Chapter 4

Loran-C

4.1 Introduction

Loran is an acronym for *lo*ng *ra*nge *n*avigation. It is an electronic system of land-based transmitter broadcasting low frequency pulsed signals that enable ships and aircraft to determine their positio A system that used this concept was first proposed in the 1930s and implemented as the British Ge system early in the Second World War. The Gee system used master and slave transmitters site approximately 100 miles apart and used frequencies between 30 and 80 MHz. The use of frequencie in the VHF band constrained the system to 'line-of-sight' distance for coverage but this was not problem at the time since the system was designed to aid bomber navigation on raids ove Germany.

The system was further developed at the Radiation Laboratory of the Massachusetts Institute o Technology and the speed of development was such that by 1943 a chain of transmitters was i operation under the control of the United States Coastguard (USCG). This early system was late known as standard loran or Loran-A. This system operated in the frequency range 1850–1950 kH with master and slave stations separated by up to 600 nmiles. Coverage of the system use groundwaves at ranges from 600 to 900 nmiles over seawater by day, and between 1250 and 150 nmiles via sky wave reception at night, using the first-hop E layer mode of propagation. Loran-A ha a typical accuracy of about 1 nmile for ground wave reception and 6 nmiles for sky wav reception.

Loran-A chains operate by measuring the difference in time arrival of the pulses from the maste and the slave stations. Every time difference produces a line of position (LOP) for a master–slave pai and a positional fix is obtained by the intersection of two such LOPs using two suitable master–slav pairs. Two adjacent chains usually have a common master transmitter station. For each chain the slav station transmission is retarded in time compared to that of the master station. Such retardation i known as the coding delay and has a value such that within the coverage area of the chain the maste pulse is always received at a receiver before the slave pulse. Known unreliable signals can be indicate by the master or slave signals, or both, being made to blink. Loran-A chains are identified by a alphanumeric which specifies the transmission frequency and the pulse repetition rate (determined b the number of pulses transmitted per second). The pulse repetition rate differs between station pair in the same chain.

Loran-A was finally phased out in the United States in 1980 and replaced by Loran-C. The use o Loran-A continued in other parts of the world for a time before a change was made to the mor universal Loran-C. The last operational Loran-A chains were based along the coast of China. Th Loran-C system evolved from Loran-A and the basic principles of both systems are the same.

4.2 System principles

The loran transmitter stations send out a stream of pulses at a specified rate known as the pulse repetition frequency (PRF) or the pulse repetition rate (PRR). The pulse repetition period is the reciprocal of the PRF. Assume the PRF is 25, i.e. 25 pulses are transmitted every second, then the period of the pulse is 1/25 s or 40 000 μs. The pulse width is 40 μs for Loran-A and 250 μs for Loran-C.

Assuming that the velocity of radio waves in free space is $3 \times 10^8\,\mathrm{ms}^{-1}$, then the distance travelled by a pulse may be measured in terms of the time taken to travel that distance, i.e. if a pulse took 1000 μs to travel a certain distance then the distance is given by:

$$d = v \times t \qquad (4.1)$$

where d = distance in metres, v = velocity of radio waves in ms^{-1}, and t = time in seconds taken for pulse to travel d metres. Then $d = (3 \times 10^8 \times 1000 \times 10^{-6})$ metres or $d = 300\,\mathrm{km}$. The velocity of light has been taken as $3 \times 10^8\ \mathrm{ms}^{-1}$ in the above calculation whereas in free space the actual value is $2.99792458 \times 108\,\mathrm{ms}^{-1}$. Also the time taken to travel a certain distance via a ground wave will be affected by the conductivity of the terrain over which it travels. The approximations made here and in the next section are for indicative purposes only.

4.2.1 Loran lines of position (LOPs)

Consider two transmitters A and B simultaneously transmitting the same pulse stream (Figure 4.1). If we assume that the distance between the transmitters is 972 nmiles or 1800 km (since 1 nmile = 1.85 km, approximately), then the time taken to cover the distance between the transmitters can be found from equation (4.1) to be:

$$t = d/v$$

$$\text{or } t = (1800 \times 10^3)\mathrm{m}/(3 \times 10^8)\mathrm{ms}^{-1} = 6000\ \mu\mathrm{s}$$

A receiver situated along the baseline joining the two transmitters would receive both pulse streams with the time of reception of each pulse stream determined by its position along the baseline. If the receiver was positioned 600 km from station A and 1200 km from station B then the pulse stream from

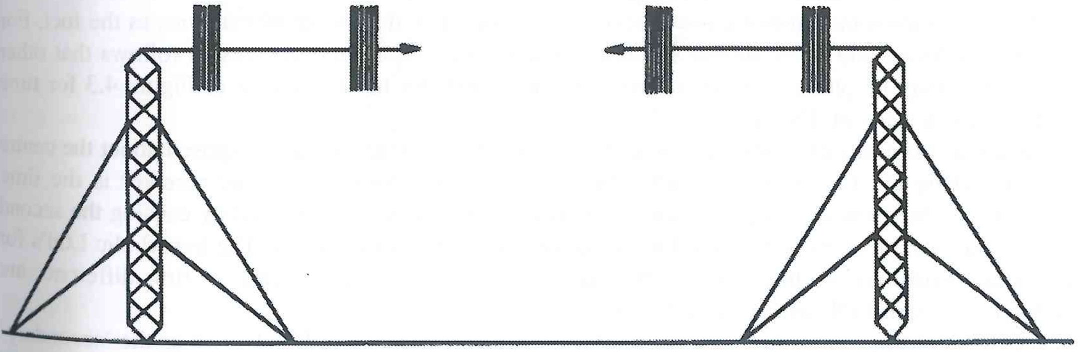


Figure 4.1 The loran system: two transmitters each radiating short pulses of specified length at a specified repetition interval.

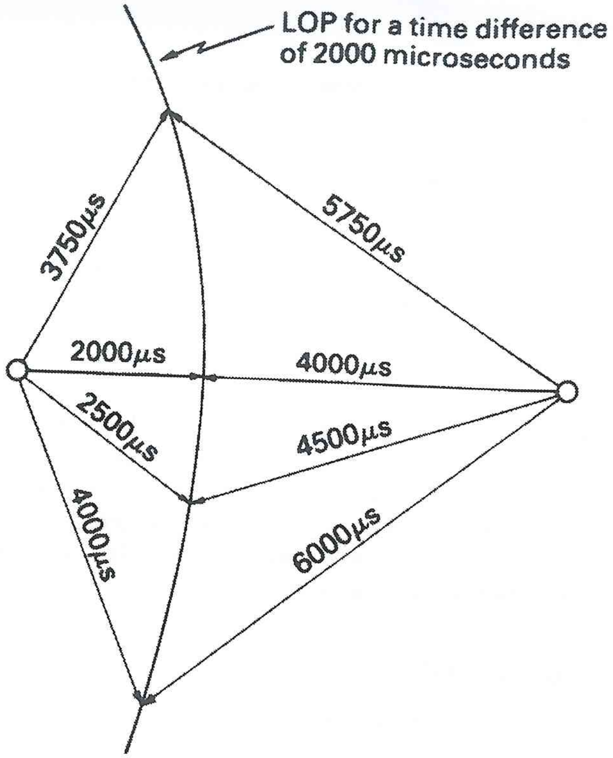


Figure 4.2 Line of constant time difference (LOP) produced from two transmitter stations emitting pulses simultaneously.

station A would arrive after 2000 µs, while that from station B would arrive after 4000 µs. This mea that there is a difference in arrival time of 2000 µs. There would be other receiver positions in th region between the transmitters, not necessarily on the baseline, where the difference in arrival tim was 2000 µs. It follows that by connecting all possible points where there is a difference in arrival tim of 2000 µs, a line of position (LOP) may be plotted. Figure 4.2 shows a plot of all possible positio where the time difference in pulse reception is 2000 µs.

The LOP shown in Figure 4.2 is a plot of a hyperbola with the transmitter stations as the foci. Fo this reason loran, and other similar systems, are known as hyperbolic systems. It follows that oth hyperbolae may be plotted for other time differences and this has been done in Figure 4.3 for tim differences in steps of 1000 µs.

Note that from this diagram the time difference LOPs are symmetrically disposed about the centr line, i.e. there are two 2000-µs LOPs. Hence if the only information at the receiver is the tim difference value then an ambiguity can occur. The ambiguity may be avoided by causing the secon station, say station B, to be triggered by the pulse received from station A. The hyperbolic LOPs fo this arrangement are no different from the original arrangement but the values of time difference ar different for each LOP, as shown in Figure 4.4.

Station A in this case is known as the 'master' station while station B is known as the 'secondary' station. This arrangement, although apparently solving the ambiguity problem, has in fact create another problem. As shown in Figure 4.4, in the region of the baseline extension for the secondar

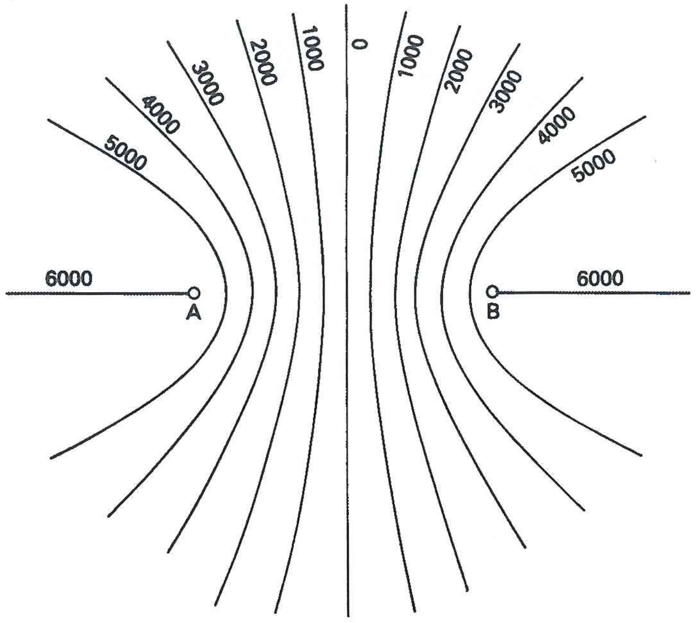


Figure 4.3 Lines of constant time difference (LOP) produced from two transmitter stations emitting pulses simultaneously.

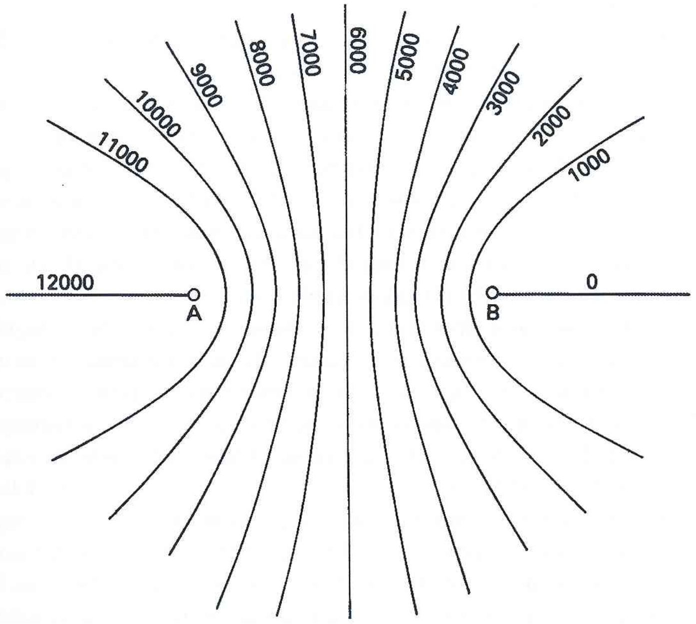


Figure 4.4 Modification of the LOPs of Figure 4.3. Station B is not allowed to transmit until triggered by a pulse from Station A.

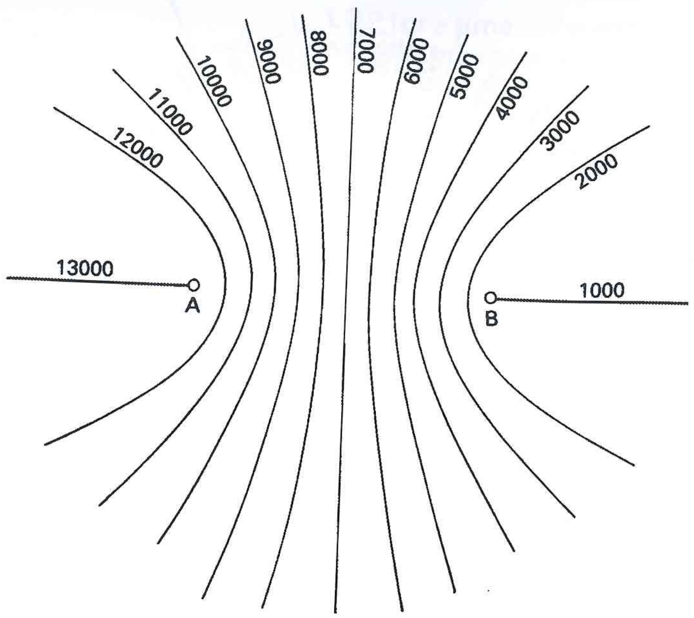


Figure 4.5 A further modification to the LOPs of Figure 4.3. Not only must Station B wait for a pul from Station A but there is also a coding delay (1000 µs in this example) which alters the time difference value of each LOP.

station B, the difference in arrival time of the two sets of pulses is smaller than the width of the act pulse and is in fact zero on the baseline extension. Hence in these regions it would be impossible separate the two pulses to measure the difference in arrival times.

This drawback is solved by delaying the transmission of the pulse from the secondary for a cert period of time after the pulse from the master has arrived. As mentioned in Section 4.1, this del period is known as a coding delay. Figure 4.5 has been drawn indicating a coding delay of 1000 µ The total elapsed time from the master transmission until secondary transmission occurs is known the emission delay. This is equal to the sum of the time taken for the master signal to travel to th secondary (baseline travel time) and the coding delay. Details of coding delay and emission del values for Loran-C transmitters may be found in Table 4.9.

Again no two LOPs have the same time difference, eliminating possible ambiguity, and the codin delay ensures that no area is unable to receive two distinctly separate pulses. It is important to ensu that the coding delay is kept accurately constant, since any variation in this value would cause erro in received time differences giving erroneous positioning of the vessel containing the receiver.

The LOPs are overprinted on charts showing the value of time difference for each LOP. Thus usi an on-board receiver which is capable of comparing the delay in reception of the pulses from th master and secondary stations, it is possible to plot the position of the vessel along a particular LO (or, by interpolation between two adjacent LOPs, if the time difference obtained is not the exact valu printed on the chart). All that is necessary to establish a position fix for the vessel is to establish th position along a second, intersecting LOP (whether actual or interpolated) using another pair o transmitting stations, i.e. the master, common to all station pairs, and a second secondary station (se Figure 4.6).

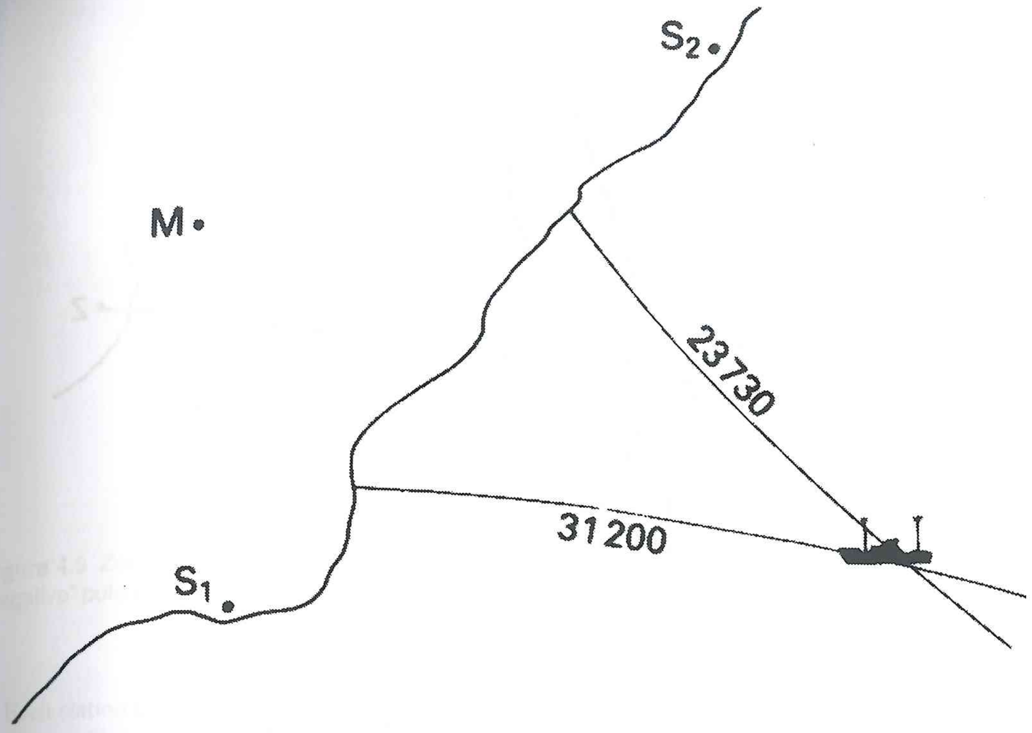


Figure 4.6 Position fixing using LOPs from two pairs of master/secondary stations.

4.3 Basics of the Loran-C System

In the early 1970s the US Department of Transportation which, through the US Coastguard, was responsible for the loran stations, decided that the existing coverage and accuracy provided by the Loran-A stations was below standard and the system of Loran-C, already extant in some regions of the US, was adopted to replace it.

The Loran-C system usually comprises a chain of from three to five land-based transmitting stations, although one chain (see Table 4.9) actually has six transmitting stations, i.e. 9610 South Central US has Victor (V) based at Gillette. One station is always designated as the master (M), while the others are known as secondary stations, whisky (W), x-ray (X), yankee (Y) and zulu (Z) (see Figure 4.7).

All transmitters are synchronized so that signals from the secondaries have precise time-interval relationships with transmissions from the master. This is achieved by the use of atomic oscillators at the stations. Radiated power from Loran-C transmitters varies from a few kW to several hundred kW. The power radiated will affect the range at which usable signals are received and hence define the coverage area of a chain.

Loran-C uses a transmission frequency of 100 kHz and this lower frequency compared with Loran-A gives greater range of reception. The pulse width is 250 µs compared to 40 µs for Loran-A. The actual pulse shape is different for both systems as Figure 4.8 shows.

Since Loran-C achieves its greater accuracy by a process of ‘cycle-matching’, i.e. matching specified cycles of the received master and secondary pulses rather than the envelope as in Loran-A, the Loran-C pulse is subject to stringent specification requirements.

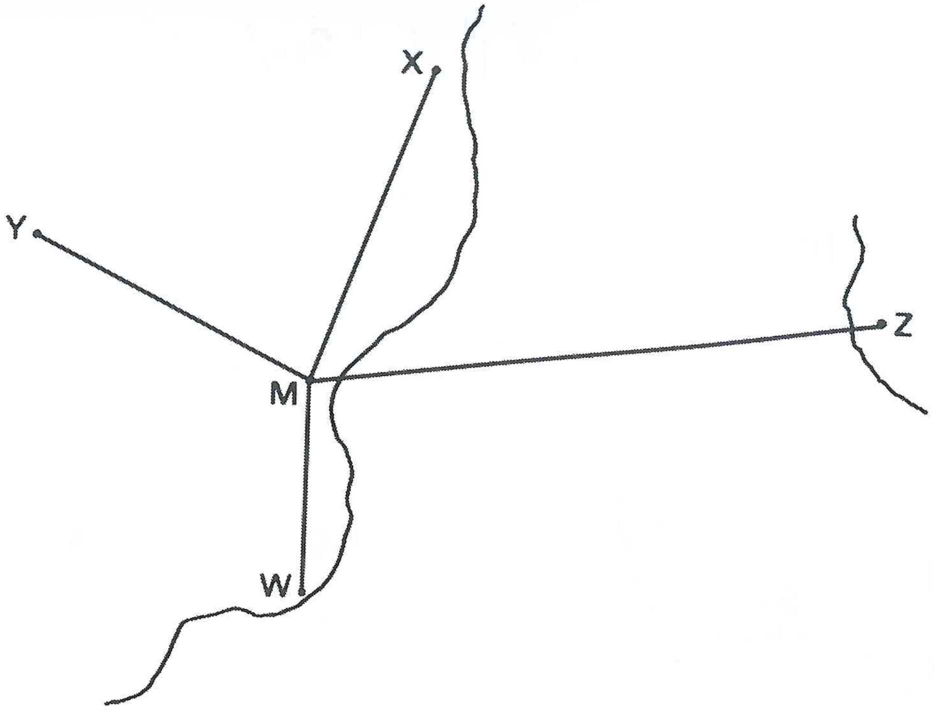


Figure 4.7 A chain may be configured from a master and up to four secondaries.

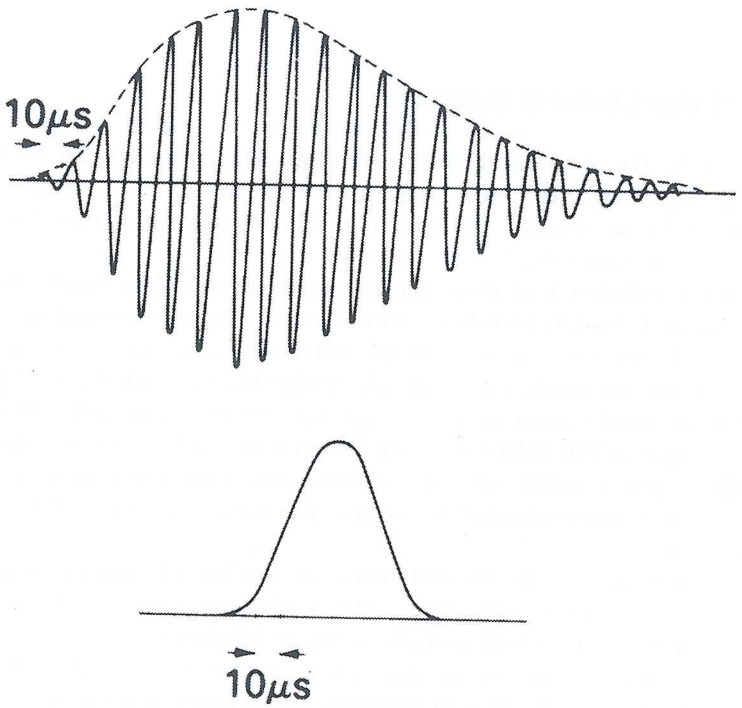


Figure 4.8 Comparison of pulses for Loran-A (lower) and Loran-C (upper).

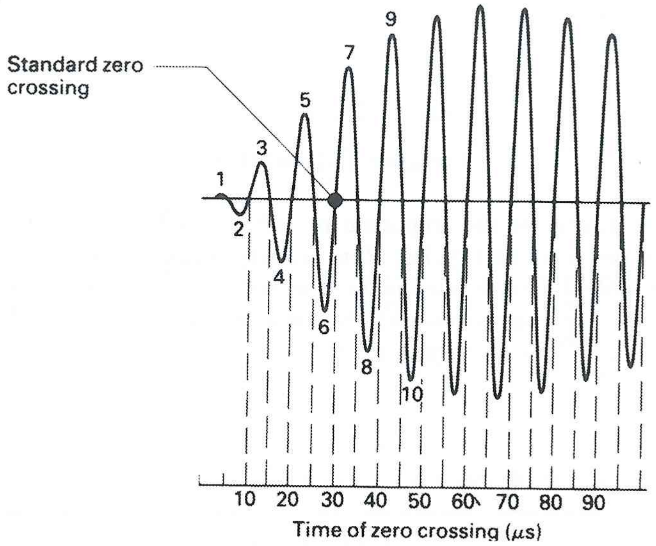


Figure 4.9 Zero crossing times and labels for half-cycles. This figure shows a 'positive' pulse. For a 'negative' pulse the polarity changes but the labels remain the same.

Each station transmits a pulse which increases rapidly in amplitude and decays at a rate depending on the particular transmitter (Figure 4.9).

The standard pulse leading edge requirement is defined as

$$i(t) = 0; \text{ for } t <_t$$
$$i(t) = A(t - \tau)^2 exp[(- 2(t - \tau))/65]sin(0.2\pi\, t + PC); \text{ for } \tau < t < (65 + \tau)$$

where $i(t)$ is the Loran-C antenna waveform, A is the normalization constant related to the peak antenna current magnitude in amperes, t is the time in μs, τ is the envelope to cycle difference (ECD) in μs, PC is the phase-code parameter, in radians, which is 0 for positive phase code and π for negative phase code.

The ECD is determined as the difference in time between the actual waveform, sampled at the first eight half-cycle peaks, and the standard leading edge as defined above. This deviation is minimized in a root-mean-square sense over ECD and the first 40 μs. The ECD of the pulse is that value which minimizes this deviation. The best nominal ECD for a transmitting station over an all-seawater path is determined from the empirical formula:

$$\text{ECD} = 2.5 + \text{NECD} - 0.00025d$$

where NECD is the nominal ECD of a transmitting station, and d is the distance in nautical miles from the transmitting station.

The pulse trailing edge (that portion of the pulse following the peak of the pulse, or 65 μs, whichever occurs first) is controlled in order to maintain spectrum requirements. At different transmitting sites, or with different transmitting equipments, the pulse trailing edge may differ significantly in appearance and characteristics. Regardless of these differences, for each pulse and for all $t > 500$ µs, $i(t)$ satisfies the pulse trailing-edge tolerances based upon pe amplitude (A).

$$\text{Category 1: } i(t) \leq 0.0014\,A$$

$$\text{Category 2: } i(t) \leq 0.016\,A$$

There is a tolerance placed on the amplitude of half-cycles both individually and as a gro (considering only the first eight half-cycles). Zero crossing times and tolerances of the first group pulses are shown in Table 4.1 for the first pulse. The zero crossing times are measured with resp to the standard zero crossing which gives a positive-going zero crossing at 30 µs for a positively cod pulse. ECDs in the range −2.5 to +2.5 µs are assumed.

Table 4.1 Zero crossing times (with respect to the standard zero crossing) and tolerances

		Tolerance (ns)	
Zero crossing (µs)	*Time (µs)*	*Category 1*	*Categor*
5	−25	±1000	±2000
10	−20	±100	±1500
15	−15	±75	±1000
20	−10	±50	±500
25	−5	±50	±250
30	Standard zero crossing	(Time reference)	
35	5	±50	±100
40	10	±50	±100
45	15	±50	±100
50	20	±50	±100
55	25	±50	±100
60	30	±50	±100

Beyond 60 µs the zero crossings conform to 100 kHz ± 1 kHz

4.3.1 Pulse groups

Each Loran-C station operates with a specified group repetition interval (GRI) which are multiples 10 µs, from 40 000µs up to 99 990µs. The particular GRI is recognized by its GRI value divided 10, i.e. 7980 would define a GRI of 79 800 µs.

Secondary pulse groups are transmitted with the same GRI as the master pulse group and are link in time to the master. The delays in transmissions from secondary stations with respect to the mas are selected to ensure that the following criteria are met wherever signals can be received for a particular chain.

- Minimum time difference between any secondary and master is 10 900 µs.
- Minimum difference of any two time differences is 9900 µs.
- Maximum time difference is the Group Repetition Interval minus 9900 µs.

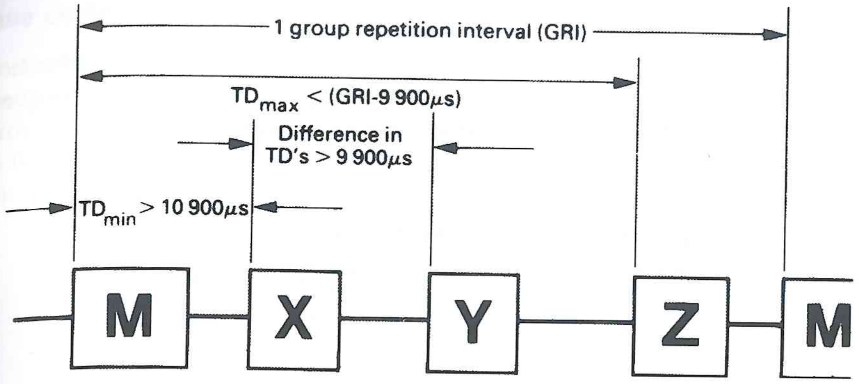


Figure 4.10 Constraints for assignment of emission delay.

- Minimum spacing between corresponding points of the last pulse of any stations group and the first pulse of the next group in the same chain is 2900 µs. The minimum spacing between the master's ninth pulse and the next secondary pulse (of the same chain), however, may be as little as 1900 µs. This is a direct result of applying the first three criteria.

Figure 4.10 gives an indication of the constraints for emission delay.

Uniformity of pulses within a pulse group

The uniformity of pulses within a pulse group depends not only on the equipment used but whether the station is single-rated (SR) or dual-rated (DR). Dual-rated means that the master station is common to two chains and transmits on two different GRIs. The amplitude of the smallest pulse in the group compared with the amplitude of the largest pulse in the same group should not differ by more than the limits specified in Table 4.2.

Percentage droop is given by:

$$D = \frac{I_{\text{pk.max}} - I_{\text{pk.min}}}{I_{\text{pk.max}}} \times 100$$

where $I_{\text{pk.max}}$ is the value of $i(t)$ at the peak of the largest pulse and $I_{\text{pk.min}}$ is the value of $i(t)$ at the peak of the smallest pulse.

Table 4.2 Pulse-to-pulse amplitude tolerance, or percentage droop (D)

	Category 1 (%)	*Category 2 (%)*
Single rate	5	10
Dual rate	10	20

4.3.2 Pulse-to-pulse ECD tolerances

The pulse-to-pulse ECD tolerances account for the pulse-to-pulse leading edge differences and pulse-to-pulse zero crossing differences. The ECD of any single antenna current pulse does not dif from the average ECD of all pulses by more than the values given in Table 4.3.

