THE DECCA NAVIGATOR SYSTEM FOR SHIP AND AIRCRAFT USE

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SUMMARY

The paper discusses the present use of the Decca Navigator radio position-fixing system as a marine and aircraft navigational aid. The permanent navigational service currently comprises 12 chains and some 4000 ship and aircraft installations; in addition, mobile chains are used for surveying and exploration. The absence of modulation permits close spacing of the chain frequencies. The receivers contain a reference system giving a common phase datum for all users.

The system is a c.w. hyperbolic one in which, in ships, the fixing co-ordinates are normally indicated as phase-meter (Decometer) readings. Aircraft normally use an automatic plotter driven from the receiver by an impulse-motor servo system. There are several different types of airborne receiver, and for certain airborne applications a servo system imparting an inertial characteristic to the displayed data is employed. The system can be combined with a navigational aid of the Doppler type to form the Dian system, and the Dectra long-range aid, also part of Dian, has common ground and airborne equipment with the parent Decca Navigator system. A recent development includes a zone-identification facility and employs a new form of transmission that substantially increases the range at which lane identification is effective at night.

(1) INTRODUCTION

The paper presents an outline of the Decca Navigator radio position-fixing system in the forms in which it is used, after 12 years of operational life, at sea and in the air. Reference is made to new developments, more especially in relation to the airborne use of the system. It is assumed that the reader is familiar with the general principles of the Decca system, and accordingly these are only briefly recalled.

(2) USE AS A MARINE NAVIGATIONAL AID

(2.1) Basic System

It is appropriate to consider the marine application first, since at sea the system continues to be used broadly in the basic form in which it was originally conceived: namely a continuous-wave phase-comparison system in which the phase-meter readings fix the user's position in terms of two intersecting hyperbolic position lines in a grid of such lines overprinted on a topographical chart (Fig. 1). Consider a master/slave pair of transmitting stations A and B, separated by a distance S, assumed to be sending pure c.w. signals of identical frequency and locked in phase. At a point in the coverage at a distance r_A from the master station and r_B from the slave, the phase difference will be

$$\phi = \frac{2\pi}{\lambda} (S + r_A - r_B)$$

where \(\lambda\) is the wavelength of the transmitted frequency. The locus of points at which \(r_A - r_B\) is constant is a hyperbola focused on the two transmitting stations, which can thus constitute a navigational position-line if the locations of the stations are known and the user is furnished with phase-comparison equipment.

The phase-meter (Decometer) cannot distinguish phase differences that are multiples of \(2\pi\), but the rotor, which makes one

 revolution per 360° of phase difference, drives subsidiary pointers which indicate the number of rotations made. The space bounded by two in-phase hyperbolas is known as a 'lane', and one of the geared pointers shows a change of one lane for each revolution of the rotor. The rotor has a fractional pointer attached to it which sweeps a scale calibrated in hundredths of a lane. At any position the lane reading, L, including fractional values, can be found from

$$L = \frac{S + r_A - r_B}{\lambda}$$

In practice there are several hundred lanes in a typical pattern, and for convenience they are divided into groups or 'zones', indicated by a second geared pointer and denoted by letters. Repeating this arrangement for a second pair of stations provides a second pattern of hyperbolic position-lines intersecting the first, and hence a position fix.

The effect of transmitting signals of equal frequency from the master and slave is achieved in the Decca system by assigning harmonically-related values to the two frequencies, so that multiplying circuits in the receiver can derive from each a common harmonic. Thus the 'red' hyperbolic pattern is the result of comparing the master and slave signals after multiplication to a common frequency of 24f, where f is a non-transmitted fundamental value of about 14 kcs/s. The master transmits a signal of frequency 6f and the slave 8f, the respective channels in the receiver being followed by \(\times 4\) and \(\times 3\) multiplier stages. Geometrically the system behaves as if the common frequency 24f (about 340 kcs) were radiated from the two sites. The three slave stations are phase-locked to the common master station in the centre and thus produce three intersecting patterns of position lines. (In practice, the user selects the two lines giving the best angle of cut at his location and rejects the third.) Table 1 shows typical frequency values for a Decca chain. It also gives typical

### Table 1

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Frequency (kcs)</th>
<th>Wavelength (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>6f</td>
<td>85 000</td>
</tr>
<tr>
<td>Red slave</td>
<td>8f</td>
<td>113 333</td>
</tr>
<tr>
<td>Green slave</td>
<td>9f</td>
<td>127 500</td>
</tr>
<tr>
<td>Purple slave</td>
<td>5f</td>
<td>70 833</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Frequency (kcs)</th>
<th>Wavelength (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>24f</td>
<td>340 000</td>
</tr>
<tr>
<td>Green</td>
<td>18f</td>
<td>255 000</td>
</tr>
<tr>
<td>Purple</td>
<td>30f</td>
<td>425 000</td>
</tr>
</tbody>
</table>

### Lane-width on base-lines

Assuming a velocity of 299 250 km/s

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Lane-width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>440 074</td>
</tr>
<tr>
<td>Green</td>
<td>586 765</td>
</tr>
<tr>
<td>Purple</td>
<td>352 059</td>
</tr>
</tbody>
</table>
values for lane-width along the inter-station base-lines, for an assumed velocity of 299 250 km/s; the interpolation to one-hundredth of a lane (or better, depending on the type of receiver used) can be realized in practice, and corresponds to a change of position of about 5 yd along the master/slave base-line.

Fig. 2(a) shows the main elements of the Decca receiver, the basic principles of which have already been fully described. The r.f. amplifier channels are followed by multiplier stages which distort the sine-wave input and select the appropriate harmonic. The phases of each pair of common harmonics are compared in a 4-diode discriminator, the d.c. output of which is amplified and passed to the Decometer field coils in the form of voltages proportional to the sine and cosine of the phase difference. Differential phase errors occurring through changes in the capacitance of the receiver aerial are balanced out in an aerial input network. Care is taken to balance out changes of phase with temperature and with different levels of amplifier gain; the test specification for a standard Mark V marine receiver allows a maximum mean phase shift for the three 'colours' of ± 0.02 lane (± 7.2° phase) over the range of signal inputs from 10 μV to 100 mV. About half this tolerance is permitted in the receivers used for hydrographic surveying (see Section 2.6).

