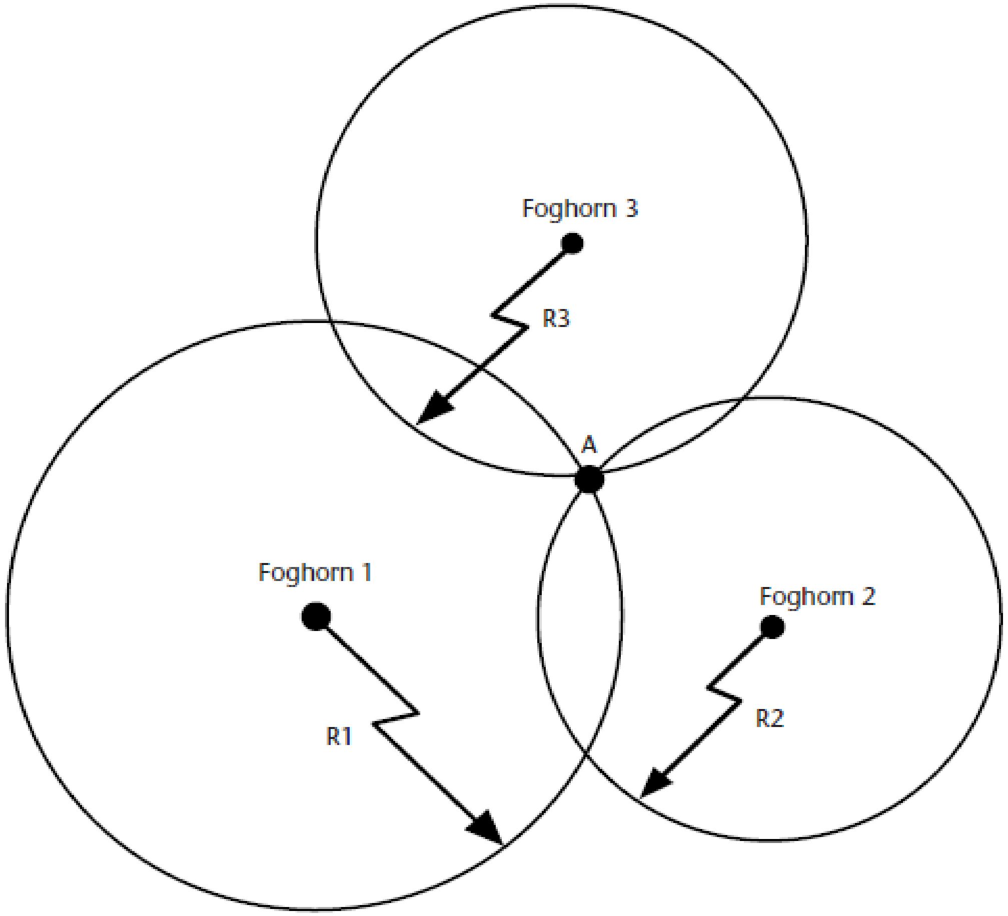

Figure 2.3 Position ambiguity removal by additional measurement. (*After:* [1].)

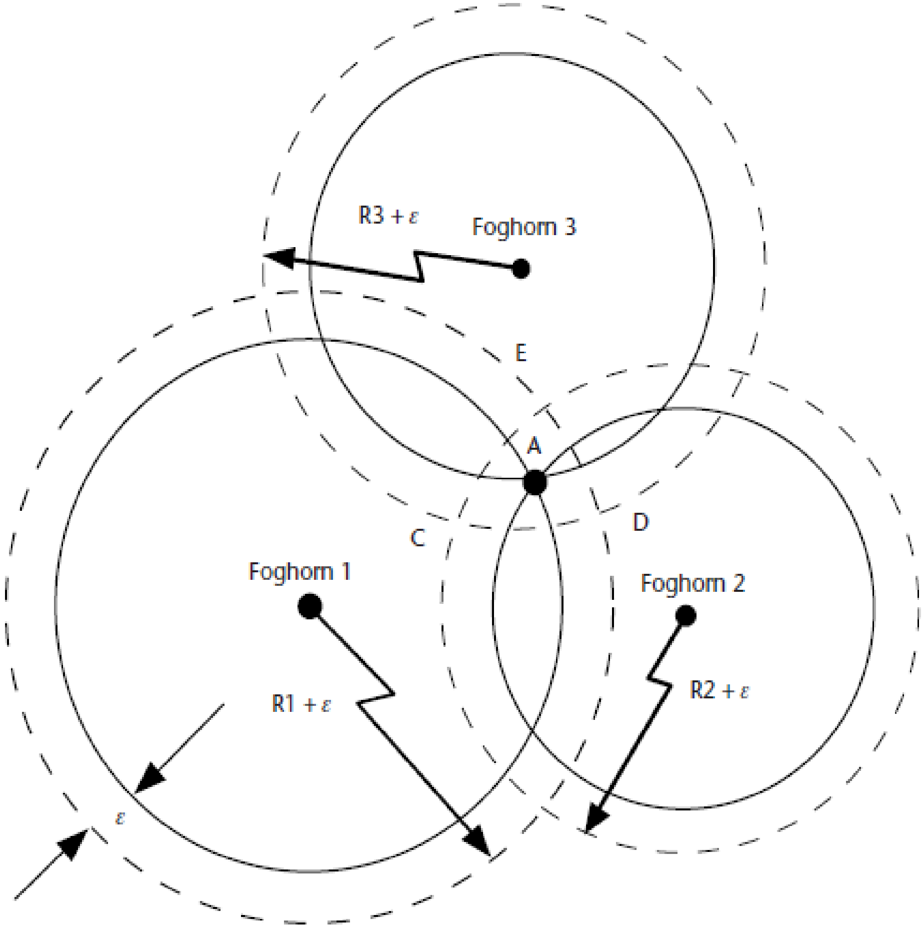

Figure 2.4 Effect of receiver clock offset on TOA measurements. (*After:* [1].)

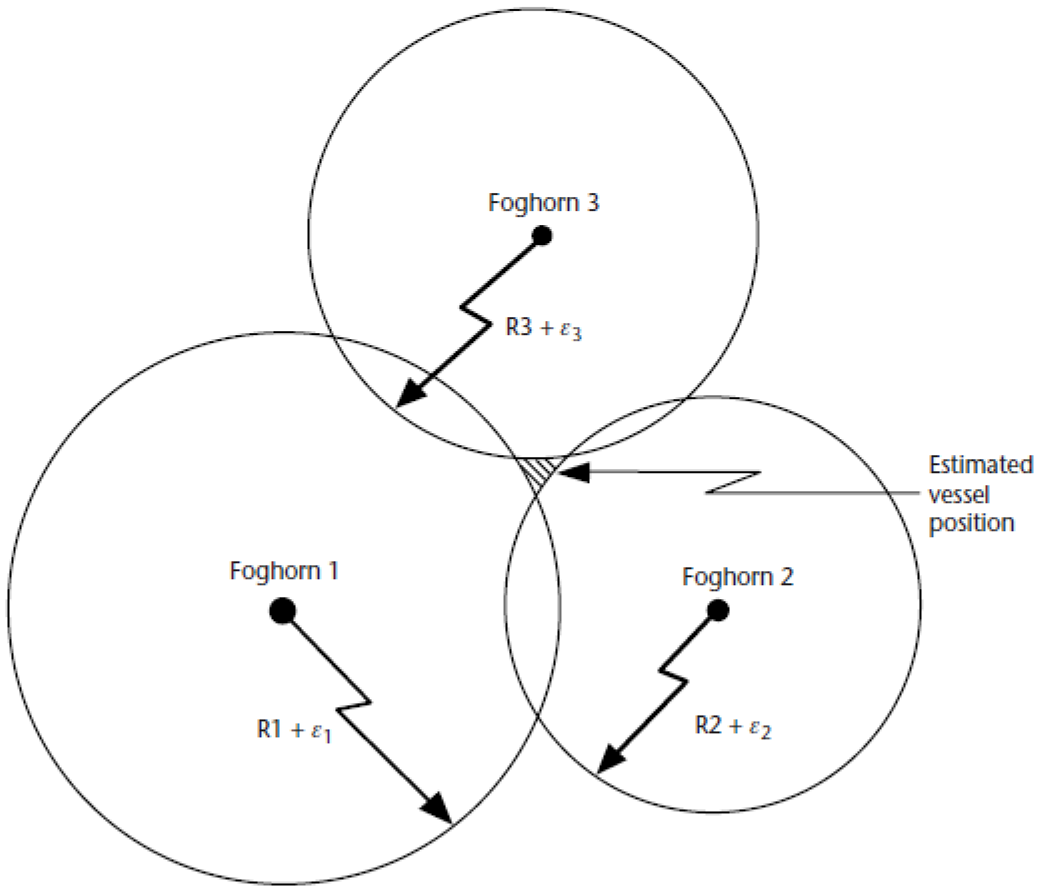

Figure 2.5 Effect of independent measurement errors on position certainty.

Contd.

Principle of Position Determination Satellite-Generated Ranging Signals

GPS employs TOA ranging for user position determination. By making TOA measurements to multiple satellites, three-dimensional positioning is achieved.

Satellite ranging signals travel at the speed of light, which is approximately 3 × 10^8 m/s. It is assumed that the satellite ephemerides are accurate (i.e., the satellite locations are accurately known).

Contd.

A clock onboard the satellite controls timing of ranging signals on broadcast. This clock and clocks onboard other satellites in the constellation are synchronized with system clock (GPS system time). User receiver also has a clock which must be synchronized to system time. Timing information is embedded in the satellite ranging signal enabling the satellite to calculate when the signal left satellite.

Knowing when the signal left from satellite and signal received at receiver, propagation time can be calculated. Propagation time X speed of light gives satellite to user range R.

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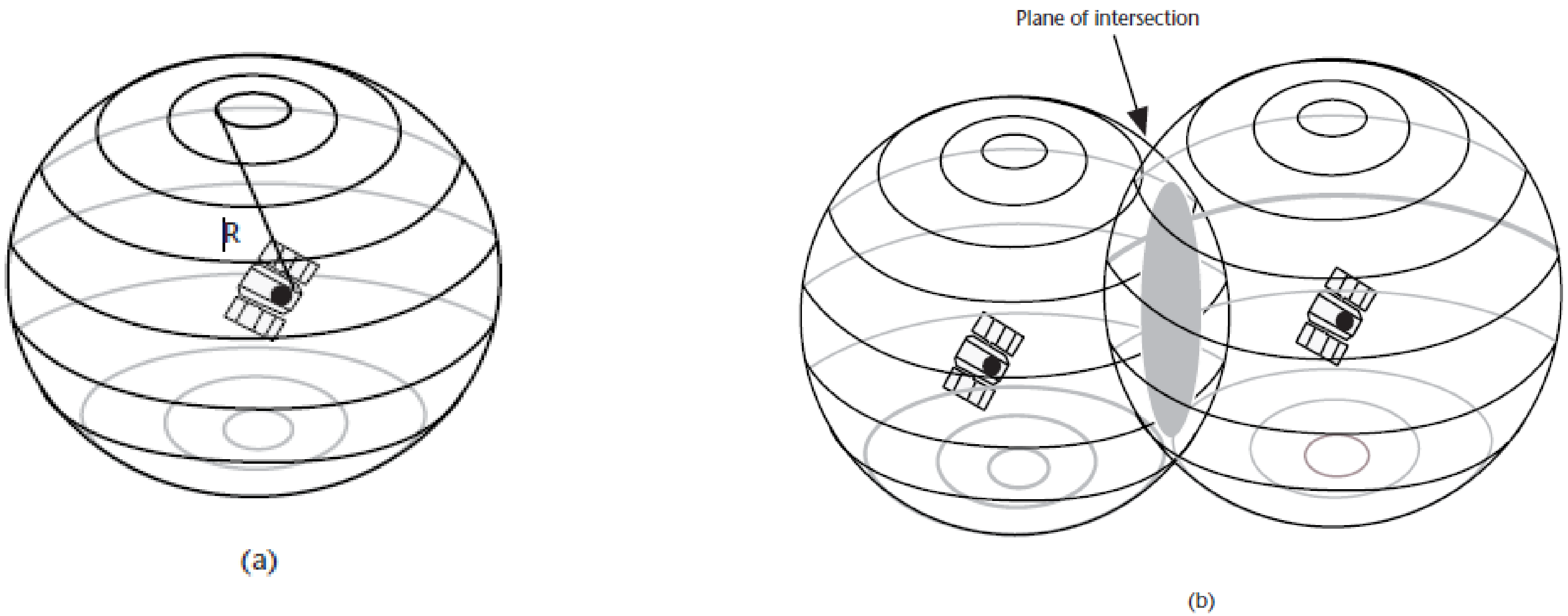

Figure 2.6 (a) User located on surface of sphere. (b) User located on perimeter of shaded circle. (*Source:* [2]. Reprinted with permission.) (c) Plane of intersection. (d) User located at one of two points on shaded circle. (*Source:* [2]. Reprinted with permission.) (e) User located at one of two points on circle perimeter.

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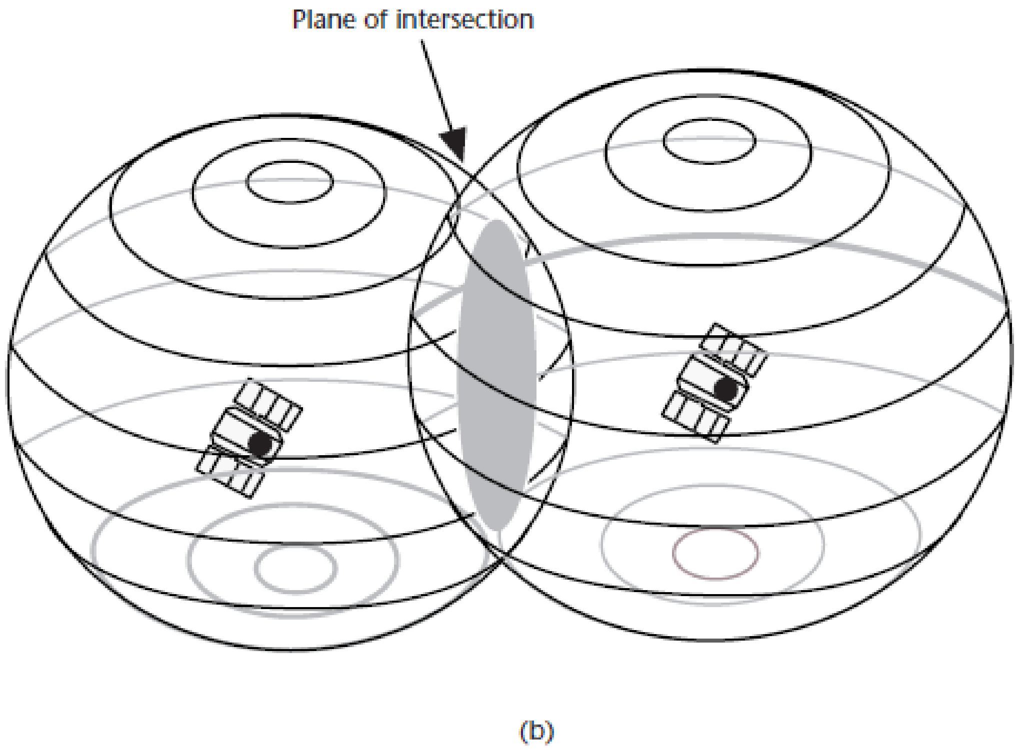

Figure 2.6 (a) User located on surface of sphere. (b) User located on perimeter of shaded circle. (*Source:* [2]. Reprinted with permission.) (c) Plane of intersection. (d) User located at one of two points on shaded circle. (*Source:* [2]. Reprinted with permission.) (e) User located at one of two points on circle perimeter.