Table 4.3 Pulse-to-pulse ECD tolerances

	Category 1 (μs)	*Category 2 (μs)*
Single rate	0.5	1.0
Dual rate	0.7	1.5

4.3.3 Transmission of Loran-C pulses

Whereas Loran-A transmitted one pulse from the master and another from the secondary, with the t pulses compared in the receiver to obtain a time delay, the Loran-C transmitter emits a series of pul from the master and secondary stations. A typical transmission sequence for a Loran-C chain is sho in Figure 4.11.

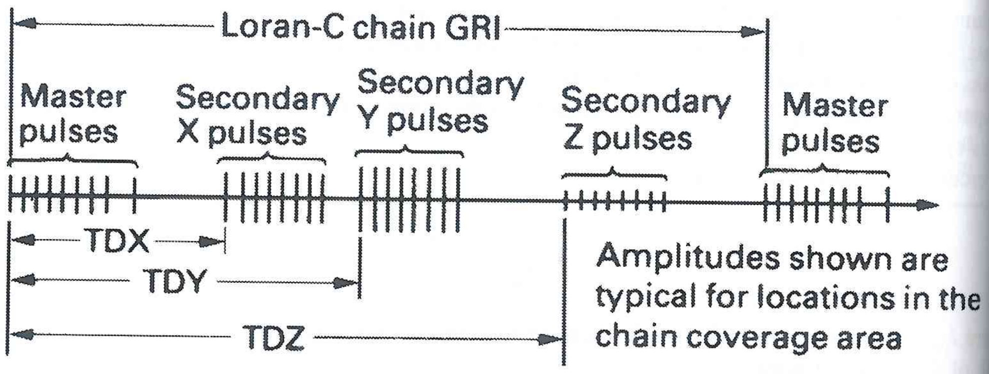


Figure 4.11 Loran-C chain group repetition interval (GRI) showing the receipt of master and X, Y and Z secondaries.

The GRI is defined as the time interval between successive pulse groups measured from the thi cycle (or zero crossover) of the first pulse of any one station in the group, to the third cycle of the fir pulse of the same station in the following pulse group. All stations in the chain have the same GR and the GRI expressed in tens of microseconds is the identifier for that chain and is called the cha 'rate'. The master transmitter sends out a series of nine pulses while the secondaries transmit on eight pulses.

4.3.4 Phase coding

Each Loran-C station phase-codes the series of pulses in accordance with Table 4.4. For identification, the first group of pulses in the sequence is labelled Group A and the second group, one GRI later, is labelled Group B. A transmission sequence (the phase-code interval or PCI) comprises both Group A and Group B, and the PCI sequence is thereafter repeated. The minus sign in Table 4.4 stands for a pulse that is 180° out of phase with the 'normal' pulse, i.e. the phase of the pulse is inverted.

Table 4.4 Loran-C phase modes

Group	*Station*	
	Master	*Secondary*
A	+ + − − + − + − +	+ + + + + − − +
B	+ − − + + + + + −	+ − + − + + − −

4.3.5 Pulse-to-pulse timing tolerances

Pulses two to eight of a group are referenced in time to the first pulse of each group. The timing relationship and tolerances of the standard zero crossings of pulses two to eight with respect to pulse one standard zero crossing are shown in Table 4.5. The ninth pulse of the master transmission is spaced 2000 μs from the eighth pulse of the group. This pulse is used primarily as a visual aid to master group identification and not as an aid to navigation.

Table 4.5 Pulse-to-pulse timing tolerances. N is the pulse number (2–8) of the pulses which follow the first pulse within each group. C is 0 for positively phase-coded pulses; |C| ≤ 150 μs for negatively phase-coded pulses. The standard zero crossing of pulse one is the time reference within each group

	Category 1	*Category 2*
Single rate	(N−1) 1000 μs ± 25 ns	(N−1) 1000 μs ± 50 ns + C
Dual rate	(N−1) 1000 μs ± 50 ns	(N−1) 1000 μs ± 100 ns + C

The use of phase coding allows automatic Loran-C receivers to distinguish between master and secondary transmissions and also assists the receiver to operate when the loran signals are weak in the presence of noise.

4.3.6 Blink

Blink is a repetitive on–off pattern (approximately 0.25 s 'on' and 3.75 s 'off') of the first two pulses of the secondary signal which indicates that the baseline is unusable for one of the following reasons:

(a) TD out of tolerance;
(b) ECD out of tolerance;
(c) improper phase code or GRI;
(d) master or secondary station operating at less than one-half of specified power output or ma
station off the air.

Blink continues until the out of tolerance condition is eliminated. The ninth pulse of the master n also be blinked simultaneously, but by itself master blink is not an indication of an out of tolera condition.

Master blink is normally only used for internal Loran-C system communication. If used, master's ninth pulse will be blinked in accordance with the code shown in Figure 4.12.

A selection of Loran-C stations together with their category status, with regard to pulse generati is shown in Table 4.6. It should be noted from this table that many stations are dual rated. For examp Dana is the zulu secondary transmitter for the Northeast US Chain (9960) and also acts as the ma transmitter for the Great Lakes chain (8970).

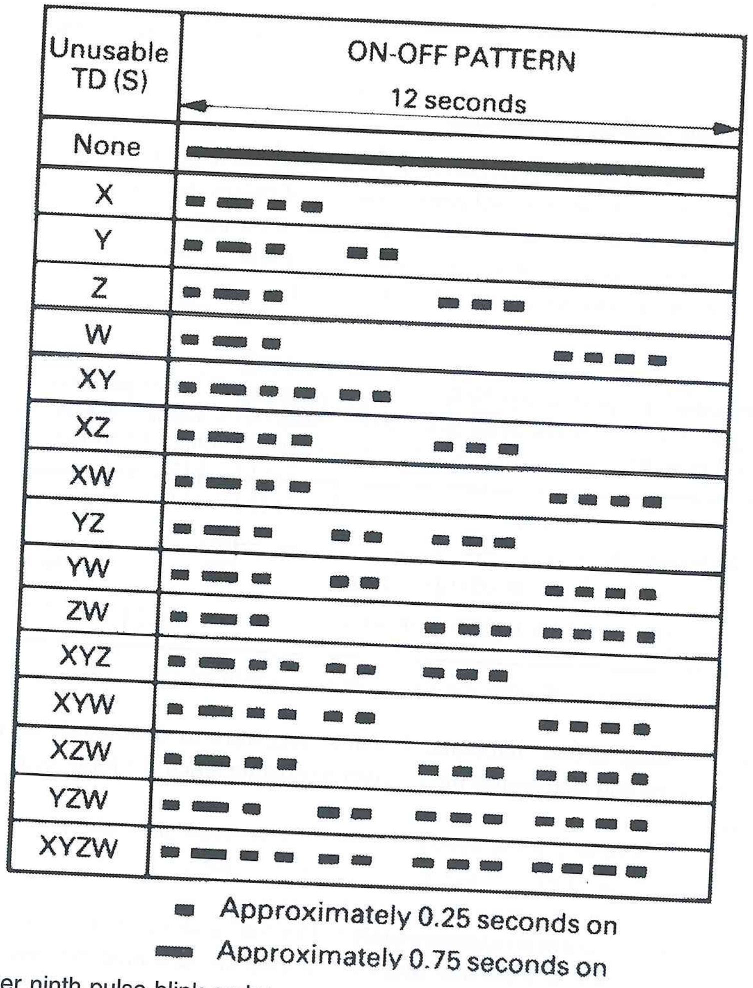


Figure 4.12 Master ninth pulse blink codes.

Table 4.6 Compliance requirements for selected Loran-C transmitter stations

Station	*Rate*	*Compliance requirements categories*				
		Pulse trailing edge	*Pulse zero crossings*	*Amplitude*	*ECD*	*Timing*
St Paul, AK	9990	2	2/1	2/1	2/1	2/1
Attu, AK	9990/5980	1	1	1	1	1
Port Clarence, AK	9990/7960	1	2/1	2/1	2/1	2/1
Kodiak, AK	9990/7960	1	2	1	1	1
Tok, AK	7960	1	1	1	1	1
Shoal Cove, AK	7960/5990	1	1	1	1	1
Williams Lake, BC	5990/8290	2	1	1	1	1
George, WA	5990/9940	1	1	1	2	1
Port Hardy, BC	5990	1	1	1	1	1
Fallon, NV	9940	2	1	1	1	1
Middletown, CA	9940	2	1	1	1	1
Searchlight, NV	9940/7980	1	1	1	1	1
Malone, FL	8970/7980	1	1	1	1	1
Grangeville, LA	7980/9610	1	1	1	1	1
Raymondville, TX	7980/9610	1	1	1	1	1
Jupiter, FL	7980	1	1	1	1	1
Carolina Beach, NC	9960/7980	1	1	1	1	1
Seneca, NY	9960/8970	1	1	1	1	1
Caribou, ME	9960/5930	1	1	1	1	1
Nantucket, MA	9960/5930	1	1	1	1	1
Dana, IN	9960/8970	2	2	1	1	1
Cape Race NFLND	5930/7270	1	1	1	1	1
Fox Harbour, LABR	8970/7270	2	1	1	1	1
Boise City, OK	8970/9610	1	1	1	1	1
Gillette, WY	8290/9610	1	1	1	1	1
Havre, MT	8290	1	1	1	1	1
Comfort Cove, NFLND	7270	1	1	1	1	1

4.3.7 Elimination of sky wave reception

Normal operation of Loran-C assumes reception by ground wave for high accuracy of position fixing. Sky waves always arrive later than ground waves although this difference in arrival time becomes less as the distance from the transmitter increases. However, the time difference is never less than 30 μs anywhere in the Loran-C coverage area. If, therefore, only the first 30 μs of the Loran-C pulse is used then sky wave contamination cannot occur.

At distances greater than 1000 nautical miles (1852 km), the ground wave is likely to be unusable because it suffers more attenuation than the sky wave. Thus the sky wave may be used beyond this range but reception of sky wave signals gives lower accuracy and corrections must be applied to compensate for the difference in path travelled compared to the ground wave.

4.3.8 Cycle matching

The technique of matching the pulse envelope, as used in Loran-A, is also used in Loran-C. However, this is only used to give coarse position fixing. Greater accuracy is obtained with cycle matching. With this technique the receiver has a flywheel oscillator which acquires the frequency and phase of incoming 100 kHz master pulses. Thus the receiver has a reference frequency which is continua updated by the master pulses and has the same phase as the master signals.

The difference in phase between the flywheel oscillator and the secondary station pulses received, is measured in the receiver and displayed as a time difference down to 0.1 µs. This possible since the period of one cycle at 100 kHz is 10 µs and the phase difference can be measur up to approximately 1/100 of a cycle. For example, suppose a phase difference of 0.63 cycle measured, then the phase difference in microseconds is given by $(0.63 \times 10)\mu s = 6.3\,\mu s$.

The envelope matching method gives the phase difference in tens of thousands, thousan hundreds, and tens of microseconds with a tolerance of ± 4 µs while the cycle-matching gives the un and tenths of a unit. Thus if envelope matching gives a time difference of, say, 52 700 µs and cyc matching gives 4.3 µs, then the accurate value of time difference is 52 704.3 µs.

One method of automatic pulse envelope matching is to compare the received pulses from t secondary station with the pulses from the receiver flywheel oscillator after the latter have been pass through a variable time delay circuit. The delay circuit is necessary because the master pulses w always arrive first anywhere in the system (this is because the secondaries are triggered after th master transmission and there is a coding delay). If the timing of the pulses does not coincide then error voltage is produced which adjusts a time delay until the start of the two pulses is caused coincide. When this happens the delay voltage is reduced to zero. The value of the delay must be th same as the delay between the received master and secondary pulses, and if displayed in digital for would give the coarse delay figure in microseconds. One method of fine matching is to use th technique as illustrated in Figure 4.13.

The received pulse is amplified by a specific amount and shifted in phase by 180°. This new wa is algebraically added to the original wave to produce a resultant wave with a well-defined minimu at a time before the value where sky wave contamination can occur. The difference in time betwe the sampling of the master pulse and the secondary pulse is determined in the same way as fo envelope matching and the result is also presented on the digital display.

An automatic method of fine matching to allow coverage on an extended range uses cycle matchin on the seventh cycle of the received pulse. A mode switch allows the operator to choose third o seventh cycle matching facility. Matching may be extended to ranges 500 nautical miles (925 km greater than with normal matching because of the greater amplitude of the seventh cycle. The inheren inaccuracies due to possible sky wave contamination must be taken into account but may b acceptable at the longer ranges involved.

4.4 Loran-C charts

Nautical charts, overprinted with Loran-C LOPs, are available from several sources, including:

- The US National Ocean Survey, for charts principally around the US coast
- The Defense Mapping Agency, for world-wide charts
- The Canadian Hydrographic Service, for charts of Canadian waters
- The UK Hydrographic Office, for charts of British waters.

Catalogues of charts and the areas covered are available from the organizations mentioned. The ch are identified in terms of the area covered and the designations of the stations serving the area; fo example, a chart serving the Southeast US may require Loran-C LOPs for a master and, say, fou

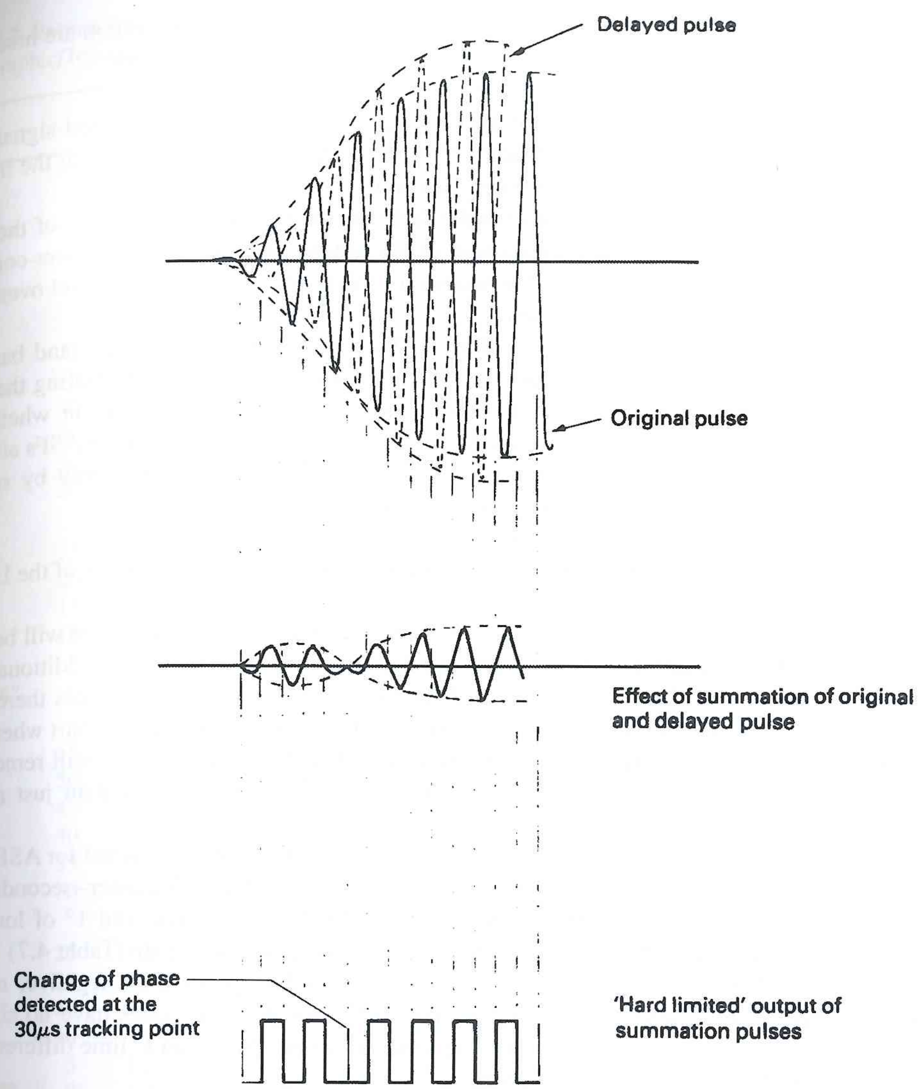


Figure 4.13 Third cycle tracking by the use of the original pulse and a pulse delayed by 5 µs, amplified and summed with the original pulse, to give a change of phase at the standard zero crossing point.

secondary stations. In this case the stations are identified by the GRI number and the secondary designation, i.e. 7980-W, 7980-X, 7980-Y and 7980-Z.

Not all LOPs are printed on charts. Usually LOPs separated by time intervals of 10 µs are used to give lines spaced at reasonable intervals. For LOPs not specified on the chart the operator must interpolate between the lines.

The National Ocean Survey first edition charts are produced with the Loran-C LOPs based on predicted coverage rather than actual field measurements. Because there are factors which affect the propagation of the loran signal, any measured time difference may be slightly in error. Correction factors may need to be applied to ensure that the designed accuracy limits of the system are met. Th are three correction factors that may be applied and these are called phase factors.

- Primary Phase Factor (PF). This allows for the fact that the speed of the propagated signal in atmosphere is slightly slower than in a vacuum. This difference is due to the fact that the index refraction of the atmosphere is slightly greater than unity.
- Secondary Phase Factor (SF). This allows for the fact that the speed of propagation of the sig is slowed when travelling over seawater because of the lower conductivity of seawater compa to land. This factor allows for the extra time needed for the propagated signal to travel over an seawater path compared to an all-land path.
- Additional Secondary Phase Factor (ASF). Because the Loran-C transmitters are land based propagated signal will travel over land and sea. The ASF may be calculated by treating the sig path as separate segments, each with a uniform conductivity value depending on whether segment path is over land or seawater. The matter is complicated by the fact that the ASFs at a fix point in the coverage area may vary with time. Such variations are caused mainly by season variations in temperature and by local weather activity.

The ASF corrections are incorporated into most Loran-C over-printed charts and many of the Loran receivers.

Since additional secondary phase factors can vary from one location to another, there will be poin on the chart where there are differences, although usually small, between the actual additional pha factor and the average value that was used for making the chart. In such circumstances there wou be a large difference between the Loran-C readings measured and the location on the chart where the readings would be plotted. It is expected that, when necessary, future chart editions will remedy th situation by using varying values for additional phase factors on a chart rather than just a sing reading.

Loran-C correction tables are available for those charts that have not been corrected for ASF erro These tables contain a complete chain and a table section is prepared for each master–secondary pa in that chain. Each page of the correction tables covers an area 3° of latitude and 1° of longitud Examples are shown for the Northeast US (NEUS) chain master–whiskey pair (Table 4.7) and th master–yankee pair (Table 4.8). The ASF corrections can be either positive or negative; negativ values are indicated by a negative sign preceding the number, the positive values have no sign. Th ASF correction tables are intended primarily for the situation where the Loran-C time differences a converted electronically to geographic co-ordinates.

To use the tables the position of the vessel must first be determined to the nearest 5 minutes of a in longitude and latitude and the relevant page of the table referred to, to find the value of th correction. The ASF correction is added algebraically to the time difference for the Loran-C pair.

Consider the following example. Loran-C receiver dial readings are 12 153.31 µs and 44451.83 µ for pairs 9960-W and 9960-Y, respectively. From these readings the computer determines a positio of 44° 15.1′ N latitude and 67°25.4′ W longitude. Entering the page index of Section W with th latitude and longitude nearest to the computed position of the vessel, the page number containing th derived geographics is found to be 17W (see Table 4.7). Entering page 17W, the correction at 44°15′N and 67°25′W is +1.5 µs. On page 17Y (Table 4.8), at the same position the correction is +2.7 µs.

The ASF corrections would be applied to the dial readings as follows:

W TD	12153.31	Y TD	44451.83
ASF correction	+ 1.5	ASF correction	+ 2.7
Corrected TD	12154.81	Corrected TD	44454.53

Table 4.7 Extract from Loran-C correction tables. (Reproduced courtesy of the Defense Mapping Agency Hydrographic/Topographic Center)

		9960-W											17W	
		68°						*Longitude west*						*67°*
LATITUDE NORTH		*0′*	*55*	*50*	*45*	*40*	*35*	*30*	*26*	*20*	*15*	*10*	*5*	*0′*
45°	0′													
	55													
	50			LAND										
	45													2.0
	40												1.7	1.6
	35									1.7	1.7	1.6	1.6	1.6
	30							1.7	1.6	1.6	1.6	1.5	1.5	1.5
	25					1.6	1.5	1.5	1.6	1.6	1.6	1.5	1.5	1.5
	20	1.6	1.5	1.6	1.6	1.5	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	15	1.6	1.5	1.5	1.5	1.5	1.5	1.5	$\boxed{1.5}$	1.5	1.5	1.5	1.4	1.4
	10	1.5	1.4	1.5	1.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.3
	5	1.4	1.4	1.5	1.4	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.3	
44°	0′	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.3	1.3			
	55	1.3	1.3	1.2	1.3	1.3	1.3	1.3	1.3	1.2				
	50	1.3	1.3	1.3	1.3	1.3	1.3	1.3						
	45	1.3	1.3	1.2	1.3	1.3	1.3							
	40	1.2	1.2	1.3	1.3	1.3								
	35	1.3	1.2	1.3										
	30	1.3	1.3	1.3										
	25	1.2	1.3	1.3					OUTSIDE CCZ					
	20	1.2	1.3	1.3	1.3									
	15	1.2	1.3	1.3	1.3	1.3								
	10	1.2	1.2	1.3	1.3	1.3								
	5	1.2	1.2	1.2	1.3	1.3	1.3							
43°	0′	1.2	1.2	1.2	1.2	1.3	1.3	1.3						
	55	1.2	1.2	1.2	1.2	1.3	1.3	1.3						
	50	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3					
	45	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3				
	40	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3			
	35	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3			
	30	1.3	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.3			
	25	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.2	1.3	1.3	1.3	1.3
	20	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.2	1.2	1.2	1.2	1.3
	15	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.2
	10	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.3	1.2	1.2	1.2	1.3	1.2
	5	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
42°	0′	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2

Table 4.8 Extract from Loran-C correction tables. (Reproduced courtesy of the Defense Mapping Agency Hydrographic/Topographic Center)

LATITUDE NORTH		9960-Y											17Y
		68°					Longitude west						
		0′	55	50	45	40	35	30	25	20	15	10	5
45°	0°												
	55												
	50												
	45			LAND									3.4
	40												3.1
	35									3.0	3.1	3.0	2.9
	30							2.9	2.9	2.9	2.9	2.8	2.8
	25					2.7	2.8	2.8	2.8	2.8	2.8	2.8	2.7
	20	2.8	2.7	2.7	2.7	2.7	2.7	2.7	2.8	2.7	2.7	2.6	2.7
	15	2.7	2.6	2.6	2.7	2.8	2.7	2.7	$\boxed{2.7}$	2.7	2.6	2.6	2.6
	10	2.7	2.6	2.6	2.7	2.7	2.6	2.6	2.5	2.5	2.6	2.6	2.6
	5	2.6	2.6	2.6	2.6	2.5	2.5	2.4	2.4	2.4	2.5	2.5	2.5
44°	0′	2.5	2.5	2.5	2.5	2.4	2.4	2.4	2.3	2.4	2.4		
	55	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4			
	50	2.4	2.4	2.4	2.4	2.4	2.4	2.4					
	45	2.4	2.4	2.3	2.4	2.4	2.4						
	40	2.3	2.3	2.3	2.4	2.4							
	35	2.4	2.4	2.4									
	30	2.4	2.4	2.4									
	25	2.4	2.4	2.4					OUTSIDE CCZ				
	20	2.4	2.4	2.4	2.4								
	15	2.4	2.4	2.4	2.4	2.4							
	10	2.4	2.4	2.4	2.4	2.4							
	5	2.4	2.4	2.4	2.4	2.4	2.4						
43°	0′	2.4	2.4	2.4	2.4	2.4	2.4	2.4					
	55	2.4	2.4	2.4	2.4	2.4	2.4	2.4					
	50	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4				
	45	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4			
	40	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4		
	35	2.5	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4		
	30	2.5	2.5	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4		
	25	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
	20	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
	15	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
	10	2.4	2.3	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
	5	2.4	2.3	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
42°	0′	2.4	2.3	2.3	2.4	2.3	2.4	2.4	2.4	2.4	2.4	2.4	2.4

The corrected dial readings are used to re-compute a new latitude and longitude for the Loran-C fix. The new position is: 44°15.4′N latitude and 67°26.4′W longitude.

The Loran-C correction tables for a particular chain may be obtained from the US Defense Mapping Agency in the LCPUB221 series.

4.5 Position fixing using the Loran-C System

For a particular location covered by more than one Loran-C chain, the operator should select the best chain available, and where possible, select a chain that can be used throughout the voyage so that the receiver can 'lock on' to the signal and 'track' throughout the trip.

Having selected a chain, it is necessary to select secondary stations which give the best fix. There may be a choice of more than two master–secondary station pairs and it is essential to choose those two pairs which give the most accurate fix. Consider Figure 4.14 which shows LOPs for two master–secondary stations, the lines shown for a particular pair being separated by 10 μs.

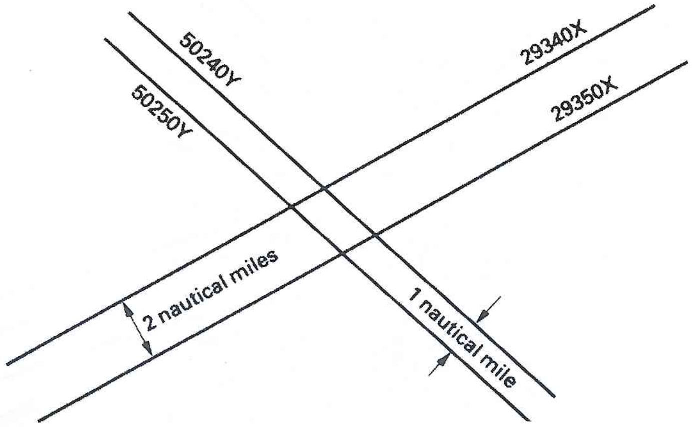


Figure 4.14 Loran-C gradients and crossing angles.

The distance between the 'Y' lines is 1 nautical mile (1.85 km), while the distance between the 'X' lines is 2 nautical miles (3.7 km). Assuming an error in the loran reading of ±0.01 μs, then the error in terms of distance is ±0.01 nautical miles (18.5 m) for the 'Y' lines and ±0.02 nautical miles (37.5 m) for the 'X' lines.

Consider now Figure 4.15 with much larger gradients for both sets of lines. In this case the order of error, assuming an accuracy of ±0.01 μs as before, is ±166.5 m for the Z lines and ±222.0 m for the W lines. Given gradients as shown in these examples, the X and Y secondaries would be chosen in preference to the W and Z secondaries.

Ideally two LOPs that cross at right angles should always be used since this would give the greatest accuracy. Since this is not always possible to achieve, then LOPs that intersect as close as possible to 90°, such as shown in Figure 4.14, should be used subject of course to suitable values of gradient.

The area in the region of the baseline extension of a master–secondary pair should never be used since, as Figure 4.16 shows, the gradients near these lines become very large, giving rise to potentially very large errors. Baseline extensions are always indicated on the charts.

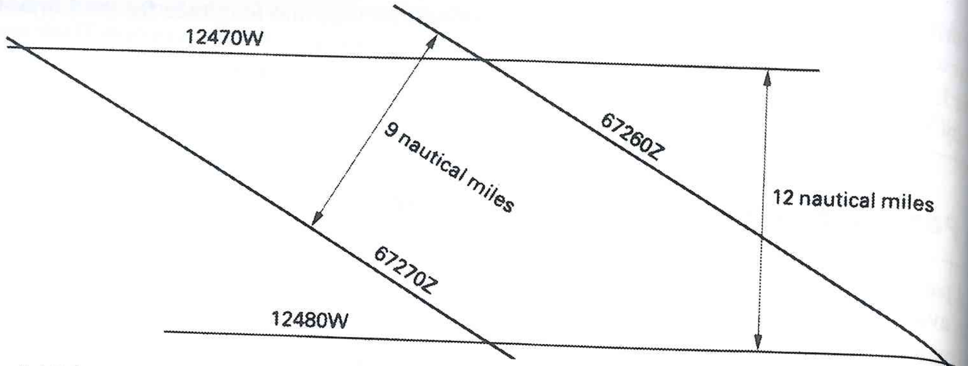


Figure 4.15 Loran-C gradients and crossing angles.

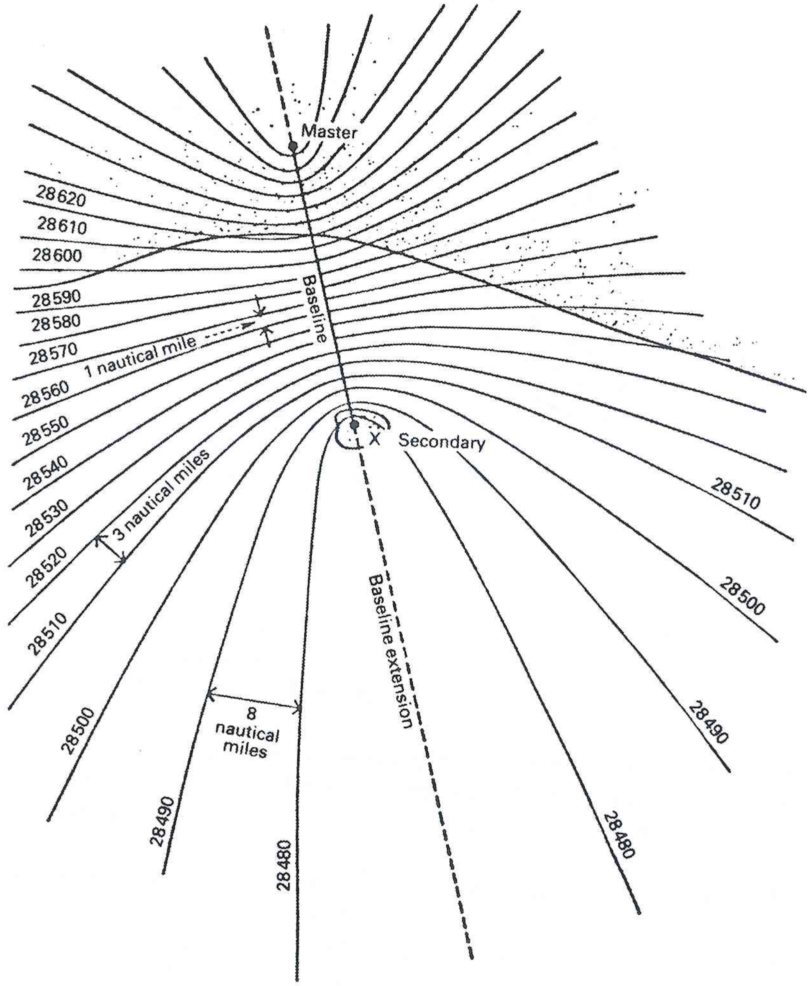


Figure 4.16 Master/slave station pair LOPs illustrating the large gradients near the baseline extension.

