Chapter 5

Satellite navigation

5.1 Introduction

It is surprising that the space technology that we rely on so heavily today had its origins over 50 years ago when, in the early 1950s, with the shock launching by the USSR of a man-made satellite into low orbit, the United States space programme was born. Although a tiny vehicle by present day standards, the USSR's 'Sputnik' had a radio transmitter on board, the frequency of which exhibited a pronounced Doppler shift when observed from any fixed point on the earth's surface. The Doppler phenomenon was well documented but this was the first time the effect had been produced by and received from a man-made orbiting satellite. Space engineers soon recovered from the initial shock and were quick to see that the effect could be exploited to create a truly accurate global positioning system, free from many of the constraints of the existing earth-bound hyperbolic navigation systems.

The first commercially available system to be developed, the Navy Navigation Satellite System (NNSS), made good use of the Doppler effect and provided the world's shipping with precise position fixing for decades. However, nothing lasts forever. The technology became old and the system was dropped on 31 December 1996 in favour of the vastly superior Global Positioning System (GPS). Although a number of NNSS Nova satellites are still in orbit, the system is no longer used for commercial navigation purposes.

5.2 Basic satellite theory

Whilst it is not essential to understand space technology, it is helpful to consider a few of the basic parameters relating to satellite orbits and the specific terminology used when describing them. A satellite is placed in a pre-determined orbit, either in the nose of an expendable launch vehicle or as part of the payload of a space shuttle flight. Either way, once the 'bird' has been delivered into the correct plane, called the 'inclination', that is the angle formed between the eastern end of the equatorial plane and the satellite orbit, it is subject to Kepler's laws of astrophysics.

Figure 5.1 shows orbits of zero inclination for the equatorial orbit, 45°, and for a polar orbit, 90°. The final desired inclination partly determines the launching site chosen. In practice it is difficult to achieve an inclination which is less than the latitude of the launching site's geographical location. A zero inclination orbit is most effectively produced from a launch pad situated on the equator, but this is not always possible and a compromise is often made. Launch normally takes place in an easterly direction because that way it is possible to save fuel, and thus weight, by using the earth's rotational speed to boost the velocity of the accelerating rocket. For an easterly launch from a site on the equator, the velocity needed to escape the pull of gravity, is 6.89 km s^{-1}, whereas for a westerly launch it is 7.82 km s^{-1}. Launch velocities also vary with latitude and the direction of the flight path.

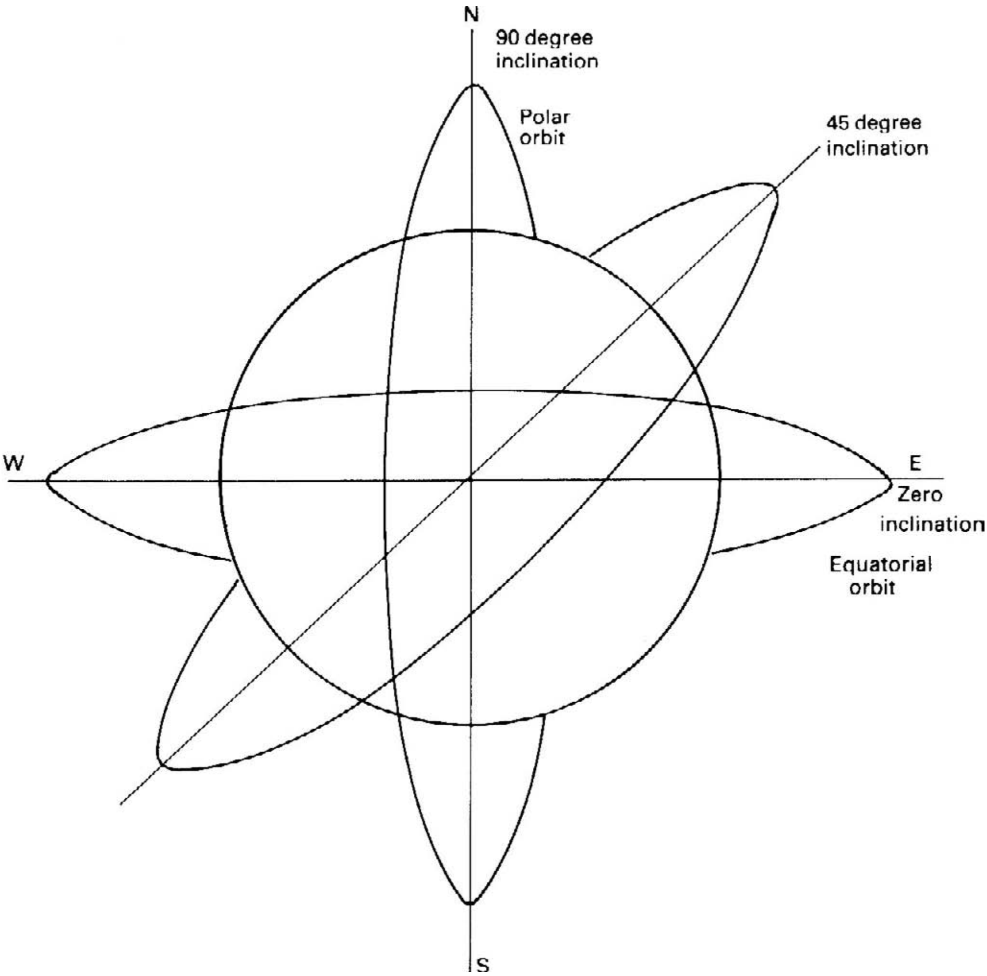

Figure 5.1 Illustration of orbital inclination.

5.2.1 Kepler's Laws

Essentially, an artificial earth-orbiting satellite obeys three laws that were predicted in the late 16th century by Johannes Kepler (1571–1630) who also developed theories to explain the natural orbits of the planets in our solar system. When applied to artificial orbiting satellites, Kepler's laws may be summarized as follows.

- A satellite orbit, with respect to the earth, is an ellipse.
- Vectors drawn from the satellite orbit to the earth describe equal areas in equal times.
- The square of the period of the orbit is equal in ratio to the cube of its mean altitude above the earth's surface.

True to Kepler, artificial earth satellites follow elliptical orbits. In some cases the ellipse eccentricity is large and is a requirement of the first stage of a launch to the higher geostationary orbit, but in most

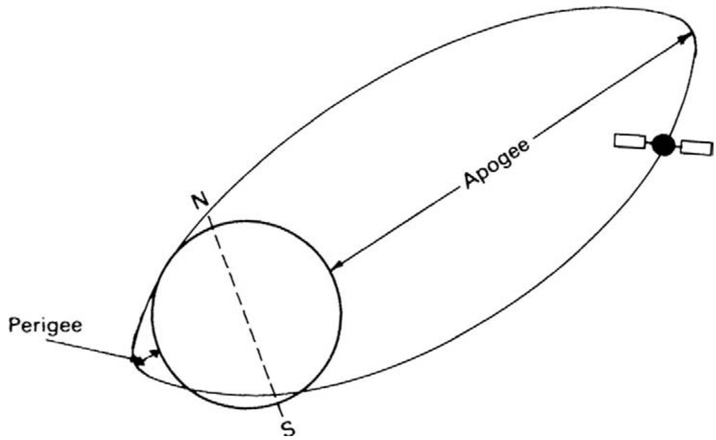

Figure 5.2 Illustration of apogee and perigee.

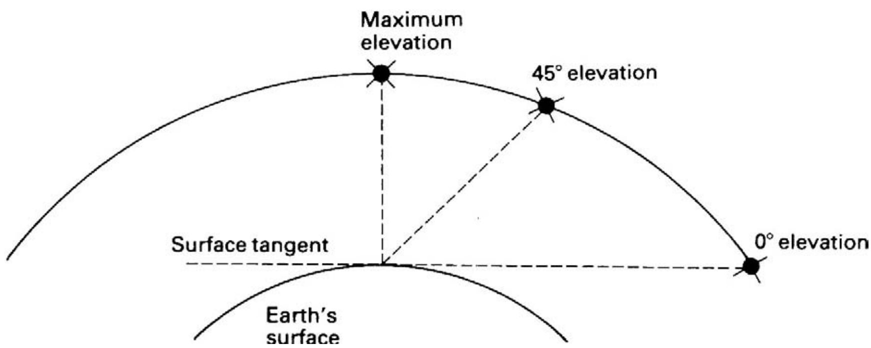

Figure 5.3 Showing the changing angle of elevation during a satellite pass. The angle reaches a maximum at the closest point of approach to the earth bound observer.

cases it is created because the earth is not a perfect sphere. The closest point of approach to the earth of any elliptical orbit is called the 'perigee' and the furthest distance away is the 'apogee', as shown in Figure 5.2. The direction vector to the satellite from a fixed point on the earth is called the 'azimuth' and is quoted in degrees. The angle between the satellite, at any instant, and the earth's surface tangent is the 'elevation' and again is quoted in degrees (see Figure 5.3).

5.2.2 Orbital velocity

A satellite can only remain in orbit if its velocity, for a given altitude, is sufficient to defeat the pull of gravity ($9.81\ \mathrm{ms}^{-1}$) and less than that required to escape it. The velocity must be absolutely precise for the orbital altitude chosen. Eventually, drag will slow the satellite causing it to drop into a lower orbit and possibly causing it to re-enter the atmosphere and burn-up. The nominal velocity for a satellite at any altitude can be calculated by using the formula:

$$V = \frac{K}{(r + a)^{\frac{1}{2}}}\ \mathrm{kms}^{-1}$$

where V = orbital velocity in kms^{-1},
a = altitude of the satellite above the earth's surface in km,
r = the mean radius of the earth (approximately 6370 km), and
K = 630 (a constant derived from a number of parameters).

The earth is not a perfect sphere and therefore its radius with respect to orbital altitude will vary. However, to derive an approximate figure for velocity, an earth radius figure of 6370 km is close enough. The velocity of a satellite with an altitude of 200 km would be:

$$V = \frac{630}{(6370 + 200)^{1/2}} = 7.77\,kms^{-1}$$

Orbital paths can be transferred to a Mercator projection chart as shown in Figure 5.4. The inclination will be the same in both northern and southern hemispheres and corresponds to latitude. The six orbits shown are for Navstar (GPS) satellites with an orbital inclination of 55°.

5.2.3 Orbital period

The time period for one complete orbit of a satellite can be readily calculated using the simple formula below:

$$P = K\left(\frac{r + a}{r}\right)^{3/2}$$

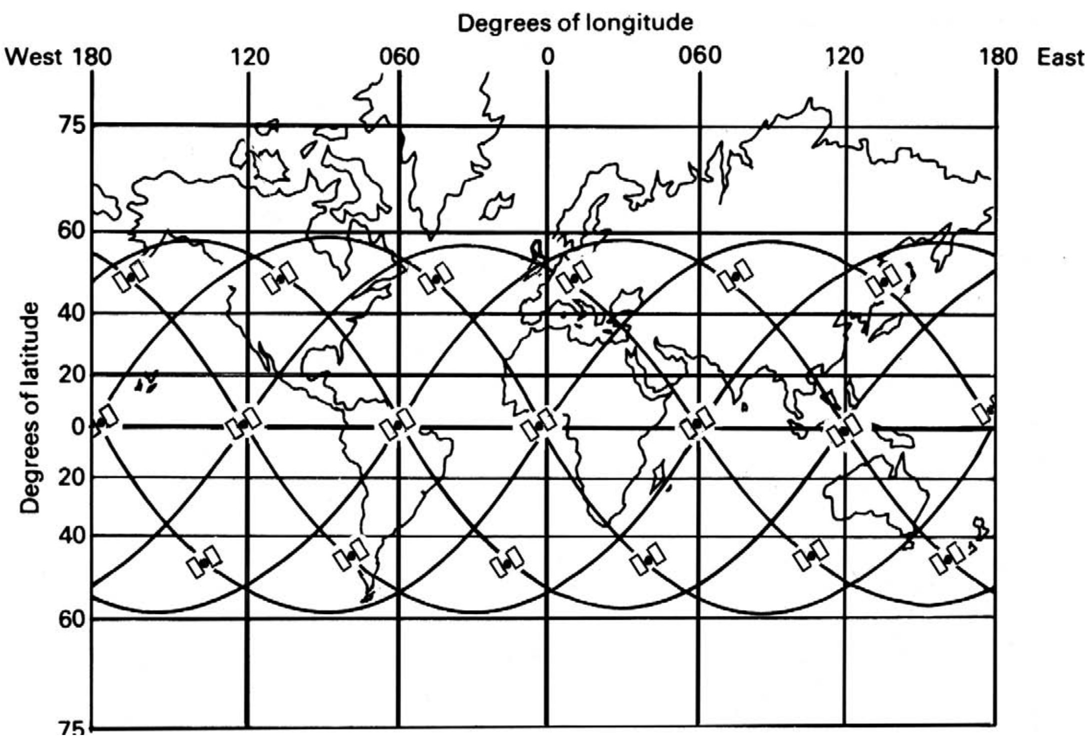

Figure 5.4 Mercator presentation of the orbital inclination paths described by satellite orbits.

where P = the period of one orbit in min,
a = the altitude of the orbit above the earth's surface in km,
r = the mean radius of the earth in km, and
K = 84.49 (a constant derived from a number of parameters).

The orbital period for a satellite at an altitude of 200 km is:

$$P = 84.49 \left(\frac{6371 + 200}{6371} \right)^{3/2} = 88.45 \text{ min}$$

5.3 The Global Positioning System (GPS)

In 1973 a combined US Navy and US Air force task-force set out to develop a new global satellite navigation system to replace the ageing Navy Navigation Satellite System (NNSS).

The original test space vehicles (SVs) launched in the new programme were called Navigation Technology Satellites (NTS) and NTS1 went into orbit in 1974 to became the embryo of a system that has grown into the Global Positioning System (GPS). GPS was declared to be fully operational by the US Air Force Space Command (USAFSC) on 27April 1995, and brought about the demise of the NNSS which finally ceased to provide navigation fixes at midnight on 31 December 1996.

The GPS, occasionally called NAVSTAR, shares much commonality with the Russian Global Navigation System (GLONASS), although the two are in no way compatible. The GPS consists of three segments designated Space, Control and User.

5.3.1 The space segment

Satellite constellation calls for 24 operational SVs, four in each of six orbital planes, although more satellites are available to ensure the system remains continuously accessible (see Figure 5.5). SVs orbit the earth in near circular orbits at an altitude of 20 200 km (10 900 nautical miles) and possess an inclination angle of 55°.

Based on standard time, each SV has an approximate orbital period of 12 h, but when quoted in the more correct sidereal time, it is 11 h 58 min. Since the earth is turning beneath the SV orbits, all the satellites will appear over any fixed point on the earth every 23 h 56 min or, 4 min earlier each day. This, totally predictable, time shift is caused because a sidereal day is 4 min shorter than a solar day and all SVs complete two orbits in one day. To maintain further orbital accuracy, SVs are attitude-stabilized to within 1 m by the action of four reaction wheels, and on-board hydrazine thrusters enable precision re-alignment of the craft as required.

This orbital configuration, encompassing 24 SVs, ensures that at least six SVs, with an elevation greater than 9.5°, will be in view of a receiving antenna at any point on the earth's surface at any time. When one considers the problems of rapidly increasing range error caused by the troposphere at low SV elevations, 9.5° has been found to be the minimum elevation from which to receive data when using a simple antenna system.

The original satellites, numbered 1–11 and designated Block I, have ceased operation. Currently, the GPS constellation is based on the next generation of SVs, designated Block II. Block II (numbers 13–21) and block IIA (numbers 22–40) satellites, manufactured by Rockwell International, were launched from Cape Canaveral between February 1989 and November 1997. Each SV holds four atomic clocks, two rubidium and two caesium, and has selective availability (SA) and anti-spoofing (A-S) capabilities, although the US Government has now given an assurance that the system

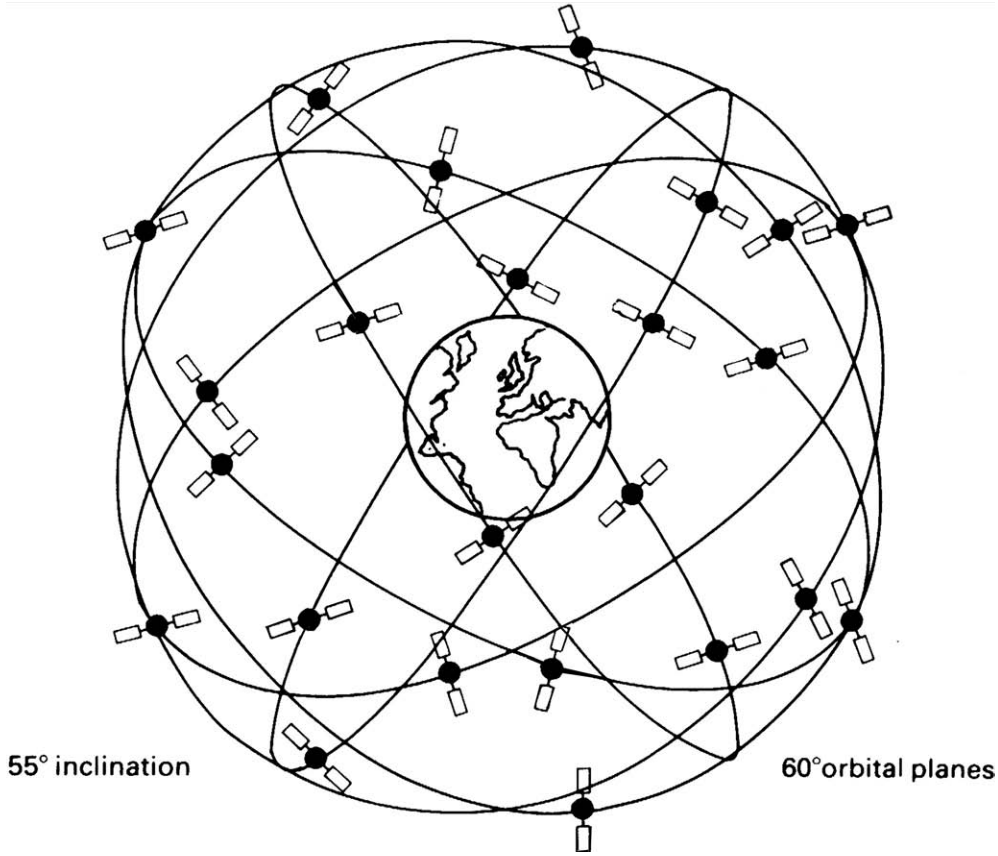

Figure 5.5 GPS satellite coverage. Twenty-four satellites provide global coverage; four in each of six orbital planes.

downgrading functions, SA and A-S, will no longer be implemented in the GPS. Block IIR SVs (numbers 41–62) are replenishment satellites and have been designed for an operational life of 7.8 years.

