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 transmitters broadcasting low frequency pulsed signals that enable ships and aircraft to determine their position. A system that used this concept was first proposed in the 1930s and implemented as the British Gee system early in the Second World War. The Gee system used master and slave transmitters sited approximately 100 miles apart and used frequencies between 30 and 80 MHz. The use of frequencies in the VHF band constrained the system to 'line-of-sight' distance for coverage but this was not a problem at the time since the system was designed to aid bomber navigation on raids over Germany.

The system was further developed at the Radiation Laboratory of the Massachusetts Institute of Technology and the speed of development was such that by 1943 a chain of transmitters was in operation under the control of the United States Coastguard (USCG). This early system was later known as standard loran or Loran-A. This system operated in the frequency range 1850–1950 kHz with master and slave stations separated by up to 600 nmiles. Coverage of the system used groundwaves at ranges from 600 to 900 nmiles over seawater by day, and between 1250 and 1500 nmiles via sky wave reception at night, using the first-hop E layer mode of propagation. Loran-A has a typical accuracy of about 1 nmile for ground wave reception and 6 nmiles for sky wave reception.

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

Loran-A was finally phased out in the United States in 1980 and replaced by Loran-C. The use of Loran-A continued in other parts of the world for a time before a change was made to the more universal Loran-C. The last operational Loran-A chains were based along the coast of China. The 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 $3 \times 10^8\,\text{ms}^{-1}$, 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:

$$d = v \times t \tag{4.1}$$

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 $d = 300\,\text{km}$. The velocity of light has been taken as $3 \times 10^8\ \text{ms}^{-1}$ in the above calculation whereas in free space the actual value is $2.99792458 \times 108\,\text{ms}^{-1}$. 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:

$$t = d/v$$

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

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

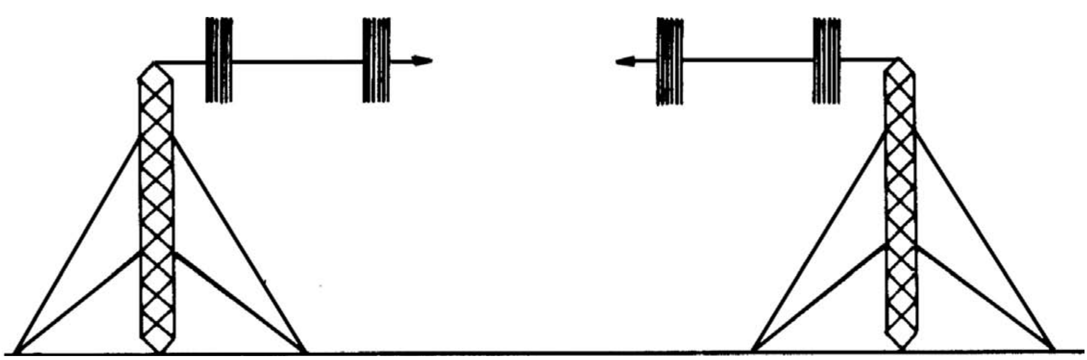

Figure 4.1 The loran system: two transmitters each radiating short pulses of specified length at a specified repetition interval.

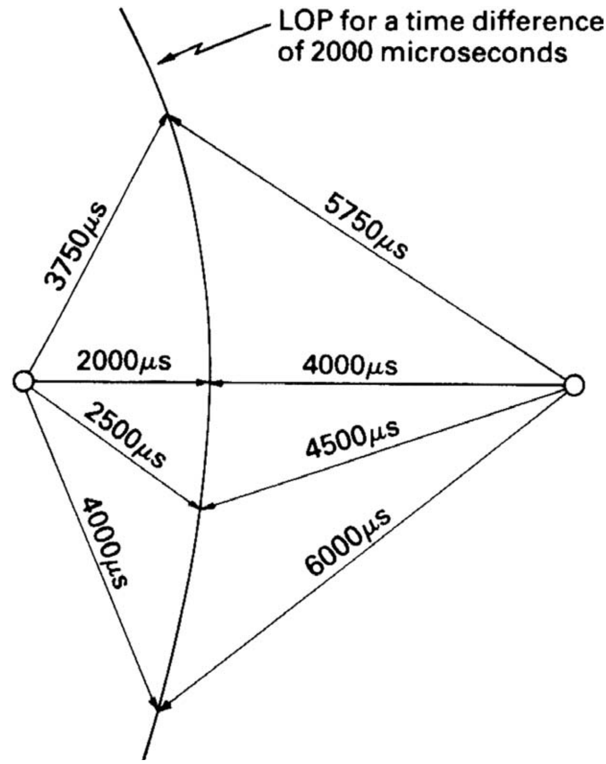

Figure 4.2 Line of constant time difference (LOP) produced from two transmitter stations emitting pulses simultaneously.

station A would arrive after 2000 μs, while that from station B would arrive after 4000 μs. This means that there is a difference in arrival time of 2000 μs. There would be other receiver positions in the region between the transmitters, not necessarily on the baseline, where the difference in arrival time was 2000 μs. It follows that by connecting all possible points where there is a difference in arrival time of 2000 μs, a line of position (LOP) may be plotted. Figure 4.2 shows a plot of all possible positions 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. For this reason loran, and other similar systems, are known as hyperbolic systems. It follows that other hyperbolae may be plotted for other time differences and this has been done in Figure 4.3 for time differences in steps of 1000 μs.

Note that from this diagram the time difference LOPs are symmetrically disposed about the centre line, i.e. there are two 2000-μs LOPs. Hence if the only information at the receiver is the time difference value then an ambiguity can occur. The ambiguity may be avoided by causing the second station, say station B, to be triggered by the pulse received from station A. The hyperbolic LOPs for this arrangement are no different from the original arrangement but the values of time difference are 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 created another problem. As shown in Figure 4.4, in the region of the baseline extension for the secondary

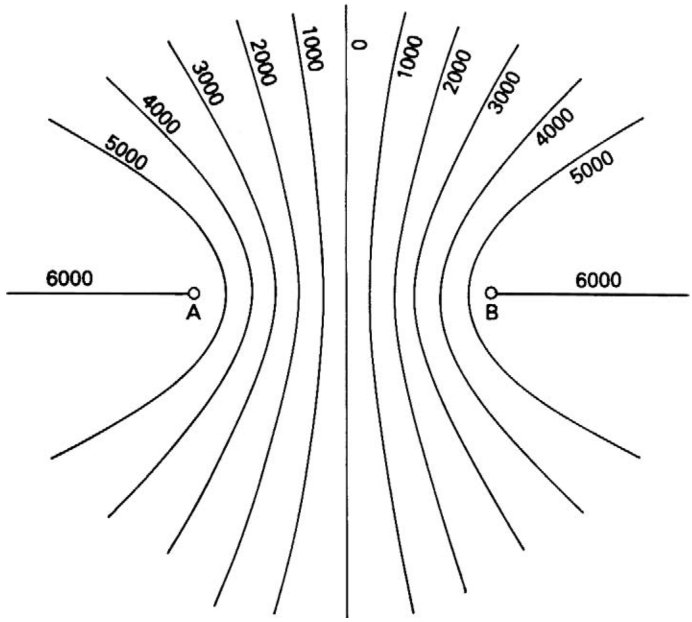

Figure 4.3 Lines of constant time difference (LOP) produced from two transmitter stations emitting pulses simultaneously.

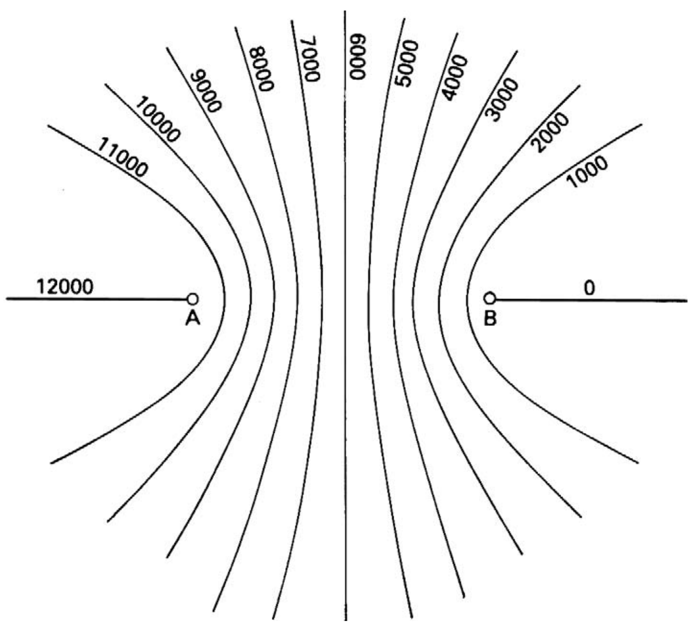

Figure 4.4 Modification of the LOPs of Figure 4.3. Station B is not allowed to transmit until triggered by a pulse from Station A.

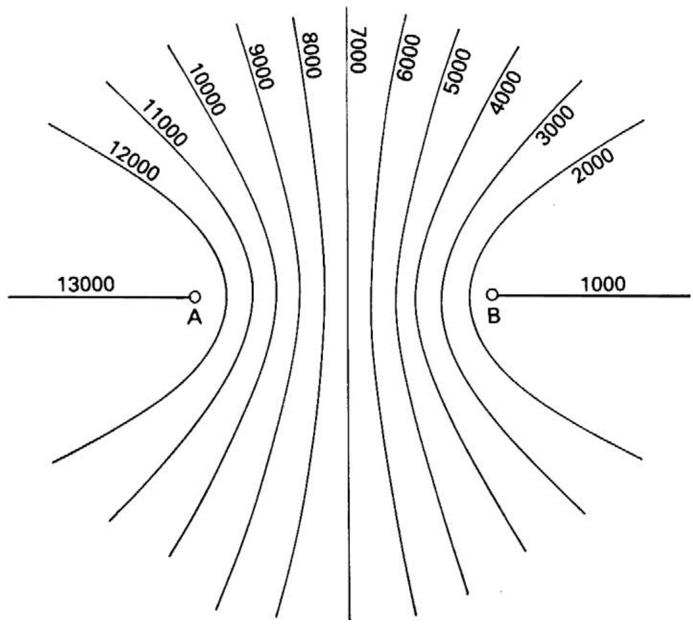

Figure 4.5 A further modification to the LOPs of Figure 4.3. Not only must Station B wait for a pulse from Station A but there is also a coding delay (1000 μs in this example) which alters the time difference value of each LOP.

station B, the difference in arrival time of the two sets of pulses is smaller than the width of the actual pulse and is in fact zero on the baseline extension. Hence in these regions it would be impossible to 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 certain period of time after the pulse from the master has arrived. As mentioned in Section 4.1, this delay period is known as a coding delay. Figure 4.5 has been drawn indicating a coding delay of 1000 μs. The total elapsed time from the master transmission until secondary transmission occurs is known as the emission delay. This is equal to the sum of the time taken for the master signal to travel to the secondary (baseline travel time) and the coding delay. Details of coding delay and emission delay 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 coding delay ensures that no area is unable to receive two distinctly separate pulses. It is important to ensure that the coding delay is kept accurately constant, since any variation in this value would cause errors 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 using an on-board receiver which is capable of comparing the delay in reception of the pulses from the master and secondary stations, it is possible to plot the position of the vessel along a particular LOP (or, by interpolation between two adjacent LOPs, if the time difference obtained is not the exact value printed on the chart). All that is necessary to establish a position fix for the vessel is to establish the position along a second, intersecting LOP (whether actual or interpolated) using another pair of transmitting stations, i.e. the master, common to all station pairs, and a second secondary station (see Figure 4.6).

