THE DECCA NAVIGATOR

PRINCIPLES AND PERFORMANCE

OF THE SYSTEM

Contents

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FOREWORD

All the information on the Decca Navigator that users are normally likely to need is contained in the Operating Instructions and Data Sheets issued with each marine receiver and in corresponding publications and briefings provided for flight crew.

This handbook gives background information on the Principles of the system and on the factors governing the accuracy of Decca position-fixing, to assist those concerned in special applications of the system and for instructional purposes generally.

Chapter 2 includes material from an earlier publication, "The Decca Navigator as an Aid to Survey", and is concerned in general with short-range, daytime operation. Chapter 3 is based on a paper presented at an international conference and describes the effects of sky wave propagation.

References to specific items of transmitting, receiving and associated equipment have been kept to the minimum throughout this handbook, which is concerned essentially with basic principles.

Chapter 1

GENERAL PRINCIPLES

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1. 1. Introduction

The Decca Navigator is a radio position-fixing system for marine, air and land use based on continuous wave signals in the low-frequency band 70-130 kHz. Except for a special version developed for hydrographic survey work, the system is of the type in which fixed transmitting stations at known locations provide hyperbolic lines of position. The range of the system depends on various factors but is typically in the order of 240 n. miles (440 km) by night and about twice that distance by day. Each user craft carries a special receiver which, in its simplest form, delivers the position lines as numerical "Decometer" readings which are plotted manually on a lattice chart. The intersection point of two such lines gives the position fix.

Automatic and computer-based methods of reducing and displaying the Decca position fix are widely used, but it is assumed throughout this publication, except where stated otherwise, that the fix is plotted manually. This assumption is made for the sake of simplicity. It will not prejudice the references in Chapters 2 and 3 to system performance since this ultimately depends, as in other radio navigational aids, more upon signal propagation and geometrical factors than upon display instrumentation.

A chain of Decca Navigator stations consists of a central master, with which is often associated a supervisory control/monitor station, together with three (in a few cases two) outlying slave stations. Each slave generates a pattern of hyperbolic position lines in conjunction with

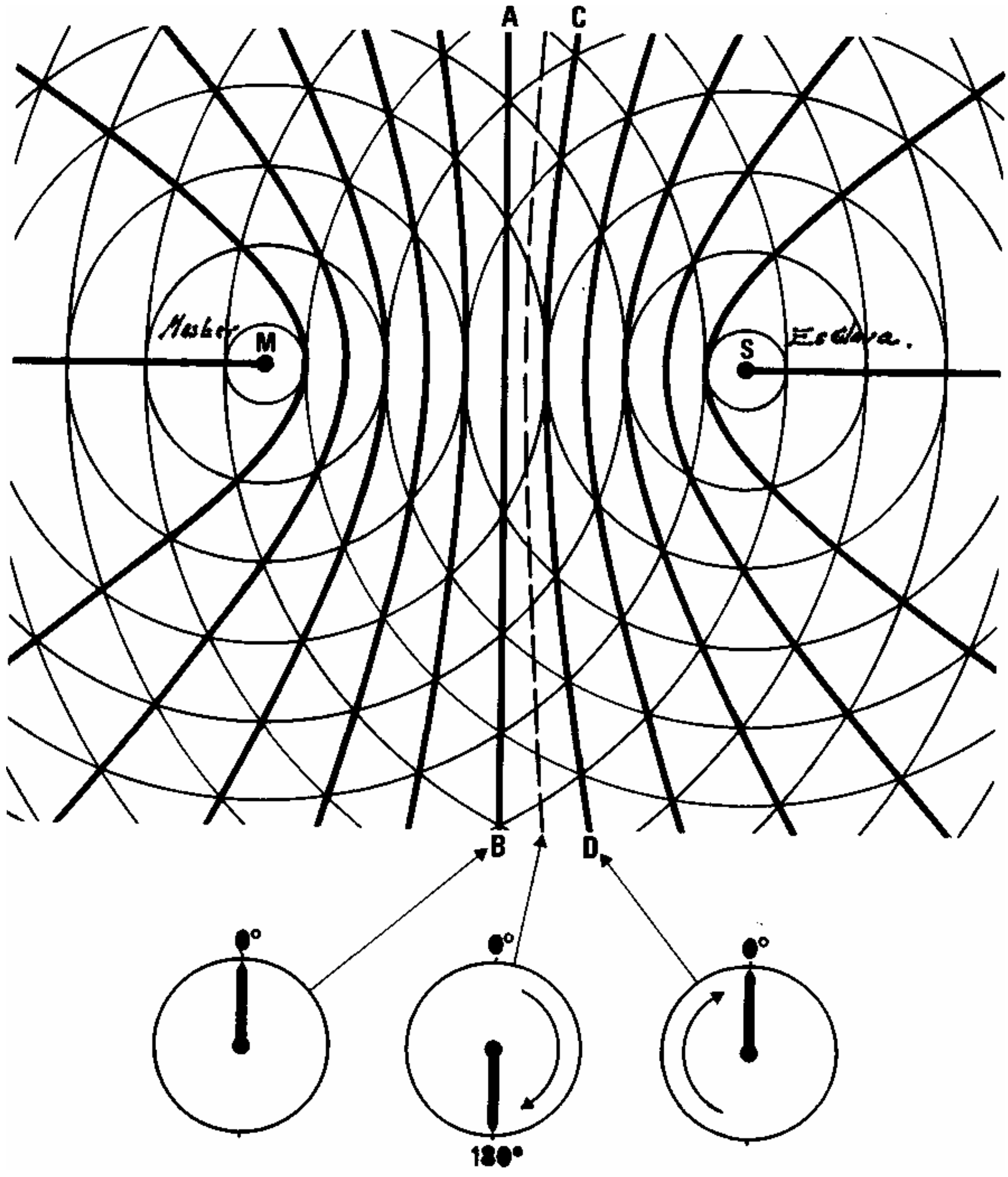


Fig. 1. 1. Hyperbolic pattern generated by phase-locked c. w. signals. The concentric circles represent successive wavelengths. The space bounded by two adjacent hyperbolae on which the signals are in phase (e. g. AB, CD) is termed a Lane. By convention the Decometer turns clockwise for movement from master to slave.

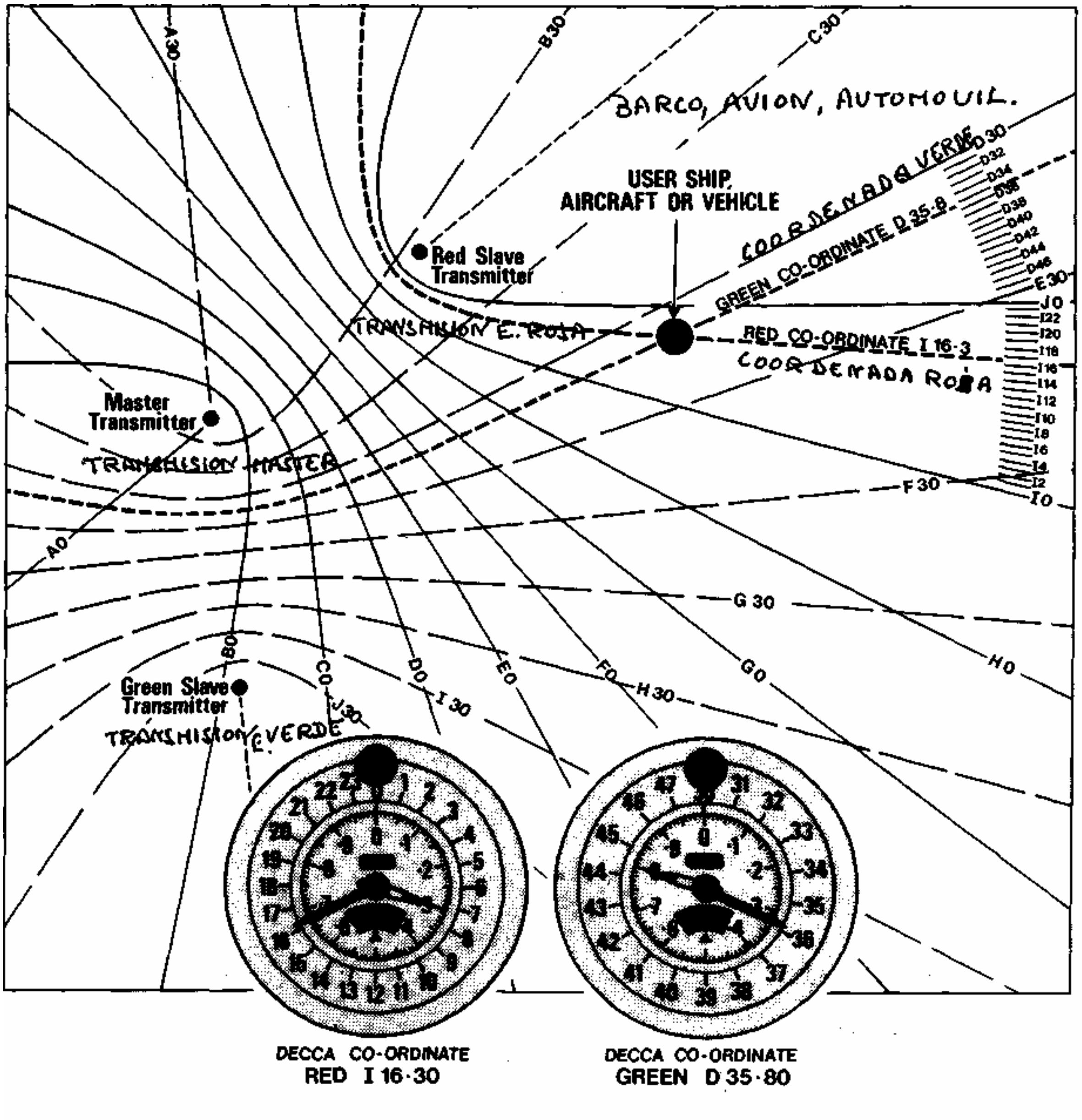


Fig. 1. 2. Simplified lattice showing plot of position-fix.

the master, and the slaves are termed red, green and purple from the colours in which the respective patterns are printed on charts. The length of the inter-station baselines is generally within the limits 40-120 n. miles (73-220 km). The factors governing the choice of baseline length and chain configuration are discussed in Chap. 2.

1.2 Position lines

A Decca position line is generated by a pair of synchronized transmitting stations. Consider a pair of stations A and B, separated by a distance S, which are 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:

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

where λ is the wavelength of the common frequency. The locus of points at which $r_A - r_B$ is constant is a hyperbola focussed on the two transmitting stations, which can thus constitute a navigational position line if the station locations are known and the user is furnished with phase comparison equipment. The principle is illustrated in Fig. 1. 1 in which the concentric rings represent the wavelengths of the common frequency and the pattern assumes the form of a set of stationary waves generated by interaction of the two signals. For simplicity, the transmission path from master to slave, i. e. S in the formula ,is ignored in Fig. 1. 1 and the stations are assumed to be transmitting in phase.

The phase meter or Decometer cannot distinguish phase differences that are multiples of 2π but the rotor, which makes one revolution per 360° of phase, drives subsidiary pointers through gearing to indicate the number of revolutions made. The space bounded by two in-phase hyperbolae is known as a "lane" and one of the geared pointers shows a change of one lane for each revolution of the rotor. Attached to the rotor is a lane fraction pointer which sweeps a scale calibrated in hundredths of a lane. At any position the lane reading L, including fractional value, can be found from

$$L = \left[\frac{S + r_A - r_B}{\lambda}\right] + k_m$$

In practice, there are several hundred lanes in a typical pattern and these are grouped into "zones" denoted by letters displayed by the other geared indicator. 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 "monitoring constant" k is generally taken as zero (para. 1.5).

The effect of transmitting signals of equal frequency from the master and slave is achieved 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 kHz. The master transmits a signal of frequency 6f and the red slave 8f, the respective channels in the receiver being followed by x4 and x3 multiplier stages. Geometrically the system behaves as if the common frequency 24f (about 340 kHz) were radiated from the two sites. The other two patterns are generated similarly (Tables 1. 1 and 1. 2).

1. 3. Position fixing and lattice charts

The three slave stations of a Decca chain are phase locked to the common master station in the centre and thus produce three intersecting patterns of position lines giving coverage in all directions around the master. In practice, the user normally reads the Decometers for the two patterns giving the best angle of cut at his location and rejects the third. Marine charts are generally overprinted with the two patterns appropriate to the area depicted.. Fig. l. 2 represents the plotting of a position fix.

The basic method of converting a pair of Decometer readings into a position-fix (as distinct from digital data processing methods, not considered here) is a lattice or grid of hyperbolic curves superimposed upon a map or chart and numbered in Decca lane units. In general, the production of Decca lattice charts for marine navigation is the responsibility of the hydrographic authorities of the countries concerned. Lattice charts for air navigation and other uses are produced by various agencies, including the Charting Department of The Decca Navigator Company Ltd., which also prepares and supplies special charts for track plotters, flight logs and other pictorial display equipment used in ships and aircraft.

1. 4. Frequencies and related values

The relationship between the frequencies, lane widths and zonewidths of a chain is shown in Tables 1. 1 and 1. 2.

Table 1. 1

RADIATED FREQUENCIES (CHAIN No. 5B)

Station	Harmonic	Frequency (kHz)
Master	6f	85. 0000
Purple slave	5f	$70.833\dot{3}$
Red slave	8f	$113.333\dot{3}$
Green slave	9f	127. 5000
All stations	8. 2f*	$116.166\dot{6}$

* "Orange" frequency for zone ident. and station control/status signals.

Table 1. 2

COMPARISON FREQUENCIES AND LANE/ZONE WIDTHS ON BASELINE (CHAIN No. 5B)

Pattern	Harmonic	Freq. (kHz)	Lane/zonewidth**
Purple lanes	30f	425	352. 1 m
Red lanes	24f	340	440. 1 m
Green lanes	18f	255	586. 8 m
Zones (all patterns)	1f	14. 1666	10562. 0 m

** equal to half-wavelength at comparison frequency, for the specified propagation speed (here 299 250 km/s).

The unmodulated transmissions occupy spot frequencies from 84. 00 to 86. 00 kHz for master stations and pro rata at the slave frequencies. In a manually operated receiver, chain selection simply involves turning a pair of selector controls to the required frequency code number and letter. Chain frequencies are allotted according to the format shown in Table 1. 3 which is based upon a nominal separation (at frequency 6f) of 180 Hz between the basic code values OB, IB, 2B, etc. Some chains deviate by 5 Hz from this separation because of factors prevailing at the time of allocation. So-called "half frequencies" OE, IE, 2E, etc. are spaced nominally at 90 Hz. The letters A and C denote frequencies 5 Hz below and above the B values. D and F are 5 Hz below and above the E values. Table 1. 4 shows as an example the six sets of frequencies forming the numerical group 5.