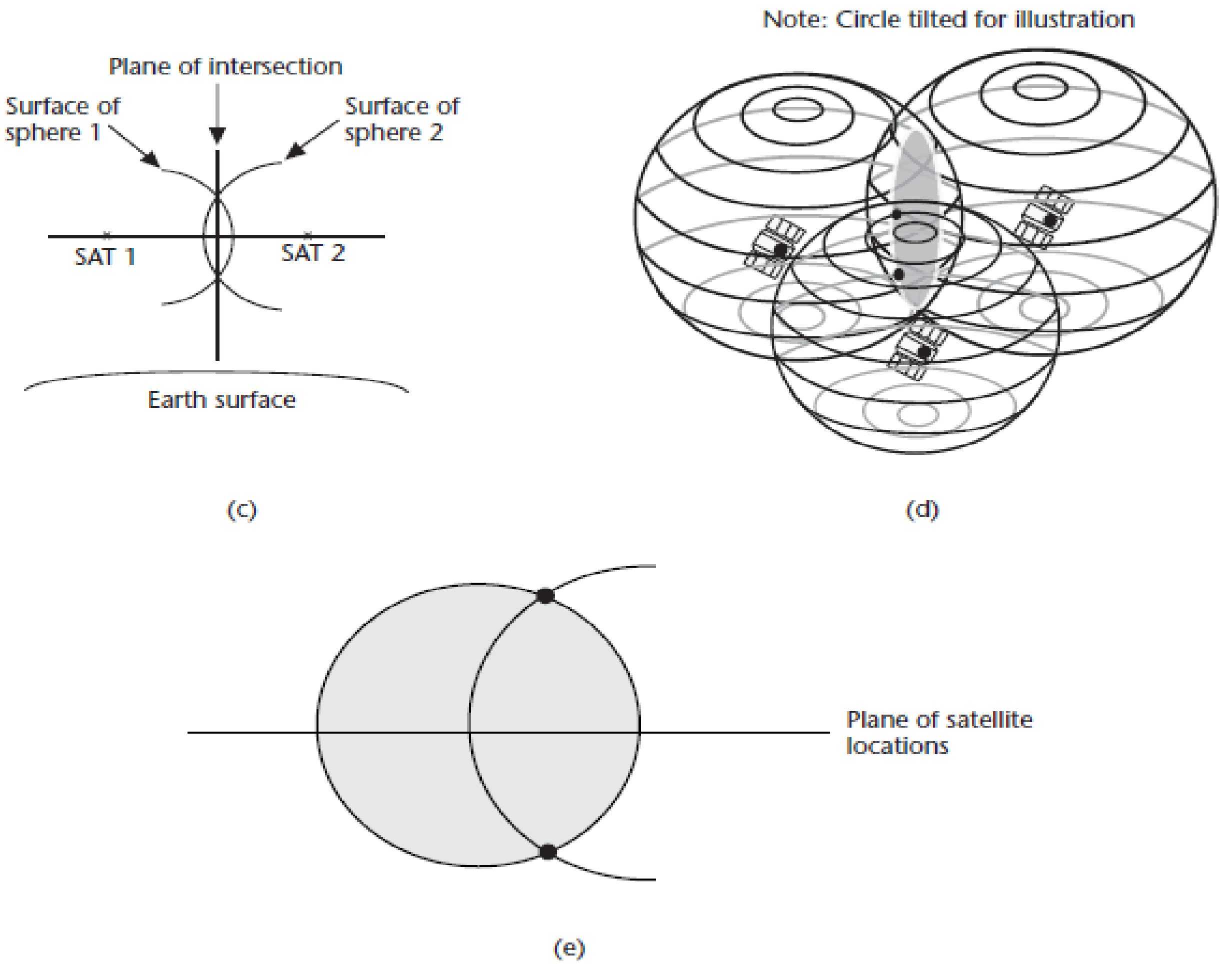

Figure 2.6 (continued.)

PPS(Precise Positioning Signal)

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- 27.7m (95%) in the vertical plane.

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Twice the drms value, or 2 drms, is the radius of a circle that contains at least 95% of all possible fixes that can be obtained with a system (in this case, the PPS) at any one place.

The PPS also provides

- a UTC time transfer accuracy within 200 ns (95%) referenced to the time kept at the U.S. Naval Observatory (USNO) and is denoted as UTC (USNO)
- Velocity measurement accuracy is specified as 0.2 m/s (95%)

Contd.

Reference Coordinate Systems

To formulate the mathematics of the satellite navigation problem, it is necessary to choose a reference coordinate system in which the states of both the satellite and the receiver can be represented. In this formulation, it is typical to describe satellite and receiver states in terms of position and velocity vectors measured in a Cartesian coordinate system.

Two principal Cartesian coordinate systems are

- Inertial Systems
- Rotating Systems.

An overview of the coordinate systems used for GPS.

- Earth-Centered Inertial Coordinate System
- Earth-Centered Earth-Fixed Coordinate System

Earth-Centered Inertial Coordinate System

- For the purposes of measuring and determining the orbits of the GPS satellites, it is convenient to use an Earth-centered inertial (ECI) coordinate system
- In this system the origin is at the center of the mass of the Earth and whose axes are pointing in fixed directions with respect to the stars.
- A GPS satellite obeys Newton's laws of motion and gravitation in an ECI coordinate system
- Determination and subsequent prediction of the GPS satellite orbits are carried out in an ECI coordinate system.

- In typical ECI coordinate systems,
  - the *xy*-plane is taken to coincide with the Earth's equatorial plane,
  - the +*x*-axis is permanently fixed in a particular direction relative to the celestial sphere,
  - the +*z*-axis is taken normal to the *xy*-plane in the direction of the north pole
  - the +*y*-axis is chosen so as to form a right-handed coordinate system.

Contd.

One subtlety in the definition of an ECI coordinate system arises due to irregularities in the Earth's motion.

The Earth's shape is oblate, and due largely to the gravitational pull of the Sun and the Moon on the Earth's equatorial bulge, the equatorial plane moves with respect to the celestial sphere.

Because the *x*-axis is defined relative to the celestial sphere and the *z*-axis is defined relative to the equatorial plane, the irregularities in the Earth's motion would cause the ECI frame as defined earlier not to be truly inertial.

The solution to this problem is to define the orientation of the axes at a particular instant in time, or *epoch*.

The GPS ECI coordinate system uses the orientation of the equatorial plane at 1200 hours UTC (USNO) on

January 1, 2000, denoted as the J2000 system.

the +*x*-axis is taken to point from the center of the mass of the Earth to the direction of vernal equinox,

the *y*- and *z*-axes are defined as described previously, all at the aforementioned epoch.

Since the orientation of the axes remains fixed, the ECI coordinate system defined in this way can be considered inertial for GPS purposes.

Earth-Centered Earth-Fixed Coordinate (ECEF) System Contd.

For the purpose of computing the position of a GPS receiver, it is more convenient to use a coordinate system that rotates with the Earth, known as an Earth-centered Earth-fixed (ECEF) system.

In such a coordinate system, it is easier to compute the latitude, longitude, and height parameters that the receiver displays.

As with the ECI coordinate system, the ECEF coordinate system used for GPS has its

xy-plane coincident with the Earth's equatorial plane.

However, in the ECEF system,

the +*x*-axis points in the direction of 0° longitude

Contd.

the +*y*-axis points in the direction of 90°E longitude.

the z-axis is chosen to be normal to the equatorial plane in the direction of the geographical

North Pole

The *x*-, *y*-, and *z*-axes therefore rotate with the Earth and no longer describe fixed directions in inertial space. In this ECEF system, (i.e., where the lines of longitude meet in the northern hemisphere), thereby completing the right-handed coordinate system.

Contd.

GPS orbit computation software includes the transformations between the ECI and the ECEF coordinate systems.

Such transformations are accomplished by the application of rotation matrices to the satellite position and velocity vectors in the ECI coordinate system.

(The broadcast orbit computation procedure described in [4] and in Section 2.3 generates satellite position and velocity in the ECEF frame.)

Precise orbits from numerous computation centers also express GPS position and velocity in ECEF.

Position Determination Using PRN Codes

- GPS satellite transmissions utilize direct sequence spread spectrum (DSSS) modulation

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- DSSS provides the structure for the transmission of ranging signals and essential navigation data, such as satellite ephemerides and satellite health.
- The ranging signals are PRN codes that binary phase shift key (BPSK) modulate the satellite carrier frequencies.
- These codes look like and have spectral properties similar to random binary sequences but are actually deterministic.
- A simple example of a short PRN code sequence is shown in Figure 2.14. These codes have a predictable pattern, which is periodic and can be replicated by a suitably equipped receiver.

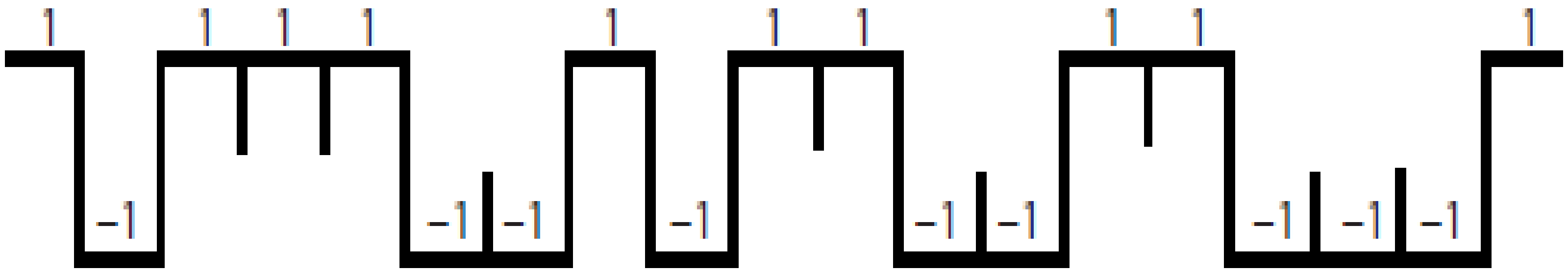

Figure 2.14 PRN ranging code.

- Each GPS satellite(at the time of this writing,) broadcasted two types of PRN ranging codes:
  - a “short” coarse/acquisition (C/A)-code
  - a “long” precision (P)-code.

  (Additional signals are planned to be broadcast. They are described in Chapter 4.)

- The C/A code has a 1-ms period and repeats constantly, whereas the P-code satellite transmission is a 7-day sequence that repeats approximately every Saturday/Sunday midnight.

Contd.

- Presently, the P-code is encrypted.

This encrypted code is denoted as the Y-code. The Y-code is accessible only to PPS users through cryptography. (Further details regarding PRN code properties, frequency generation, and associated modulation processes

are contained in Chapter 4.)

Determining Satellite-to-User Range

- We examined the theoretical aspects of using satellite ranging signals and multiple spheres to solve for user position in three dimensions.
- That example was predicated on the assumption that the receiver clock was perfectly synchronized to system time.
- actuality, this is generally not the case. Prior to solving for three-dimensional user position, we will examine the fundamental concepts involving satellite-to-user range determination with nonsynchronized clocks and PRN codes.

Contd.

- There are a number of error sources that affect range measurement accuracy (e.g., measurement noise and propagation delays) however, these can generally be considered negligible when compared to the errors experienced from nonsynchronized clocks.
- Therefore, in our development of basic concepts, errors other than clock offset are omitted.

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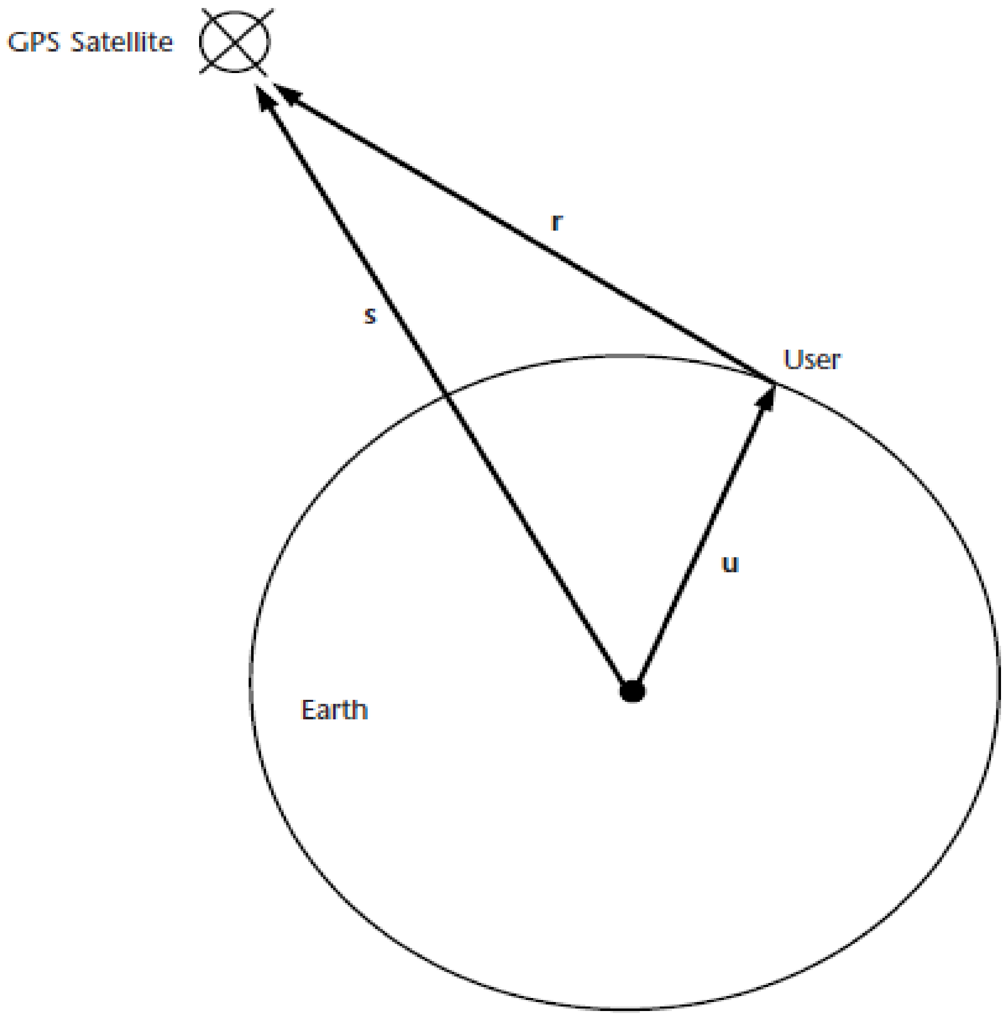

Figure 2.15 User position vector representation.