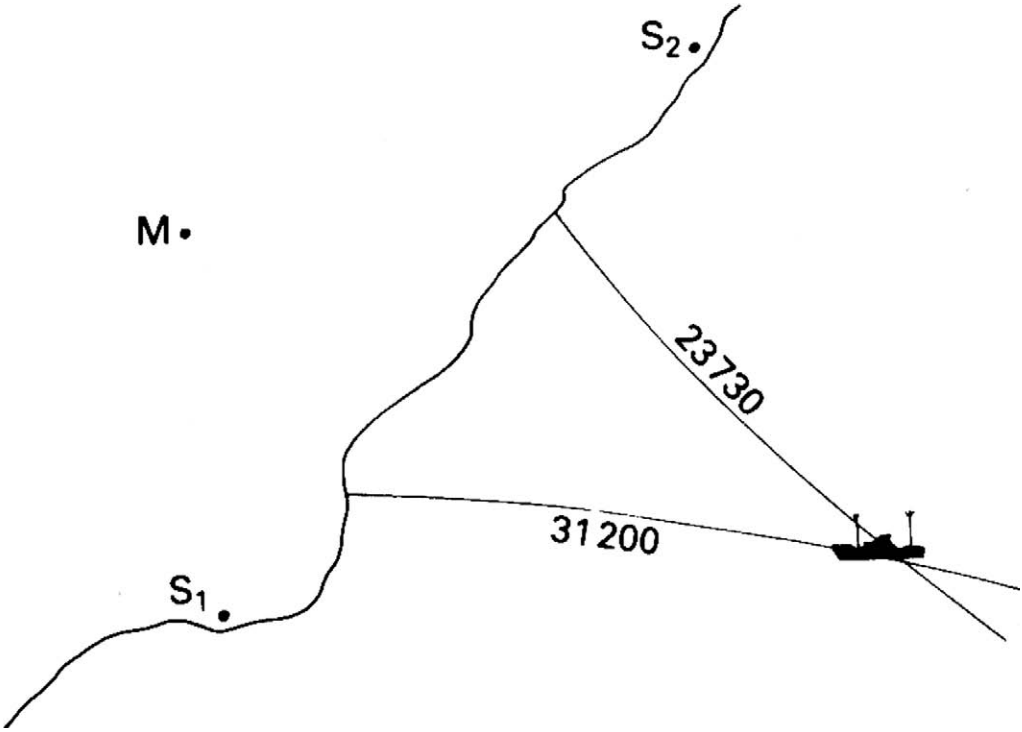

Figure 4.6 Position fixing using LOPs from two pairs of master/secondary stations.

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.

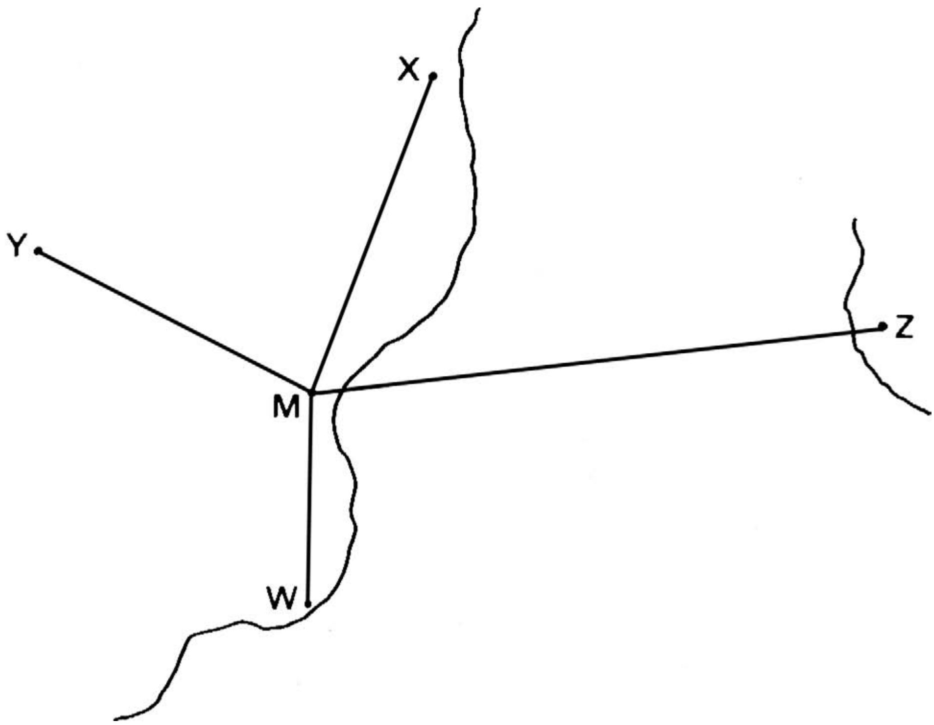

Figure 4.7 A chain may be configured from a master and up to four secondaries.

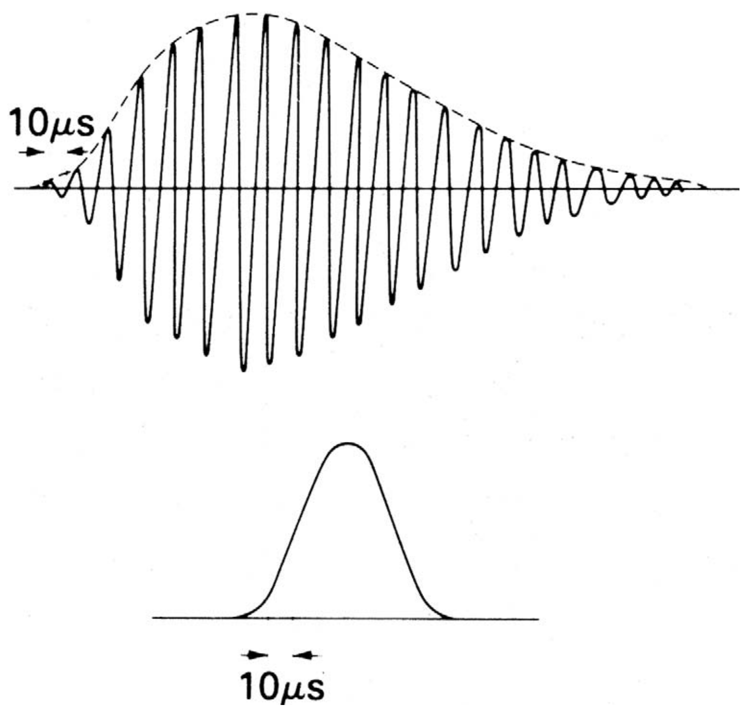

Figure 4.8 Comparison of pulses for Loran-A (lower) and Loran-C (upper).

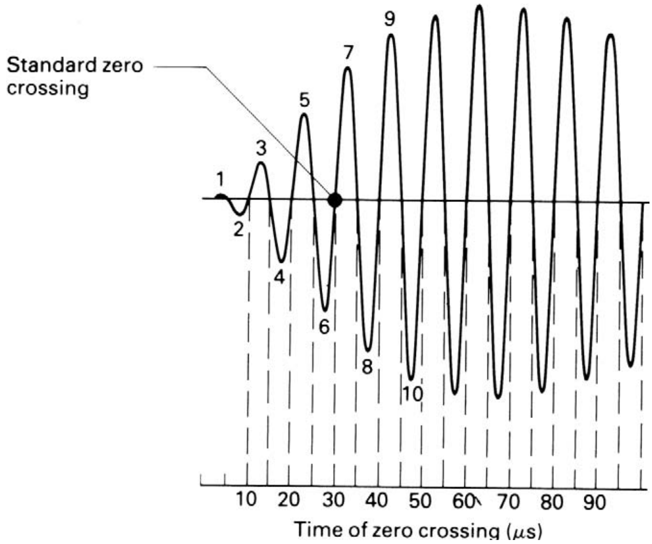

Figure 4.9 Zero crossing times and labels for half-cycles. This figure shows a 'positive' pulse. For a 'negative' pulse the polarity changes but the labels remain the same.

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 peak 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 group (considering only the first eight half-cycles). Zero crossing times and tolerances of the first group of pulses are shown in Table 4.1 for the first pulse. The zero crossing times are measured with respect to the standard zero crossing which gives a positive-going zero crossing at 30 µs for a positively coded 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*	*Category 2*
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 of 10 µs, from 40 000µs up to 99 990µs. The particular GRI is recognized by its GRI value divided by 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 linked in time to the master. The delays in transmissions from secondary stations with respect to the master are selected to ensure that the following criteria are met wherever signals can be received for any 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.

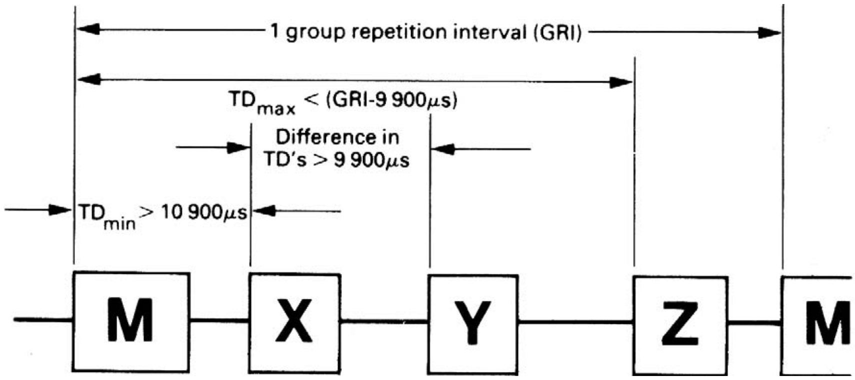

Figure 4.10 Constraints for assignment of emission delay.

- 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 the pulse-to-pulse zero crossing differences. The ECD of any single antenna current pulse does not differ 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 two pulses compared in the receiver to obtain a time delay, the Loran-C transmitter emits a series of pulses from the master and secondary stations. A typical transmission sequence for a Loran-C chain is shown in Figure 4.11.

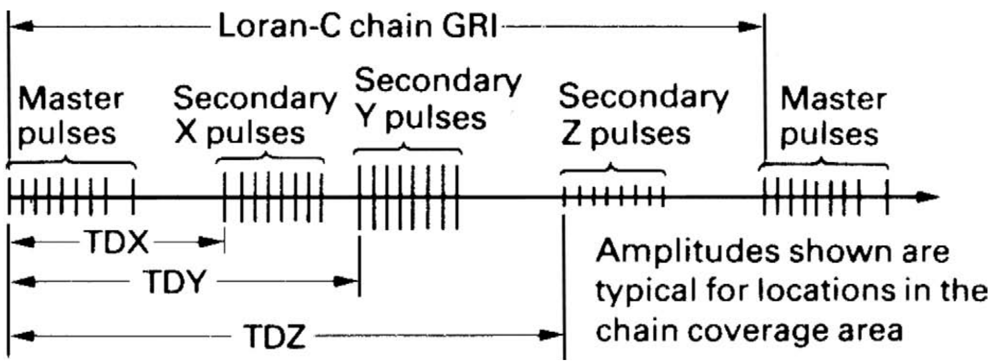

Figure 4.11 Loran-C chain group repetition interval (GRI) showing the receipt of master and X, Y and Z secondaries.

The GRI is defined as the time interval between successive pulse groups measured from the third cycle (or zero crossover) of the first pulse of any one station in the group, to the third cycle of the first pulse of the same station in the following pulse group. All stations in the chain have the same GRI, and the GRI expressed in tens of microseconds is the identifier for that chain and is called the chain ‘rate’. The master transmitter sends out a series of nine pulses while the secondaries transmit only 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; $|C| \leq 150$ 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 master station off the air.

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

Master blink is normally only used for internal Loran-C system communication. If used, the 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 generation, is shown in Table 4.6. It should be noted from this table that many stations are dual rated. For example, Dana is the zulu secondary transmitter for the Northeast US Chain (9960) and also acts as the master transmitter for the Great Lakes chain (8970).

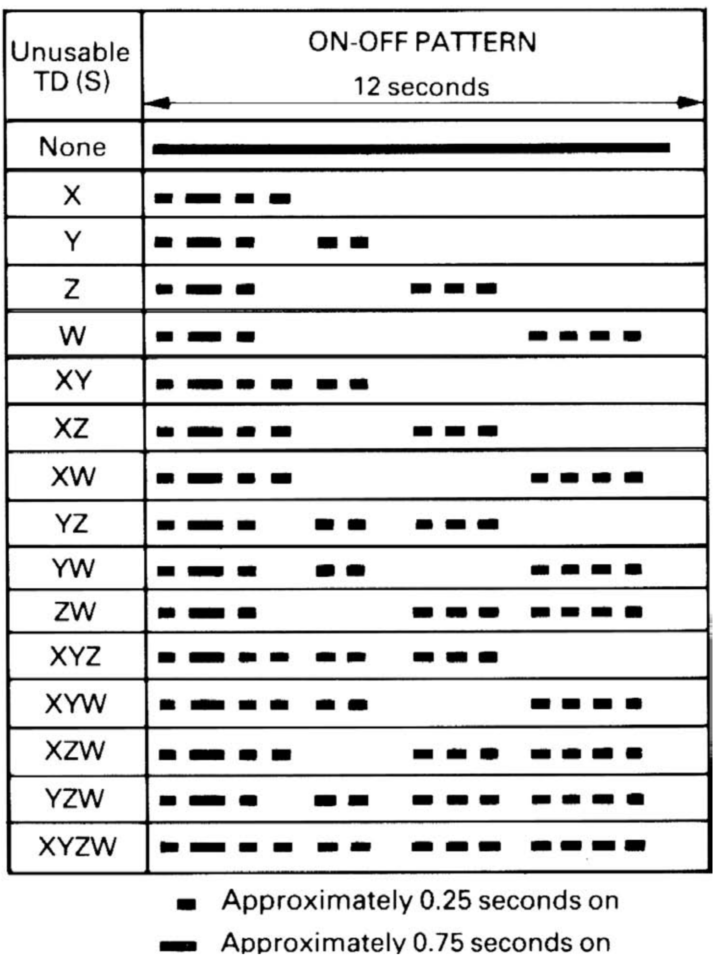

Figure 4.12 Master ninth pulse blink codes.