Table 1.3

DECCA CHAIN FREQUENCY GROUPING IN kHz Nominal

frequency (B) and "half frequency" (E) groups

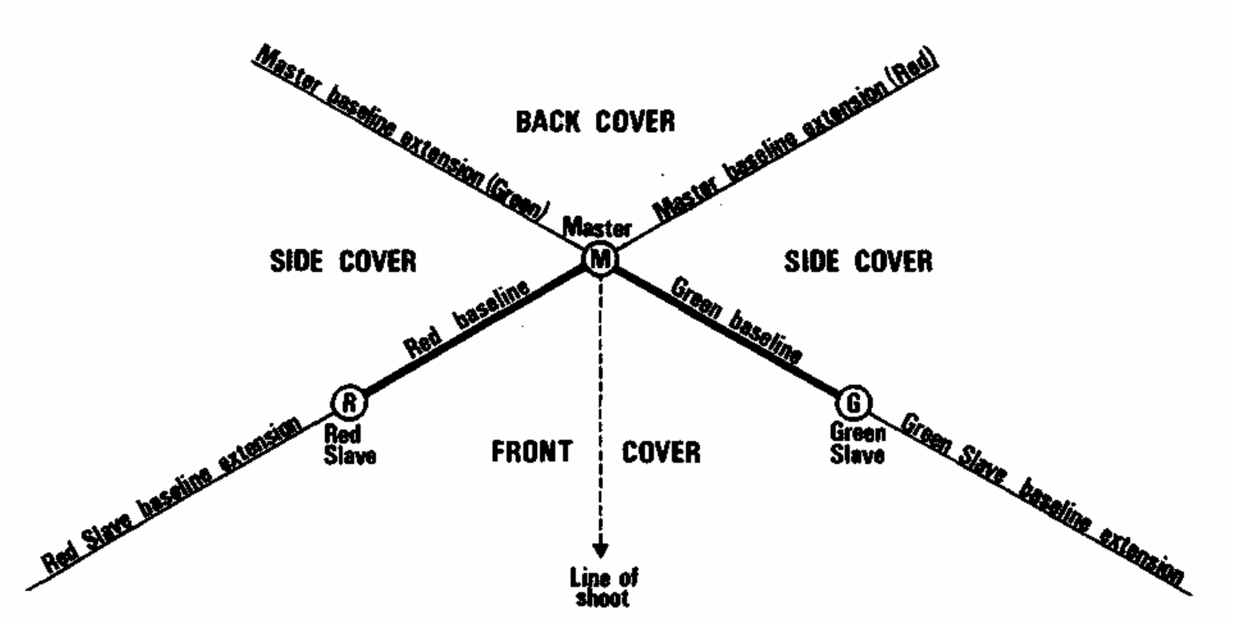
Chain code	1f (not radiated)	5f Purple	6f Master	8f Red	8.2f Orange	9f Green
0B	14.01750	70.0875	84.1050	112.1400	114.9435	126.1575
0E	14.03250	70.1625	84.1950	112.2600	115.0665	126.2925
1B	14.04667	70.2333	84.2800	112.3733	115.1827	126.4200
1E	14.06167	70.3083	84.3700	112.4933	115.3057	126.5550
2B	14.07667	70.3833	84.4600	112.6133	115.4287	126.6900
2E	14.09167	70.4583	84.5500	112.7333	115.5517	126.8250
3B	14.10750	70.5375	84.6450	112.8600	115.6815	126.9675
3E	14.12250	70.6125	84.7350	112.9800	115.8045	127.1025
4B	14.13750	70.6875	84.8250	113.1000	115.9275	127.2375
4E	14.15250	70.7625	84.9150	113.2200	116.0505	127.3725
5B	14.16667	70.8333	85.0000	113.3333	116.1667	127.5000
5E	14.18167	70.9083	85.0900	113.4533	116.2897	127.6350
6B	14.19667	70.9833	85.1800	113.5733	116.4127	127.7700
6E	14.21167	71.0583	85.2700	113.6933	116.5357	127.9050
7B	14.22750	71.1375	85.3650	113.8200	116.6655	128.0475
7E	14.24250	71.2125	85.4550	113.9400	116.7885	128.1825
8B	14.25750	71.2875	85.5450	114.0600	116.9115	128.3175
8E	14.27250	71.3625	85.6350	114.1800	117.0345	128.4525
9B	14.28667	71.4333	85.7200	114.2930	117.1507	128.5800
9E	14.30167	71.5083	85.8100	114.4130	117.2737	128.7150
10B	14.31667	71.5833	85.9000	114.5330	117.3967	128.8500

Table 1. 4

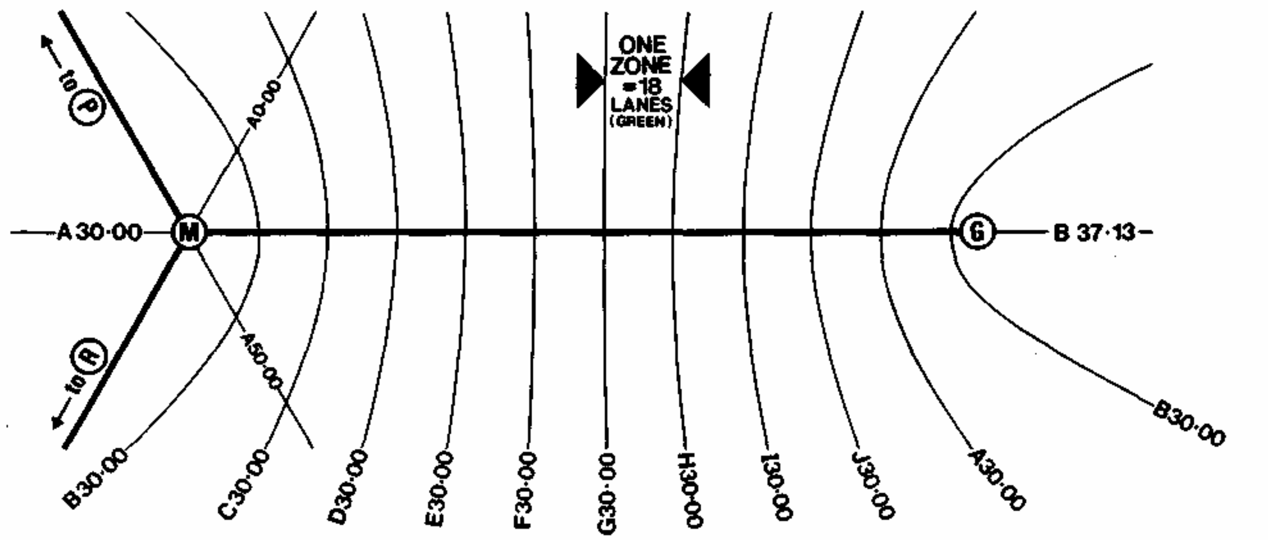
SAMPLE GROUP OF DECCA FREQUENCIES

Showing relationship of A-B-C-D-E-F spot frequencies (in kHz)
for one complete numerical group

Chain code	1f (not radiated)	5f Purple	6f Master	8f Red	8.2f Orange	9f Green
5A	14.16583	70.8292	84.9950	113.3266	116.1590	127.4925
5B	14.16667	70.8333	85.0000	113.3333	116.1667	127.5000
5C	14.16750	70.8375	85.0050	113.3400	116.1735	127.5075
5D	14.18083	70.9042	85.0850	113.4467	116.2828	127.6275
5E	14.18167	70.9083	85.0900	113.4533	116.2897	127.6350
5F	14.18250	70.9125	85.0950	113.4600	116.2695	127.6425



(a) Coverage areas and baseline extensions for a 2-slave chain. This diagram applies similarly to red/purple and green/ purple in a 3-slave chain.



(b) Pattern phasing and zone labelling. Example represents a "green" baseline 120 km long. Assuming a lanewidth on the baseline of 585 m, the total lane number would be 205. 13, i. e. 11 zones 7. 13 lanes.

Fig. 1. 3. Decca pattern terms and conventions.

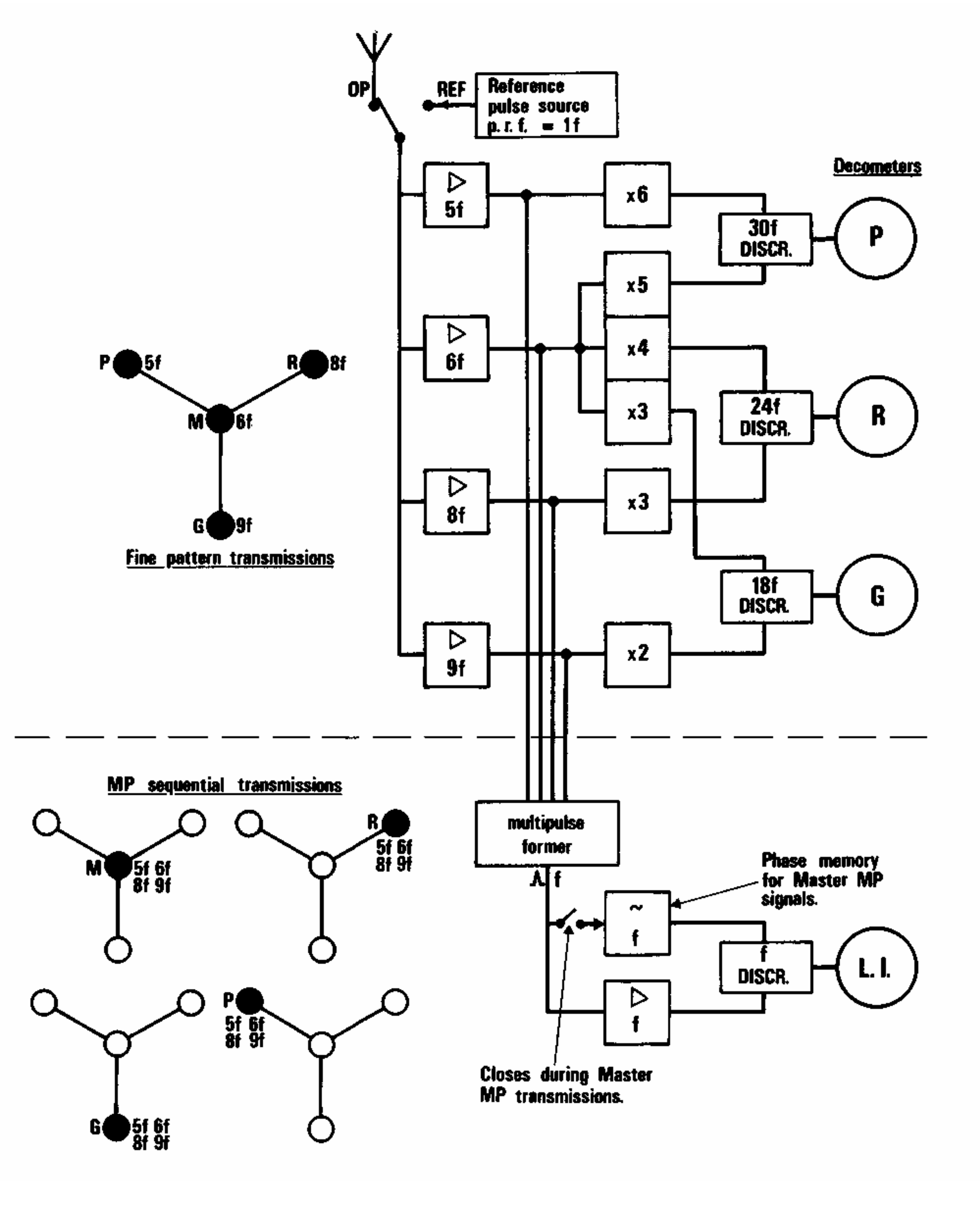


Fig. 1.4. Basic elements of a multi plying -type receiver (of no specific Mark) with MP lane identification. The chain transmissions and receiver elements associated with the fine patterns are shown above the dotted line, those for lane ident. below. Typically the lane ident. display is either a meter with three concentric scales, covering one zone, or a digital/numerical readout.

1.5. Pattern phasing and labelling

The length of the master/slave baseline is not critical and need not be made equal to a whole number of lanes (as is done, for simplicity, for the very short baseline in Fig. 1. 1). Generally the phase of the slave transmission with respect to the master is so adjusted that the baseline extension at the master end of the pattern has the fraction value zero (i. e. $k_m = 0$, see para. 1. 2). At the slave end the baseline extension then has the value of the residual lane fraction, as shown in Fig. 1. 3. Several chains depart from this convention, however.

There are 18 green, 24 red and 30 purple lanes in a zone, the zones being of the same width for each colour. On charts, and on the lane dials of the corresponding Decometers, the lanes are numbered 0-23 for red, 30-47 for green and 50-79 for purple, running from master to slave. Zones are labelled A-J, repeating after J. Certain equipment, for special applications, may have a readout (and associated charts) calibrated in zone fractions.

1.6. Master/slave phase locking

Under normal conditions, the necessary synchronism between the master and slave transmissions is ensured by the control equipment at the slave station, which receives the master signal and holds the transmission in a constant predetermined phase relationship (para. 1. 5) with the master at the common comparison frequency. In Chap. 2 and 3 it is assumed, except where stated, that this conventional method of phase locking is in operation.

In the case of certain chains, however, local conditions are such that propagation variations on the locking path can impair the phase stability of the master signal received at the slave, so reducing the stability of the transmitted pattern. In such cases, provision is made for operating the master and the slave station(s) in a mode based on the use of frequency-stable sources at the stations. These take the form of rubidium-referenced oscillators. The stability of the pattern is monitored from the control centre and phase/frequency corrections are applied at the slave stations as necessary. The procedure for implementing this mode varies from chain to chain, and may alternatively entail a combination of normal phase locking at favourable times of the day with reliance on the stable oscillators to preserve pattern stability in the intervening periods.

1.7. The receiver

The main elements of a receiver are shown in Fig. 1. 4. The four receiving channels for the respective stations are normally of the superhet type, but the conversion to intermediate frequency has no effect so far as lanewidth and response to the patterns is concerned; this is because a fixed and stable phase relationship is maintained between the local oscillator signals in the respective channels with the result that a given change of phase difference between the r. f. signals from master and slave, due to movement of the craft, produces the same change of phase difference at the intermediate frequency.

The phases of each pair of common harmonics, produced by frequency multiplication, are compared in a discriminator circuit. The amplified output of the discriminator takes the form of d. c. currents proportional to the sine and cosine of the phase difference angle. These outputs are fed to the field coils of the Decometer phase meter which are at right angles, and a magnetised disc forming the rotor takes up an angular position equal to the resultant phase difference value. The rotor shaft carries the lane fraction pointer referred to earlier and drives the lane and zone counting pointers through gearing. The mechanical Decometer is likely to be superseded eventually by an electronic version.

Differential phase errors in the signal channels and subsequent sections of the receiver are corrected by a "reference" facility in which pulses recurring at frequency f are applied to the receiver input. The pulse is of short, steep-fronted form such that the harmonics corresponding to the transmitted Decca frequencies are substantially equal in amplitude and have a fixed phase relationship. The reference input thus forms a phase datum whereby the Decometers should read zero in the absence of error. When an error is observed, the user restores the zero reading by turning either the Decometer stator or a phase shifter in the appropriate receiver channel. The reference facility performs the important function of ensuring uniformity of reading between individual receivers at a given location, and it is also employed as a phase datum in receiving equipment at the slave stations.

All Decca receivers for marine and survey use, and those for air applications in which the full accuracy of the system is required, are of the "multiplying" type described above, and the use of this form of receiver is assumed in the discussion of accuracy which follows. For aircraft use, the positional sensitivity of a multiplying receiver is often unnecessarily high, and a superior signal/noise performance can be secured by avoiding frequency multiplication and deriving by frequency division a common phase comparison frequency equal to the fundamental value f.

1.8. Lane identification

The receiver as described so far would rely upon the counting action of the Decometers to keep track of the whole zones and lanes that the craft passes through; the indicators would have to be set to the correct whole number values at the start point and reception would have to be uninterrupted. (Computer-type methods of lane integration are neglected in this description). To provide an independent means of reducing the lane ambiguity, so that a user can set-in or check the lane numbers when uncertain of his position to within a lane, each chain radiates lane identification signals three times per minute.

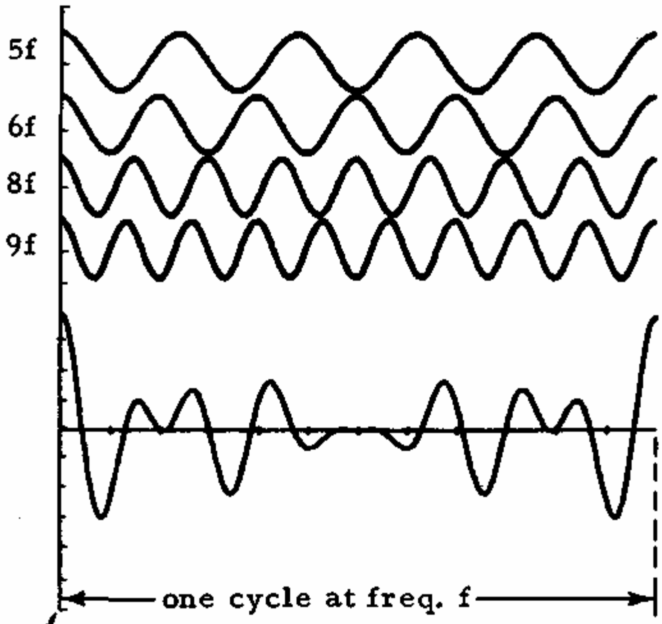
For this purpose the chain transmissions are periodically interrupted and re-grouped so that the receiver can extract a signal of frequency f from the master and from each slave. Comparing the phase of these signals generates a coarse hyperbolic pattern confocal with the fine one, such that one cycle of phase difference embraces 18 green, 24 red and 30 purple lanes. An additional phase difference meter responds to the coarse pattern and gives periodic readings which indicate, in turn, the correct lane of each pattern within a known zone. In some receivers, instead of actuating a meter, the lane identification transmissions automatically resolve the cycle ambiguity in the individual signals, thus eliminating the lane ambiguity at its source.

In the early years of the system, lane identification was of the "V" type, in which the master transmitted a 5f signal phase-coherent with the 6f during the half-second identification period in place of the normal 5f signal from the purple slave; the receiver extracted the desired If frequency master signal as the beat note. Similarly each slave in turn sent 9f and 8f together to provide a beat note of the same frequency. The present multipulse (MP) type of lane identification has been in use since the late 1950"s and derives the required If signal from each station by a method in which twice as much information is transmitted as in the V mode. This has the result that the MP generates a coarse pattern having greater integrity at long ranges than the fine patterns: the reverse tended to apply to the earlier method. The development of the MP technique ensured the long-term viability of the Decca Navigator as a practical navigational aid.

For MP lane identification each station in turn, starting with the master, radiates all four Decca frequencies (5f, 6f, 8f, 9f) simultaneously in a phase-coherent relationship (see Fig. 1. 5a). In the receiver, the four harmonics in each such transmission are summed so as to derive a pulse train having the fundamental value f; given means of memorising the master signal so that it can be compared with the successive slaves, this reconstituted pulse signal forms the basis of the desired f-frequency coarse pattern. The short pulse recurring at the fundamental frequency is the dominant feature of the summation waveform (Fig. 1. 5a), and has the important property that it remains stable in phase in the presence of large mutual phase shifts in the constituent harmonics.

(a)

The periodic MP transmission from a station consists of four sinewave harmonic components, synchronized with peaks in coincidence as shown. By summing the components, the receiver derives a waveform of which the dominant feature is a short pulse recurring at the fundamental frequency.