Table 4.9 Loran-C chain information in WGS 84 co-ordinates

Chain	*Latitude*	*Longitude*	*Emission delay*	*Coding delay*	*Power (kW)*
5543 Calcutta					
M Balasore	21°29′08.000″N	86°55′18.000″E			45
W Diamond Harbour	22°10′18.000″N	88°12′25.000″E	18510.68	18000	11
X Patpur	20°26′48.000″N	85°49′47.000″E	36542.75	36000	11
5930 Canadian East Coast					
M Caribou	46°48′27.305″N	67°55′37.159″W			800
X Nantucket	41°15′12.046″N	69°58′38.536″W	13131.88	11000	350
Y Cape Race	46°46′32.286″N	53°10′27.606″W	28755.02	25000	1000
Z Fox Harbour	52°22′35.252″N	55°42′27.862″W	41594.59	38000	900
5980 Russian-American					
M Petropavlovsk	53°07′47.584″N	157°41′42.900″E			700
W Attu	52°49′44.134″N	173°10′49.528″E	14467.56	11000	400
X Alexandrovsk	51°04′42.800″N	142°42′04.950″E	31506.50	28000	700
5990 Canadian West Coast					
M Williams Lake	51°57′58.876″N	122°22′01.686″W			400
X Shoal Cove	55°26′20.940″N	131°15′19.094″W	13343.60	11000	560
Y George	47°03′48.096″N	119°44′38.976″W	28927.36	27000	1400
Z Port Hardy	50°36′29.830″N	127°21′28.489″W	42266.63	41000	400
6042 Bombay					
M Dhrangadhra	23°00′14.000″N	71°31′39.000″E			11
W Veraval	20°57′07.000″N	70°20′13.000″E	13862.41	13000	11
X Billamora	20°45′40.000″N	73°02′073.02″E	40977.61	40000	11
6731 Lessay					
M Lessay	49°08′55.224″N	01°30′17.029″W			250
X Soustons	43°44′23.029″N	01°22′49.584″W	13000	10992.53	250
Y Loop Head	52°35′03.000″N	09°49′06.000″W	27300	24968.61	250
Z Sylt	54°48′29.975″N	08°17′36.856″E	42100	39027.54	250
6780 China South Sea					
M Hexian	23°58′03.847″N	111°43′10.298″E			1200
X Raoping	23°43′25.951″N	116°53′44.826″E	14464.69	12700	1200
Y Chongzuo	22°32′35.452″N	107°13′21.665″E	26925.76	25300	1200
7001 Bø					
M Bø	68°38′06.216″N	14°27′47.350″E			400
X Jan Mayen	70°54′51.478″N	08°43′56.525″W	14100	11014.42	250
Y Berlevåg	70°50′43.014″N	29°12′15.980″E	29100	27032.68	250
7030 Saudi Arabia South					
M Al Khamasin	20°28′02.025″N	44°34′52.894″E			1000
W Salwa	24°50′01.631″N	50°34′12.574″E	13620.00	11000	1000
X Afif	23°48′36.952″N	42°51′18.184″E	27265.00	26000	1000
Y Ash Shaykh Humayd	28°09′15.997″N	34°45′40.544″E	41414.00	40000	1000
Z Al Muwassam	16°25′56.028″N	42°48′04.884″E	57664.00	56000	1000
7270 Newfoundland East Coast					
M Comfort Cove	49°19′53.570″N	54°51′42.570″W			250
W Cape Race	46°46′32.286″N	53°10′27.606″W	12037.49	11000	500
X Fox Harbour	52°22′35.252″N	55°42′27.862″W	26148.01	25000	900

Table 4.9 Continued

Chain	*Latitude*	*Longitude*	*Emission delay*	*Coding delay*
7430 China North Sea				
M Rongcheng	37°03′51.765″N	122°19′25.954″E		
X Xuancheng	31°04′07.937″N	118°53′09.625″E	13459.70	11000
Y Helong	42°43′11.562″N	129°06′27.213″E	30852.32	28000
7499 Sylt				
M Sylt	54°48′29.975″N	08°17′36.856″E		
X Lessay	49°08′55.224″N	01°30′17.029″W	14100	11027.54
Y Værlandet	61°17′49.435″N	04°41′46.618″E	29500	26986.19
7950 Eastern Russia ‘Chayka’				
M Alexsandrovsk	51°04′42.800″N	142°42′04.950″E		
W Petropavlovsk	53°07′47.584″N	157°41′42.900″E	14506.50	11000
X Ussuriisk	44°31′59.702″N	131°38′23.403″E	33678.00	30000
Y Tokachibuto	42°44′37.214″N	143°43′09.757″E	49104.15	46000
Z Okhotsk	59°25′02.050″N	143°05′22.916″E	64102.05	61000
7960 Gulf of Alaska				
M Tok	63°19′42.884″N	142°48′31.346″W		
X Narrow Cape	57°26′20.301″N	152°22′10.708″W	13804.45	11000
Y Shoal Cove	55°26′20.940″N	131°15′19.094″W	29651.14	26000
Z Port Clarence	65°14′40.372″N	166°53′11.996″W	47932.52	44000
7980 Southeast U.S.				
M Malone	30°59′38.870″N	85°10′08.751″W		
W Grangeville	30°43′33.149″N	90°49′43.046″W	12809.54	11000
X Raymondsville	26°31′55.141″N	97°49′59.539″W	27443.38	23000
Y Jupiter	27°01′58.528″N	80°06′52.876″W	45201.88	43000
Z Carolina Beach	34°03′46.208″N	77°54′46.100″W	61542.72	59000
7990 Mediterranean Sea				
M Sellia Marina	38°52′20.707″N	16°43′06.713″E		
X Lampedusa	35°31′20.912″N	12°31′30.799″E	12755.98	11000
Y Kargabarun	40°58′21.066″N	27°52′.02.074″E	32273.29	29000
Z Estartit	42°03′36.629″N	03°12′16.066″E	50999.71	47000
8000 Western Russian				
M Bryansk	53°07′50.600″N	34°54′44.800″E		
W Petrozavodsk	61°45′32.400″N	33°41′40.400″E	13217.21	10000
X Slonim	53°07′55.200″N	25°23′46.000″E	27125.00	25000
Y Simferopol	44°53′20.600″N	33°52′32.100″E	53070.25	50000
Z Syzran (Karachev)	53°17′17.600″N	48°06′53.400″E	67941.60	65000
8290 North Central U.S.				
M Havre	48°44′38.589″N	109°58′53.613″W		
W Baudette	48°36′49.947″N	94°33′17.915″W	14786.56	11000
X Gillette	44°00′11.305″N	105°37′23.895″W	29084.44	27000
Y Williams Lake	51°57′58.876″N	122°22′01.686″W	45171.62	42000
8390 China East Sea				
M Xuancheng	31°04′07.937″N	118°53′09.625″E		
X Raoping	23°43′25.951″N	116°53′44.826″E	13795.52	11000
Y Rongcheng	37°03′51.765″N	122°19′25.954″E	31459.70	29000
8830 Saudi Arabia North				
M Afif	23°48′36.952″N	42°51′18.184″E		
W Salwa	24°50′01.631″N	50°34′12.574″E	13645.00	11000
X Al Khamasin	20°28′02.025″N	44°34′52.894″E	27265.00	25000
Y Ash Shaykh Humayd	28°09′15.997″N	34°45′40.544″E	42645.00	40000
Z Al Muwassam	16°25′56.028″N	42°48′04.884″E	58790.00	56000

Table 4.9 Continued

Chain	*Latitude*	*Longitude*	*Emission delay*	*Coding delay*	*Power (kW)*
8930 North West Pacific					
M Niijima	34°24′11.943″N	139°16′19.473″E			1000
W Gesashi	26°36′25.038″N	128°08′56.920″E	15580.86	11000	1000
X Minamitorishima	24°17′08.007″N	153°58′53.779″E	36051.53	30000	1100
Y Tokachibuto	42°44′37.214″N	143°43′09.757″E	53349.53	50000	600
Z Pohang	36°11′05.450″N	129°20′27.440″E	73085.64	70000	150
8970 Great Lakes					
M Dana	39°51′07.658″N	87°29′11.586″W			400
W Malone	30°59′38.870″N	85°10′08.751″W	14355.11	11000	800
X Seneca	42°42′50.716″N	76°49′33.308″W	31162.06	28000	800
Y Baudette	48°36′49.947″N	94°33′17.915″W	47753.74	44000	800
Z Boise City	36°30′20.783″N	102°53′59.487″W	63669.46	59000	800
9007 Ejde					
M Ejde	62°17′59.837″N	07°04′26.079″W			400
W Jan Mayen	70°54′51.478″N	08°43′56.525″W	14200	10983.83	250
X Bø	68°38′06.216″N	14°27′47.350″E	28000	23951.92	400
Y Værlandet	61°17′49.435″N	04°41′46.618″E	41100	38997.27	250
Z Loop Head	52°35′03.000″N	09°49′06.000″W	55700	52046.62	250
9610 South Central U.S.					
M Boise City	36°30′20.783″N	102°53′59.487″W			800
V Gillette	44°00′11.305″N	105°37′23.895″W	13884.48	11000	400
W Searchlight	35°19′18.305″N	114°48′16.881″W	28611.81	25000	550
X Las Cruces	32°04′18.130″N	106°52′04.388″W	42044.93	40000	400
Y Raymondsville	26°31′55.141″N	97°49′59.539″W	56024.80	52000	400
Z Grangeville	30°43′33.149″N	90°49′43.046″W	69304.00	65000	800
9930 East Asia					
M Pohang	36°11′05.450″N	129°20′27.440″E			150
W Kwang Ju	35°02′23.966″N	126°32′27.295″E	11946.97	11000	50
X Gesashi	26°36′25.038″N	128°08′56.920″E	25565.52	22000	1000
Y Niijima	34°24′11.943″N	139°16′19.473″E	40085.64	37000	1000
Z Ussuriisk	44°31′59.702″N	131°38′23.403″E	54162.44	51000	700
9940 U.S. West Coast					
M Fallon	39°33′06.740″N	118°49′55.816″W			400
W George	47°03′48.096″N	119°44′38.976″W	13796.90	11000	1600
X Middletown	38°46′57.110″N	122°29′43.975″W	28094.50	27000	400
Y Searchlight	35°19′18.305″N	114°48′16.881″W	41967.30	40000	550
9960 Northeast U.S.					
M Seneca	42°42′50.716″N	76°49′33.308″W			800
W Caribou	46°48′27.305″N	67°55′37.159″W	13797.20	11000	800
X Nantucket	41°15′12.046″N	69°58′38.536″W	26969.93	25000	400
Y Carolina Beach	34°03′46.208″N	77°54′46.100″W	42221.65	39000	800
Z Dana	39°51′07.658″N	87°29′11.586″W	57162.06	54000	400
9990 North Pacific					
M Saint Paul	57°09′12.350″N	170°15′06.245″W			325
X Attu	52°49′44.134″N	173°10′49.528″E	14875.25	11000	625
Y Port Clarence	65°14′40.372″N	166°53′11.996″W	32068.95	29000	1000
Z Narrow Cape	57°26′20.301″N	152°22′10.708″W	46590.45	43000	400

4.6 Loran-C coverage

Loran-C coverage is dependent on land-based transmitters grouped into chains. The cu information relating to the chains, their group repetition interval (GRI), location, emission and co delay and nominal radiated power is shown in Table 4.9.

Diagrams are available which show the predicted ground wave coverage for each chain. Briefl coverage diagrams are generated as follows.

- **Geometric-fix accuracy limits.** Each of two LOPs in a chain is assigned a TD standard devia of 0.1 µs. The geometric-fix accuracy is assigned a value of 1500 feet, $2d_{RMS}$ where d_{RMS} is radial or root mean square error. Using these constraints a contour is generated within the chain representing the geometric-fix accuracy limits.
- **Range limits.** Predicted atmospheric noise and cross-rate Loran-C interference is compared estimated Loran-C signal strength for each Loran-C transmitting station to obtain an expected SNR (signal-to-noise ratio) range limits for each transmitted signal.
- **Predicted accuracy.** The predicted Loran-C coverage for each chain is the result of combining geometric-fix accuracy limits and predicted SNR range limits. Where the geometric-fix accu limits extend beyond the range limits, the range limits are used on the coverage diagrams and versa.

Figure 4.17 shows the $2d_{RMS}$ coverage for various station pairs in the Northeast US (NEUS) ch Diagram A, for example, shows the accuracy contours for the master–whiskey and the master–yan station pairs. The solid line in the diagrams show the $2d_{RMS}$ contour of 1500 ft absolute accuracy, dashed line 1000 ft and the dotted line 500 ft. Similar diagrams for other pair combinations are shown in Figure 4.17.

A composite coverage diagram for the NEUS (9960) chain is shown in Figure 4.18.

Associated with each chain (not shown in Figure 4.18) are unmanned monitor sites (lormansi which continuously check the loran signals received to detect any out-of-tolerance conditions so corrections can be relayed back to the transmitting site for implementation of those corrections.

Clarinet Pilgrim (CP) and Clarinet Pilgrim with TTY2 is a system used, at specified stations, wh certain pulses in each group are subject to pulse position modulation of ± 1 µs to provide back administrative and control signals.

Radial or root mean square error, d_{RMS}, is defined as the radius of the error circle produced fr the square root of the sum of the square of the sigma error components along the major and minor a of a probability ellipse (see Figure 4.19). The ellipse is produced by virtue of the deviation expec along each LOP as indicated by $\delta 1$ and $\delta 2$ in Figure 4.22, and varies according to the gradient a angle of cut of the LOPs at that point.

$1d_{RMS}$ is defined as the radius of a circle obtained when $\delta x = 1$, and δy varies from 0 to 1. $2d_{R}$ is defined as the radius of a circle obtained when $\delta x = 2$ and δy varies from 0 to 2. The relations between $\delta 1, \delta 2$ and $\delta x, \delta y$ and the probability values associated with $1d_{RMS}$ or $2d_{RMS}$ values beyond the scope of this book but may be obtained from standard reference books.

As far as the accuracy of Loran-C coverage is concerned the coverage diagram (Figure 4.18) sho that for ground wave reception areas, the fix probability is 95% ($2d_{RMS}$) at 1500 ft with a standa deviation of 0.1 µs and 1/3 SNR. Sky wave reception will extend the coverage area but accura cannot be guaranteed.

For the Loran-C system the absolute accuracy, i.e. the ability to determine the true geograph position (latitude and longitude), is claimed to be from 0.1 to 0.25 nautical mile (185–463 depending on the position of the receiver within the coverage area. Repeatable accuracy is the meas

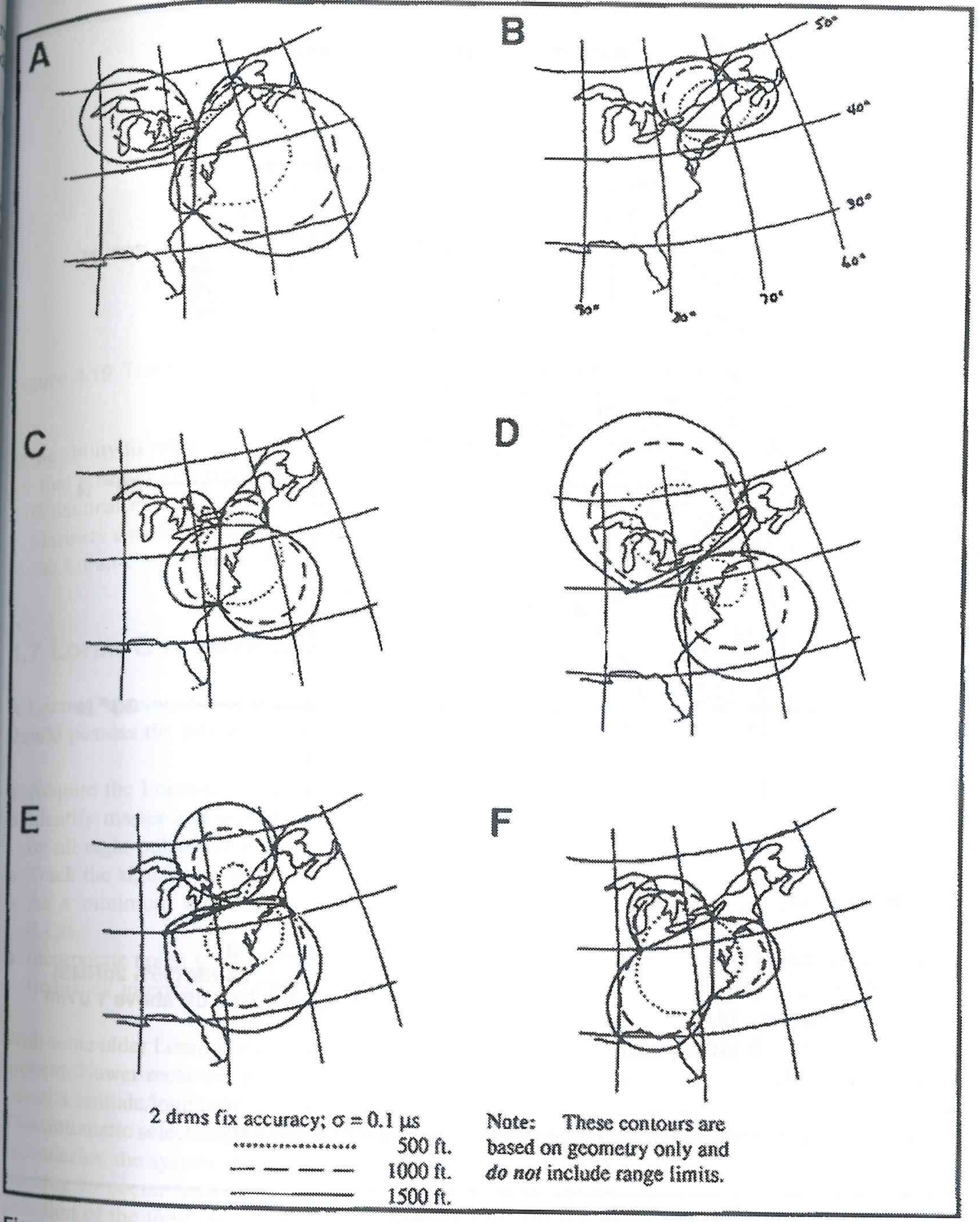


Figure 4.17 Contours of equal $2d_{rms}$ for various triads in the 9960 Loran-C chain.

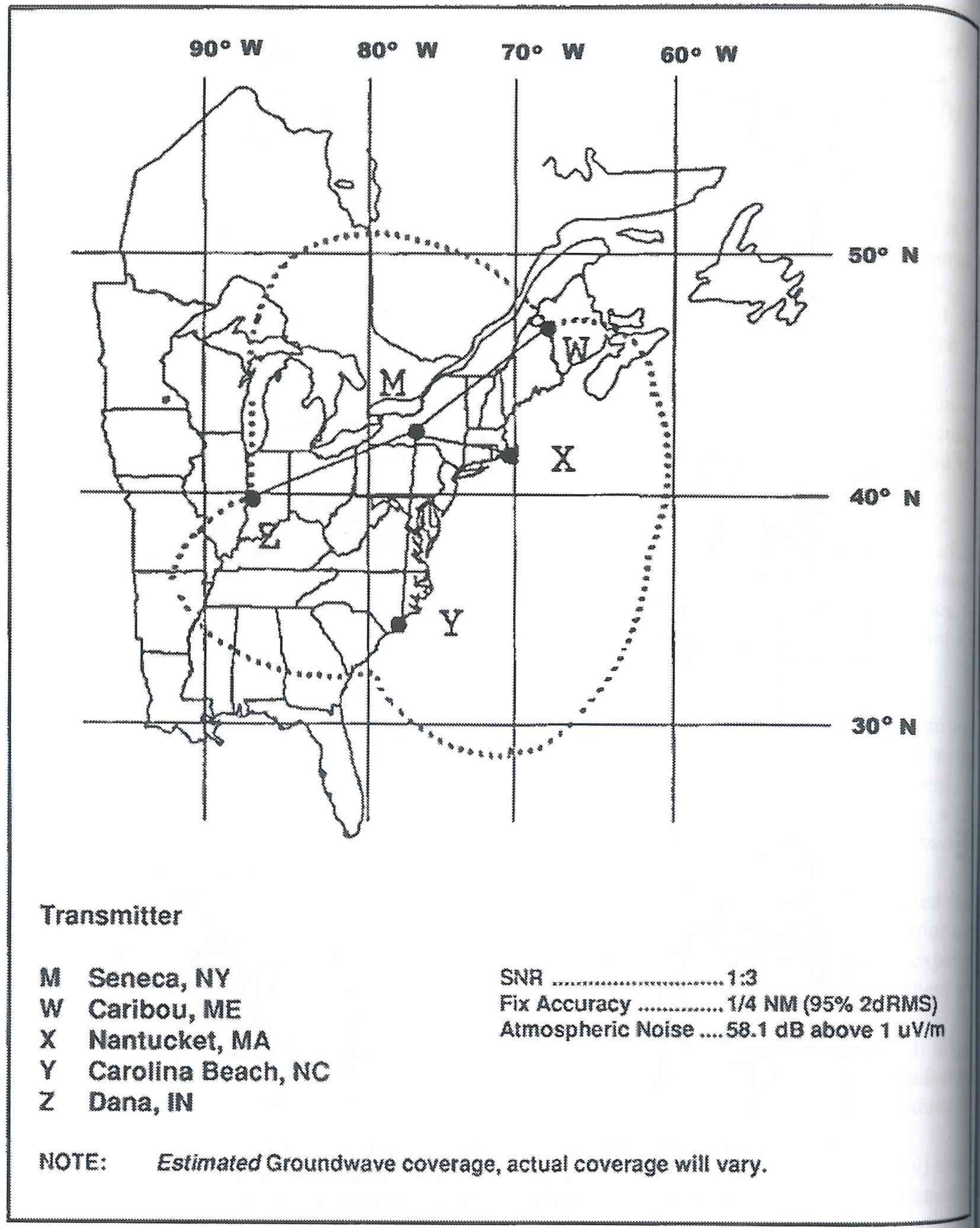


Figure 4.18 Loran-C GRI 9960 Northeast US (NEUS) chain.

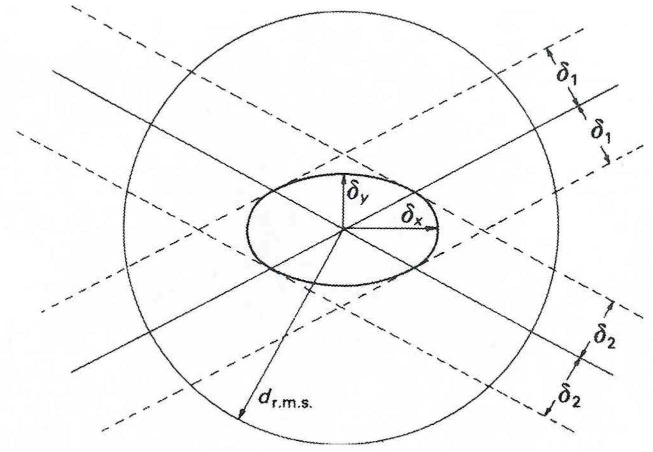


Figure 4.19 The error ellipse.

of the ability to return to a previously plotted position, time and time again by using Loran-C readings for that position as a reference. For Loran-C the repeatable accuracy is claimed to be from 0.008 to 0.05 nautical mile (15–90 m). The global Loran-C coverage is shown in Figure 4.20.

Mariners should consult relevant local Notice to Mariners, whereby official notification of changes to the Loran-C system can be found.

4.7 Loran-C receivers

A Loran-C receiver which is capable of measuring position with the claimed accuracy for the system should possess the following characteristics.

- Acquire the Loran-C signals automatically.
- Identify master and secondary ground wave pulses automatically, and accomplish cycle matching on all eight pulses for each master–secondary pair used.
- Track the signals automatically once acquisition has been achieved.
- As a minimum requirement, display two time-difference readings, to a precision of at least 0.1 μs.
- Incorporate notch filters, adjusted by the manufacturer if required, to minimize the effects of radio frequency interference in the area in which the user expects to operate.

With some older Loran-C receivers it is necessary to select the chain and station pairs during the set-up process. Newer receivers possess an automatic initialization process whereby the operator enters the vessel's latitude/longitude and the receiver selects the best chain and station pairs for that position. This automatic selection process can be overridden if necessary. Having selected a suitable master and secondaries, the system should then acquire the signals with sufficient accuracy to permit settling and tracking to occur. Settling involves the detection of the leading edge of the signal pulse and the selection of the third cycle of the pulse for tracking purposes. Tracking involves the maintenance of the synchronization of the third cycle of the master and secondary signals. The time taken for the receiver to complete the 'acquire–settle–track' process will depend on the characteristics of the receiver and the S/N ratio of the received signals.

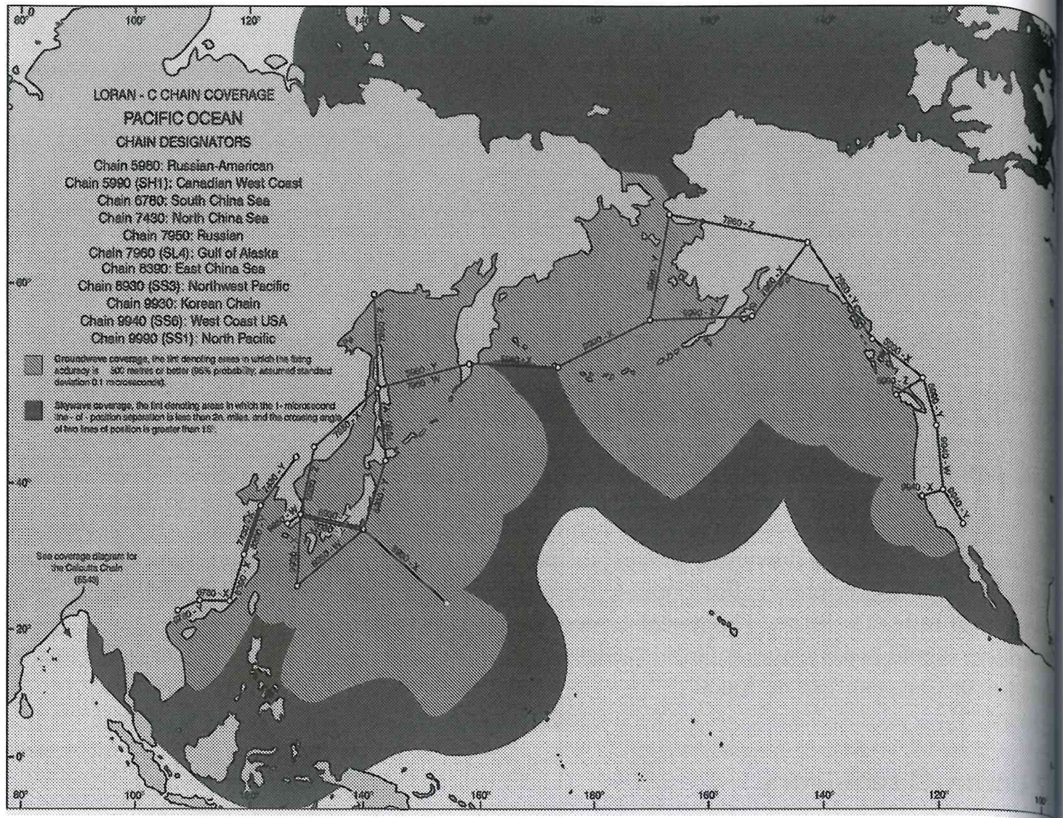


Figure 4.20a Loran-C global coverage. (Reproduced from Admiralty List of Radio Signals volume 2 by permission of the Controller of Her Majesty's Stationery Office and the UK Hydrographic Office.)

Signal reception may be impaired by interference from other signals which could act as a nois input and reduce the S/N ratio of the received loran signal and degrade positional accuracy. Notc filters within the receiver can assist in minimizing the effect of the interference. The notch filters ma be either preset by the manufacturer or be adjustable on site.

Modern Loran-C receivers are designed with a front panel that contains a display element (usuall a liquid crystal display (LCD) which is easily read under all lighting conditions and energy efficien and a keypad with function keys and numeric keys to enter data and change the data displaye Displays will indicate information such as: status and warning data; information on the GRI in use an the secondaries chosen; alarm settings; positional information in time differences (TDs) or as latitud longitude and navigation information such as waypoint indicators; bearing and distance to waypoin time to go (TTG); cross-track errors (XTE); speed and course etc. Some displays may use pages o information that can be selected as required by the operator. Time differences are measured by th receiver and may be converted to latitude/longitude by computer algorithms; such algorithms woul most likely incorporate additional secondary factor (ASF) corrections, which are stored in th computer memory.