Residual differential errors in the r.f. and subsequent sections of the receiver itself are corrected by the reference system, in which a local oscillator, frequency-controlled by the master signal, generates pulses at a recurrence frequency f, the steep-fronted pulse is such that the fifth, sixth, eighth and ninth harmonics of f, i.e. the Decca carrier frequencies, are substantially equal in amplitude and have a fixed phase relationship. When applied to the receiver input in place of the aerial, the reference signals form a phase datum whereby all three Decometers read zero in the absence of error. The zero reading is restored by a manual adjustment of the Decometer stator or, in survey-type receivers, by adjusting a phase-shifter in the receiver. The reference facility also ensures uniformity of reading between individual receivers and is included in the receiving equipment at the slave stations as a datum for the phasing of the patterns.

A particular characteristic of all the receivers, and indeed of the system itself, is relevant to some of the developments outlined later, namely the unmodulated nature of the transmissions and hence the very narrow receiver passband. A bandwidth of ± 30 c/s at half-amplitude is typical. Each of the four r.f. channels in the receiver contains a series-acceptance crystal filter, the appropriate crystals being brought into circuit by turning a chain selector switch to receive the desired chain. To gain supplementary discrimination against the unwanted Decca chains within range, the same switch connects the spare crystals in the receiver as rejectors: Fig. 3 shows a typical overall selectivity curve for a purple channel in a 9-chain receiver using this standard technique.
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Fig. 3.—Typical overall r.f. response curve for 9-chain Decca Navigator receiver, switched to receive chain 5 (Table 2).

Numbers on curves refer to chain designations.

One of the benefits deriving from pure c.w. transmission is, of course, the number of chains that can be accommodated in a small part of the frequency spectrum. Table 2 shows the frequencies assigned to the eight chains forming the present permanent European service and to the four Eastern Canadian from which it will be seen that the 12 master stations (for example) together occupy a band of less than 1.5 kc/s. The four Canadian chains have the same nominal frequencies as four of those in Europe; a 5 kc/s separation in master frequency being assigned as a precaution against the possibility of mutual interference. In Table 2, (b) denotes that the master is assigned the nominal frequency, (a) and (c) indicating -5 kc/s and +5 kc/s, respectively.

Table 2

<table>
<thead>
<tr>
<th>Chain number</th>
<th>Chain</th>
<th>Master kc/s</th>
<th>Red kc/s</th>
<th>Green kc/s</th>
<th>Purple kc/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(b)</td>
<td>S.W. British</td>
<td>84-280</td>
<td>112-373</td>
<td>126-420</td>
<td>70-233</td>
</tr>
<tr>
<td>2(b)</td>
<td>E. Newfoundland</td>
<td>84-461</td>
<td>112-615</td>
<td>126-691</td>
<td>70-384</td>
</tr>
<tr>
<td>3(b)</td>
<td>N.W. British</td>
<td>84-645</td>
<td>112-860</td>
<td>126-967</td>
<td>70-537</td>
</tr>
<tr>
<td>4(b)</td>
<td>Swedish</td>
<td>84-825</td>
<td>113-100</td>
<td>127-238</td>
<td>70-888</td>
</tr>
<tr>
<td>5(b)</td>
<td>English</td>
<td>85-000</td>
<td>113-333</td>
<td>127-500</td>
<td>70-833</td>
</tr>
<tr>
<td>6(b)</td>
<td>W. Newfoundland</td>
<td>85-180</td>
<td>113-573</td>
<td>127-777</td>
<td>70-987</td>
</tr>
<tr>
<td>7(b)</td>
<td>N. Scottish</td>
<td>85-185</td>
<td>113-580</td>
<td>127-777</td>
<td>70-987</td>
</tr>
<tr>
<td>8(b)</td>
<td>Danish</td>
<td>85-365</td>
<td>133-820</td>
<td>128-047</td>
<td>71-137</td>
</tr>
<tr>
<td>7(b)</td>
<td>Nova Scotia</td>
<td>85-370</td>
<td>113-827</td>
<td>128-055</td>
<td>71-142</td>
</tr>
<tr>
<td>9(b)</td>
<td>French</td>
<td>85-545</td>
<td>114-060</td>
<td>128-317</td>
<td>71-287</td>
</tr>
<tr>
<td>9(b)</td>
<td>German</td>
<td>85-720</td>
<td>114-293</td>
<td>128-580</td>
<td>71-433</td>
</tr>
<tr>
<td>9(b)</td>
<td>Quebec</td>
<td>85-725</td>
<td>114-300</td>
<td>128-587</td>
<td>71-437</td>
</tr>
</tbody>
</table>

(2.2) Lane Identification

The hyperbolic patterns so far considered contain a large number of recurring lanes or phase-difference cycles, and hence an equal number of ambiguous position lines. Accordingly, the ship's position must be known at the start of a journey to within half a lane, i.e. to within a few hundred yards, so that the Deecom lane pointers can be correctly set, and reception thereafter must be continuous in order to preserve integration of the lanes. The risks of uncertainty implicit in the latter process are small, especially if regular plots are made in accordance with sound navigational practice. (Several hundred of the ships at present equipped with Decca still carry receivers giving only this basic pattern information.) However, there are many contingencies in which a built-in lane-identification system is necessary, and this has formed part of all permanent Decca chains since 1948.