All SVs transmit a navigation message comprising orbital data, clock timing characteristics, system time and a status message. They also send an extensive almanac giving the orbital and health data for every active SV, to enable a user to locate all SVs once one has been acquired and the data downloaded.

5.3.2 The control segment

The GPS is controlled from Schriever Air Force Base (formerly Falcon AFB) in Colorado. It is from there that the SV telemetry and upload functions are commanded. There are five monitor stations (see Figure 5.6), which are situated in the Hawaii Islands in the Pacific Ocean, on Ascension Island in the Atlantic, on Diego Garcia in the Indian Ocean, on Kwajalein Island, again in the Pacific, and at Colorado Springs on mainland US territory. SV orbital parameters are constantly monitored by one or more of the ground tracking stations, which then pass the measured data on to the Master Control Station (MCS) at Schriever. From these figures the MCS predicts the future orbital and operational

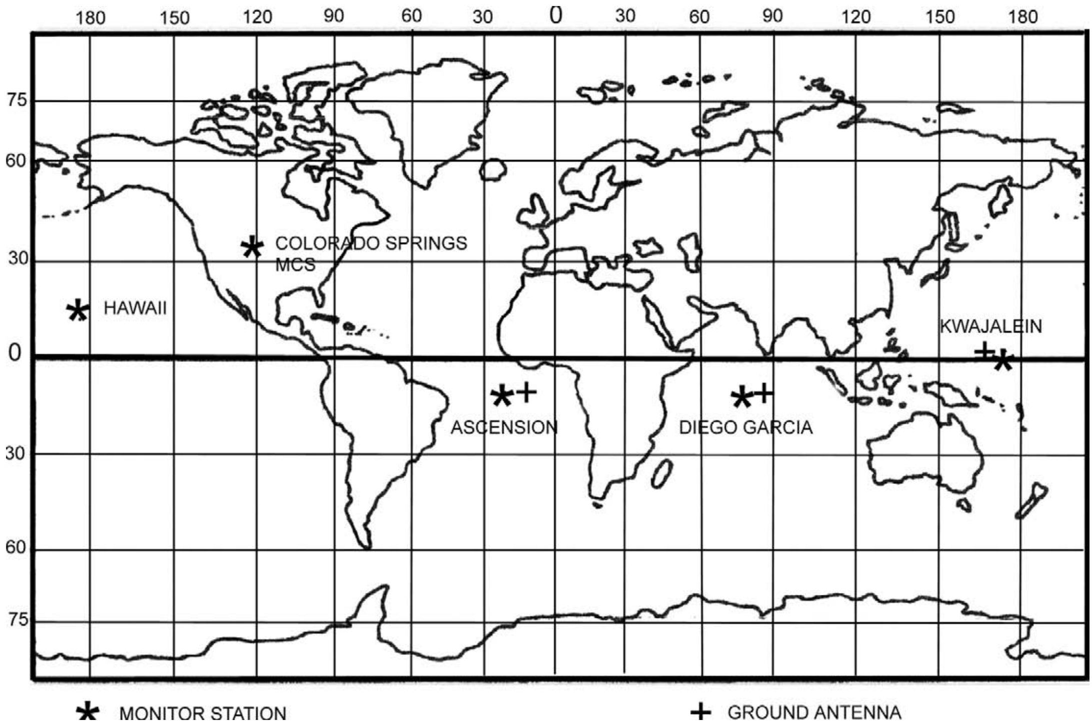

Figure 5.6 GPS control segment stations.

parameters to be fed to the Upload Stations (ULS) on Ascension, Diego Garcia and Kwajalein Islands. All ground station locations have been precisely surveyed with respect to the World Geodetic System 1984 (WGS-84). Data are transmitted to each SV from a ULS, to be held in RAM and sequentially transmitted as a data frame to receiving stations.

Signal parameters

Navigation data are transmitted from the SV on two frequencies in the L band (see Table 5.1). In practice the SV clock is slightly offset to a frequency of 10.229 999 995 45 MHz to allow for the effects of relativity. SV clock accuracy is maintained at better than one part in 10^{12} per day. Dual frequency transmission from the SV ensures that suitably equipped receivers are able to correct for signal delay (range error) caused by the ionosphere. Ionosopheric delays are proportional to $1/f^2$ hence the range error produced will be different on each frequency and can be compensated for in the receiver.

The C/A (Coarse and Acquire) code, see Figure 5.7, is a PRN (pseudo random noise) code stream operating at 1.023 megabits/s and is generated by a 10-bit register. C/A code epoch is achieved every 1 ms (1023 bits) and quadrature phase modulates the L_1 carrier only. This code has been designed to be easily and rapidly acquired by receivers to enable SPS fixing. Each SV transmits a unique C/A code that is matched to the locally generated C/A code in the receiver. A unique PRN is allocated to each SV and is selected from a code series called Gold codes. They are specifically designed to minimize the possibility that a receiver will mistake one code for another and unknowingly access a wrong satellite. Navigation data is modulated onto the L_1 C/A code at a bit rate of 50 Hz.

Table 5.1 SV transmission frequencies

Band	*Derivation (MHz)*	*Frequency (MHz)*	*Wavelength (cm)*	*Code*
L_1	154×10.23	1575.42	19	C/A
L_2	120×10.23	1227.60	24.5	C/A & P

Both carriers are derived from the SV clock frequency 10.23 MHz

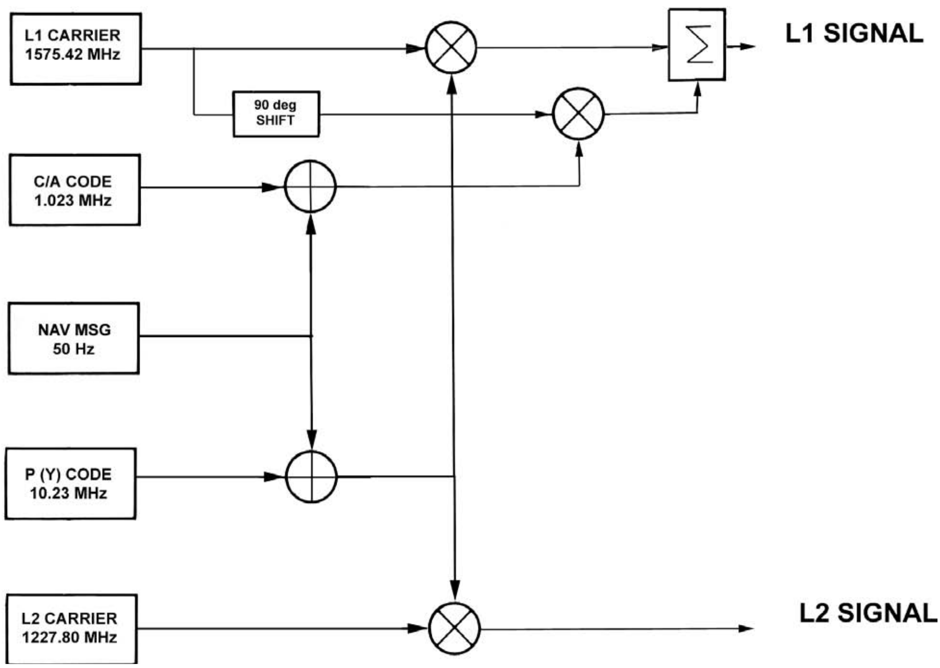

Figure 5.7 Schematic diagram of a SV modulation circuit.

The P (Precise) code, operating at 10.23 MHz, is a PRN code produced as the modulo 2 sum of two 24-bit registers, in the SV, termed X1 and X2. This combination creates a PRN code of 2^{48-1} steps equating to a complete code cycle (before code repetition occurs) of approximately 267 days. Each SV employs a unique and exclusive 7-day long phase segment of this code. At midnight every Saturday, GPS time, the X1 and X2 code generators are reset to their initial state (epoch) to re-initiate the 7-day phase segment at another point along the 267-day PRN code cycle. Without prior knowledge of the code progression, it is not possible to lock into it.

The navigation data message

A 50-Hz navigation message is modulated onto both the P code and C/A codes. One data frame is 1500 bits and takes 30 s to complete at the bit rate of 50 bit s^{-1}. Navigation data are contained in five subframes each of 6 s duration and containing 300 bits. Table 5.2 shows the data format structure.

Table 5.2 Data format structure

Five words 300 bits each with a total of 6 s			
	30 bits	*30 bits*	*240 bits*
01	TLM	HOW	Data block 1: Clock correction data. Accuracy and health of the signal.
02	TLM	HOW	Data block 2: Ephemeris data. Precise orbital parameters to enable a receiver to compute the position of an SV.
03	TLM	HOW	Data block 3: Ephemeris. Continued.
04	TLM	HOW	Data block 4: Almanac. Orbital data, low-precision clock data, simple health and configuration status for every SV, user messages, ionosopheric model data and UTC calculations.
05	TLM	HOW	Data block 5. Almanac. Continued.

Subframes 4 and 5 hold low precision data, common to all SVs, and less critical for a satellite to acquire quickly.

As shown in Figure 5.8, each of the five subframes commences with a 14-bit TLM word (telemetry) containing SV status and diagnostic data. This is followed by a 17-bit handover word (HOW). HOW data enables a receiver, which has knowledge of the code encryption, to acquire the P code. Data subframe block 1 contains frequency standard corrective data enabling clock correction to be made in the receiver. Data blocks 2 and 3 hold SV orbit ephemeris data. The two blocks contain such data as orbit eccentricity variations and Keplerian parameters. Message block 4 passes alphanumeric data to the user and is only used when the ULS has a need to pass specific messages. Block 5 is an extensive almanac that includes data on SV health and identity codes.

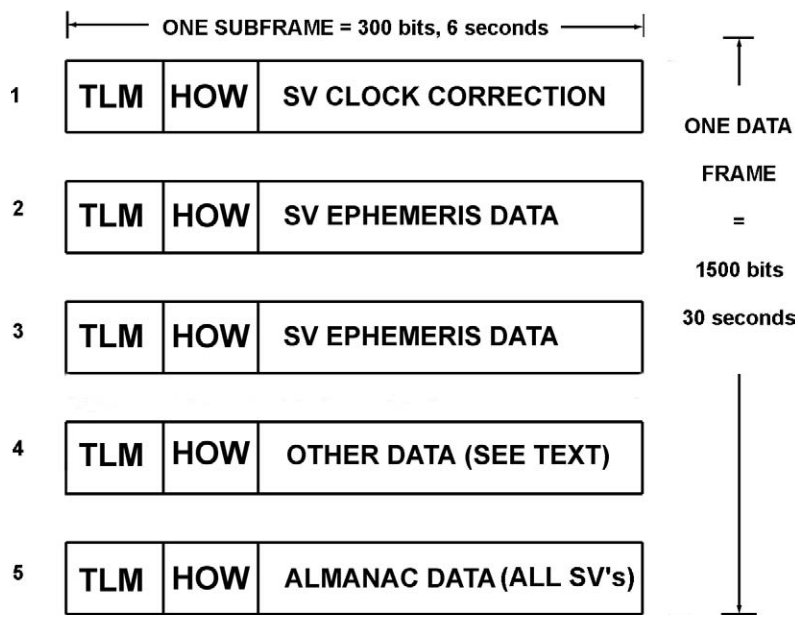

Figure 5.8 Navigation data format.

Table 5.3 Summary of data in a 30-s frame

A	SV orbital parameters
B	SV clock error data
C	Sidereal correction figures
D	Almanac of all operational SVs
E	Polar wander data (Earth axis wander)
F	SV performance status
G	Time of last data inject
H	Data to enable P code acquisition (HOW)
I	Telemetry data (TLM)
J	SV number
K	Specific messages as required (i.e. an indication that an SV is off station)
L	Receiver clock correction data

At the 50-Hz transmission rate, it takes 6 s to download a subframe, 30 s for one data frame (see Table 5.3) and a full 12.5 min to access all 25 frames.

The L_1 signal carrier is BPSK-modulated by both the P and C/A PRN codes and the navigation message. Modulation possesses both in-phase and quadrature components as shown in Figure 5.9.

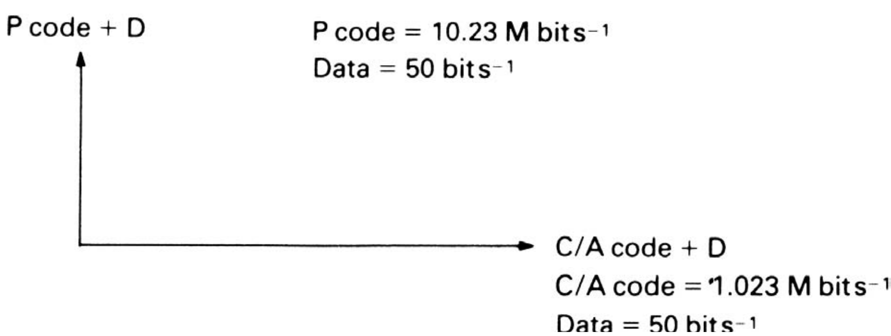

Figure 5.9 Phase relationship between the P and C/A codes.

P code amplitude is –3dB down (half the power level) on the C/A code signal strength, thus the slower C/A code provides a better signal-to-noise ratio at the antenna. This makes the C/A code easier to access. The L_2 carrier is BPSK-modulated by the P code and the navigation message. The use of BPSK modulation causes a symmetrical spread of the code bandwidth around the carrier frequency. The frequency spectrum produced by both P and C/A codes on the L_1 carrier is shown in Figure 5.10. The bandwidth of the C/A code is 2.046 MHz and that of the P code is 20.46 MHz. The C/A code component of the L_1 signal possesses a power of –160 dBW (with respect to 1 watt), the L_1 P code a power of –163 dBW, and the L_2 P code signal has a power level of –166 dBW.

It should be noted that data modulation at 50 bit s^{-1} produces a bandwidth of 100 Hz that is impossible to illustrate on this scale. Signal bandwidth, code matching and data stripping are further explained in the GPS receiver pages later in this chapter.

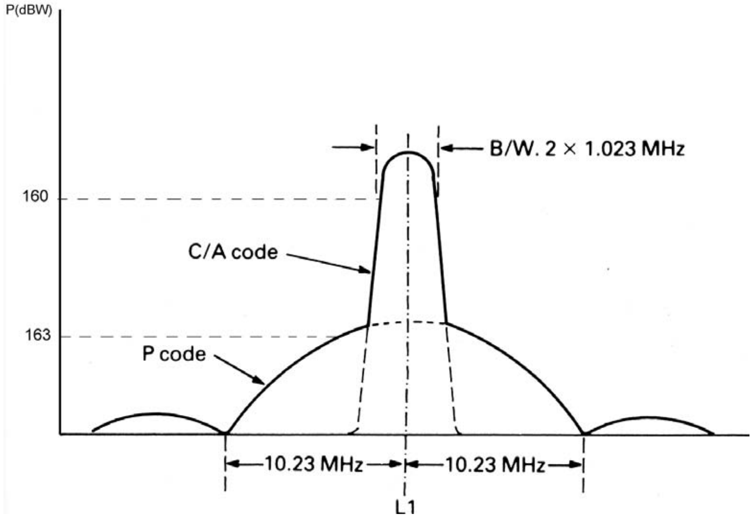

Figure 5.10 Bandwidth power distribution curves for the P and C/A codes.