(b)

The MP waveform (3 cycles) as it appears in the absence of any phase shifts in the individual components. Comparing the phase of the If pulse trains from master and a slave produces the required coarse hyperbolic pattern for lane identification.

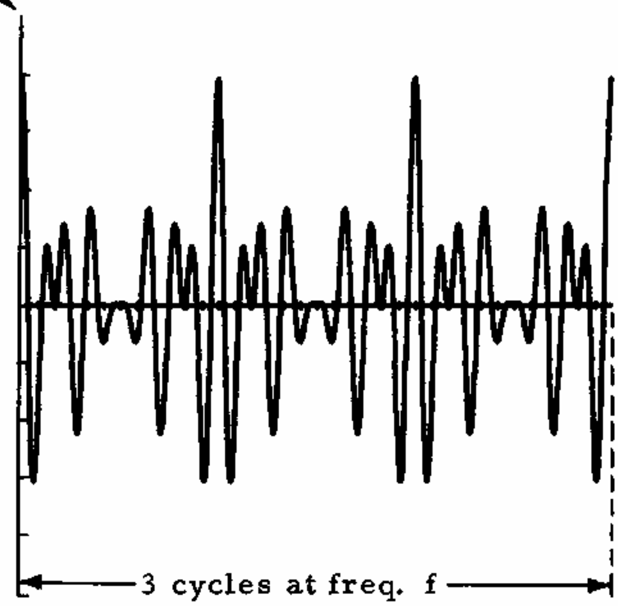
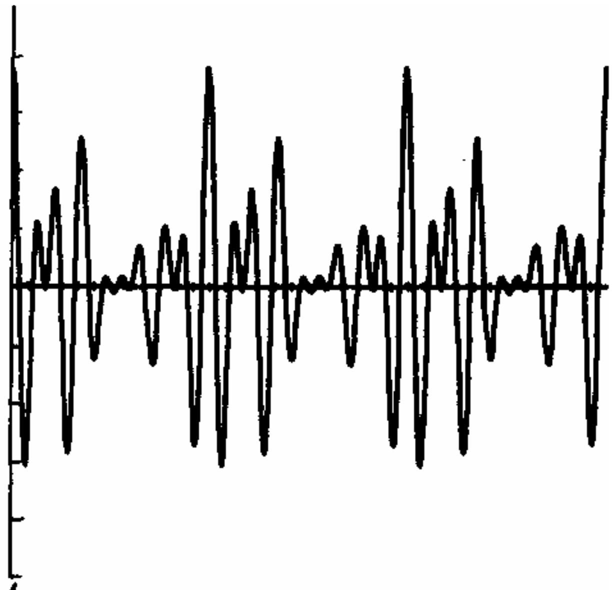


Fig. 1. 5(a) and (b). Computer plots showing derivation of MP lane ident. signal and its characteristic waveform under ideal reception conditions.

(c)

MP waveform (3 cycles) when the phase of the components *is* shifted by +16° for 5f, 8f and -16° for 6f, 9f. This is the least favourable combination of signs. Phase of pulse train remains unaltered.



(d)

MP waveform (3 cycles) when the phase of the components is shifted by +33° for 5f, 8f and -33° for 6f, 9f. Phase of pulse train remains unaltered but unwanted peak of same amplitude intrudes.

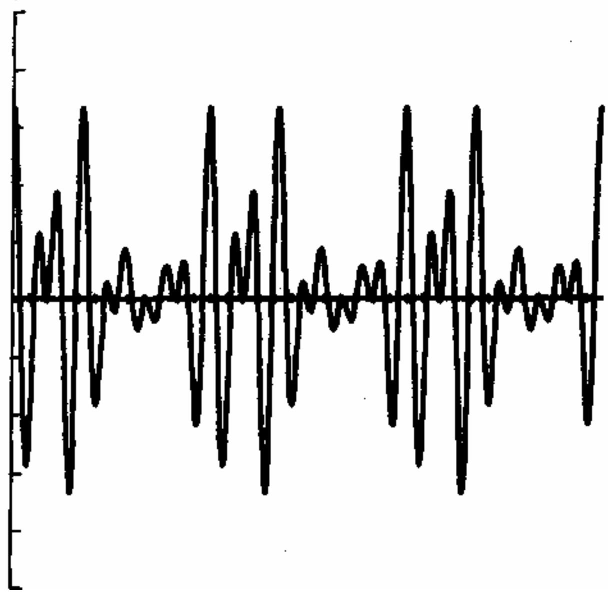


Fig. 1. 5(c) and (d). Computer plots showing effect on MP waveform of phase shifts in component sinewaves.

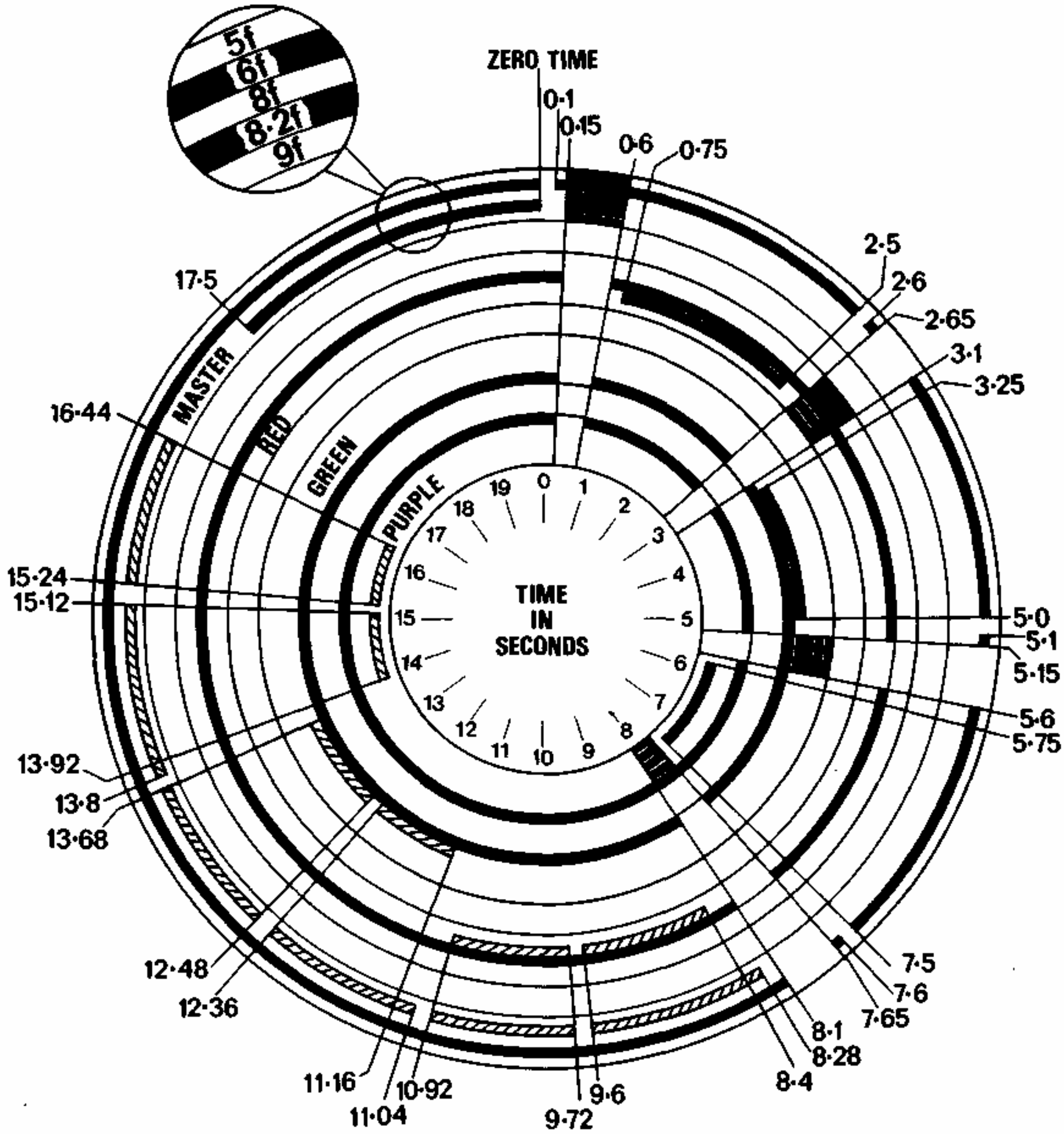


Fig. 1. 6. 20-second transmission sequence for MP Decca Navigator chain. Hatched periods denote 8. 2f command and data transmissions for chain control and surveillance.

In Fig. 1. 5c, for example, the summation waveform is shown when all four harmonics have been shifted in phase by 16 ; the phase of the pulse is unaltered and its amplitude clearly exceeds that of the rest of the waveform. The 16 phase shift in the harmonics corresponds to the condition of 28% skywave which represents the limit of reliable V mode lane identification. Fig. 1. 5d shows the result of shifting all four harmonics by 33 in the least favourable combination of signs, and depicts the point at which the summation waveform breaks down, as a If phase datum, through the intrusion of another peak. The 33 shifts correspond to a sky wave/groundwave ratio of 55%, a condition which would be expected to occur only at night and at distances from the stations beyond the nominal 240 n. miles (440 km) radius of the chain.

As indicated earlier, the If hyperbolic pattern derived from the MP signals has a higher integrity at the fringe of the chain coverage by night than the fine pattern. For this reason the lane identification readings are often used in place of the Decometers by night to provide the basic position-fix. In general the transition from Decometers to MP readings is made at distances where the night-time standard deviations of the normal patterns tend to be greater than 0. 1 lane (see Fig. 3. 7), that is to say at distances greater than some 100-150 miles (180-275 km) from the stations. Beyond these distances, a fix from MP readings is about 20% more accurate than the fine-pattern fix; as range is further increased, there comes a point at which the fine patterns become insufficiently reliable and the MP frequencies are then the sole means of fixing. The limit of night-time coverage is set by the tendency of the synthesized pulse to break down as a phase datum, as shown in Fig. 1. 5d.

1. 9. Zone identification

The complete transmission sequence of an MP chain is shown in Fig. 1. 6. Every 20 seconds the stations transmit the MP signals in the order MRGP-, together with an 8. 2f component. The MP signals last 0. 45 seconds and are spaced at 2. 5 second intervals. In receivers which include the zone identification facility, this is based on the beat note between the 8. 2f and 8. Of signals from the respective stations, giving a hyperbolic pattern of which one phase difference cycle embraces 5 zones. Normally, the zone identification information is displayed on a separate meter on which the scale is divided into five sections, AF, BG, CH, DI, EJ. It is assumed that of the two 5-zone groups represented by these markings, the user knows which he is located in.

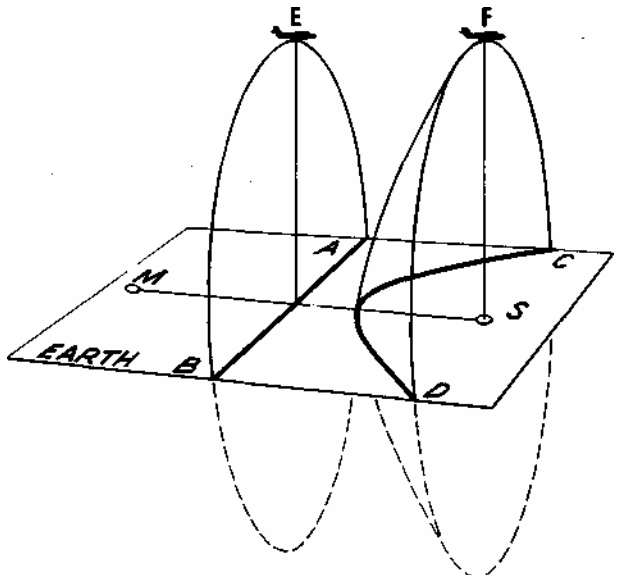


Fig. 1. 7. Effect of altitude on position-line. In an aircraft at E, in the vertical plane of the central hyperbola AB, error due to altitude is zero. At F, over a station, the uncorrected readout would give hyperbola CD as the position line, (from Ref. 1. See page 3. 20).

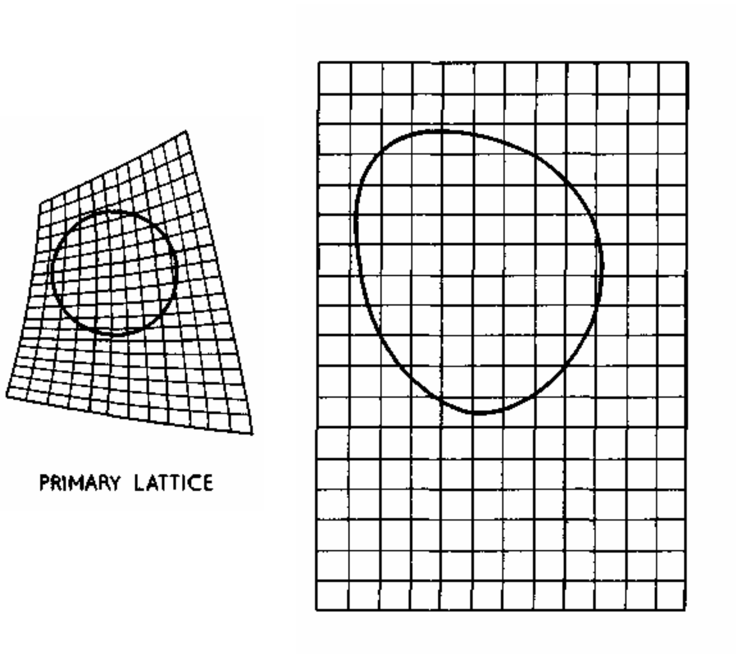


Fig. 1. 8. Inverse lattice drawn for 90 angle of cut, showing distortion of a circular track.

1. 10. The third dimension

In considering the basic principles of the Decca Navigator/ it should be noted that a hyperbolic position line on the earth's surface is the result of the intersection of a three-dimensional surface of revolution with the plane containing the stations as shown in Fig. 1. 7. In an aircraft, when the height of the receiver above the ground is other than very small compared with the distance to a station, an error in the position fix can result from the fact that the signals propagate along the direct paths from the stations to the aircraft. This so-called slant range error is zero mid-way between a master and a slave station, and maximum over one station or the other. In general, the effect is only of navigational significance in high-flying aircraft on a route passing over a chain; the error at a given height can readily be calculated, and in practice is normally circumvented by using (for example) the three slave stations for position fixing when the route lies over the master.

1. 11. Secondary patterns

When a Decca receiver is used in conjunction with an automatic plotter having axes at right angles, e. g, a chart moving vertically in response to one hyperbolic pattern and a pen or bug moving laterally in response to the other, a continuous positional display is provided. The simplest chart for such a display is drawn on the basis of an "inverse lattice" in which the two patterns are assumed to be straight and parallel lines of uniform spacing and intersecting at right angles. In principle this special form of map projection introduces no error, but it distorts the map detail in the manner shown in Fig. 1. 8.

One method of reducing inverse-lattice distortion was to introduce a systematic cross-feed between the two inputs to the display. This "skewing" process enabled the chart to be drawn for some constant angle of cut other than 90° and approximately to the average angle for the area covered by the chart. Another method involved the use of the so-called secondary patterns which are derived by adding or subtracting the Decometer readings from different primary patterns; these can form a co-ordinate system giving a marked reduction in distortion, particularly in areas where the angle of cut is small (Fig. 1. 9). The inverse-lattice technique and the means of reducing its distortion were eventually superseded by the more rigorous co-ordinate transformations that the development of on-board digital computers made possible, but one particular secondary pattern is worth noting here since it has other applications.

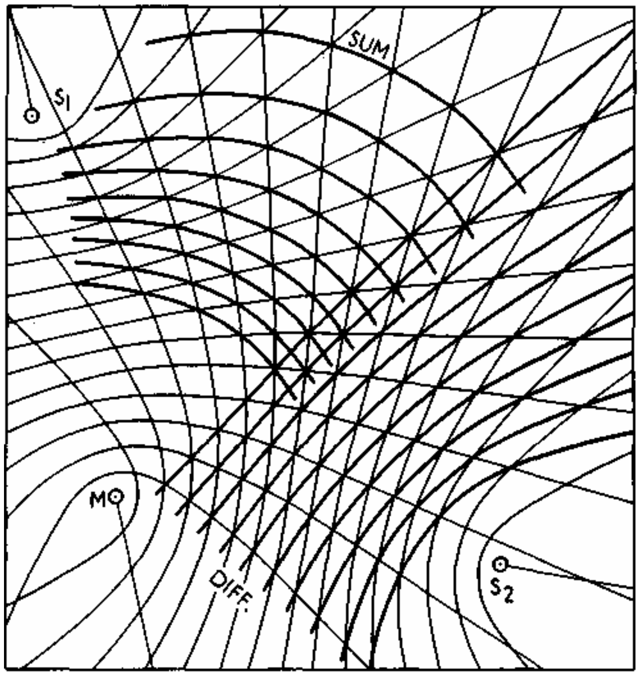


Fig. 1.9. Sum and difference patterns formed from primary zone patterns. The secondary patterns intersect at a large angle where the primary angle of cut is small (Ref. 1. Page 3. 20).