The lane-identification system generates a coarse hyperbolic pattern confocal with each fine pattern in turn. The coarse pattern corresponds to the comparison frequency $f$; hence one of its 'lanes' embraces 18 green lanes, 24 red and 30 purple, i.e. one complete zone of each pattern. The effect of a signal of frequency $f$ radiated from the stations is achieved in the case of the master by transmitting, together with the normal $6f$ signal, a $5f$ (purple) signal during the $\frac{1}{2}$ sec period occupied by each identification transmission. Simultaneously, the normal purple slave transmission is shut off. An $f$ signal emanating from the master station can thus be obtained by subtraction in a mixer circuit in the receiver. Similarly, momentary transmissions of $9f$ and $8f$ together provide an $f$ signal from each slave station in turn; for red identification this involves shutting off the green transmission and sending that frequency ($9f$) momentarily with the normal red $8f$ transmission from the red slave station, and vice versa for green identification. For purple identification, signals of $9f$ and $8f$ momentarily replace the normal $5f$. The lane-identification sequence (red, green, purple) is repeated every minute with 15 sec between transmissions. The necessary regrouping of the transmissions and the switching within the users' receivers are initiated by coded frequency-shift signals from the master station.

In the Mark V marine receiver the lane-identification information is displayed on an additional phase-meter having three concentric scales calibrated respectively in 24 red, 18 green and 30 purple lanes, a function of the triggering signal just mentioned being to key the illumination of the relevant scale. Thus the rearrangement of the receiver elements during lane identification, shown in Fig. 2(b), is the same for each colour. To increase the accuracy of lane identification, a signal of frequency $6f$ is extracted from the lane-identification signals from the slave stations, by beating their multiplied values in the receiver $(24f - 18f = 6f)$, and is compared with the $6f$ master signal. This gives a pattern of lanes six times finer than those of the $f$ pattern. If this phase-difference output were to actuate a normal Deecometer, however, the rotor of the latter would make six revolutions for one revolution of the coarse pointer; to resolve this ambiguity the additional Deecometer movement, mounted concentrically with the coarse indicator, drives a 6-arm (vernier) pointer through $1:6$ gearing. The coarse or 'sector' pointer now serves only to indicate which of the six vernier pointers to read, being fan-shaped and of a width such that it must enclose one vernier pointer.

(2.3) Transmitting Stations

The general arrangement of the central master and the three outlying slave stations of a Decca chain is similar from the aerial back to the transmitters but differs in the nature of the signal sources and the method of drive. At the master, an oscillator using a quartz crystal of low temperature-coefficient, mounted in a thermostatically controlled oven, provides the basic carrier of frequency $6f$. The additional $5f$ signal transmitted for lane identification is phase-locked to the master signal. The two transmitters, each with a power output of approximately 2.4 kW, feed the aerial system through a double-wound tuning coil
having a Q-factor (fully loaded) of about 500. The aerial comprises either a vertical base-insulated tower some 300 ft high or three 168 ft towers in line supporting a T-aerial.

The slave stations have a 6/7 oscillator as the signal source, which after division by 5 is multiplied by the appropriate factors to provide the normal lane-identification frequencies (8/7 and 9/7). A sample of each signal is obtained from a pick-up loop close to the aerial coil and is phase-compared with the input signal, the error voltages thus derived being applied to reactor phase-control circuits in order to correct phase shifts taking place in the transmitters and aerial. A similar phase control is exercised on the 6/7 oscillator with respect to the received master signal, so as to lock the slave phase with that of the master. Relays complete the lane-identification transmitter drive circuit for half a second when the appropriate frequency-shift triggering signal is received from the master, and shut off the normal-pattern transmitter input when that frequency is used for the other lane-identification transmissions in the cycle as described in Section 2.2.

The transmitter drive circuits at the master and slave stations are installed in triplicate, and the transmitters are sectionalized to permit valve replacement without interrupting the service. These precautions, together with the use of automatic alarm systems and alternative power supplies, ensure a degree of continuity appropriate to a navigational aid; while the exact total duration of out-of-service time is difficult to estimate, it does not in general amount to more than 2 or 3 min for a full year of 24-hour operation. This excludes interruptions of which users are forewarned, such as a scheduled change-over to the reserve aerial system for maintenance purposes.

(2.4) Coverage and Accuracy

Figs. 4 and 5 show the coverage of the present European and Canadian chains, together with two contours of constant fixing-accuracy corresponding to the values given in Table 3. The position-fixing accuracy available to shipping varies from a few tens of yards by daytime, in areas where the geometry is favourable, to a few nautical miles in the presence of sky-wave interference at night at the nominal 240 n.m. limit of range. Information on the accuracy, performance and wave-propagation aspects of the system is extensive, and more than a decade of continuous transmission has provided a great volume of practical data.

In relation to the performance required by shipping, it is interesting to note that the largest single class of user—trawlers and seine-net vessels, now totalling some 1400—are considered as much with the accuracy or repeatability of the system as with the absolute precision of a fix with respect to the earth’s surface. Apart from the aid to general navigation that the system provides, it enables trawlers to recover any particular point in the open sea on any number of successive occasions, and thus to concentrate on localities where fishing conditions have proved favourable. Although the absolute accuracy of the system approaches to the relative in most sea areas, i.e. systematic errors are mostly moderate or capable of correction, the facility of repeatability is one of the most important contributions that the introduction of radio techniques has made to position fixing at sea; even in perfect visibility and with an abundance of known landmarks, there is no visual counterpart to the direct radio-navigation of a ship, without reducing speed or waiting for observations, to a point or along a track whose co-ordinates have been determined by previous observation.

(2.5) Interpretation

A fix can be plotted after a few minutes’ introduction by anyone familiar with reading instruments. It follows, of course, that the system should be treated as an aid to navigation and used with an understanding of its errors and limitations. Here it should be recalled that the Decca system and radar are complementary aids to navigation; ships are now generally equipped with both.

The hyperbolic chart, by means of which the Dectometer readings are transformed into navigational fixes, undoubtedly represents the simplest and cheapest analogue computer yet invented for the purpose, and the process of manual plotting is likely to remain standard practice for some time to come.
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While the construction of the charts is outside the scope of the present paper, it is noteworthy that the basic computations involved in preparing latticed charts have already been much accelerated by the use of electronic digital techniques. An obvious future development is the extension of such techniques to the receiving equipment itself, automatically reducing the hyperbolic data output into Cartesian or geographical terms, although the need for this development arises more particularly in the use of Decca for surveying purposes and in aircraft rather than at sea.