Frequency stability

SV clock frequency stability is of major importance in any system that relies upon the accurate measurement of range for its operation. Stability is not easy to maintain in an electronic unit that is subjected to constantly varying ambient temperatures. The SV is travelling through a hostile environment where temperatures can vary by as much as 300°C. In addition, at the high altitudes of any SV, there is little protection from the sun's radiation. For these reasons the clock oscillators in SVs are under constant scrutiny

Since the early days of radiocommunication development, oscillator stability has been a major problem and it is one that has been compounded with the need to send clock oscillators into space. Older SVs, such as the Transit and Nova range on which the earlier NNSS sat-nav system was based, used quartz-controlled clock oscillators to give a short-term stability of 10^{-11} with a 24-h change less than 10^{-9}. Timation SVs, the first to provide navigation capability by the calculation of the range between satellite and receiver, carried a quartz clock oscillator with a stability of 1 part in 10^{-11} per day. Timation SVs carried a new frequency standard unit formed by a quartz oscillator locked to an atomic resonance line of rubidium.

The technology used in rubidium and caesium clock oscillators is beyond the scope of this book. However, it should be noted that use of this type of oscillator in NTS1 produced the two transmission signals (UHF and L band) to an accuracy of 1 part in $l0^{-12}$ per day. Caesium/quartz units offer even greater frequency stability and in 1975 the second generation of NTS vehicles was launched into orbit. NTS2 carried a caesium frequency standard unit from which were produced the carrier frequencies (SHF, L_1 and L_2) with an accuracy of 1 part in 10^{-13} per day. These oscillators are still in orbit and still being tested by the armed forces. Caesium clocks, however, require regular updating from the ground and in an effort to further improve and maintain stability for extended periods, clock units using hydrogen maser technology are being considered.

The clock oscillators used in current Navstar SVs are caesium/quartz with rubidium/quartz back-up units.

System time

GPS system time is locked to the Master Clock (MC) at the USNO and further synchronized to UTC from which it will never deviate by more than 1 μs . Actual system time is given by its Composite Clock (CC) or, as it is often called a 'paper' clock, which had its epoch at 0000 UTC on 17 June 1990. Information about the GPS time difference and rate of system time against UTC (USNO) is contained in the navigation message transmitted to all users. Once a satellite has been accessed the user equipment clock is corrected.

5.4 The position fix

The GPS provides two levels of service known as Precise Positioning Service (PPS) and Standard Positioning Service (SPS), the accuracy of which were defined in the 1994 US Federal Radionavigation Plan. The PPS predictable accuracy is given in Table 5.4.

Table 5.4 PPS predictable accuracy

Horizontal accuracy	21 m
Vertical accuracy	27.7 m
Time transfer accuracy	197 ns

Based on a 95% Rayleigh distribution probability

PPS fixes are based on range measurement and the acquiring and integrating of the C/A code and the complex P code transmitted on both the L_1 and L_2 carrier frequencies. The method provides highly accurate positioning, timing and velocity figures for users authorized by the US Government. PPS users were generally the US military, government agencies and approved allied forces, but since 1 May 2000, when selective availability was ended, PPS fix accuracy is available to anyone with suitable equipment.

Selective availability (SA) was the name given to a process employed by the US Department of Defence to deny PPS accuracy to civilian users. SA was applied by offsetting SV clock frequency (dithering), and/or manipulating navigation orbit data (epsilon). To guard against the fake transmission of SV data, a system called anti-spoofing (A-S) was used whereby the P code was encrypted becoming the Y code. By Presidential order, on 1 May 2000, the US Government ceased to apply SA to the GPS and thus there is now little difference between SPS and PPS fix accuracy (see Table 5.5).

Table 5.5 SPS predictable accuracy

	Prior to 1 May 2000	*Subsequent to 1 May 2000*
Horizontal error	100 m	25 m
Vertical error	156 m	30 m
Time transfer error	340 ns	200 ns

Based on a 95% Rayleigh distribution probability
Note: On 1 May 2000, Selective Availablity (S/A) was set to zero and SPS accuracy was thus improved by a factor of almost 10. The figures in column 3 are an approximation.

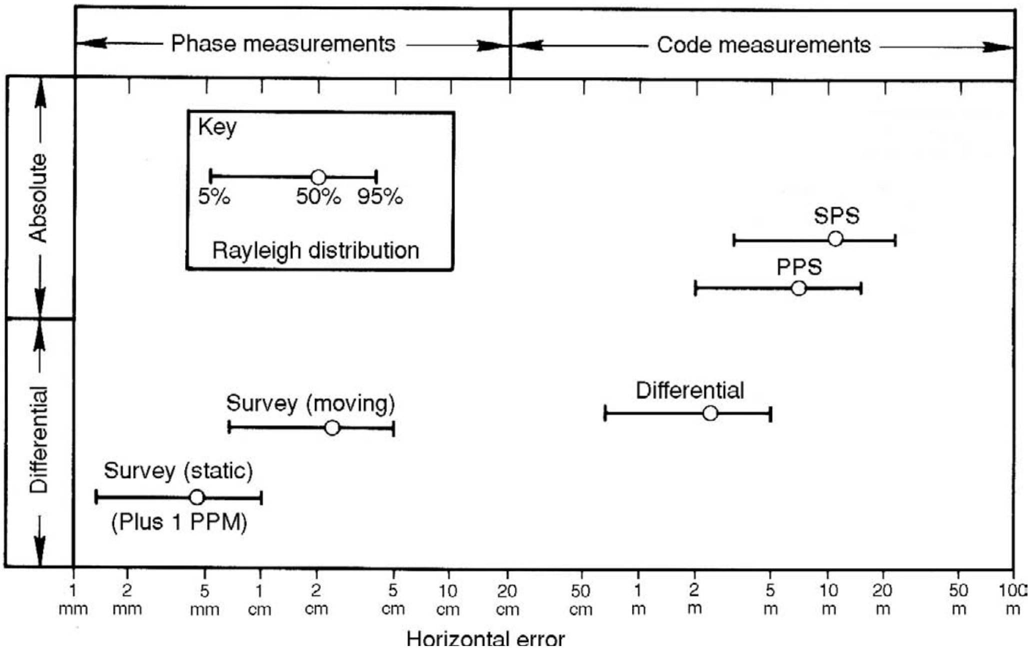

Figure 5.11 Levels of GPS accuracy. (Reproduced courtesy of Magnavox.)

The decision to remove SA from the GPS was taken because it would have minimal impact on national security. Based on threat assessment analysis, it is possible for the US Government to selectively deny GPS signals on a regional basis if national security is threatened.

SPS fixes are based on acquiring and integrating the C/A code data transmitted on the L_1 carrier frequency, measuring ranges and decoding the navigation message. SPS fix accuracy can be extensively improved by using Differential GPS (see Figure 5.11). Data is received, at both a mobile and a ground station, from multiple SVs and, after the computation of correction figures at the fixed station, is retransmitted to the mobile receiver. The process is achieved in real time although because of the relatively short distances travelled by a ship between fixes it is possible to apply corrections to subsequent computations.

The upper part of Figure 5.11 shows the anticipated levels of accuracy of a standard position fix without the aid of differential techniques, whereas the lower half shows fix accuracy for receivers with a differential input. It also demonstrates that the use of phase measurement in addition to code measurement improves the fix still further. All fix lines are shown as Rayleigh distribution data.

GPS position fixes are achieved by the precise measurement of the distance between a number of SVs and a receiver at an instant in time and/or by phase measurement. It is possible for a receiver, with a precise clock and with a knowledge of altitude above the earth reference spheroid, to fix its position in three dimensions by interrogating a minimum of three SVs. But in practice, modern equipment provides for more precise position fixing using the data from four or more SVs. By interrogating multiple SVs it is possible to obtain accurate fixes in three dimensions (XYZ) plus time. All fixes computed by a receiver are known as earth-centred-earth-fixed (ECEF) locations and therefore navigation fixes are often quoted as ECEF XYZ positions.

To measure the precise distance between the transmitter and the receiver requires highly accurate time clocks in both vehicles. The satellite clock is monitored from the ground and is corrected by atomic standard time. During calculations, it is accepted therefore, that this clock, which is used to generate the transmission frequencies, is accurate and the receiver clock may be in error.

For this reason range measurements are termed false or 'pseudo-ranges', and must be corrected in the receiver. The pseudo-range measurement for a receiver with an imprecise clock is given as:

$$PsR = Rt + C\Delta td + C(\Delta tu - \Delta ts)$$

where range figures are in metres and time in seconds, PsR = pseudo-range between satellite and receiver, Rt = true range, C = speed of light (3×10^8 ms^{-1}), Δts = satellite clock error from GPS time, Δtu = receiver clock error from GPS time, and Δtd = propagation delays due to both the ionosphere and the troposphere.

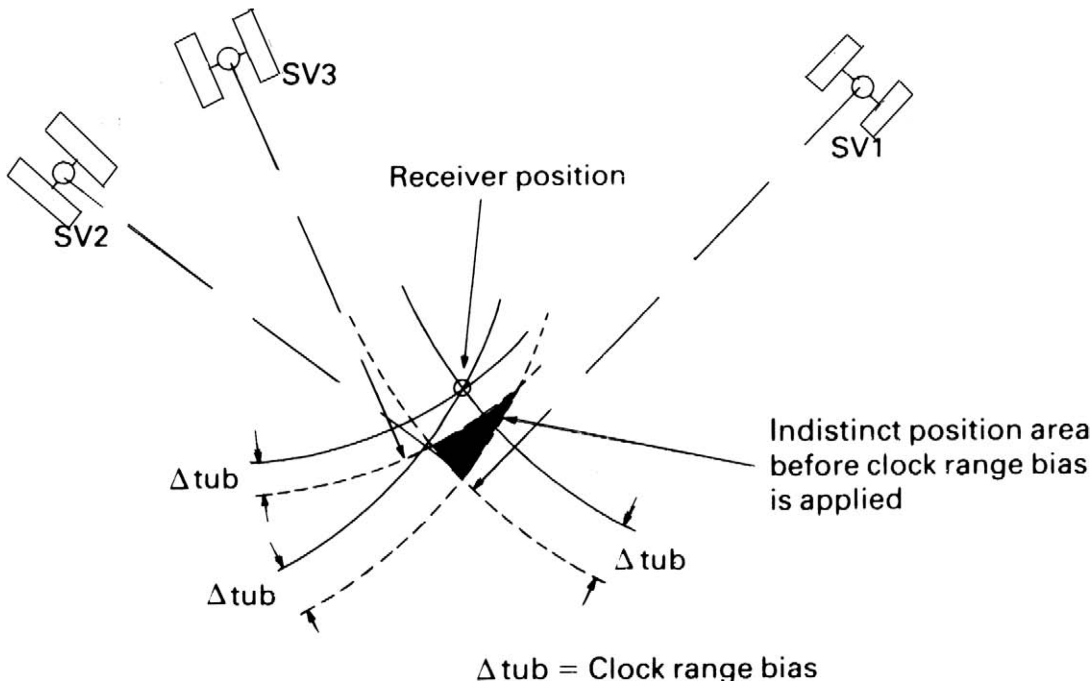

Figure 5.12 Showing the indistinct position fix obtained from three SVs before clock range bias is applied.

The GPS receiver calculates the pseudo-range time taken for the transmission by measuring the phase shift of the P code and comparing it with a locally generated code in the receiver computer. Figure 5.12 illustrates that the pseudo-ranges calculated for three satellites will not converge at a specific point unless the receiver clock error is corrected.

The computed position in XYZ co-ordinates is converted as a function of the receiver algorithm to geodetic latitude, longitude and altitude above the reference ellipsoid. The ship's position is solved with reference to Cartesian co-ordinates as shown in Figure 5.13 with reference to a minimum of three celestial 'fixed' points (the SVs).

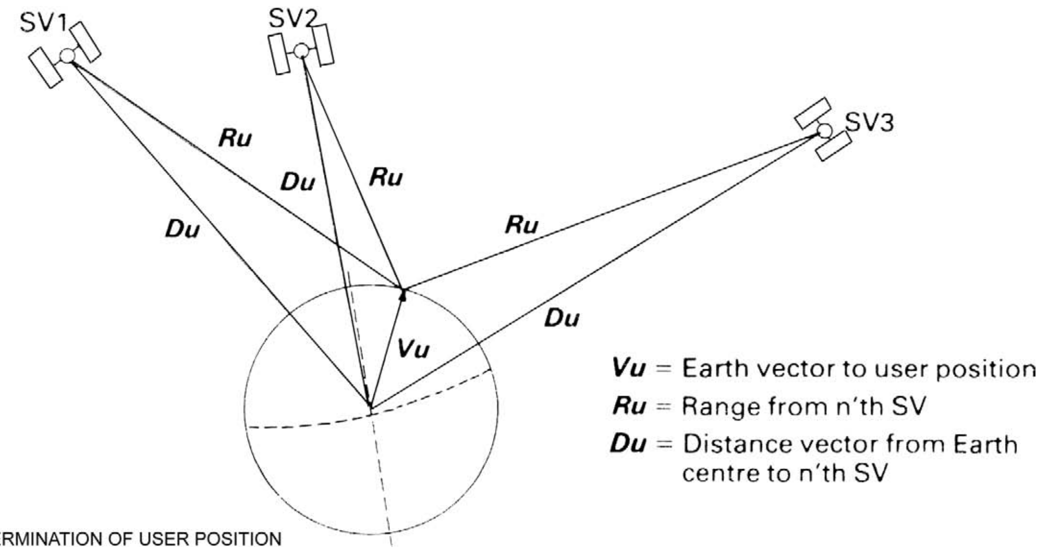

Figure 5.13 Using Cartesian co-ordinates to determine an earth centred position fix.

5.5 Dilution of Precision (DOP)

Dilution of Precision (DOP) is a term used for expressing the mathematical quality of a solution. DOP can exist in one dimension only. Examples are; time DOP (TDOP); horizontal DOP; vertical DOP and geometric DOP, referring to SV geometry. But it is the position dilution of precision, PDOP, that is of most value to a navigator. PDOP in the GPS has an optimum value of unity. If the figure is higher the solution is degraded (diluted). The PDOP will approach unity when a solution is made with a satellite overhead and three other satellites evenly spaced at low elevation angles. Alternatively, if all satellites are in the same plane, PDOP would be near infinity and the navigation fix solution would be unsound. The PDOP figure has a direct bearing on user range error (URE). For example, for a URE of 50 m and a PDOP of unity, the best fix accuracy is 50 m. If the PDOP is 2, the accuracy drops to 100 m. Modern GPS receivers may be programmed to reject a position solution if the PDOP level is high.

The geometry of the satellite orbital cage can seriously affect the accuracy of a position fix. With 24 satellites in six orbits there is a better than average chance that as many as six will be in view of a receiver at any given time. When pseudo-ranges are measured from SVs that are close together in the sky (Figure 5.14(a)), the result is an enlarged area of improbability resulting in a bad GDOP, as shown above. Alternatively if the SVs are well spaced, the improbability area will be smaller. Modern GPS receivers pick the optimum SVs from those available before correcting timing errors.

5.6 Satellite pass predictions

The system is so well documented and controlled that it has become increasingly easy to predict satellite passes at a given location. Trimble Navigation Limited, one of the biggest manufacturers of GPS equipment, operates a world wide web site that will be of interest to students. It is called GPS Mission Planning and is accessed on http://www.trimble.com/cgi/satview.cgi. It is also interactive and

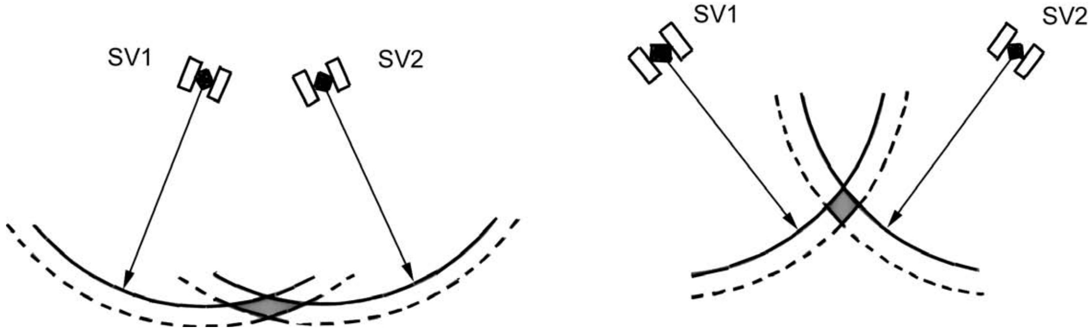

Figure 5.14 Fix accuracy can be improved by selecting appropriate SVs. (a) Two SVs giving a poor GDOP and (b) two SVs providing a much better solution.

provides six different charts of predictions. User parameters for all the plots are input into boxes as shown below. Latitudes south of the equator and longitudes west of the Greenwich Meridian are identified with a minus sign. The time input in GMT is in two figures between 00 and 23.

Using this system it is easy to predict SV passes at a given location and consequently it is simple to select the appropriate SVs to give a good GDOP.

Latitude:	32.43	Date:	00–00–2000
Longitude:	–117.10	Starting hour GMT:	00 hours
Mask:	15.0 degs.	Duration:	4 hours

The six plots are as follows.