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- In Figure 2.15, we wish to determine vector **u**, which represents a user receiver's position with respect to the ECEF coordinate system origin.
- The user's position coordinates *xu, yu, zu* are considered unknown.
- Vector **r** represents the vector offset from the user to the satellite.
- The satellite is located at coordinates *xs, ys, zs* within the ECEF Cartesian coordinate system.
- Vector **s** represents the position of the satellite relative to the coordinate origin.

Contd.

- Vector **s** is computed using ephemeris data broadcast by the satellite.

- The satellite-to-user vector **r** is $\mathbf{r} = \mathbf{s} - \mathbf{u}$
- The magnitude of vector **r** is $r = \|\mathbf{s} - \mathbf{u}\|$

Let *r* represent the magnitude of **r**

$$r = \|\mathbf{s} - \mathbf{u}\|$$

Contd.

The distance *r* is computed by measuring the propagation time required for a satellite-generated ranging code to transit from the satellite to the user receiver antenna.

The propagation time measurement process is illustrated in Figure 2.16.

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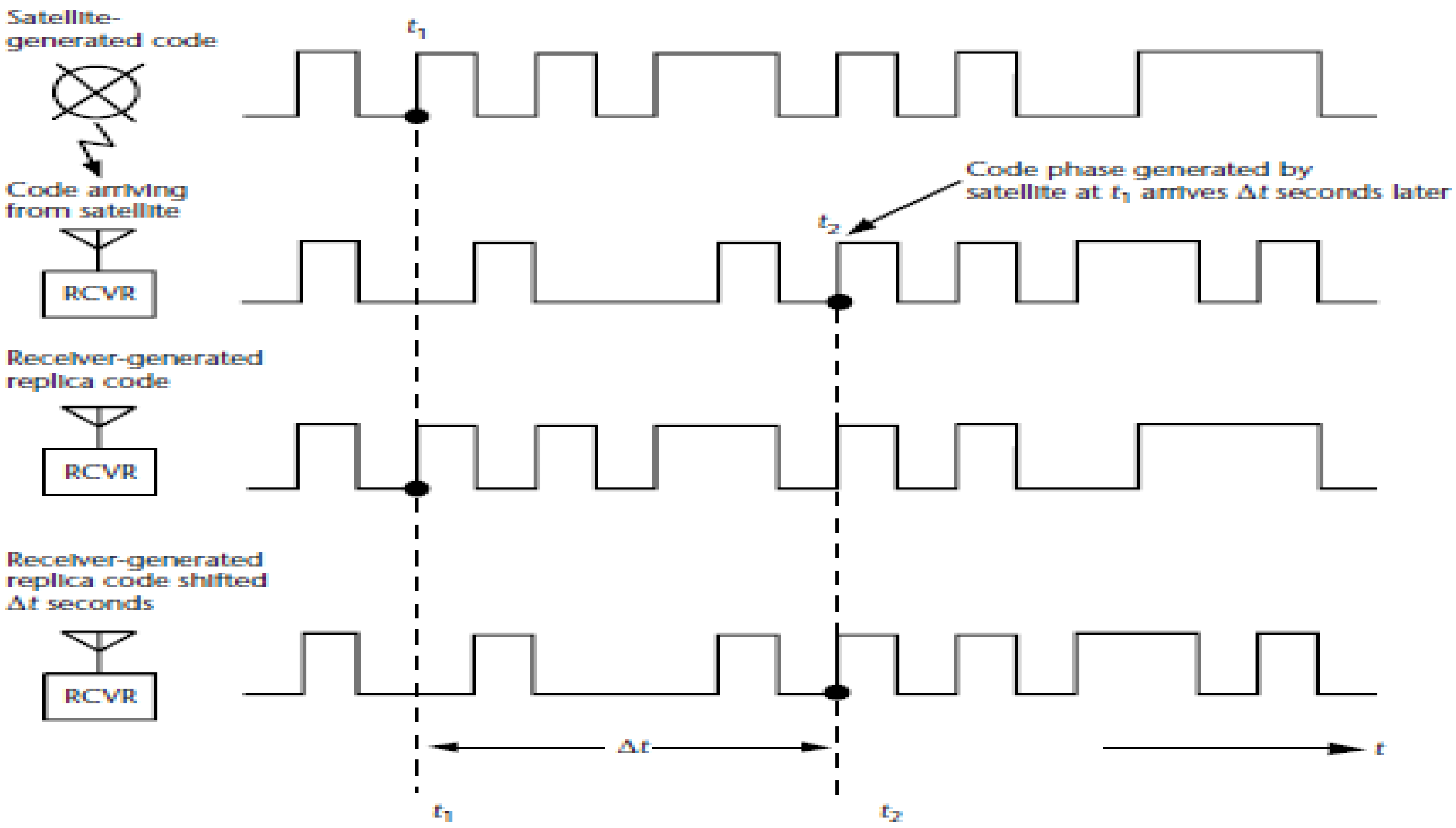

Figure 2.16 Use of replica code to determine satellite code transmission time.

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- As an example, a specific code phase generated by the satellite at t1 arrives at the

  receiver at t2.
- The propagation time is represented by Δt.
- Within the receiver, an identical coded ranging signal is generated at t, with respect to the receiver clock.
- This replica code is shifted in time until it achieves correlation with the received

  satellite-generated ranging code.
- If the satellite clock and the receiver clock were perfectly synchronized, the correlation process would yield the true propagation time.

Contd.

- By multiplying this propagation time, Δt, by the speed of light, the true (i.e., geometric) satellite-to-user distance can be computed.
- However, the satellite and receiver clocks are generally not synchronized. The receiver clock will generally have a bias error from system time.
- Further, satellite frequency generation and timing is based on a highly accurate free running cesium or rubidium atomic clock, which is typically offset from system time.

Contd.

- Thus, the range determined by the correlation process is denoted as the pseudorange . The measurement is called *pseudorange* because it is the range determined by multiplying the signal propagation velocity, ***c***, by the time difference between two

  non-synchronized clocks (the satellite clock and the receiver clock).

- The measurement contains

  (1) the geometric satellite-to-user range,

  (2) an offset attributed to the difference between system time and the user clock,

Contd.

(3) an offset between system time and the satellite clock.

- The timing relationships are shown in Figure 2.17, where:

  Ts = System time at which the signal left the satellite

  Tu = System time at which the signal reached the user receiver

  t = Offset of the satellite clock from system time

  [advance is positive; retardation (delay) is negative] *tu* = Offset of the receiver clock from system time

Ts + *t* = Satellite clock reading at the time that the signal left the satellite

Tu + *tu* = User receiver clock reading at the time the signal reached the user receiver

c = speed of light

Geometric range $r = c(Tu-Ts)= c\Delta t$

Pseudo range ρ- $c[(T_u+tu)- (Ts-\delta t)]= c(Tu-Ts)+c(tu-\delta t)$

$= r +c(tu-\delta t)$

Rewritten as ρ- $c[(t_u+\delta t)= ||\mathbf{s}-\mathbf{u}||$

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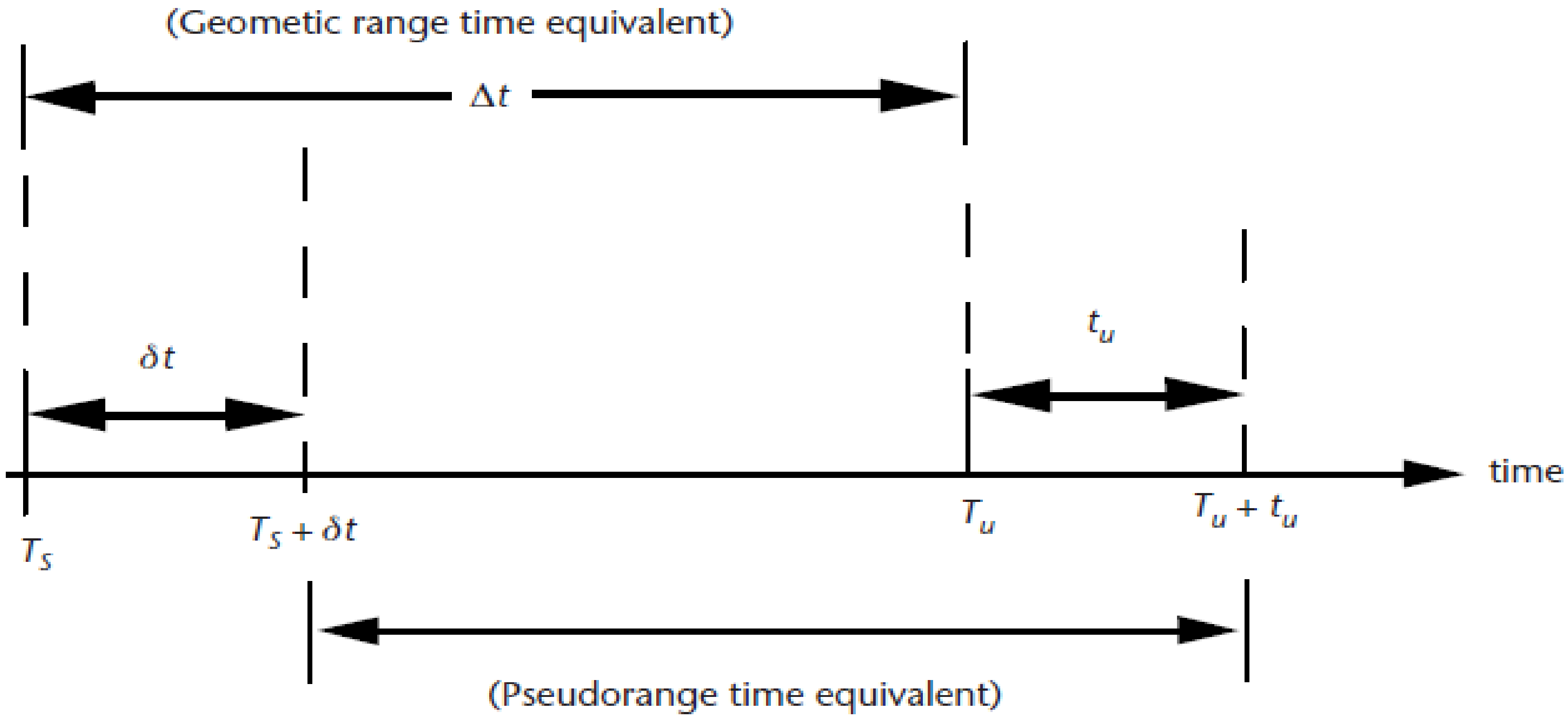

Figure 2.17 Range measurement timing relationships.

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tu= advance of receiver clock wrt system clock, δt is advance of satellite clock wrt system clock, c= speed of light.

GPS User Segment

The user receiving equipment, typically referred to as a **GPS receiver**,

IT processes the L-band signals transmitted from the satellites to determine PVT.

Technology trends in component miniaturization and large-scale manufacturing have led to a proliferation of low-cost GPS receiver components.

GPS receivers are embedded in many of the items we use in our daily lives such as cellular telephones, PDAs, and automobiles.

These first receivers were primarily analog devices for military applications and were large, bulky, and heavy.

Today, receivers take on many form factors, including chipsets, handheld units, and Industry Standard Architecture (ISA) compatible cards.

In fact, there are many single- chip GPS receivers that have leveraged low-voltage bipolar complementary metal oxide semiconductor (BiCMOS) processes and power-management techniques to meet the need for small size and low battery drain of handheld devices.

Selection of a GPS receiver depends on the user's application

(e.g., civilian versus military, platform dynamics, and shock and vibration environment).

Following a description of a typical receiver's components, selection criteria are addressed.

GPS Set (Receiver set) Characteristics

- A block diagram of a GPS receiving set is shown in Figure 3.23.
- The GPS set consists of five principal components:

antenna, receiver, processor, input/output (I/O) device such as a control display unit (CDU), and a power supply.