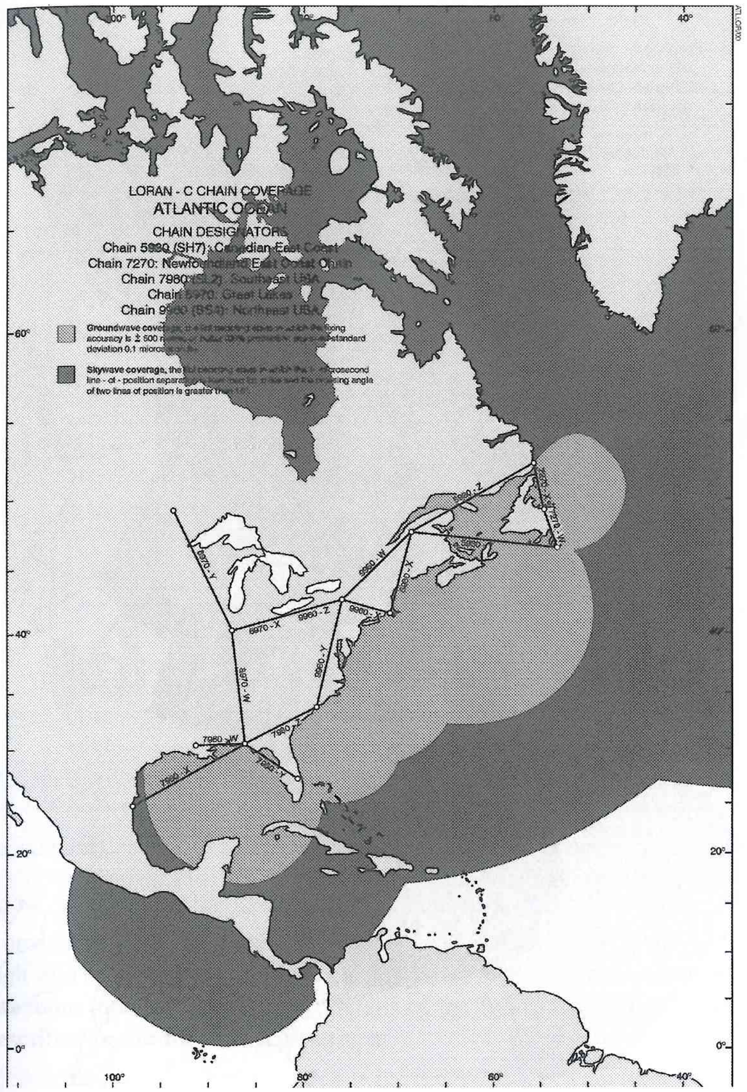


Figure 4.20b (continued).

Modern receivers have the facility for the operator to monitor the progress of the voyage and allo for course corrections as necessary. The receiver gives a position (in TD or latitude/longitude) and ha a precise clock so that it is possible to produce navigational information, such as vessel's speed an course. A waypoint is a set of co-ordinates that indicate a location of interest to the navigator, such as wrecks, buoys, channel information, and previously productive fishing areas. Waypoints can usually be stored in the receiver memory by entering the waypoint co-ordinates or as a distance and bearing from another waypoint before pressing the appropriate control button. Waypoints may be used by the navigator as route indicators for a planned route. The receiver can track progress between waypoints allowing the operator to monitor data, such as bearing to the next waypoint, time-to-go (TTG) to reach the next waypoint, and cross-track error (XTE). The latter indicates a deviation from the planned course and shows the perpendicular distance from present position to the intended track between waypoints.

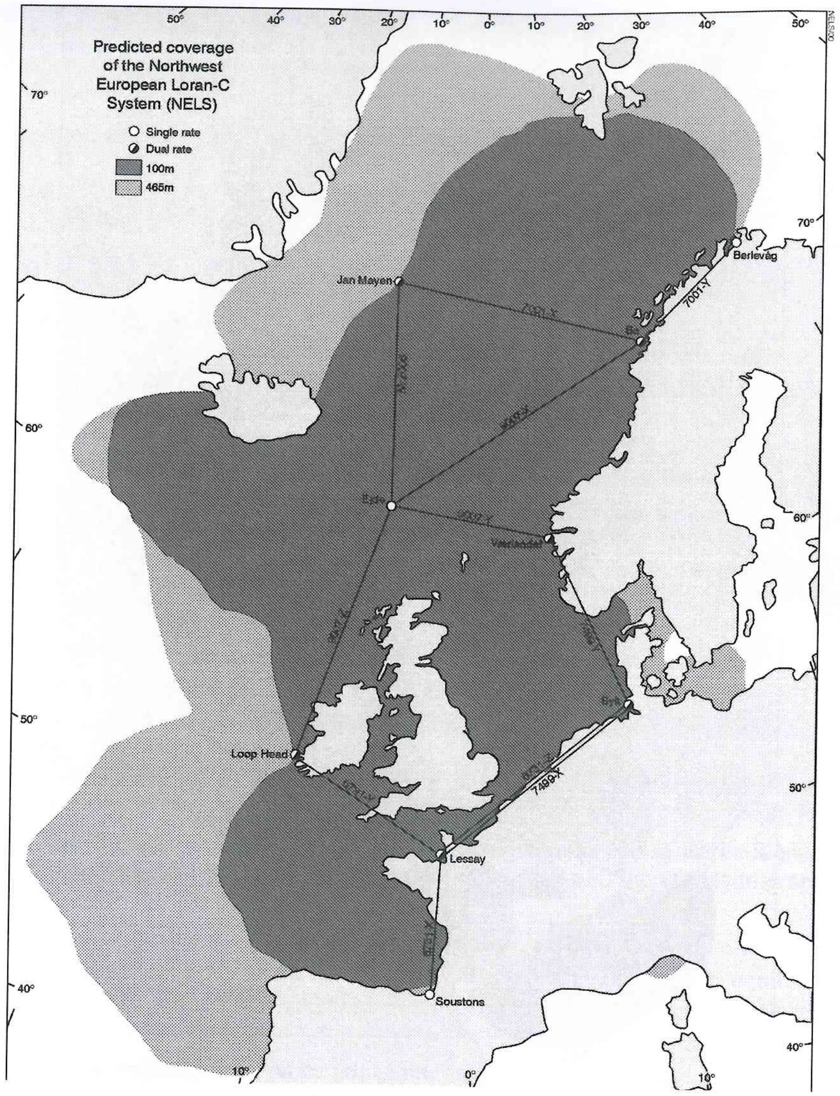


Figure 4.20c (continued).

In addition, magnetic variation data apposite to the loran coverage area may be stored in mem allowing the operator to navigate with reference to either true or magnetic north. The use of magn north would be indicated by some means on the display to inform the operator that directions are w reference to magnetic and not true north.

Loran receivers may stand alone or be integrated with other equipment, such as a plotter or GP (Global Positioning System). In addition, modern receivers are able to provide outputs to oth electronic equipment using protocols such as the NMEA (National Marine Electronics Associatio 0180, 0182, 0183 and 2000 formats where applicable. Such outputs may thus be connected t autopilots, plotters, radars etc, while it is also possible to connect with a gyrocompass and speed l to enable the set and drift of the current to be determined.

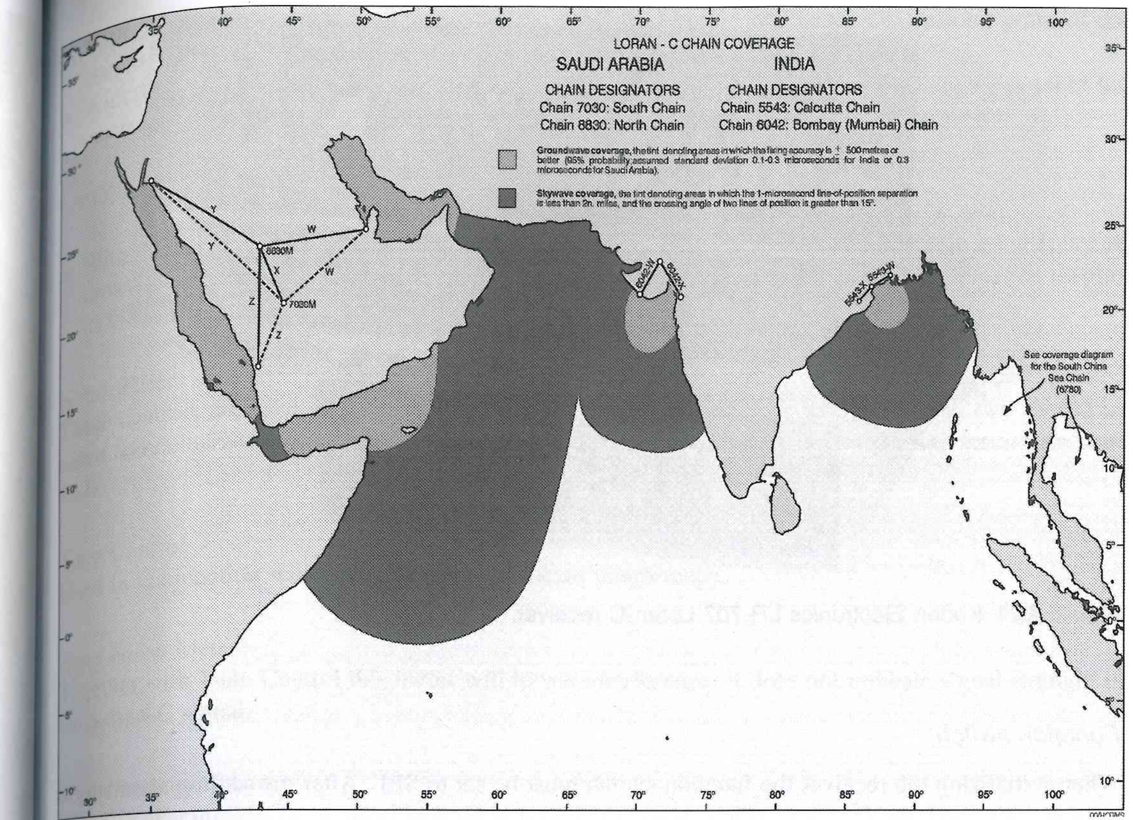


Figure 4.20d (continued).

A typical automatic receiver is illustrated in Figure 4.21. This is the Koden Electronics LR-707 receiver. Although this receiver is of an older generation of receivers, the way in which it operates is no different to its more modern counterparts. Details of the functions offered by this receiver and its operation are described in the following paragraphs.

4.7.1 Station selection

Switches S1 and S2 control the two time displays. When the receiver is first initialized (see p. 124) display 2 will be rolling, i.e. displaying various secondary time differences in an ascending sequence. The roll frequency is once every 3 s. When the required secondary time difference appears on display 2, pressing switch 2 will retain that output. If it is required to change the chosen secondary time difference, pressing S2 again will restore the roll action. S1 serves the same function as S2 except that it controls display 1.

An exception to the functions performed by the two switches is that if display 1 is adjusted for roll, display 1 will indicate all time differences including that being shown by display 2. With S1 adjusted for non-roll, S2 will indicate a time difference reading other than that indicated on display 1, i.e. it will skip that time difference. As a result of this feature, when only two secondaries are acquired (or available) and Sl is adjusted for non-roll, S2 will also appear to be adjusted for non-roll. The S1 display is also used to indicate certain alarm functions and to supply technical data.

Figure 4.21 Koden Electronics LR-707 Loran-C receiver.

Function switch

When initializing the receiver the function switch must be set to SEL. After the settling alarms hav been extinguished, the function switch should be placed in NORM position to inhibit cycle selectio of all stations and to enable certain functions of +/MEMO and –/RECALL (see under the appropria heading for a description of these functions). Setting the function switch in either Sl, M or S2 positio allows the time difference of the selected station to be manipulated using the +/MEMO an –/RECALL controls.

The cycle selection process is inhibited for all other stations except the selected station. With th function switch set to SEL, the cycle selection process is activated for all stations. In addition, th +/MEMO and –/RECALL buttons will jump all stations by 10 µs depending on the button chosen an the number of times it is pressed. If the control is left in this position, the readings should return t correct values provided propagation conditions are normal and the +/MEMO and –/RECALL butto have not been pressed excessively, which would cause the tracking point to move off the puls Simultaneously pressing +/MEMO and –/RECALL will initialize the receiver.

+/MEMO

- With the function switch in TEST and +/MEMO pressed, the display will indicate the oscillat offset frequency. Pressing the button again will restore the normal technical information to th display.
- With the function switch set to SEL, the tracking points of all stations will shift by +10 µs each tim the button is pressed.
- With the function switch in NORM, pressing the +/MEMO button will 'freeze' the display an place all acquired time differences into memory. Pressing +/MEMO again will restore the displa to time difference readings.

- With the function switch in Sl, pressing the +/MEMO button will cause the tracking point of the station appearing on display 1 to move +10 µs.
- With the function switch set to M, pressing the +/MEMO button will cause the tracking point of the master station to move by +10 µs, causing S1 and S2 display to indicate 10 µs lower.

–/RECALL

- With the function switch set to NORM, pressing the –/RECALL button will recall and display all time differences previously entered into the memory. Pressing the button again will restore display to the normal tracking mode.

Notch Filters
These controls are used to eliminate interference that is sinusoidal. When not in use, two should be tuned fully clockwise and two tuned fully anticlockwise, or improper operation may result (see page 122).

Tune Control
Used in conjunction with the tune meter to locate interference.

Tune Noise Meter
Together with Tune Control this meter will locate interference. It does not indicate signal strength of the Loran-C signal.

Signal-to-noise Alarms
When lit, these indicate a possible problem with the associated station. When operating at great distances from the station or under adverse weather conditions, these alarms may light from time to time. Simultaneous flashing of all three alarms indicates that the RECALL control has been activated.

Settling Alarms
These indicate that the associated station is settled and is ready for tracking. Simultaneous flashing of all three alarms indicates that the +/MEMO control has been activated.

Dimmer Control
This controls the intensity of both displays and all six LED alarms.

Chain Selector
This must be used prior to initializing the receiver to select the required Loran-C chain. To determine the setting of the required GRI number, reference should be made to the appropriate Loran-C chart for the area of operation. Only the first three digits of the chain identification need be set since the last (fourth) digit is always zero.

4.7.2 Normal operation

The chain selector should be set for the chain of the area in which the vessel is operating. Next the function switch should be set to SEL and the notch filters detuned by setting two of them completely clockwise and two completely anticlockwise. The dimmer switch should also be set f clockwise.

The power switch should then be turned ON and after about 4 s both displays should sequenti indicate all secondaries acquired. When the required time difference appears on the display, wanted secondaries can be selected by pressing display control S1 and S2. When the settling ala are no longer alight the function switch should be set to NORM. The unit will then have acquired wanted signals and will track those signals.

Use of the notch filters

Rotate Tune Control and check for signal interference. When Tune Control is in the '6-o'clock' positio it indicates the centre of the loran frequency and the tune meter should indicate a reasonably la deflection. When rotated either side of the central position, the tune meter should indicate a small deflection. Any 'bouncing' or increased deflection of the meter indicates the presence of noise.

Noise may be eliminated by using the notch filters which are highly tuned circuits and can sharp reduce the signal level of any frequency if the filters are tuned to that frequency. Thus, if Tune contr finds any interfering signals in the frequency range of the loran signals, the notch filter controls m be adjusted to eliminate that interference. The technique to be used is described as follows.

(a) Turn all notch filter knobs fully clockwise.
(b) Set the Tune Control knob to its centre ('6 o'clock') position and note the deflection on the tu meter which is an indication of the loran signal.
(c) Turn the Tune Control knob slowly anticlockwise and note the abrupt deflection on the tune mete A similar effect should be found if the knob is rotated slowly clockwise. See Figure 4.22(a).
(d) Set the Tune Control knob to the point where the meter deflection is greatest in the anticlockwi direction.
(e) Reset notch filter knob N1 to the centre position and slowly rotate it anticlockwise until the mete deflection is minimized.
(f) Check that the meter deflection for the interference signal is less than the loran signal and if no repeat steps (d) and (e) above using the notch filter N2.
(g) Reset the Tune Control knob to its centre position and slowly rotate clockwise until th interference frequency below the loran centre frequency is found.
(h) Reset notch filter knob N3 to its centre position and slowly rotate clockwise until the mete deflection is minimized.
(i) Use the notch filter N4, by turning it clockwise from its centre position, if the use of notch filte N3 has not reduced the interference signal level below that of the wanted loran signal.
(j) Repeat step (c) and note that the levels of the interference signals are reduced below the level o the loran signal above and below the loran centre frequency. See Figure 4.22(b).

Receiver alarm indications

The various alarms that are possible with this receiver as an aid to the operator are as follows.

(a) **Secondary blink.** This is indicated when the third and fourth digit of either display is flashin During the blink alarm, only the time difference reading of the secondary station at fault will flash This station should not therefore be used for position fixing. The blink alarm will not automaticall reset itself. When two or more secondaries are flashing, it is usually an indication of problems with the master station and all time difference readings should be used with extreme caution.

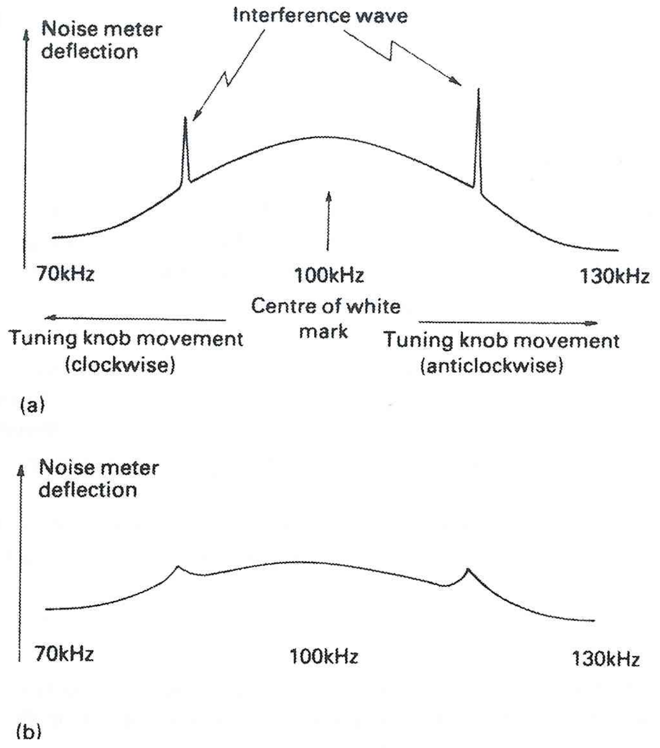


Figure 4.22 (a) Possible interference levels prior to adjustment of the tuning controls.(b) Possible interference levels after adjustment of the tuning controls. The interference level should always be set to less than the level of the loran signal.

(b) **Test alarm.** When the function switch is set to TEST, the second digit of both displays will flash once every 3 s.
(c) **Memo alarm.** When the display is 'frozen' by activating the +/MEMO button, all three settling alarms will flash once every 3 s.
(d) **Recall alarm.** When the –/RECALL control has been activated, all three signal-to-noise alarms will flash once every 3 s.
(e) **Function switch alarm.** If the function switch was in any position other than SEL when power was applied to the receiver, the number 9 will appear in the window of each display. To correct, the receiver should be turned OFF and the function switch set to SEL before restoring the supply.
(f) **Signal-to-noise alarms.** When lit, the signal-to-noise alarms indicate a poor signal-to-noise ratio. If the alarm is lit for 50% or more of the time, the tracking capabilities on the problem station will be severely impaired or, in some cases, impossible to track. This alarm should be ignored during the settling process.
(g) **Settling alarm.** This alarm will light any time the cycle selection circuit is not satisfied with a decision. Since propagation conditions are variable, the settling alarm may light even though the displayed time difference reading is correct. With the function switch in the NORM position, no 10-μs jump will occur even though a jump is indicated by the settling alarm. If the function switch is in the SEL position, a jump will occur automatically.

To cancel any alarm function, first turn the function switch to TEST and then back to NORM. If the receiver detects that the alarm condition still exists, the alarm will, after a short delay, become active again.

Other functions of the display

When the function switch is moved to TEST, both displays will automatically indicate the number in each position, allowing the operator to check that all display segments are operating correctly. In addition the cycle selection alarms and the signal-to-noise alarms will light. This type of display will remain for 3 s, then the following information becomes available.

- The first two digits of each display indicate the station under observation. The first two digits correspond to the first two numbers of the respective time differences (99 indicates the master).
- The second digit will flash, indicating a non-tracking condition for the displays.
- The third digit of the time difference indicates the signal condition at the beginning of the pulse.
- The fourth digit indicates the signal condition at the tracking point of the pulse.
- The fifth digit indicates the signal condition at the crest of the pulse. In each of these cases '0' is the lowest value and '9' is the highest value.
- The sixth digit indicates the mode of the receiver, with 4 being the final and tracking mode.

When the +/MEMO button is pressed, the oscillator offset frequency is displayed on a scale of -20 to +20, with '0' indicating no offset. Press again to reset. If zeros appear in the first to fourth digits the frequency is low. The converse is true if no zeros appear.

Initializing procedure

The receiver is initialized in four stages. The modes can be checked by the sixth digit when the function switch is set to TEST.

- **Mode 1 stage.** For those loran signals received from a chain, the GRI of which is preset on the front panel, the received pulse is compared with an internally generated pulse. The master pulse is detected first and then the secondary pulses. The time difference values are displayed on the display panels.
- **Mode 2 stage.** The detection and tracking of the zero cross point of the carrier is commenced and the tracking point is transferred to the start of the loran signal in 10-μs steps until the signal becomes zero in the signal-to-noise detection circuit; the noise indicator lamps will then light. This operation is performed for master and secondary stations independently.
- **Mode 3 stage.** The tracking point is now transferred in the signal direction in 10-μs steps until the signal is detected. The noise indicator lamps should now be extinguished. Once again the operation is performed independently for master and secondary stations. The function of modes 2 and 3 is to ensure that the pulses for master and secondary stations are overlapped correctly, i.e. pulse 1 of the master is overlapped with pulse 1 of the secondary station.
- **Mode 4 stage.** At the end of mode 3 stage, the 10-μs step operation switches from the signal-to-noise detection circuit to the third-wave detection circuit. The tracking point is now set to the correct tracking position, namely the point after the third wave as seen from the pulse leading edge. The set indicator lamps are then extinguished. The initialization operation is now complete. When the function switch is set to SEL, the check operation continues and if the circuit decides that the previously determined position is incorrect, the 10-μs step sequence is re-started and the set indicator lamps are then lit. The indicator lamps will only be extinguished after a second setting-up routine has been performed.

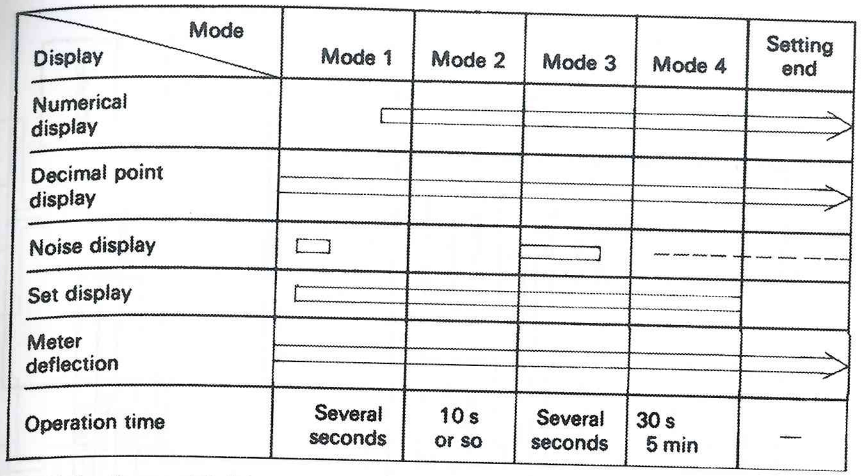


Figure 4.23 Initialization and lighting/extinction of indicator lamps.
Notes: (1) It is possible that if the signal level is lower than -20dB or the S/N ratio (SNR) is very low, mode 1 will not proceed to the next stage, and no display appears. (2) The noise indicator lamp may light during mode 4 operation or after setting ends if the S/N ratio (SNR) is too low.

Refer to the diagram of lamp lighting sequence for the initialization routine (Figure 4.23).

4.7.3 Circuit description

This receiver uses a microprocessor and associated logic circuitry to detect and track the Loran-C 100-kHz pulse trains from master and secondary transmitter stations. The system also presents the time differences between the receipt of the master and secondary pulse trains as a direct visual display. Two such time differences can be indicated which give a position fix as the point of intersection of the two time difference lines (LOPs). The microprocessor used is a Motorola 6800 equivalent. The means of detection, sampling and tracking the signals is initiated by the use of interrupt signals IRQ (interrupt request) and NMI (non-maskable interrupt). A basic block diagram is shown in Figure 4.24.

The antenna coupler provides some filtering and gives some initial amplification prior to connection to the receiver block. The receiver block provides bandpass filtering and amplification. Separate circuits are provided for the CYCLE and ENVELOPE outputs, with the signals hard limited to give digitized values. The bandpass filter allows for a restriction on the received signal frequencies to a range of 70–130 kHz. The notch filter can be used to minimize the effects of noise signals within the pass band. The logic block is shown in more detail in Figure 4.25.

The incoming CYCLE signal to the logic block is fed to a sampling circuit consisting of 50-bit shift registers and a D-type flip-flop. The shift registers are integrated circuits 9C, 10C, 12C and 13C while the flip-flop is integrated circuit 8C.

The loran signal format is eight pulses of 100 kHz, each pulse lasting for 250 μs. The signal, after passing through the receiver and being hard limited, appears as digital pulses. The pulse train is

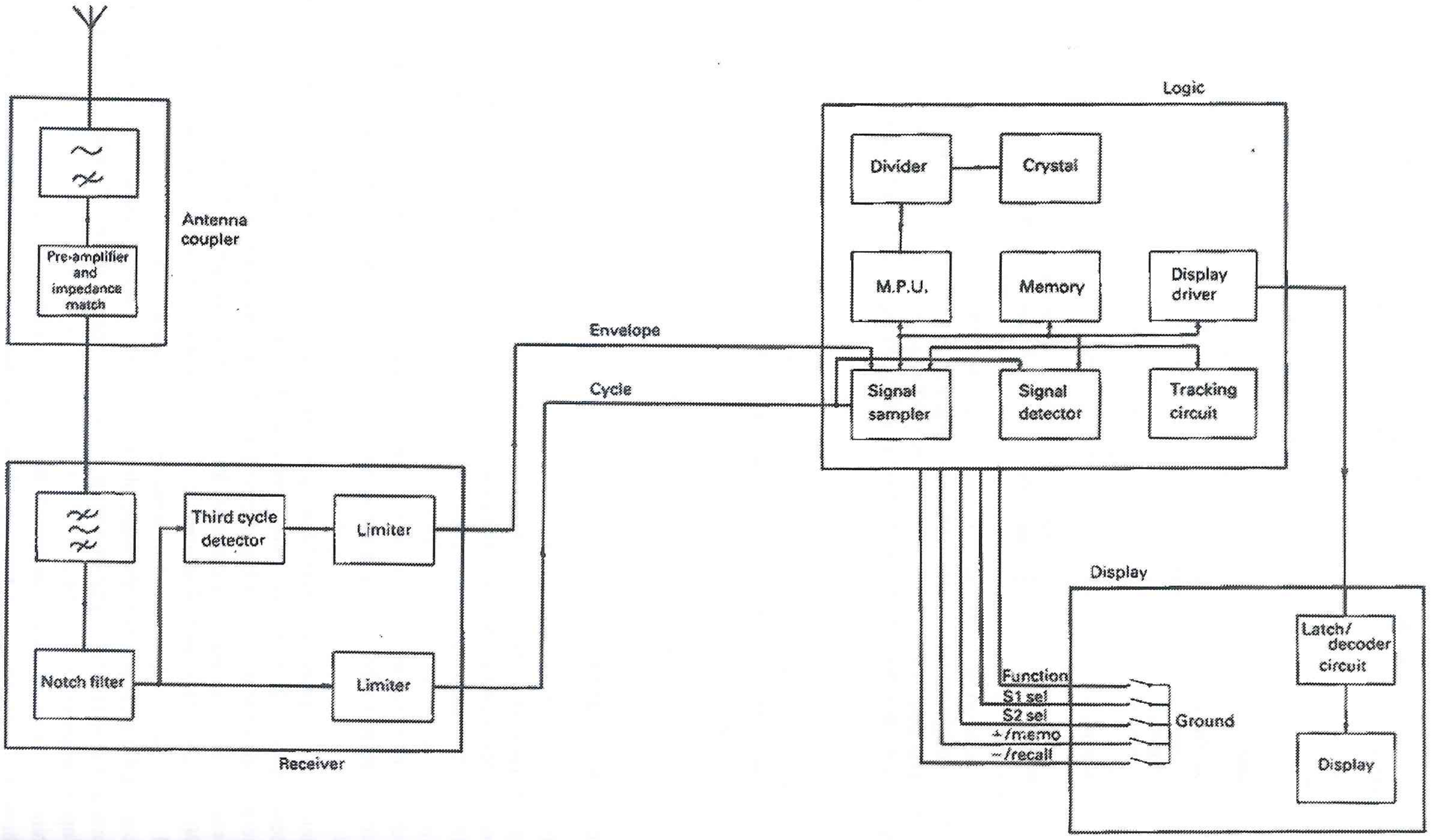


Figure 4.24 Basic block diagram of Loran-C receiver.