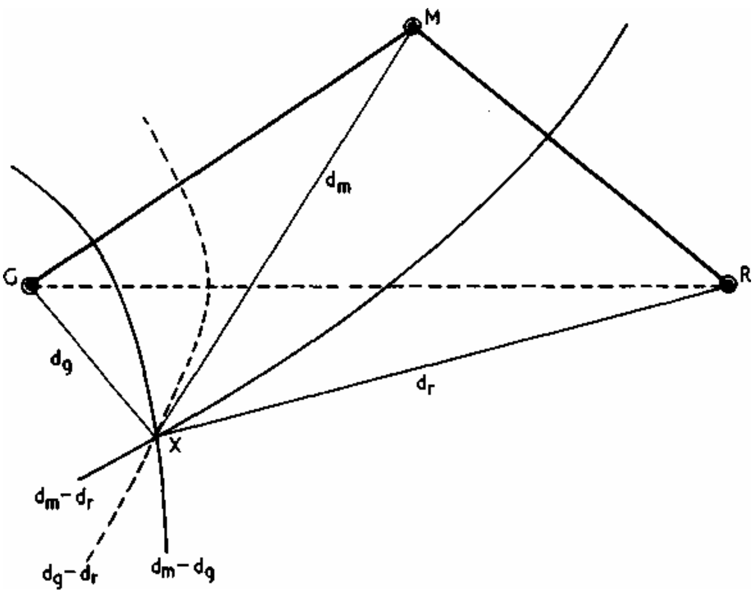


Fig. 1. 10. Hyperbolic position lines from a three-station chain. At any point X there are two independent position lines. Difference pattern position line and baseline are dotted.

In a chain with master station M and two slaves R and G, used by a receiver located at distances d_m, d_r and d_g from the respective stations as in Fig. 1. 10, the position-fix normally consists of the intersection of the red position line corresponding to the distance-difference $d_m - d_r$ with a green position line $d_m - d_g$. A third hyperbolic pattern exists on the slave/slave baseline GR since the slaves are mutually phase-locked through being locked to the master; normally this pattern is ignored since it contains no additional information, as can be seen from the relationship between the distance difference which is such that

$$d_g - d_r = (d_m - d_r) - (d_m - d_g)$$

In taking the difference between, say, the red and green Decometer readings the scaling factor has to be included to take account of the different basic lane widths of the two patterns. By multiplying the red and green readings by 3 and 4 respectively, the difference value then relates to the common comparison frequency 72f and the hyperbolic pattern so derived has a lane width on the slave/slave baseline corresponding to that frequency. This method is the basis of the "brown" pattern which provides across-track guidance along a harbour approach channel in the coverage of a Decca chain, the red and green slave stations being so disposed as to bring the centre line of the difference pattern into coincidence with the channel. Normal shipborne receivers are used, and the multiplication, .subtraction and display functions are performed in a plug-in ancillary unit called the Brown Box.

Difference patterns can also be derived in terms of zone and zone fractions, by subtracting the lane identification readings for the two patterns concerned. No scaling factors are required since the comparison frequency (1f) is the same for all three lane identification patterns. This has proved useful in long-range ocean navigation for optimising a fix derived from one Decca and one Loran position line. Difference patterns are also used in airborne equipment as a means of avoiding slant range error when over-flying a master station (para. 1. 10), for example by using red minus green as one position line and purple minus green as the other.

1. 12. The Doppler effect

When there is relative motion between a receiver and a transmitter the received signal is said to suffer a Doppler frequency-shift; this is simply another way of saying that the phase of the received signal is changing by reason of the changing length of the transmission path. While there is no need to invoke the Doppler effect as such when describing the principles of the Decca Navigator, the operation of the system is in fact a manifestation of that effect rather than being, as is often thought, adversely affected by it. The confusion may arise from the fact that receiver performance will suffer if a tracking filter of the type used in Decca equipment should fail to follow the changes in Doppler shift that occur through manoeuvres of the craft. The following example shows that the basic operation of the system can be described either by reference to Doppler or otherwise, according to choice.

Consider a ship moving at a speed of 3 metres per second (6 kt) along the baseline between the master and the red slave stations and passing across successive lanes of that pattern. Assume for simplicity that the speed of signal propagation is 300 metres per microsecond. On the baseline the lanes have a constant width equal to half a wavelength at 340 kHz, giving a red lanewidth of 441 m; the ship's speed is such that it will traverse one lane, and the red Decometer fraction pointer will make one revolution, in 147 seconds. Considering the same case in terms of Doppler shifts, the ship's speed of 3 m/s is exactly $1/10^8$ of the propagation speed. The signal from the station ahead of the ship will therefore be received with a positive Doppler shift equal to $1/10^8$ of the comparison frequency while the frequency of the signal from the other station will be shifted negatively by the same amount. The received master and slave signals will thus differ in frequency by $(2/10^8 \times 340)$kHz, which would cause the Decometer fraction pointer to turn at the rate of 0. 0068 Hz; this is equal to one revolution in 147 seconds.

1. 13. Effects of noise

In principle, the range of the system and the accuracy of the Decometer readings are both dependent upon the ratio of the signal strength to the ambient noise. In practice, however, the level of radiated power of the main chain Decca stations is such that the required coverage is ensured under all but highly exceptional and transitory atmospheric noise conditions. In regard to accuracy, random variations in the Decometer readings will increase in magnitude as the signal/noise ratio diminishes, but variations from this cause are to a considerable extent amenable to smoothing; moreover, when the system is being used with maximum accuracy as the prime requirement, the receiver will generally be located in a geometrically favourable area where transmission paths are short and signal strength correspondingly high. The receiver can, of course, be interfered with by locally-generated noise of high intensity, such as precipitation static on an aircraft. Suitable precautions (e. g. the fitting of wick dischargers) must be taken against such interference, and also against the possibility of radio-frequency interference from other electronic equipment in an installation.

1. 14. Field strength and range

The number of parameters involved in determining the working range or service area of a chain is such that sufficient data could not be provided in this handbook to allow satisfactory range calculations to be made. In practice, such calculations are seldom necessary since every permanent chain is designed from the outset to ensure the effective coverage of a specified area. The main parameters are, however, noted below for general information, together with data on the relationship between field strength, range and the characteristics of the transmission path.

The accuracy of the position-line given by a Decca receiver will depend on the signal/noise ratio of the received master and slave signals. The tolerable minimum signal/noise ratio for satisfactory operation can vary over a wide range (more than 20 dB) depending on a number of factors. These include the bandwidths and other characteristics of the Mark of receiver concerned; the receiver function being considered, e. g. lane integration or lane identification; and the required standards of accuracy and serviceability expressed as probability levels. As a very approximate indication, which will be subject to wide variations for the reasons stated and with the future evolution of receiver design, a figure of 10 dB may be taken as a representative signal/noise ratio for satisfactory receiver operation. The main source of noise at the Decca frequencies is the equatorial thunderstorm belt and the predicted level of this atmospheric noise varies widely from place to place and with time and season.

The field strength of the received groundwave signal depends upon the degree of attenuation to which it has been subjected along the transmission path, the attenuation being the result of losses through imperfect electrical conductivity in the land or water over which the signal passes. Typical conductivity figures in electromagnetic units (e. m. u.) are shown in Table 1. 5 for sea water and for various types of terrain. The conditions covered by the "very bad" category are only found in a few parts of the world.

Table 1. 5.

TYPICAL CONDUCTIVITY DATA

Quality	Example of medium	Value (e. m. u.)
Best	Sea water	5×10^{-11}
Good	Land of S. England, E. Anglia	1×10^{-13}
Average	Approaches to Pennines	2×10^{-14}
Poor	Pennines, Exmoor, sandy desert	1×10^{-14}
Bad	Scottish highlands, parts of Scandinavia.	5×10^{-15}
Very bad	Parts of Norway, N. Canada, Greenland.	1×10^{-15} to 1×10^{-16}

Tables 1. 6 and 1. 7 show the field strength of the groundwave signal received at various ranges for five mean conductivity values, taking the frequencies of 70 kHz and 127 kHz to represent the lower and upper limits of the Decca band. Table 1. 8 indicates the rule-of-thumb relationship between field strength expressed in dB above 1 μV/m and in absolute units.

Table 1. 6.

GROUNDWAVE FIELD STRENGTH AT 70 kHz

for radiated power of 100 W, for five conductivity values (e. m. u.)

Range		Field strength in dB above 1 μV/m				
km	(n. mile)	5×10^{-11}	1×10^{-13}	2×10^{-14}	1×10^{-14}	5×10^{-15}
50	(27)	65	65	64	63	62
100	(54)	59	59	58	57	56
150	(81)	55	55	54	53	51
200	(108)	52	52	51	49	46
250	(135)	50	50	48	46	43
300	(162)	48	48	46	44	39
350	(189)	46	46	44	41	36
400	(216)	44	44	42	39	33
450	(243)	43	43	40	37	30

Table 1. 7.

GROUNDWAVE FIELD STRENGTH AT 127 kHz

for radiated power of 100 W, for five conductivity values (e.m. u.)

Range		Field strength in dB above 1 μV/m				
km	(n. mile)	5×10^{-11}	1×10^{-13}	2×10^{-14}	1×10^{-14}	5×10^{-15}
50	(27)	64	64	63	61	58
100	(54)	58	58	57	55	52
150	(81)	55	55	52	50	45
200	(108)	51	51	49	45	38
250	(135)	49	49	46	41	33
300	(162)	47	47	43	38	28
350	(189)	45	44	40	34	24
400	(216)	44	43	38	31	19
450	(243)	42	41	35	28	16

Table 1. 8.

APPROXIMATE RELATIONSHIP BETWEEN FIELD STRENGTH EXPRESSED IN dB RELATIVE TO 1 |J.V/m AND DIRECTLY IN μV/m

dB	μV/m	dB	μV/m
0	1	40	100
10	3	50	300
20	10	60	1000
30	30	70	3000

1. 15. Radiated power of stations

In general, a main-chain Decca transmitting antenna consists either of a single base-insulated mast some 100 m in height, with the upper portions of the stay wires forming an "umbrella" capacity top, or three 50 m masts in line supporting a horizontal top and fed at the bottom of the central mast. The height of the 100 m mast corresponds to only about one-thirtieth of a wavelength at the average transmitted frequency, so that in absolute terms the antenna efficiency is low. A compensating factor is that the receivers can employ an extremely narrow r. f. bandwidth, in the order of tens of cycles, by reason of the fact that the only intelligence conveyed by the signals is their relative phase.

As shown in Fig. 1.6, a given station radiates on a single frequency for most of the time, but periodically transmits on five different frequencies simultaneously. The transmitter power amplifiers therefore comprise five separate channels and feed a multiple-tuned antenna circuit. Each channel delivers an output having a nominal power of 1. 2 kW into the antenna circuit. Table 1. 9 shows the measured radiated power at the different frequencies from stations equipped with the two different types of antenna system. These figures are representative but the power at a given frequency can vary between stations of the same specification, by up to a factor of 2 depending on the ground conductivity at the sites.

1. 16. Transmission quality control

While many Decca transmitting stations operate unattended, a basic part of each chain is the manned control centre which is normally located at or near the master station. At the control centre, the radiated position-line patterns and the MP signals are continously monitored,

Table 1. 9.

RADIATED POWER (W) FROM 100 m AND 5 0 m ANTENNA SYSTEMS.

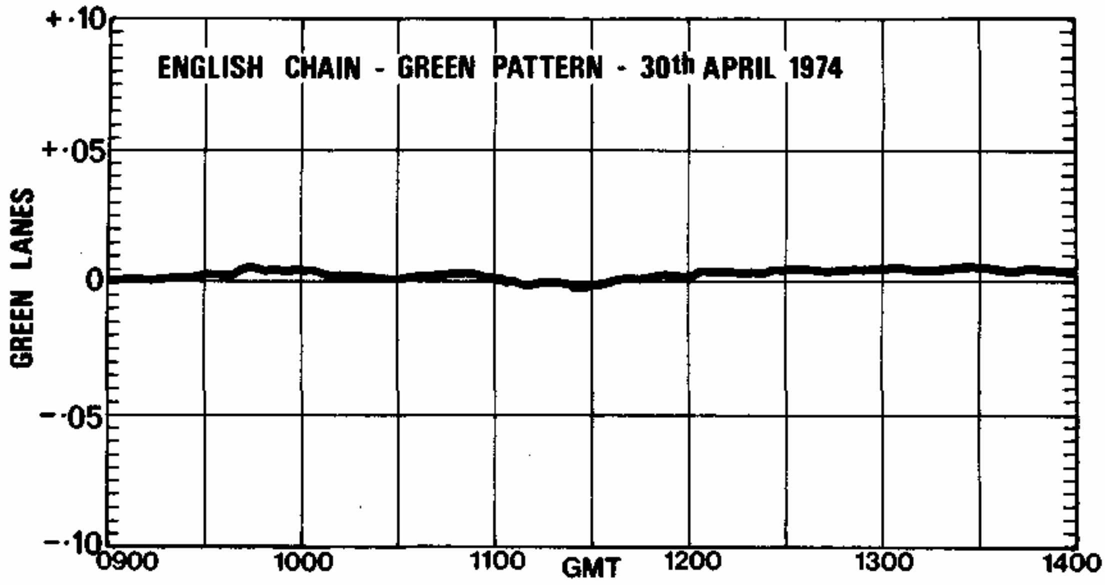
Frequency	100 m single mast	50 m 3-mast T
5f	93.8	43.0
6f	97.9	49.5
8f	116.8	58.0
8. 2f	122.0	62.5
9f	131.5	66.5

and the state of the main items of equipment on each station is displayed and recorded by means of periodic data transmissions. The slave stations use the 8. 2f frequency for the status signals (Fig. 1. 6), and the same frequency is used by the master for remote-control commands to the slaves. This comprehensive monitoring/surveillance/ control system, combined with extensive equipment redundancy and back-up facilities at the individual stations, ensures transmissions of high quality and integrity. The stability of the transmitted patterns is normally maintained at 0. 01 lanes (standard deviation). Examples of monitor records are shown in Fig. 1. 11.

1. 17. Baseline measurement

When mobile Decca Navigator chains were used for survey work, before the introduction of the Hi-Fix survey systems, the stations were sometimes set up at approximately-known or unknown positions and used in a relative mode of position fixing. The length of the baselines could, however, be determined provisionally from Decometer readings alone, enabling the patterns to be computed and drawn with respect to the chain as an arbitrary framework. The baseline measurement depended on counting the total number of lanes in the pattern. A similar but converse procedure remains in occasional use as an initial check on the total lane number, assuming the baseline lengths to be known, when a new chain starts test transmissions.

The length of an unknown baseline is found from Decometer readings by first crossing, say, the master baseline extension in a suitable craft equipped with a Decca receiver and noting the minimum value to which the respective Decometer reading falls. The extension line is self-identifying by the change in the sense of the Decometer rotation on crossing it, and the crossing can take place at any point farther than about 10 km from the master (nearer the station there is



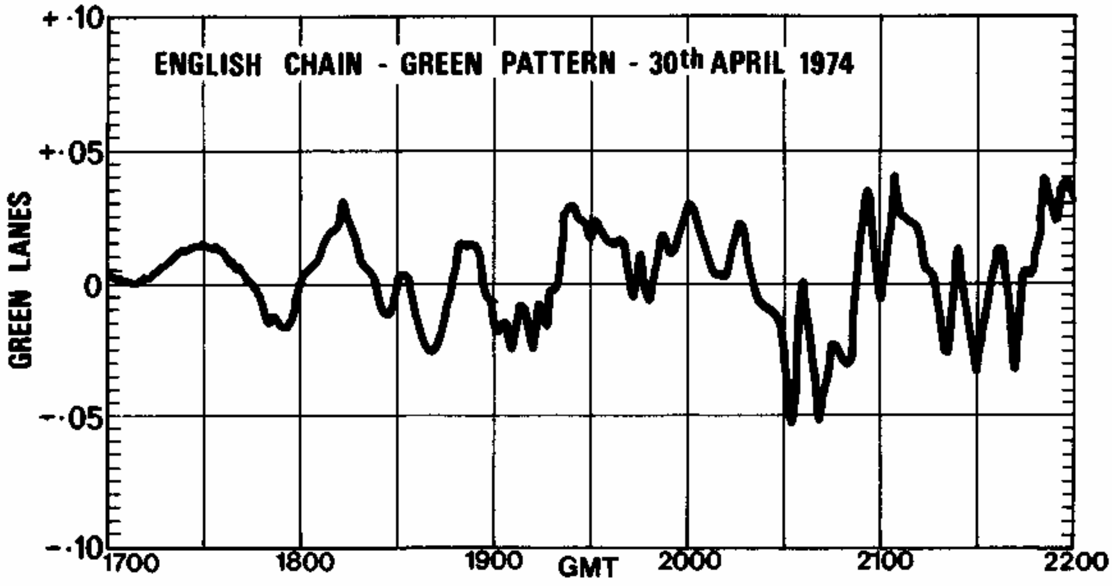


Fig. 1. 11. Monitor records from a Decca main chain (5B) showing sample 5-hour periods by day and night.

the possibility of phase distortion through the local induction field). Airborne crossings are made at an altitude low enough to avoid the slant range error described in para. 1. 10. The receiver is then taken around the pattern so as to count the number of lanes and the total lane number plus fraction is found by noting the maximum reading on crossing the slave baseline extension and comparing it with the master extension reading. Thus a slave extension reading of 350. 65 (neglecting the conventional lane notation) and a fractional reading on the master extension of 0. 75 would indicate a total lane number of 349. 90. Since the lane width on the baseline is equal to half a wavelength, the baseline length can be found given the wavelength for the known frequency and the assumed propagation speed.

