LORAN C [*]

A PRACTICAL INTRODUCTION TO THE OPERATION AND PERFORMANCE OF THE SYSTEM

by C. POWELL and A.R. WOODS
(The Decca Navigator Compagny)

---

1. — Introduction

The Loran C radio position-fixing system has been described in technical detail at international conferences and elsewhere. This paper tries to convey the general " feel " of the system and its characteristics and to indicate, with as few irrelevancies as possible, what sort of process makes the two readout counters go round and give the navigator his position fix. The equipment to which the paper refers is the AN/SPN-31 marine Loran C receiver, which was designed and produced by Decca to a U.S. Bureau of Ships specification. Individual makes of Loran C set differ in various ways, but SPN-31 will serve for illustrative purposes.

Like other members of the Loran family and the Decca Navigator, Loran C provides a position-fix by the intersection of two hyperbolic position lines. Along each such line the signals from two stations (master and slave) arrive with a constant time difference; assuming the speed of radio wave propagation to be constant, we say that a constant difference in arrival time connotes a certain constant difference in the distance from the receiver to the two stations. The master and slave stations are therefore the focal points of a pattern of hyperbolic position lines drawn on the Earth's surface. Hyperbolic fixing was first used — in reverse, as it were — in the 1914-18 war, for locating enemy guns by comparing the arrival time of the sound at spaced microphones. Its adoption for radio navigation springs partly from the high positional sensitivity that derives from the wide spacing between the focal stations, and partly from the self-evident ability of such a layout to serve a wide area.

2. — Pulse and continuous wave methods

There are two ways of measuring the time difference in the arrival of a pair of synchronized radio signals so as to get a hyperbolic position line. One involves sending the signals in the form of pulses and measuring the difference in their arrival time directly; this is the basis of Loran A and of the Gee system. The other method is to transmit continuous sine-wave signals by some method which allows the receiver to extract a signal of the same frequency from each station, and then to measure the time difference in terms of the difference in phase between the two. This is done in the Decca Navigator and its derivatives, and in the various hyperbolic surveying systems that owe their origin to the work of Honoré in France. Loran C (and its shorter-range derivative Loran D) gains the best of these two worlds by using the pulse and the continuous wave method in combination.

To summarize the advantages of the two techniques, the pulse method presents no ambiguity, if we discount that which obtains in any hyperbolic system through the symmetry of the position-line pattern about its baseline; the pulse method also offers the possibility of eliminating the unwanted skywave mode of propagation. On the other hand, phase comparison systems can measure time difference more accurately, they occupy less space in the radio-frequency spectrum, and they can use transmissions of relatively low power.

Turning to the disadvantages, pulse systems have a rather low information content with respect to time — one can say that for most of the time no information is radiated at all — and the transmissions have to be of high peak power and cover a wide frequency band. The continuous-wave phase comparison systems contain no means of distinguishing the skywave from the groundwave and thus suffer severe derelection in performance when the signals received by the two modes are other than widely different in strength, and they are inherently productive of ambiguities. Obviously an amalgam of the two methods has much to offer, and this was foreseen [1] as long ago as 1945; that a practical system on these lines did not emerge for many years thereafter is perhaps a measure of the technical difficulties involved.

3. — The Loran C pulse

Figure 1 (a) shows what the master and slave stations each transmit : namely, recurring pulses of 100 kc/s carrier wave, rising to peak value as rapidly as engineering expertise will permit and then falling off to give a total duration of some 250 to 350 microseconds — the trailing edge of the pulse is of little interest to the navigator, as will be seen later. Such pulses follow each other in rapid succession, but the rate at which they
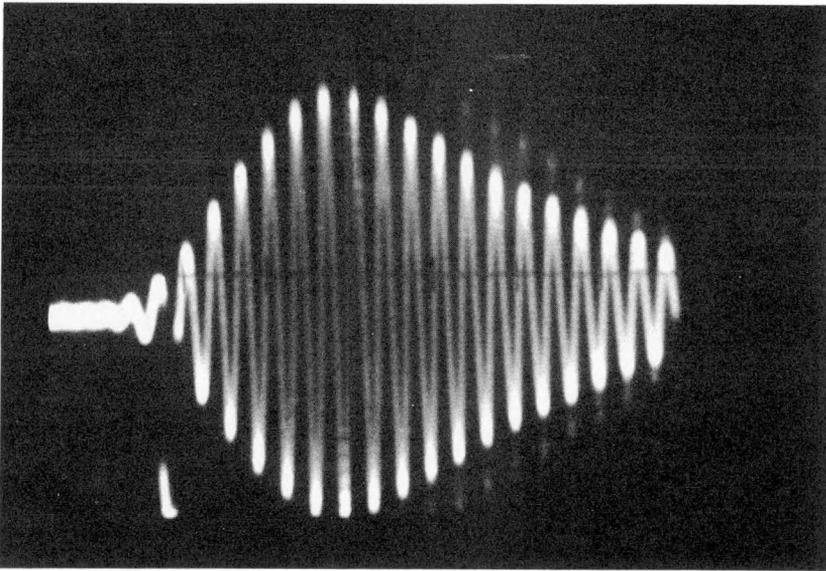
Fig. 1 (a). — Pulse signal seen on receiver c.r.t. at short range from station, showing gate pulse (referred to later) on third cycle.