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 the incoming 100 kHz master pulses. Thus the receiver has a reference frequency which is continually 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 as received, is measured in the receiver and displayed as a time difference down to 0.1 µs. This is possible since the period of one cycle at 100 kHz is 10 µs and the phase difference can be measured up to approximately 1/100 of a cycle. For example, suppose a phase difference of 0.63 cycle is 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, thousands, hundreds, and tens of microseconds with a tolerance of ± 4 µs while the cycle-matching gives the units and tenths of a unit. Thus if envelope matching gives a time difference of, say, 52 700 µs and cycle 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 the secondary station with the pulses from the receiver flywheel oscillator after the latter have been passed through a variable time delay circuit. The delay circuit is necessary because the master pulses will always arrive first anywhere in the system (this is because the secondaries are triggered after the master transmission and there is a coding delay). If the timing of the pulses does not coincide then an error voltage is produced which adjusts a time delay until the start of the two pulses is caused to coincide. When this happens the delay voltage is reduced to zero. The value of the delay must be the same as the delay between the received master and secondary pulses, and if displayed in digital form would give the coarse delay figure in microseconds. One method of fine matching is to use the technique as illustrated in Figure 4.13.

The received pulse is amplified by a specific amount and shifted in phase by 180°. This new wave is algebraically added to the original wave to produce a resultant wave with a well-defined minimum at a time before the value where sky wave contamination can occur. The difference in time between the sampling of the master pulse and the secondary pulse is determined in the same way as for 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 matching on the seventh cycle of the received pulse. A mode switch allows the operator to choose third or 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 inherent inaccuracies due to possible sky wave contamination must be taken into account but may be 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 charts are identified in terms of the area covered and the designations of the stations serving the area; for example, a chart serving the Southeast US may require Loran-C LOPs for a master and, say, four

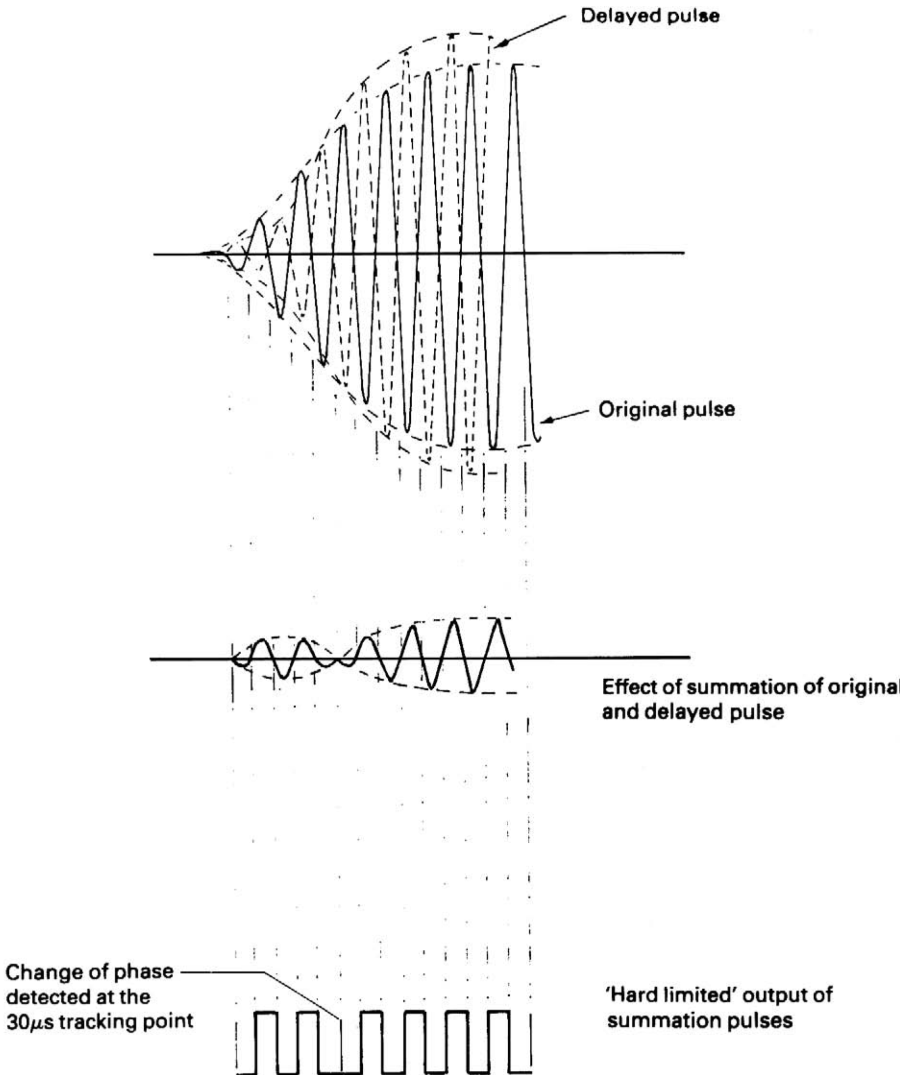

Figure 4.13 Third cycle tracking by the use of the original pulse and a pulse delayed by 5 μs, amplified and summed with the original pulse, to give a change of phase at the standard zero crossing point.

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

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

Loran-C correction tables are available for those charts that have not been corrected for ASF errors. These tables contain a complete chain and a table section is prepared for each master–secondary pair in that chain. Each page of the correction tables covers an area 3° of latitude and 1° of longitude. Examples are shown for the Northeast US (NEUS) chain master–whiskey pair (Table 4.7) and the master–yankee pair (Table 4.8). The ASF corrections can be either positive or negative; negative values are indicated by a negative sign preceding the number, the positive values have no sign. The ASF correction tables are intended primarily for the situation where the Loran-C time differences are 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 arc in longitude and latitude and the relevant page of the table referred to, to find the value of the 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 μs for pairs 9960-W and 9960-Y, respectively. From these readings the computer determines a position of 44° 15.1′ N latitude and 67°25.4′ W longitude. Entering the page index of Section W with the latitude and longitude nearest to the computed position of the vessel, the page number containing the 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)

								9960-Y					*17Y*	
		68°						*Longitude west*						*67°*
LATITUDE NORTH		*0′*	*55*	*50*	*45*	*40*	*35*	*30*	*25*	*20*	*15*	*10*	*5*	*0′*
45°	0°													
	55													
	50													
	45			LAND									3.4	
	40												3.1	3.0
	35									3.0	3.1	3.0	2.9	2.9
	30							2.9	2.9	2.9	2.9	2.8	2.8	2.8
	25					2.7	2.8	2.8	2.8	2.8	2.8	2.8	2.7	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	2.6
	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	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	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	2.5
	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	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	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	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	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	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.

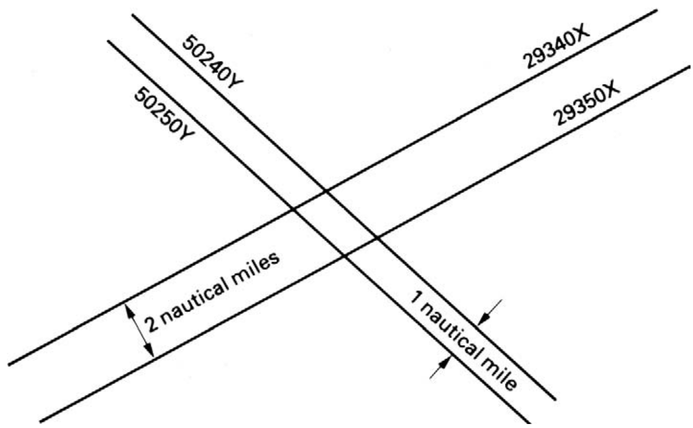

Figure 4.14 Loran-C gradients and crossing angles.

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.

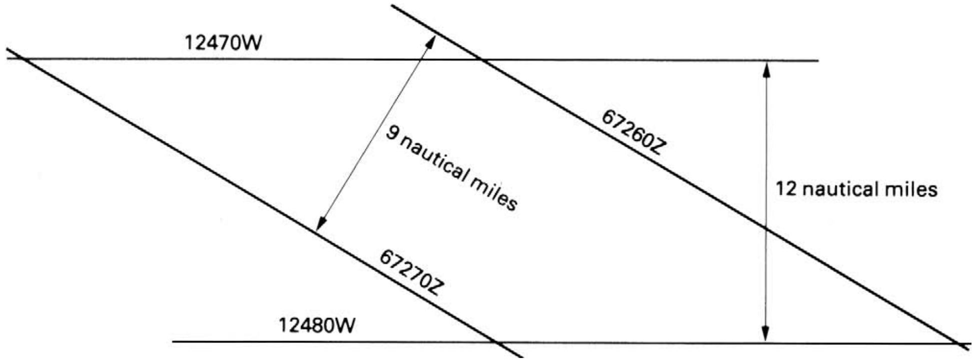

Figure 4.15 Loran-C gradients and crossing angles.

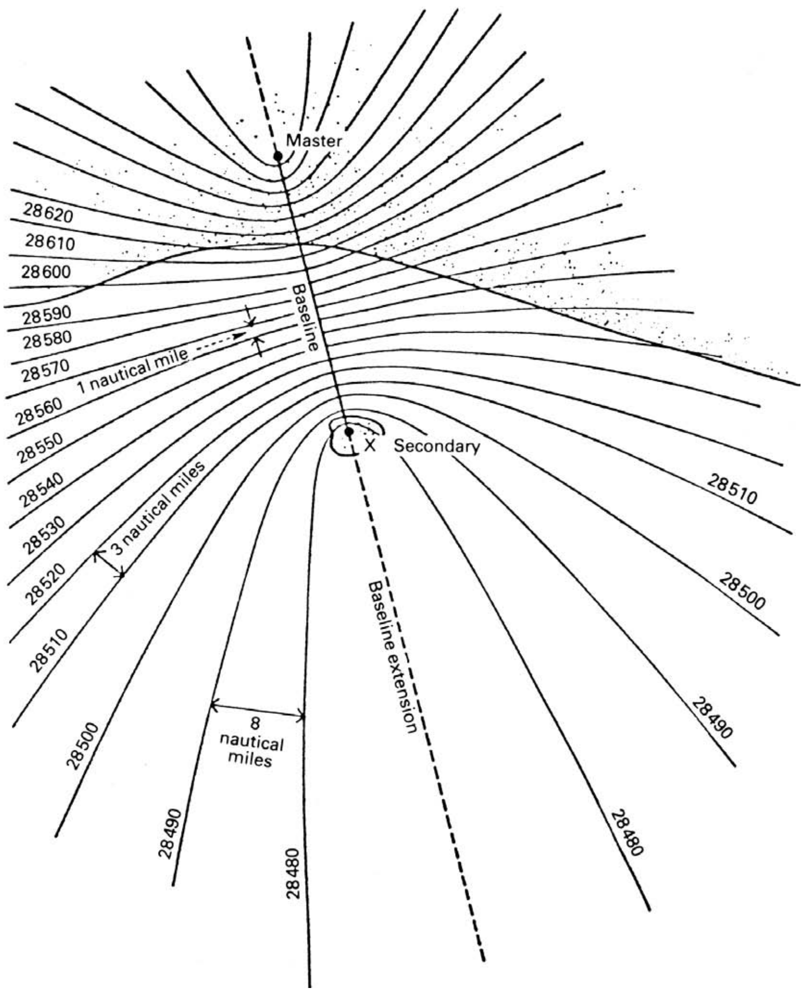

Figure 4.16 Master/slave station pair LOPs illustrating the large gradients near the baseline extension.