The existing marine automatic plotter, in which a pen is moved in two co-ordinates by servo-mechanisms in response to the receiver output, represents a partial advance towards 'geographical' presentation and is the marine counterpart of the airborne pictorial display system mentioned later. The automatic and continuous record of track-made-good and, through annotation marks, of events occurring along that track, such as the firing of seismic shots by oil-exploration vessels, is a useful aid. Any predetermined track can be steered without monopolizing one or more operators on manual plotting. The plotted record also provides a check on lane integration. The instrument is primarily used in exploration and special projects, but it is also employed on ferries and other repetitive voyages and may well prove useful should it become necessary to separate opposing lines of traffic near the coast in 'thick weather' 2

(2.6) Surveying at Sea

In addition to general navigation at medium ranges and around the coast, which includes an accurate indication of landfall by ships arriving on long voyages from outside the coverage, Decca is used for a large number of special purposes at sea; e.g. speed and manouvring trials of new vessels, salvage work, towing by river and deep-sea tugs, under-water cable-laying and maintenance, buoy positioning and maintenance, fishery research, geophysical exploration, and hydrographic surveying. By no means least among these specialized maritime applications is the last-mentioned i.e. fixing the position of ships engaged in making or revising hydrographic charts and for allied work in connection with oil exploration. Low-power mobile chains, some carried on the survey ships themselves, are deployed in various parts of the world for this work. The normal practice is to alter the chain string progressively so as to keep a good angle of cut in the area where surveying is in progress. Lane identification is generally dispensed with in the interests of simplicity and portability, and the operations usually take place in the hours of daylight and at distances from the stations not exceeding 200 miles.

A special receiver is used for survey work, incorporating measures to raise the instrumental accuracy to the maximum possible level. Chief of these is the use of a goniometer phase-shifter for calibrating the Decometers; the normal discriminator/Decometer combination has a non linearity of phase measurement amounting to about ±0.02 degree (and hence negligible for normal navigational purposes), the goniometer having a precision some seven times greater. Position-fixing accuracy in the range 5-50 m are commonly obtained in this work, depending on geometrical and other factors, and the system has been used for the detailed examination of shoals at plotting scales as large as 1 : 2500 or 25 in/mile.

In a variant known as Two-Range Decca the two slave stations are on shore but the master is sited on the surveying ship itself, together with a receiver. The Decometer readings then indicate and record the total number of lanes plus fraction in the two patterns, thus fixing the ship's position in terms of the ranges to the two slave stations. Using the previous notation, \( r_s \) becomes zero and the sense of Decometer rotation is reversed so that the lane number increases with the distance \( r_b \) to the slave. Hence

\[
L = \frac{S + \alpha r_b}{\lambda} + \alpha
\]

where \( \alpha \) is the so-called 'locking constant', which includes factors such as the permanent displacement of the master signal phase at the receiver due to the latter's close proximity to the master transmitting aerial. Where the limitation of the service to a single ship can be accepted, the Two-Range layout offers certain advantages compared with the hyperbolic (also widely used for surveying), which includes a simpler co-ordinate system, one less shore site, and a much increased area within which, accurate fixing, e.g. a standard error of 10 m, is possible.

(3) USE AS AN AIRCRAFT NAVIGATIONAL AID

(3.1) Presentation

Pictorial presentation of the Decca position is an occasional requirement in marine navigation but is of paramount importance in aircraft; it is largely this facility, apart from the traditional facilities in regard to weight, housing and power supply, which distinguishes the airborne from the marine installations. Although the Decometers and manual plotting can be used in certain types of aircraft performance rigidly circumscribed tasks, it was clear from the outset that a direct and automatic form of display would be required if the potentialities of the system were to be realized in the air. It was evident also that the routine nature of the Decca receiver output would lend itself well to the actuation, through servo mechanisms, of an automatic plotter in which a pen represents the aircraft would move across a map or chart in response to the receiver's movement through the hyperbolic pattern. Such an instrument is the Decca Flight Log, which forms the presentation system in most of the civil and military aircraft now using Decca.

The evolution and principles of the Flight Log have been described elsewhere,6 as has one of the two types of servo system which effect the torque amplification and the various other functions involved in transforming the Decca receiver output into a map display of suitable characteristics. The Flight Log servo system now generally employed makes use of impulse or stepping motors. The primary element comprises three Decometer movements, one for each colour, which accept the receiver output. In each meter, the normal fractional poiter is replaced by a platinum-iridium con act arm; a slight angular movement of +14.5 degrees drives it against one or other of a pair of contacts on a disc mounted coaxially with the Decometer, the contacts being connected through slip rings and relays to the forward and reverse windings of an impulse motor. Each time the arm touches one of the contacts the motor moves on or back step under the control of a mechanical escapement. The impulse-motor shaft moves a wiper arm over a series of studs arranged in a ring, and as the arm moves on to a stud it completes the circuit for a second impulse motor in the display head itself, which moves the marking stylus or pen to the position of, say, the x co-ordinate. Repeating this mechanism for the y coordinate completes the basic arrangement and produces a system in which the pen automatically and continuously plots the Decometer information and hence records the track of the aircraft on the chart.

Since the instrument will be required to handle charts of many difference map scales, so as to cater for the contingencies of precise air traffic control and airfield approach in limited areas as well as en route navigation over relatively long distances, the equipment linking the receiver with the Flight Log display head, collectively known as the 'computer', must include a number of
alternative input/output ratios. It must also contain means whereby the correct ratios, as well as the correct patterns and senses of rotation for the required area, can be set in instantly. The charts themselves generally form a roll housed within the display head, a portion of the roll measuring about 4in × 10in being visible; the roll is carried on sprocketed rollers and this movement forms one of the two plotting co-ordinates. The second co-ordinate is provided by the lateral movement of the marking pen on a lead-screw.