do so has no bearing on this description (the rate does in fact differ for each Loran C chain and is the means of identifying a chain). We can get a feel for how the system works by considering just one pulse from the master and one from the slave and " take it as read " that the process goes on continuously.

From a given station this pulse will arrive at the receiver by two routes : directly over the surface of the Earth (the groundwave) and by reflection from the ionosphere (the skywave). The groundwave path is obviously the shorter and the more stable, and the object of the system is to extract the time and phase information from the groundwave pulse during the short initial period before the skywave signal has had time to arrive (see figure 1 (b). To be certain of discriminating against the skywave in this way under all conditions entails selecting the third cycle of the pulse and confining the phase-comparison measurement to that cycle; as shown in figure 2, the skywave can start to arrive less than 40 microseconds after the groundwave. One of the penalties of this method of eliminating the skywave is that at the third cycle the pulse has not had time to reach its peak value, but this sacrifice is worth making if one can expect a position-line accuracy corresponding, let us say, to a standard deviation of better than 500 ft at 500 miles from the stations irrespective of time or season.

Before considering how the equipment works, it is worth looking at what the transmission of a steep-fronted pulse of 100 kc/s means in terms of frequency spectrum usage (figure 3). The points are plotted from a recording made at the Sylt Loran C station by the U.S. Coast Guard and show the signal occupying the whole of the allotted band from 90-110 kc/s
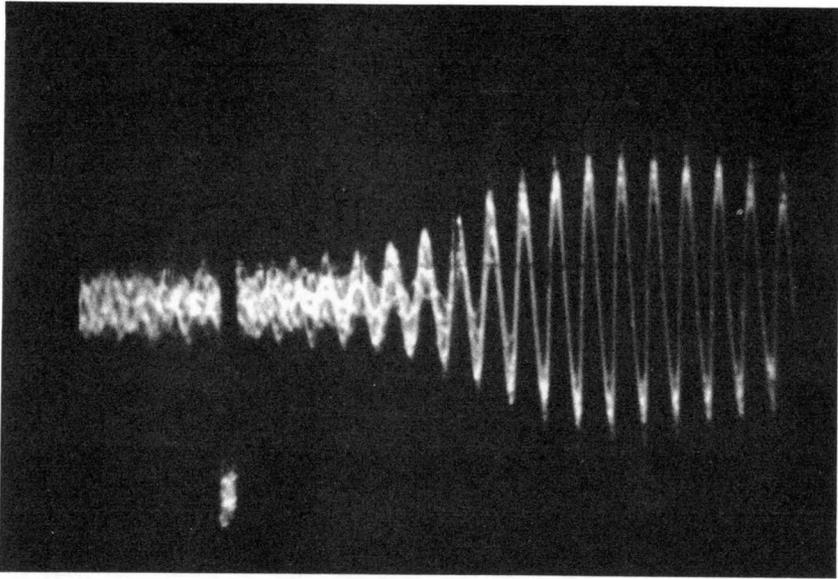
FIG. 1 (b). — Signal received at long range, with strong skywave component
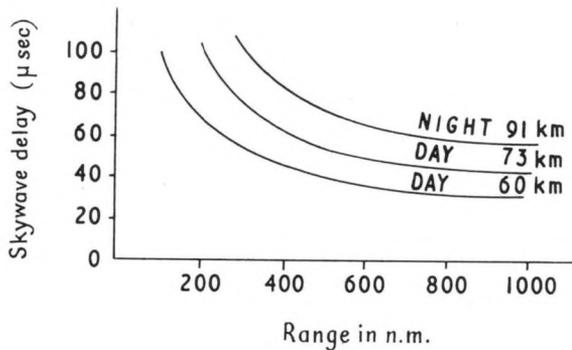arriving after gate pulse.