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*	*Power (kW)*
7430 China North Sea					
M Rongcheng	37°03′51.765″N	122°19′25.954″E			1200
X Xuancheng	31°04′07.937″N	118°53′09.625″E	13459.70	11000	1200
Y Helong	42°43′11.562″N	129°06′27.213″E	30852.32	28000	1200
7499 Sylt					
M Sylt	54°48′29.975″N	08°17′36.856″E			250
X Lessay	49°08′55.224″N	01°30′17.029″W	14100	11027.54	250
Y Værlandet	61°17′49.435″N	04°41′46.618″E	29500	26986.19	250
7950 Eastern Russia ‘Chayka’					
M Alexsandrovsk	51°04′42.800″N	142°42′04.950″E			700
W Petropavlovsk	53°07′47.584″N	157°41′42.900″E	14506.50	11000	700
X Ussuriisk	44°31′59.702″N	131°38′23.403″E	33678.00	30000	700
Y Tokachibuto	42°44′37.214″N	143°43′09.757″E	49104.15	46000	600
Z Okhotsk	59°25′02.050″N	143°05′22.916″E	64102.05	61000	10
7960 Gulf of Alaska					
M Tok	63°19′42.884″N	142°48′31.346″W			550
X Narrow Cape	57°26′20.301″N	152°22′10.708″W	13804.45	11000	400
Y Shoal Cove	55°26′20.940″N	131°15′19.094″W	29651.14	26000	550
Z Port Clarence	65°14′40.372″N	166°53′11.996″W	47932.52	44000	1000
7980 Southeast U.S.					
M Malone	30°59′38.870″N	85°10′08.751″W			800
W Grangeville	30°43′33.149″N	90°49′43.046″W	12809.54	11000	800
X Raymondsville	26°31′55.141″N	97°49′59.539″W	27443.38	23000	400
Y Jupiter	27°01′58.528″N	80°06′52.876″W	45201.88	43000	400
Z Carolina Beach	34°03′46.208″N	77°54′46.100″W	61542.72	59000	800
7990 Mediterranean Sea					
M Sellia Marina	38°52′20.707″N	16°43′06.713″E			165
X Lampedusa	35°31′20.912″N	12°31′30.799″E	12755.98	11000	325
Y Kargabarun	40°58′21.066″N	27°52′.02.074″E	32273.29	29000	165
Z Estartit	42°03′36.629″N	03°12′16.066″E	50999.71	47000	165
8000 Western Russian					
M Bryansk	53°07′50.600″N	34°54′44.800″E			1150
W Petrozavodsk	61°45′32.400″N	33°41′40.400″E	13217.21	10000	1150
X Slonim	53°07′55.200″N	25°23′46.000″E	27125.00	25000	1150
Y Simferopol	44°53′20.600″N	33°52′32.100″E	53070.25	50000	1150
Z Syzran (Karachev)	53°17′17.600″N	48°06′53.400″E	67941.60	65000	1150
8290 North Central U.S.					
M Havre	48°44′38.589″N	109°58′53.613″W			400
W Baudette	48°36′49.947″N	94°33′17.915″W	14786.56	11000	800
X Gillette	44°00′11.305″N	105°37′23.895″W	29084.44	27000	400
Y Williams Lake	51°57′58.876″N	122°22′01.686″W	45171.62	42000	400
8390 China East Sea					
M Xuancheng	31°04′07.937″N	118°53′09.625″E			1200
X Raoping	23°43′25.951″N	116°53′44.826″E	13795.52	11000	1200
Y Rongcheng	37°03′51.765″N	122°19′25.954″E	31459.70	29000	1200
8830 Saudi Arabia North					
M Afif	23°48′36.952″N	42°51′18.184″E			1000
W Salwa	24°50′01.631″N	50°34′12.574″E	13645.00	11000	1000
X Al Khamasin	20°28′02.025″N	44°34′52.894″E	27265.00	25000	1000
Y Ash Shaykh Humayd	28°09′15.997″N	34°45′40.544″E	42645.00	40000	1000
Z Al Muwassam	16°25′56.028″N	42°48′04.884″E	58790.00	56000	1000

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 current information relating to the chains, their group repetition interval (GRI), location, emission and coding delay and nominal radiated power is shown in Table 4.9.

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

- **Geometric-fix accuracy limits**. Each of two LOPs in a chain is assigned a TD standard deviation of 0.1 μs. The geometric-fix accuracy is assigned a value of 1500 feet, $2d_{RMS}$ where d_{RMS} is the radial or root mean square error. Using these constraints a contour is generated within the chain area representing the geometric-fix accuracy limits.
- **Range limits**. Predicted atmospheric noise and cross-rate Loran-C interference is compared with estimated Loran-C signal strength for each Loran-C transmitting station to obtain an expected 1:3 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 the geometric-fix accuracy limits and predicted SNR range limits. Where the geometric-fix accuracy limits extend beyond the range limits, the range limits are used on the coverage diagrams and vice versa.

Figure 4.17 shows the $2d_{RMS}$ coverage for various station pairs in the Northeast US (NEUS) chain. Diagram A, for example, shows the accuracy contours for the master–whiskey and the master–yankee station pairs. The solid line in the diagrams show the $2d_{RMS}$ contour of 1500 ft absolute accuracy, the dashed line 1000 ft and the dotted line 500 ft. Similar diagrams for other pair combinations are also 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 (lormansites) which continuously check the loran signals received to detect any out-of-tolerance conditions so that 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, where certain pulses in each group are subject to pulse position modulation of ± 1 μs to provide back-up administrative and control signals.

Radial or root mean square error, d_{RMS}, is defined as the radius of the error circle produced from the square root of the sum of the square of the sigma error components along the major and minor axes of a probability ellipse (see Figure 4.19). The ellipse is produced by virtue of the deviation expected along each LOP as indicated by $\delta 1$ and $\delta 2$ in Figure 4.22, and varies according to the gradient and 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. $2d_{RMS}$ is defined as the radius of a circle obtained when $\delta x = 2$ and δy varies from 0 to 2. The relationship between $\delta 1,\delta 2$ and $\delta x,\delta y$ and the probability values associated with $1d_{RMS}$ or $2d_{RMS}$ values are 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) shows that for ground wave reception areas, the fix probability is 95% ($2d_{RMS}$) at 1500 ft with a standard deviation of 0.1 μs and 1/3 SNR. Sky wave reception will extend the coverage area but accuracy cannot be guaranteed.

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

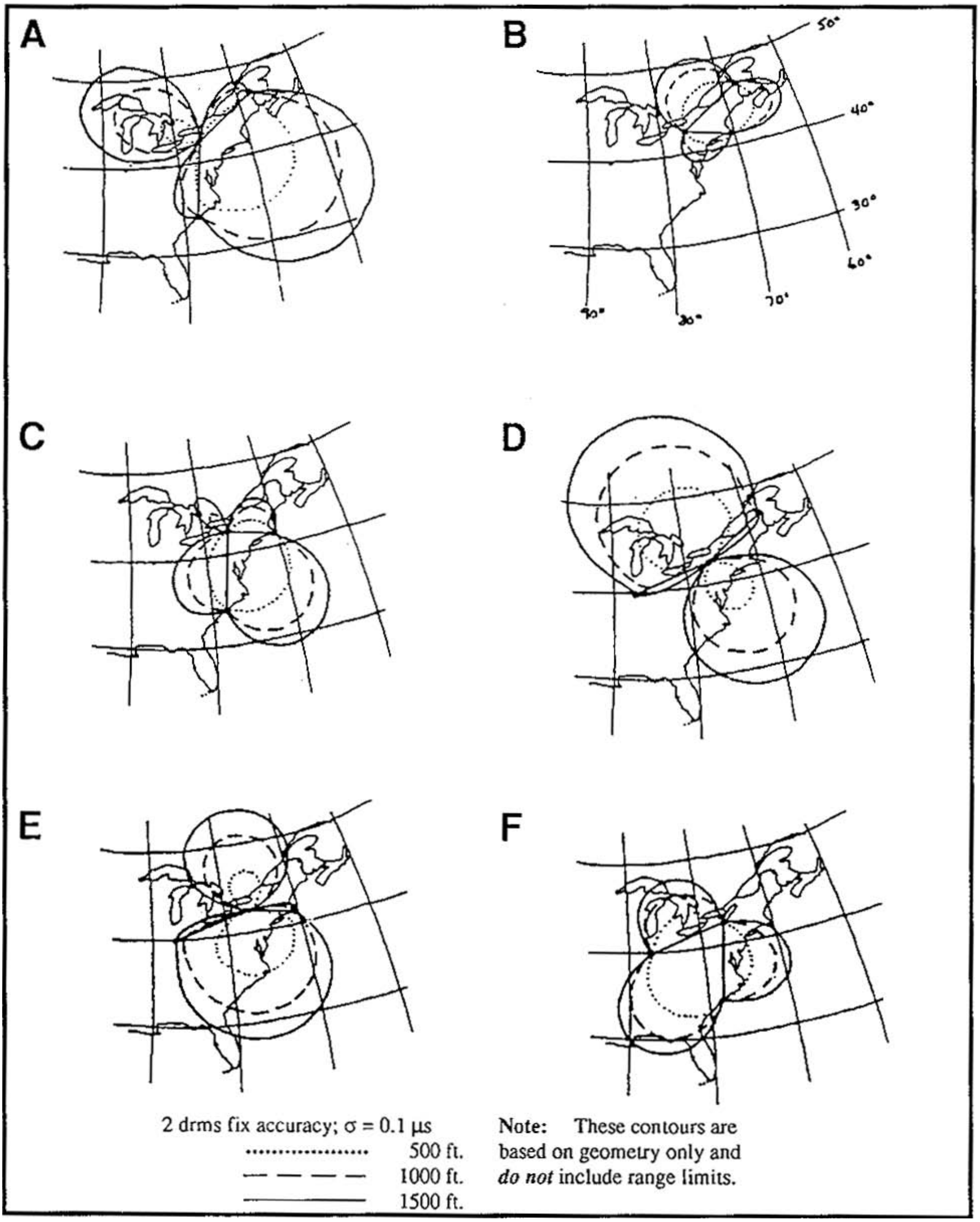

Figure 4.17 Contours of equal $2d_{\mathrm{rms}}$ for various triads in the 9960 Loran-C chain.

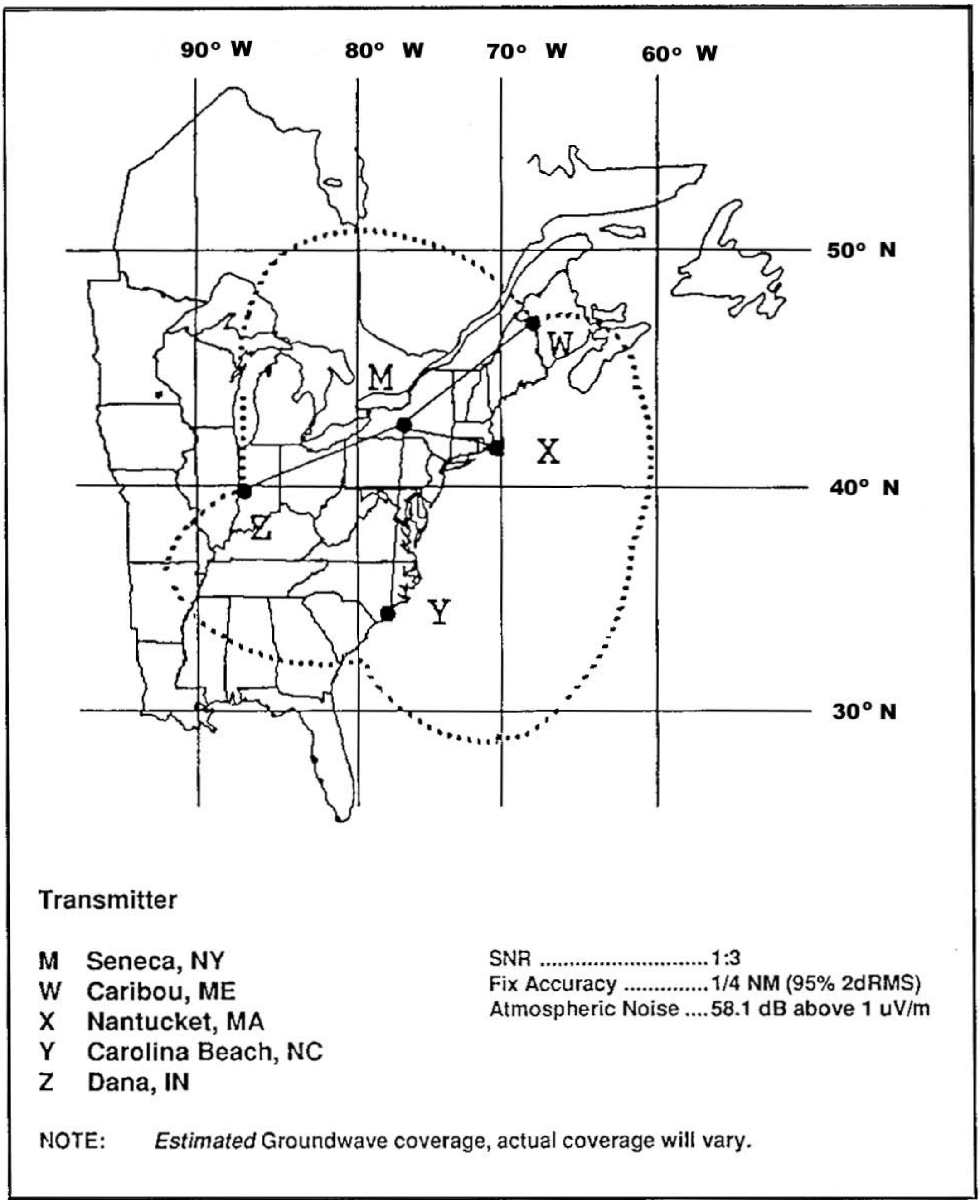

Figure 4.18 Loran-C GRI 9960 Northeast US (NEUS) chain.