- *Azimuth Plot.* Use this plot to locate SVs with optimum azimuth angle for a given location.
- *DOP Plot.* A low DOP indicates a high probability of accuracy, whereas a high DOP shows a low probability. The plot shown in Figure 5.15 is the result of calculations evaluating the geometry of four available SVs that will provide the most accurate fix. The plot has three data lines corresponding to HDOP, VDOP and PDOP predictions.
- *Elevation Plot.* This plot (Figure 5.16) shows the paths of all the satellites in view for a specified time period at a specific location. An SV reaching an elevation of 90° will pass directly overhead.
- *Sky Plot.* This plot (Figure 5.17) is oriented so that the GPS receiver is in the centre of concentric rings spaced at 15° intervals. The outer ring represents the horizon. Using this plot it is easy to see if a SV could suffer signal block from buildings or trees because it is low on the horizon.
- *Total-in-View Plot.* This is a graph showing the total SVs in view over a specified elevation angle. It is particularly useful for checking if sufficient satellites will be in view to make a good fix.
- *Visibility Periods Plot.* Another form of presentation showing the time periods when satellites will be in view above the angle of elevation specified.

5.7 System errors

Errors in any system arise from a number of sources. They can be predictable or not and avoidable or not. The GPS is no exception. If suffers from error-inducing factors which will downgrade its

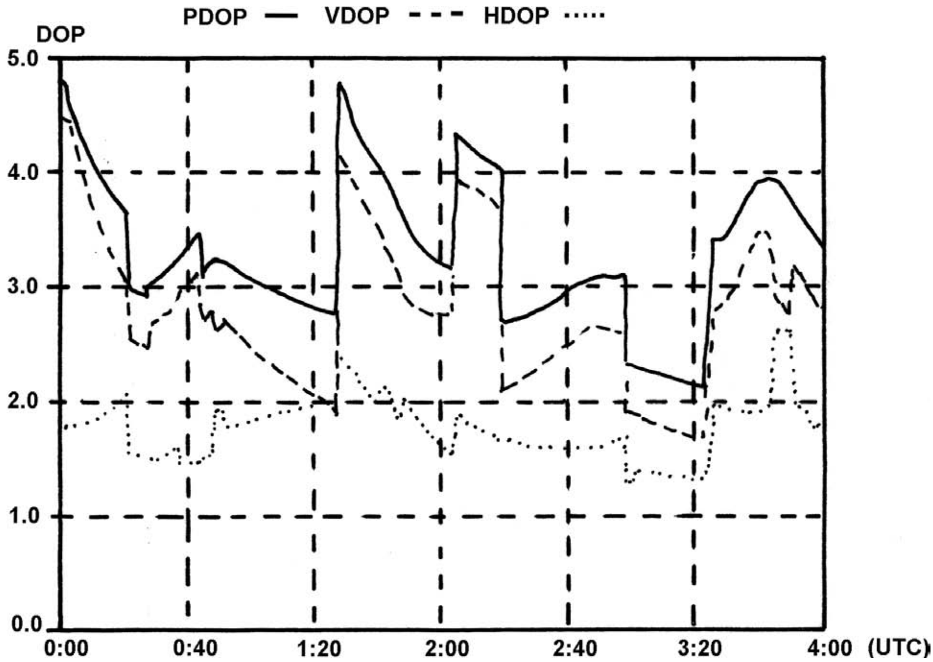

Figure 5.15 Trimble mission planning DOP graph taken over 4 hours. A low DOP indicates a high level of accuracy.

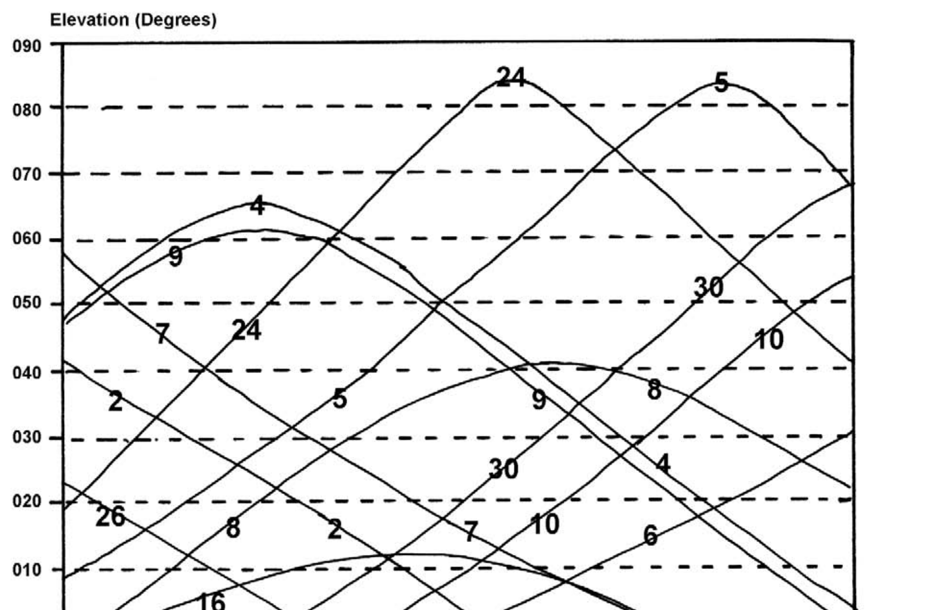

Figure 5.16 Trimble SV elevation plot. A 4-h plot showing all SVs in view.

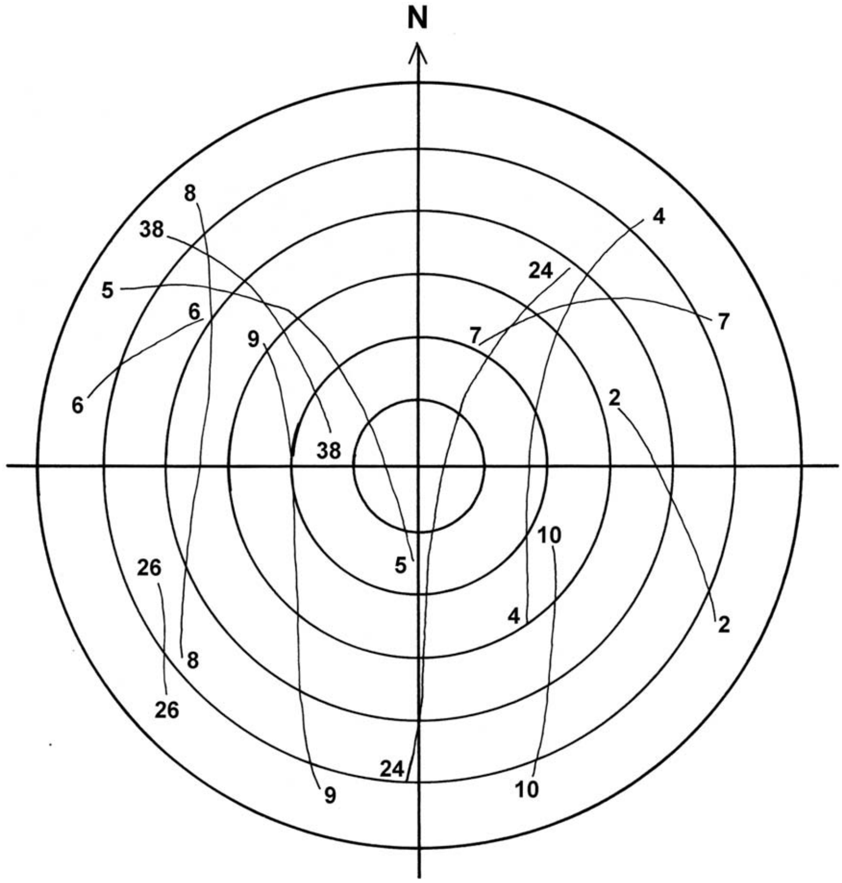

Figure 5.17 Trimble SV sky plot presentation. A GPS receiver is in the centre of concentric circles. The outer ring represents the horizon or zero elevation.

performance as a position fixing system. However, the total error produced by a combination of all error-producing factors is very small. Assuming that the system is free from operator error (corrupt data inputting), the error most likely to downgrade system accuracy is an error in the SV clock, which in turn will cause range measurement error.

GPS accuracy is promulgated in a number of ways as indicated below.

- *Circular Error Probable (CEP).* This represents an accuracy figure achievable 50% of the time in two dimensions only. This is a fix error in latitude and longitude.
- *Spherical Error Probable (SEP).* An accuracy that is achievable 50% of the time in all three dimensions.
- *Root Mean Square Radial Distance error (d_{RMS}).* A circle around the true position containing 95% of the fix calculations.
- *User Equivalent Range Error (UERE).* This is determined by summing the squares of the individual range errors and then taking the square root of the total.

The following errors affect the accuracy of GPS position fixes.

Satellite clock error

It has already been stated that a satellite clock oscillator is a precision instrument, but it is still necessary to re-adjust it from the ground support network. Error introduced by SV clock error is unlikely to exceed 1 m and regular uplinking of clock data reduces it to a minimum. Block IIA and Block IIR satellites, the latest SVs, carry better clock oscillators and will consequently provide higher accuracy fixes.

Ionospheric delay error

As the two transmitted carriers must pass through the ionosphere, a speed reduction caused by refraction of the radio wave occurs. The extent of the delay, and consequently the error introduced into the pseudo-range measurement calculation, is dependent upon the electron density the radio wave encounters along the signal path. Electron density is itself dependent upon three main factors:

- the time of day
- the SV elevation
- the latitude of the receiver.

Fortunately, ionospheric error is inversely proportional to the square of the carrier frequency. GPS SVs transmit on two frequencies so that the delay may be quantified in the receiver, an error correction figure calculated and applied to the final fix solution. After all corrective data has been applied to the solution in a single frequency GPS receiver system, fix error due to the ionosphere is unlikely to exceed 10 m.

Tropospheric delay error

Extending from the earth's surface to an altitude of 70 km, the troposphere also introduces a delay into the pseudo-range calculation. Unfortunately the error is independent of frequency, but it is predictable. GPS receivers hold a software solution in the form of a mathematical model to eliminate the effect of this delay. Figures for relative humidity, pressure and temperature are interfaced with the processor computer to produce corrective data which is then applied to fix calculation. Error from this source is unlikely to exceed 1 m.

Both ionospheric and tropospheric errors are reduced if ranges are measured from SVs showing a high elevation from the receiver. Modern receivers are capable of automatically selecting SVs with the highest elevation or those exceeding pre-set limits.

Multipath error

This results from the reception of the same SV signal from more than one source. A major contributor to this error is the reflected wave from an object close to the receiving antenna. Each receiver position is unique and therefore the error is not consistent. Final fix errors in the region of 1 metre can be produced by this effect. Careful positioning of the antenna will eliminate this error.

Relativity error

A commonly referred error is that produced by the effects of relativity. It is entirely predictable and is effectively cancelled in the GPS but it is briefly described here.

Albert Einstein stated that time is compressed by the mass of the earth. Time on the surface of the globe is compressed by $1.4 \times 10^{-9}\,\mathrm{ms}^{-2}$ compared to time in free space. It is evident that as one travels further away from the earth's surface towards free space, the compression of time is of less significance. At the altitude of a GPS SV, time compression is calculated to be $0.4 \times 10^{-9}\,\mathrm{ms}^{-2}$. An effective rate range time error of 1 ns therefore exists between the time on board the SV and that in the receiver. At the accepted propagation velocity of radio waves, i.e. $300 \times 10^{6}\,\mathrm{ms}^{-1}$, an error of 1 ns corresponds to a range error of 0.3 m. In addition, a second time error is produced by time compression caused as the SV moves at $26.61\,\mathrm{kms}^{-1}$ through space. To compensate for all relativity errors, the SV clock oscillator frequency is slightly offset. By the time that the radio wave arrives at the receiving antenna the effects of relativity will have been cancelled and the pseudo-range can be more accurately calculated.

These are by no means the only factors that affect the accuracy of the GPS system but they are often referred to in papers on this subject. A combined position error produced by all the above factors is unlikely to exceed 12 m.

User Range Error (URE)

This is a parameter for the estimated error in range calculation due to unknown factors. These include multipath, unmodelled atmospheric effects, operator error and unpredictable orbital errors. The URE figure is sent from SVs to GPS receivers and may be displayed in metres.

5.8 Differential GPS (DGPS)

As has already been stated, the accuracy of GPS fixes can be vastly improved using differential techniques. Experimental differential systems have been in use for some years as part of earlier hyperbolic earth-based navigation systems. DGPS is merely an improvement of those now outdated systems. The principle, as shown in Figure 5.18, is that GPS data from SVs are downloaded to both a mobile station and a fixed station at a precise location. A computer at the fixed site calculates the pseudo-range from GPS SVs and then compares it with the known ranges for that precise geographic location. It then computes a range error figure which is transmitted to mobile stations where it is used to correct the pseudo-range system errors.

The use of DGPS does not eliminate errors introduced by multipath reception or receiver noise.

For maritime use, DGPS differential monitor stations have been established around the coast of some 28 countries. As examples, the US Coast Guard maintains DGPS transmission stations around the continental coastline of the USA (see Figure 5.19 and Table 5.6), and in the UK beacons are operated by Trinity House and the General Lighthouse Authority (see Figure 5.20 and Table 5.7).

Corrective data are transmitted from the beacons on frequencies in the lower medium frequency band and as a result the range over which they can be reliably received is limited to between 100 and 250 km. But DGPS can and does assist in waters where freedom to manoeuvre is restricted.

The US Coast Guard and the International Association of Lighthouse Authorities (IALA) support the International Telecommunications Union (ITU) Recommendation M.823 which allows for DGPS data to be transmitted as supplementary information on the radiobeacon band 283.5–315 kHz (285–325 kHz in some parts of the world). The transmission protocol RTCM SC-104 (developed by the Radio Technical Commission for Maritime Services Special Committee 104) is used to determine the speed and data format of the transmission. DGPS data is phase shift keyed onto the carrier at a rate of 100 or 200 bits per second.

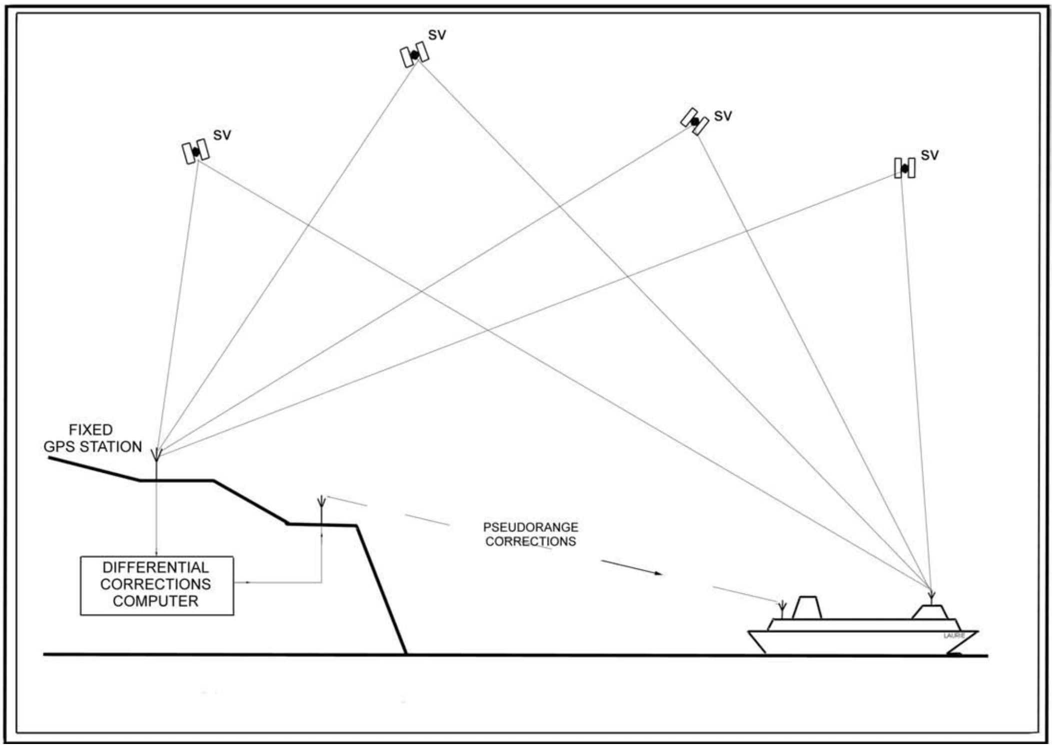

Figure 5.18 Principle of operation of DGPS.