FIG. 2. — Average delay of single-hop skywave for three ionosphere heights
(60 km height applies only to high northern latitudes).

and rather more in addition. Interference with other services has tended
to retard the deployment of Loran C, especially in Europe. Similar records
taken on panoramic receivers at distant monitor stations show the unmo-
dulated Decca transmissions as a series of vertical lines representing their
spot frequencies. The Decca frequencies, particularly those of the red
stations near 113 kc/s, are such that Decca receivers can be interfered
with the Loran C transmissions, but this is generally confined to areas
close to the Loran C stations; from the Decca point of view it is indeed
an advantage thot Loran C sends no information for most of the time.
Even so, Loran C transmissions are now in the process of being equipped
with " holes " at the Decca frequencies which are only a few cycles wide
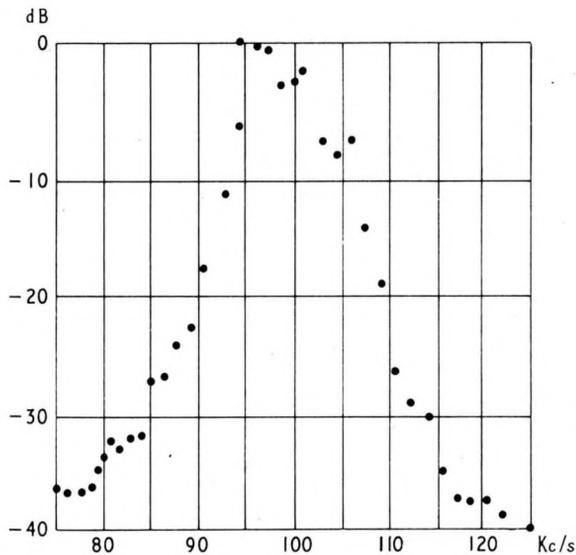and do not materially affect the shape of the Loran pulse.

Fig. 3. — Approximate envelope of radiated spectrum at Sylt Loran C station.

4. — The position-line pattern

Figure 4 shows master and slave on a 1 200 km baseline, which is a fairly typical length. Above the baseline are marked the time differences that would obtain if the two stations sent their pulses at the same instant, as one tends to imagine them doing when starting from first principles. The biggest time difference would then be 4 000 microseconds (we never talk about milliseconds with this system), at the extensions of this length of baseline. In practice, however, sending the two pulses together would result, near the axis, in time differences too small to measure, and also the receiver would not know which signal was the first to arrive. It is therefore arranged that the master always transmits first and the slave follows it, after a so-called coding delay, sufficiently late to ensure that nowhere in the coverage could the slave signal arrive before the master. Typical numbering in microsecond units, for a practical chain, is shown below the baseline. At the bottom are drawn some position lines at the 100 microsecond intervals which are adopted for the majority of Loran C charts. Such an interval represents 15 km on the baseline. The 100 microsecond intervals are sometimes further divided into 50 microsecond units, as shown.

Certain Loran C receivers provide the position line by two discrete measurements and readouts : a coarse determination which measures the difference in arrival time of the leading edge of the pulse envelopes, and a fine measurement which compares the phase of the third cycles. In the SPN-31 receiver, the phase comparison is the basic measurement and a servo-driven shaft rotates in response to the 100 kc/s " lanes " and drives