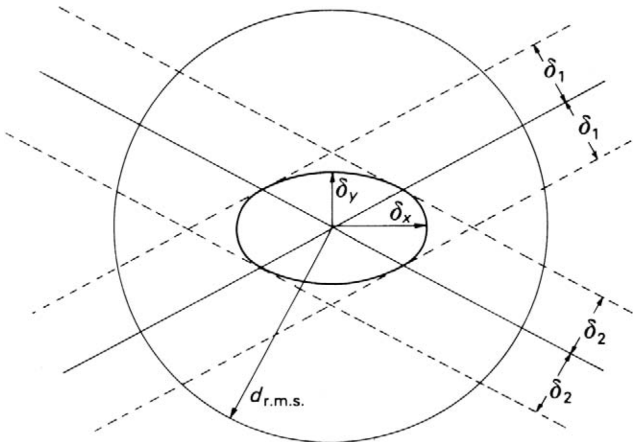

Figure 4.19 The error ellipse.

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.

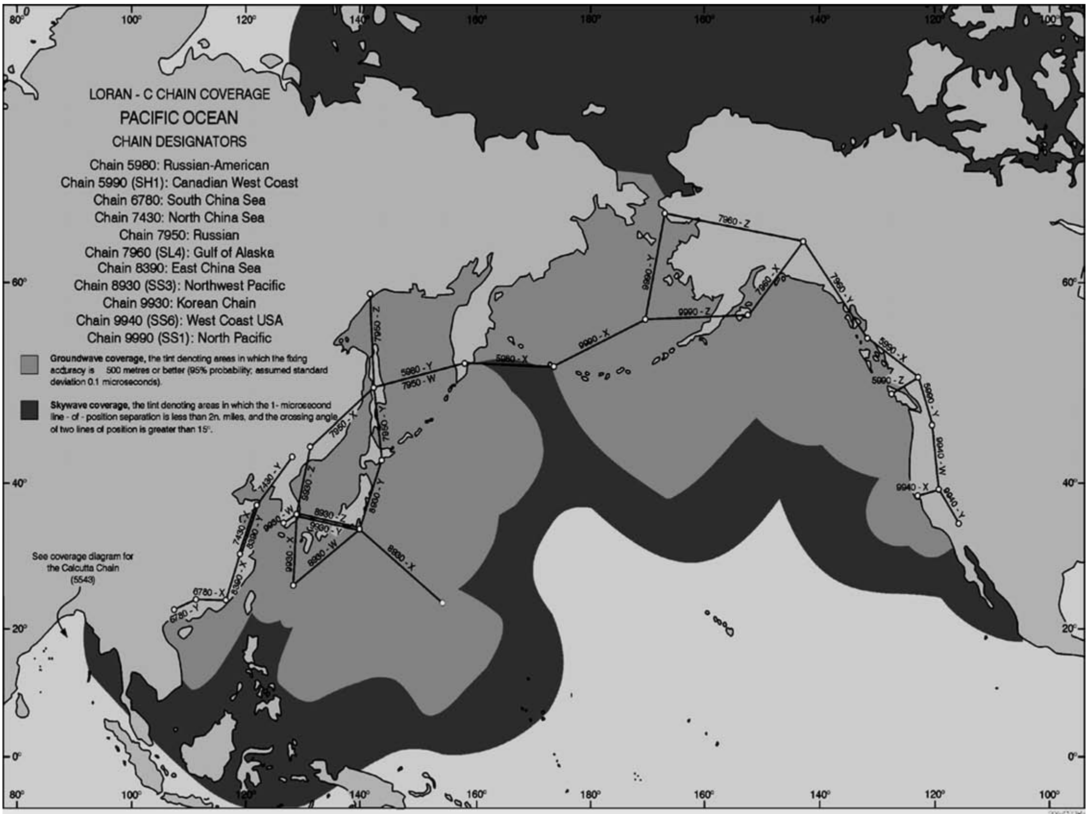

Figure 4.20a Loran-C global coverage. (Reproduced from Admiralty List of Radio Signals volume 2 by permission of the Controller of Her Majesty's Stationery Office and the UK Hydrographic Office.)

Signal reception may be impaired by interference from other signals which could act as a noise input and reduce the S/N ratio of the received loran signal and degrade positional accuracy. Notch filters within the receiver can assist in minimizing the effect of the interference. The notch filters may 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 (usually a liquid crystal display (LCD) which is easily read under all lighting conditions and energy efficient) and a keypad with function keys and numeric keys to enter data and change the data displayed. Displays will indicate information such as: status and warning data; information on the GRI in use and the secondaries chosen; alarm settings; positional information in time differences (TDs) or as latitude/longitude and navigation information such as waypoint indicators; bearing and distance to waypoint; time to go (TTG); cross-track errors (XTE); speed and course etc. Some displays may use pages of information that can be selected as required by the operator. Time differences are measured by the receiver and may be converted to latitude/longitude by computer algorithms; such algorithms would most likely incorporate additional secondary factor (ASF) corrections, which are stored in the computer memory.

Modern receivers have the facility for the operator to monitor the progress of the voyage and allow for course corrections as necessary. The receiver gives a position (in TD or latitude/longitude) and has a precise clock so that it is possible to produce navigational information, such as vessel's speed and

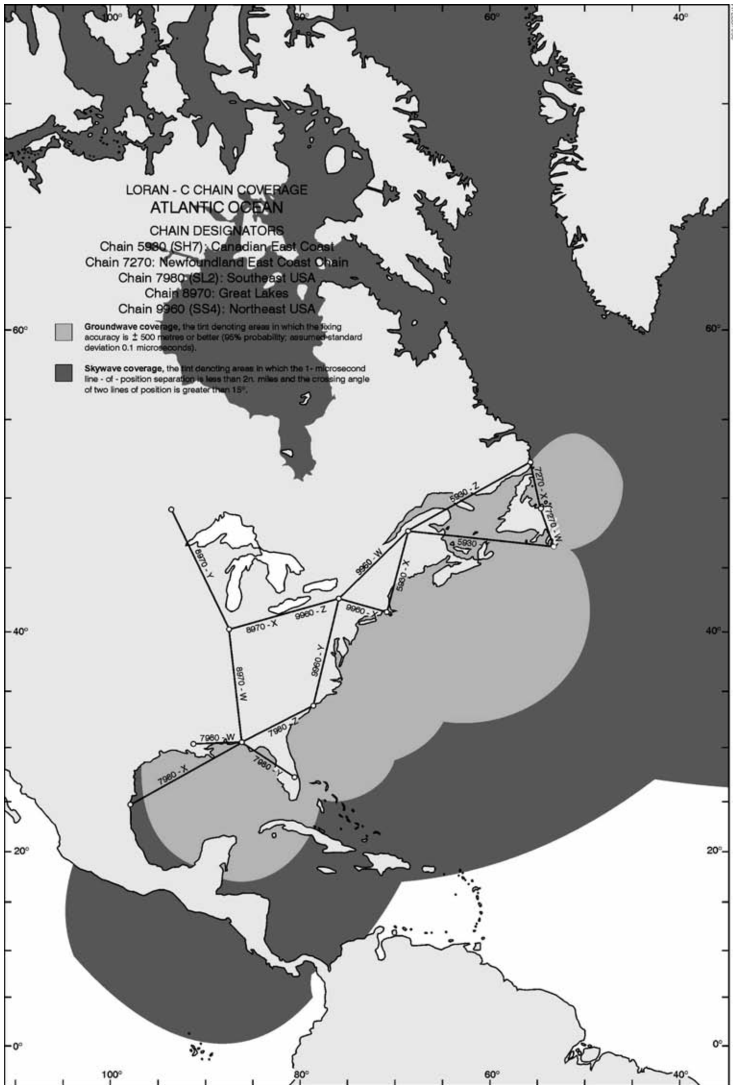

Figure 4.20b (continued).

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.

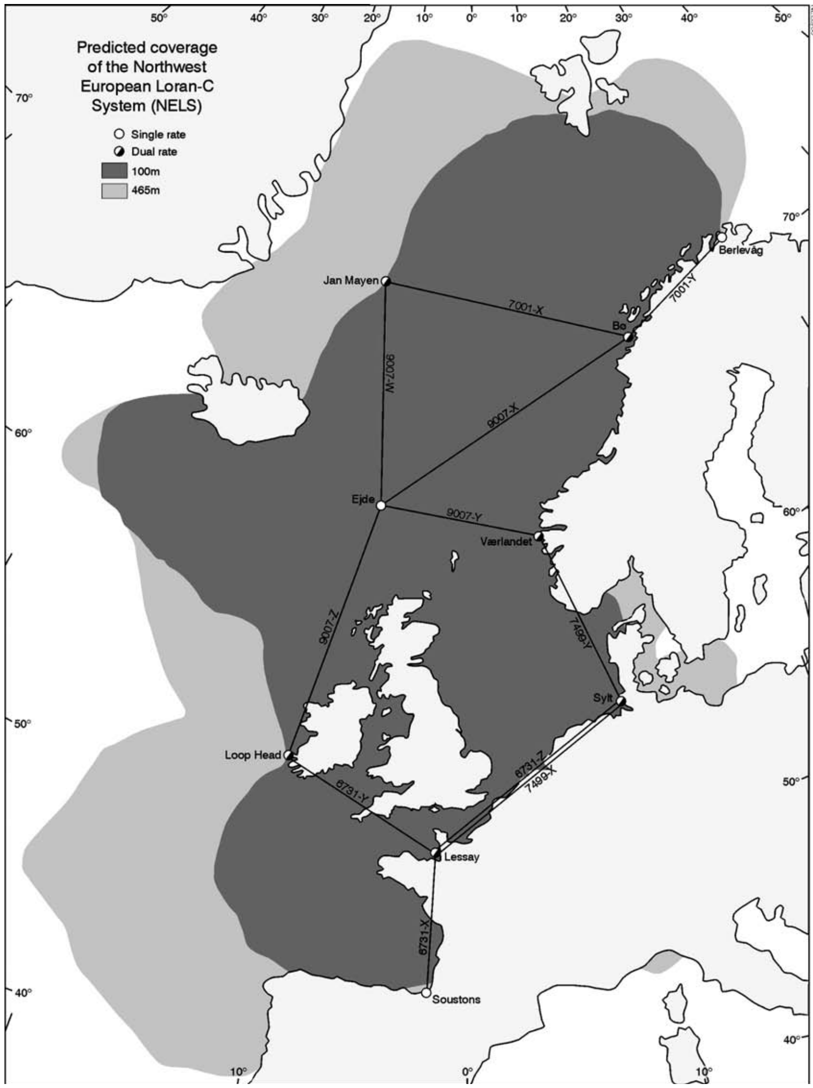

Figure 4.20c (continued).