To reduce manipulation to the minimum possible, each different chart has a corresponding metal key assigned to it on which the number and position of the wards represent the scale, choice of colour, sense of rotation and other characteristics of the chart; all the keys for a particular chart roll are inserted in a multi-contact switch assembly (the turret switch), a single movement of which brings the desired key into operation. The wards of the selected key engage with the corresponding fixed contacts and complete the appropriate relay and other circuits necessary to adjust the computer for the characteristics of the required chart. In one type of Flight Log, which uses composite charts with sections having different map scales, the necessary changes in the computer settings are effected automatically as the pen crosses from one section to the next.

Since the co-ordinates of the plotter are at right angles, a special chart termed the 'inverse lattice' is used, in which the Decca lanes are represented as an orthogonal grid. The consequent distortion of the chart decreases as the chain is approached and as the angle of cut of the hyperbolas approaches 90°, and can be tolerated in areas close to the chain so long as sufficient data are included on the map (which also contains topographical features), such as constant-range 'circles' and distance-to-go marks.

In areas where the angle of cut is small and the distortion would prove excessive, the information is fed to the display head after transformation into a co-ordinate system more closely resembling an orthogonal grid and hence with a marked decrease in distortion. The two new co-ordinate outputs are derived by subtracting and adding, respectively, the two primary Decometer rotations. Subtraction produces a shaft rotation which can be shown to respond to a hyperbolic pattern of lanes focused on the two relevant slave stations, while the summation pattern is of roughly elliptical form, with lines forming an obtuse angle with those of the difference pattern. In the impulse-type computer, the summation and subtraction processes are carried out by the controlled addition or cancellation of impulses delivered to the Flight Log driving motors. The computation of the various elements in the computer mechanism, controlled by bringing the appropriate key into the circuit as already described, includes the selection and connection of the appropriate sum and difference patterns for the required chart.

The effect of alternative ratios of rotation, as between the primary Decometers and the computer output to the display head, is obtained by interconnecting, in appropriate groups, the studs on the rotary switch driven by the primary servo-mechanism, so as to control the number of primary impulses required to produce one output impulse. The Flight Log computer system using impulse motors is essentially flexible and is amenable to the addition, without drastic modification, of various automatic functions. For example, information can be stored in terms of a length of steel wire corresponding to a certain number of impulses, wound on a drum, and fed back when required; this is the basis of a so-called 'memory' function, which allows an aircraft to fly beyond the boundary of a Flight Log chart and return to the charted area without developing an error in the indicated position. Another facility increasingly used with the Flight Log is known as the 'skewed primary' technique, which enables the orientation of the chart to be adjusted so as (for example) to give a north-upwards picture; this involves feeding a controlled proportion of one co-ordinate output on to both plotting axes.

By showing the pilot his position continuously and directly with respect to his required route and to specific points such as diversion airfields, and enabling him to follow any prescribed track simply by steering so that the pen follows the required line, an automatic plotter such as the Flight Log represents an important contribution to air navigation technique, particularly in air traffic control. Even by night at 200 miles, an aircraft can be kept within a 10 n.m. airway, thereby significantly reducing the track separation tolerance previously called for. Similarly, an aircraft can descend through cloud and be held continuously to within 8 n.m. of a desired point. At up to 150 n.m. from the master station by night, in the front coverage of the chain, parallel tracks can be flown within a 10 n.m. airway; an aircraft can be led on to a runway to facilitate a straight-in approach; and it can be held continuously to within 4 n.m. of a desired point in such a way that the pilot knows at all times his position in the holding pattern (i.e. the track assigned to aircraft while awaiting permission to land). Aircraft can be sequenced for rapid landings, nominally at 3 min intervals, without requiring detailed guidance from Air Traffic Control.7 The Ministry of Transport and Civil Aviation has issued modified separation standards for Decca-equipped aircraft flying in United Kingdom airways.

(3.2) Airborne Receivers

The Mark V marine receiver dates from 1947, and an airborne counterpart was introduced concurrently. The present version of the latter receiver, Mark VIII, is used in its basic form in aircraft whose speed is such as to take advantage of the positional accuracy, or more properly the sensitivity, available from the hyperbolic patterns. Helicopters are a conspicuous example, taking advantage of uninterrupted service while flying at low altitudes among hills or high buildings. Much experience with the system has been gained by the British European Airways Helicopter Unit,8 and in the past year a series of trails has been carried out in the United States with a mobile Decca chain, the results of which indicate that the system, used in conjunction with an accurate terrain-clearance indicator, can form the basis of a blind-flying and -approach system for rotary-wing aircraft.

Fixed-wing aircraft of moderate speed also make use of this receiver for a variety of tasks, some of which require an accuracy of position fixing much greater than is called for in general navigation. Examples are photographic and magnetometer surveys for the Directorate of Ordnance Survey and the Geological Survey of Great Britain, and the checking and calibration of other radio aids by aircraft of the Ministry of Transport and Civil Aviation. Some of the Ordnance Survey map-revision flying in the United Kingdom, on which the system is used for flight-line guidance, has called for a track separation of 220 yd with an off-track tolerance of ±20 yd. Certain short-distance repetitive types of operation, such as an air ferry, make use of a Decca receiver stripped down to the essentials indicated in Fig. 2(a) but driving only an automatic plotter. Lane identification and the referencing system are dispensed with, since the errors due to phase drift are small owing to the long periods during which the receiver is kept running. (In any case such errors are insignificant at the map scale generally used for such operations.) This receiver is considerably smaller than the other airborne sets, occupying less than half a cubic foot and consuming, together with the associated Flight Log equipment, a total of 7 amp at 24 volts.

In the use of the receivers so far mentioned, there exists a
limitation on the speed of an aircraft. The lanes average about 1,000 yd wide over the coverage area of a chain, and when flying across a pattern the rate of rotation of the Deccos and Flight Log servo systems may be such as to preclude, respectively, the interpolation of readings to small fractions of a lane or the use of charts of the scale that can be employed in a slow-moving vehicle. Furthermore, where the lanes are narrow, as on the inter-station baselines, the rate of rotation could be sufficiently high to introduce the risk of loss of lane integration if reception were interrupted for more than a fraction of a second.