Time differences (μsec.)
if M & S pulses were sent
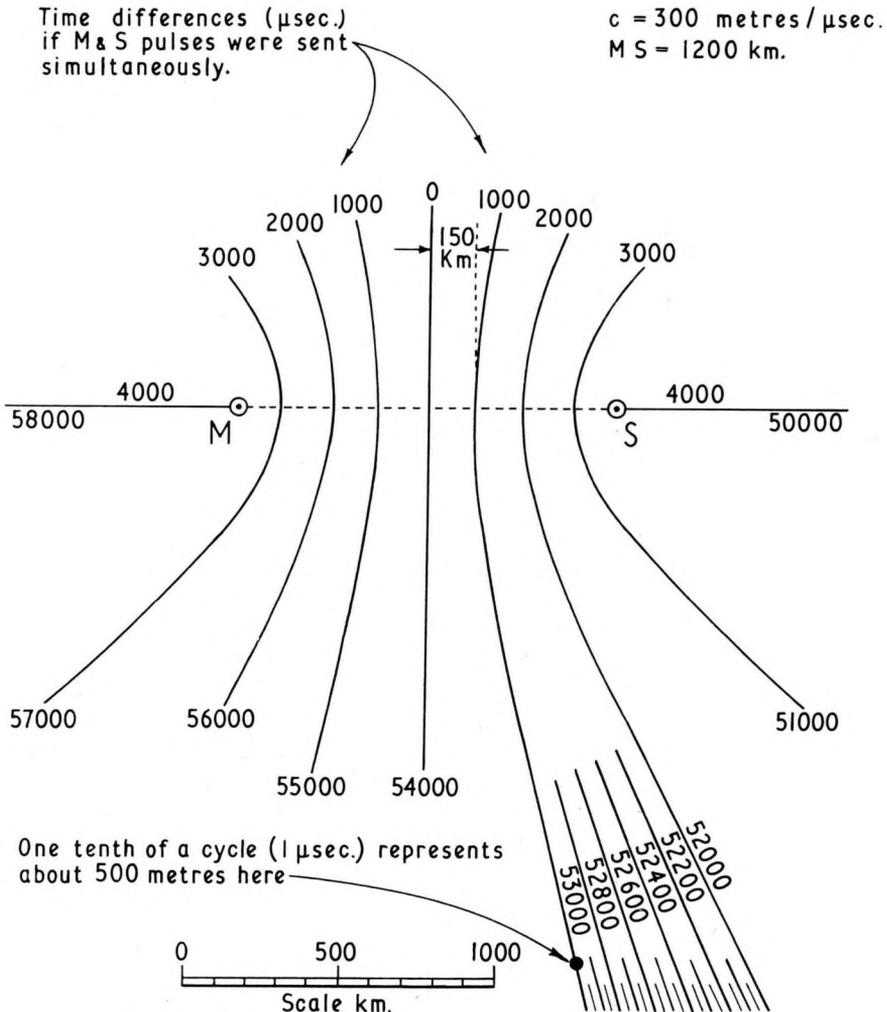simultaneously.

c = 300 metres / μsec.
M S = 1200 km.

FIG. 4. — Typical Loran C pattern numbering (microseconds).

the whole readout mechanism, as will be shown later. The unambiguous property of the pulse comparison is, of course, retained but it is used in conjunction with meter and warning-lamp indications rather than with the actual readout.

A whole cycle at 100 kc/s occupies 100 microseconds, and on the baseline this represents a distance of 1 500 metres. The fine counter can be read to better than one hundredth of a cycle. The length of the base-lines in relation to the area covered is such that lane expansion is gene-rally not greater than a factor of about 4. At a point in the Atlantic at 50 N. 25 W., which is roughly 1 000 n.m. from the three stations of the Norwegian Sea Loran C chain at Iceland, Faroes and Sylt, one whole cycle or lane of either pattern is only about 3 n.m. wide. The possibility that the readout might be in error by one whole cycle, which sometimes arises

as discussed below, would not therefore necessarily represnt an unacceptable error in navigational terms.

5. — Time-difference measurement

The process of reading the two time-difference values needed for a fix involves no manipulation and can be as continuous as the operator likes (in contrast with earlier Loran A equipment, in which only one position line could be determined at a time). Figure 5 shows the method, reduced to its barest essentials, by which the receiver measures the master/slave time difference and drives the 5-digit readout. To do this, it generates a train of narrow " gate " pulses which recur at a precisely-known frequency, and may be said to use these as a yardstick by counting the number of pulses — plus the fraction, if any, of a pulse interval — that fall within the time interval to be measured.