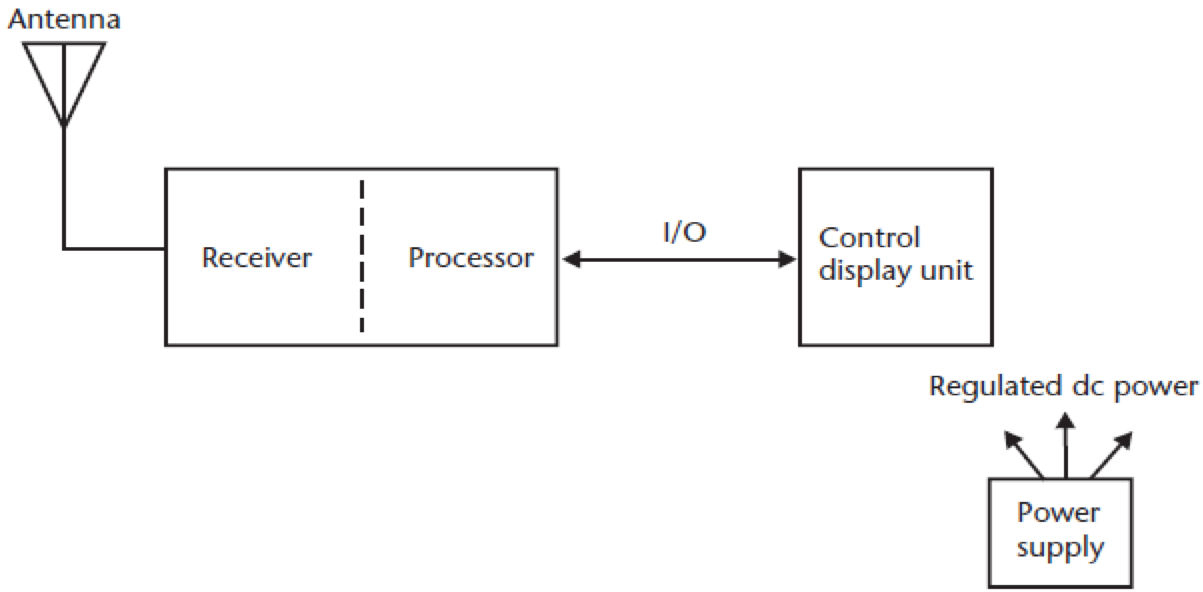

Figure 3.23 Principal GPS receiver components.

Power Supply

Can be integral, external or combination of two. Alkaline or lithium batteries are used (typ) for integral or self contained ie. Portable units.

Integrated application (board mounted receiver installed within a server to provide accurate time) uses existing power supplies.

Airborne , automotive and shipboard GPS set installations use platform power but have built in ac-dc or dc-dc power converters and regulators.

To maintain data in volatile RAM ICs, an internal battery is used and if platform power is disconnected, to operate a built in time piece (data/time clock).

Contd.

- Satellite signals are received via the antenna, which is right-hand circularly polarized (RHCP) and provides near hemispherical coverage.
- Typical coverage is 160° with gain variations from about 2.5 dBic at zenith to near unity at an elevation angle of 15°.
- The RHCP antenna unity gain also can be expressed as 0 dBic = 0 dB with respect to an isotropic circularly polarized antenna.). Below 15°, the gain is usually negative.
- An example antenna pattern is shown in Figure 3.24. This pattern was produced by a stacked-patch antenna element embedded in a dielectric substrate

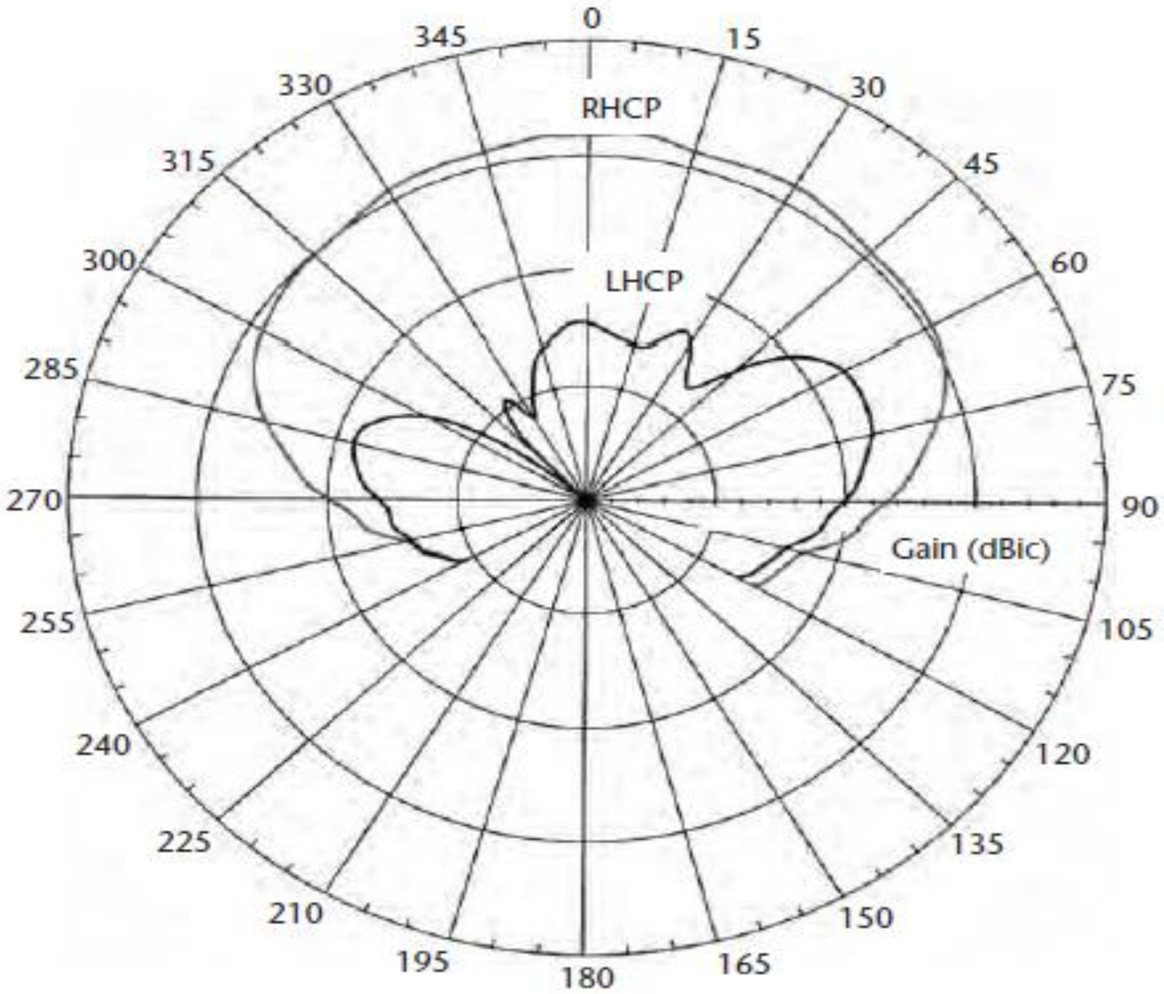

Figure 3.24 Example of RHCP hemispherical antenna pattern.

Receiver

Most receivers have multiple channels, each channel tracks transmission from a single satellite. The generic SPS receiver is shown in fig.3.25

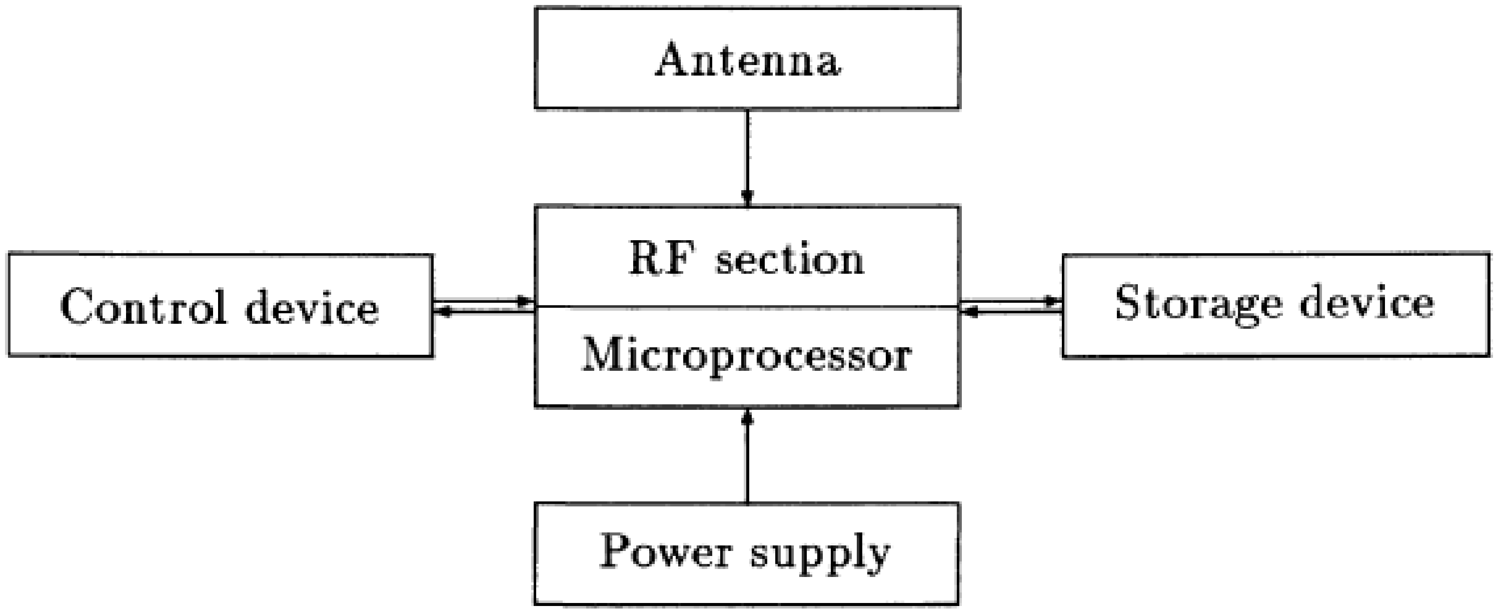

Fig. 5.5. Basic concept of a receiver unit

S

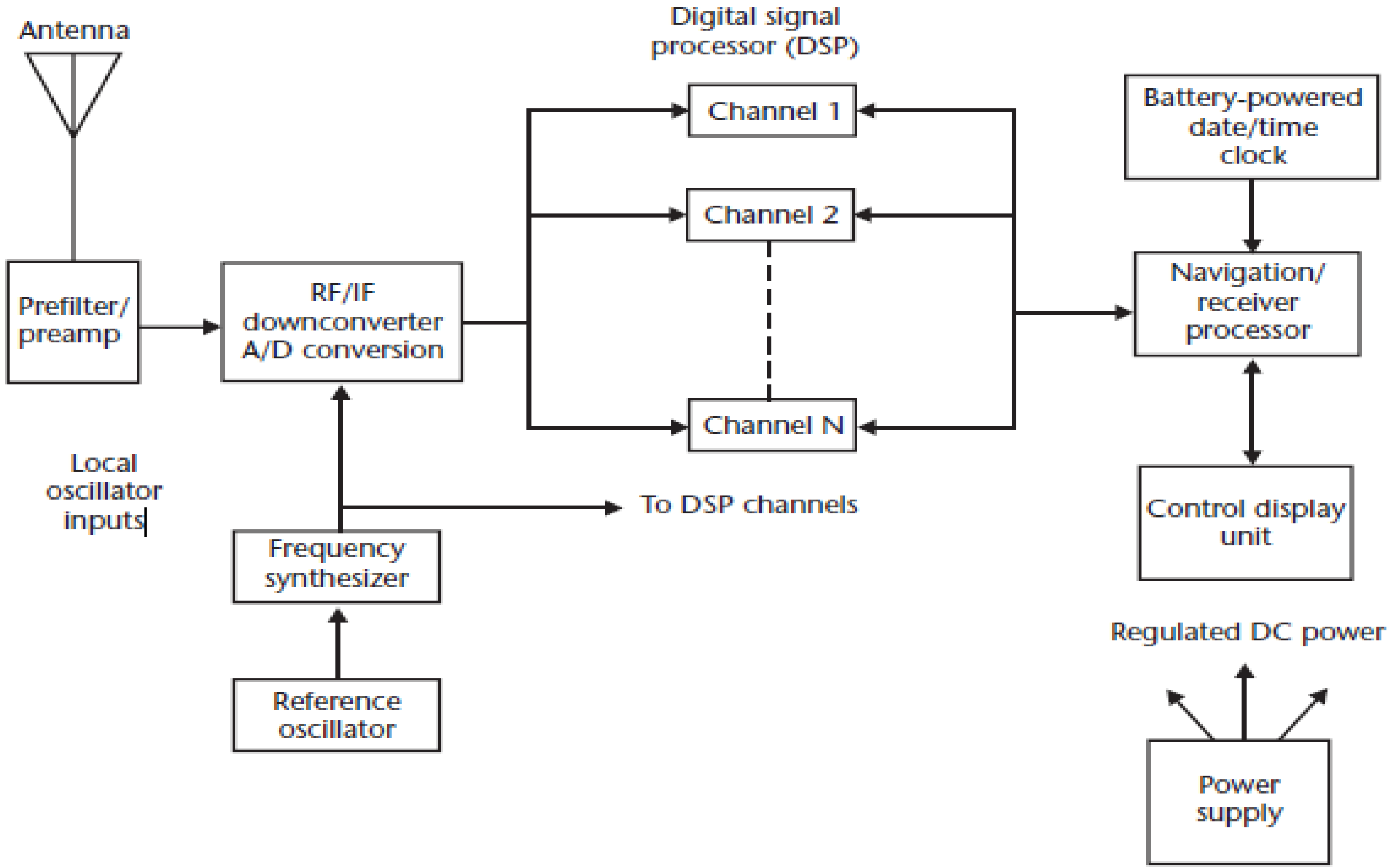

Figure 3.25 Generic SPS receiver.

Contd.

The received RF CDMA satellite signals are usually filtered by a passive band pass filter. This is normally followed by a preamplifier.

GPS receivers designed for use in handheld devices must be power efficient.

Interference resistant receivers need high dynamic range front end and the necessary components high bias voltage levels. Trade off is between low power supply drain and high susceptibility to interferers.

Navigation/ Receiver Processor:

Processor controls and commands the receiver through its operational sequence starting with channel signal acquisition and followed by signal tracking and data collection. The processor may also form a PVT solution from receiver measurements.

Contd.

Most processors provide an independent PVT solution on a 1-Hz basis.

Receivers designated for autoland aircraft precision approach and other high dynamic applications normally require computation of independent PVT solutions at a minimum 5Hz. These formulated data are forwarded to I/O devices.

I/O Device: Interface between GPS and user. They are basically of two types integral and external. For many applications I/O device is a CDU which permits data entry, displays status of navigation solution parameters , usually access numerous navigation functions (way point entry and time to go).

Most handheld units have integral CDU. Interface with existing instruments or control panels.