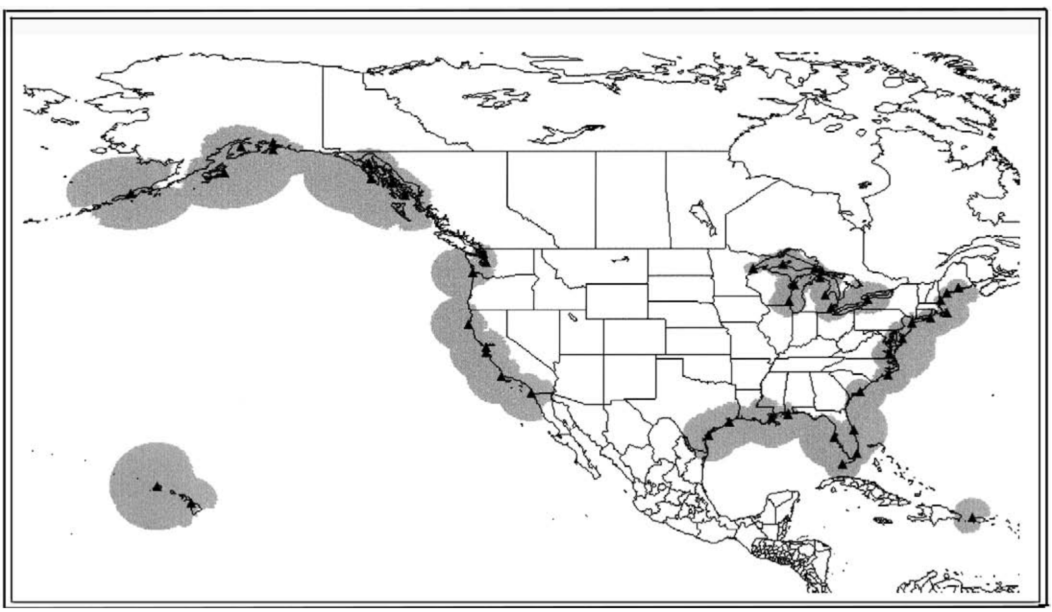

Figure 5.19 Maritime DGPS coverage of the United States. (Reproduced courtesy of the United States Coast Guard.)

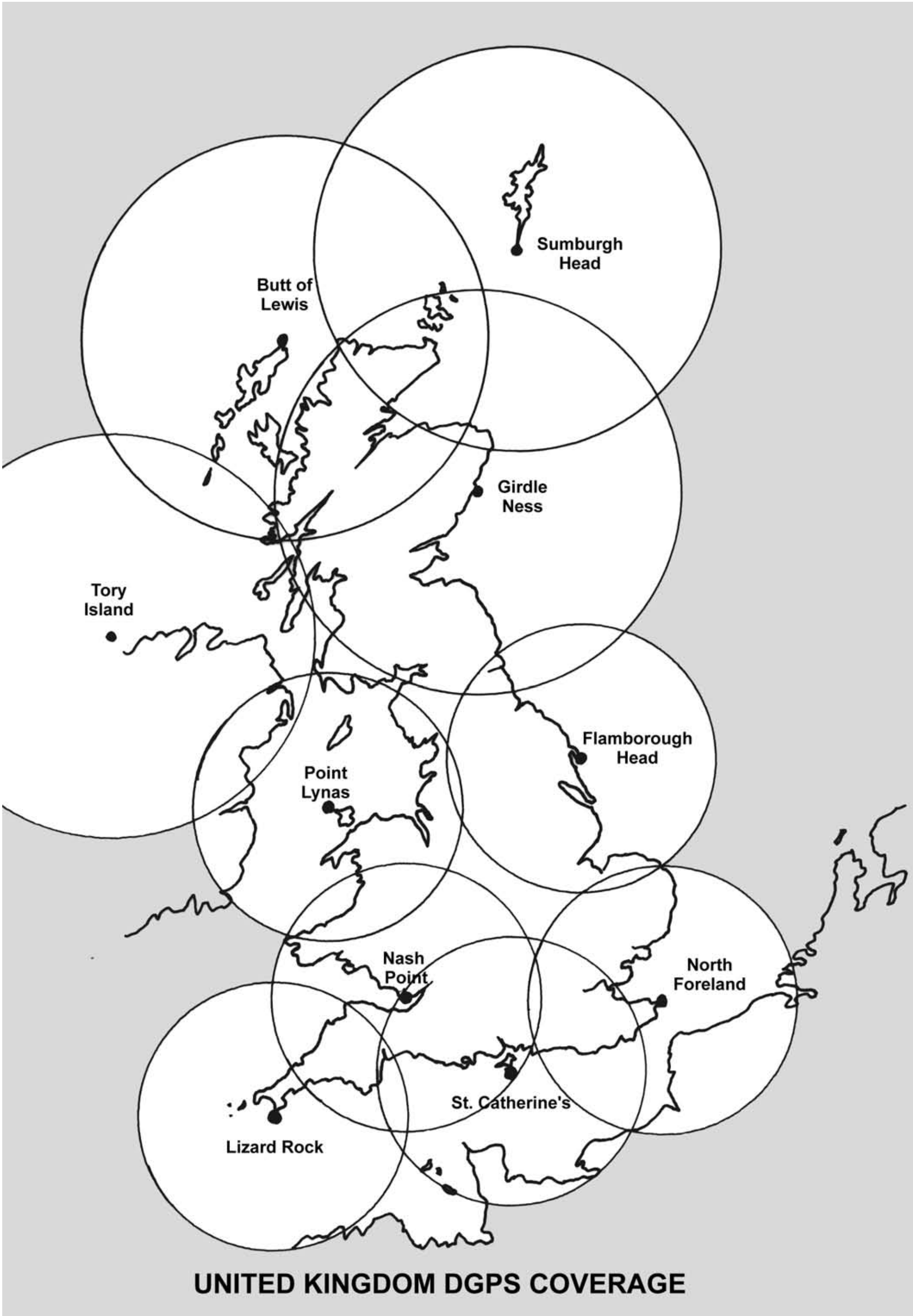

Figure 5.20 DGPS coverage of the UK coastline.

Table 5.6 Florida differential GPS stations data

Station	*Location*	*Frequency (kHz)*	*Nominal range (km)*
Cape Canaveral	28.27 N 80.32 W	289	200
Miami	25.43 N 80.09 W	322	75
Key West	24.34 N 81.39 W	286	75
Egmont Key	27.36 N 82.45 W	312	200

Source: United States Coast Guard.

Table 5.7 UK differential GPS station data

Station	*Location*	*Frequency (kHz)*	*Nominal range (km)*
Sumburgh Head	59.51 N 01.16 W	304.0	275
Butt of Lewis	58.31 N 06.16 W	294.0	275
Girdle Ness	57.08 N 02.03 W	311.0	275
Tory Island	55.16 N 08.15 W	313.5	275
Flamborough Head	54.07 N 00.05 W	302.5	185
Point Lynas	53.25 N 04.17 W	305.0	185
Nash Point	51.24 N 03.33 W	299.0	185
North Foreland	51.23 N 01.27 E	310.5	185
St. Catherine's	50.35 N 01.18 W	293.5	185
Lizard Rock	49.58 N 05.12 W	284.0	185

Source: Trinity House

5.8.2 Wide Area Differential GPS (WDGPS)

WDGPS is a real-time global differential system currently under consideration for future implementation. Using the INMARSAT communications network, differential data will be transmitted to ships throughout the world enabling better fixes to be made. It is still in the discussion stage.

5.9 GPS antenna systems

Arguably the antenna is the most critical part of any radiocommunications system but unfortunately it is the piece of hardware that is most often ignored. Carefully designed and constructed, an antenna sits, open to the elements, on board a vessel's superstructure in a position where routine maintenance can be difficult. GPS antennas are small and rigidly constructed and to ensure that they survive the elements they are protected by a raydome.

In common with the INMARSAT communications antenna, a GPS antenna ideally requires an unobstructed view through 360° from the horizon up to 90° in elevation. Radiated energy from other microwave transmission systems can damage sensitive pre-amplifier circuitry inside the GPS protective dome. It is wise, therefore, to mount the GPS antenna below the INMARSAT raydome and outside the radar transmission beamwidth as shown in Figure 5.21.

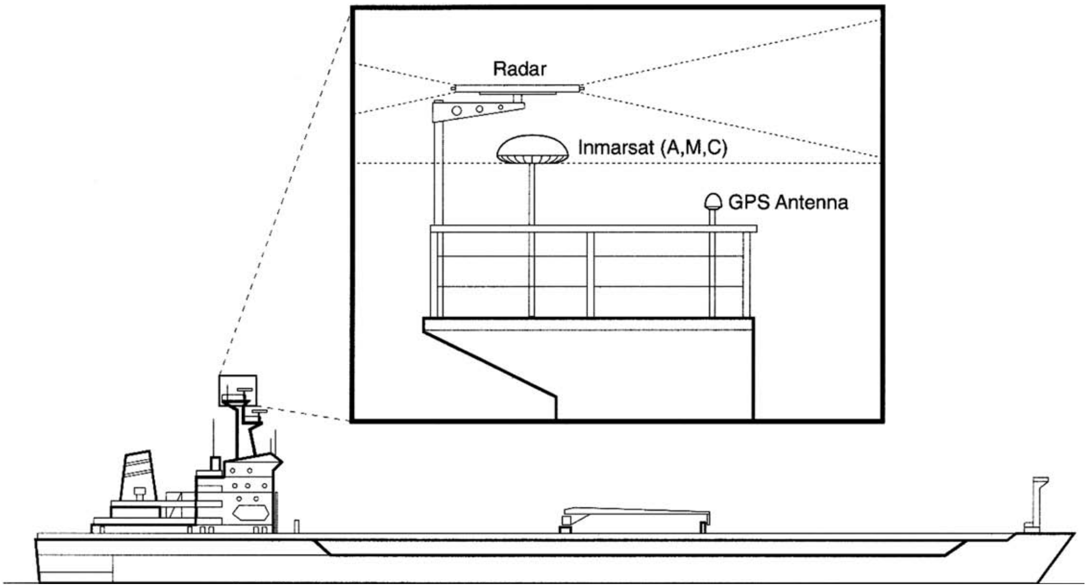

Figure 5.21 A GPS antenna mounted below other microwave system antennas on the superstructure of a merchant vessel. (Reproduced courtesy of Trimble Navigation Ltd.)

Other factors to be considered when siting an antenna are as follows.

- Mounting the antenna on the top of a tall mast will accentuate range errors caused by the vessel's motion especially if DGPS is used. The range error is dependent upon the extent of the vessel's motion and is therefore unpredictable.
- No special ground plane is required, but a large open deck space below the antenna will reduce the error caused by reflected multipath signals.
- Stays, masts and dry sails in the path between the SV signal and the antenna will have little effect of the received signal.
- GPS systems use an active (containing some electronic circuitry) antenna head which can be affected by severe vibration. Mount the antenna away from other antennas, engine housings or exhaust stacks.

5.10 GPS receiver designation

Because GPS is freely available to all users throughout the world, the range of available user equipment is vast. There are thousands of manufacturers producing a bewildering range of fixed and mobile equipment, all of which must comply with GPS standards. GPS receiver architecture varies depending upon how it is to be used. The following list itemizes the most popular GPS receiver systems currently produced. The more commonly found commercial receivers are listed first.

Multiplex (MUX) Receivers

Amongst the cheapest GPS receiver architecture, MUX receivers are commonly found in the commercial sector. A MUX receiver continuously tracks multiple SVs by continuously switching its single channel between them. Time measurements and data streams are held in memory algorithms and 'topped-up' when data is made available by the MUX switch rate. Receiver architecture is less complex and consequently cheaper. MUX receivers are only used on slow moving platforms such as merchant vessels.

Sequential Receivers

Receiver architecture is designed to track one SV at a time and calculate the pseudo-range. The data is held in memory until four SVs have been interrogated, when the position–velocity–time (PVT) fix is calculated. These receivers are the least expensive and possess the slowest time-to-first-fix (TTFF) performance.

Single Channel Sequential Receivers

As the title suggests, these receivers use a single channel to sequentially measure the pseudo-ranges from four SVs. Each SV is fully interrogated in sequence and the final fix made from stored data. Any uncorrected movement of the receiver during this process reduces the fix accuracy.

Dual Channel Sequential Receivers

The only advantage of this type of receiver is that, in using two channels, it reduces the time it takes to calculate a fix. They tend to be used on medium velocity platforms, such as aircraft.

All-in-View Receivers

An All-in-View receiver has the necessary hardware to search the sky and track all the SVs that it finds. Whilst four SVs are needed to give a good PVT fix, it is likely that satellites will be lost before they can be fully interrogated. This type of receiver architecture can track seven or eight SVs continuously so if some SVs drop out of its view the PVT fix should still be good. If satellite data is not lost during tracking, a fix is produced from the data of more that four SVs. In general, the more satellites that provide data for a fix, the better the fix.

Continuous Tracking Receivers

This type of GPS receiver possesses multiple channels to track four SVs simultaneously whilst acquiring new satellites. TTFF figures are the lowest for any receiver architecture and PVT fix accuracy can be maintained on high velocity platforms such as fighter aircraft and missiles. Continuous tracking receivers offer the best performance and versatility but, as you would expect, they are the most expensive.

Differential GPS Receiver

DGPS receivers are now in common use on maritime vessels that require better PVT fix accuracy than can be obtained with a basic receiver. Vessel's trading in confined waters use DGPS receivers. They are more expensive, but the cost is justified. (See the section on DGPS.)

Time Transfer Receiver

This type of GPS receiver provides an accurate time source. It may be integrated into one of the receiver systems previously described or the time figure may be used in other navigation fix solutions.

5.11 Generic GPS receiver architecture

This section includes the description of a simple receiver and then goes on to consider specific modern systems. Figure 5.22 shows a generic GPS receiver system.

5.11.1 SV selection and acquisition

If the receiver can immediately 'recognize' a SV it will target that satellite and begin a tracking sequence. This is possible if the receiver has already downloaded almanac data from any SV, if not it will enter a 'search' mode and systematically hunt the sky looking for a recognizable PRN code. Once this is received, tracking will be initiated, lock will be achieved and the navigation message can be interrogated. The current almanac will then be cross-examined and the health status of all the other satellites will be determined. The computer then selects the best subset of visible SVs, or, all-in-view. In practice, data from a minimum of four SVs is required to provide a reliable navigation fix, but the greater the number that can be tracked and accessed, the better.

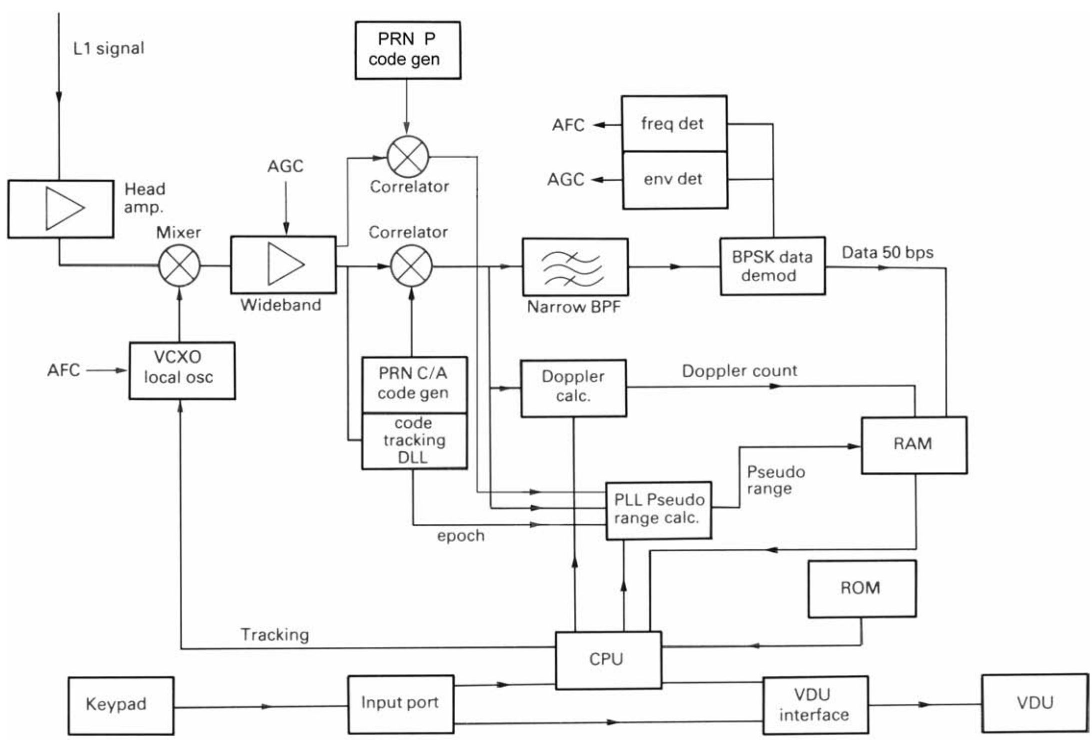

Figure 5.22 A generic GPS receiver system.

Because of limited satellite transmitter power, spread spectrum modulation techniques and ionospheric attenuation, the satellite signal power received at the earth's surface is far less than the receiver's natural or thermal noise level. This minute signal is received by a compact, fixed, above-deck unit using an isotropic antenna with ground plane radial reflectors, a low noise pre-amplifier and filters. Circularly polarized radio waves from the SV, are received by the isotropic antenna whilst the radial reflectors reduce the problem of multipath errors caused by the earth's surface reflected signals. The head unit should be mounted in such a way that the antenna has a clear view of the whole area in azimuth from the zenith to the horizon. Input to the receiver is therefore the amplified SV signal at 1575.42 MHz, plus a slight Doppler frequency shift and possessing a very poor signal-to-noise ratio.

The single signal mixer down-converts the L_1 carrier to an intermediate frequency. Frequency conversion is achieved using a Variable Frequency Local Oscillator (VCXO) under the control of both the Central Processing Unit (CPU) and a signal derived Automatic Frequency Control (AFC). CPU input to the VCXO enables initial SV tracking to be achieved and the tiny direct current AFC, derived from the received signal, maintains this lock. A wideband IF amplifier is used to permit reception of the 20.46 MHz bandwidth P code enabling future modification of the receiver to be made if required. Output from this amplifier is coupled to a correlator along with the locally generated PRN C/A code.