The gate pulses recur at 10 microsecond intervals, i.e. at a pulse reccurrence frequency of 100 kc/s, and are the divided-down output of a stable
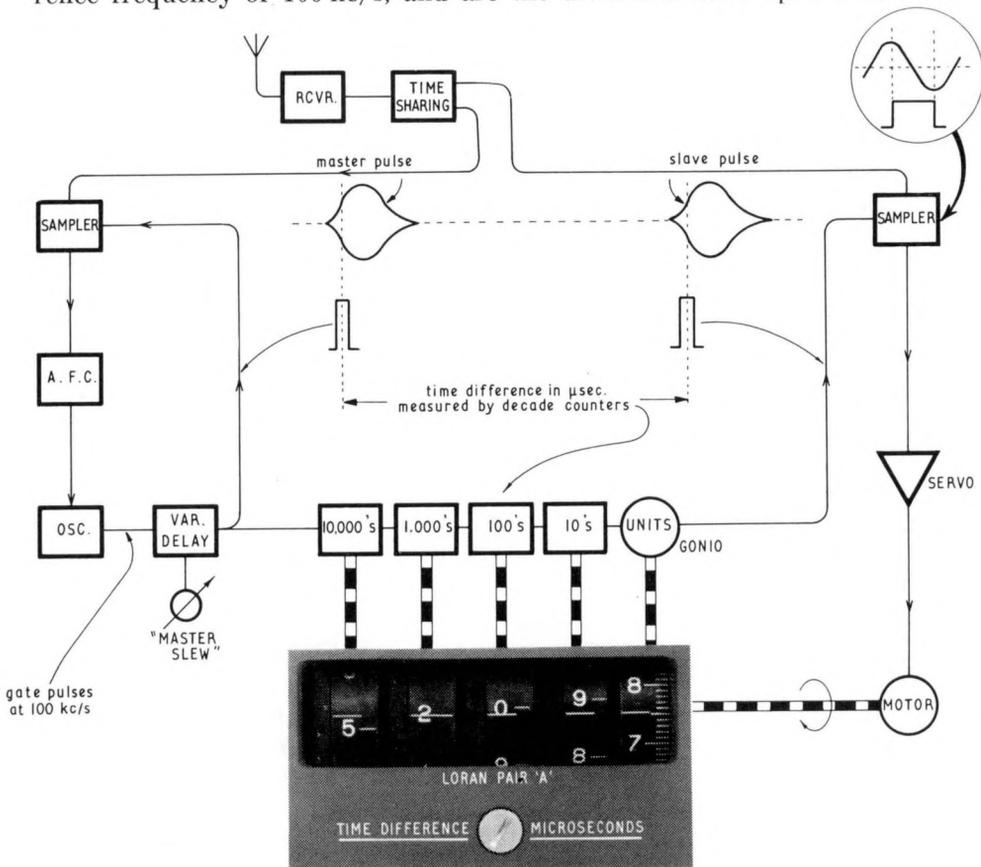

FIG. 5. — Loran C receiver AN/SPN-31 : method of deriving position line.

oscillator working at 5 Mc/s. The oscillator is frequency-locked to the incoming master signal, by the servo loop shown on the left, and as part of this process a gate pulse is held in time coincidence with a cycle (identified as the third cycle by the separate " indexing " process described later) in the received master pulse envelope. The gate pulse is initially brought into approximate coincidence with the master pulse either by an automatic " slewing " process or (more rapidly) by the manual control shown in the diagram. The basic measurement is of the time delay between the master gate pulse and a corresponding gate pulse locked to a cycle of the received slave signal, together with a fine measurement which interpolates within the 10-microsecond period.

In effect the decade pulse counters combine to select a slave gate pulse representing the delay of the slave signal with respect to the master, and the " units " phase-shifter (goniometer) brings the slave gate pulse into precise coincidence with a cycle (again assumed to be the third) of the slave carrier wave. The decimal readout indicators are geared together in 1/10 steps and each is connected to its respective decade pulse counting circuit; the readout thus displays the master/slave time difference value in microseconds, i.e. the hyperbolic position-line reading.

As the ship moves, the servo motor drives the counter assembly so as constantly to match the time difference value. The motor turns in response to an error signal which is developed in the sampling circuit as soon as the ship's movement is such as to displace the selected cycle in the slave pulse envelope by more than a degree or two of phase with respect to the gate pulse; if the latter is exactly centralized on the cycle, as shown in the inset, there is no error signal and the servo balances. The counters can be turned manually in one-tenth-revolution steps (except the fine one, which takes up its own position in exactly the same way as the fine pointer of a decometer) and thus the overall time delay figure can initially be set in by hand. Although the servo performs a useful integrating function, this is not an integrating system except in that particular sense : the coarse measurement of the time difference has to be satisfied before the fine phase comparison becomes operative, and Loran C is therefore a system which gives an essentially unambiguous hyperbolic position fix.