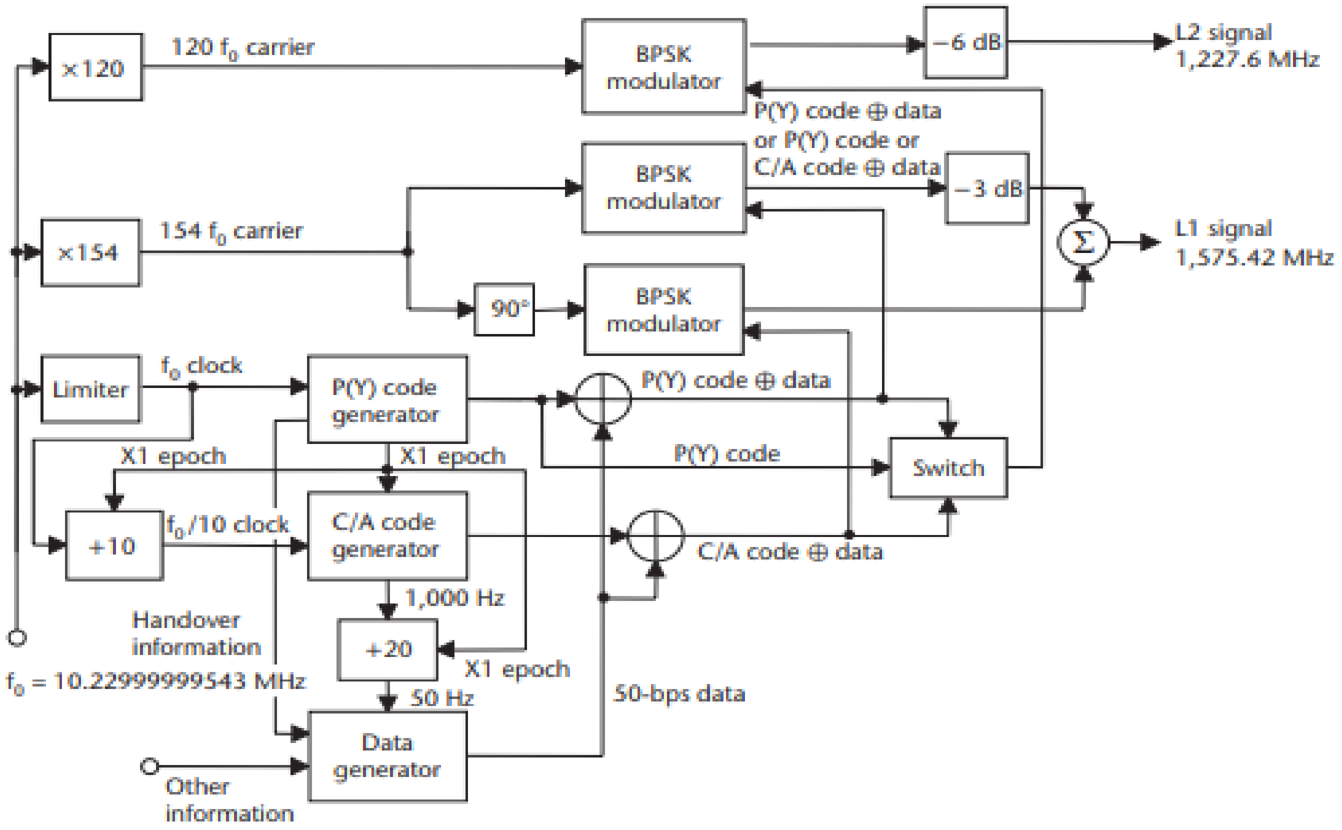

Figure 4.5 Legacy GPS satellite signal structure.

Contd.

A digital data interface to input and output data when integration with other sensors is required.

Navigation Format:

For navigation, BPSK modulation is used. In this the carrier signal is transmitted as is or 180deg phase shift depending on signal whether it is 0 or 1 to be conveyed. Direct sequence spread spectrum adding a spreading PRN waveform of much high rate than signal.

This PRN code is completely known to the intended receiver

In navigation broadcasting multiple signals is needed from a satellite constellation, from a single satellite or even upon a single carrier frequency. FDMA or FDMA is used. When a common transmitter is used, QPSK is employed.

Contd.

Legacy GPS SVs transmit navigation signals on two carrier frequencies called L1, the primary frequency and L2 secondary frequency. Carriers are modulated by DSS using unique PRN sequence.

Both C/A and P(Y) code signals are modulated by 50BPS data, providing user with necessary information to compute the precise locations of each visible satellite and time of transmission for each navigation signal and also auxiliary information.

Auxiliary information used to assist the equipment to in acquiring new satellites to translate from GPS system time to UTC to correct for errors in range measurements. Here main features of GPS navigation message format.

Contd.

GPS navigation message is transmitted in five 300 bit subframes as in fig.4.19.

First two words of each subframe Bits 1-60 are telemetry data (TLM) and handover word (HOW). TLM is first 10 of words in each subframe. Useful in assisting user in locating beginning of each subframe.

Each TLM word also includes 14 bits of data, meaningful only for authorized users.

HOW allows the user equipment to handover from C/A code tracking to P(Y) code tracking, provides GPS time of week (TOW) modulo 6 seconds corresponding to leading edge of following subframe.

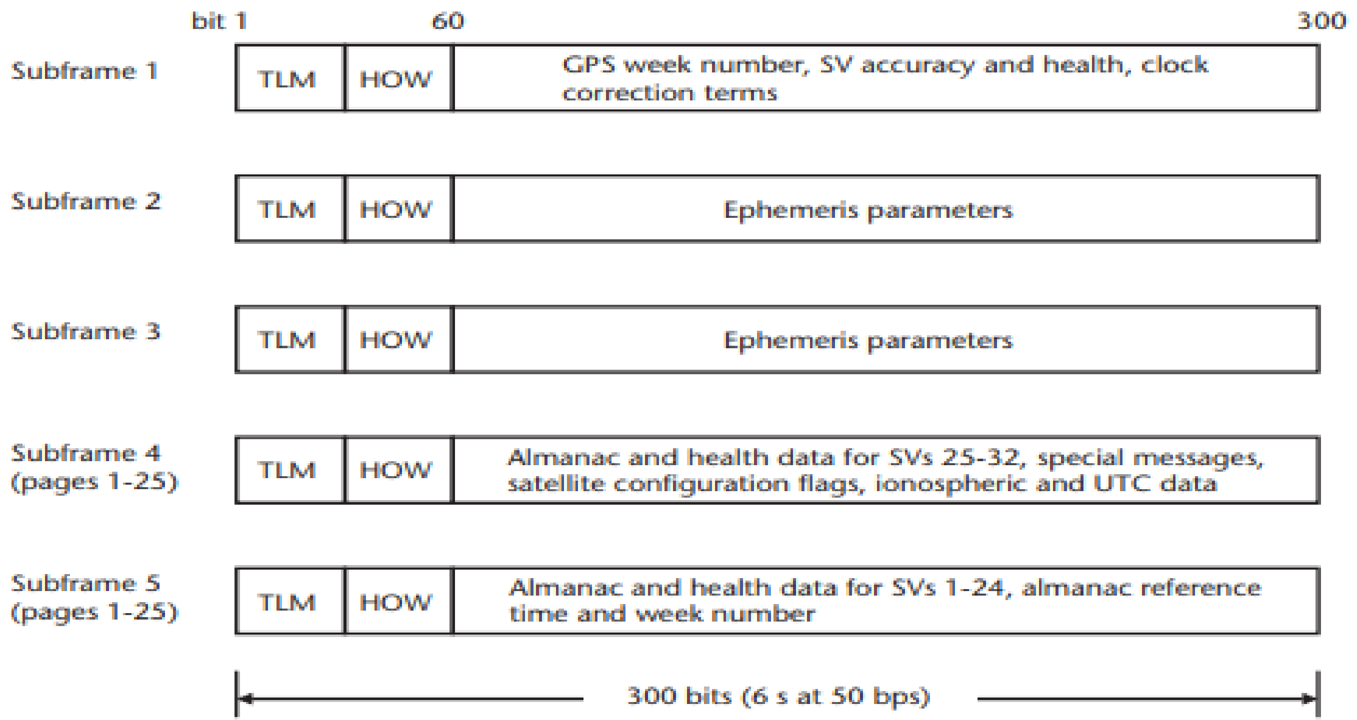

Figure 4.19 Navigation message format.

Contd.

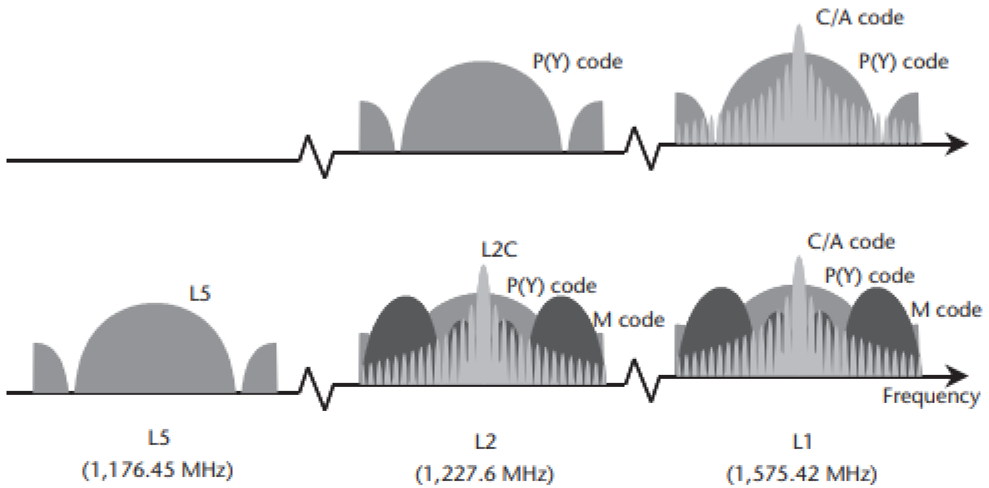

Figure 4.20 Legacy (top) and modernized GPS signals (bottom).

Contd.

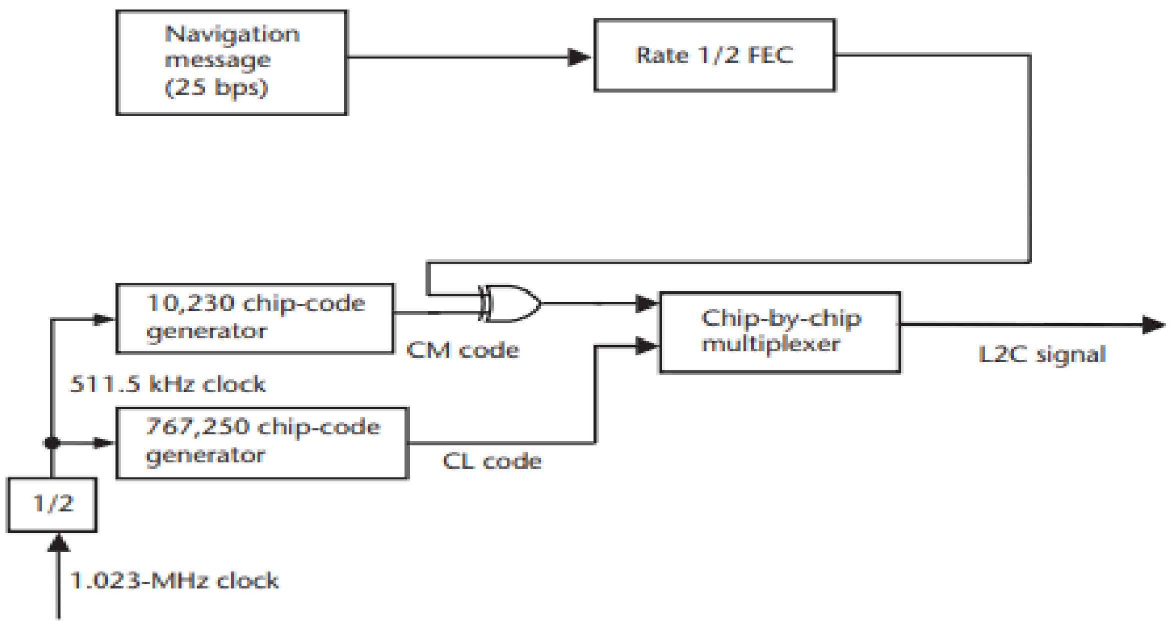

Figure 4.21 Baseband L2C signal generator.

Contd.

Civil moderate (CM), first PRN code , employs a sequence that repeats every 10230 chips, moderate length, civil long(CL) code is extremely long of length 767250 chips. These two codes are generated as in fig.4.21. These are generated using 27 stage linear feedback shift register as in fig. 4.22.

CM and CL codes for different satellites are generated by different initial loads of register. Register is reset for every 10230 chips for CM and every 767250 chips for CL.

GPS L5 is generated as in fig.4.24. QPSK is used to combine an in phase signal component I5 and a quadrature signal component Q5.

The rate half constraint length FEC scheme used to encode 25bps L2C navigation data into a 50- baud bit stream, generated as in fig.4.23. Minimum received L5 power level for signals broadcast from the Block IIF satellites is -154.9dBW.

Contd.

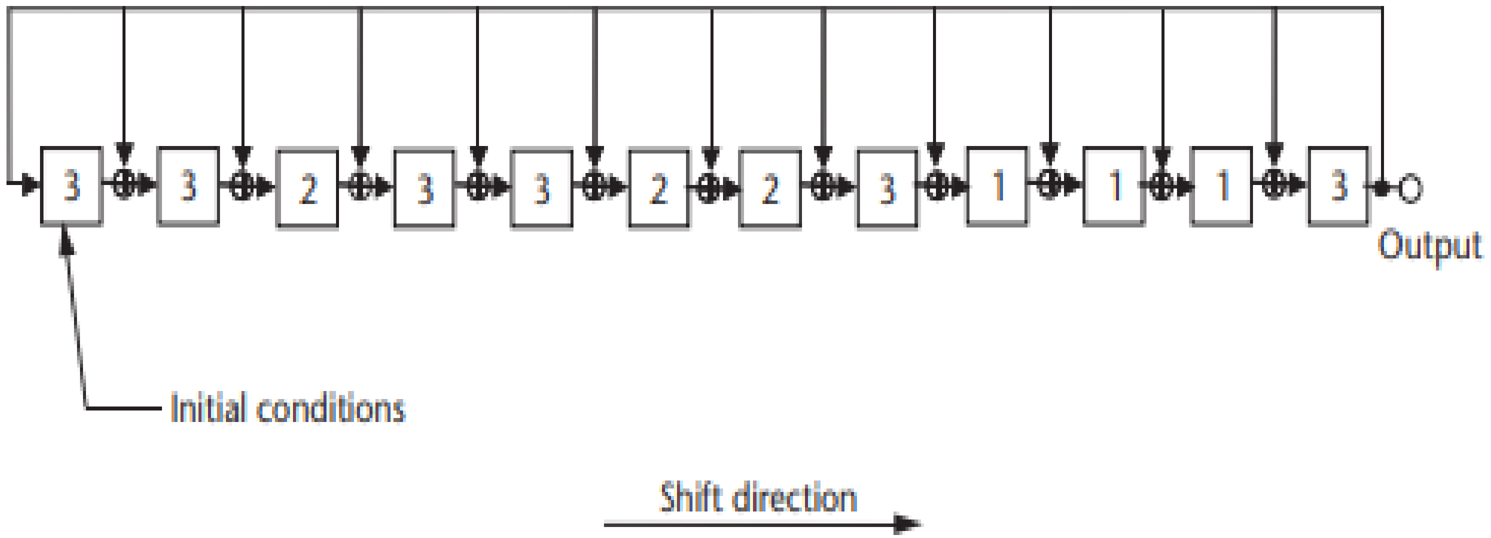

Figure 4.22 CM and CL PRN code generation.