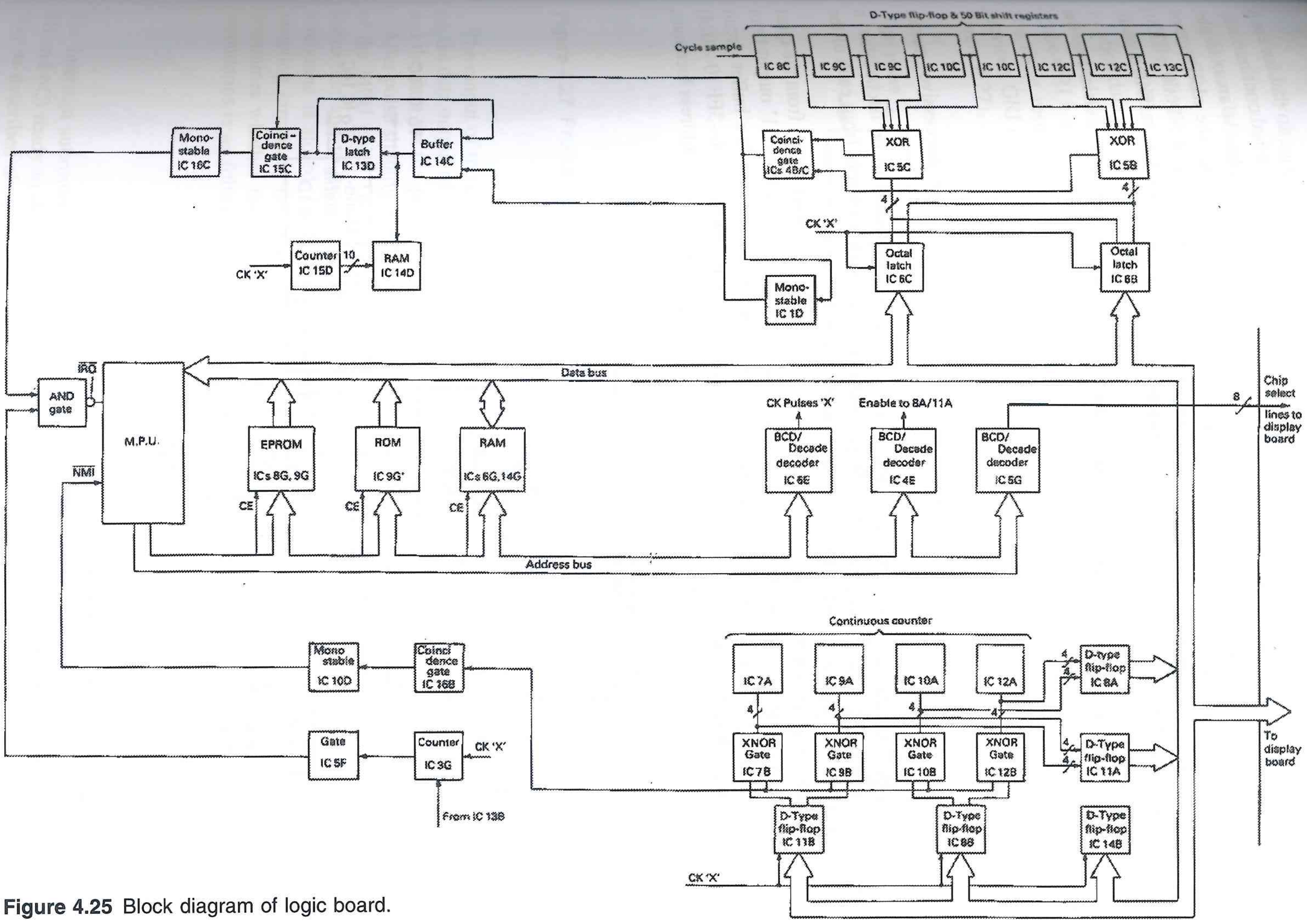


Figure 4.25 Block diagram of logic board.

clocked through the shift registers using a clock-pulse duration of average value 20 μs, so that for ea pulse period of the received pulse train of 1000 μs there are 50 bits. These bits are shifted continuou through the registers recording the presence, or absence, of a pulse as the case may be. As an examp considering master transmissions only and with a GRI of, say, 79600 μs, then after the reception the eighth pulse (ignoring the ninth pulse for the moment) there is a time difference of (79600 – 725 μs or 72350 μs, before the next pulse is received. Obviously the receipt of secondary station signa will occur during this period.

Considering only master signals for the moment, the phase coding of the eight pulses has th form:

Group A + + − − + − + −
Group B + − − + + + + +

and the phase code interval (PCI) has the form A, B, A, B etc., for successive maste transmissions.

For the receipt of a master pulse train the CPU can cause the A and B code to be latched into D-type octal latch. The required code could be output and compared with a sample from each of th outputs of the 50-bit registers (and D-type flip-flop) as shown in Figure 4.26.

The coincidence of a sampled signal with, say, the A code results in an output signal from the qua XOR gates that is logic ‘0’ and this, through the gate circuit shown, results in a logic ‘1’ output fro the gate circuit. The coincidence output is shaped by a monostable circuit and fed via a buffer circu to the input of a RAM 1024 × 4 bit memory circuit. The memory circuit address 000–3FF (0–1024 is selected by the output of a binary counter. The rate of data input to the memory address locations governed by the counter, is 100 μs. Since the counter has 1024 locations to access before resetting there is a total of 102 400 μs to be represented by the 1024 bits of the memory. The bits corresponding to GRI can be represented within the memory since no GRI exceeds 99 900 μs and the counter is reset every GRI.

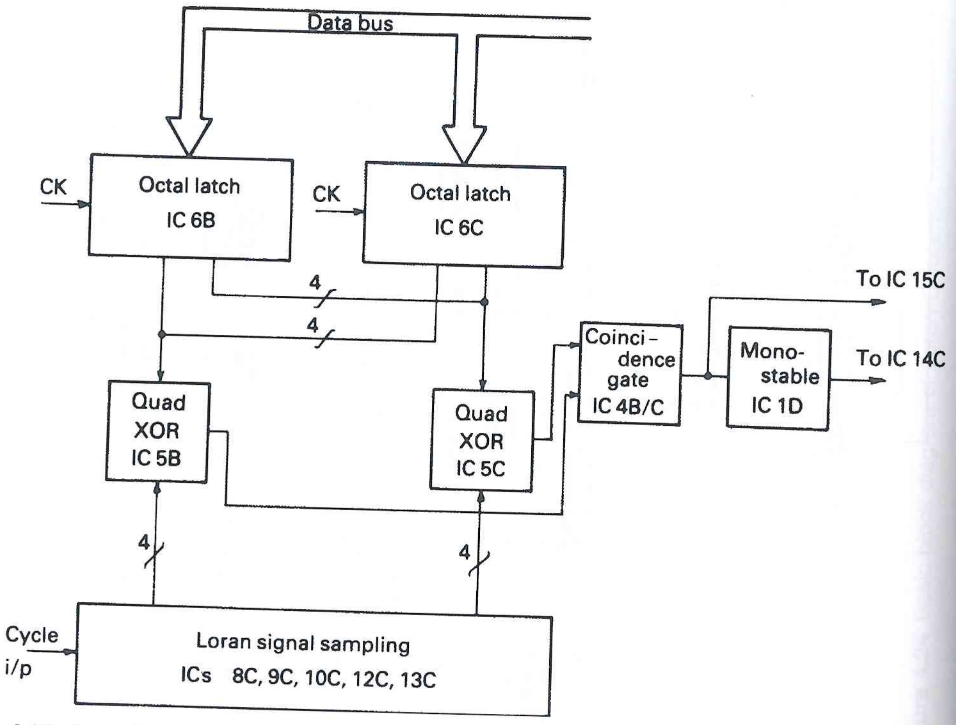


Figure 4.26 Sampling and coincidence circuit.

After the memory has been loaded for 1GRI and the counter is reset, the procedure is repeated for 2GRI, 3GRI etc. The memory chip is configured as four rows of 1024 locations and for each address location data is latched from row 1 to row 2, row 2 to row 3, and row 3 to row 4 as new data are written into row 1. This means that row 1 is used for the latest GRI with the previous GRI latched into row 2; the GRI before that is in row 3 etc. Thus the results of four previous GRIs are held in the memory and these results are available on the output data lines as each memory is accessed. These four previous GRI outputs are checked, together with outputs of present GRI, in a coincidence gate (see Figure 4.27).

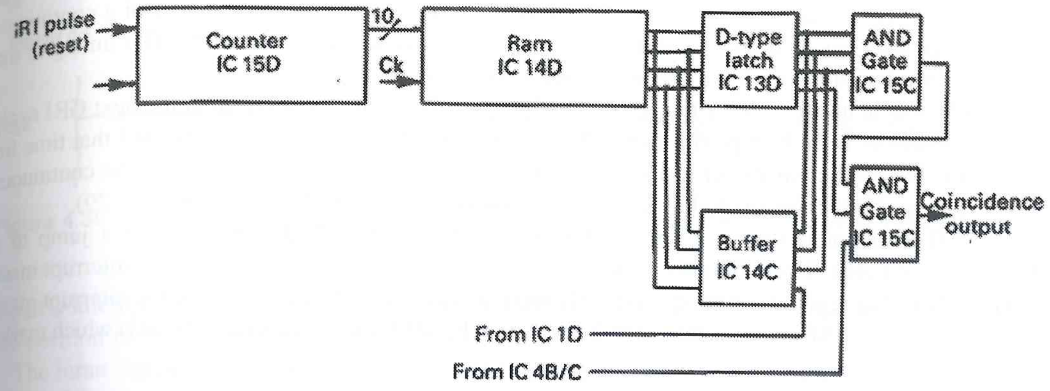


Figure 4.27 Production of coincidence (IRQ) circuit.

The output of the coincidence AND-gate arrangement is only a logic ‘1’ if all inputs are logic ‘1’, i.e. the data output of each address location accessed for the four rows (each of the four previous GRI) and the data for the present GRI are all identical at logic ‘1’.

After pulse shaping, the coincidence output is used as an input to the interrupt request (IRQ) input of the MPU chip. The receipt of an IRQ input causes the microprocessor to finish any current instruction and to move to a high order address location where the starting address of a required subroutine is stored. In this case the routine causes the MPU to read the flip-flop (IC 8C) in the sampling circuit to determine whether the master signal was detected by an A or B code. This determines whether the phase coding of the secondaries should be A or B code. The code for the secondaries is as follows:

Group A + + + + + − − +

Group B + − + − + + − −

The interrupt subroutine causes the correct code to be latched into the phase code latch circuit (ICs 6B and 6C) ready to detect the received secondary signals, which are processed in exactly the same way as described above for the master signals.

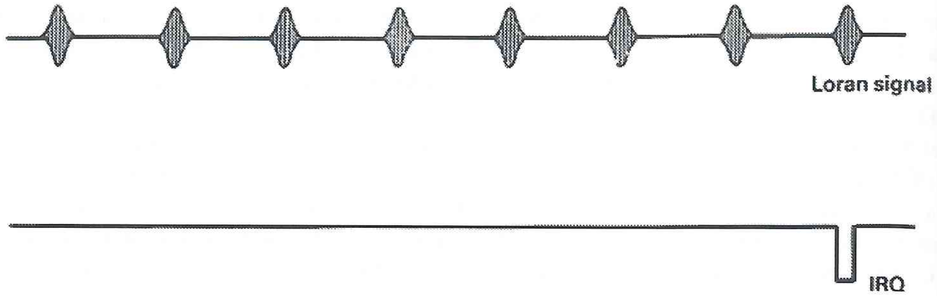


Figure 4.28 Timing of IRQ pulse with received loran signal.

The MPU outputs the GRI pulse which resets the counter (IC 15D) ready for the next GRI inpu data sequence. The coincidence output (GRI signal) is also used to latch the outputs of a continuou counter to the data bus, using D-type flip-flops (ICs 8A and 11A), and to the MPU. The timing of the IRQ pulse in relation to the loran signal is shown in Figure 4.28.

The MPU calculates the time 2 ms before the first position of the loran signal in the next GRI cycle to set the values of octal D-type flip flops (ICs 8B, 11B and 14B). The MPU waits until that time for an interrupt. When the values set in the D-type flip-flops coincide with the values of the continuou counter then an NMI (non-maskable interrupt) signal is sent to the MPU (see Figure 4.29).

The NMI interrupt performs a similar function to that of the IRQ signal in that a jump to a subroutine is initiated. The difference is that the IRQ request will only be obeyed if the interrupt mask bit in the MPU flag register is not set. The NMI request will always be obeyed since the interrupt mask bit has no effect on NMI. On receipt of the NMI signal the MPU clears a counter (IC 3G) which masks

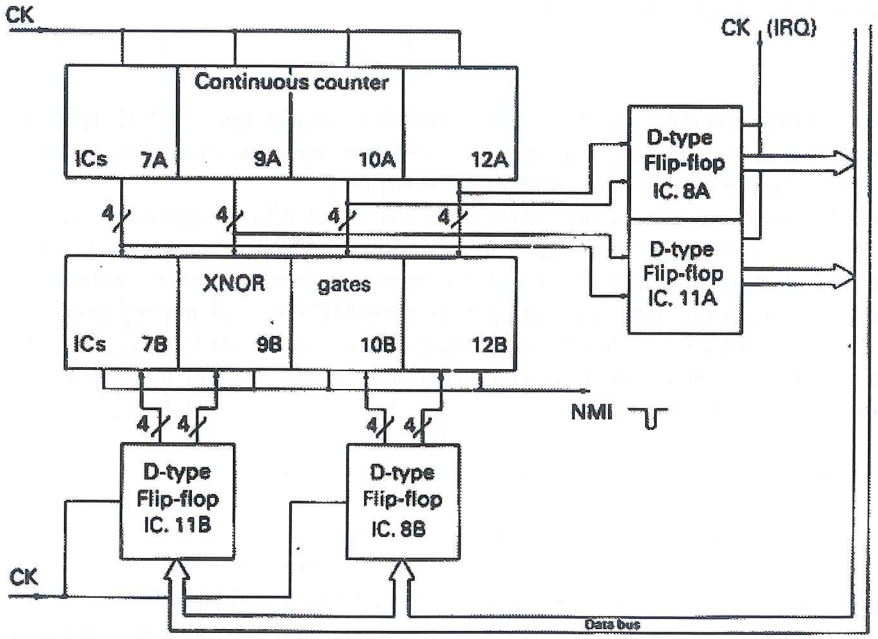


Figure 4.29 Production of the NMI interrupt pulse.

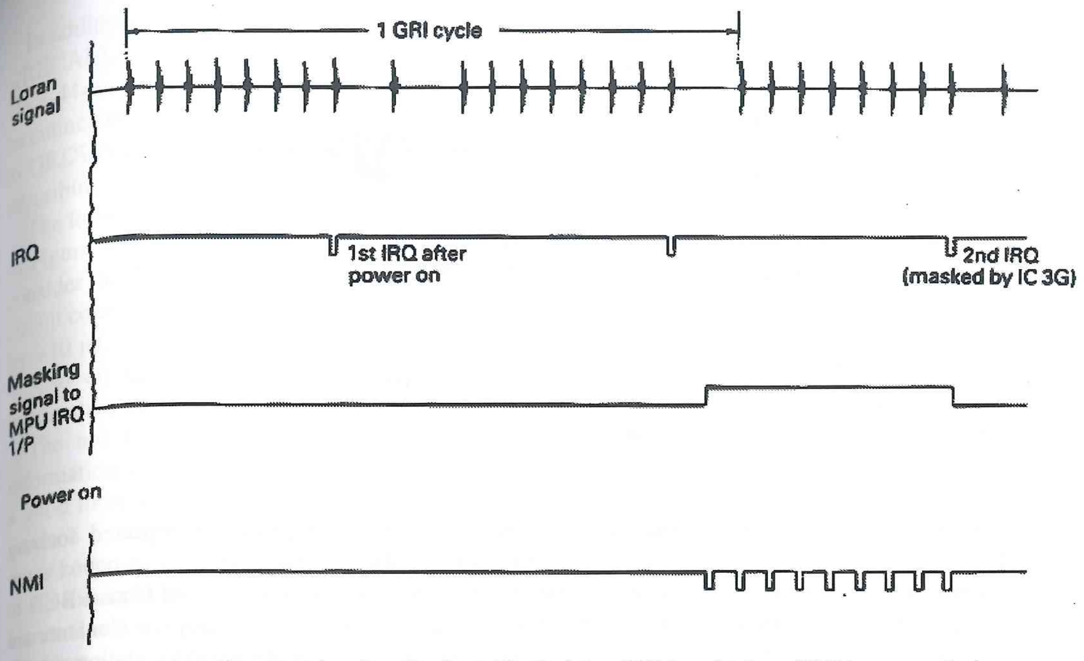


Figure 4.30 Timing diagram showing the 'masking' of the IRQ input when NMI is generated.

the IRQ interrupt for about 9 ms [* (read data) + 1GRI – approximately 9 ms = time about 2 ms before the position of loran signal in the next cycle]. See Figure 4.30.

The loran signal tracking point is set by the MPU by adding 2 ms to the value obtained previously (see * above) and setting this value, via the data bus, to the octal D-type flip-flops. The MPU then waits for an interrupt, which recurs after 2 ms and coincides with the reception of the first loran pulse.

The first loran signal pulse is sampled when the MPU outputs a CYCLE ENV pulse (see Figure 4.31).

After sampling, the MPU adds 1 ms to the previously set value of the octal D-type flip-flops and waits for another interrupt pulse. This second loran pulse is sampled as for the first pulse. This

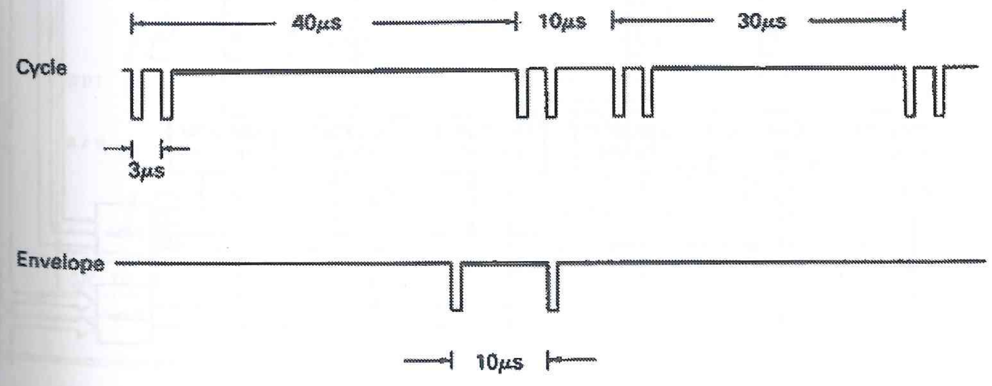


Figure 4.31 Timing diagram for loran signal sampling.

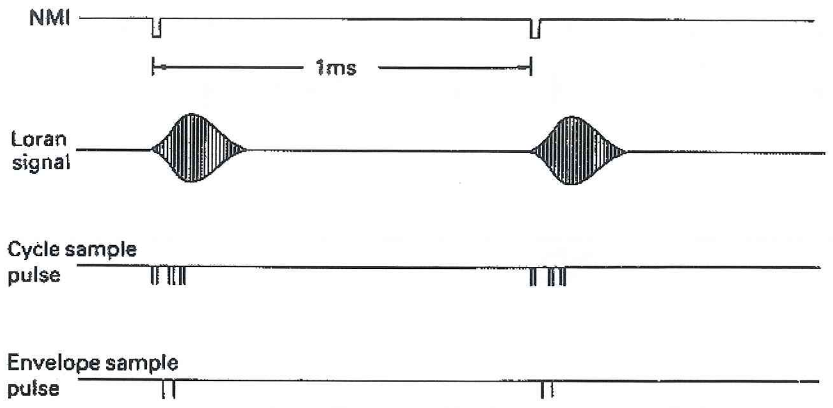


Figure 4.32 Timing sequence for NMI pulses.

procedure is repeated for all the loran pulses and the complete sequence is repeated for any secondaries that need to be tracked. Figure 4.32 should make the sequence clear.

The display board contains two sets of six-filament displays, each of which is fed from a BCD to a seven-segment C-MOS decoder/driver with integral latch. The six-filament display elements are arranged to give the time differences between the reception of master and secondary station signals in tens of thousands, thousands, hundreds, tens, units and tenths of microseconds. Each decoder is fed from four of the eight data bus lines, so that time multiplexing is employed to give a full display. Figure 4.33 shows the arrangement.

Although only one set of display elements is shown, the other circuit is an exact duplicate. Each pair of decoders is enabled via a chip select line, which will go active low, to latch data into the decoders. The chip select line is in turn fed from a BCD to decimal decoder on the logic board, which operates under the control of the MPU.

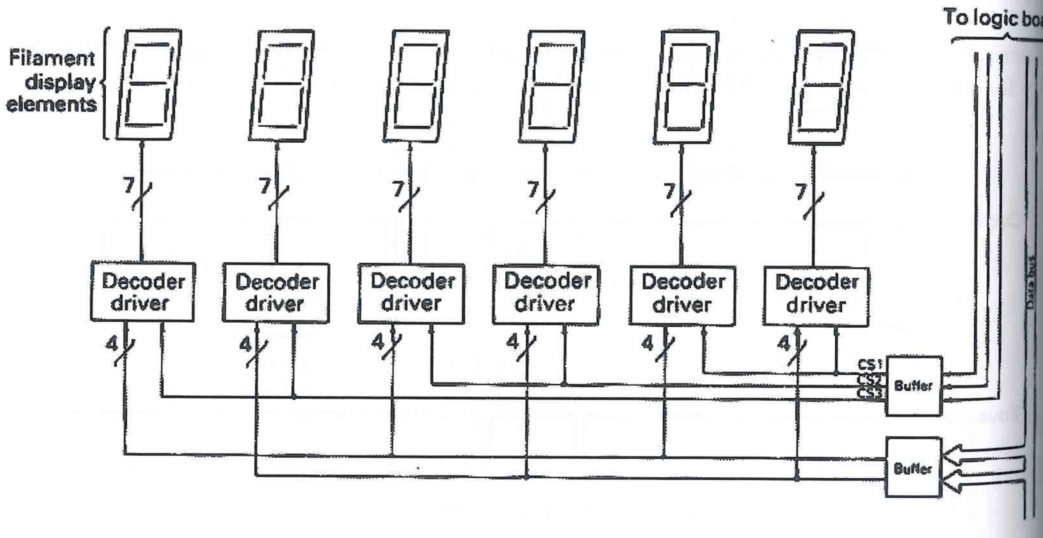


Figure 4.33 Display elements, buffers and drivers.

In addition, the display board contains the function switch and the S1 SEL, S2 SEL, +/MEMO and -/RECALL switches. Connections when made will connect GROUND to that input on the logic board via a 44-way plug and socket arrangement which allows the data line inputs and chip select lines to be connected to the display board from the logic board. Connecting an input, or combination of inputs, to GROUND will, via the logic circuitry, fulfil the conditions as explained in pages 119–125 when describing receiver function.

The logic circuits on the logic board concerned with the function switch inputs have not been shown in Figure 4.25 in order to keep the diagram simple. As an example, however, of the circuit action, consider the case when the function switch is set to S1 and the +/MEMO switch is pressed. The logic circuit concerned would cause the value set in to the D-type flip-flops (ICs 8B, 11B and 14B) to change by +10 μs.

Also on the display board and connected via the data bus, when chip select allows, is the information regarding the settling alarm and signal-to-noise alarm indication using LEDs.

The use of microprocessors for Loran-C receivers has improved the reliability of positional information and its presentation for the operator's use; the Koden Electronics LR-707 receiver gives a good indication of this. Although Koden may no longer manufacture Loran-C receivers they still produce a range of marine electronic equipment (details may be obtained from their website at www.koden-electronics.co.jp).

An example of a modern Loran-C receiver which meets, or exceeds, the USCG standard for a Loran-C receiver and Automatic Co-ordinate Conversion System is the Furuno Model LC-90 Mark-II, the front panel of which is illustrated in Figure 4.34.

As can be seen from Figure 4.34, the front panel has a touchpad section for entering data and a five-line liquid crystal display that indicates system data. The top two lines provide positional information in either time difference (TD) format or latitude/longitude. The remaining three lines can provide different computed navigational data, as required by the operator. Additional lines at the top and bottom of the display give a constant readout of alarm and system status. The LC-90 Mark-II provides an automatic selection of optimum master and secondaries or, if preferred, it can allow the operator to override the automatic functions manually. The use of automatic selection will provide

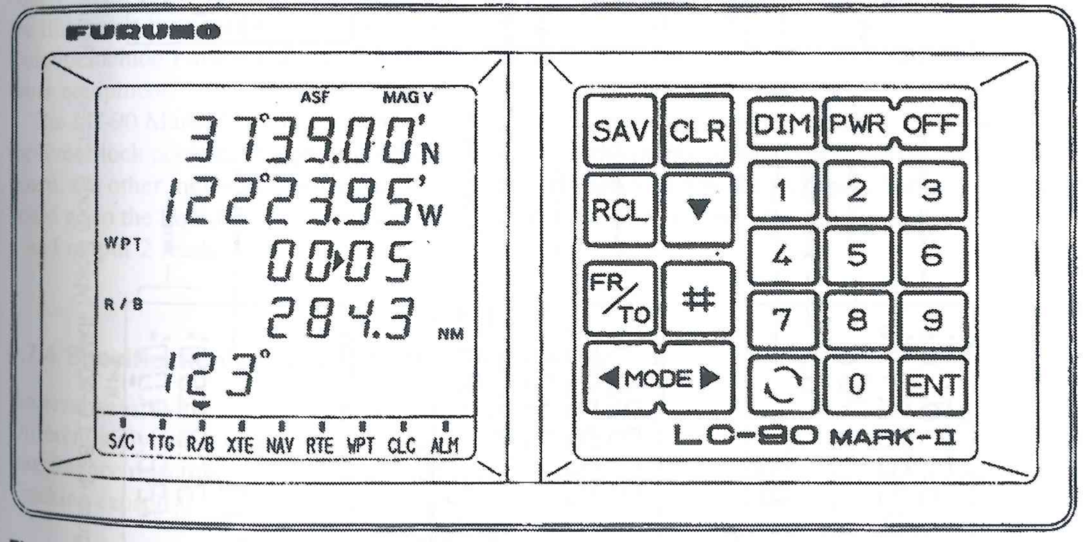


Figure 4.34 LC-90 MkII front panel layout. (Reproduced courtesy of Furuno Electric Co. Ltd.)

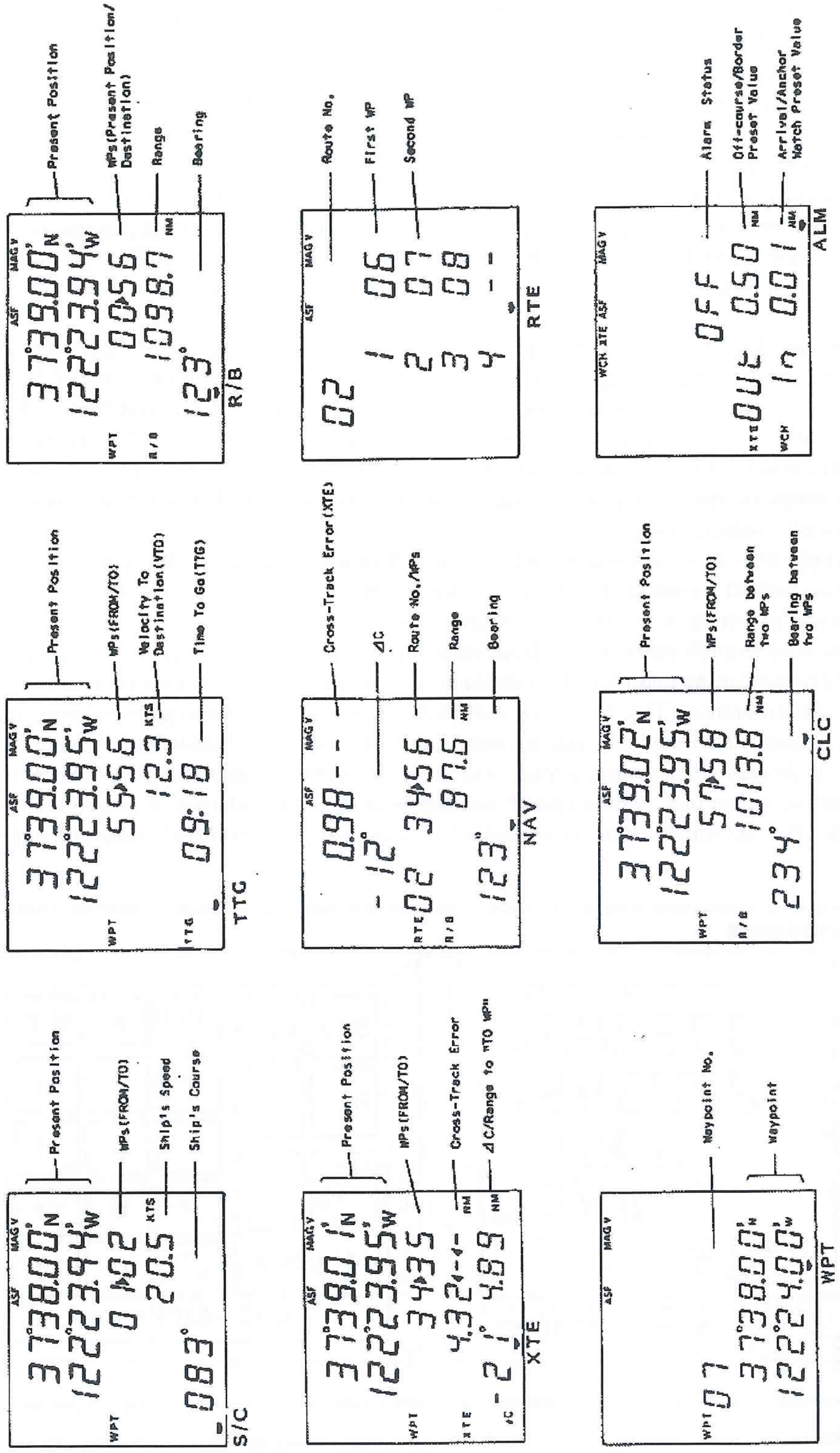


Figure 4.35 LC-90 MkII typical mode screens. (Reproduced courtesy of Furuno Electric Co. Ltd.)