6. — Indexing

Conspicuous items on the front panel of the SPN-31 receiver are the three indexing meters for the master and the two slave channels. Indexing in this context means " selecting the third cycle ", and a deflection on one of the centre-zero meters warns the user that the respective gate pulse is locked to some cycle other than the third. Since the successful operation of a Loran C receiver depends largely on its ability to identify the third cycle, it is worth considering how this is achieved. It would be easy to create in the receiver some pulse train or signal that would serve as

a 30-microsecond yardstick, but the difficulty would be how to line it up with the start of a possibly weak and noisy pulse. In pratice, there is no alternative but to extract the 30 microsecond time datum from the received pulse itself. The method used is sketched in figure 6, in which (a) represents the leading edge of the " top half " of the received pulse and depicts this, between 0 and 50 microseconds, as a straight line. The problem is to pick out precisely the point on this line that is 30 microseconds from its start.
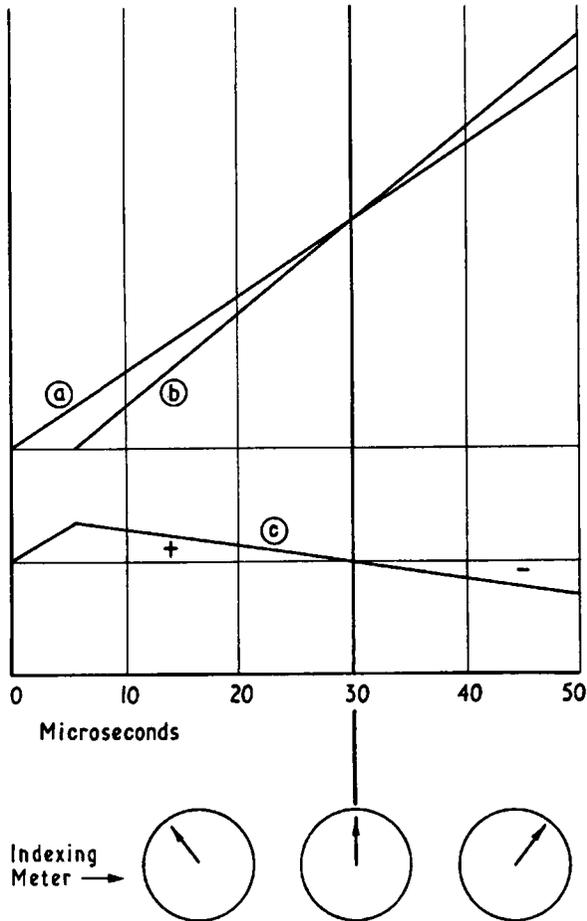

FIG. 6. — Generation of indexing control signal from received pulse. Waveform (a), representing start of received pulse, is delayed and amplified to produce waveform (b) such that the two reach equal amplitude at the required 30 microsecond point. Subtracting (b) from (a) results in the control signal (c), which operates the meter as shown.

If the envelope waveform (a) is fed into a circuit having a time delay of 5 microseconds and an amplification factor of 1.2, the output waveform (b) will have a correspondingly steeper slope and will reach equality of amplitude with (a) at the 30 microsecond point. If one signal is now

algebraically subtracted from the other, the resulting output (c) will be, say, positive up to the cross-over point; at the cross-over point, zero; and thereafter negative. Thus the cross-over point is the datum and this can be made the basis of a zero meter indication (or servo signal) which shows whether or not the sampling gate is in coincidence with the third cycle. If the gate became shifted to the second cycle, the meter would move to the left, and to the right if the gate moved to the fourth cycle. A servo performing automatic indexing would respond in the same way.

This description is grossly over-simplified — for instance, the leading edge of the pulse is far from straight — but it points to the fact that the resultant control signals at, say, 20 and 40 microseconds are only of the order of one-tenth of the amplitude of the originating signal envelope. The circuits that follow must therefore possess a high order of stability, but nevertheless the identification of the 30 microsecond point may break down in the presence of large noise signals, and at long ranges where propagation effects can distort the shape of the pulse. Thus when the signal strength is low, an error of one or more whole cycles can be introduced through one of the signals being incorrectly indexed. If master and slave were both operating on, say, the fourth cycle instead of the third there would be no error due to this cause, but the possibility of skywave contamination might then arise as it does with Decca.