Contd.

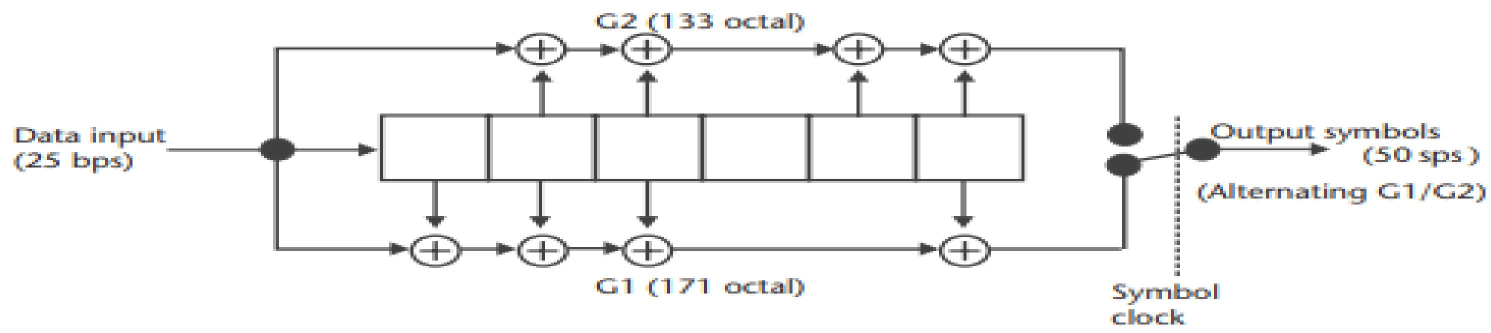

Figure 4.23 L2C data convolution encoder.

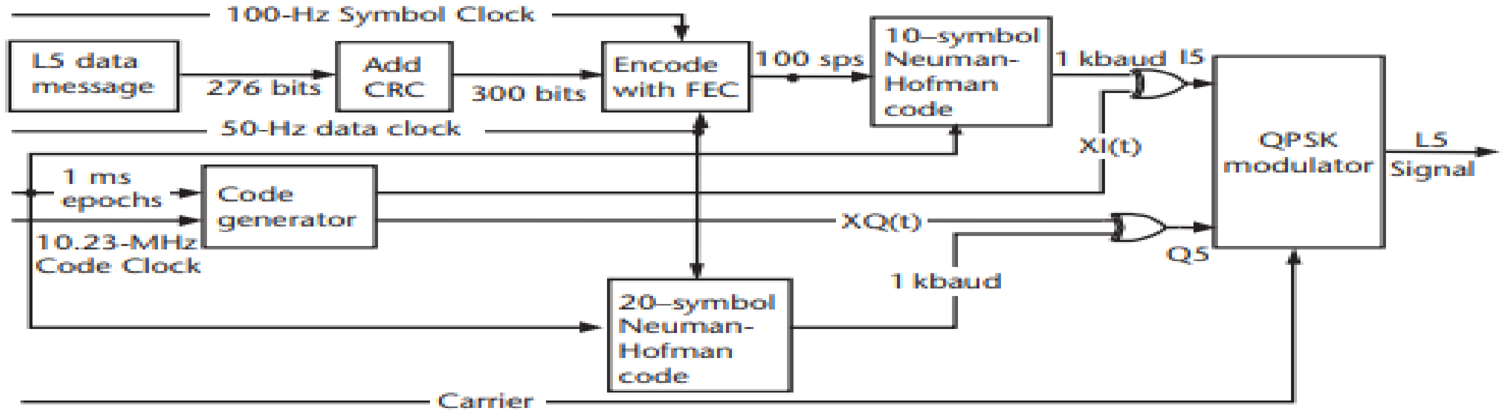

Figure 4.24 L5 signal generation.

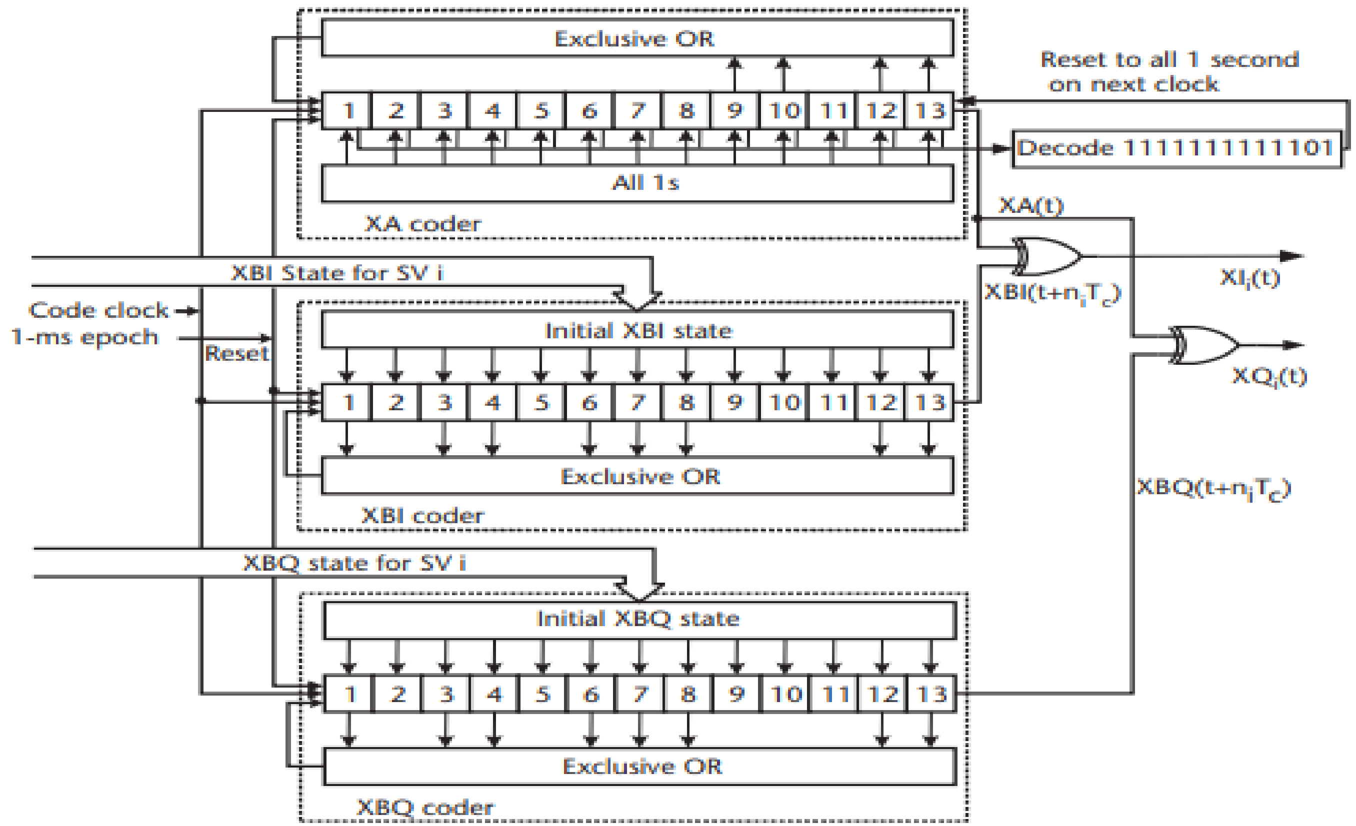

Figure 4.25 I5 and Q5 PRN code generation.

Contd.

Modernized military signal (M code)- used exclusively for military is intended to replace P(Y) code is generated as in fig.4.26. M code is with chip rate 5 x 10.23Mchips/s.

The primary military benefits that M code

- Improved security plus spectral isolation from the civil signals to permit noninterfering higher power M code modes that support antijam resistance.
- Enhanced tracking and data demodulation performance, robust acquisition, and compatibility with C/A code and P(Y) code.
- It accomplishes these objectives within the existing GPS L1 (1,575.42 MHz) and L2 (1,227.60 MHz) frequency bands.

Contd.

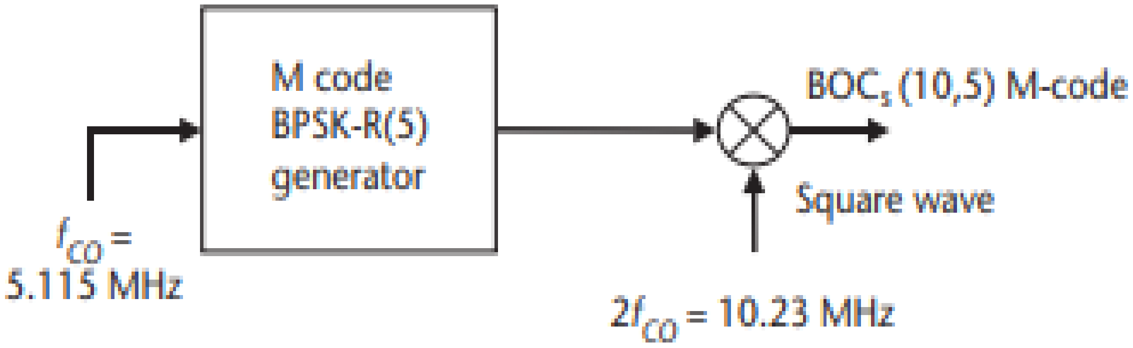

Figure 4.26 M code signal generation.

Table 4.10 Summary of GPS Signal Characteristics

Signal	*Center Frequency (MHz)*	*Modulation Type*	*Data Rate (bps)*	*Null-to-Null Bandwidth (MHz)**	*PRN Code Length*
L1 C/A code	1,575.42	BPSK-R(1)	50	2.046	1023
L1 P(Y) code	1,575.42	BPSK-R(10)	50	20.46	P: 6187104000000 Y: cryptographically generated
L2 P(Y) code	1,227.6	BPSK-R(10)	50	20.46	P: 6187104000000 Y: cryptographically generated
L2C	1,227.6	BPSK-R(1)	25	2.046	CM: 10,230 CL: 767,250 (2 PRN sequences are chip-by-chip multiplexed)
L5	1,176.45	BPSK-R(10)	50	20.46	I5: 10,230 Q5: 10,230 (two components are in phase quadrature)
L1 M code	1,575.42	BOC(10,5)	N/A	30.69*	Cryptographically generated
L2 M code	1,227.6	BOC(10,5)	N/A	30.69*	Cryptographically generated
L1C	1,575.42	BOC(1,1)	N/A	4.092*	N/A

* For binary offset carrier modulations, null-to-null bandwidth is defined here as bandwidth between the outer nulls of the largest spectral lobes.

Contd.

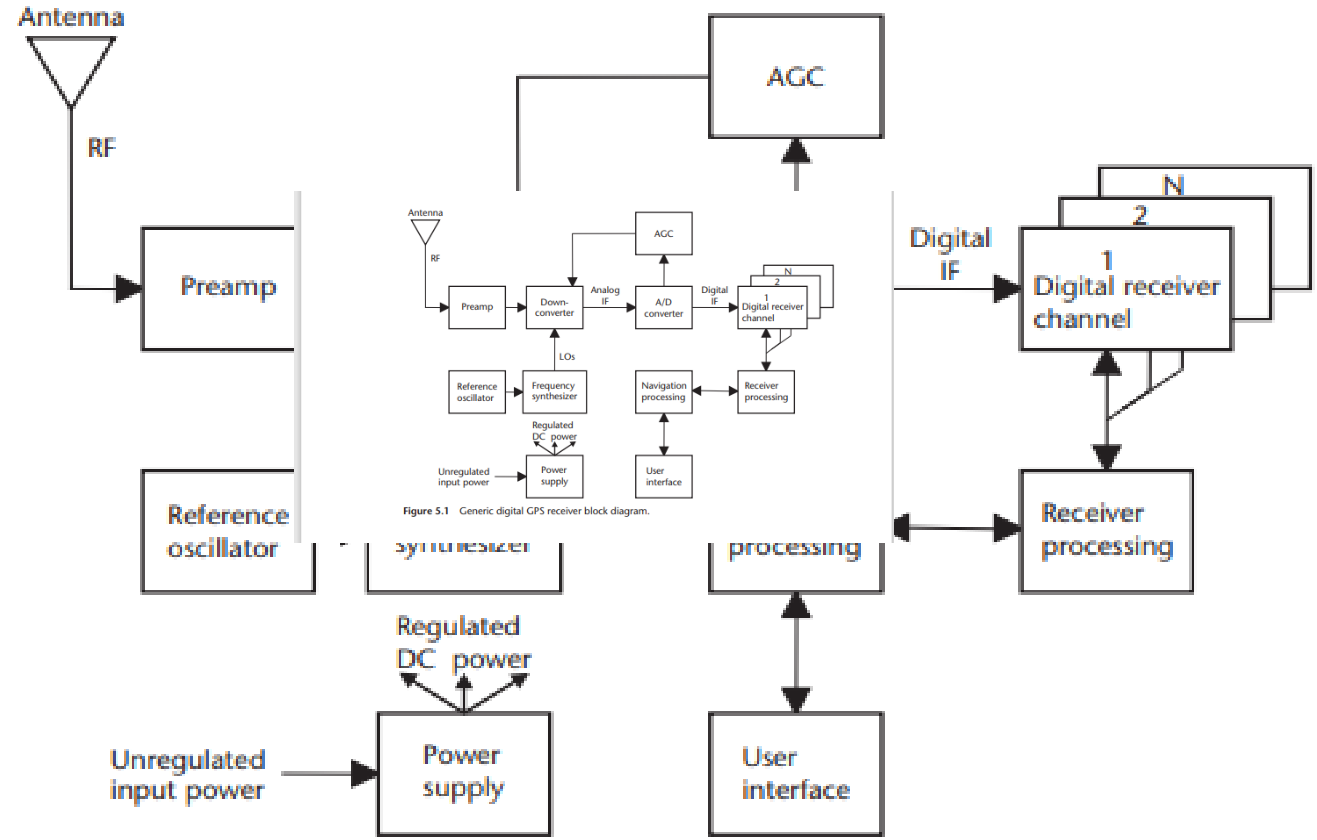

Figure 5.1 Generic digital GPS receiver block diagram.