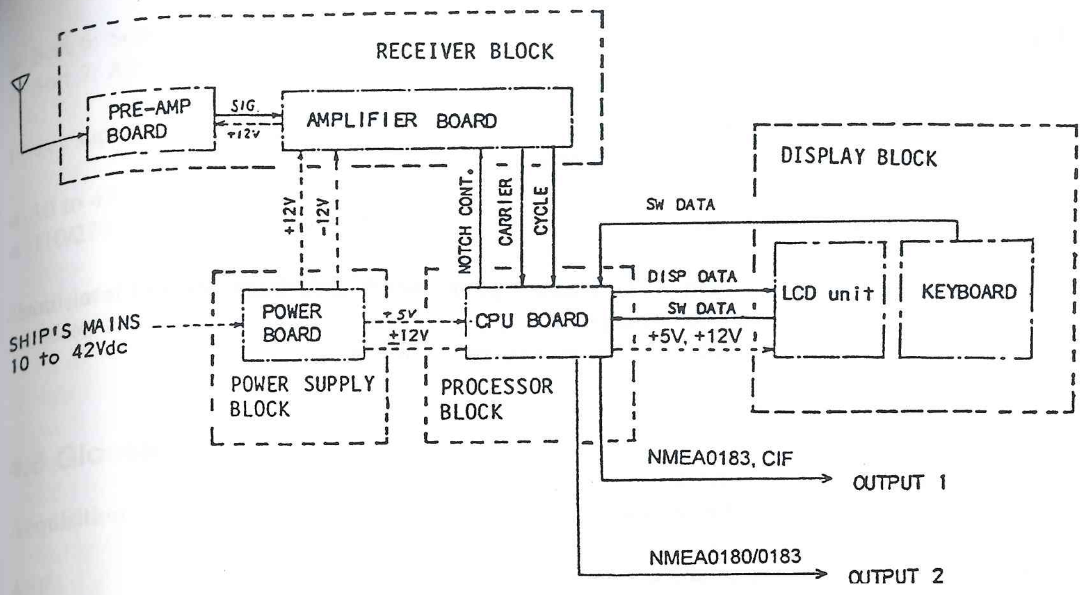


Figure 4.36 Block diagram of the LC-90 MKII receiver. (Reproduced courtesy of Furuno Electric Co. Ltd.)

compensation for ASF and magnetic variations and set all four notch filters to eliminate interference. Entering an estimated local latitude and longitude will enable the LC-90 Mark-II receiver to determine the best available chain, and compute the correct latitude and longitude corresponding to the ship's position.

Up to 100 waypoints can be entered by either TD, latitude/longitude or range/bearing from any position. Also by use of the SAV (save) key up to 20 events can be stored in TD or latitude/longitude. The display will provide data on: range/bearing to a waypoint and between waypoints, speed and course made good, velocity and time to go, cross-track error, and course offset. Typical mode screens are illustrated in Figure 4.35. The information from the display is also indicated using values shown. Outputs include Furuno CIF, NMEA 0180 and NMEA 0183 outputs, which can be used as inputs to other equipment.

The LC-90 Mark-II receiver can be subdivided into four basic blocks as shown in Figure 4.36. The receiver block consists of a pre-amplifier and amplifier, the output of which is passed to the processor board, the other inputs to which come from the display block as SW data. Outputs from the processor board go to the liquid crystal display unit and are also available to feed other equipment via the output 1 and output 2 leads.

4.7.4 Specification of the LC-90 Mark-II Receiver

Receiver sensitivity:	1 μV/m
Differential dynamic range:	80 dB
Interference rejection:	Six notch filters, four of which are auto and two are preset.
Tracking capacity:	Master and up to a maximum of five secondaries. Tracking speed 80 knots nominal.
Settling time:	Nominally 5 min, depending on signal conditions.

Display resolution

- TD: 0.1 µs
- L/L: 0.01 min
- Range: 0.01 nautical miles

Display of signal status and alarms

- Status: S/N, CYC, tracking point, interference frequency and level, no filter settings etc.
- Alarms: XTE, border, arrival, anchor watch.

Computation base:

- TD to L/L conversion: WGS-72
- Range/bearing: Great circle

Save function (entry of waypoint and event):

- Waypoint memory: 100 points (from no.00 (OS position) to no. 99)
- Event memory: 20 points (from no.100 to no. 119).

Other functions:

- Ground speed and true course display
- Range and bearing display to waypoint
- Velocity to destination and time-to-go display
- Range and bearing from waypoint to waypoint
- Route planning and automatic route following
- Manual compensation for TD and L/L
- Auto or manual compensation for magnetic variation
- Automatic selection of ASF or manual correction factors
- Memory back-up
- Cross-track error, course to steer to get back to an intended track.

Output (dual ports provided):

CIF

- Ship L/L, TD, Wp L/L, ship speed/course, event L/L, system time.

NMEA 0183

- Sort 1; $LCGLL/$LCAAM/$LCXTE/$LCBOD/$LCBWC/$LCVTG
- Sort 2; $LCBWW/$LCWNC/$LCWCV/$LCZTG/$LCWPL
- Sort 3; Sort 1 plus Sort 2
- Sort 4; $LCRMA/$LCRMB
- Sort 5; Sort 1 plus Sort 4

- Sort 6; Sort 2 plus Sort 4
- Sort 7; All data.

Power supply

- 10 to 42 VDC, universal, 9 W
- 110/220 VAC, 50–60 Hz CW/Rectifier Unit)

Details of the Furuno LC-90 Mk-II Loran-C receiver, and other marine electronic equipment, may be found on their website, www.furuno.com.

4.8 Glossary

Acquisition	Reception and identification of Loran-C signals from a master and selected secondaries to allow a measurement of time differences (TDs) to be made.
ASF	Additional Secondary Phase Factor. Factors caused by variation in the conductivity of the surface of the earth depending on whether the loran signal path is over land or sea. The factor could cause errors in the measured Loran-C position.
Attenuation	A reduction in signal strength of a signal as it travels further from its source. The signal could be travelling in free space or in a transmission line.
Baseline	That segment of a great circle that defines the shortest distance between a master and secondary station in a loran chain.
Baseline extension	The extension of a baseline beyond the master and secondary stations in a loran chain. Measurements in the region of a baseline extension should be avoided because of possible large measurement errors in that area.
Blink	An indication that the master or secondary signals received from a loran chain are out of tolerance and would not produce reliable measurements. There are both master and secondary blink conditions.
Co-ordinate conversion	That process which changes co-ordinates produced using one system to co-ordinates in another system, i.e. when using Loran-C changing from time differences (TDs) to geodetic co-ordinates. This could be achieved by interpolation on Loran-C overprinted charts or automatically by the Loran-C receiver.
Coverage area	That coverage provided by loran signals where signal reception is of sufficient level to allow the determination of position to a specified level of accuracy and at a specified signal-to-noise ratio (SNR).
Coverage diagram	A diagram showing the coverage area for a particular master–secondary pair in a Loran-C chain.
Cross track error	See under XTE.
Dual-rated (DR)	A term used to indicate that a station in one Loran-C chain is also used in another Loran-C chain. The stations could be a master or a secondary station.
Emission delay	That time difference measured in microseconds between the emission of a signal from a master station and the emission of a signal from a specified secondary in that chain. The emission delay is the sum of the time taken for

	the master transmission to cover the baseline and the secondary coding delay.
Envelope to cycle difference (ECD)	A time difference between the phase of a Loran-C carrier. and the time origin of the pulse envelope waveform. ECD is zero when the 30-µs point of the Loran-C pulse envelope coincides in time with the third positive zero crossing of the 100-kHz carrier.
Group repetition interval (GRI)	That time interval between the start of a transmission from a master station in a Loran-C chain and the start of the next. Time is measured in microseconds and the chain is designated by its GRI value with the last zero term omitted, i.e. the North West Pacific chain has a GRI of 89 300 µs and the chain designation is 8930.
IRQ	Interrupt Request. A signal used in a microcomputer system to service an external device and which causes the current program to be interrupted to run a subroutine used to service the external device. Once the subroutine is finished the computer restores the original program and continues to execute it from the point where it was interrupted. The IRQ can be enabled/disabled according to the setting of an interrupt flag in the processor flag register.
LCD	Liquid Crystal Display. A form of display commonly used with Loran-C receivers. The display elements are typically dark coloured alphanumerics on a grey screen. The display is easily read, even in bright light conditions.
LED	Light Emitting Diode. A form of display with, typically, red alphanumerics on a dark background. Less popular than the LCD display and less easily read in strong light conditions.
LOP	Line of Position. In loran terms, a line where the time difference (TD) of signals received from the master and a specified secondary in a chain has a constant value.
Loran	*Lo*ng *ra*nge *n*avigation.
Loran monitor site (lormonsite)	A monitor site used to observe parameters of a transmitted signal as received in the coverage area.
Master station	The station in a Loran-C chain that transmits the signals identifying that chain (i.e. its GRI) and is the common base against which all time differences are established.
MPU	Microprocessor. That integrated circuit (IC) which forms the central processing unit (CPU) of a microcomputer.
Nautical mile	That unit of distance used at sea which is equivalent to 1852 metres.
NECD	Nominal ECD of a transmitting station.
NEUS	Northeast US chain. The Loran-C chain operating with a GRI designation of 9960.
NMEA	National Marine Electronics Association. An organisation comprising manufacturers and distributors. Responsible for agreeing standards for interfacing between various electronic systems on ships. NMEA 0183 version 2.3 is the current standard.
NMI	Non-maskable Interrupt. Unlike the IRQ interrupt which can be enabled or disabled by the setting of an interrupt flag, the NMI cannot be disabled and must execute the appropriate service subroutine when activated by an external device.
PCI	Phase Code Interval. That interval over which the phase code repeats. For Loran-C, phase codes repeat every two GRIs.
PF	Primary Phase Factor. A correction factor applied to a Loran-C signal reading made necessary by the difference in signal propagation through the atmosphere as opposed to propagation in free space. The speed of Loran-C signals through the atmosphere is equal to the speed through free space divided by the atmospheric index of refraction. The speed is taken as $2.996\,911\,62 \times 10^8\,\text{ms}^{-1}$.
PRF/PRR	Pulse Repetition Frequency/Pulse Repetition Rate. The number of pulses transmitted in a specified time. For the Loran-C system the PRF/PRR is given by the reciprocal of the GRI. Hence a chain with a GRI of 80000 µs would have a PRF/PRR of 12.5 Hz.
Root mean square (RMS)	That value of a time varying signal which has the equivalent heating effect to that of a d.c. quantity.
Secondary coding delay	That time interval in microseconds between when a secondary station receives the master transmission and a transmission occurs from the secondary station.
Secondary phase factor (SF)	That amount of time, in microseconds, by which the predicted time differences (TDs) of a pair of Loran-C station signals travelling over an all-seawater path differ from those that travel through the atmosphere.
Secondary station	One of the possible maximum number of five stations that, together with the master station, comprise the Loran-C chain.
Signal-to-noise ratio (SNR or S/N)	The ratio of signal strength compared to the strength of electrical noise present with the signal in a given bandwidth. The coverage diagrams for Loran-C are calculated using an SNR of at least 1:3. SNR is often quoted in decibels (db) where the db value is given by $20\log_{10}(\text{SNR})$ so that with an SNR of 1:3, the decibel value is –9.54, which is often approximated to –10db.
Single-rated (SR)	Those stations in a Loran-C chain which do not share transmissions with other chains. Compare with Dual-rated.
Speed	Rate of travel. For a vessel travelling relative to the water over a horizontal distance the speed of the vessel is measured in knots.
Time difference (TD)	In Loran-C, TD is the time difference in microseconds between the receipt of the master and secondary transmitted signals.
Time to go (TTG)	The time calculated to elapse before the next waypoint is reached. Time obtained by dividing distance to go by the groundspeed.
Waypoint	A point entered into a loran receiver and used as a reference point for navigational calculations. Planned voyages would have a series of waypoints indicating legs of the voyage. A modern Loran-C receiver is capable of storing multiple waypoints.
XOR	Exclusive-OR gate. A digital circuit that, for a two-input gate, only produces a logical 1 output when the two inputs are of opposite sign.
XTE	Cross-Track Error. That distance between the vessel's actual position and the direct course between two specified waypoints.

4.9 Summary

- Loran-C is an electronic system of land-based transmitters broadcasting low-frequency pulsed signals capable of reception aboard a ship, or aircraft, and being used by the receiver to determine position in time difference or longitude/latitude.

- Loran-C uses a chain of typically three to five transmitters broadcasting at 100 kHz with a specially shaped pulse of 250 μs duration repeated at a particular rate.
- One transmitter of a Loran-C chain is designated the master (M) while the others are secondary stations known as whisky (W), x-ray (X), yankee (Y) and zulu (Z). The chain is formed of master–secondary pairs, i.e. M–W, M–X, M–Y and M–Z.
- The master station always transmits its signal first and this signal is used to trigger emissions from the secondary stations. An additional time delay is added at the secondary station. The total elapsed time between master transmission and secondary transmission is known as the emission delay.
- The emission delay ensures no ambiguity in reception within the coverage area for a chain. The unique time difference between reception of the master pulse and reception of a relevant secondary gives a specific line-of-position (LOP) for that pair. A unique LOP for a second master–secondary pair gives a point of intersection which determines the position of the receiver.
- Each Loran-C station operates with a specified group repetition interval (GRI) which are multiples of 10 μs from 40 000 up to 99 990 μs. A Loran-C chain is designated by its GRI value divided by 10, i.e. the Northeast US (NEUS) chain is designated 9960 which defines a GRI of 99 600 μs.
- Each Loran-C pulse is mathematically defined and transmissions are monitored to ensure compliance with the specified model.
- Normal operation of Loran-C assumes reception by ground waves. A ground wave signal will always arrive before a sky wave signal with a time difference of not less than 30 μs anywhere in the Loran-C coverage area, hence if only the first 30 μs of a pulse is used it will be a ground wave. Sky waves can be used at greater distances (>1000 nautical miles) where ground wave reception is unreliable but sky wave correction factors will need to be applied.
- There are possible corrections to be applied to data produced by received signals to allow for different conductivity of the surfaces over which the transmitted signal travels. The corrections, known as additional secondary phase factor (ASF) corrections, are incorporated with most Loran-C overprinted charts and many Loran-C receivers.
- Loran-C coverage is defined by geometric-fix accuracy and range limits to give what is known as the $2d_{\mathrm{RMS}}$ value with a 1:3 SNR.
- A Loran-C receiver should be able to acquire the signal automatically, identify the master and secondary pulses of a given chain pair and track the signal. As a minimum requirement it should display the time difference readings with a precision of at least one tenth of a microsecond. The receiver should also possess notch filters, used to eliminate unwanted interference, and alarms which can be used to inform the operator about signal status and receiver conditions.

4.10 Revision questions

1. Explain briefly the concept behind the use of low-frequency pulsed signals transmitted from land-based stations to determine the position of a ship, or aircraft, that carries a receiver suitable for the reception of such signals.
2. A transmitter emits a pulse which is intercepted by a second transmitter 150 km away. If the speed of transmission of the pulse is $3 \times 10^8\,\mathrm{ms}^{-1}$, how long does it take the pulse to travel between the stations?
   [Answer: 500 μs]

3. What would be the time taken in question 2 if the speed of transmission of the pulse was $2.997\,924\,58 \times 10^8\,\mathrm{ms}^{-1}$?
   [Answer: 500.1257 μs]
4. A transmitter emits a pulse which is intercepted by a second transmitter 1000 μs later. If the speed of transmission of the pulse is $3 \times 10^8\,\mathrm{ms}^{-1}$, how far away is the second transmitter?
   [Answer: 300 km]
5. How far away would the second transmitter be in question 4 if the speed of transmission of the pulse is taken as $2.997\,924\,58 \times 10^8\,\mathrm{ms}^{-1}$?
   [Answer: 299.792 458 km]
6. Explain what you understand by emission delay for a master–secondary pair in a loran system. A Loran-C master–secondary pair transmit with an emission delay of 12 000 μs of which 10 000 μs is coding delay. Sketch a typical series of LOPs, including baseline extensions, for such a master–secondary pair. What is the time difference value in microseconds of the LOP that bisects the line joining the master–secondary pair? What is the time difference value in microseconds of the baseline extensions?
   [Answer: 12 000 μs; 14 000 μs (beyond master station); 10 000 μs (beyond secondary station]
7. Loran-C stations operating in a chain have a particular GRI designation and secondary pulse groups are transmitted at the same GRI and linked in time to the master. Secondary transmission delays are selected to ensure certain criteria are met for signal reception. What are the values specified below?
   (a) Minimum time difference between any secondary and master.
   (b) Minimum time difference of any two time differences.
   (c) Maximum time difference.
   (d) Minimum spacing between corresponding points of the last pulse of any station group and the first pulse of the next group.
8. What is meant by the terms single-rated and dual-rated, as applied to a Loran-C station? Give an example of a dual-rated Loran-C station.
9. What do you understand by the term phase coding as applied to a Loran-C signal? What is the phase code for group A for both the master and secondary of a Loran-C pair? What is the phase code for group B for both the master and secondary of a Loran-C pair?
10. What is meant by the term 'blink' as applied to a Loran-C signal? Give an example of the use of blink.
11. Explain the technique, used in Loran-C receivers, known as 'cycle matching'. What is the claimed advantage of such a technique?
12. Explain why it is preferable to use LOPs from two master–secondary pairs that cross at right angles to each other. Why should areas in the region of baseline extensions never be used?
13. What factors are taken into account to produce the predicted ground wave coverage for a chain? What do you understand by the term $2d_{\mathrm{RMS}}$? What is the specified SNR range limit for each transmitted signal?
14. What are the main features of a Loran-C receiver, which are necessary to measure position with the claimed accuracy for the system?
15. For the Koden Electronics LR-707 receiver shown in Figure 4.21 briefly explain the purpose of switches S1 and S2. What are the effects of moving the function switch to each of its different settings?
16. For the Koden Electronics LR-707 receiver shown in Figure 4.21 briefly explain the function of the +/MEMO and -/RECALL buttons.
17. For the Koden Electronics LR-707 receiver shown in Figure 4.21 briefly explain the use of the notch filters.

18 Using the basic block diagram of the Koden Electronics LR-707 receiver shown in Figure 4.2 describe the basic function of each block.

19 Using the logic board diagram and the sampling and coincidence circuit diagram of the Kode Electronics LR-707 receiver shown in Figures 4.25 and 4.26, respectively, describe how th incoming CYCLE signal is converted into a time difference reading fed to the display.

20. Using the information given in the text, make a comparison between an older type of receiv such as the Koden Electronics LR-707, and a more modern receiver, such as the Furuno LC- Mk-II. Comment on any major differences.

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.

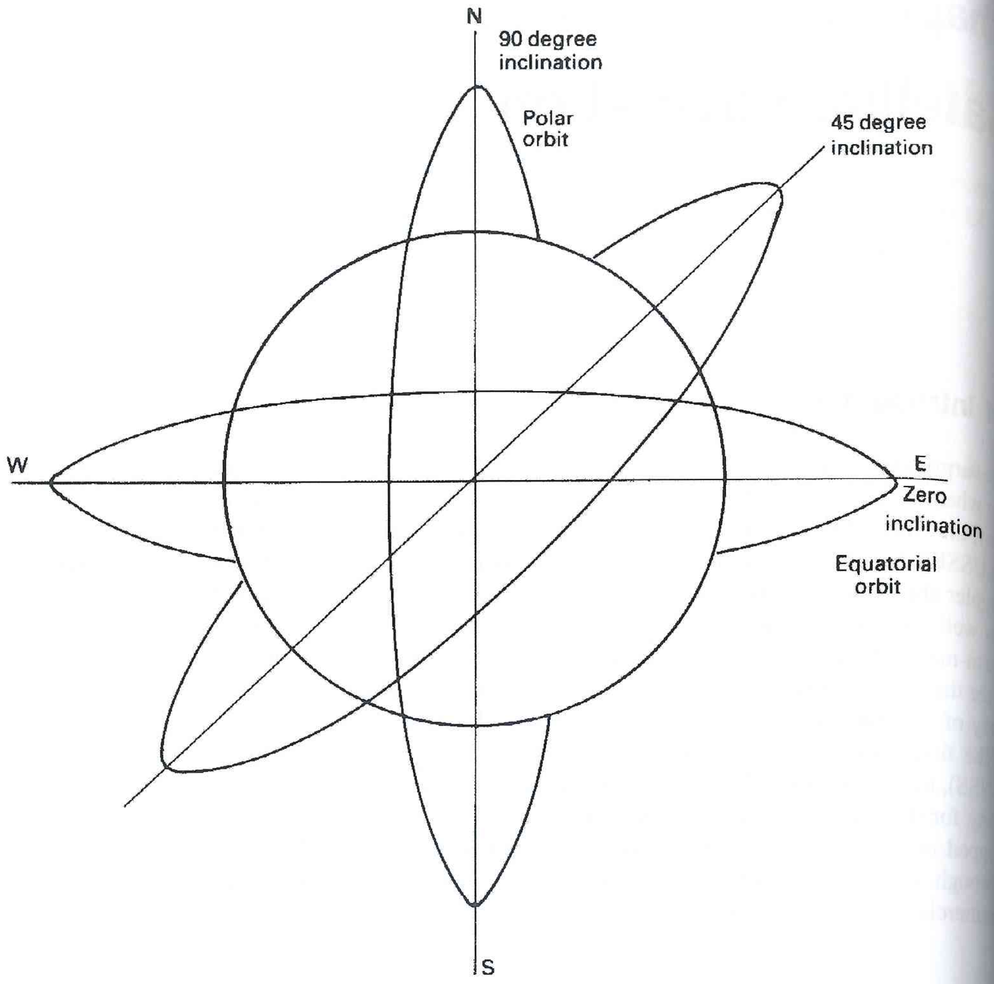


Figure 5.1 Illustration of orbital inclination.

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 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).

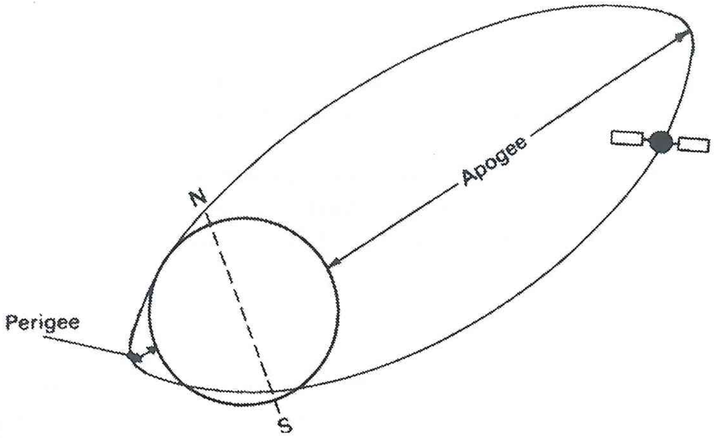


Figure 5.2 Illustration of apogee and perigee.

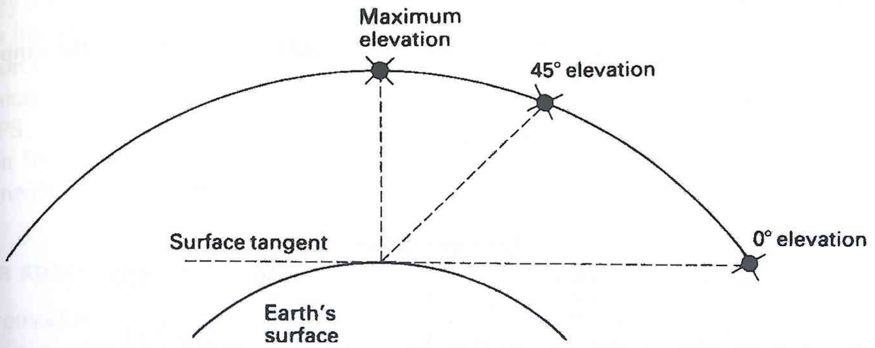


Figure 5.3 Showing the changing angle of elevation during a satellite pass. The angle reaches a maximum at the closest point of approach to the earth bound observer.

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 ($9.81\,\text{ms}^{-1}$) 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:

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

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 va However, to derive an approximate figure for velocity, an earth radius figure of 6370 km is clo enough. The velocity of a satellite with an altitude of 200 km would be:

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

Orbital paths can be transferred to a Mercator projection chart as shown in Figure 5.4. Th inclination will be the same in both northern and southern hemispheres and corresponds to latitud 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 formu below:

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

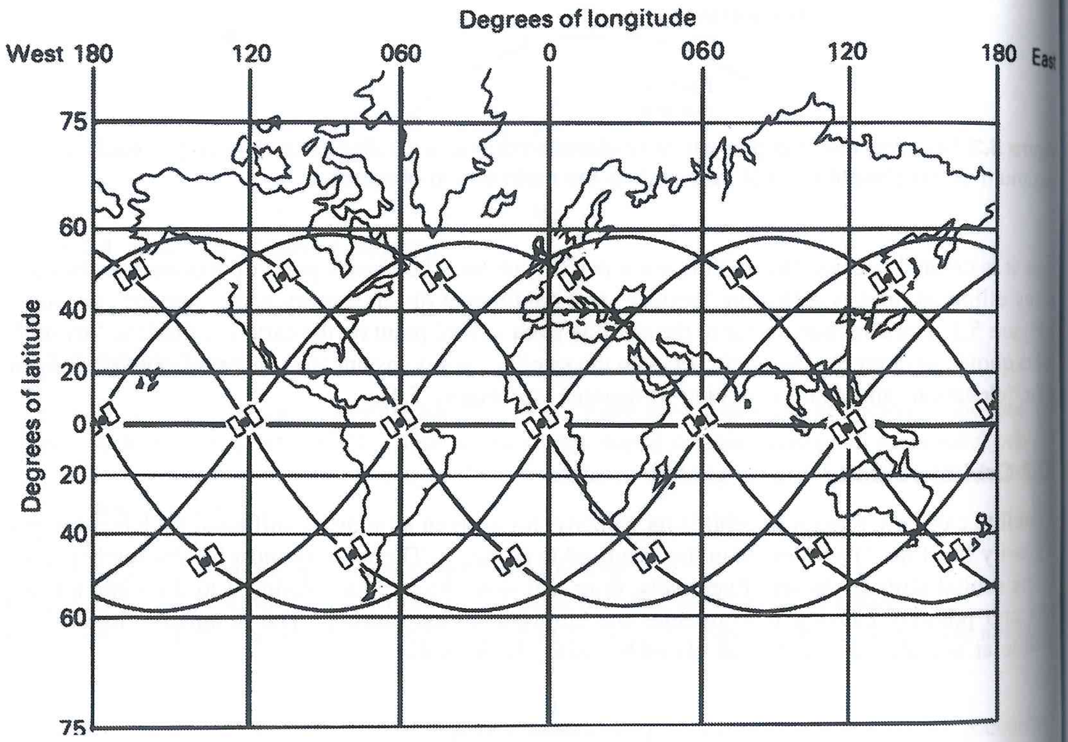


Figure 5.4 Mercator presentation of the orbital inclination paths described by satellite orbits.

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

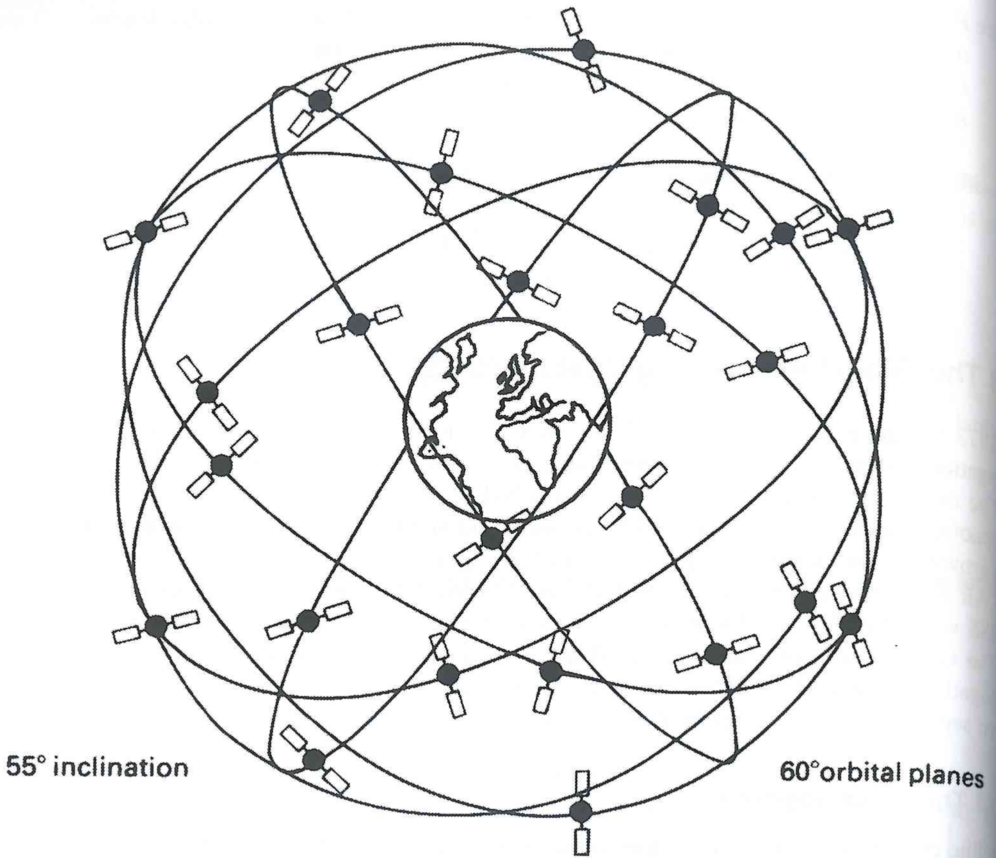


Figure 5.5 GPS satellite coverage. Twenty-four satellites provide global coverage; four in each of six orbital planes.