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

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

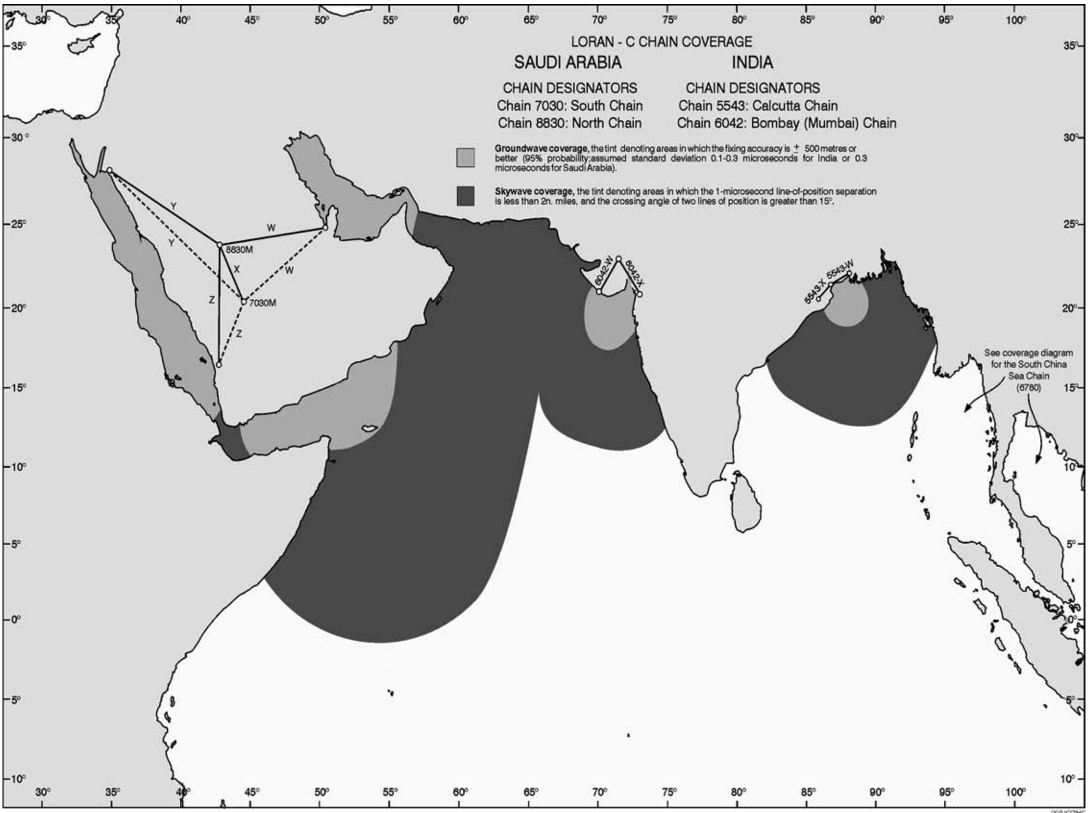

Figure 4.20d (continued).

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 have been extinguished, the function switch should be placed in NORM position to inhibit cycle selection of all stations and to enable certain functions of +/MEMO and –/RECALL (see under the appropriate heading for a description of these functions). Setting the function switch in either Sl, M or S2 position allows the time difference of the selected station to be manipulated using the +/MEMO and –/RECALL controls.

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

+/MEMO

- With the function switch in TEST and +/MEMO pressed, the display will indicate the oscillator offset frequency. Pressing the button again will restore the normal technical information to the display.
- With the function switch set to SEL, the tracking points of all stations will shift by +10 µs each time the button is pressed.
- With the function switch in NORM, pressing the +/MEMO button will ‘freeze’ the display and place all acquired time differences into memory. Pressing +/MEMO again will restore the display 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 fully clockwise.

The power switch should then be turned ON and after about 4 s both displays should sequentially indicate all secondaries acquired. When the required time difference appears on the display, the wanted secondaries can be selected by pressing display control S1 and S2. When the settling alarms are no longer alight the function switch should be set to NORM. The unit will then have acquired the 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' position, it indicates the centre of the loran frequency and the tune meter should indicate a reasonably large deflection. When rotated either side of the central position, the tune meter should indicate a smaller 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 sharply reduce the signal level of any frequency if the filters are tuned to that frequency. Thus, if Tune control finds any interfering signals in the frequency range of the loran signals, the notch filter controls may 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 tune 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 meter. 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 anticlockwise direction.
(e) Reset notch filter knob N1 to the centre position and slowly rotate it anticlockwise until the meter deflection is minimized.
(f) Check that the meter deflection for the interference signal is less than the loran signal and if not, 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 the 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 meter deflection is minimized.
(i) Use the notch filter N4, by turning it clockwise from its centre position, if the use of notch filter 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 of 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 flashing. 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 automatically 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.

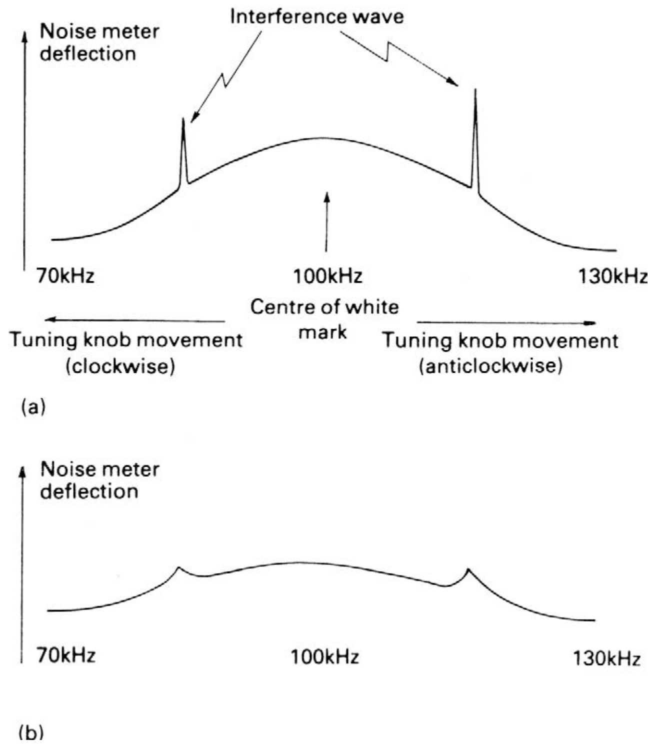

Figure 4.22 (a) Possible interference levels prior to adjustment of the tuning controls.(b) Possible interference levels after adjustment of the tuning controls. The interference level should always be set to less than the level of the loran signal.

(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 8 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

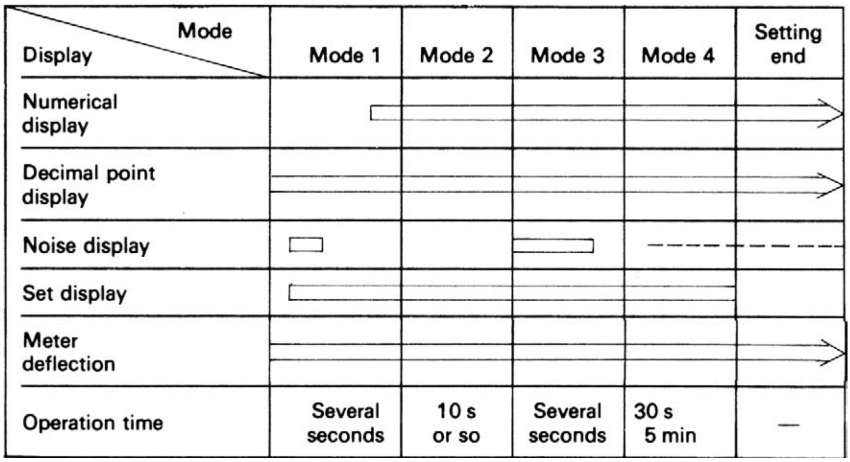

Figure 4.23 Initialization and lighting/extinction of indicator lamps.
Notes: (1) It is possible that if the signal level is lower than -20dB or the S/N ratio (SNR) is very low, mode 1 will not proceed to the next stage, and no display appears. (2) The noise indicator lamp may light during mode 4 operation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

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.

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

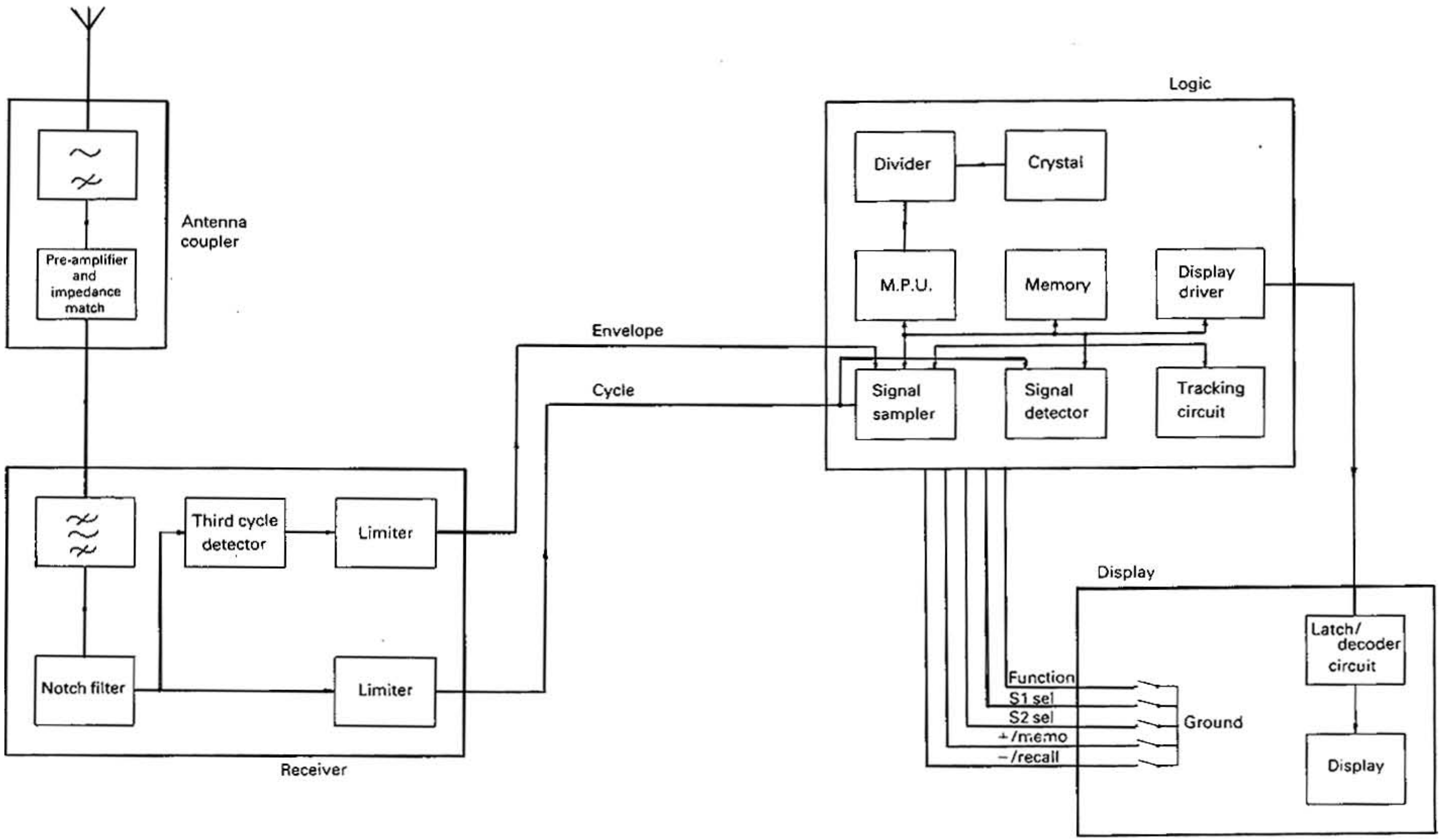

Figure 4.24 Basic block diagram of Loran-C receiver.

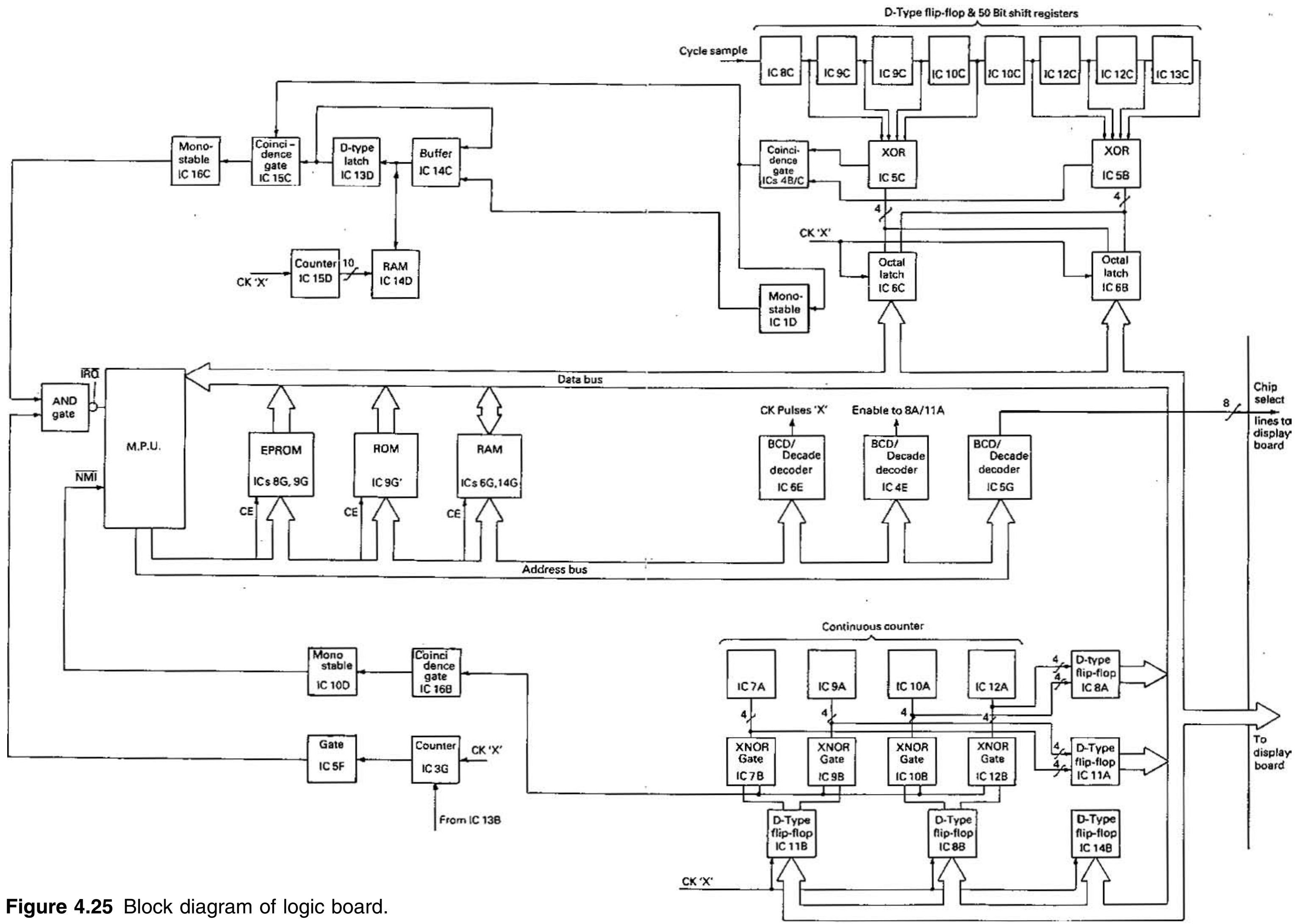

Figure 4.25 Block diagram of logic board.