Accordingly the Mark VII receiver was developed, which responds to patterns having wider lanes than those of the basic system. This is achieved by comparing phase at the slave carrier frequencies, thereby increasing the lane-widths by factors of 2, 3 and 6 for green, red and purple, respectively. The master signal is converted to the respective slave frequencies by division to frequency f and subsequent multiplication to the slave values 9f, 8f and 5f. The 6-fold ambiguity in the phase of the 6f/driver output, with respect to the master signal, is resolved (or ‘notched’) by comparing the f output of the divider with a phase datum in the form of the f signal extracted during lane-identification transmissions from the master station in the manner described in Section 2.2.

The Mark VII receiver has an improved performance in the presence of noise pulses, due partially to the reduced comparison frequency and also to the use in the master channel of a 6f oscillator phase-locked to the received master signal, which constitutes a virtually noise-free input to the divider and hence to the master phase-comparison channels. Comprehensive tests have been carried out on this receiver in tropical areas of high noise intensity; it also forms the basis of the standard equipment installed in the Viscount aircraft of British European Airways.

(3.3) The Receiving Aerial

Whereas a few feet of insulated wire serve adequately as the receiving aerial for most shipborne Decca installations, the design of aircraft aerals is relatively complex, owing to the need for aerodynamic cleanliness and for protection against certain types of noise interference, including the direct impact of charged droplets. These factors call for the use of flush-mounted or suppressed aerals, placed at a point which will be wholly or largely free from droplet impact, e.g. at a wing-root fillet, behind the cockpit canopy or on the fin well back from the leading edge. The aerial can be either on the neutral plane of the aircraft. In the Viscount 802’s of British European Airways, the Decca aerial is in the under-surface of the wing-root fillet. This arrangement has been shown by switch-over tests to give a better performance than the fin-mounted aerial of the Viscount 701’s; an under-fuselage aerial is also fitted to a number of Bristol Freighter aircraft.

In view of the small effective height of the collector plate and its distance from the receiver, a head-amplifier/impedance-transformer unit is used with the aerial. With early versions of the amplifier, unaccountable breakdowns of reception in static were noticed several times, and these were finally traced to severe overloading from a signal produced by the passage of droplets close to the collector plate without actually touching it. At an airspeed of 300 knots, this signal appeared as noise, centred on a frequency of 6 or 7kc/s, which overloaded the final stage of the amplifier and generated harmonics at one or more of the Decca frequencies. The effect was eliminated by modifying the circuit to accept a large input at the droplet recurrence frequency without overloading.

It is essential that Decca-equipped aircraft should be fitted with static dischargers of the wick or wire type, and that in any event the receiving aerial should not be placed near a part of the structure so shaped as to be likely to give rise to discharges. The latter problem is tending to diminish with the increasing aerodynamic cleanliness of jet aircraft, and there is also some evidence to show that the jet efflux itself can provide a discharge path.

(3.4) The Repeater Unit

Recently a different approach has been made to the problem of preserving lane integration at high aircraft speeds and at high noise levels. As already shown, the r.f. pass-band of a Decca receiver can be made narrow, since the only intelligence extracted from the radiated signals is their relative phase; the effective bandwidth of the receiver and the display can, however, be further reduced by applying a severe degree of negative acceleration feedback to the servo system linking the receiver with the display. This principle is embodied in the repeater unit, which is used in conjunction with the Mark VIII type of ‘fine-pattern’ aircraft receiver. In addition to providing strong discrimination against sudden changes in the rate of rotation, such as tend to occur in the presence of noise interference, the use of acceleration feedback obviates the need for the RC damping circuits of long-time-constant normally used and eliminates the lag error due to these circuits at high rates of Deccometer rotation.

The unit incorporates an automatic dead-reckoning facility, by which the input from the receiver is cut off as soon as the torque falls below a pre-set minimum level, the output servos then continuing to turn at a memorized rate. The maximum safe duration of an interruption depends on the duration of clean signal immediately preceding the interruption; as this maximum duration is also affected by operational variables, such as the speed through the phase patterns and the magnitude of changes in course during the interruption, the assessment of exact performance figures is a complex process. Typically, however, the unit will override a break lasting 2 min if preceded by 1 min of clean signal, or a break of 10 sec if preceded by 0.25 sec of clean signal. The servo characteristics can be adapted to suit different types of vehicle, ranging from supersonic aircraft to surface vessels.

With high-accuracy tasks in mind, such as aerial surveys, the repeater-unit servo system includes a method of automatic referencing of the receiver, by sensing and effecting the appropriate angular corrections when the in-phase reference signals are applied. During this process the memory function takes over, so as to preserve lane integration while normal reception is interrupted.

(3.5) Position Reporting

To satisfy future operational requirements a version of the repeater unit is under development which contains a means of translating the Deccometer readings into digital terms for tele-metering purposes, e.g. for continuously reporting the position of an aircraft to a controller on the ground; with the steadily increasing number of aircraft being handled by Air Traffic Control it is expected that the need for position reporting will become pressing. The receiver output to a Deccometer is basically in the form of voltages representing the sine and cosine of the phase difference, and this information will be converted in the repeater unit into a binary digital code. The required red, green and purple data each contain 10 bits, and one unit corresponds to 1/1024 of a zone (about 0.024, 0.018 and 0.030 lane for red, green and purple, respectively). The output information will be unambiguous up to a total of not more than 32 zones, calling for 5 additional bits and hence a total of 15 for each pattern.

By this means the Deccometer readings can be reconstituted on the ground and a ground-based Flight Log can reproduce the aircraft’s track continuously. While this form of data trans-
mission is economical in bandwidth and in frequency utilization,  
the total bandwidth necessary to transmit the information  
declares on many different factors, such as the number of  
aircraft to be handled simultaneously and the amount of  
aircraft speed, acceleration and rate of turn.