In survey work, the third side of the triangle, and hence the included angle between the master/slave baselines, could be determined by using the difference pattern which is focussed on the slave stations (para. 1. 11); for this purpose the readings of both Decometers were recorded when crossing the extensions of the inter-slave line and the lanes of both patterns were counted on flying along-or round that line. In principle all the baselines could be measured on a single flight around the chain. Alternatively, the inter-slave distance could be found by static observations in which, say, the red Decometer reading was observed on a receiver located at the green slave station, given that the lengths of the master/slave baselines and the red whole lane number at the observing receiver had been determined. This technique was ultimately refined to the point of forming the basis of a geodetic trilateration procedure (Ref. 2)*.

1. 18. <u>Two-range fixing</u>

In the early 1950's the "Two-range Decca" technique was introduced in response to requests by hydrographers for a mobile position-fixing system dealing in direct range measurements rather than in distance differences. Later versions included a non-standard frequency relationship (master 12f, slaves 9f and 8f) and, in the Lambda system, lane identification. The latter employed an additional signal (1 If) from the master together with counter-changing of the slave frequencies. The user ship carried the master transmitting station together with the receiver, and the two slave stations were set up at known points on shore. The technique was one of direct distance measurement in which the slaves operated virtually as transponders. If the speed of propagation is known, the total lane number in the pattern produced by the master and a slave is a measure of the inter-station distance; with the master and receiver on board the ship, a circular position line pattern was thus provided about each slave station and hence a two-range fix. A note on the accuracy of the fix is given in Chap. 2 (para. 2. 11).

* References are listed at the end of Chap. 3.

The slave phase control equipment performed its normal function of holding the slave transmission at a fixed phase difference (generally zero degrees in these systems) with the received master signal. On the ship the receiver displayed the distances to the slaves as Decometer readings, a change of half a wavelength in the distance giving a change in the reading of one lane. With a standard receiver the readings would decrease as the receiver/slave distance increased and the wiring was accordingly modified to reverse the sense of rotation. The position of the ship was sometimes monitored ashore by means of a receiver sited at a known position between the slaves; this receiver gave the fix in hyperbolic co-ordinates, identical with those which would have been generated if the monitor receiver had been replaced by the master transmitter.

Chapter 2

DAYTIME ACCURACY AND COVERAGE

Contents

List of Illustrations

DAYTIME ACCURACY AND COVERAGE

2. 1. Introduction

This chapter is written from the point of view of a hydrographic surveyor or similar user who requires the highest possible accuracy of position fixing from a Decca Navigator chain. Except where stated, the chain is assumed to be of the main or permanent type. Such a user would generally employ a survey-type Decca receiver, in which special steps are taken to minimise instrumental errors, and he would operate at short or moderate distances from the chain and at times and seasons at which skywave interference is minimal.

While the following paragraphs refer to this special case, they also serve to introduce the d. rms criterion used in general random error calculations for the system, and to show how the coverage and accuracy vary with different geometrical chain configurations. A note on the two-range version of the system is included.

2. 2. Random errors

Random errors arise from such causes as minute-to-minute changes in ionospheric conditions, short-term phase changes in the equipment, errors in readings, etc. Decometer readings taken at a given point will therefore be distributed with some degree of spread about the computed Decca co-ordinates of that point. A fair estimate for the standard deviation about the mean value of a large number of such readings, for daytime use of a chain at distances less than 150 miles (275 km) from the stations, and assuming sea-water transmission paths, is 0. 01 mean lanes. A "mean lane" is a convenient unit having a width on the baseline that is roughly the average of the red and green lanewidths, namely 500 m, and corresponds to a fictitious comparison frequency of 300 kHz. A change of 0. 01 mean lanes therefore represents a change of position of 5 m along a master/slave baseline.

The standard deviation is not wholly independent of range. During summer daylight the increase is very small, of the order of 0. 003 (1 + d) where d is the range from the mid-point of the baseline in hundreds of miles. In winter this figure may be approached for a few hours in the middle of the daylight period, but is subject at other times of day to an increase by a factor of up to four or more. At night, the patterns are in general much less stable, due to increased interference by the skywave-propagated signal with the groundwave signal to which the lattice computations are related. The effects of skywave are considered in Chapter 3.

The Gaussian or normal distribution gives the best general fit for the spread of random errors in the Decca position lines under short-range daylight conditions. To describe the likely degree of uncertainty of a single Decca fix taken at a given point in the coverage, the root mean square error criterion is used. Taking for example a red/green fix, the r. m. s. error is given by

$$d_{rms} = \cos ec\beta\sqrt{\sigma_1^2 + \sigma_2^2 + 2k + \sigma_1\sigma_2 + \cos\beta}$$

Where β is the angle of cut between the position lines

k is the correlation factor between the instantaneous deviations of the red and green co-ordinates from their mean values

σ_1 is the standard deviation of the red co-ordinate in units of distance, derived as follows:

$$\sigma_1 = \sigma_R W_R \cos ec\frac{\gamma_R}{2}$$

where σ_R is the standard deviation of the red co-ordinate in lanes

W_R is the lanewidth on the red baseline

γ_R is the angle subtended by the red baseline at the point of observation.

$\cos ec\frac{\gamma_R}{2}$ is termed the "lane expansion factor", which is multiplied by W_R to give the lanewidth at the observation point, see Fig. 2. 1)

σ_2 σ_G W_G γ_G similarly for the green co-ordinate

The r. m. s. error can be described as the radius of a circle which, symmetrically drawn on the fix distribution, includes approximately 68% of the plots. The odds against a single plot falling outside this circle would thus be about 2 : 1. This level of probability is generally used in survey work with Decca, but it is worth noting that doubling the radius of the circle would include some 95% of the plots.

Over the area in which a Decca chain is likely to be used for surveying, the correlation factor K between the two co-ordinates forming the Decca fix (due to the master transmission path being common to both patterns) is in general a small positive quantity under daylight conditions and can be taken as zero with negligible effect on the value of the r.m. s. error. The standard deviations of the error distribution in the green,

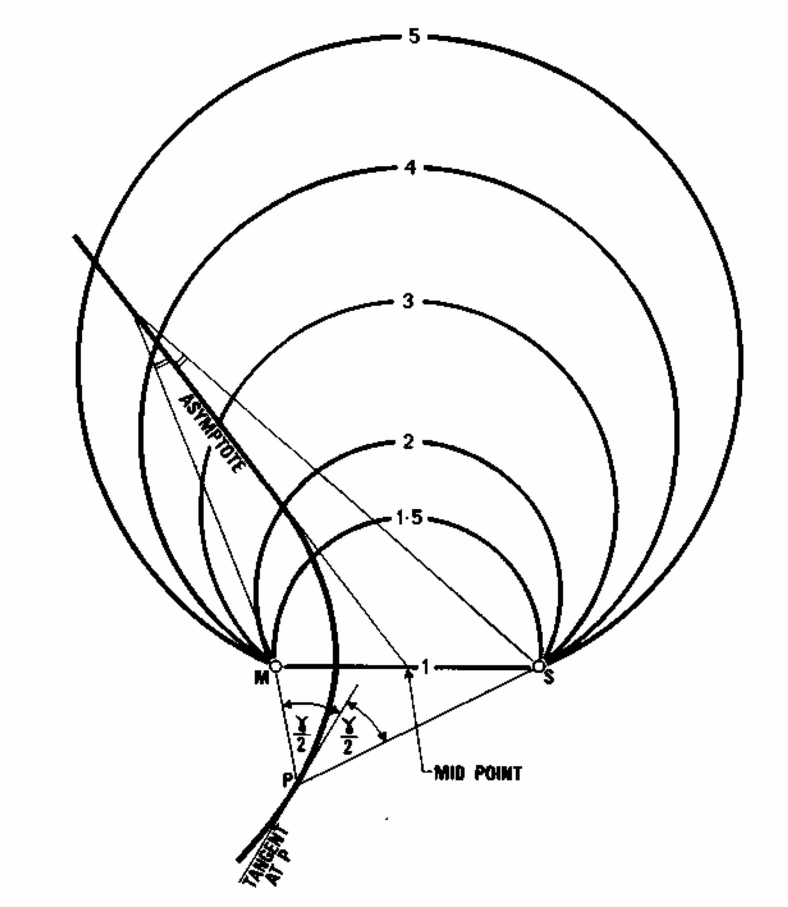


Fig. 2. 1. Contours for lane expansion factors 1-5. Expansion factor is cosec γ/2 equal to where y is the angle subtended by the stations M, S. At receiving point P the tangent to the position-line bisects the angle MPS.

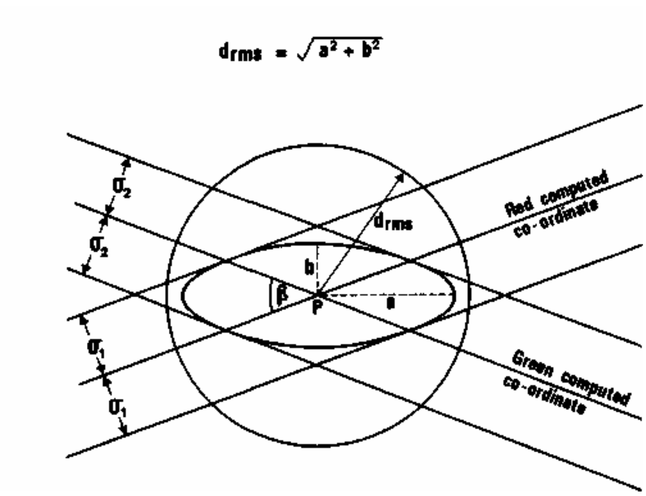


Fig. 2. 2. Relationship between d. rms and error ellipse (daytime operation, correlation factor K = 0).

red and purple readings tend to increase in that order at corresponding points in the respective patterns; but as the quantities represented by σ_1, σ_2 above are the standard deviations in lanes multiplied by the corresponding lanewidths on the baseline, and as these widths decrease for the three colours in the order quoted, a simple approximation can be assumed whereby each pattern is assigned the same standard deviation in mean lanes as defined earlier.

Taking 0. 01 mean lanes as a representative standard deviation for survey work, the factors in the above formula reduce to

$$\sigma_R W_R = \sigma_G W_G = 5 \text{ metres}$$

$$d_{rms} = 5 \cos ec\beta \sqrt{\cos ec^2 \frac{\gamma_R}{2} + \cos ec^2 \frac{\gamma_G}{2}} metres$$

K=0

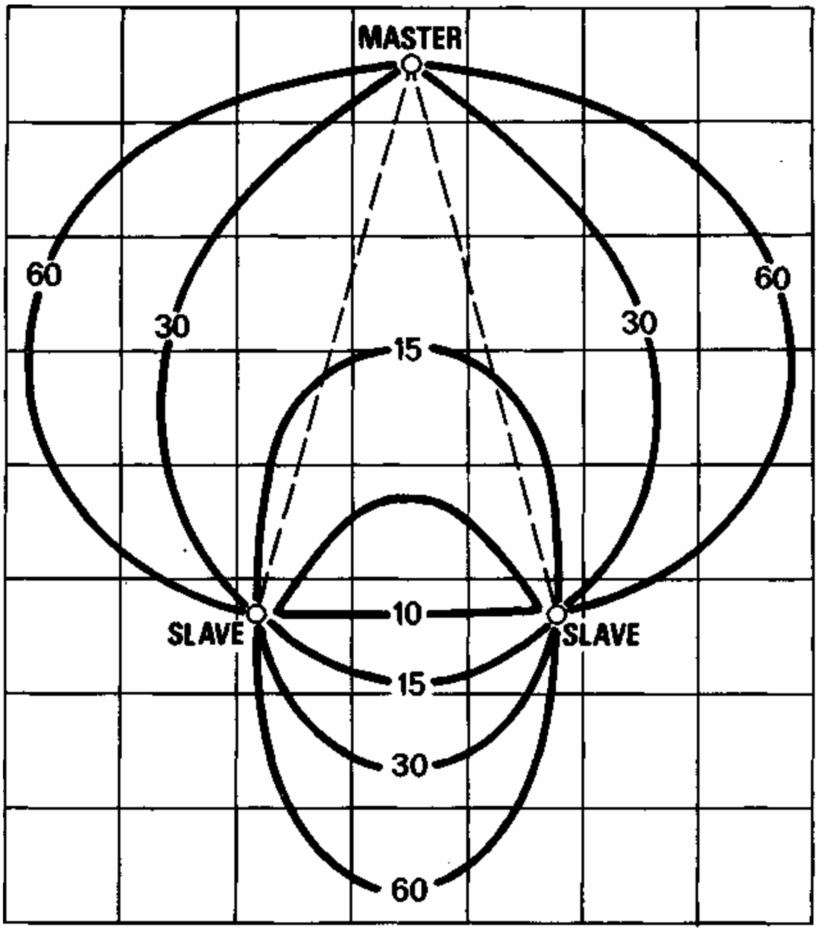
The r. m. s. error then becomes a function only of the standard deviation and the angles subtended by the baselines at the observing point. This formula is used in computing the contours of constant accuracy which are the standard method of depicting the coverage of a Decca chain. The d. rms criterion is conservative in the sense that it is expressly designed to take no account of the direction in which the error displaces the Decca fix from the true position. The error distribution is of elliptical form and the ratio of major to minor axis increases with range from the chain. At a given observation point, therefore, the error may be considerably less in certain directions than the d. $_{rms}$ value assigned to that point.

Fig. 2. 2 shows the computed red and green position lines passing through the observation point P and the erroneous position lines displaced plus and minus σ_1 , σ_2 from the computed lines. If the standard deviation corresponded to a probability of 68. 26%, the parallelogram formed by the displaced position lines would contain 68.26% x 68.26% = 46.6% of a large number of fixes taken at P. As already stated, the circle drawn about P of radius equal to the r. m. s. error would contain approximately 68% of the plots, the exact percentage being dependent on the ratio of major to minor axis of the ellipse (termed the a ellipse) enclosed by the parallelogram.

2. 3. Chain layouts

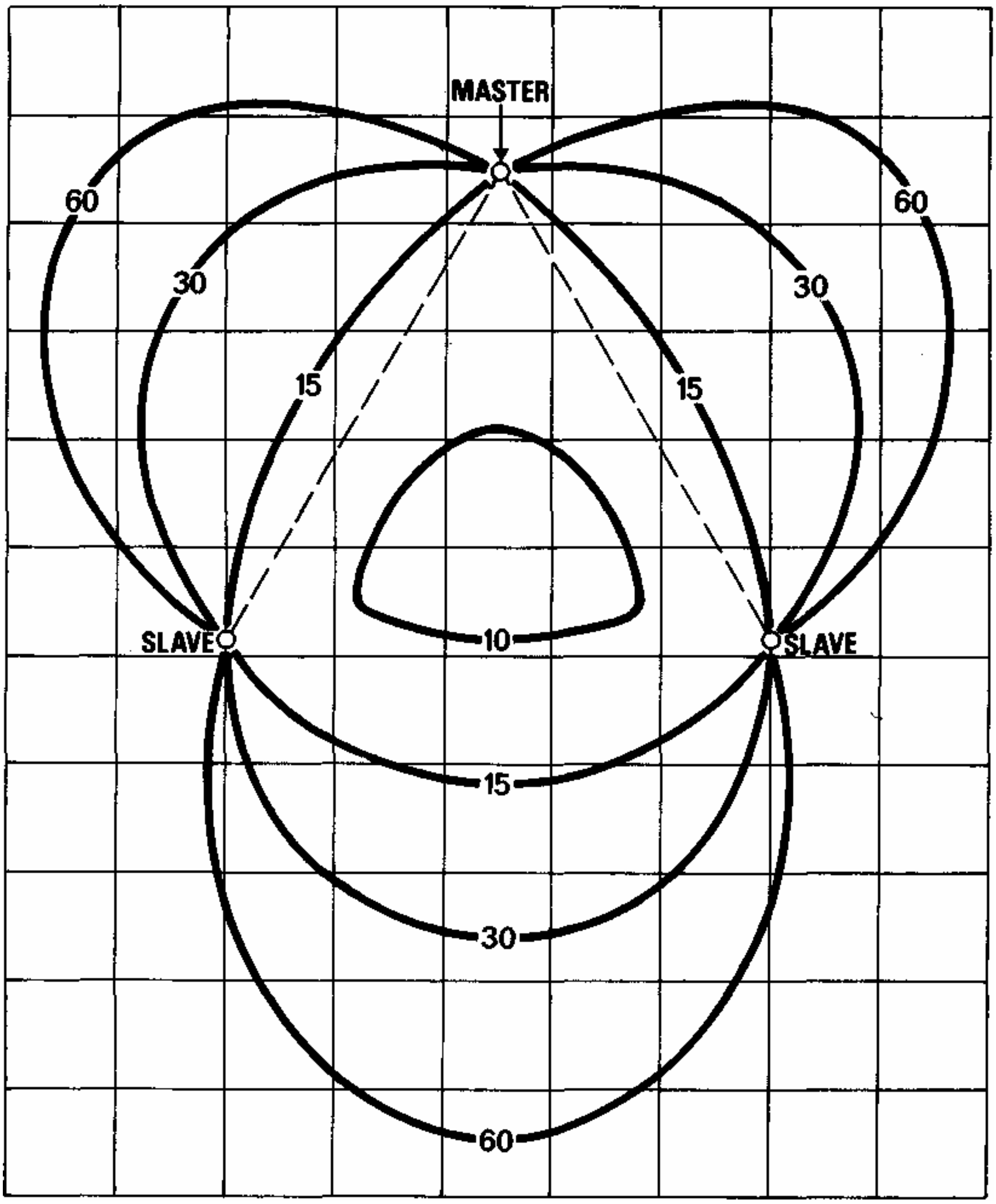
Decca chains vary considerably in layout. The extent of the coverage at a given fix-accuracy depends on geometrical factors such as the length of the two baselines involved in the fix and the angle between them. Fig . 2. 3 to 2. 8 show accuracy contours for four values of