It is essential that the receiver tracks the received signal precisely despite the fact that it is at an amplitude which is hardly above the locally generated noise level. To achieve tracking the received signal is applied to a Delay Lock Loop (DLL) code tracking circuit that is able to synchronize the locally generated PRN code, by means of the EPOCH datum point, with the received code to produce the reconstituted code to the narrow bandpass filter. The DLL is able to shift the local PRN code so that it is early or late (ahead or behind) when compared to the received code. A punctual (Pu) line output to the correlator is active only when the two codes are in synchronism. PRN codes are described in more detail at the end of this chapter.

Output of the correlator is the autocorrelation function of the input and local PRN C/A codes. The bandwidth of the narrow band bandpass filter is 100 Hz so that data is passed only to the BPSK data demodulator where code stripping occurs. The autocorrelated C/A code is also used for both Doppler and pseudo-range measurement. The PLL used for pseudo-range measurement has a clock input from the CPU to enable clock correction and an EPOCH input each millisecond for alignment.

All receiver functions are controlled by a microprocessor interfaced with a keypad and a VDU display. The use of a microprocessor ensures economy of design. In this outline description most of the control lines have been simplified for clarity. The receiver operating sequence is given in Table 5.8.

5.11.2 Autocorrelation of random waveforms

The main function of the correlator in this receiver is to determine the presence of the received PRN code that is severely affected by noise. Correlation is a complex subject and the brief description that follows attempts to simplify the concept. Both the C/A and P codes are 'chain codes' or 'pseudo-random binary sequence' (PRBS) codes that are actually periodic signals. Within each period the code possesses a number of random noise-like qualities and hence is often called a 'pseudo-random noise code' (PRN code). The PRN binary sequence shown assumes that the code has a period of 15 samples, i.e. it repeats every 15 bits. The GPS P code possesses a period of 267 days and the C/A code a period of 1 ms. It is obvious therefore that a PRN code can possess any period.

To establish the autocorrelation function, both the received C/A code and the locally generated C/A code are applied to the correlator. Consider the local code to be shifted three stages ahead or behind (early or late) on the received code by a time period (t) known as parametric time. To obtain the product of the two codes, add each received bit to a locally generated bit shifted in time, as shown in Figure 5.23.

Table 5.8 Receiver operating sequence

01	Initialize
02	Search for an SV
03	Identify L_1 carrier
04	Acquire L_1 C/A code
05	Track L_1 C/A code
06	Strip data
07	Measure pseudo-range
08	Measure Doppler frequency shift
09	Store data
10	Commence next SV search and repeat steps 03–09
11	Commence next SV search and repeat steps 03–09
12	Commence next SV search and repeat steps 03–09
13	Compute navigation position
14	Output position data to display

The product is achieved by adding bits of data using the terms:

$(+1) + (+1) = +1$
$(-1) + (-1) = +1$
$(+1) + (-1) = -1$
$(-1) + (+1) = -1$

The average value of the products thus produced is –1/15. If the local code is now shifted one bit to the right and the products are noted again, the average value of the products is –3/15. When the two

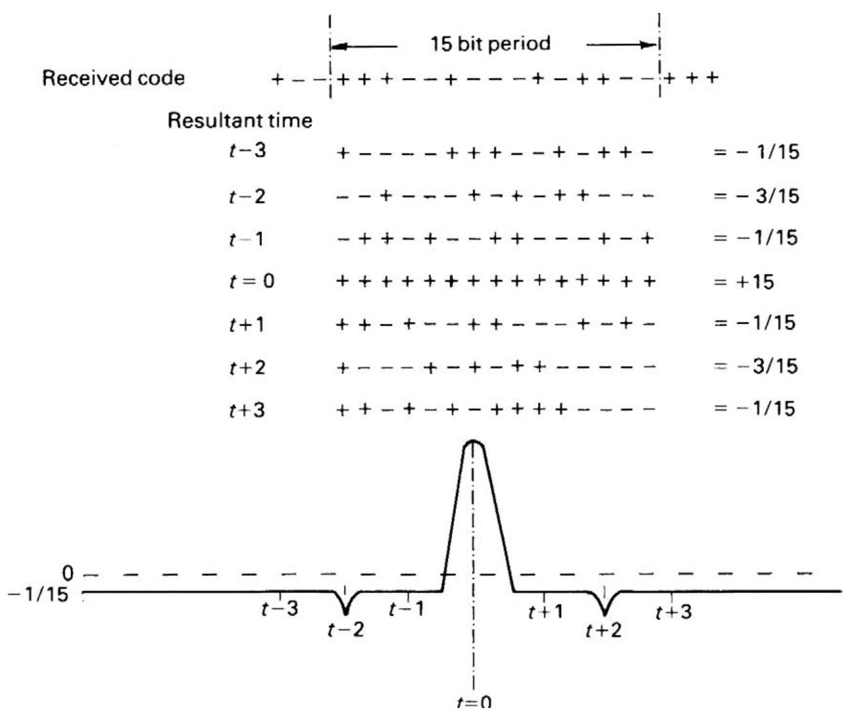

Figure 5.23 Autocorrelation function of a random waveform.

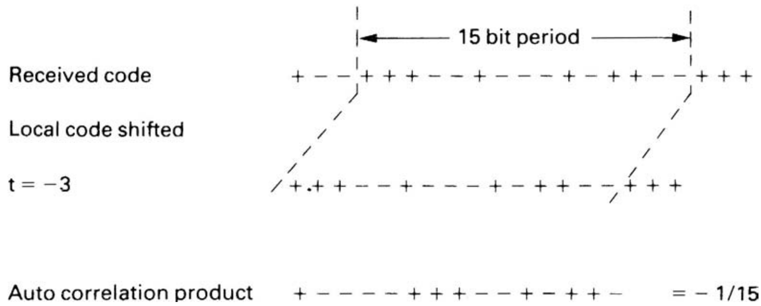

Figure 5.24 The autocorrelation product of a random waveform.

codes are synchronized the product of all bits is +1. Therefore the average value of the products is also +1. This is the only time per code period when all the code products are +1. The peak thus produced is called the autocorrelation function (see Figure 5.24) and enables the received code to be identified, even in the presence of noise which is essentially an amplitude variation.

The PRBS is periodic, therefore the autocorrelation function is periodic and repeats at the rate of the original signal. It is possible to determine the period of the received code by noting the periodicity of the peaks produced in parametric time. Thus the C/A code can be acquired even when it is severely affected by noise. The autocorrelation function peak also indicates the power density spectrum of the received code signal. A signal with a wide bandwidth (the P code) produces a sharper narrower correlation spike, whereas a wide correlation spike indicates a narrow bandwidth signal (C/A code). Obviously the width of the correlation spike is inversely proportional to the bandwidth of the received signal code.

The user equipment just described demonstrates many of the principles of GPS reception. However, equipment manufacturers will have their own ideas about how a GPS receiver should be configured.

5.12 GPS user equipment

The GPS is the undisputed leader in modern position fixing systems and, when interfaced with various shipboard sensors, GPS equipment forms the heart of a precise navigation system offering a host of facilities. Modern equipment is computer controlled, and this fact along with a versatile human interface and display means that the equipment is capable of much more than that produced for earlier position fixing systems.

There is a huge selection of GPS equipment available from a large number of manufacturers. Much of this equipment is designed for the small craft market, more is specifically designed for geodesy and earth mapping, still more is designed for the aeronautical market, and more for trucking operators. In fact it appears that the GPS has found a range of diverse uses in every corner of the globe. This book is written for the maritime navigation sector of this huge market and equipment is described to demonstrate the versatility and flexibility of modern GPS receivers.

Two huge companies that offer a full range of GPS equipment and services are Trimble Navigation Ltd. based in the heart of silicon valley at Sunnyvale, California, and Garmin based at Olathe, Kansas in the USA.

5.12.1 Trimble GPS receiver specifications

At the top of the Trimble's GPS range is the NT300D, a 12-channel parallel GPS receiver, capable of tracking up to 12 satellites simultaneously and also containing a dual-channel differential beacon receiver. The equipment is capable of submetre accuracy derived from carrier-phase filtered L_1 pseudo-range calculations. In addition, vessel velocity is obtainable from differentially corrected Doppler measurements of the L_1 carrier. Position information is displayed on a backlit LCD screen in one of two main navigation modes.

Interfacing with other navigation equipment is via one of the two serial RS-422 data ports using a variety of protocols including NMEA-0183 output and RTCM SC-104 in/out. Speed data output is available at the standard rate of 200 ppnautical mile.

Receiver operation

At switch on, the equipment automatically begins to acquire satellites and calculate range error to produce a position fix. TTFF varies between 30 s and 2–3 min depending upon the status of the GPS almanac, ephemeris data stored in the NT GPS's memory, and the distance travelled while the unit was switched off. During the acquisition process, the equipment operates on dead reckoning and shows this by displaying a DR in the top right corner of the display.

Figure 5.25 shows the user interface of the Trimble Navigation GPS NT200D. The buttons/keypads data input controls have been ergonomically designed to be easily operated and user friendly. A 15 cm (6 inch diagonal), high resolution, 320 × 240 pixel, backlit, LDC displays navigation data that can be easily read in most lighting conditions. Referring to Figure 5.25, the numbered functions are as follows.

1 Power key
2 Display
3 Brightness and contrast keys. Standard up/down scrolling key for screen viewing parameters.
4 Numeric keypad. Used to enter numeric data as well as controlling chart information layers when in the chart mode of operation.
5 Cursor controls. Arrow keys permitting movement of the cursor on those screens where it is present. When inputting data they are used to move through the programming functions.
6 Function keys. Used to access various functions.
   SETUP: used when customizing the operation of the equipment.
   STATUS: used to display various GPS parameters such as signal strength.
   NAV: toggles between NAV1 and NAV2 displays.
   SAVE: pressing this displays current position and time and gives the user a choice of entering the position as a waypoint or selecting the position as an emergency destination – the 'man overboard' function.
   WAYPT: used to access waypoint and route libraries.
7 Soft keys. So named because the functions they perform changes from screen to screen.
8 Menu key. Toggles the soft key labels on and off.
9 Plot key. Toggles between an electronic chart display and a Mercator grid display.

The NAV 1 screen shown is a graphic depiction of the vessel's relationship to the intended course. The intended course, represented by the central lane in the graphic, is based on the active route and current leg. The next waypoint is shown, by number and name, in the box located above the central lane.

At the top of the page, the screen header displays the current mode of operation. This may be DGPS, GPS, DR or EXT (external). External mode indicates that the equipment is receiving updates from an external device.

In the centre of the display is a circular symbol with crossed lines representing the ship's position. An arrow intersecting the screen centre indicates the ship's current heading (course over ground

(COG)) relative to the destination. When this arrow points at the next waypoint (course to waypoint (CTW)), the ship is heading in the correct direction; COG = CTW.

A right or left offset of the ship's symbol signifies the cross-track error (XTE). No error exists when the symbol is shown in the centre of the lane. XTE limits can be set using the main Setup screen. The relative velocity of the ship is indicated by the rate of advance of the horizontal lines located outside the central lane.

Other data fields may be selected for display. In Figure 5.25 the following have been selected: true course over ground (COG), speed over ground (SOG) in knots, XTE in NmR, and the ship's true heading (HDG) in degrees. Other options are CTW, speed (SPD), distance to waypoint (DTW), distance to destination (DTD), velocity made good (VMG), and distance made good (DMG).

An alternative display, NAV 2 in Figure 5.26, shows a graphic representation of a compass displaying the vessel's course COG and the bearing to the next waypoint CTW. The compass card graphic consists of an inner ring with a COG arrow and an outer ring with a CTW indicator arrow. When the two arrows are in alignment, COG = CTW, the vessel is on course. The compass graphic defaults to a north-up presentation but may be changed to a head-up display.

At the bottom of the display a steering indicator, labelled XTE, shows any cross track error in nautical miles. When the two arrowheads are in alignment at the centre of the bar, XTE is zero.

As a further indication of the capabilities of a modern electronic system, the Trimble NT GPS range may be fitted with a Smart Card Reader to read Navionics chart cards.

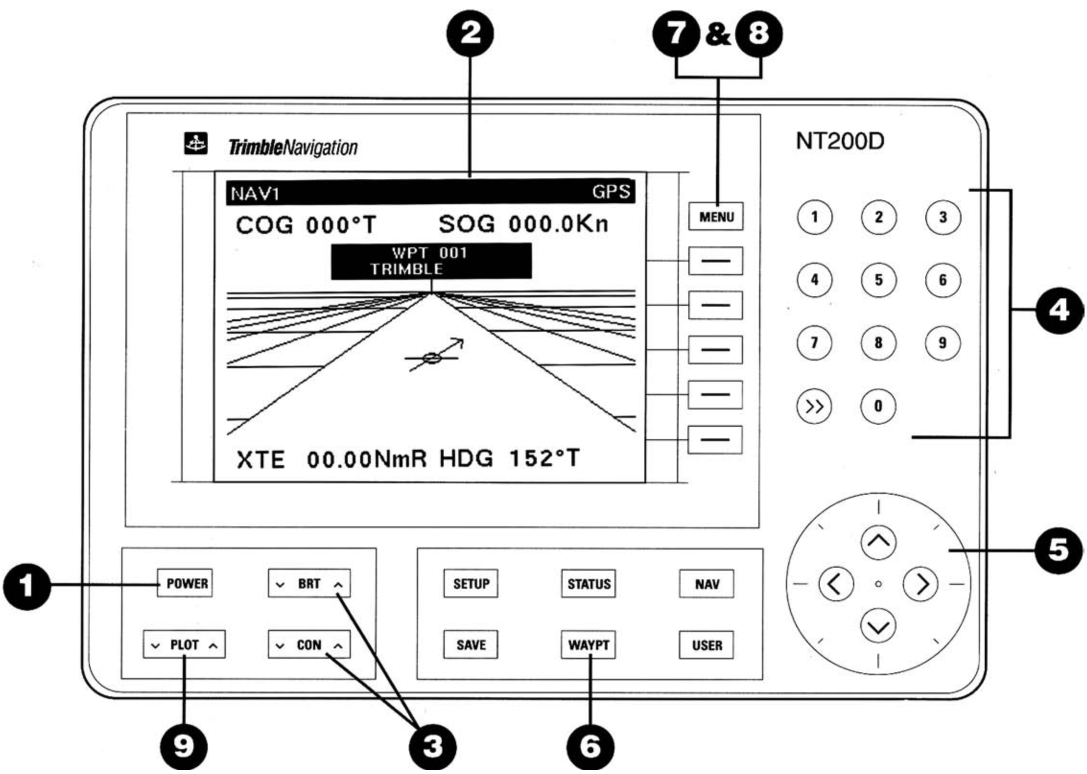

Figure 5.25 The NT200D GPS receiver displaying the NAV1 navigation display. (Reproduced courtesy of Trimble Navigation Ltd.)

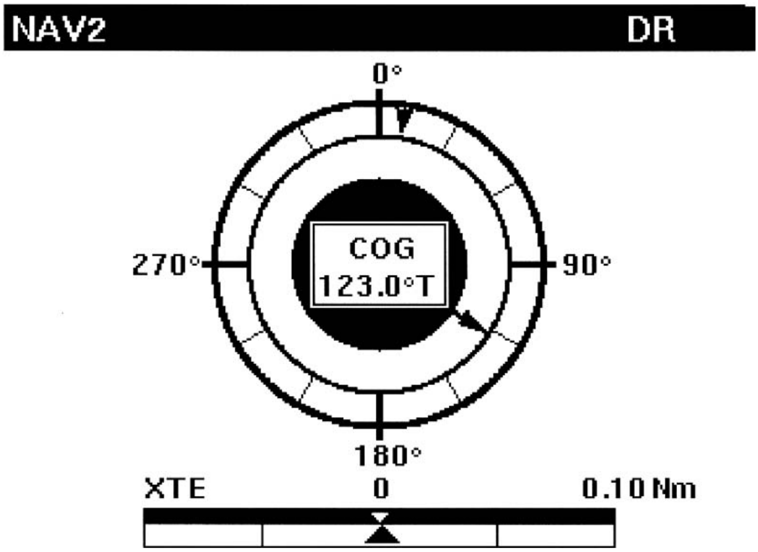

Figure 5.26 NAV 2 display. (Reproduced courtesy of Trimble Navigation Ltd.)

Each Navionics card holds the data necessary to give a screen display in the form of a maritime chart for a specified geographical area. The display then integrates the GPS data with the chart data, producing a recognizable nautical chart and the vessel's course and speed. Figure 5.27 shows a vessel (a flashing icon) with a track (a solid line) taking it under the western part of the Bay Bridge and a residual course (a line of dots) extending back to Alameda.

To avoid cluttering the chart, not all available data is shown on the Bay Area chart in Figure 5.27. Additional key commands are able to bring up the following information: depth contours, XTE lines, COG indicator, names (of cities, ports, bodies of water etc.), track, lighthouses and buoys, waypoints, landfill (for a clearer display of coastlines), maps, and much more. It is also possible to zoom in/out to show greater detail.