7. — The operator

As in Loran A there is considerable scope for the exercise of operating skill, and the ability to observe intelligently the signals on the monitor cathode ray tube results in a degree of confidence that one would be reluctant to part with even if the equipment was otherwise made fully automatic. In very bad conditions an adroit operator can, by deliberately choosing to work " further back in the pulse ", where the amplitude is greater, preserve navigational continuity while accepting the possibility of an error due to skywave. The appearance of the AN/SPN-31 receiver may tend to give an exaggerated impression of the degree of skill involved, by reason of the number of controls and indicators, but many of these have special purposes associated with the specification of this particular set and only the two readout counters are used in the actual process of taking a fix.

8. — Phase coding

In practice the master and slave pulses are sent in groups of eight, with a ninth identifying pulse for the master group, the pulses in each group of eight being spaced one millisecond apart. This is a way of getting more information into the time available, but it also permits a process known as phase coding to be used which, among other functions,

assists in the process of initial locking-in, particularly if the set is of the type which can do this automatically. The term " phase coding " means that in a group of eight some of the pulses are based on a carrier wave having opposite phase to that of the remaining pulses. By synthesizing gate pulses in the receiver having this known polarity distribution, the effect is given of a lock which can only be opened by a key with wards and gaps in the right places.

9. — Notes on performance

Turning finally to the question of accuracy and performance, another paper would be needed to do justice to these topics, but some reference to them should be made here. Loran C has often been described as having an accuracy of one foot in a mile; in fact this sweeping generalization has proved to be not too wide of the mark for the repeatability of the SPN-31 receiver, up to ranges of several hundred miles from the stations. To take a specific example, an official trial showed a root mean square error of repeatability in the position-line measurement, measured by observations lasting some three weeks, of a quarter of a microsecond at a distance of 825 n.m. by day and 700 n.m. by night from the more distant of the two stations concerned. On the baseline, a quarter of a microsecond represents just over 100 ft and one would have expected a lane expansion factor of about 2 at the observing point; there would then be the other position line to consider, and the resulting repeatability of fixing (as opposed to the single position line) could well have been not more than 700 or 800 ft. The reduced range at night would have been due to increased noise.

Whereas Loran C scores heavily by being able to discriminate completely against the unwanted skywave signal up to distances of the order of 1 000 n.m., so securing a remarkably low level of random error, it is no less subject to systematic errors through the difference between the effective speed of propagation over land and sea, than any other such system; as with other systems, these errors — susceptible though they may be to calibration and correction — can easily be ten or twenty times larger than the random error. The range over land in the groundwave mode is in general a few hundred miles less than over sea water, and the stations are sited with due regard to this attenuation effect.