(continued on page 2. 15)



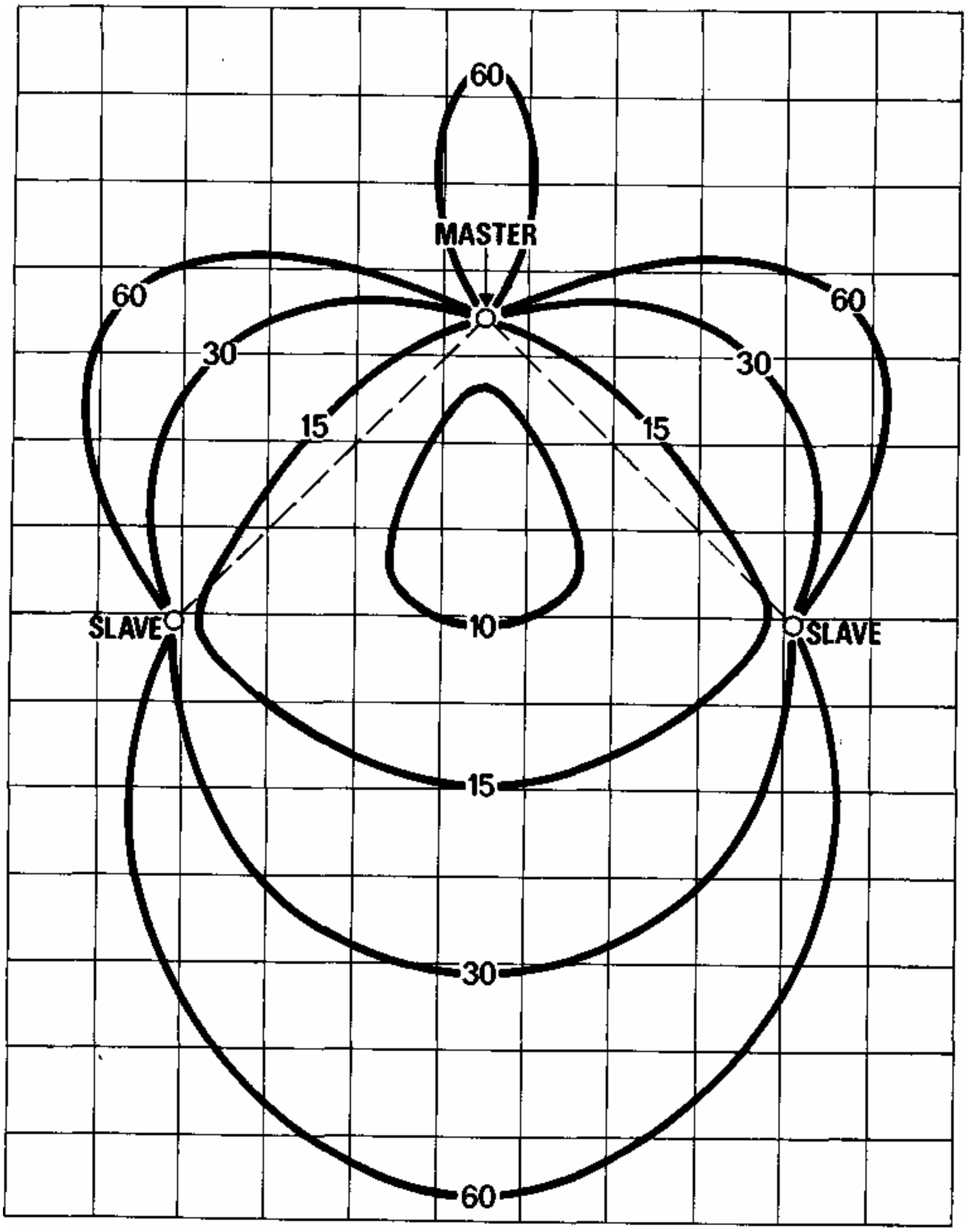
BASELINES AT 30°

Fig. 2. 3. Accuracy contours in metres for a standard deviation of 0. 01 mean lanes. The squares have sides one-fifth the baseline length, for estimation of ranges and areas.



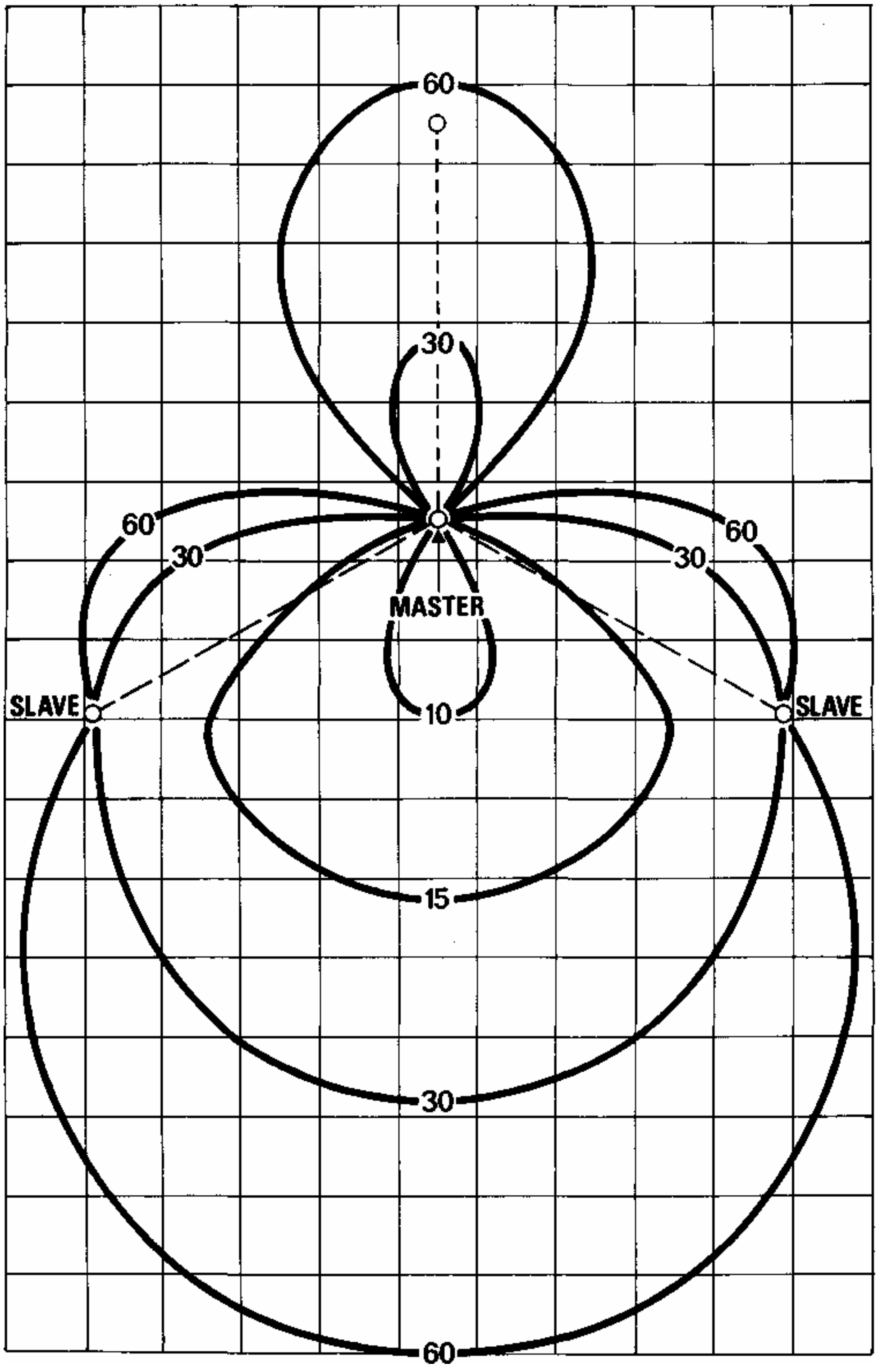
BASELINES AT 60°

Fig. 2. 4. Accuracy contours in metres for a standard deviation of 0. 01 mean lanes. The squares have sides one-fifth the baseline length, for estimation of ranges and areas.



BASELINES AT 90°

Fig. 2. 5. Accuraty contours in metres for a standard deviation of 0. 01 mean lanes. The squares have sides one-fifth the baseline length, for estimation of ranges and areas.



BASELINES AT 120°

Fig. 2. 6. Accuracy contours in metres for a standard deviation of 0. 01 mean lanes. The squares have sides one-fifth the baseline length, for estimation of ranges and areas.

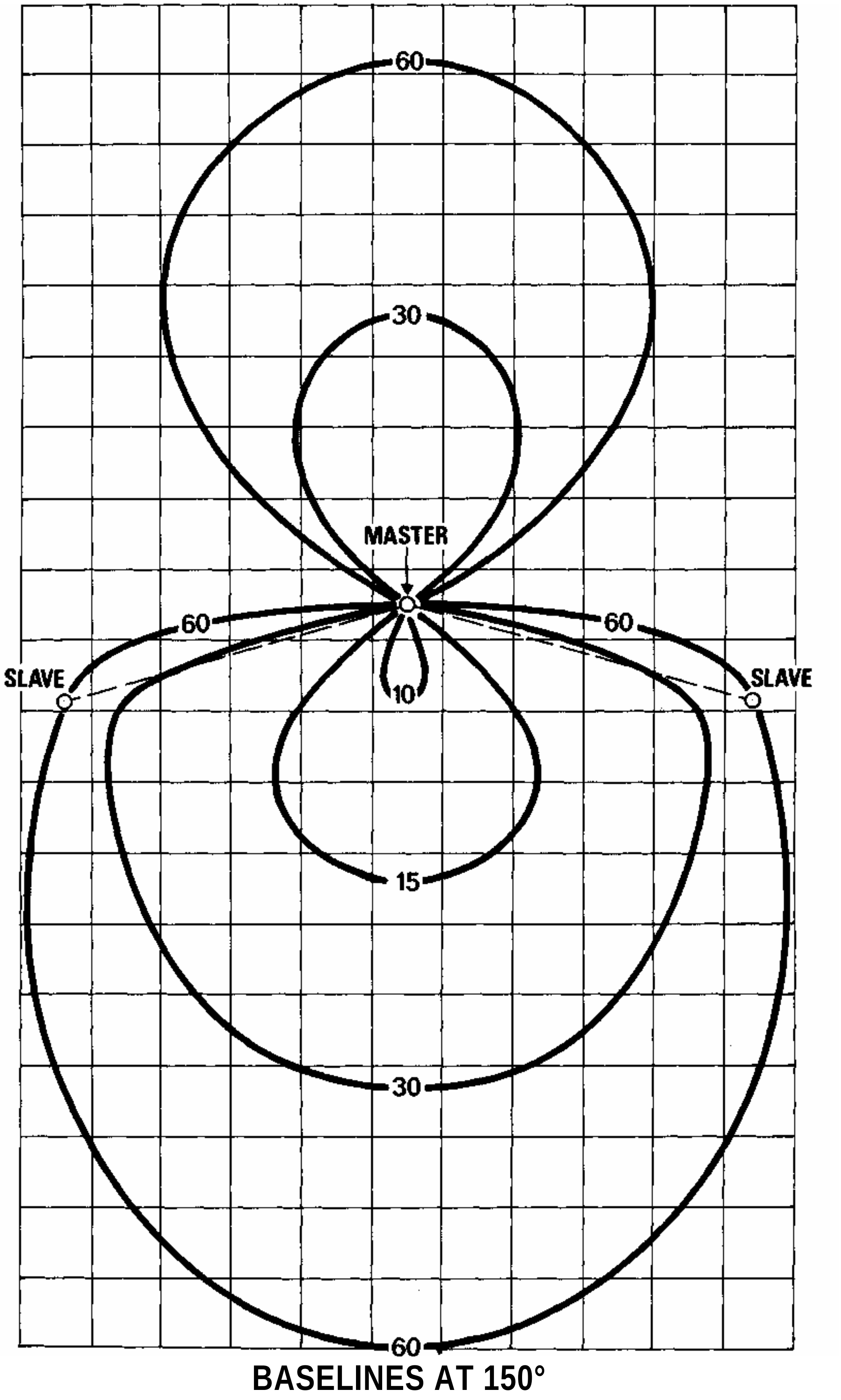


Fig. 2. 7. Accuracy contours in metres for a standard deviation of 0. 01 mean lanes. The squares have sides one-fifth the baseline length, for estimation of ranges and areas.

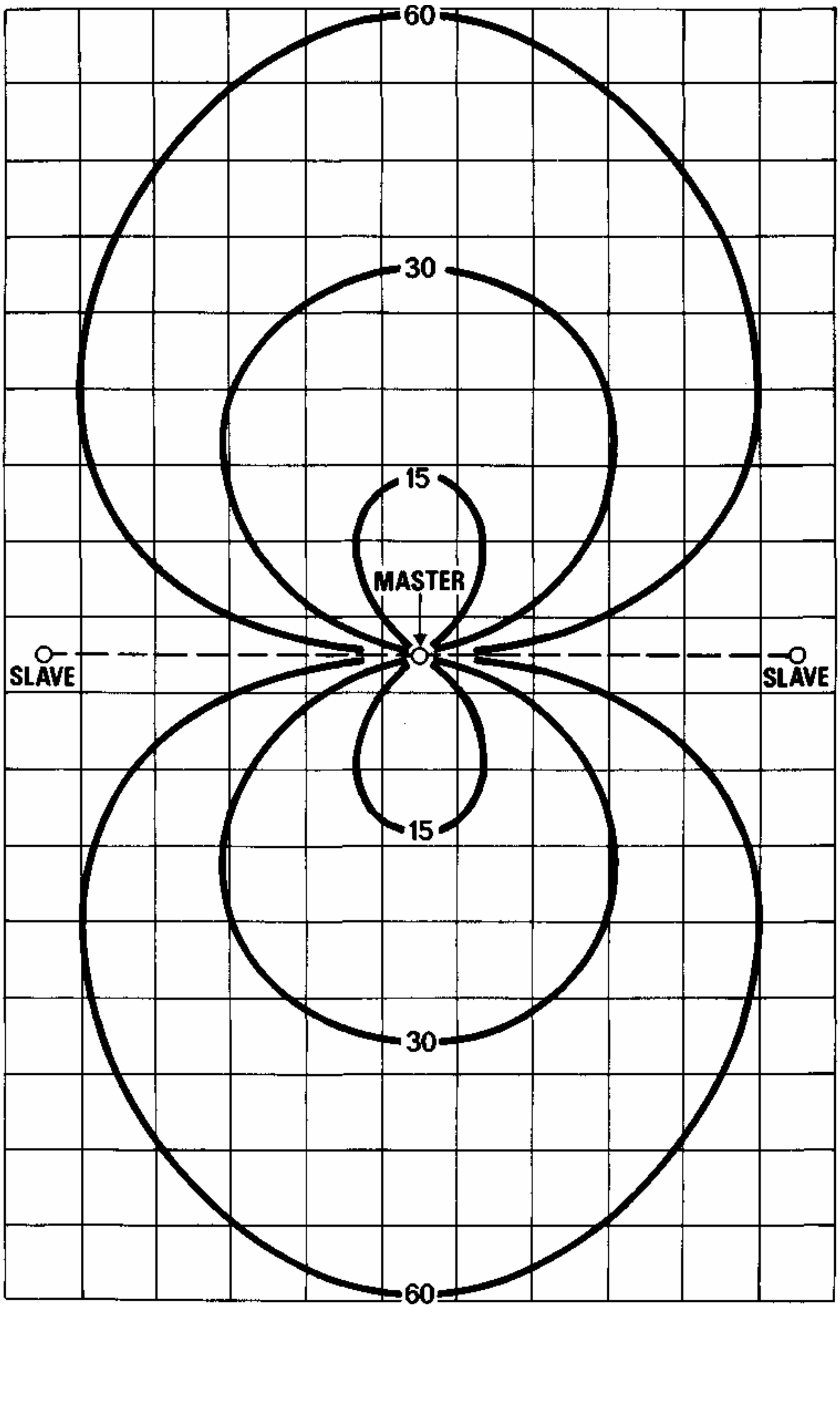


Fig. 2. 8. Accuracy contours in metres for a standard deviation of 0. 01 mean lanes. The squares have sides one-fifth the baseline length, for estimation of ranges and areas.