Another navigation screen display is the Mercator grid plot (Figure 5.28) showing the vessel's current position, the track history and the waypoints and legs in the active route. There are several scale or zoom levels ranging from 010 to 1000 km plus nautical miles or Mi increments.

Modern equipment is capable of much more than simply calculating and displaying position and track information and the NT200D is no exception. The versatility of its display coupled with adequate computing power and reliable data processing circuitry means that a wealth of other information can be accessed and presented to users. Set-up screens, system health checks, interface information, status displays, waypoint information, routes and more can be selected for display. Two displays in the status directory (Figure 5.29), of interest to students, present information about the satellites in view.

In Figure 5.29(a), the vessel is at the centre of concentric circles with a radial arrow indicating the current COG. The outer ring of the plot represents the horizon (0° elevation) and the inner rings, 30° and 60° elevation, respectively. Satellites in the centre of the plot are directly overhead (90° elevation). A satellite's true position in azimuth is shown relative to the north-up plot or may be determined relative to the vessel's COG.

Blackened icons indicate satellites being tracked by the receiver. Received data from the others falls below the parameters selected for their use. The table on the right shows the number of the SV and

Figure 5.27 Chart display of San Francisco Bay and approaches using data input from a smart card. (Reproduced courtesy of Trimble Navigation Ltd.)

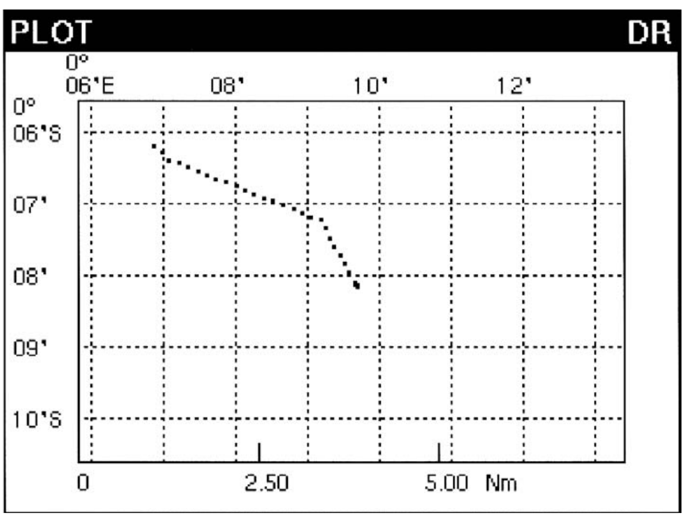

Figure 5.28 The Mercator grid plot screen display of the GPS receiver DR track. The vessel's current position is indicated by a flashing icon in the centre of the screen. (Reproduced courtesy of Trimble Navigation Ltd.)

(a)

(b)

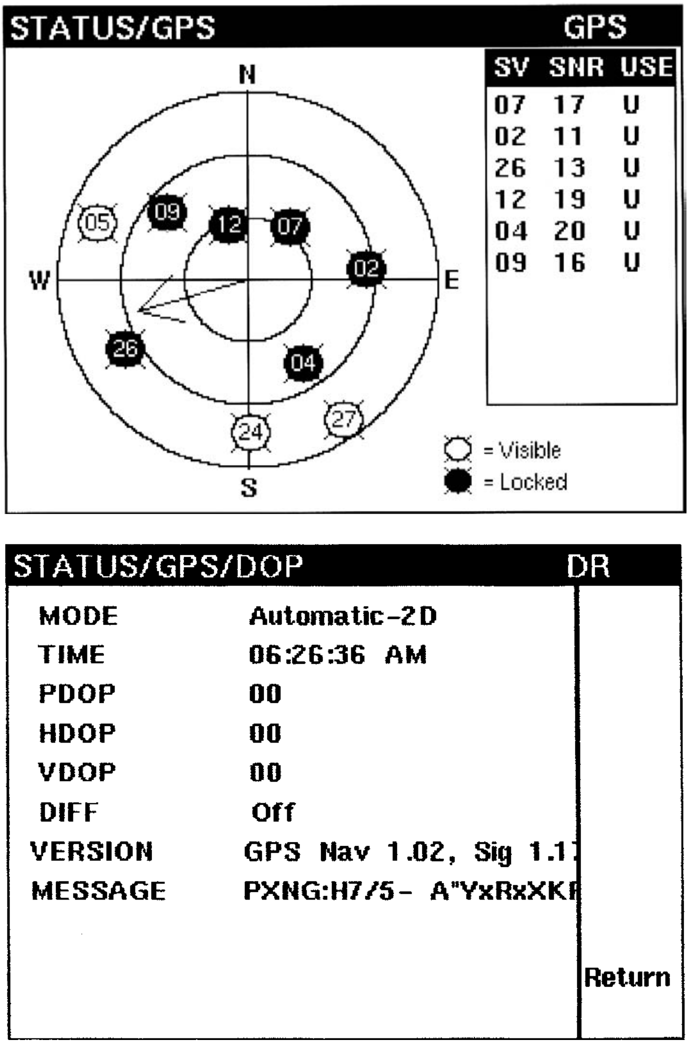

Figure 5.29 Satellite status/GPS display. Darkened icons are the numbered satellites currently being tracked by the receiver. Light icons represent received satellites that fall below the parameters selected for their use. The vessel is in the centre of the display and its course-over-ground is indicated by an arrow. (Reproduced courtesy of Trimble Navigation Ltd.)

the signal-to-noise ratio (SNR) for each satellite tracked. A SNR of 15 is considered good, 10 is acceptable and a SNR below 6 indicates that the satellite should not be relied upon for a position solution. A 'U' shows that an SV is being used and a 'D' that the equipment is receiving differential correction data for the satellite.

The second Status/GPS display is the dilution of precision screen (Figure 5.29(b)). PDOP, HDOP, and VDOP are numerical values based on the geometry of the satellite constellation used in a position solution. A figure of unity, 1.0, is the best DOP achievable. The most important of these parameters is the PDOP, the position dilution of precision. The lower the PDOP figure, the more precise the solution will be and the better the position fix. In practice a PDOP figure greater than 12 should be used with caution. A PDOP in the range 1–3 is excellent, 4–6 is good, 7–9 acceptable, 10–12 marginal and 12+ should be used with caution.

HDOP represents the accuracy of the latitude and longitude co-ordinates in two- or three-dimensional solutions, and VDOP is the accuracy of the altitude in a three-dimensional solution.

The display also shows the current GPS operating mode, the time of the last GPS fix, the current DGPS operating mode DIFF, the receiver firmware version, and the GPS system message.

For further information about Trimble GPS products see www.trimble.com

5.12.2 Garmin GPS receiver specifications

Amongst a range of GPS equipment designed for the maritime market, Garmin offers a 12-channel GPS receiver (with an optional DGPS receiver) combined with a navigation plotter. This versatile equipment, known as the GPSMAP 225, is representative of the way that system integration is making life easier for the maritime navigator. The GPSMAP 225 effectively presents an electronic charting/navigation system based on a 16-colour active-matrix TFT display that modern navigators will feel comfortable with.

Figure 5.30 shows the front panel of the receiver including the main operator controls and a sample chart showing own ship as a wedge icon. Note that the equipment is operating in a simulation mode.

Figure 5.30 Front panel of the Garmin GPSMAP 225 system showing operator controls and a sample navigation map generated in the simulation mode. (Reproduced courtesy of Garmin.)

Operator controls

ZOOM key	Changes the map display scale to one of 16 settings, or the highway display scale to one of five settings.
CTR key	Eliminates the cursor and centres own vessel on the screen.
ARROW keys	Controls the movements of the cursor and selects screen options and positions.
ENT key	Used to confirm data entry and execute various on-screen function prompts.
MAPS key	Returns the display to the Map page and/or displays the outlines of chart coverage in use.

PAGE key	Scrolls through the main screen pages in sequence.
DATA key	Turns the data window on or off in map mode and toggles the displayed data on other pages.
MENU key	Turns the softkey menu on or off in the map mode.
MARK key	Captures present position for storage as a waypoint.
MOB key	Marks present GPS position and provides a return course with steering guidance.
GOTO key	Enables waypoints or target cursor position as a destination and sets a course from current position.
SOFT keys	Perform route, waypoint and set-up functions. Also enable custom set-ups and many navigation functions from the map display.

Navigation and plotting functions

By using the built-in simulator mode for full route and trip planning, the GPSMAP system is capable of relieving a navigator of some of the more mundane navigation exercises. The system also includes the following specification to assist with the day-to-day navigation of a vessel.

- Over 1900 alphanumeric waypoints with selectable icons and comments.
- Built-in worldwide database usable from 4096 to 64 nautical miles scales.
- 20 reversible routes with up to 50 waypoints each.
- Graphic softkeys for easy operation of the chart display.
- G-chart™ electronic charting for seamless, worldwide coverage (see Figure 5.33).
- On-screen point-to-point distance and bearing calculations.
- 2000 track log points with time, distance or resolution settings.
- Built-in simulator mode for full route and trip planning.
- Conversion of GPS position to Loran-C TD co-ordinates.

Loran-C TD conversion

The GPSMAP unit automatically converts GPS co-ordinates to Loran-C TDs (time delay) for users who have a collection of Loran fixes stored as TDs. When the unit is used in this mode, it simulates the operation of a Loran-C receiver. Position co-ordinates may be displayed as TDs, and all navigation functions may be used as if the unit was actually receiving Loran signals. The expected accuracy is approximately 30 m.

GPSMAP system operation

At power-up, the satellite status page will appear. This gives a visual reference of satellite acquisition and status, with a signal bar graph and satellite sky view in the centre of the screen. In Figure 5.31, satellites 5, 8, 15, 21, 23, 25, 29, 30, and 31 are all currently being tracked, with the corresponding signal strength bars indicating the relative strength of the signals. Satellites 3 and 9 (shown with highlighted numbers) are visible but are not being tracked. The Dilution of Precision (DOP) figure is shown as 2 giving an estimated position error (EPE) of 49 feet.

The outer circle of the satellite sky view represents the horizon (north-up), the inner circle 45° above the horizon, and the centre point at a position directly overhead.

The GPSMAP Map page (see Figure 5.32), the primary navigation page, provides a comprehensive display of electronic cartography, plotting and navigational data. The Map page is divided into three main sectors: chart display, data window and softkey menu.

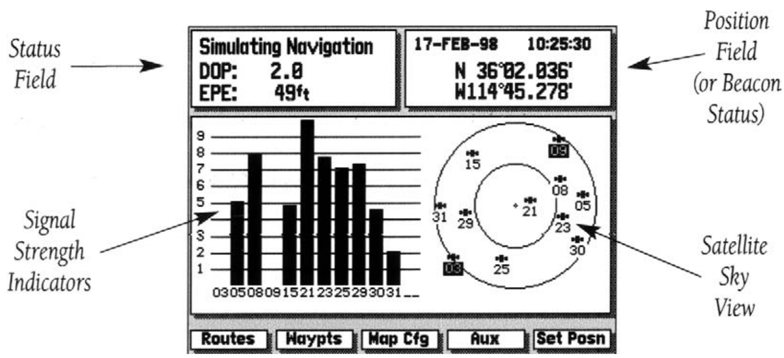

Figure 5.31 The satellite status display of the Garmin GPSMAP 225 system.

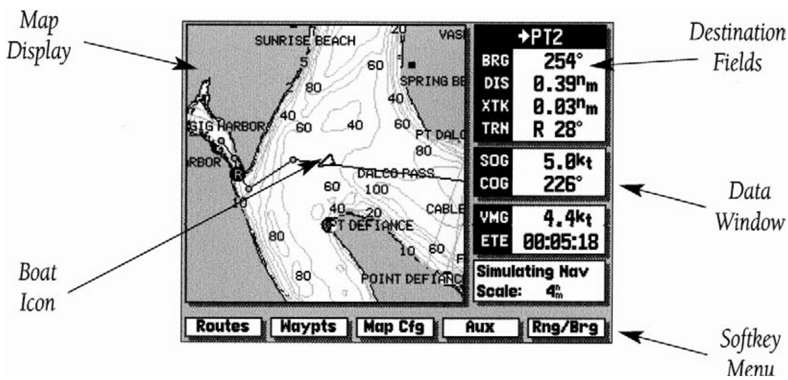

Figure 5.32 The MAP page, the main navigation display of the Garmin GPSMAP 225 system showing own vessel and track.

The chart display shows the user's vessel on an electronically generated chart, complete with geographical names, navaids, depth contours and a host of other chart features. A wedge icon represents the vessel's position, with its track plot shown as a solid yellow line. Routes and waypoints that have been created are also displayed. An on-screen cursor permits panning and scrolling to other map areas showing distance and bearing to a selected positions and waypoints as required. The GPSMAP system, using Garmin G-chart™ data cartridges, has a worldwide database to 64 nautical miles and a global coverage as shown in Figure 5.33.

The Map page also displays a wealth of navigation data in digital form. The destination fields show the bearing (BRG), in this case 254°, and the distance (DIS) 0.39 nautical miles to a destination waypoint or to the cursor. Cross-track error (XTE, 0.03 nautical miles) and turn (TRN, R 28°) information for an active destination is also displayed. The XTE value is the distance the vessel is off a desired course (left or right), whilst TRN represents the direction (left or right) in degrees between the vessel's course-over-ground (COG) and the bearing to the destination. The present speed-over-ground (SOG) is 5.0 knots and course-over-ground (COG) is 226°. This information and the terms used are illustrated in Figure 5.32.

Below this is the arrival and status field. The velocity-made-good (VMG), in this case 4.4 knots, is the speed of the vessel on a destination along a desired track, and the estimated time en route (ETE),

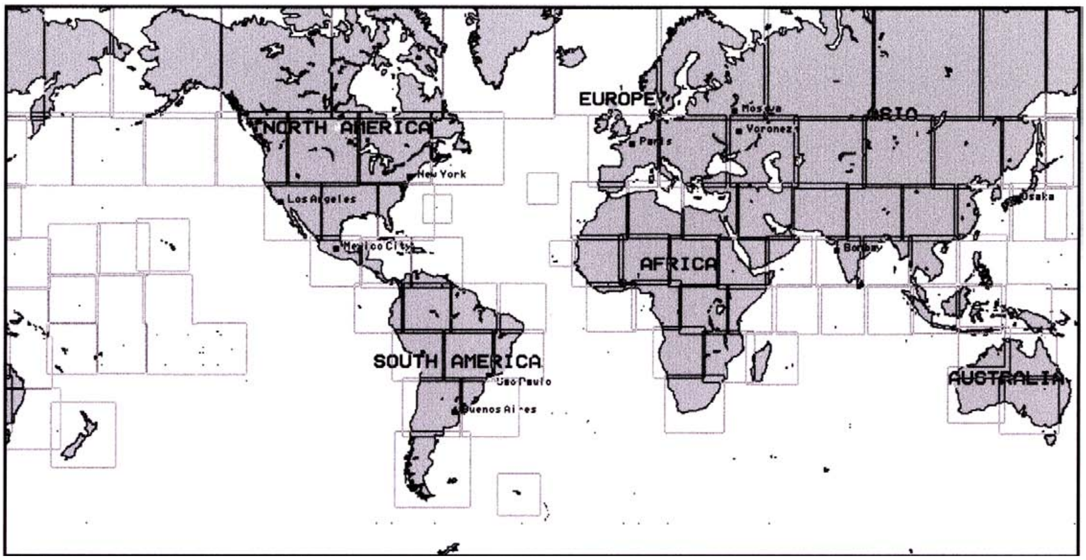

Figure 5.33 Global coverage chart showing the Garmin GPSMAP's built-in database for chart coverage down to 64 nautical miles.

00:05:18, is the estimated time remaining on the voyage leg. The status field indicates the operating mode, in this case simulating navigation, and the scale shows the map display depth, 4 nautical miles.

The GPSMAP's built-in worldwide database includes chart coverage down to 64 nautical miles (120 km) for the areas shown in Figure 5.33.

Switching to the GPSMAP Highway page (see Figure 5.34) provides a large character display of navigation data and graphic steering guidance to an active waypoint via a planned highway. The active destination point is displayed at the top of the screen with the ETE and ETA based on the present speed and course shown at the bottom.

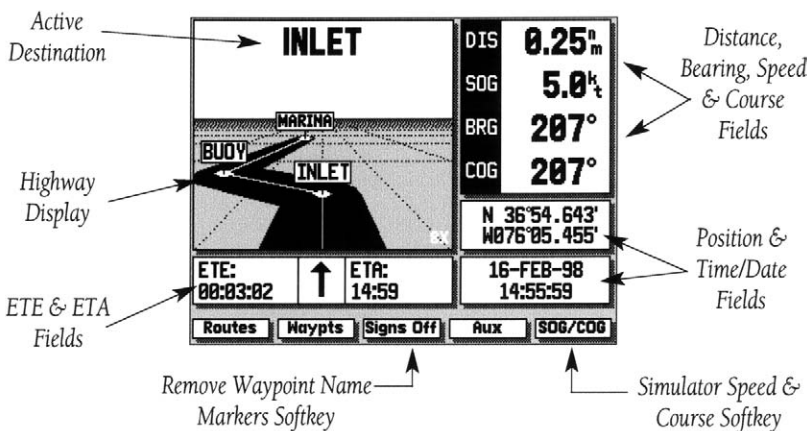

Figure 5.34 A sample Highway page of the Garmin GPSMAP 225 system used when navigating a route to an active waypoint.