clocked through the shift registers using a clock-pulse duration of average value 20 µs, so that for each pulse period of the received pulse train of 1000 µs there are 50 bits. These bits are shifted continuously through the registers recording the presence, or absence, of a pulse as the case may be. As an example, considering master transmissions only and with a GRI of, say, 79600 µs, then after the reception of the eighth pulse (ignoring the ninth pulse for the moment) there is a time difference of (79600 – 7250) µs or 72350 µs, before the next pulse is received. Obviously the receipt of secondary station signals will occur during this period.

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

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

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

For the receipt of a master pulse train the CPU can cause the A and B code to be latched into a D-type octal latch. The required code could be output and compared with a sample from each of the 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 quad XOR gates that is logic ‘0’ and this, through the gate circuit shown, results in a logic ‘1’ output from the gate circuit. The coincidence output is shaped by a monostable circuit and fed via a buffer circuit 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,

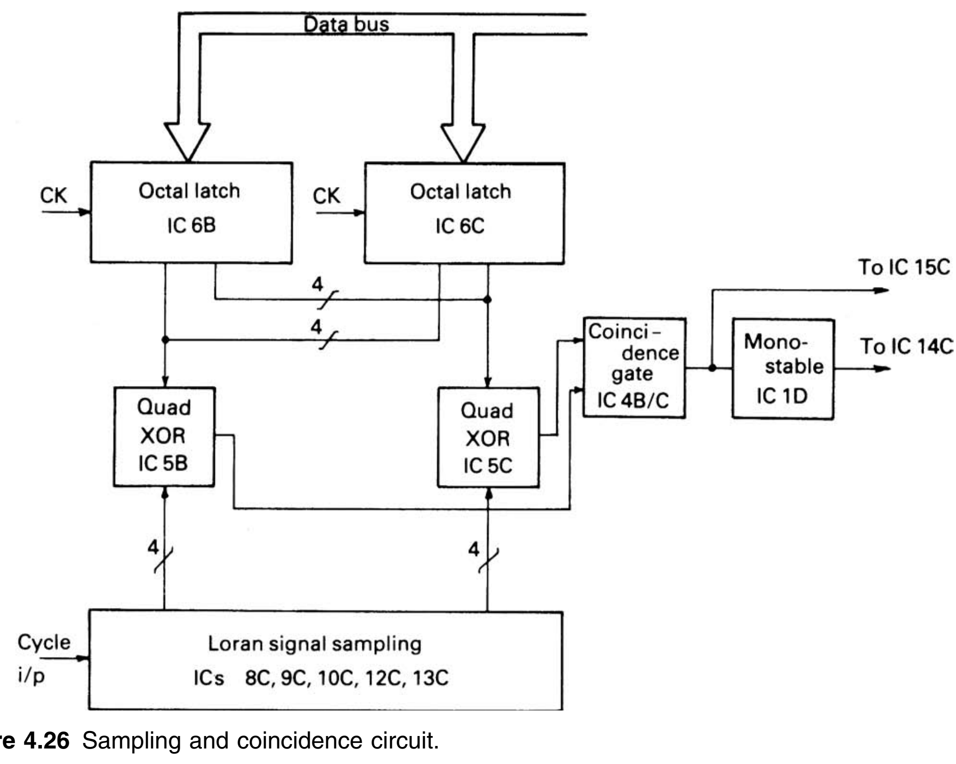

Figure 4.26 Sampling and coincidence circuit.

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 GR1 can be represented within the memory since no GRI exceeds 99 900 μs and the counter is reset every GRI.

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).

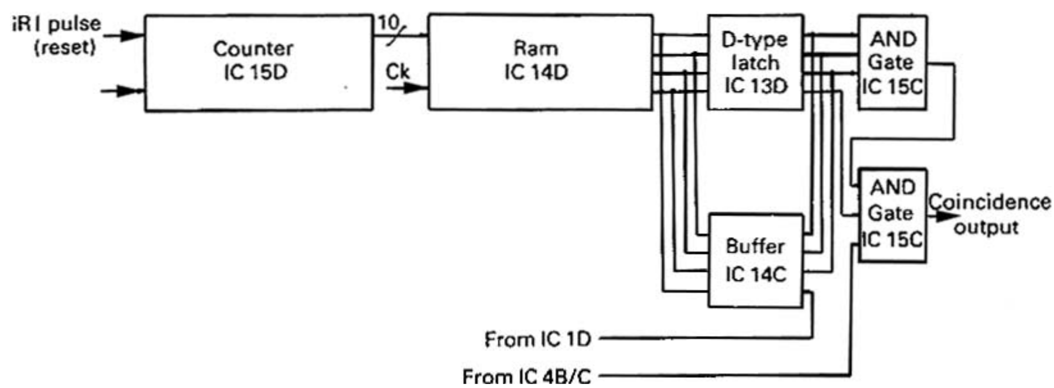

Figure 4.27 Production of coincidence (IRQ) circuit.

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.

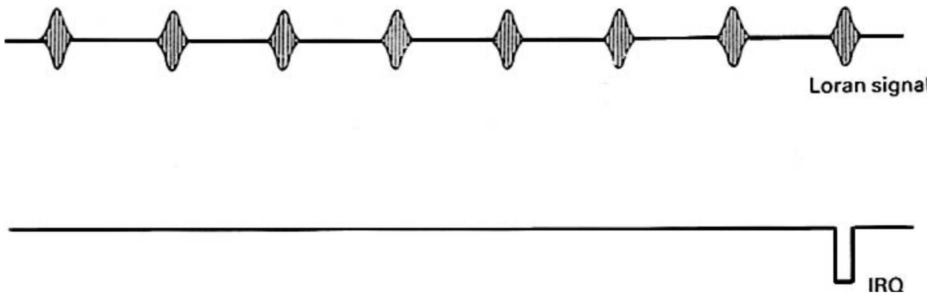

Figure 4.28 Timing of IRQ pulse with received loran signal.

The MPU outputs the GRI pulse which resets the counter (IC 15D) ready for the next GRI input data sequence. The coincidence output (GRI signal) is also used to latch the outputs of a continuous 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, 1lB 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 continuous 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

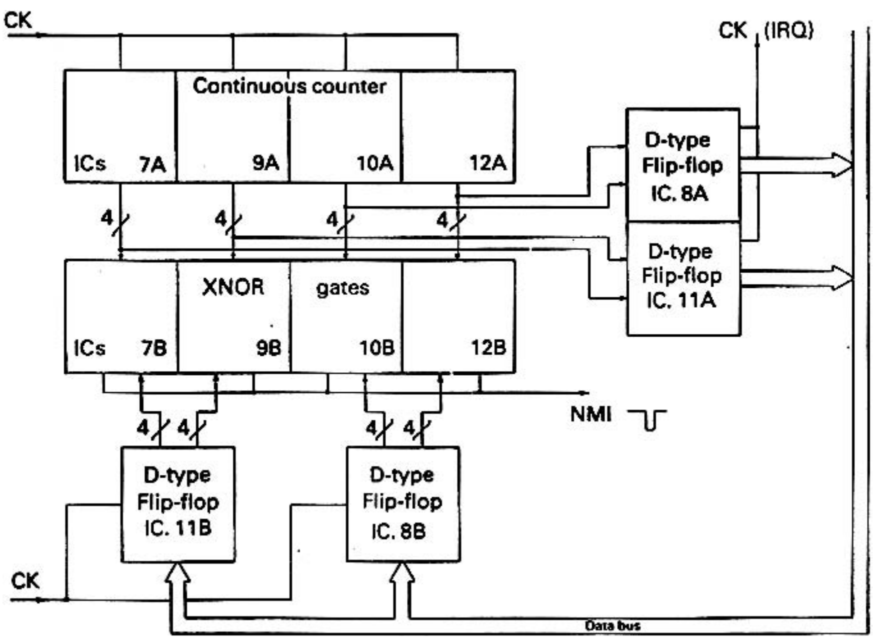

Figure 4.29 Production of the NMI interrupt pulse.

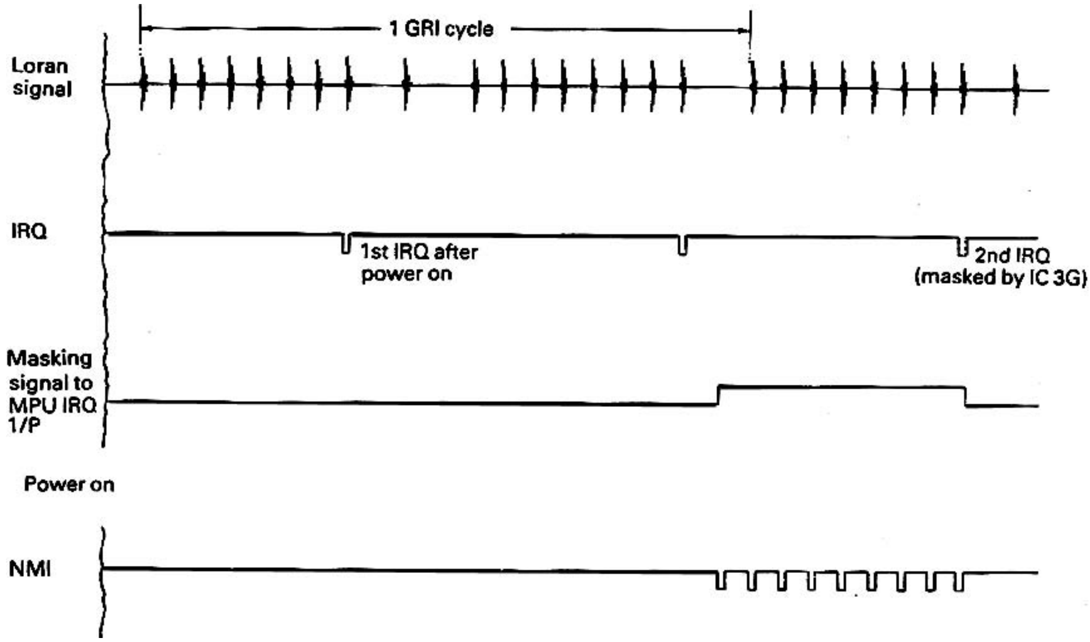

Figure 4.30 Timing diagram showing the 'masking' of the IRQ input when NMI is generated.