(3.6) The Decca/Doppler Combination

It is an axiom that the navigator should make use of as many  
agents of information as are available to him, and the use of  
different radio aids in combination is especially significant  
when their characteristics are complementary. This is true to  
a marked degree of the Decca Navigator and the Doppler type of  
airborne navigation aid; Doppler comprises an entirely self-  
contained airborne instrument which furnishes speed and  
drift information independently of external radio transmis-  
sions, while lacking the common-reference facility and freedom  
from cumulative error that are fundamental characteristics of  
a system such as Decca. A systematic combination of the two,  
embracing also the Decca long-range aid referred to below, is  
the Decca Integrated Air Navigation system (Dian), which  
employs a common Flight Log pictorial map display.

(3.7) Dectra

Much of the airborne and the ground-based equipment of  
Dectra is common with the parent Decca Navigator system.  
The Dectra chain at present undergoing operational trials takes  
the form of a pair of stations in Newfoundland; integral with two  
of the four stations of the East Newfoundland Decca chain,  
operating with one single station in the United Kingdom integral  
with the recently re-sited purple slave station of the North British  
Decca chain.

The two stations in Newfoundland combine to form a hyper-  
bolic tracking pattern, the central portion of which runs in an  
East-West direction across the Atlantic. Phase is compared at  
the radiated frequency $5f$, using the previous notation, the  
master and slave signals being transmitted as part of the normal  
lane-identification cycle. The purple Decca slave transmission  
forms the master signal for Dectra; the Decca slave transmission  
is provided by the $5f$ signal from the Decca master station,  
intermittently transmitted for lane-identification purposes as  
already described. The three $5f$ lane-identification signals sent  
each minute from the Decca master are supplemented for Dectra  
 purposes by five additional transmissions, giving a total of eight  
$\frac{1}{2}$ sec Dectra slave transmissions per minute at $7\frac{1}{4}$ sec intervals.  
An oscillator in the airborne receiver, locked to the Dectra  
master transmission, reproduces the master phase, which is  
compared in a discriminator with the successive slave signals.  
The phase difference, giving the tracking position-line, is displayed  
on a Decometer and also as the lateral Flight Log co-ordinate.  
The Flight Log and its associated computer is common to the  
Dectra and Decca equipment in the aircraft.

A hyperbolic ranging pattern lying across the tracking lanes is  
provided by phase-locking the North British purple slave station  
with the Decca master signal received from Newfoundland.  
The ranging pattern is the result of yet another method of  
deriving pairs of signals of a common frequency for phase com-  
parison; the two ranging frequencies $f_1$ and $f_2$ are so chosen that  
each is an integral multiple of a common sub-harmonic $f_3$,  
approximately 150 c/s, so that

$$f_1 = n f_3$$
$$f_2 = (n + 1) f_3$$

The ranging element of the airborne receiver and the phase-  
locking of the two stations each involve phase comparison of  
the beat note $f_3$ between the two transmissions with the $f_3$ signal

<table>
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<tr>
<th>FREQUENCIES AND RELATED DATA FOR THE N. ATLANTIC DECTRA CHAIN</th>
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<tr>
<td>Function</td>
</tr>
<tr>
<td>Master and tracking slave $f_1 = 70 - 384 \text{ kcf/s (Decca frequency 2, purple)}$</td>
</tr>
<tr>
<td>Ranging slave transmission $f_2 = 73 - 537 \text{ kcf/s (Decca frequency 3, purple)}$</td>
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<tr>
<td>Ranging discriminator frequency $f_3 = 153 - 342 \text{ c/s}$</td>
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<td>Division ratio $n = 459$</td>
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obtained by frequency division of the $f_3$ signal. It can be shown  
that the lines indicated by the ranging Decometer, and the  
associated Flight Log co-ordinate, correspond not to the common  
discriminator frequency $f_3$ but to the frequency $f_2$, giving a lane  
width of some 2300 yd. Table 4 shows the frequency values for  
the present Dectra chain.

(3.8) The Mark X Decca Navigator

The evolution of a radio aid to air navigation must, if possible,  
anticipate the trends of aircraft design and of operating condi-

tions. On this premise there are two respects in which the  
existing Decca Navigator system requires adaptation to the condi-
tions soon to be imposed by the increasing speed and numbers of  
transport aircraft. First, the reliability of lane identification  
by night at ranges greater than about 170 n.m. from the stations  
is insufficient to avoid a degree of lane ambiguity that could  
prove unacceptable in fast aircraft; secondly, even the low  
ambiguity represented by the recurring groups of lanes (zones)  
within which the present identification system operates may  
prove excessive. The Mark X development caters for both  
these requirements (the second by a zone-identification system)  
and involves changes to the ground stations as well as to the  
airborne installation, while remaining compatible in the technical  
sense with the normal system. One aspect only is considered  
here, namely the method of extending the distance at which  
lane identification is reliable under night-time sky-wave  
conditions.

It will be recalled that the coarse hyperbolic pattern generated  
for identifying the Decca lanes corresponds to a comparison  
frequency $f$ of roughly 14 kcf/s, this frequency being derived in  
the receiver for the master by taking the beat note of the $6f$ and  
$5f$ signals transmitted therefrom, and similarly for each slave in  
turn by the beat note between $7f$ and $8f$. At night, as with the  
basic patterns, variations in the phase of the ionospheric wave  
with respect to the ground-wave give rise to random variations of  
the phase-meter reading about the true value. The effect of  
these errors on the lane-identification process can be such as to  
cause the incorrect lane to be indicated or, more precisely, such  
as to cause the sector pointer to pick out the wrong log (Section 2.2) if the phase difference between, say, the normally  
in-phase $5f$ and $6f$ signals from the master exceeds 180 after  
multiplication to the common value. This is liable to occur at  
ranges where the r.m.s. amplitude of the sky-wave reaches about  
28% of that of the ground-wave; in practice, assuming ground-
wave attenuation appropriate to terrain of average conductivity,  
this sky-wave/gound-wave ratio may be expected to obtain at  
distances of the order of 170 n.m. from a station.10 As that  
distance is exceeded, there is an increasing chance that incorrect  
lane-identification readings will be observed. In marine naviga-
tion this limitation is relatively unimportant, since consecutive readings over a period of 2 or 3 min can be taken when necessary, but such a procedure is out of the question in any but the slowest aircraft.