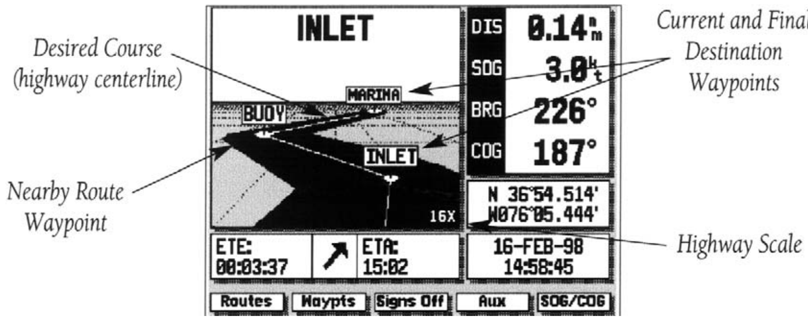

Figure 5.35 A sample Highway page of the Garmin GPSMAP 225 system used when navigating a route to an active waypoint.

The distance and bearing to the destination waypoint, along the present SOG and COG, are shown along the right-hand side. The SOG and COG fields may be changed to display the velocity-made-good and the turn value (VMG and TRN). The position field shows the present GPS position and the date/time field displays the current date and time as calculated from GPS satellites.

The Highway page's graphic display occupies the majority of the screen (see Figure 5.35). It provides visual guidance to the destination waypoint and keeps the vessel on the intended course line. The vessel's course is represented by a centre line down the middle of the graphic highway. As the vessel progresses towards its destination, the highway perspective changes to indicate progress and which direction should be steered to remain on course. When navigating a route, the highway display shows each route waypoint in sequence. Nearby waypoints not in the steered route also will be displayed.

This brief description demonstrates that GPS receivers have moved away from the simple positional display in latitude and longitude. In future the use of more powerful computers and further integration will no doubt see GPS as merely a small but valuable input to a huge electronic charting system (for further details see Chapter 7).

Interface details

The following interface formats are supported by the GPSMAP system for connection to up to three NMEA devices.

NMEA 0180
NMEA 0182
NMEA 0183 version 1.5

Approved sentences-
GPBWC, GPGLL, GPRMB, GPRMC, GPXTE, GPVTG, and GPWPL

Proprietary sentences-
PGRMM (map datum), PGRMZ (altitude) and PSLIB (beacon receiver control input)

NMEA 0183 version 2.0

Approved sentences-
GPGGA, GPGSA, GPGSV, GPRMB, GPRMC, GPRTE and GPWPL

Proprietary sentences-
PGRME (estimated error), PGRMM (map datum), PGRMZ (altitude) and PSLIB (beacon receiver control input)

For further information and explanation about the NMEA format see Appendix 3. For further information about Garmin GPS products see www.garmin.com

5.13 GPS on the web

GPS enjoys massive coverage on the world wide web and there are simply far too many sites to list here. However, some of the better sites are worth a visit and are listed below.

http://www.navcen.uscg.mil
An essential site for all navigators. United States Coast Guard site with numerous pages of data on GPS, Loran-C and US coastal navigation notices.

ftp://tycho.usno.navy.mil/pub/gps
Massive amounts of detail about GPS time transfer, current constellation status and health.

http//:www.spatial.maine.edu/~leick/alpha.htm
GPS and GLONASS alphabetical index link site to dozens of other relevant sites.

http://www.apparent-wind.com/gps.html
Another index site with useful links to other GPS and maritime sites.

http://www.trimble.com
GPS tutorials, fact sheets, satellite plots etc. from one of the biggest GPS equipment manufacturers. One of the best sites on the net.

http://www.trinityhouse.co.uk/dgps.htm
Details of the differential GPS beacons, parameters and availability around the UK coast.

http://www.utexas.edu/depts/grg/gcraft/notes/gps/gps.html
Extensive high-tech education notes on the GPS system from the University of Texas. Intended for use by university students.

http://www.igeb.gov
Interagency GPS Executive Board site. Includes the latest news about the GPS.

http://www.ngs.noaa.gov
National Oceanic and Atmospheric Administration (NOAA) and the National Geodetic Survey Site. Lots of detailed statistics about GPS health and status.

http://www.notams.faa.gov
The FAA's site holding Notices to Airmen (NOTAMs) listed interruptions in the GPS service. Coastal area NOTAMs are of use to mariners.

http://www.garmin.com
A huge informative site belonging to a major manufacturer of GPS equipment, holding a wealth of information about a huge range of equipment.

GPS continues to be updated and improved. It has been announced that two new civilian signals designed to carry data to enhance the civilian and commercial service will be added to the GPS. Furthermore, 18 additional satellites are to be used to support the system.

5.14 Global Orbiting Navigation Satellite System (GLONASS)

The Russian Federation's GLONASS was developed in parallel with GPS to serve the same primary function, that is, as a weapons navigation and guidance system. And like GPS, GLONASS has been released for international position fixing use, albeit in a downgraded form.

GLONASS is owned and operated by a Military Special Forces team at the Russian Ministry of Defence. SV time synchronization, frequency standards and receiver technology development are controlled from The Russian Institute of Navigation and Time in St. Petersburg. The system possesses similar architecture to the GPS and is equally capable of highly accurate position fixing.

5.14.1 Space segment

Work on the system began in the early 1970s and the first satellites were launched into orbit in 1982. Since then a full constellation has been established and GLONASS became fully operational in early 1996.

The space segment is based on 24 SVs, eight in each of three, almost circular orbital planes spaced at 120° intervals and inclined at 64.8° and at an altitude of 25 440 km. Each SV completes one earth orbit in 11 h 25 min and of course two orbits in 22 h 50 min in real time. Taking into account the length of a sidereal day, the westerly shift of each orbit brings all SVs back to an earth epoch point every 8 days, and the entire cycle repeats naturally.

All GLONASS SVs transmit on two frequencies to allow for correction of ionospheric signal delay, but unlike the GPS system, each SV uses different frequencies. Phase modulated onto the two carrier frequencies are a Coarse/Acquisition (C/A), a Precise code (P) and navigation data frames.

5.14.2 Ground segment

All ground control stations are located in former Soviet Union territory. The Ground Control and Operations Centre and Time Standard Centre are in Moscow. SV telemetry and tracking stations are located in Eniseisk, Komsomolsk-na-Amure, St. Petersburg and Ternopol.

5.14.3 Signal parameters

Initially all SVs were designed to transmit on different carrier frequencies, but in 1992, following the World Administrative Radio Conference (WARC-92) frequencies were grouped. Then in 1998 they were again changed. Currently, the L_1 transmission frequency band is 1598.0625–1609.3125 MHz and the L_2 band 7/9ths below this between 1242.9375 and 1251.6875 MHz (see Table 5.9).

Both L_1 and L_2 carriers are BPSK-modulated at 50 bauds with the navigation message. L_1 also carriers a PRN Coarse/Acquisition (C/A) code and L_2 both a Precision (P) code and the C/A code. The P code has a clock rate of 5.11 MHz and the C/A code is 0.511 MHz.

As in the GPS, the GLONASS navigation message contains timing, SV position and tracking data. All SVs transmit the same message (see Table 5.10).

5.14.4 Position fixing

GLONASS navigation fixes are obtained in precisely the same way as those for GPS. Pseudo-range calculations are made and then corrected in the receiver to obtain the user location in three dimensions. Precise timing is also available.

Table 5.9 SV carrier frequency designation

Channel no.	*L1 carrier (MHz)*	*L2 carrier (MHz)*
–7	1598.0625	1242.9375
–6	1598.6250	1243.3750
–5	1599.1875	1243.8125
–4	1599.7500	1244.2500
↓		
+13	1609.3125	1251.6875

Expression for channel increment:

L1 = 1598.0625 + 0.5625 MHz
L2 = 1242.9375 + 0.4375 MHz

Note: The ratio of L2/L1 channels is 7/9.

Table 5.10 GPS – GLONASS system comparison

Parameter	*GPS*	*GLONASS*
Orbital		
Altitude:	20 180 km	19 130 km
Period:	11 h 58 min	11 h 15 min 40 s
Inclination:	55°	64.8°
Planes:	6	3
Number of SVs	24	24
Carrier frequency		
L1:	1575.420 MHz	1598.6250–1609.3125 MHz
L2:	1227.600 MHz	1242.9375–1251.6875 MHz
Code clock rate		
C/A:	1.023 Mbit s^{-1}	0.511 Mbit s^{-1}
P:	10.23 Mbit s^{-1}	5.11 Mbit s^{-1}
Time reference	UTC	UTC
Navigation message		
Rate:	50 bit s^{-1} (baud)	50 bit s^{-1} (baud)
Modulation:	BPSK NRZ	BPSK Manchester
Frame duration:	12 min 30 s	2 min 30 s
Subframe:	6 s	30 s
Almanac content	Timing and orbital parameters	Timing and orbital parameters

5.14.5 User equipment

Because of the initial secrecy surrounding the system and the scarcity of detailed parameters, it is to be expected that there is little user equipment available. In the past, western manufacturers have had little incentive to invest heavily in the development of receivers when the GPS has been freely available. However, this situation could well change in the future.

5.15 Project Galileo

At the time of writing, the European Commission has produced a working paper for a European-based Global Navigation Satellite Service (GNSS) called the Galileo. It is to be designed to be totally independent of both GPS and GLONASS and thus will end the reliance of countries within the European Commission on systems beyond their control. It remains to be seen if the finance and indeed the impetus to create the system will be forthcoming.

5.16 Glossary

Almanac data	Satellite constellation information including location and health status.
Apogee	The furthest point away from the earth reached by a satellite in orbit.
Azimuth	The direction vector drawn to a satellite from a fixed point on earth.
BNM	USCG Broadcast Notice to Navigators.
BPSK	Bi-phase shift keying.
BRG	Bearing.
C/A code	Coarse/Acquire code. A PRN code operating at 1.023 $\mathrm{Mbit\,s^{-1}}$
CEP	Circular area probable. An accuracy figure achievable for 50% of the time in two dimensions; latitude and longitude.
COG	Course over ground.
CSOC	Consolidated Space Operations Centre.
dB	A unit for measuring power in a communications system.
DTK	Desired track. The compass course between the start and finish waypoints.
DGPS	Differential GPS. A method to improve the accuracy of a GPS fix by the use of corrective data transmitted on medium frequency to coastal shipping.
DMA	US Defence Mapping Agency.
DoD	US Department of Defence.
DOP	Dilution of Precision. A term used for expressing the mathematical quality of a solution.
d_{RMS}	A circle around the true position containing 95% of the fix calculations.
ECEF	Earth-centred-earth-fix. A GPS fix solution is quoted in ECEF co-ordinates.
EPE	Estimated position error.
ETA	Estimated time of arrival.
ETE	Estimated time en route. The time remaining to a destination.
FAA	US Federal Aviation Authority.
GDOP	Geometric dilution of precision. A measure of the quality of a solution.
GLONASS	Global Orbiting Navigation Satellite System. The Russian Federation system.
GMT	Greenwich mean time. Often referred to as Zulu.
GNSS	Global Navigation Satellite System.
GPS	Global Positioning System.
Ground speed	The vessel's velocity referenced to the ocean floor.
HDOP	Horizontal dilution of position. A measure of the quality of a solution in terms of latitude/longitude.
Inclination	The angle formed between the eastern end of the equatorial plane and a satellite orbit. For GPS orbits it is 55°.
Kepler's laws	Satellites in orbit follow an ellipse as defined by Johannes Kepler.
L_1	The GPS primary transmission frequency; 1575.42 MHz.

L_2	The GPS secondary transmission frequency; 1227.6 MHz.
MCS	The GPS Master Control Station situated at Colorado Springs.
NMEA	National Maritime Electronics Association. An organization of manufacturers and distributors responsible for agreeing the standards of interfacing between various electronic shipboard systems.
NOTAM	FAA's Notice to Airmen regarding GPS service interruption.
P code	Precision code. A PRN code operating at 10.23 MHz.
PDOP	Precision dilution of position.
Perigee	The closest point of approach to the earth reached by an orbiting satellite.
PPS	GPS Precise Positioning Service.
PRN	Pseudo-random noise.
RTCM	Radio Technical Commission for Maritime Services.
SEP	An accuracy that is achievable 50% of the time in all dimensions.
SOG	Speed over ground.
SPS	GPS Standard Positioning Service.
SV	Space vehicle – a satellite.
TDOP	Time dilution of precision.
TTFF	Time to first fix. Used to identify how long a GPS receiver takes before a fix is available.
TTSF	Time to subsequent fix.
TRN	Turn.
URE	User range error.
UERE	User equivalent range error. Determined by summing the squares of the individual range errors and then taking the square root of the total.
USCG	United States Coast Guard.
USNS	United States NOTAM Service.
ULS	Satellite uplink station.
UTC	Universal time co-ordinated.
UTM	Universal transverse mercator. A grid co-ordinate system that projects global sections onto a flat surface.
VDOP	Vertical dilution of precision.
VMG	Velocity made good.
WADGPS	Wide area differential GPS. An experimental system for improving the accuracy of GPS fixes globally.
WGS-84	World Geodetic Survey 1984.
XDOP	Cross-track dilution of precision.
XTE	Cross-track error.

5.17 Summary

- The GPS has replaced the Navy Navigation Satellite System (NNSS).
- Satellites, called space vehicles (SVs), follow elliptical orbits conforming to Kepler's laws of astrophysics.
- The GPS, occasionally called NAVSTAR, has three segments: Space, Control and User.
- There are 24 operational SVs, four in each of six orbital planes inclined at 55°.
- SVs orbit the earth at an altitude of 20 200 km and possess an approximate 12-h orbital period.

- SVs transmit two codes to enable receivers to acquire the signal. The Coarse and Acquire (C/A) code is a pseudo-random noise (PRN) code stream operating at 1.023 Mbit s^{-1}. The precise (P) code is also a PRN stream operating at the faster rate of 10.23 MHz.
- The C/A code epochs every 1 ms and has been designed to be easily acquired while the P code has an epoch every 267 days and is difficult to acquire.
- Navigation data is transmitted at 50 bit s^{-1} and is modulated onto both codes.
- The L_1 signal carrier frequency (1575.42 MHz) is modulated with the C/A code, the P code and the navigation message, whilst the L_2 carrier carries only the P code and the navigation message.
- There are two levels of fix available. The Precise Positioning Service (PPS) and the Standard Positioning Service (SPS). Until May 2000 the SPS was downgraded by a factor of 10, but on that date downgrading, called Selective Availability, was removed and now SPS and the PPS fixes have virtually the same accuracy.
- GPS position fixes are achieved by the precise measurement of the distance between a number of SVs and a receiver at an instant in time and/or by phase measurement. It is assumed that the receiver clock is in error and therefore the range measured is called a pseudo-range (false range). The receiver processor corrects the range measurement to produce a precise fix.
- The fix, in XYZ co-ordinates (latitude/longitude and altitude) is converted to earth-centred co-ordinates called ECEF (earth-centred-earth-fix).
- Dilution of precision (DOP) is the term used for expressing the mathematical quality of a fix solution. TDOP, HDOP, VDOP, and PDOP are also used in the GPS.
- System errors may cause an imprecise fix. Fix error and thus GPS accuracy is quoted using one of the figures CEP, SEP, d_{RMS} and UERE.
- Differential GPS (DGPS) is a system whereby SV signals are received at a fixed location, errors are corrected and the new data is transmitted on MF to vessels in the local area.
- GPS uses an active antenna with a ground plane to reduced the effect of reflected signals.
- There is a huge range of GPS equipment available ranging from simple hand-held units to sophisticated dual-channel systems used for survey purposes.
- The Russian Federation's satellite navigation system, GLONASS, is operational but is not compatible with GPS.

5.18 Revision questions

1. What are the basic principles of Kepler's laws of astrophysics?
2. How are the orbital period and the velocity of a space vehicle (SV) related?
3. How many SVs are used in a full GPS constellation and how many are there in each orbital plane?
4. What are the GPS transmission frequencies?
5. Why do Navstar SVs transmit on two frequencies?
6. How long does it take an SV to transmit an entire navigation data message of 25 frames?
7. The GPS uses two codes, the P code and the C/A code, for encryption purposes. Why is this?
8. Why is the P code more difficult for a receiver to lock onto than the C/A code?
9. Why is it essential to maintain SV transmit frequency stability?
10. PPS fixes require the use of more complex receiving equipment. Why is this?
11. What is a pseudo-range measurement?
12. How does the choice of SVs used for a fix affect the PDOP?
13. What is ECEF XYZ?
14. Which of the error-inducing factors is likely to introduce the largest error?

15 How is the figure for UERE derived?
16 The use of DGPS offers improved fix accuracy. Over what range would you expect to receive DGPS data?
17 Why does a GPS antenna need a ground plane?
18 Why is the C/A code generated (or held in memory) in a receiver and applied to the correlator?
19 Autocorrelation is used in the signal processing stages of a GPS receiver. Why is this?
20 The Russian Federation satellite navigation system, GLONASS, offers similar features and accuracy of position fixing to the GPS. Are the two systems compatible?