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

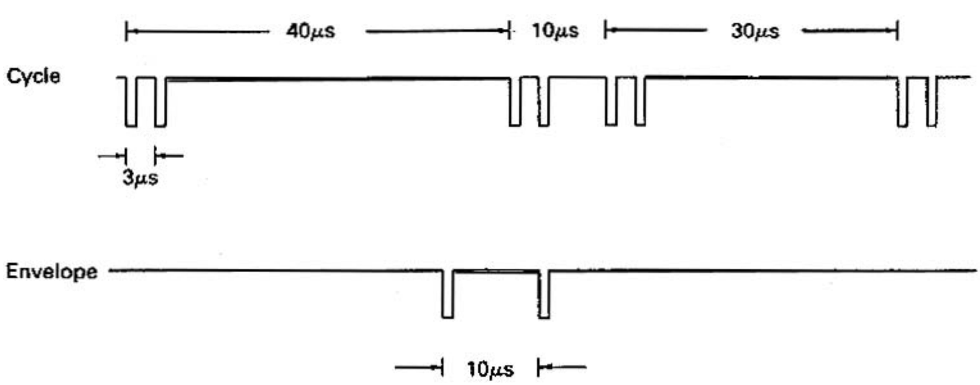

Figure 4.31 Timing diagram for loran signal sampling.

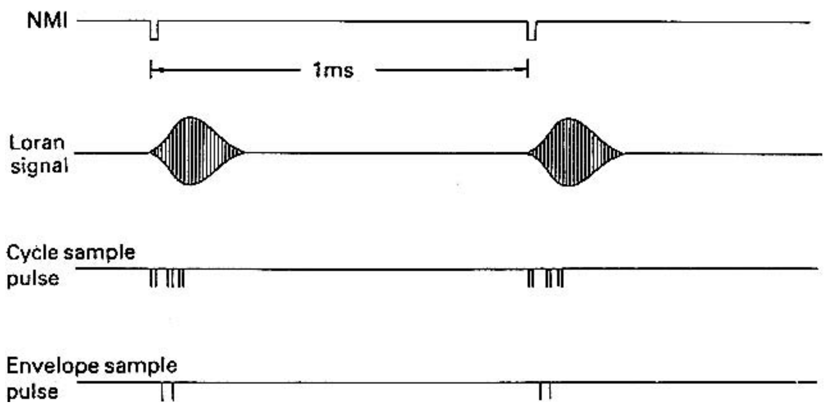

Figure 4.32 Timing sequence for NMI pulses.

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 decoder. 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.

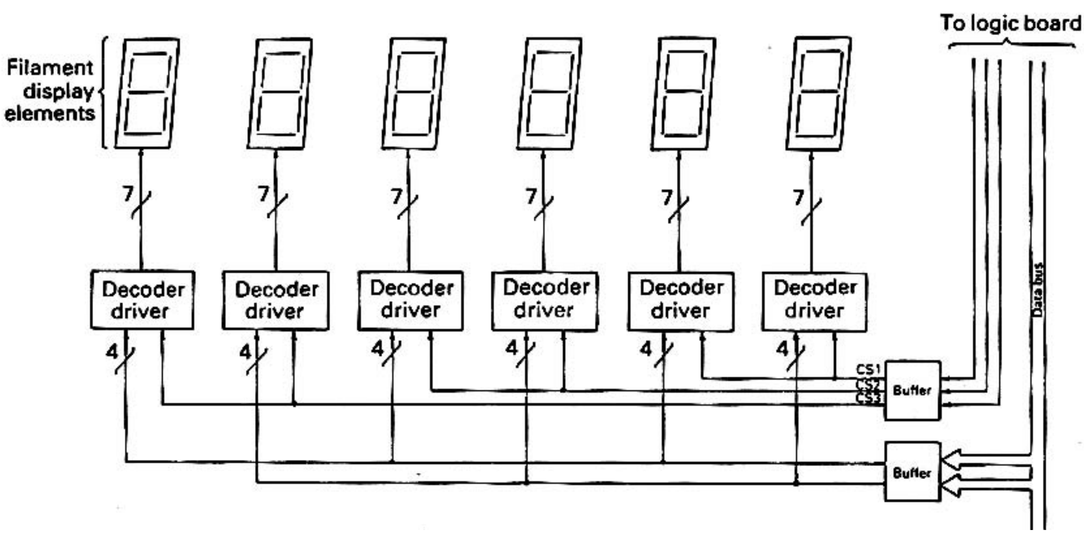

Figure 4.33 Display elements, buffers and drivers.

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

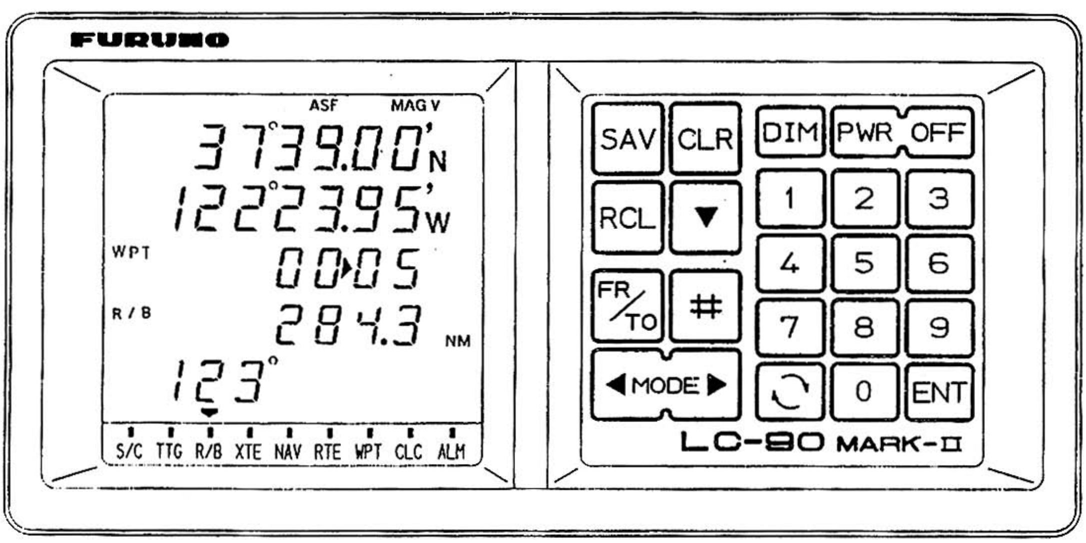

Figure 4.34 LC-90 MkII front panel layout. (Reproduced courtesy of Furuno Electric Co. Ltd.)

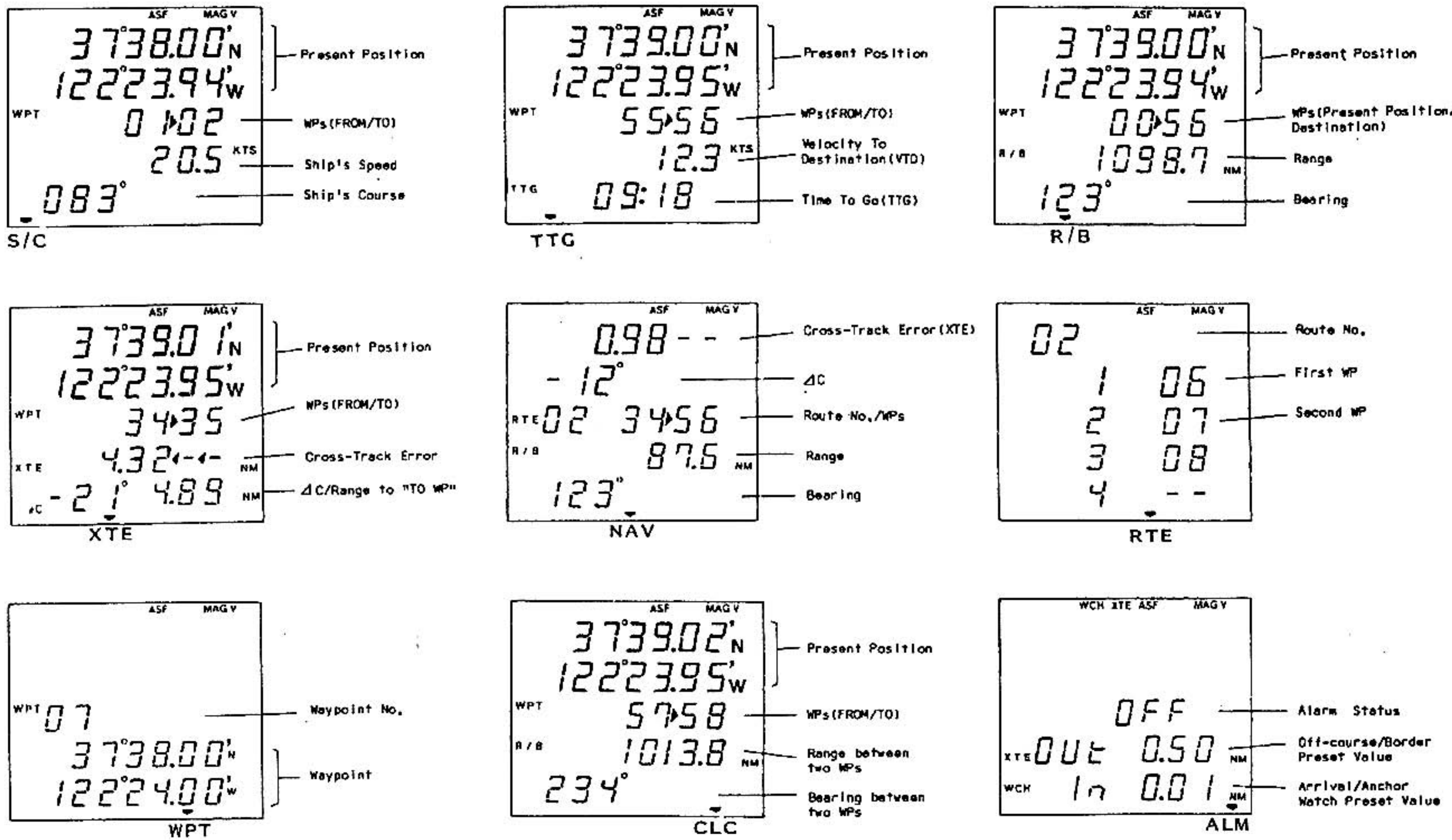

Figure 4.35 LC-90 MkII typical mode screens. (Reproduced courtesy of Furuno Electric Co. Ltd.)

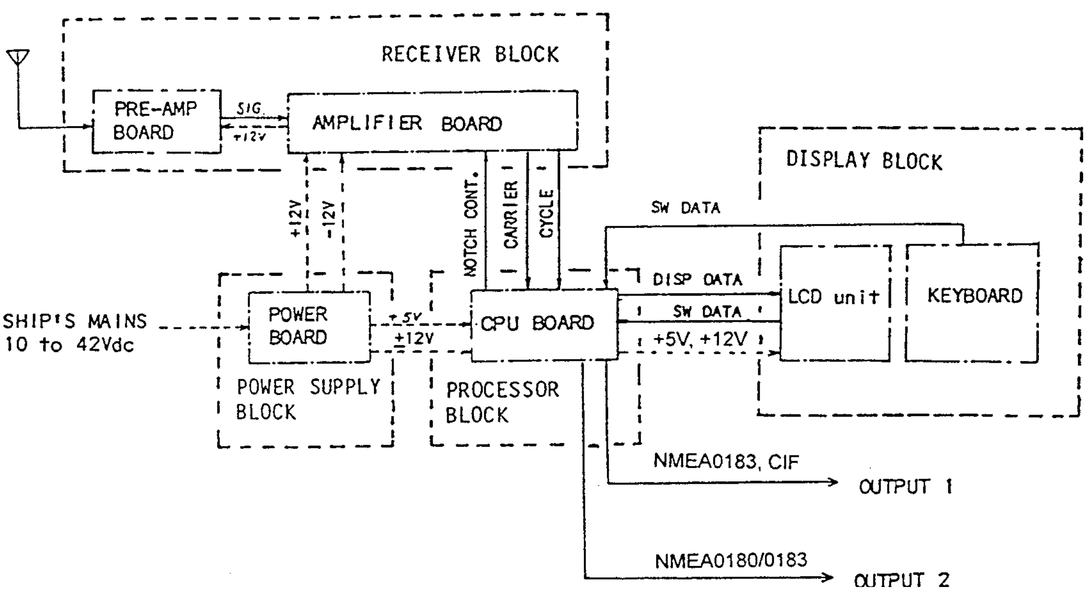

Figure 4.36 Block diagram of the LC-90 MKII receiver. (Reproduced courtesy of Furuno Electric Co. Ltd.)

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, notch 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 $2d_{RMS}$ 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 $\times 10^8\,ms^{-1}$?
[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 $3 \times 10^8\,ms^{-1}$, 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 $\times 10^8\,ms^{-1}$?
[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 $2d_{RMS}$? 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 4.24, describe the basic function of each block.

19 Using the logic board diagram and the sampling and coincidence circuit diagram of the Koden Electronics LR-707 receiver shown in Figures 4.25 and 4.26, respectively, describe how the 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 receiver, such as the Koden Electronics LR-707, and a more modern receiver, such as the Furuno LC-90 Mk-II. Comment on any major differences.