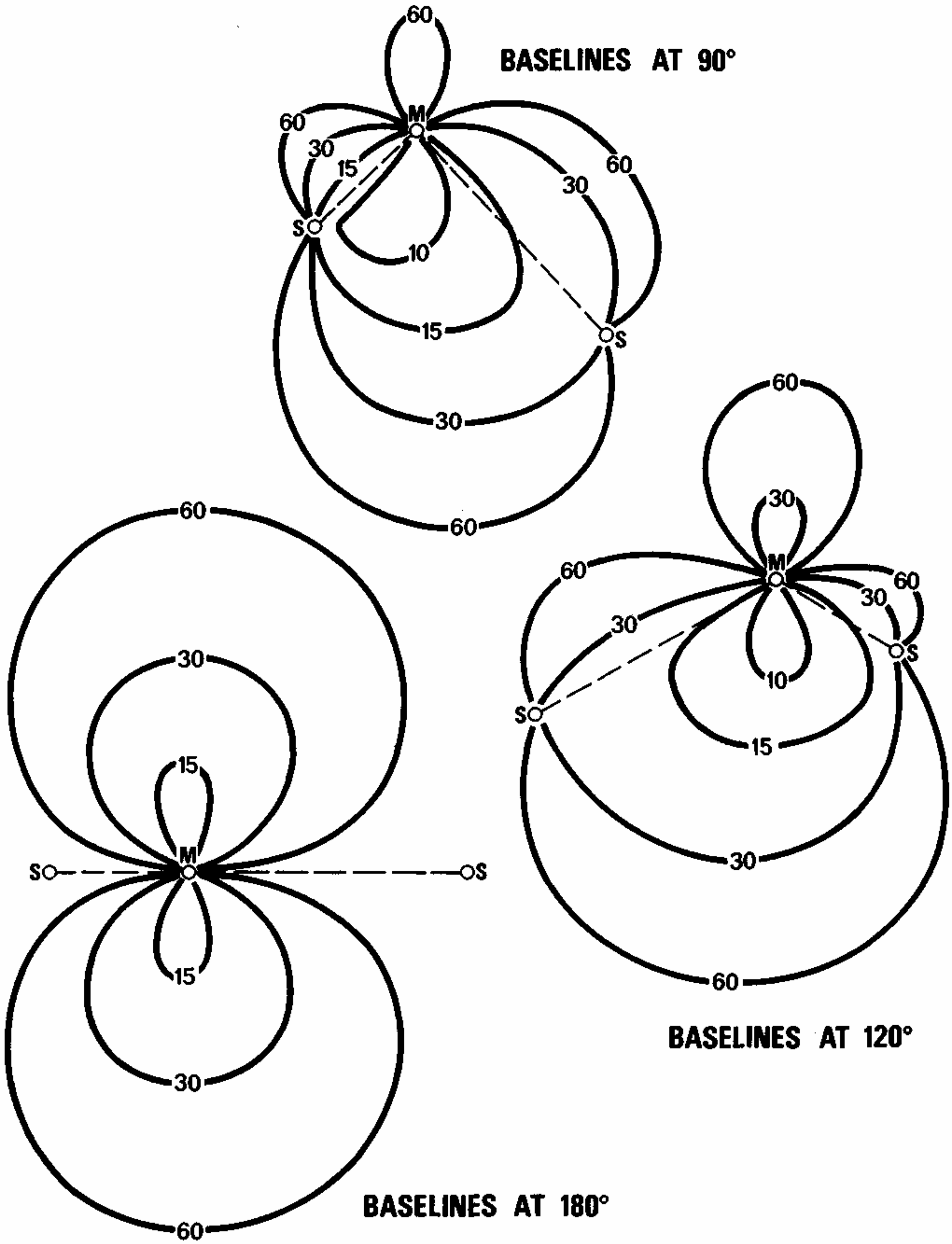


Fig. 2.9. Examples of accuracy contours (metres) for asymmetrical chains.

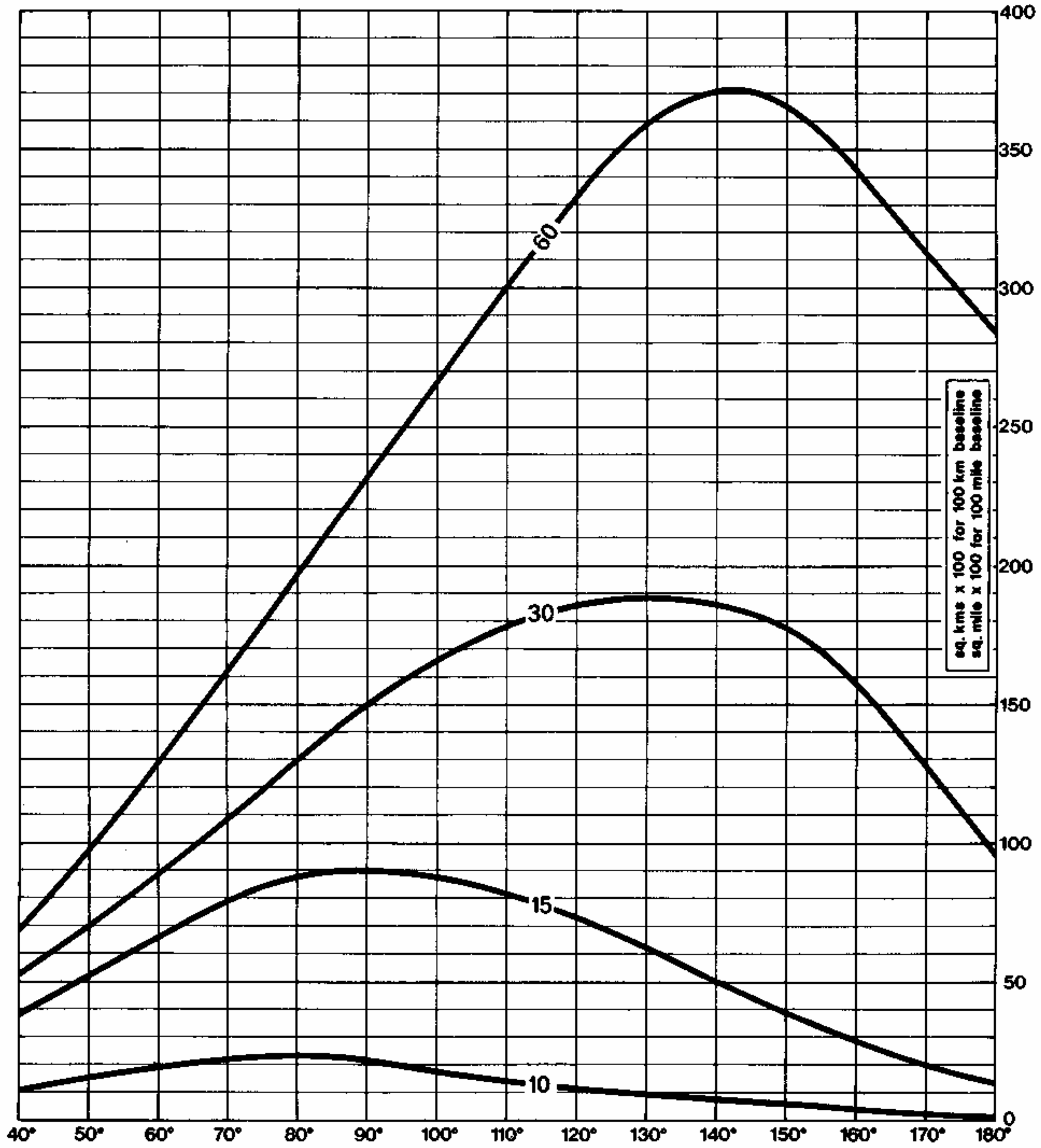


Fig. 2. 10. Areas enclosed by accuracy contours for 10, 15, 30 and 60 m (front cover only) showing effect of baseline angle.

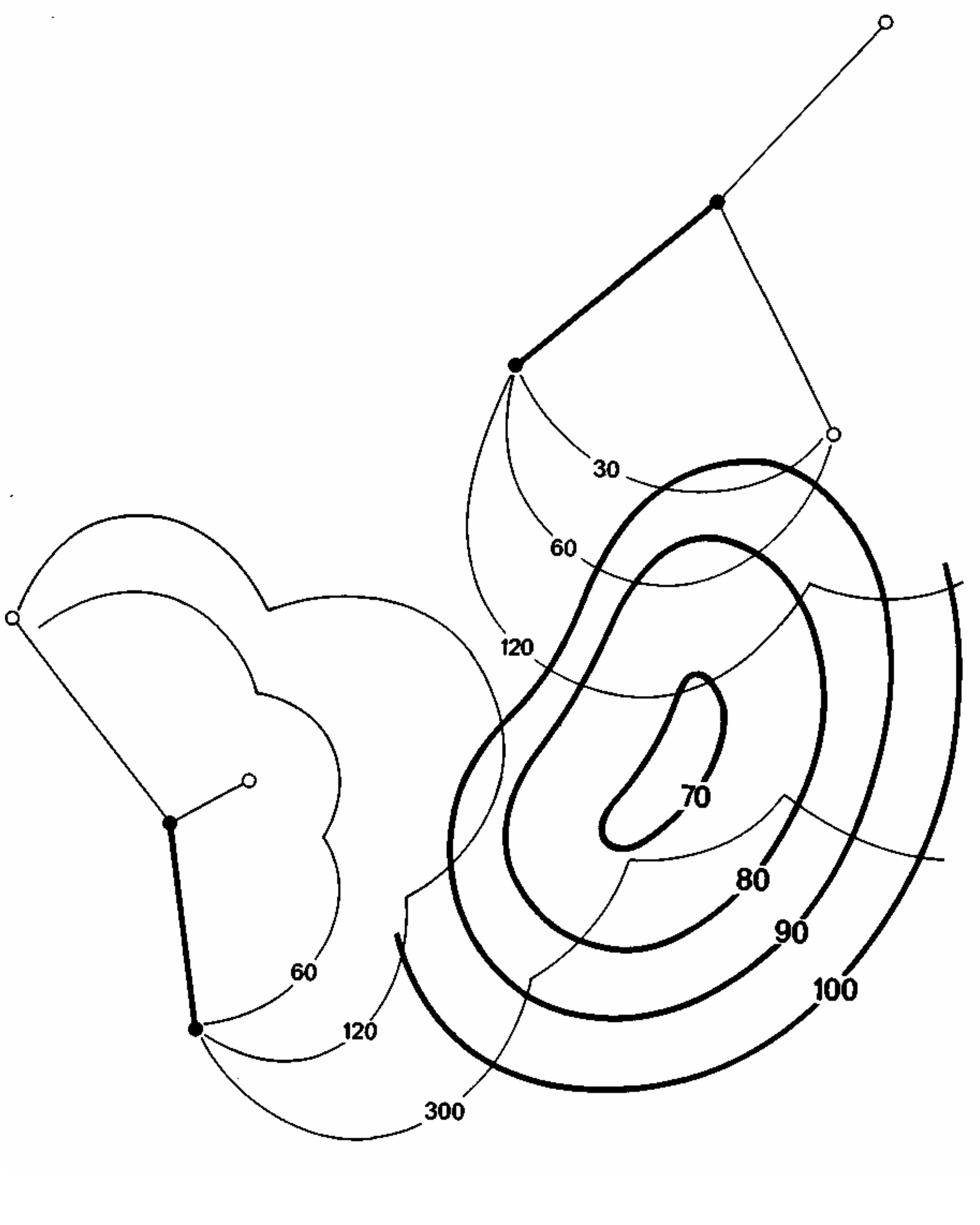


Fig. 2. 11. Example of improvement in accuracy gained by two-chain fixing. The contour values are in metres (68% probability, 0. 02 lane SD) and refer to the full daylight condition. The two baselines used, and the resulting contours, are shown as thick lines.

d. rms (10, 15, 30 and 60 metres) for included angles ranging from 30 to 180 . For convenience, the baselines are made equal in these diagrams but examples of asymmetrical layouts are shown in Fig. 2. 9. As the included angle is increased above about 90 , the area enclosed within the higher accuracy contours decreases and the area within those of lower accuracy increases, as shown in Fig. 2. 10.

2. 4. Two-chain fixing

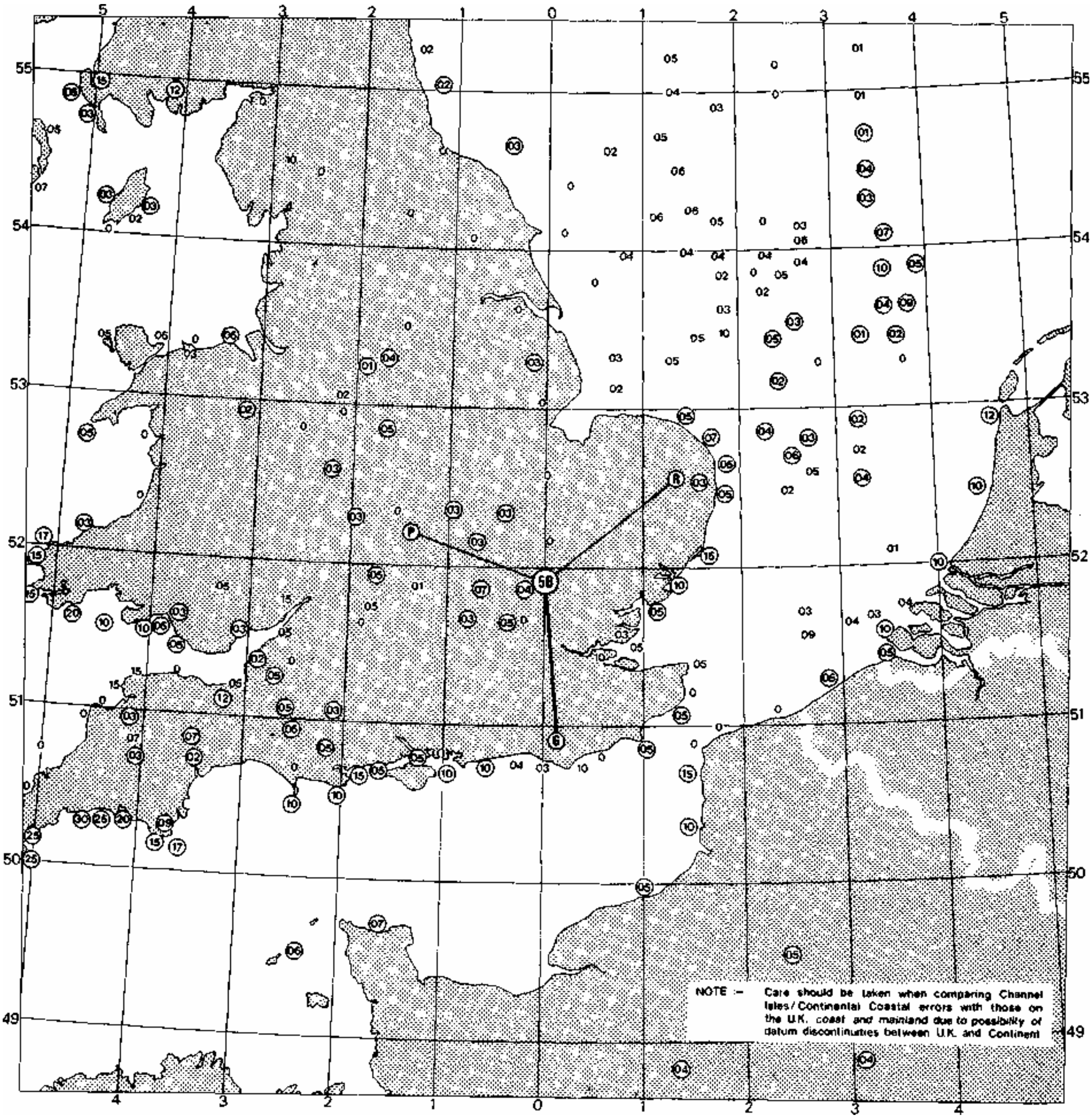
This procedure, known also as inter-chain fixing, takes advantage of the improved angle of cut that may be obtained at long offshore ranges by using one position-line from each of two adjacent chains to form the fix (Fig. 2. 11). Special charts are issued for areas where this yields a significant improvement over fixes from a single chain, with a lattice comprising one pattern from each chain. The method relies upon the effectiveness of the multipulse (MP) mode of lane identification which permits the correct lane number to be immediately determined when switching to the second chain; it lends itself more to day than to night operation since it entails long-range working and the range limit at night tends to be set by skywave interference (see Chapter 3) rather than by geometrical factors.