The essence of the Mark X technique is to derive the signals of frequency \( f \) from master and slave by a method in which more information is transmitted and which is markedly less sensitive to phase variations in the component signals. This is achieved in a transmission cycle wherein all four Decca frequencies together (5\( f \), 6\( f \), 8\( f \), 9\( f \)) are momentarily radiated from the master station and then all four from the slave. Since the four signals are harmonics of a fundamental value \( f \), a pulse of recurrence frequency \( f \) for each station can be generated in the receiver by summation of the four frequencies; this pulse forms the basis of the lane-identification pattern and remains devoid of significant phase error even in the presence of very large variations in the phase of the components. The Mark X receiver gives Deccanometer readings which, like those of the Mark VII (Section 3.2), are ambiguous in respect of slave-frequency lanes, and the function of the lane-identification pattern produced by the pulse synthesis just described is therefore to provide a position-line accuracy better than half a slave-frequency lane for each pattern. Green calls for the highest accuracy of the three, being of frequency 9\( f \), and requires the \( f \) pattern to be correct at all times to within \( \pm 10^\circ \) or 20° of the \( f \) cycle. Examination of the summation waveform shows that under no combination of phase shifts in the components is this tolerance in the phase of the pulse exceeded until all four are displaced by a phase angle equivalent to the sky-wave variation obtaining well outside the nominal service area of the chain. Moreover, the tolerance is then exceeded only for certain combinations of relative sign of the four phase shifts.

An essential tool in the development of the Mark X technique has been a multiple signal-generator comprising four sine-wave sources at the four harmonic frequencies, adjustable for equal amplitude and each variable in phase over the full 360°. A goniometer is used in each channel so that a specific phase angle can be set in with an accuracy of about \( \pm 1^\circ \). Fig. 6(a) shows the summation waveform thus produced with no phase shifts in the components, peaks of the four harmonics having first been aligned individually against a reference pulse of recurrence frequency \( f \) (shown on the upper trace). In the illustrations the operative part of the summation waveform is the upper or positive-going half. Three cycles at frequency \( f \) are shown in each case, and the synthesized pulses appear immediately below the reference pulses. Fig. 6(b) shows the summation waveform after all four harmonics have been shifted in phase by an amount (approximately 16°) corresponding to the condition of 28% sky-wave, which, as mentioned above, represents the present limit of reliable lane identification. It will be seen that the phase of the synthesized pulse has altered negligibly, and that its amplitude still greatly exceeds that of the other peaks in the complex waveform.

Fig. 6(c) shows the result of applying a phase shift of 35° to all four signals. The required pulse is now almost equalled in amplitude by one of the subsidiary peaks; the circuits receiving the summation signal can discriminate against the unwanted peak until it reaches 99% of the amplitude of the required peak, and the condition shown in Fig. 6(c) is therefore close to the limit beyond which a large error in the phase of the summation signal will occur when the unwanted pulse gains the greater amplitude and takes over as the phase datum. Reference to the vector diagram representing the relationship between the groundwave amplitude and the r.m.s. amplitude of the sky-wave shows that a phase shift \( \theta = 35^\circ \) in the resultant corresponds to a skywave/ground-wave ratio of \( \sin \theta = 0.57 \) or 57%; this condition

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Fig. 6.—Summation waveforms associated with the Mark X technique.

Three cycles shown.
(a) No phase shifts in the four component harmonic frequencies.
(b) \( +16^\circ \) phase shift applied to fifth and eighth harmonics, \( -16^\circ \) applied to sixth and ninth.
(c) \( 35^\circ \) phase shifts applied to the four harmonics as in (b).
would be expected to prevail only at distances from the stations considerably exceeding the nominal 240 n.m. radius of the chain, however, and even then the probability of its occurring on all four transmission paths simultaneously is small. Also, there are only two of the possible 16 combinations of relative sign for the four 35° phase shifts under which the limiting condition shown about to occur in Fig. 6(c) is reached. If all four shifts of 35° are in the same sense, for example, the unwanted peak in the summation waveform is of relatively small amplitude and the phase-shift in the synthesized pulse is negligible in relation to the 20° tolerance for green lane identification. The least favourable sign combinations are the two in which the sixth and ninth harmonics are of opposite sign to the fifth and eighth, one of these combinations was used for Figs. 6(b) and 6(c).

While much theoretical work remains to be done, it can be predicted on the basis of empirical results of the type outlined above that the synthesized-pulse technique will yield a reliable lane-identification service at all times and seasons over the whole service area, out to the distance at which lane integration in the fine patterns tends to break down through sky-wave/ground-wave interference. This limiting distance, approximately 240 n.m., is taken as that at which the ground-wave field strength is 2.14 times the r.m.s. sky-wave field strength, i.e. 47% of sky-wave, corresponding to a resultant phase shift of 28°. In the ground observations and test flights carried out at night as part of the development programme, no incorrect lane-identification reading has yet been recorded at any point within the coverage of the English chain. The latter chain has been fully equipped for Mark X transmissions and the necessary modifications are to be made to other chains in sequence.

It is considered that the technique represents a notable step forward by combining in a large degree the attributes of pulse and c.w. systems. Since a steep-fronted pulse is synthesized from only four pure c.w. signals, the accuracy of ambiguity resolution is high without excessive demands being made in regard to frequency space. The residual ambiguity of the system is very low, owing to the incorporation of a zone-identification facility; this uses one additional transmission (8.2 f) from each station, which, mixed with the 8f component in the receiver, generates a coarse hyperbolic pattern having a comparison frequency of 0.2f and hence embracing five zones. From a practical point of view, an important characteristic of the new system is that, in gaining some of the advantages of pulse techniques, it retains the essentially rotary nature of the Decca Navigator output data, thus remaining readily amenable to automatic pictorial presentation by an instrument of the Flight Log type.

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(5) REFERENCES