Contd.

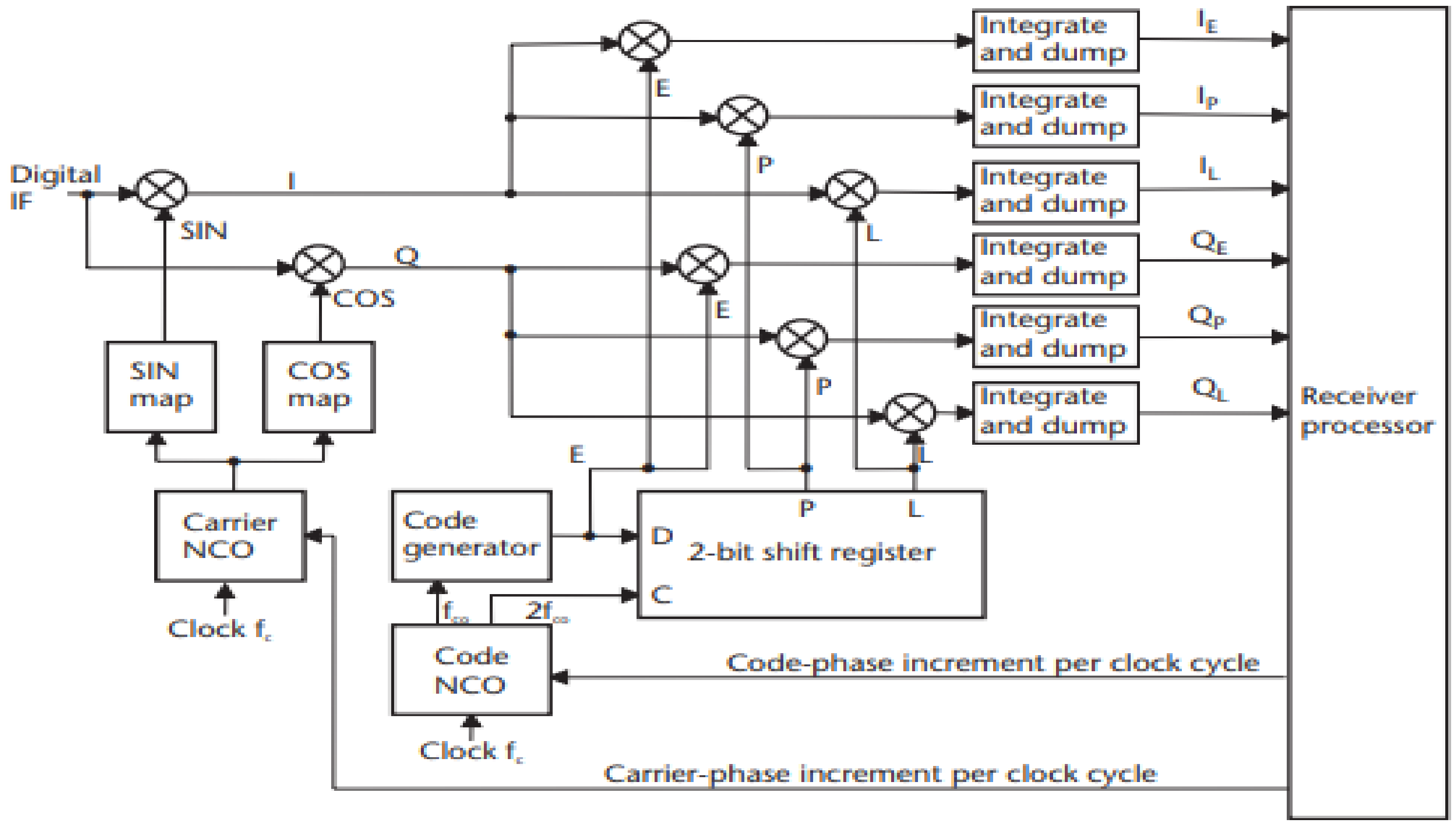

Figure 5.2 Generic digital receiver channel block diagram.

Contd.

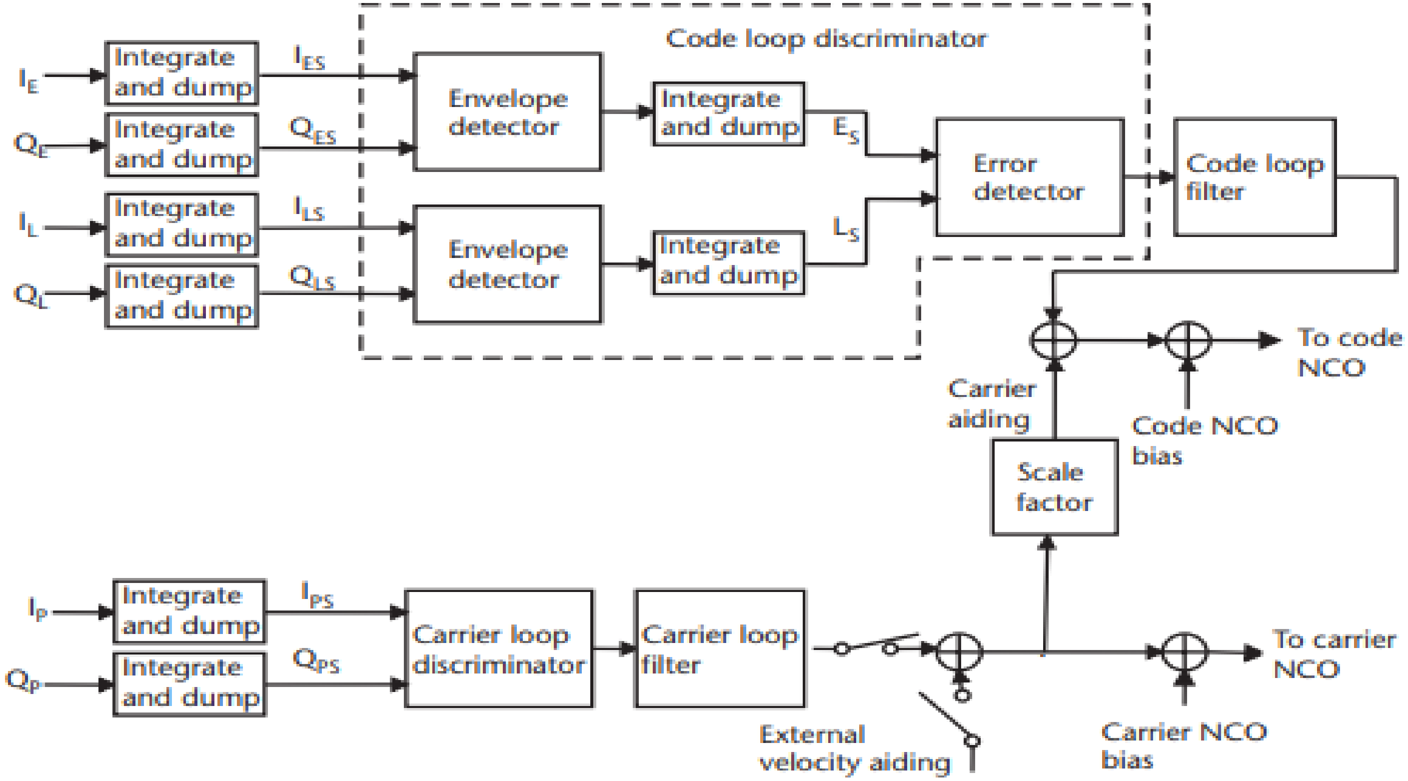

Figure 5.3 Generic baseband processor code and carrier tracking loops block diagram.

Cond.

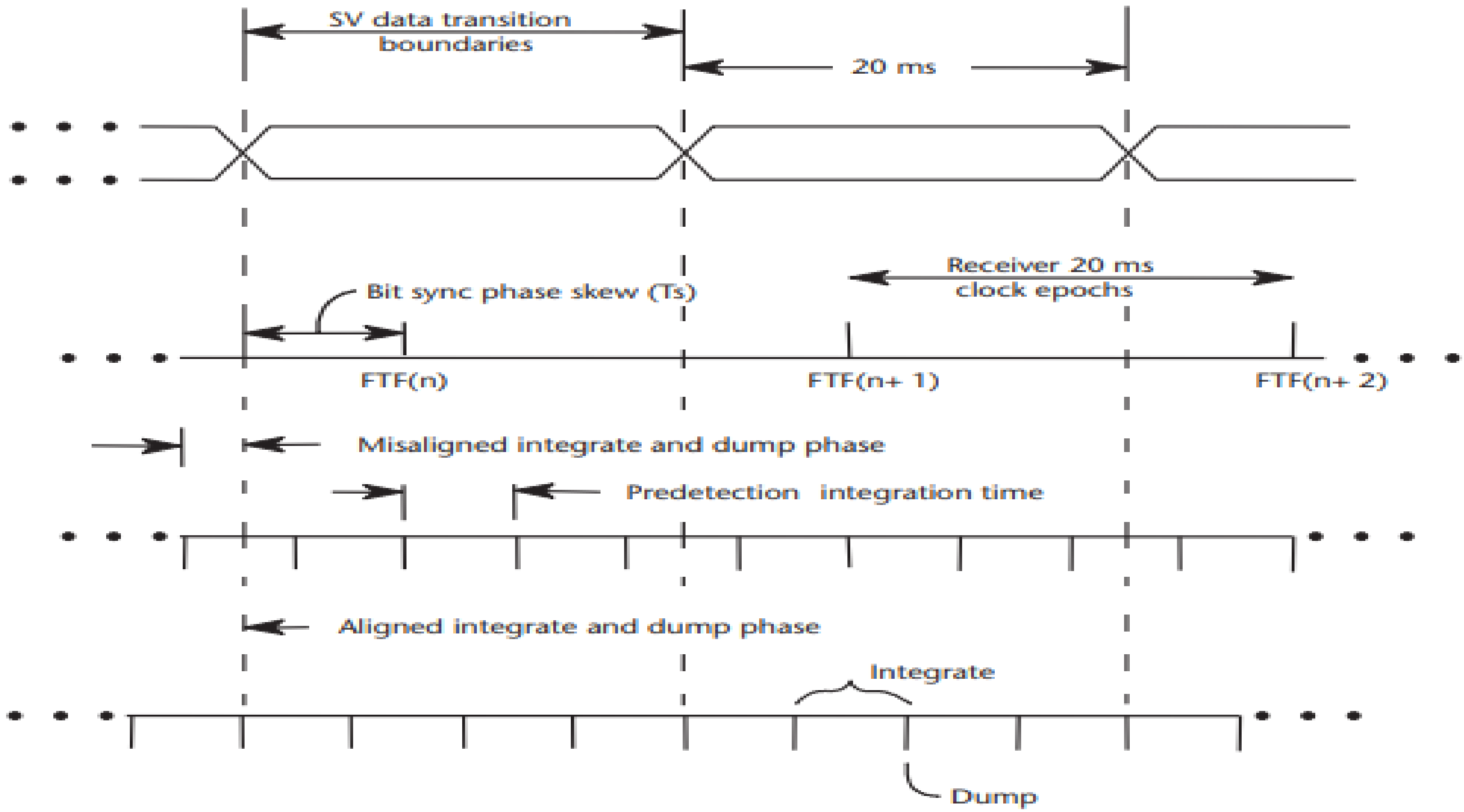

Figure 5.4 Phase alignment of predetection integrate and dump intervals with SV data transition boundaries.

Contd.

Table 4.8 C/A Code Maximum Cross-Correlation Power (Zero Doppler Differences)

Cumulative Probability of Occurrence	*Cross-Correlation for Any Two Codes (dB)*
0.23	–23.9
0.50	–24.2
1.00	–60.2

Table 4.9 C/A Code Maximum Cross-Correlation Power Summed for All 32 Codes (Increments of 1-kHz Doppler Differences)

Cumulative Probability of Occurrence	*Cross-Correlation at $\Delta = 1$ kHz (dB)*	*Cross-Correlation at $\Delta = 2$ kHz (dB)*	*Cross-Correlation at $\Delta = 3$ kHz (dB)*	*Cross-Correlation at $\Delta = 4$ kHz (dB)*	*Cross-Correlation at $\Delta = 5$ kHz (dB)*
0.001	–21.1	–21.1	–21.6	–21.1	–21.9
0.02	–24.2	–24.2	–24.2	–24.2	–24.2
0.1	–26.4	–26.4	–26.4	–26.4	–26.4
0.4	–30.4	–30.4	–30.4	–30.4	–30.4

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	Number of bits	Transmission time
Total message	1 500	30 seconds
Subframe (1–5)	300	6 seconds
Word (1–10)	30	0.6 seconds

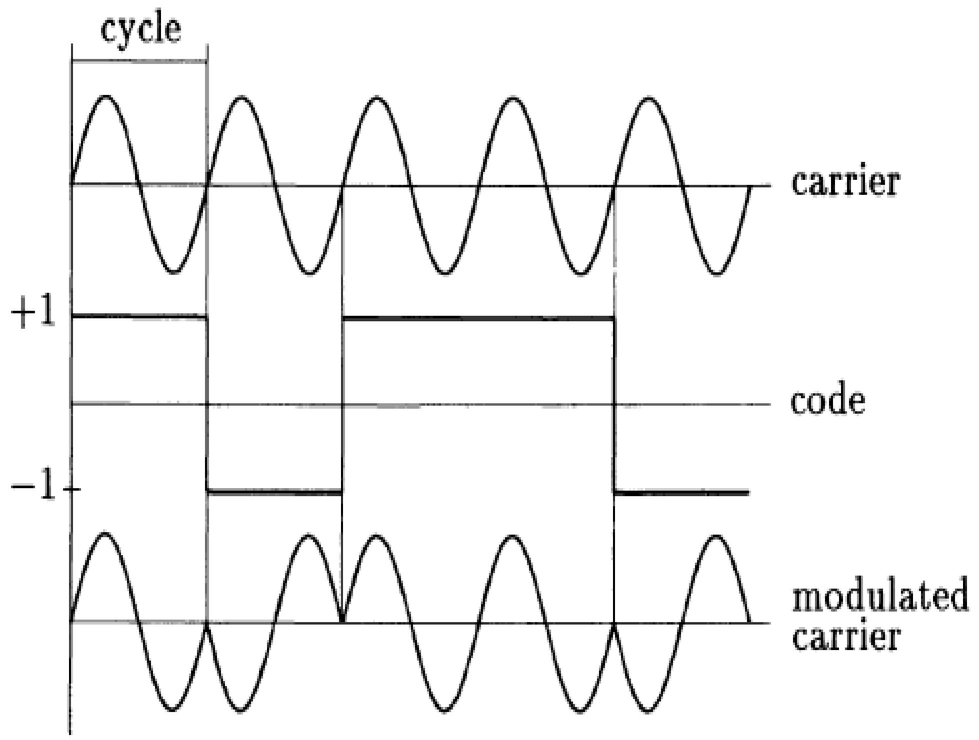

Fig. 5.1. Biphase modulation of carrier wave

Contd.