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 7.5 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

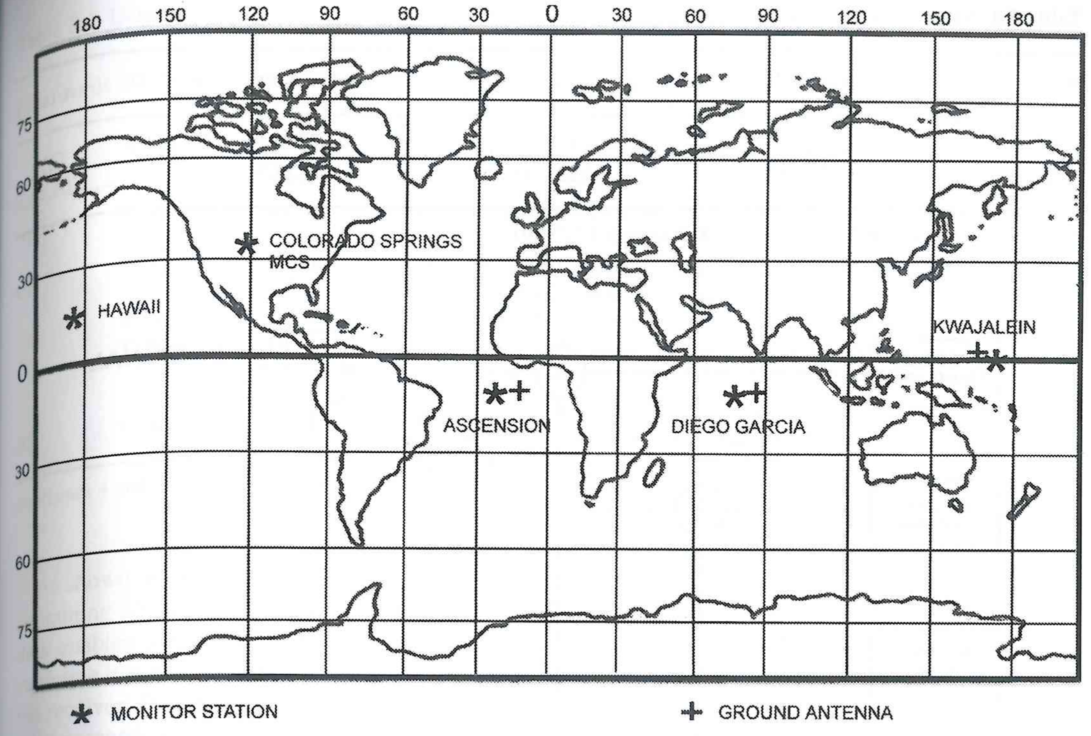


Figure 5.6 GPS control segment stations.

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 &

Both carriers are derived from the SV clock frequency 10.23 MHz

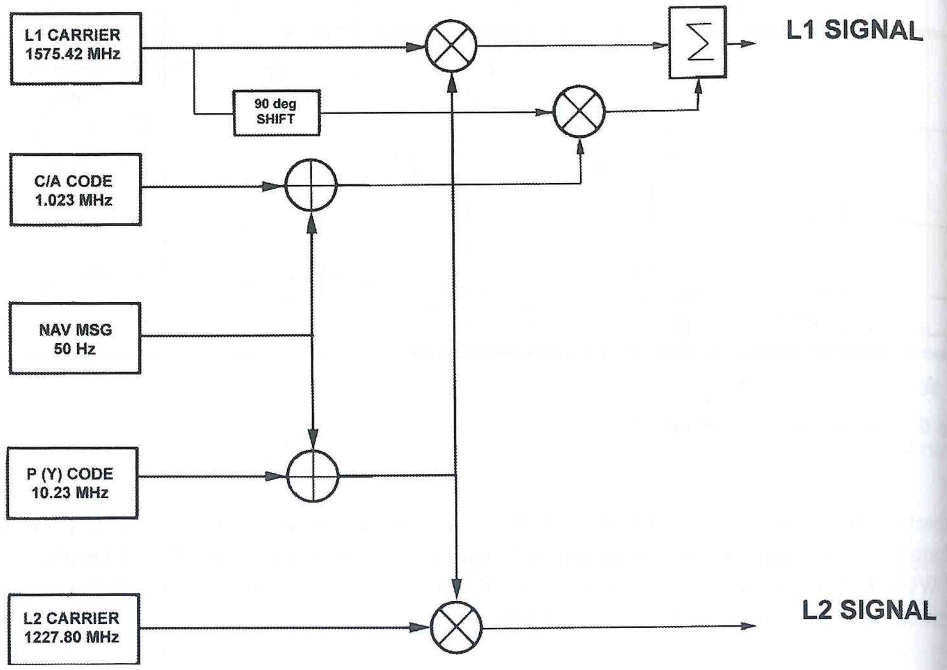


Figure 5.7 Schematic diagram of a SV modulation circuit.

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.

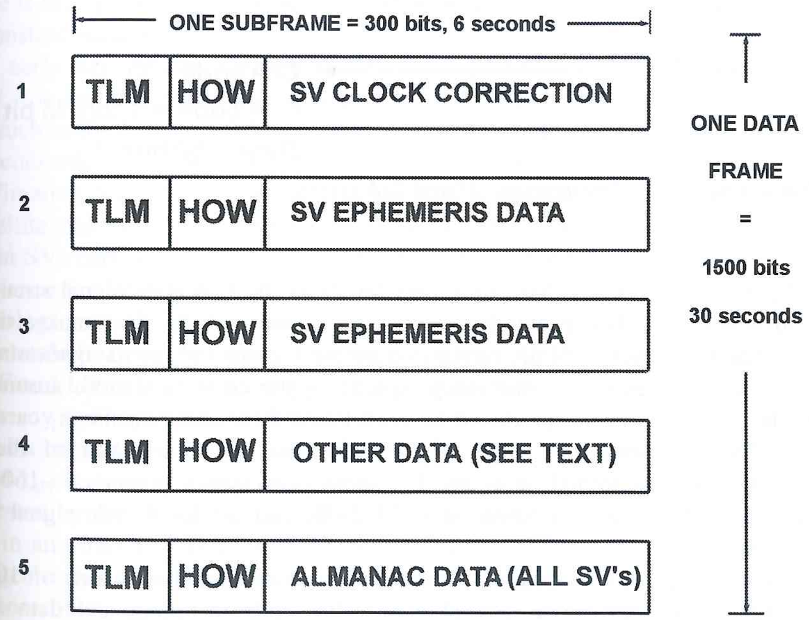


Figure 5.8 Navigation data format.

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.

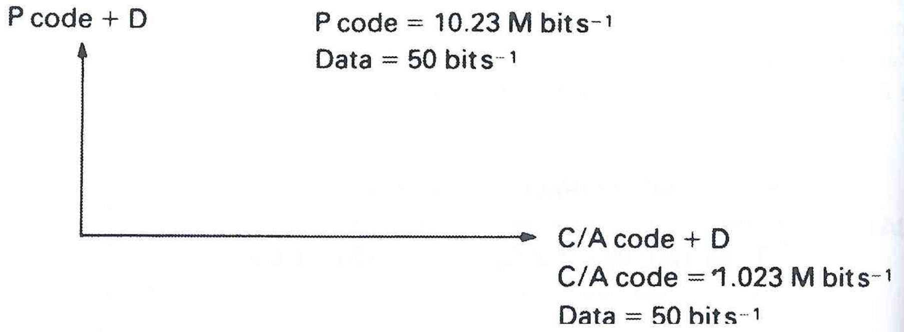


Figure 5.9 Phase relationship between the P and C/A codes.

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.

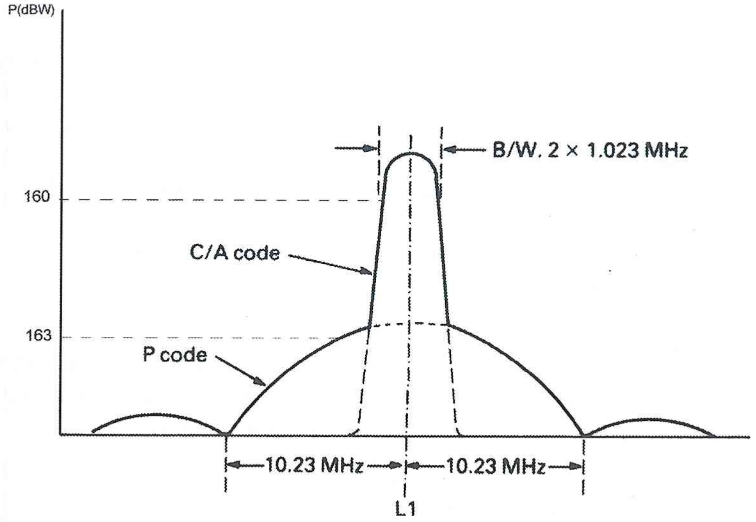


Figure 5.10 Bandwidth power distribution curves for the P and C/A codes.

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 10^{-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.

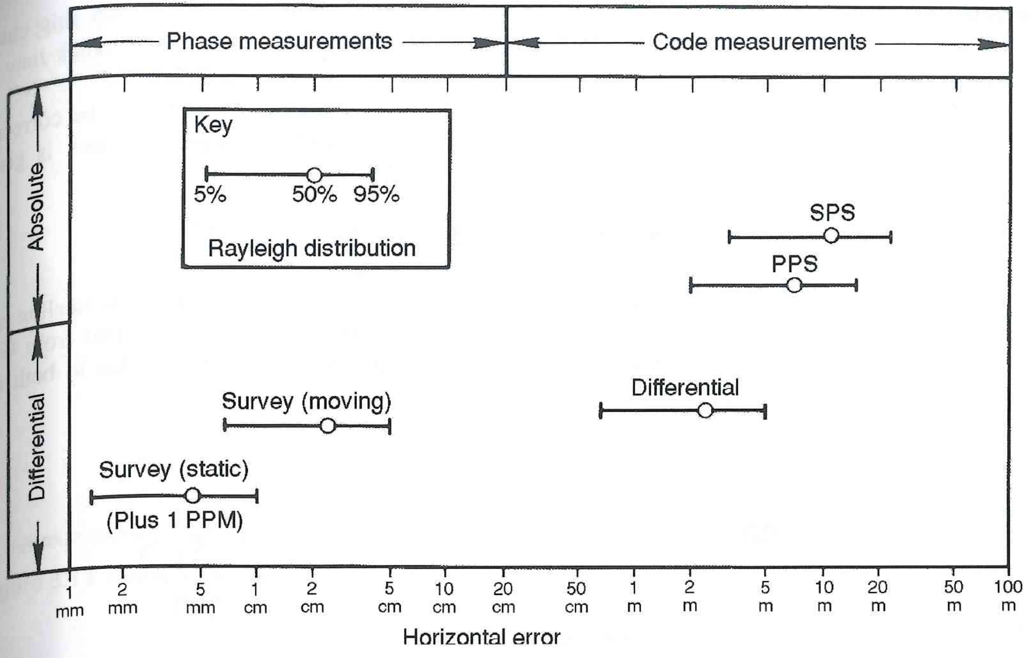


Figure 5.11 Levels of GPS accuracy. (Reproduced courtesy of Magnavox.)

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.

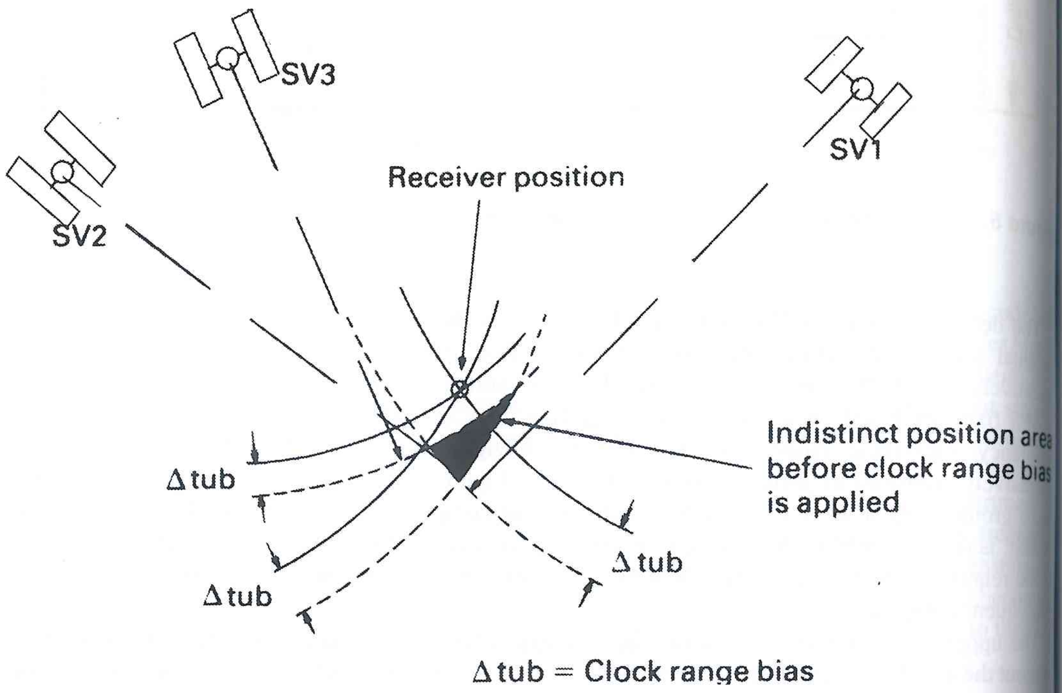


Figure 5.12 Showing the indistinct position fix obtained from three SVs before clock range bias is applied.

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).

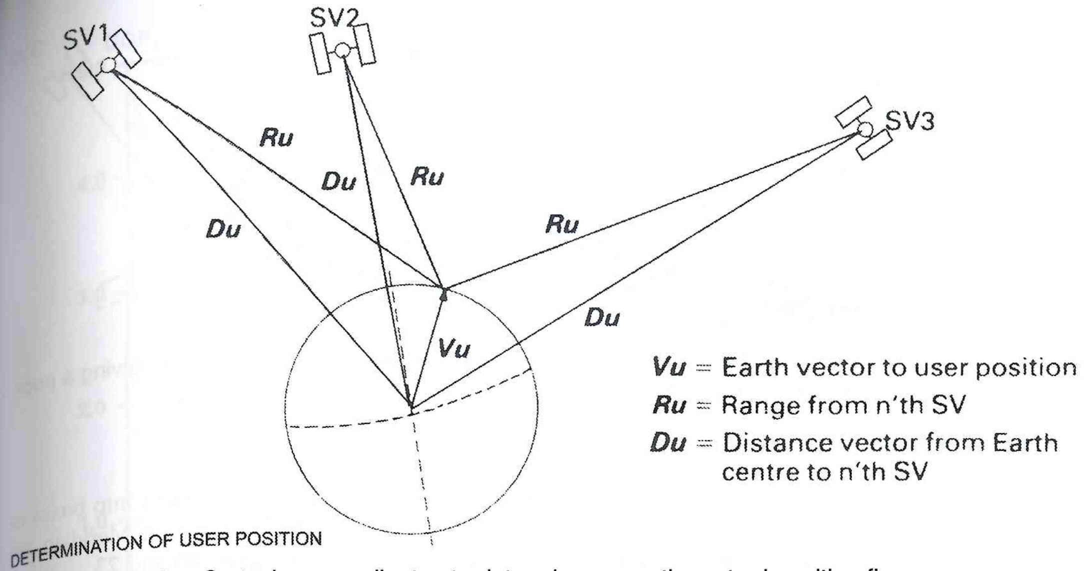


Figure 5.13 Using Cartesian co-ordinates to determine an earth centred position fix.

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

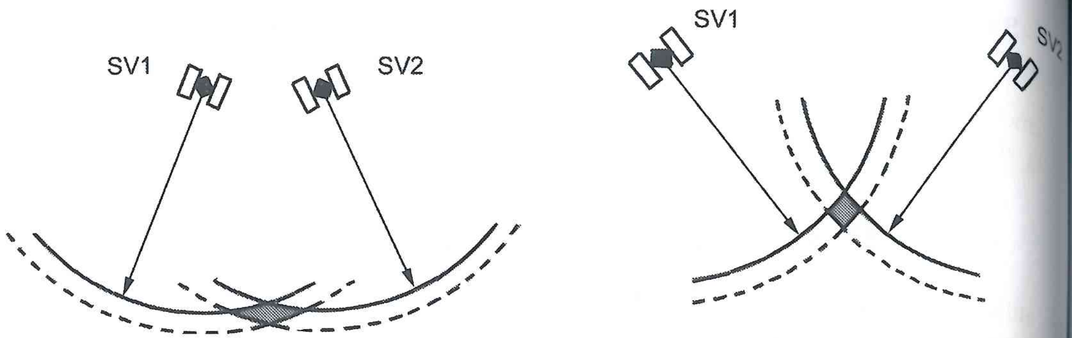


Figure 5.14 Fix accuracy can be improved by selecting appropriate SVs. (a) Two SVs giving a poor GDOP and (b) two SVs providing a much better solution.

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

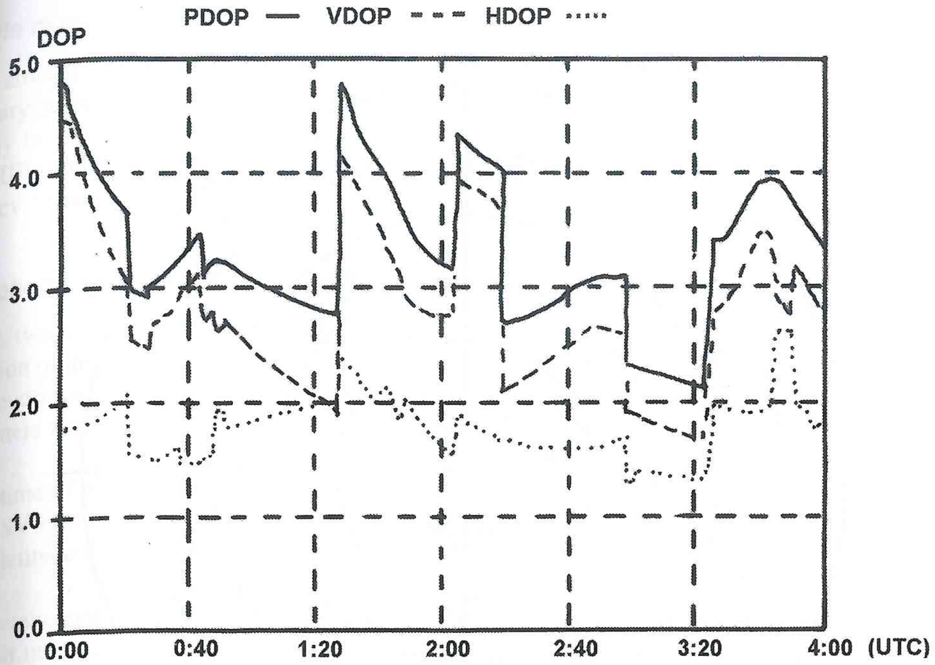


Figure 5.15 Trimble mission planning DOP graph taken over 4 hours. A low DOP indicates a high level of accuracy.

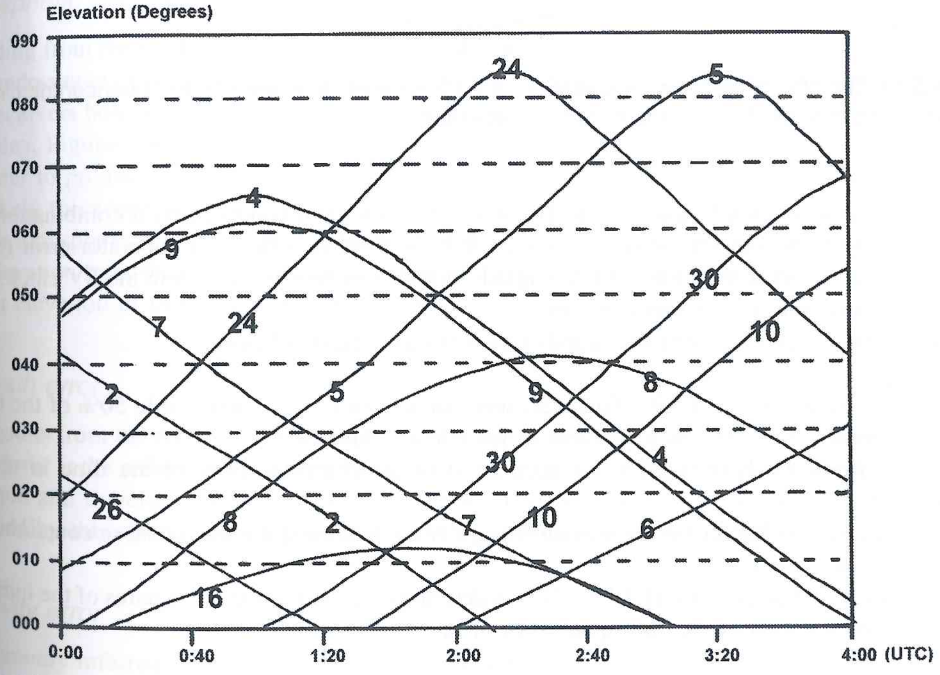


Figure 5.16 Trimble SV elevation plot. A 4-h plot showing all SVs in view.

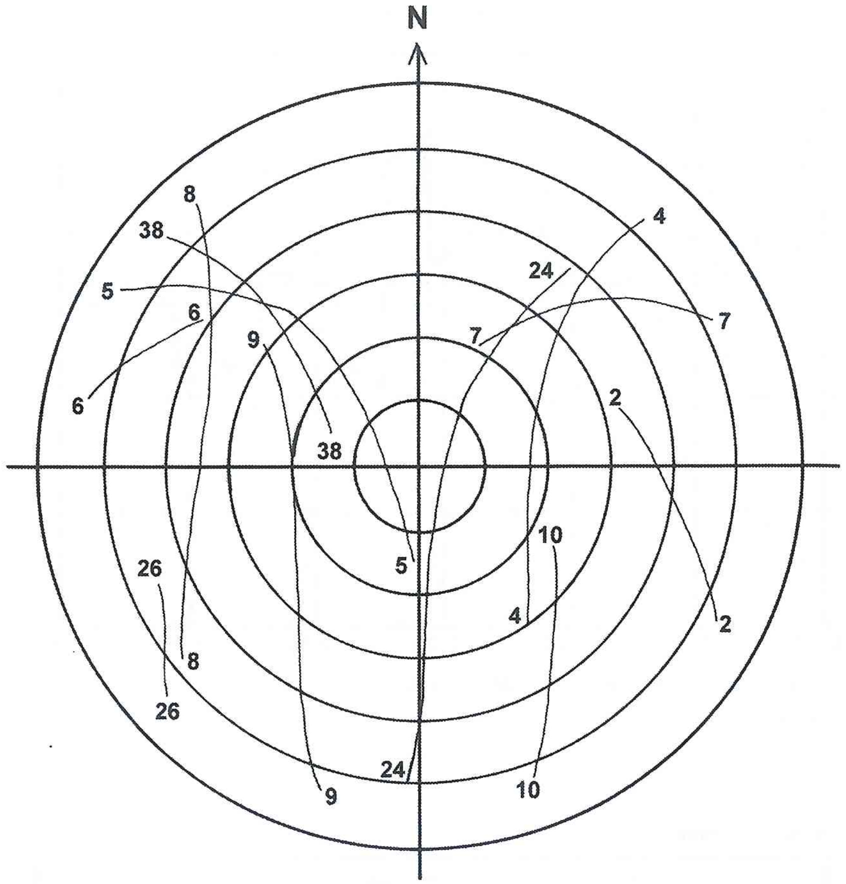


Figure 5.17 Trimble SV sky plot presentation. A GPS receiver is in the centre of concentric circles. The outer ring represents the horizon or zero elevation.

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.

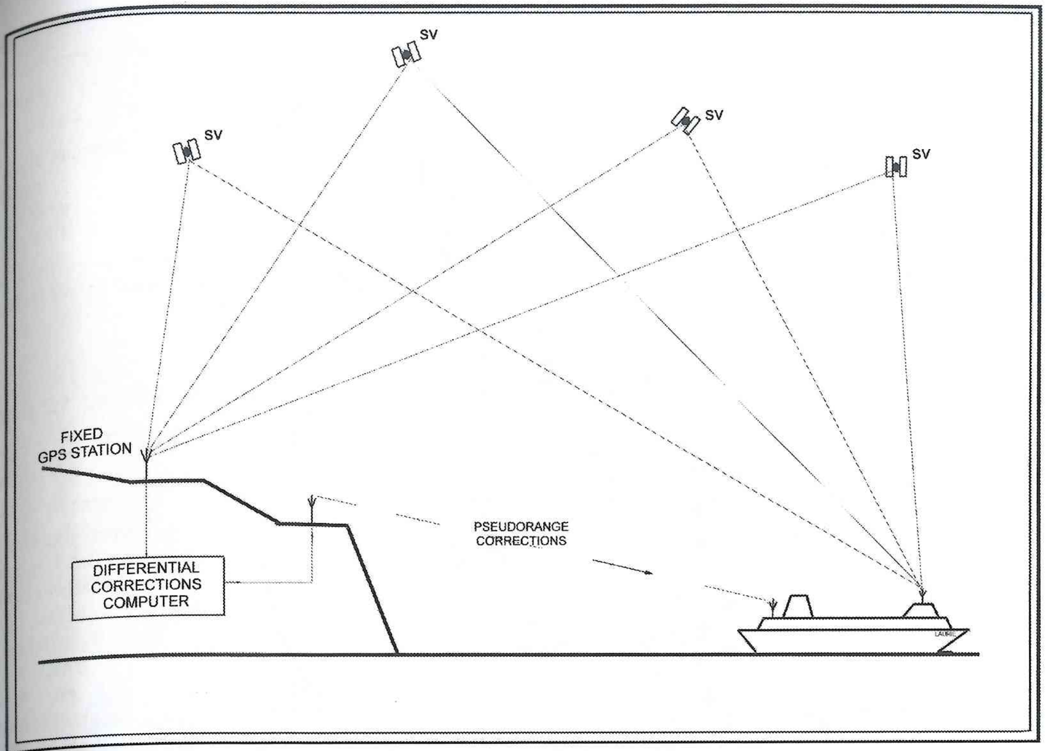


Figure 5.18 Principle of operation of DGPS.

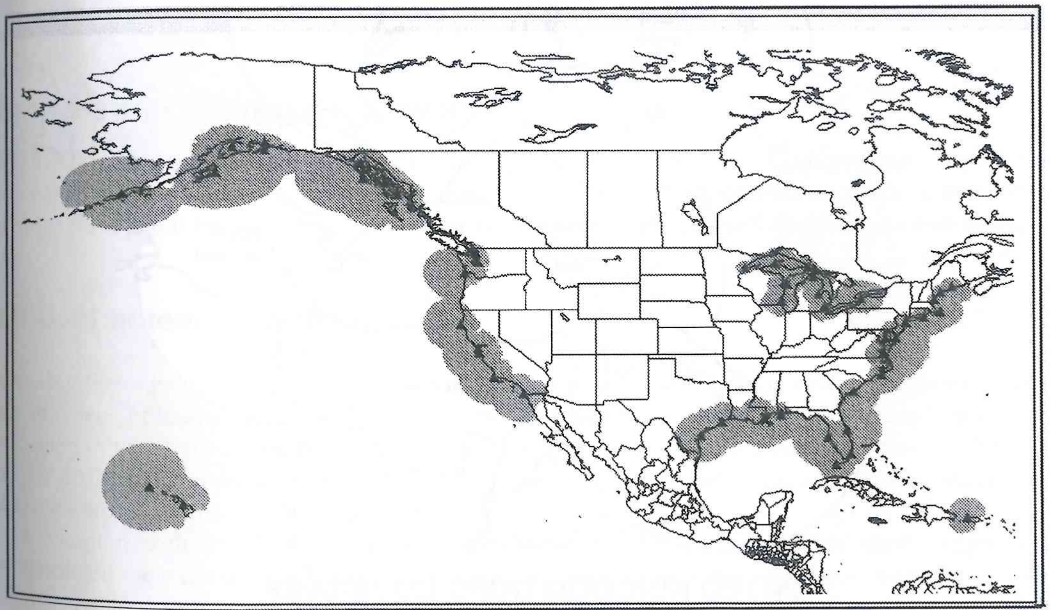


Figure 5.19 Maritime DGPS coverage of the United States. (Reproduced courtesy of the United States Coast Guard.)