The contour in figure 7 represents a fix error of 5 n.m. at the 95 per cent probability level and is drawn mainly on the basis of the results obtained with SPN-31 receivers in aircraft rather than in ships. Several hundred flying hours' experience has been gained, largely in the course of official trials in which yardstick data have been available; no major modifications have been required in order to use this essentially marine receiver in the air other than a change in the gear ratio of the servo system driving the counters, and a change in time constant.
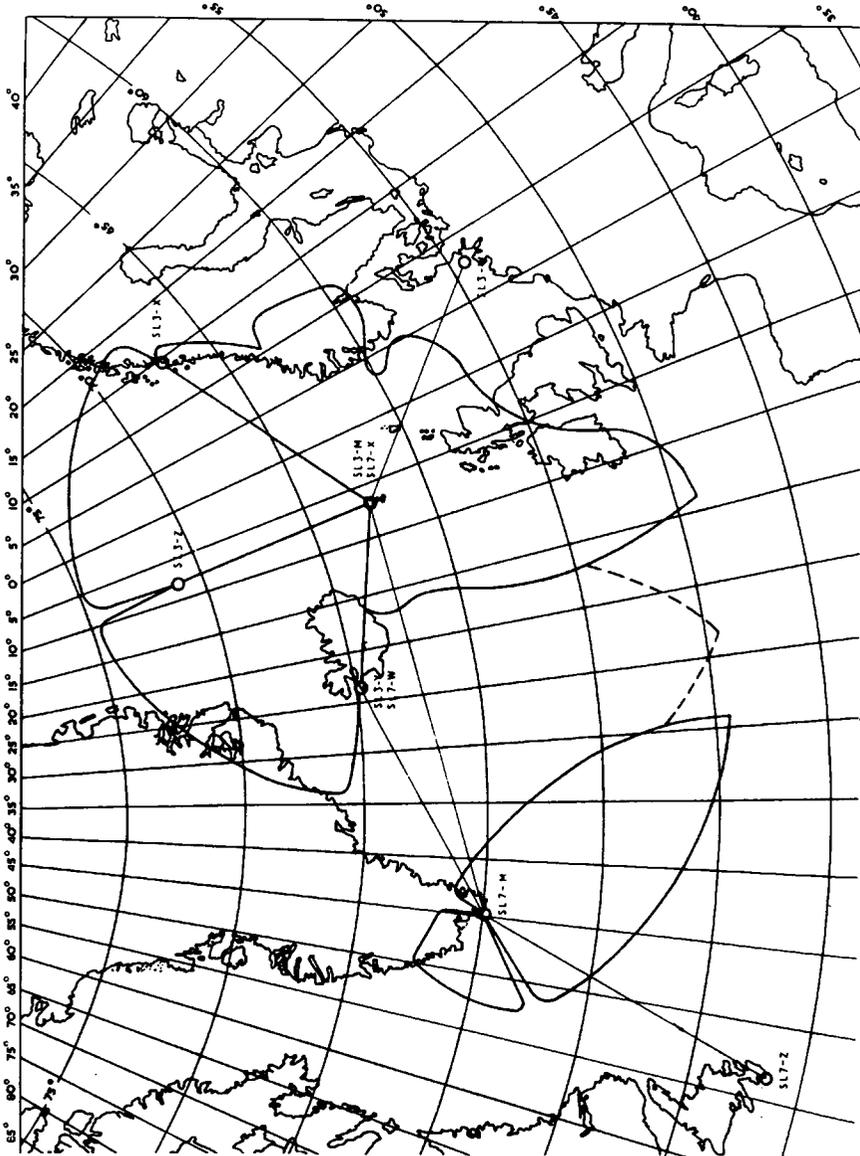
Fig. 7. — Estimated 5 n.m. (95 per cent) contour for Loran C in N. Atlantic area.
This contour is based mainly on flight tests in the area. A maximum over-sea range
of 1 000 n.m. per station is assumed, together with the presence of a 10-microsecond
error due to fourth-cycle indexing. Station deployment is as predicted for March 1966.
The dotted contour shows the coverage from Greenland-Iceland-Faroes, if this combination
is retained.

In arriving at the figure of 5 n.m. the assumption is made that at
distances beyond about 700 n.m. from the farthest station, an error of
one whole cycle is present in the master channel, but not in the slaves,
through working on the fourth cycle instead of the third : in other words,
that the main contribution to the 5 n.m. figure at the longer ranges is

an error of 10 microseconds in the measurement of the master/slave time differences through incorrect indexing. This assumption is thought to be realistic since a wide range of skill and experience on the part of the operators has to be taken into account. A skilled operator would often be able to secure third-cycle operation on all channels at the 1 000 n.m. over-water distance from the stations that the contours represent, with a large consequent improvement in accuracy — such as to turn the contour figure of 5 n.m. into nearer 0.5 n.m.

Anywhere on and inside these contours, one could expect to switch on an SPN-31 receiver, as when surfacing in a submarine, and rapidly lock it in to the transmissions with no more than the one-cycle indexing error already assumed; once the set was properly locked in, however, experience has shown that on moving outside the contours and away from the stations the receiver would probably retain integration, and third or fourth cycle operation, for several hundred miles beyond the contour limits. It is believed that some of the early reports of the very long ranges achieved with Loran C were related to the specific case of aircraft which had first locked-in when within good coverage and then moved farther away, rather than to the range at which a user could expect to lock-in when entering the coverage from outside.

10. — Summary

It is difficult, and even rash, to attempt to summarize in a few words a subject which evidently contains so many different factors, but it is reasonable to say that Loran C, as interpreted by the SPN-31 ships' recei-ver, is a " no-holds-barred " system which exacts penalties in terms of frequency spectrum usage, equipment complexity and hence cost, and operator training. In return, it can give the user his position on or over an ocean, when 1 000 miles from land, more accurately than any other technique available today.

Acknowledgments

Reference

[1] PIERCE, J. A. (1964). — An introduction to hyperbolic navigation with particular reference to Loran. *J. Instn elect. Engrs*, 93, 243-50.