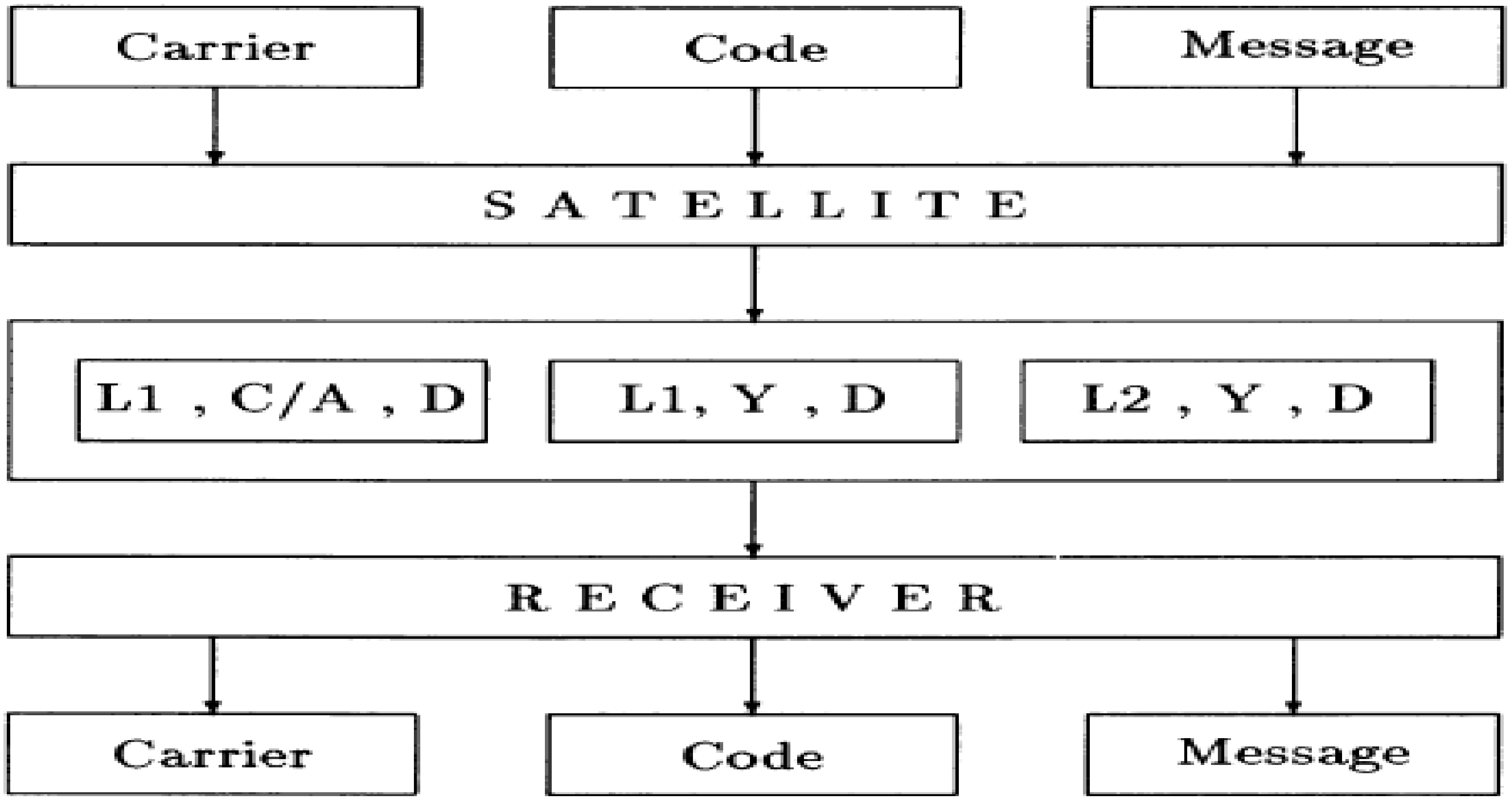

Fig. 5.4. Principle of signal processing

Contd.

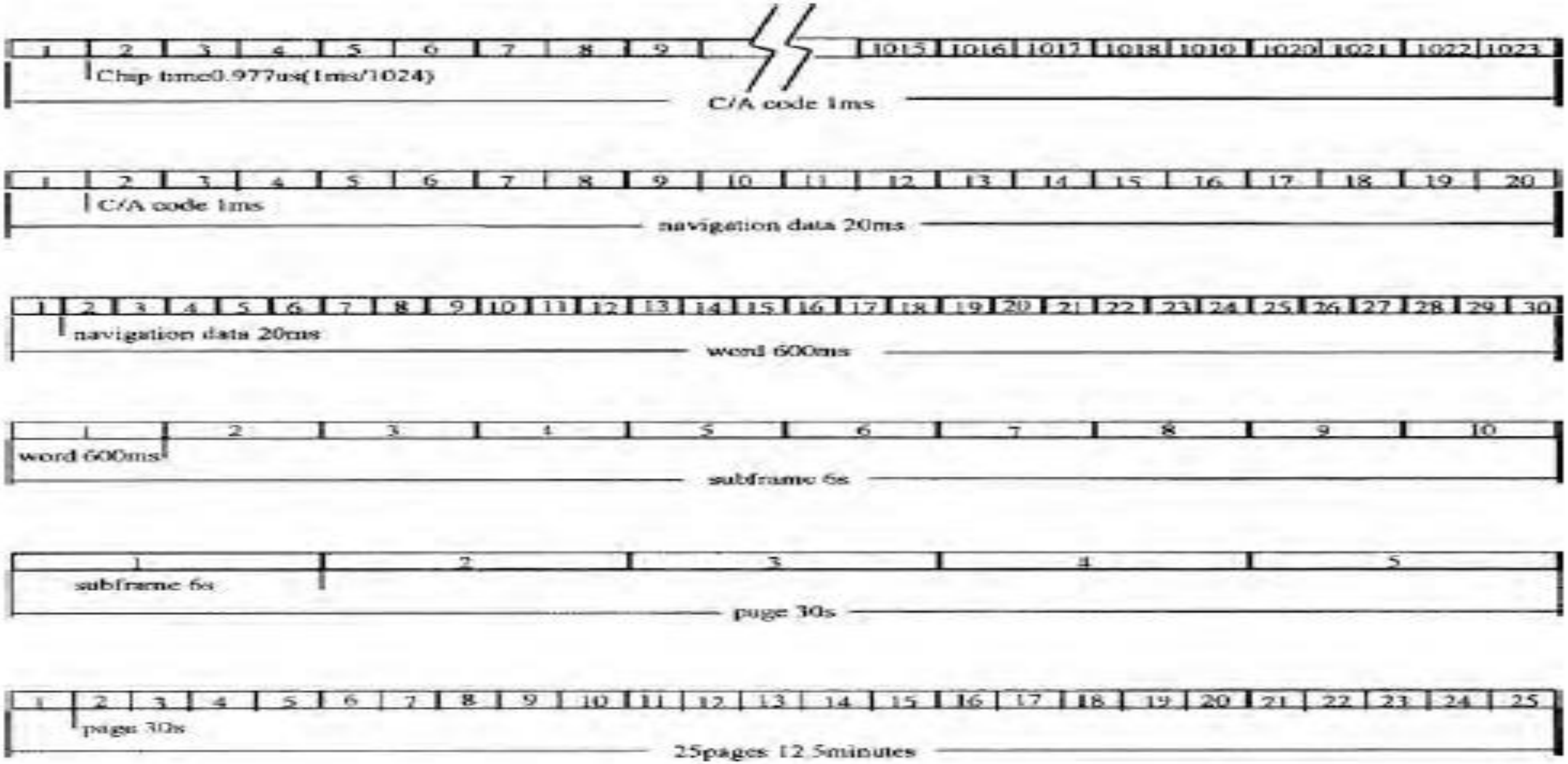

FIGURE 5.3 GPS data format.

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Although there are provisions for a loss of ground contact, normally the control segment uploads critical navigation data elements once or twice per day per satellite.

In this nominal mode of operation, the same critical navigation data elements (e.g., satellite ephemeris and clock correction data) are broadcast repeatedly over 2-hour time spans (except if an upload occurs during this interval).

On 2-hour boundaries, each satellite switches to broadcasting a different set of these critical elements, which are stored in tables in the satellite's RAM.

The control segment generates these message elements based upon its current estimates of each satellite's position and clock error and prediction algorithms on how these parameters will change over time.

Contd.

The first two words of each subframe (bits 1–60) contain telemetry (TLM) data and a handover word (HOW).

The TLM word is the first of the 10 words in each subframe and includes a fixed preamble, a fixed 8-bit pattern 10001011 that never changes.

This pattern is included to assist the user equipment in locating the beginning of each subframe.

The first two words of all the subframes are the telemetry (TLM) and hand over word (HOW). Each word contains 30 bits and the message is transmitted from bit 1 to bit 30.

These two words are shown in Figure 5.7.

The TLM word begins with an 8-bit preamble, followed by 16 reserved bits and 6 parity bits. The bit pattern of the preamble is shown in the figure.

The bit pattern of the preamble will be used to match the navigation data to detect the beginning of a subframe.

The HOW word can be divided into four parts.

1. The first 17 bits (1–17) are the truncated time of week (TOW) count that provides the time of the week in units of 6 seconds.

2. The next two bits (18, 19) are flag bits. For satellite configuration 001 (block II satellite) bit 18 is an alert bit and bit 19 is antispoof.

Satellites are procured in blocks. Most block I satellites are experimental ones and all the satellites in orbit are from block II.

Contd.

When bit 18 = 1, it indicates that the satellite user range accuracy may be worse than indicated in subframe1 and the user uses the satellite at the user's own risk.

Bit 19 = 1 indicates the antispoof mode is on.

3. The following three bits (20–22) are the subframe ID and their values are 1, 2, 3, 4, and 5 or (001, 010, 011, 100, and 101) to identify

one of the five subframes. These data will be used for subframe matching.

4. The last 8 bits (23–30) are used for parity bits

- Subframe 1 provides the GPS transmission week number, which is the number of weeks modulo 1,024 that have elapsed since January 5, 1980. The first rollover of the GPS week number occurred on August 22, 1999. The next rollover will occur in April 2019.
- It is necessary that the GPS receiver designer keep track of these rare but inevitable rollover epochs in nonvolatile memory. Subframe 1 also provides the following satellite clock correction *af*0, *af*1, *af*2, and time of clock, *toc*, which are extremely important for precise ranging, since

Contd.

they account for the lack of perfect synchronization between the timing of the SV broadcast signals and GPS system time.

- A 10-bit number referred to as issue of data, clock (IODC) is included in subframe 1 to uniquely identify the current set of navigation data.
- User equipment can monitor the IODC field to detect changes to the navigation data.
- The current IODC is different from IODCs used over the past seven days.

Contd.

- Subframe 1 also includes a group delay correction, *Tgd*, a user range accuracy (URA) indicator, a SV health indicator, an L2 code indicator, and an L2 P data flag.

- *Tgd* is needed by single- frequency (L1- or L2-only) users since the clock correction parameters refer to the timing of the P(Y) code on L1 and L2, as apparent to a user that is using a linear combination of dual-frequency L1/L2 P(Y) code measurements to mitigate ionospheric errors.
- The URA indicator provides the user with an estimate of the 1-sigma range errors to the satellite due to satellite and control segment errors (and is fully applicable only for L1/L2 P-code users).

Contd.

The SV health indicator is a 6-bit field that indicates whether the satellite is operating normally or whether components of the signal or navigation data are suspected to be erroneous.

The L2 code indicator field indicates whether the P(Y) code or C/A code is active on L2.

Contd.

Subframes 2 and 3

- Subframes 2 and 3 include the osculating Keplerian orbital elements that allow the user equipment to preciselyFinally, the L2 P data flag indicates whether navigation data is being modulated on to the L2 P(Y) code
- determine the location of the satellite.
- Subframe 2 also includes a fit interval flag and an age of data offset (AODO) term.

Contd.

The fit interval flag indicates whether the orbital elements are based upon a nominal 4-hour curve fit (that corresponds to the 2-hour nominal data transmission interval described earlier) or a longer interval.

Subframes 2 and 3

- The AODO term provides an indication of the age of the elements based on a navigation message correction table (NMCT) that has been included in the GPS navigation data since 1995.
- Both subframes 2 and 3 also include an issue of data ephemeris (IODE) field. IODE consists of the 8 least significant bits (LSBs) of IODC and may be used by

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the user equipment to detect changes in the broadcast orbital elements.

- Pages 2–5 and 7–10 of subframe 4 and pages 1–24 of subframe 5 contain almanac data (coarse orbital elements that allow the user equipment to determine approximate positions of other satellites to assist acquisition) for SVs 1–32.
- Page 13 of subframe 4 includes the NMCT range corrections. Page 18 of subframe 4 includes ionospheric correction parameters for single-frequency users and parameters so that user equipment can relate UTC to GPS system time.

Contd.

Page 25 of subframes 4 and 5 provide configuration and health flags for SVs 1–32.