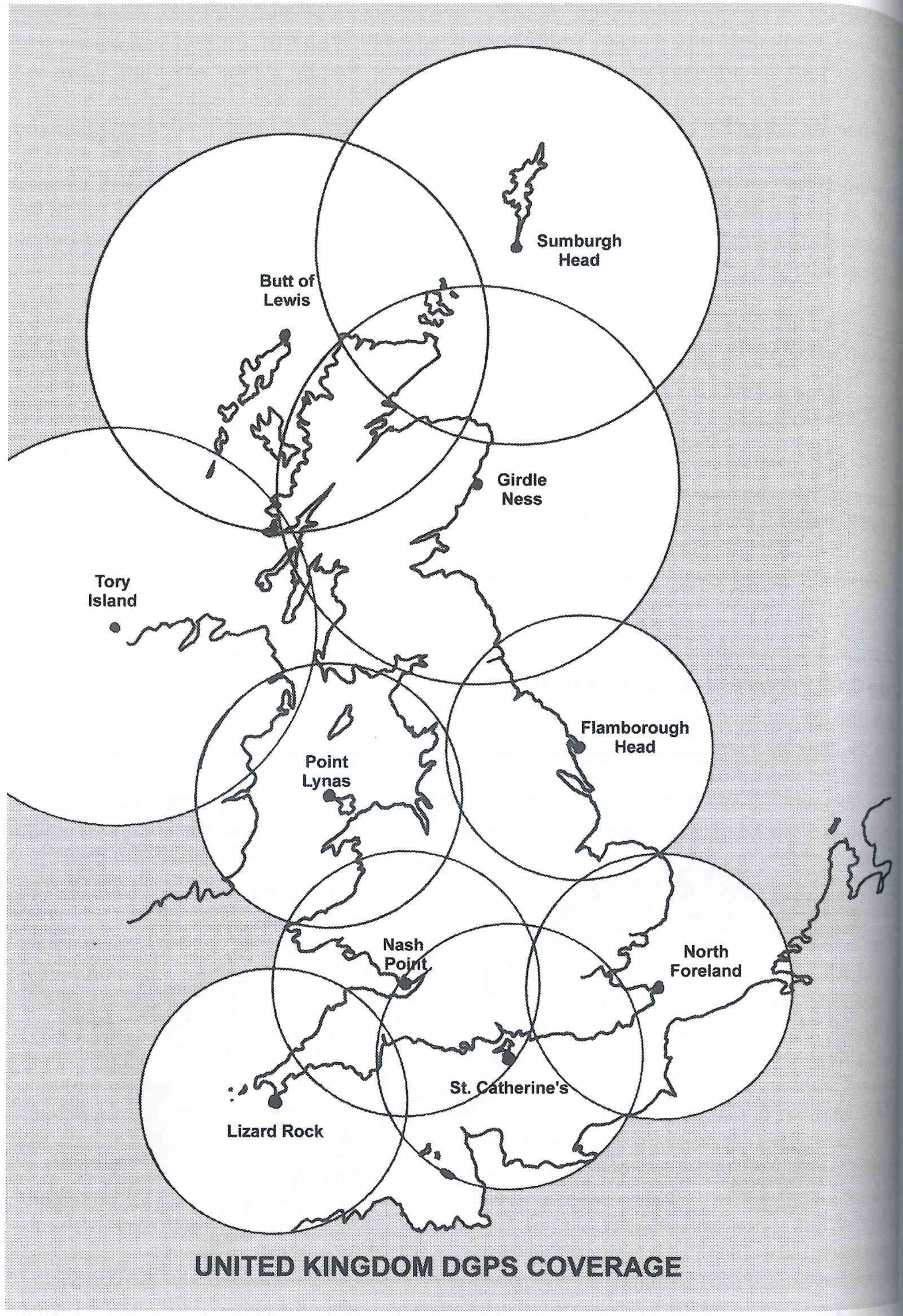


Figure 5.20 DGPS coverage of the UK coastline.

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.

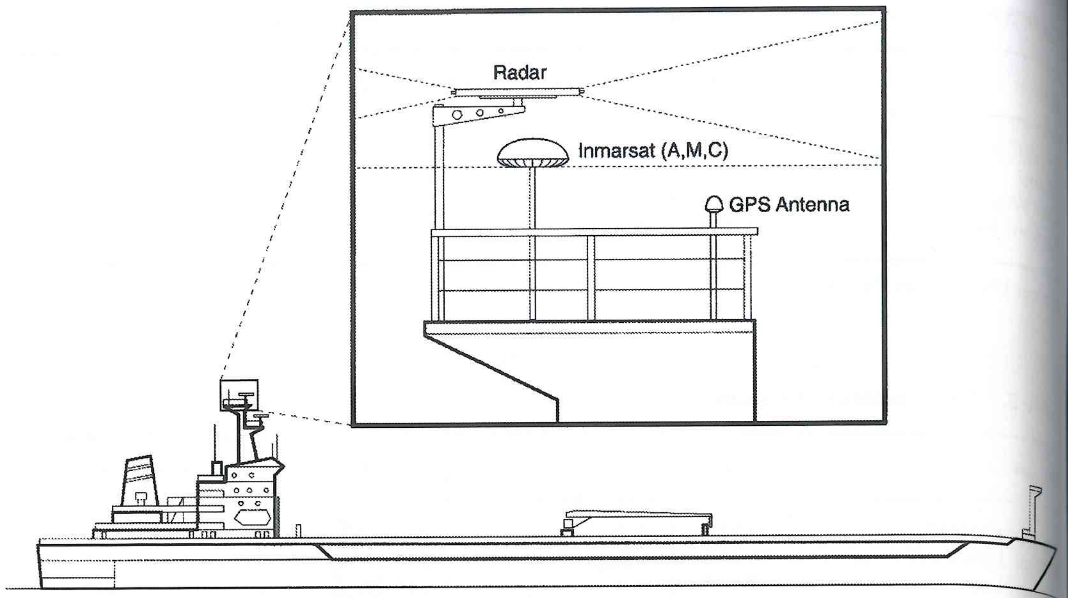


Figure 5.21 A GPS antenna mounted below other microwave system antennas on the superstructure of a merchant vessel. (Reproduced courtesy of Trimble Navigation Ltd.)

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.

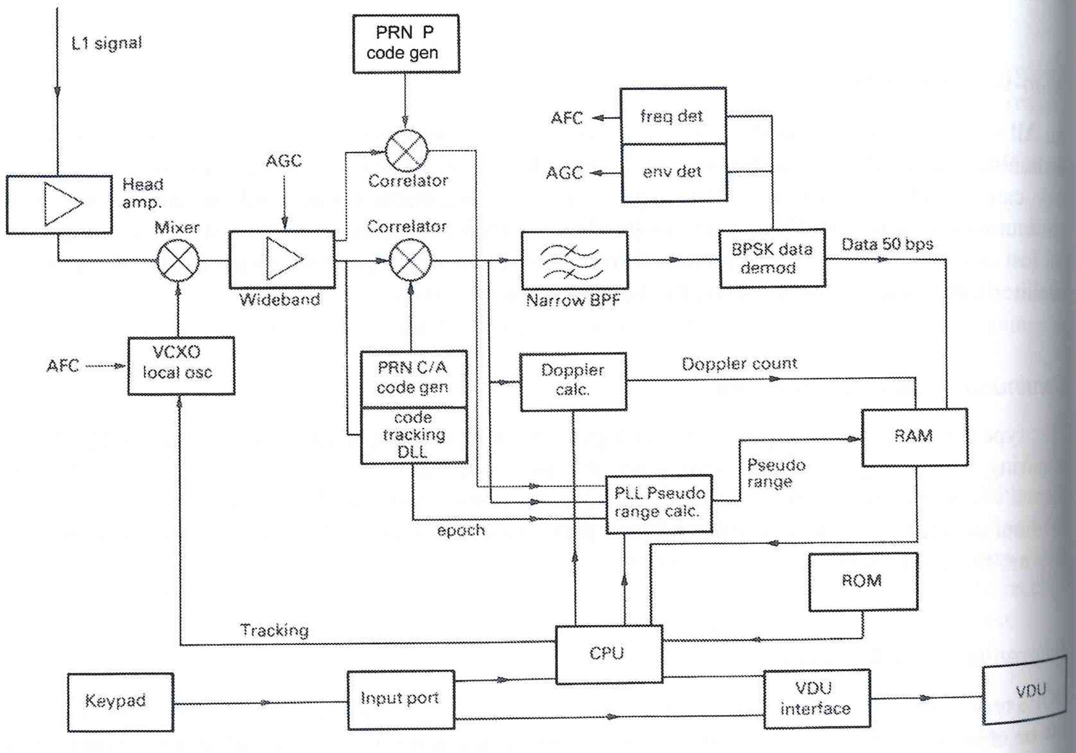


Figure 5.22 A generic GPS receiver system.

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 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.

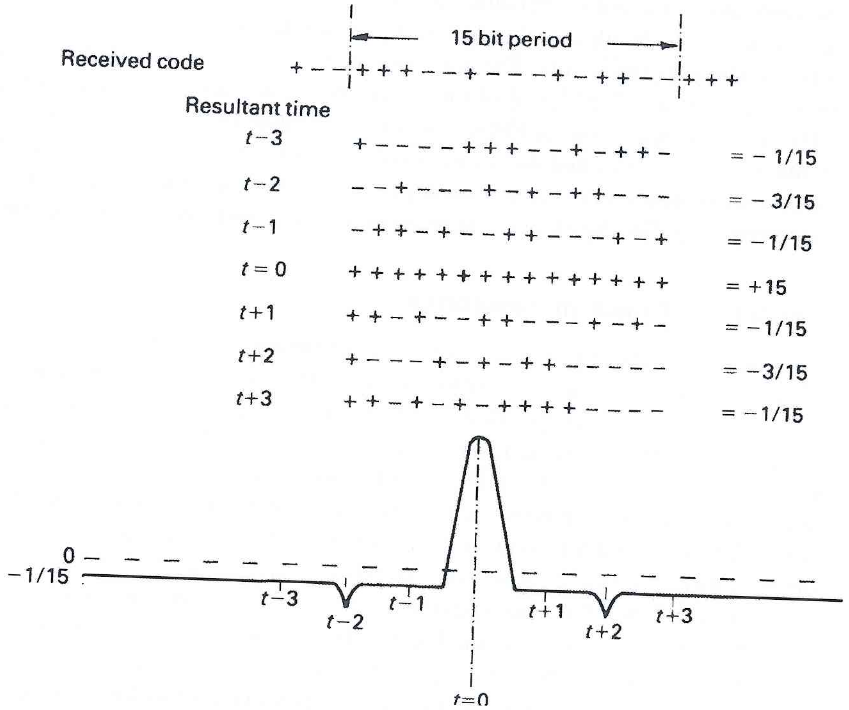


Figure 5.23 Autocorrelation function of a random waveform.

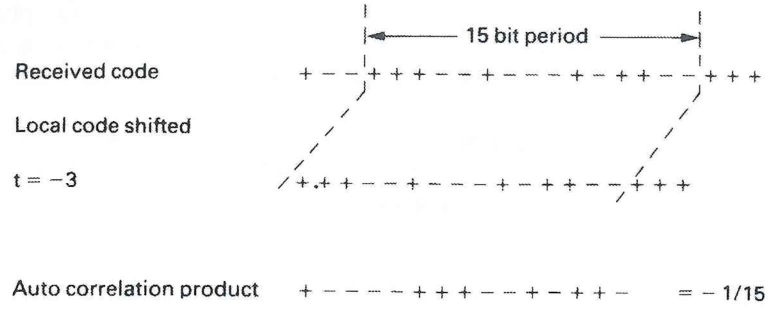


Figure 5.24 The autocorrelation product of a random waveform.

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.

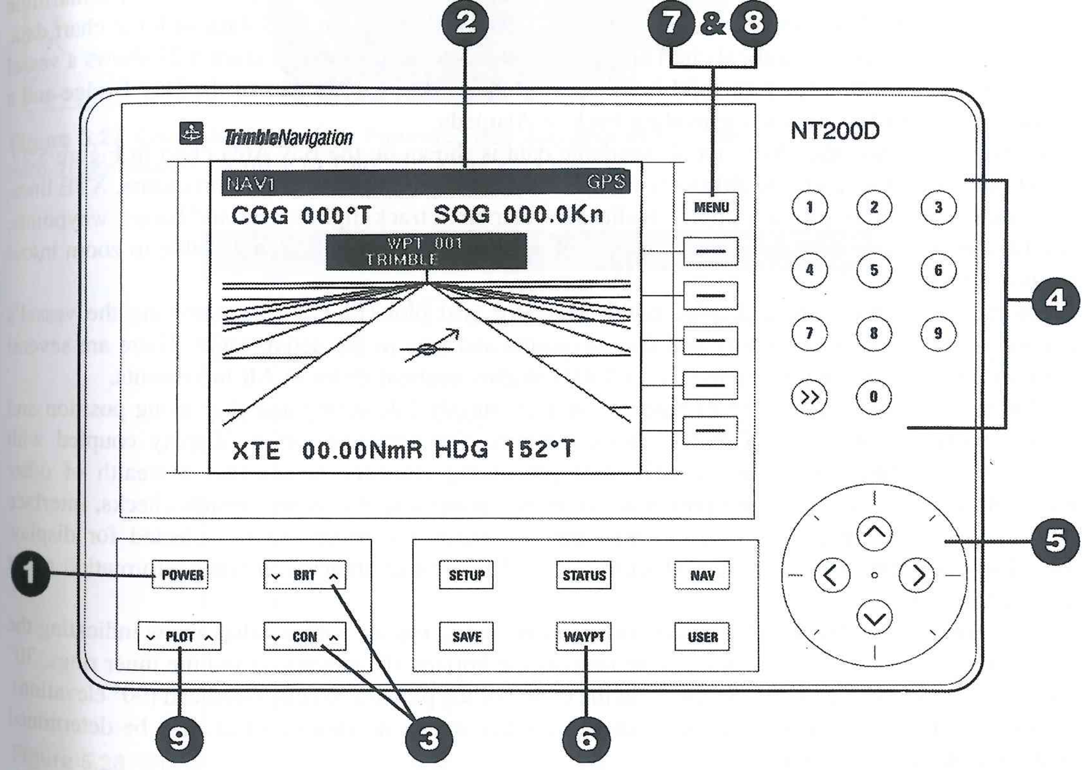


Figure 5.25 The NT200D GPS receiver displaying the NAV1 navigation display. (Reproduced courtesy of Trimble Navigation Ltd.)

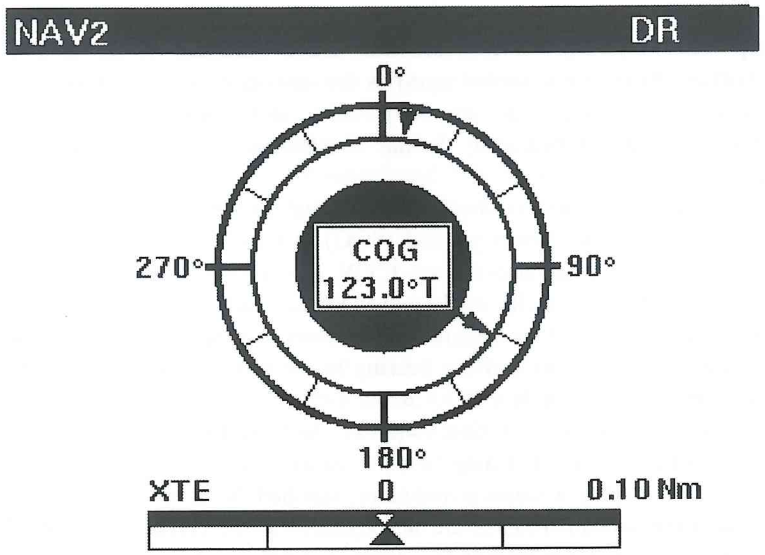


Figure 5.26 NAV 2 display. (Reproduced courtesy of Trimble Navigation Ltd.)

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

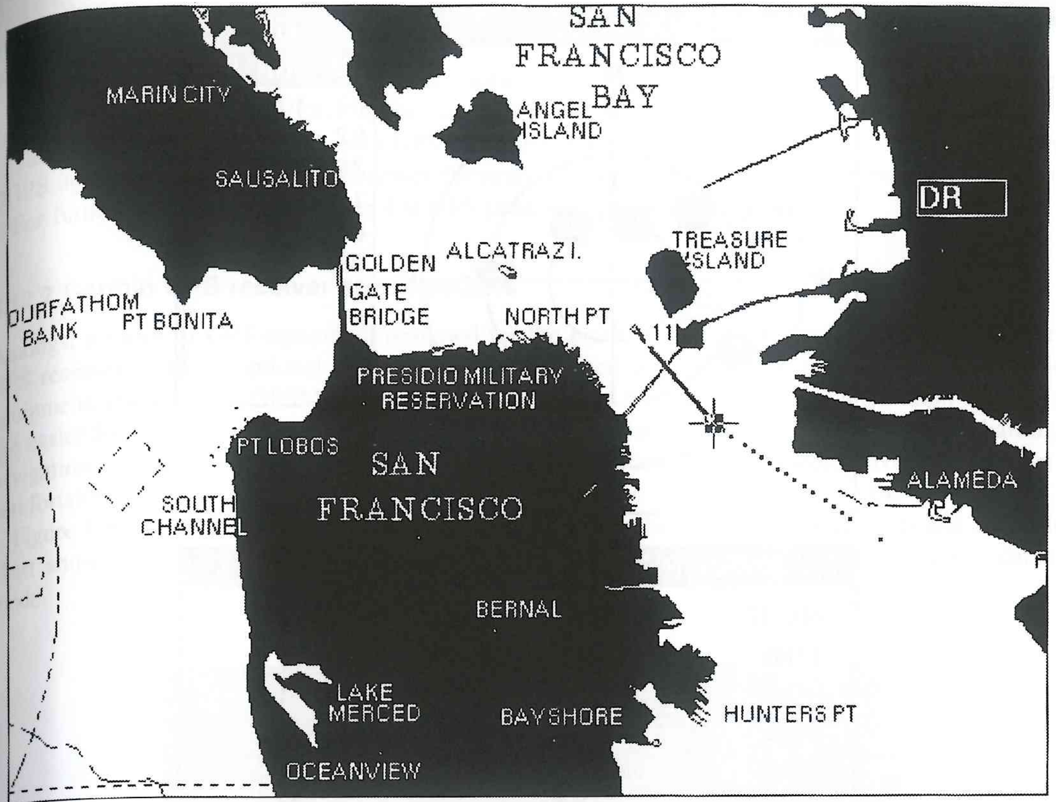


Figure 5.27 Chart display of San Francisco Bay and approaches using data input from a smart card. (Reproduced courtesy of Trimble Navigation Ltd.)

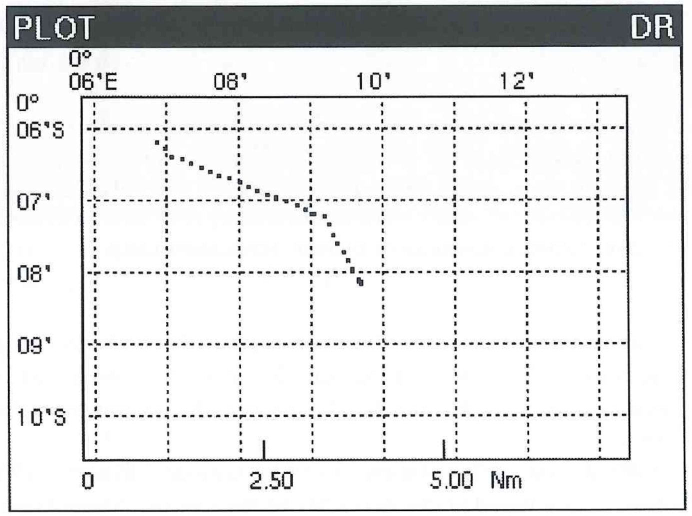
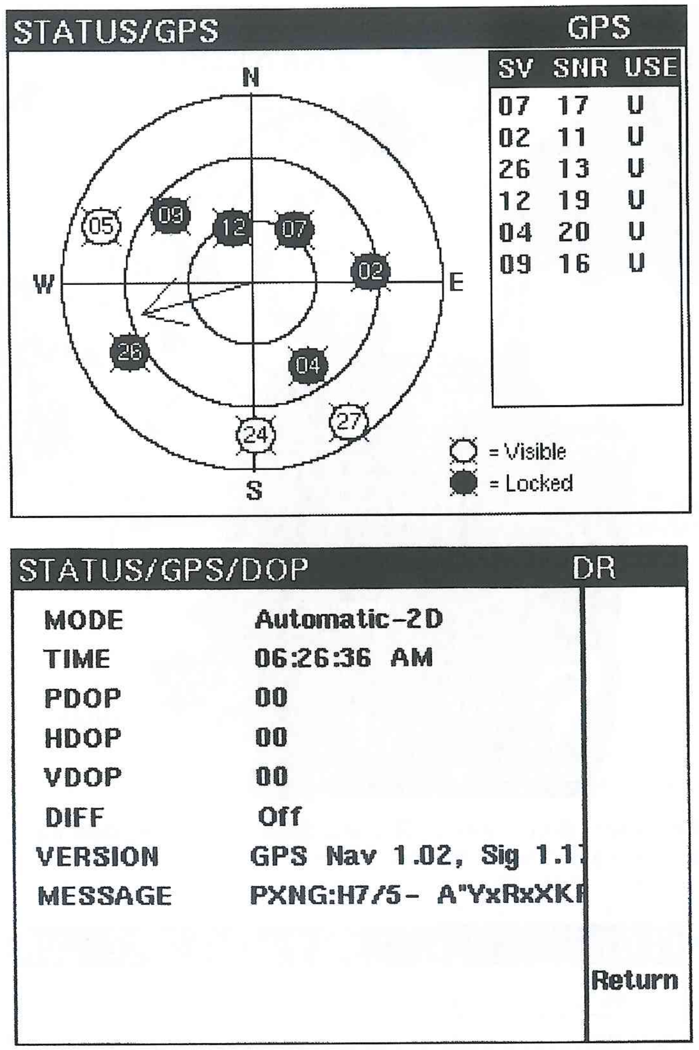


Figure 5.28 The Mercator grid plot screen display of the GPS receiver DR track. The vessel's current position is indicated by a flashing icon in the centre of the screen. (Reproduced courtesy of Trimble Navigation Ltd.)



(a)

SV	SNR	USE
07	17	U
02	11	U
26	13	U
12	19	U
04	20	U
09	16	U

(b)

MODE Automatic-2D
TIME 06:26:36 AM
PDOP 00
HDOP 00
VDOP 00
DIFF Off
VERSION GPS Nav 1.02, Sig 1.1
MESSAGE PXNG:H7/5- A"YxRxXK

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.

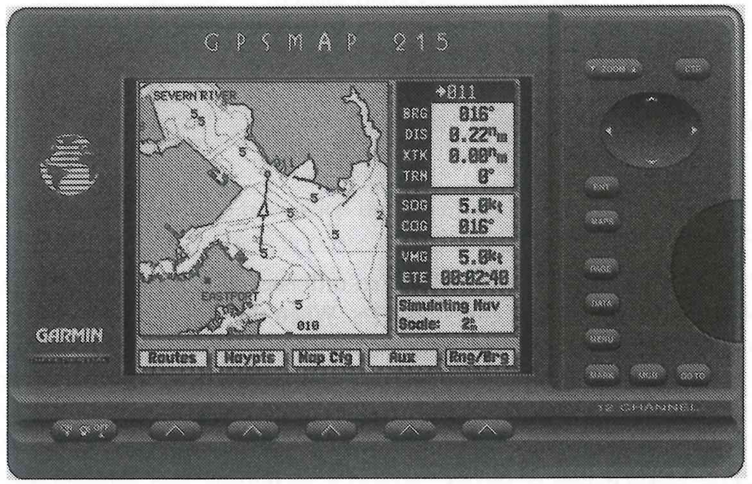


Figure 5.30 Front panel of the Garmin GPSMAP 225 system showing operator controls and a sample navigation map generated in the simulation mode. (Reproduced courtesy of Garmin.)

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

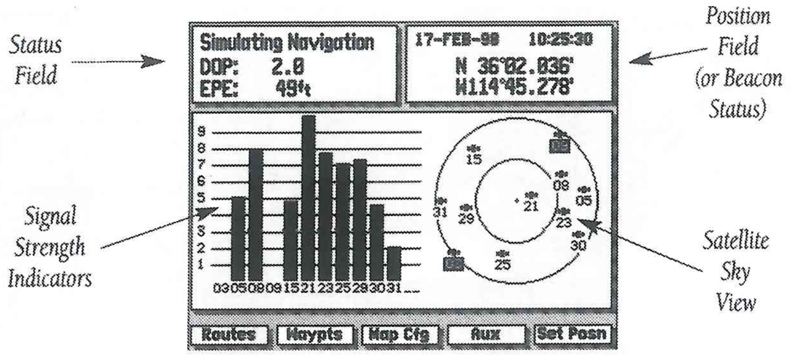
The GPSMAP unit automatically converts GPS co-ordinates to Loran-C TDs (time delay) for users who have a collection of Loran fixes stored as TDs. When the unit is used in this mode, it simulates the operation of a Loran-C receiver. Position co-ordinates may be displayed as TDs, and all navigation functions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


Simulating Navigation
DOP: 2.0
EPE: 49ft

17-FEB-98 10:25:30
N 36°02.036'
W114°45.278'

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

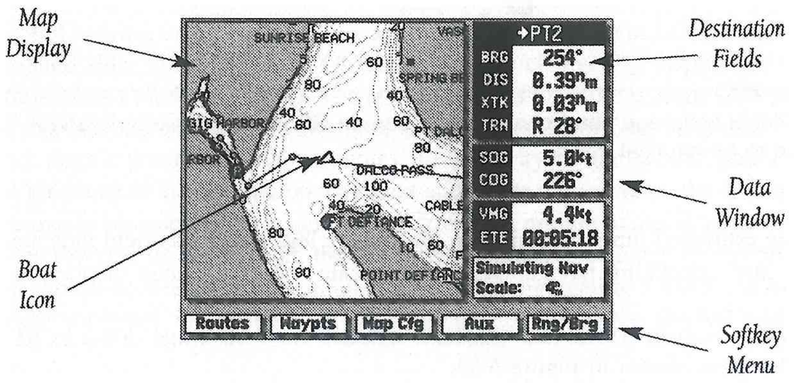

➔PT2
BRG 254°
DIS 0.39nm
XTK 0.03nm
TRN R 28°
SOG 5.0kt
COG 226°
VMG 4.4kt
ETE 00:05:18
Simulating Nav
Scale: 4

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),

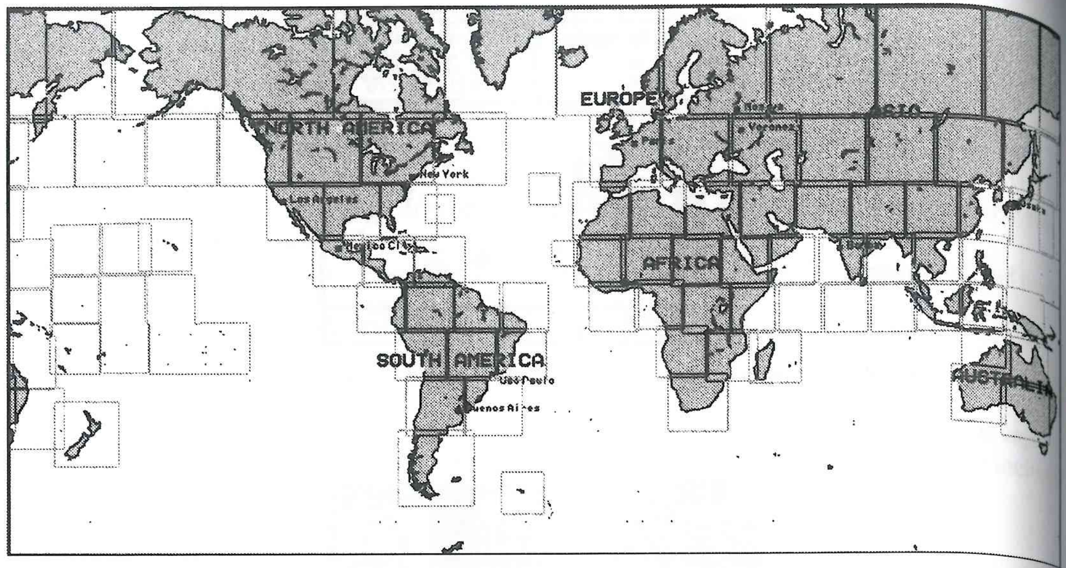


Figure 5.33 Global coverage chart showing the Garmin GPSMAP's built-in database for chart coverage down to 64 nautical miles.

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.

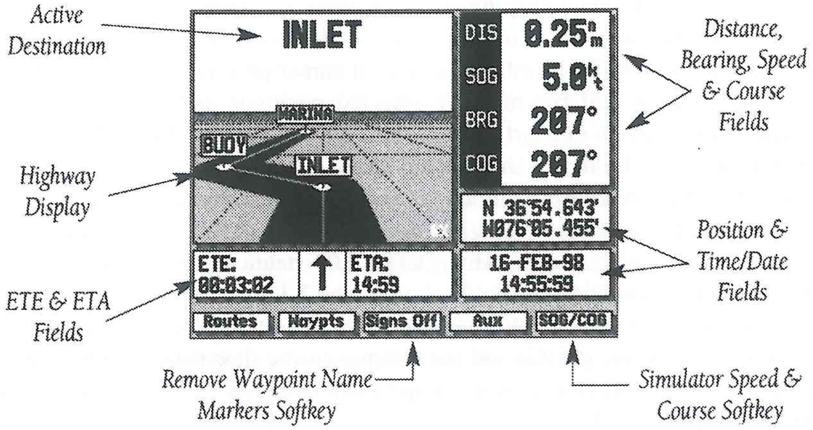


Figure 5.34 A sample Highway page of the Garmin GPSMAP 225 system used when navigating a route to an active waypoint.

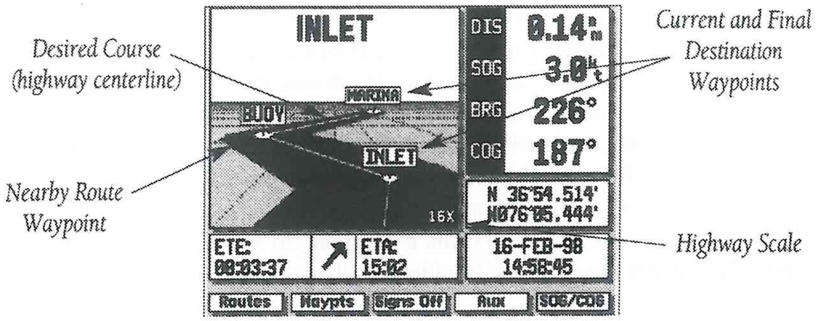


Figure 5.35 A sample Highway page of the Garmin GPSMAP 225 system used when navigating a route to an active waypoint.

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 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?