2. 5. Systematic errors

If the mean observed value of a Decca co-ordinate at a given point differs from the computed value for that point, and the difference remains unaltered with time, a systematic error in the pattern is said to exist at that point. Errors of this type result almost entirely from effects taking place along the paths between the transmitters and the receiver. A systematic error would result from an incorrect assumption of the mean velocity of wave propagation* in computing the hyperbolic pattern; relatively local systematic errors also occur, mainly through differences in mean propagation speed as between the transmission paths to the observer from the master and slave stations of a pair. Such uncertainties must be regarded as contributing in some measure to the random error, since the resulting pattern shifts may vary from place to place although they remain constant with time. The contribution to the random error would be greater in broken and mountainous country, for example, than over flat ground of uniform soil conductivity, and would be negligible in the case where the transmission paths lay wholly over sea-water.

The standard deviation of 0. 01 mean lanes may be taken as a reliable guide to the performance obtained in offshore surveying with a chain sited on or near a coastline. In unfavourable terrain conditions, however, for example in polar coastal regions where there is a juxta-

* See page 2. 22, 2nd full para, line 8 et seq.



THE DECCA NAVIGATOR SYSTEM - ENGLISH CHAIN (5B)

GREEN PATTERN FIXED ERROR CORRECTIONS

CORRECTIONS TO APPLY TO OBSERVED GREEN DECOMETER READINGS TO OVERCOME FIXED ERRORS

VALUES SHOWN ARE IN HUNDREDTHS OF A LANE UNITS

FIGURES ENCIRCLED SHOULD BE SUBTRACTED
FIGURES NOT ENCIRCLED SHOULD BE ADDED

Fig. 2. 12. Example of systematic error map (from "Decca Navigator Operating Instructions and Data Sheets").

position of sea-water with ground of extremely low conductivity, a standard deviation as high as 0. 1 mean lanes might have to be assumed to take account of changes in fixed error from place to place. Users of the permanent Decca Navigator chains are furnished, in the Data Sheets, with the fullest possible details of fixed errors prevailing in the coverage of the various chains and an example of the charts used for this purpose is shown in Fig. 2. 12. While systematic errors of the kind discussed above remain, in general, unaltered with time, there is some evidence of a small seasonal fluctuation in error values in certain cases of chains sited in regions of low conductivity.

2. 6. Charting discrepancies

The systematic errors referred to so far are those due to radio propagation effects. An apparent error or discrepancy in the Decca readings observed at a given geographical position can also occur through factors associated with the lattice map or chart. For example, if the chart in use should be based on a different survey datum from that which was used in determining the positions of the stations, there may be positional discrepancies in lat/long, and hence in Decca co-ordinates, with respect to a chart based on the same datum as the stations. Many reports of systematic errors have been traced to the chart itself and this possibility should be borne in mind whenever an apparently un-accountable systematic error is reported. Apparent systematic errors have also resulted from an error or uncertainty in determining the geodetic position of a station or stations in a chain.

2. 7. Chain calibration

When a chain is set up the patterns are computed provisionally on the basis of the allocated frequency code, the geodetic positions of the stations which will normally have been determined in advance, and an estimated value for the speed of propagation. For a chain in which the transmission paths lie wholly over sea-water, the estimated propagation speed is likely to be accurate, but especially where land paths are in-volved, it will need to be confirmed by observation before preparing the official lattice charts.

As soon as the new chain is radiating stable signals, it is the practice to carry out field trials in which the observed Decometer readings are compared with provisionally computed values at various known positions. On the basis of these results, that value of propagation speed is chosen for each pattern which minimizes the scatter of the observed errors about zero, and the phasing of each slave transmitter is adjusted to bring the mean of the remaining errors to zero in the main area of interest. Under perfectly uniform propagation conditions a value of zero would then be observed on the master baseline extension, in accordance with the convention used in computing the patterns, but in practice the calibration may leave some residual value which is generally close to zero.

2. 8. Local terrain effects

When a Decca receiver is operated on land, errors can occur through attenuation and/or re-radiation of the signals by elevated objects such as trees, high buildings and overhead wires. Long experience in making accurate observations on land has led to the general rule that the receiver should be kept clear of an elevated object by a distance equal to at least three times the height of the object. At distances equal to or less than the height of the object, gross errors and signal loss can occur, particularly in the case of overhead wires. Overhead power lines can additionally radiate noise interference, especially in wet or cold weather, and for these it is advisable to double the clearance rule to at least six times the height when accurate readings are required.

In general, the multiplying type of Decca receiver is unsatisfactory for navigation or position reporting on land among trees or buildings, because of the tendency to repeated lane loss through the local variations in phase and signal strength. The multipulse information, however, can remain effective in severe conditions of this kind owing to its intrinsic ability to accept mutual variations in the phase and amplitude of the component signals? used directly rather than as a means of lane identification, the MP readings can serve as the basis of a viable position fixing or position reporting system in, say, an urban environment. Tests show that in a city located in geometrically good coverage, the accuracy of the MP readings corresponds to a standard deviation of about one-tenth of a (fine) lane, compared with about 0. *2* lane for the Decometer readings.

2. 9. Overflying mountains

When a Decca-equipped aircraft flies over mountainous terrain, the effects of reflection and diffraction tend to produce a fluctuation in the position line readings, by a mechanism similar to that of the flutter of a TV picture when the signal is reflected from a passing aircraft. The periodicity is generally in the order of a few seconds or tens of seconds: at Mach 1 it takes about 10 s to travel through one wavelength at the Decca frequency. The effects of this type of noise can be largely smoothed by eye, in the case of a meter or pictorial display, or by computer filtering.

When flying at heights well above those of the mountain peaks, the errors are thus more or less transient and unimportant. When flying below the level of nearby peaks, however, the strength of the groundwave signal will tend to fall with aircraft height; this will cause a decrease in accuracy, particularly at night, by reason of the reduced ratio of groundwave to skywave signal strength. While total screening of the type associated with high-frequency systems tends to occur only under extreme conditions at the Decca frequencies, as when flying along a narrow valley between high mountains, the likelihood of reduced low-altitude performance should be taken into account in any proposed use of the system in mountainous terrain. Where possible, flight tests should be carried out in the areas of interest since the reflection pattern tends to be too complex for theoretical prediction.

2. 10. Pattern characteristics

Here it may be useful to summarise some characteristics of the hyperbolic pattern produced by a single master/slave pair of Decca stations such as the effects which result in principle from changes in slave phasing and in the assumed or the effective speed of propagation. Where phase differences are mentioned, these refer throughout to the common comparison frequency.

(1) A change in the phase setting at the slave station produces the same change, in hundredths of a lane, at all points in the coverage.

(2) The lane fraction value on the slave baseline extension is in principle equal to the phase difference between the master signal received at the slave station and the signal at the slave transmitting antenna.

(3) If the wrong propagation speed had been chosen in drawing the lattice, but the observed slave baseline extension value was correct, the resulting pattern error would in principle increase towards the master and would be maximum on the master baseline extension.

(4) A change in the phase of the transmitted master signal produces no change in the pattern since the slave phase control equipment maintains the slave transmission at a predetermined phase relationship with the master. (This rule does not apply when the stations are operating under rubidium-oscillator control).

(5) If a shipborne receiver is at a position where the slave signal, but not the master, passes over a land mass, the effective speed of propagation of the slave signal will be reduced. This corresponds to a lengthening of the slave path and the Decometer reading will be less than the computed value. Land in the master and not the slave path would produce a positive Decometer error.

(6) A rough guide to the lane expansion factor at a given point is obtained by dividing the mean distance from the point to the master and slave by half the baseline length.

(7) At any point the tangent to the hyperbolic position line bisects the angle subtended by the stations.

(8) When the distance from the receiving point to the stations is long compared with the baseline length, the tangent passes through the mid-point of the baseline.

The following rules of thumb relating to the position fix given by a master and two slave stations may be noted.

(9) Given (7) it can be shown that the locus of points at which the two position lines intersect at right angles is the straight line joining the slave stations.

(10) When there are errors in the position lines, the resultant fix error tends to be greatest along the straight line joining the receiving point and the master station. (This rule does not hold good inside the triangle formed by the stations).

2. 11. Two-range operation

The full expression for measurement of the distance between the ship and a slave station by the Two-Range or Lambda system is

$$d = \frac{\lambda_{cf}}{2}(\phi - a - \psi)$$

Where d is the distance from the "electrical centre" of the ship to the mid-point between the receiving and transmitting aerials at the slave stations;

$\frac{\lambda_{cf}}{2}$ is the lanewidth in metres for the appropriate pattern, assuming free-space velocity;

ϕ is the observed Decometer reading (whole lane number plus fraction);

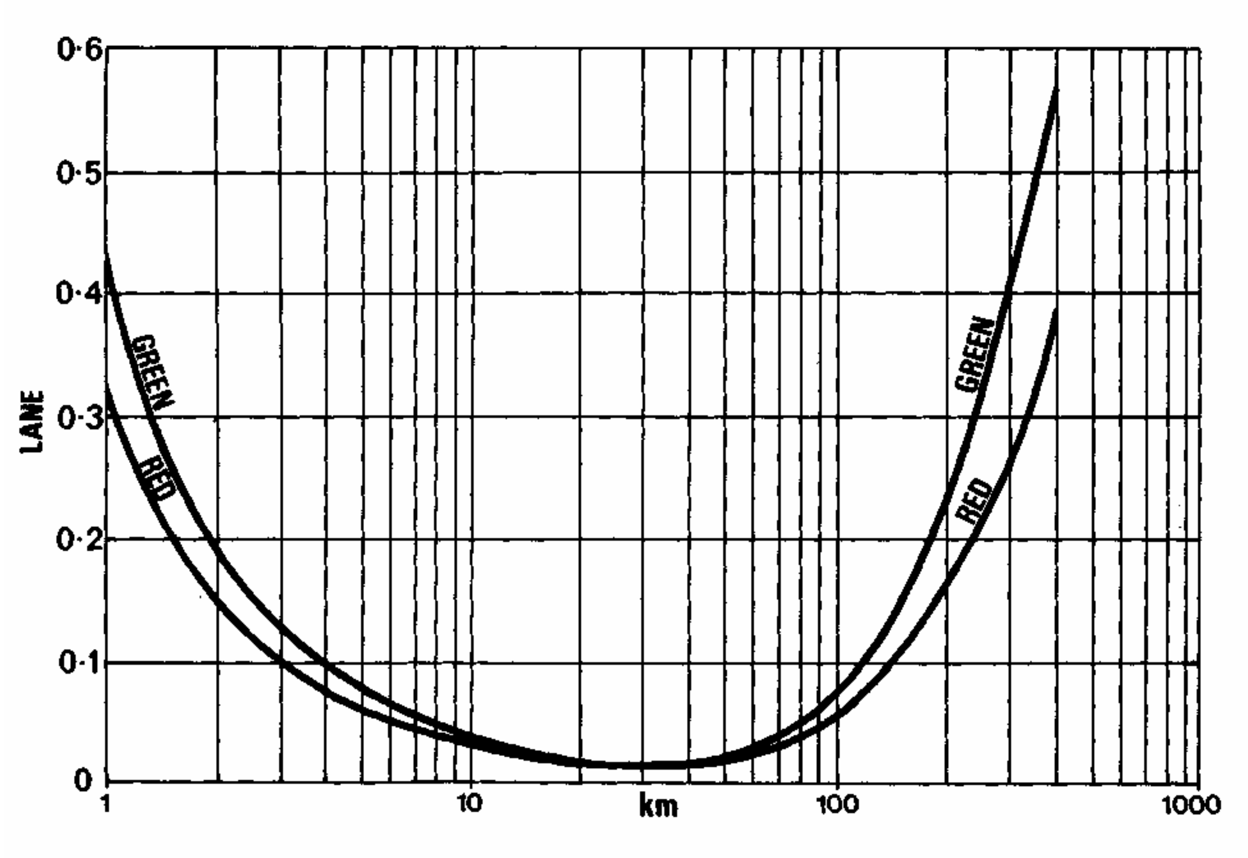


Fig. 2. 13. Two-Range Decca (12f type) and Lambda correction curves, for assumed constant propagation speed of 299 776 km/s. (Ref. 3).

a is the "locking constant".

ψ is a correction to the free-space value of the velocity of propagation.

The electrical centre of the ship is not necessarily the mid-point between the master transmitting aerial and the receiving aerial. Its exact location varies with different types of vessel and is found by calibration at a known distance and on a number of different headings. The locking constant is the name given to the overall phase shift resulting from two causes, namely the close proximity of the receiver to the master transmitter (placing the former in the "induction field") and, at the slave station, a possible fixed displacement from the nominal zero phase-difference condition that is assumed to exist between the received master signal and the outgoing slave transmission. The value of the locking constant for each pattern is found at the start of a survey by observations at exact known distances from the slaves, and is thereafter subtracted from all observed Decometer readings.

The quantity ψ refers to the dependence of the effective velocity of propagation upon the nature of the medium over which the signals are transmitted. Fig. 2. 13 shows a practical set of phase-lag correction curves for the red and green patterns of the Lambda system. The increase in the correction value at short ranges is the result of the complex field existing around the transmitter, and the increase with distance beyond 100 km or thereabouts is the effect of the phase-lag. The effective speed of propagation resulting from the phase-lag varies widely with the electrical characteristics of the medium; for example, the sum of experience so far points to a mean speed of 299 650 km/s over sea-water transmission paths, while a corresponding figure for land paths of the lowest soil conductivity yet-encountered (of the order of $\sigma = 5x10^{-15}$ e.m.u.) amounts to about 297000 km/s.

In practice it is possible to apply corrections for different path conductivities, and also to some extent for paths of mixed conductivity such as the case where a large island or promontory intervenes between the ship and the shore. The application of the corrections shown in Fig. 2. 13 for transmissions over sea-water leaves a residual uncertainty in distance measurement amounting to one or two parts in 10 000.

In most Two-Range Decca systems, a special harmonic relationship is used in order to raise the master frequency and so obtain an acceptable radiated power from the relatively small transmitting mast that can be installed on a survey ship. Where f is the fundamental value in the region of 14 kHz, the master radiates 12f and the slaves 8f and 9f, giving lane patterns corresponding to 24f and 36f. (The term lane pattern is valid, since this exists on each baseline, although the receiver responds only to changes in the total lane number.) In Lambda, an additional frequency llf from the master is used for lane identification, producing at the receiver a beat note of If with the stored 12f master frequency, and the slave stations counter-change their 8f and 9f transmissions to yield a If difference frequency for each.

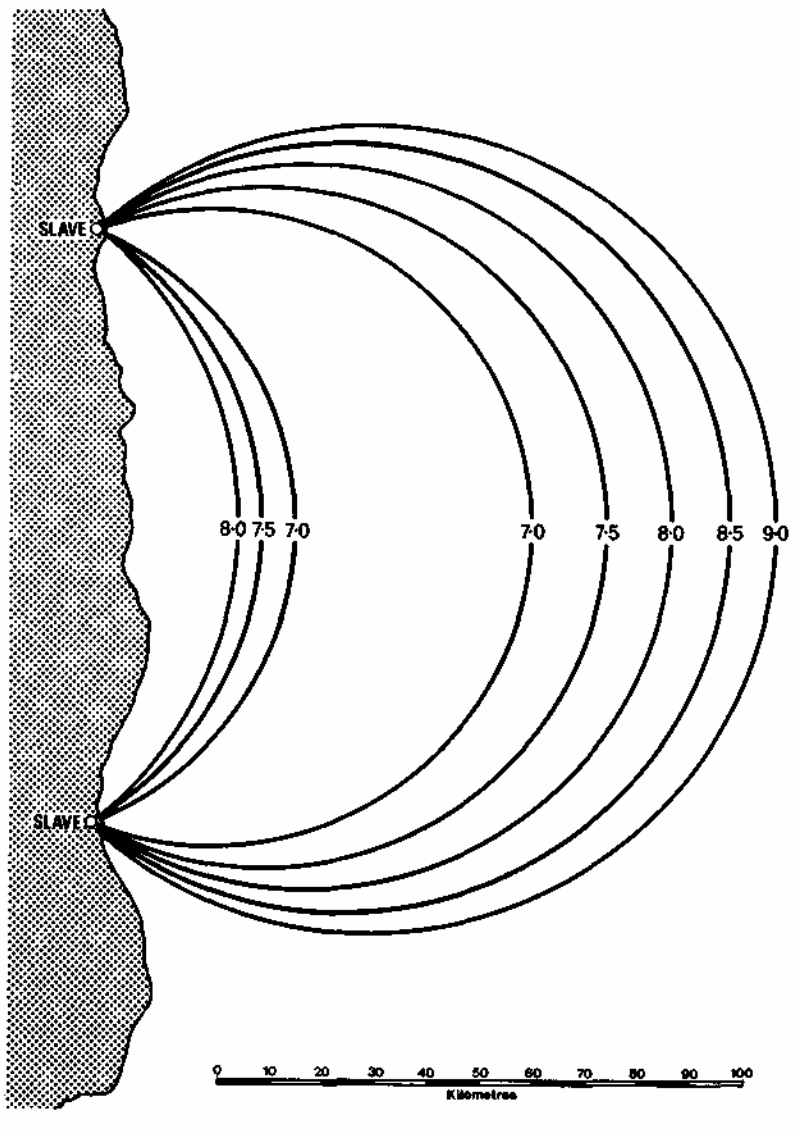


Fig. 2. 14. Accuracy contours in metres for a two-range chain, assuming a standard deviation of 0. 01 mean lanes.

Chapter 3

NIGHT-TIME ACCURACY AND COVERAGE

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NIGHT-TIME ACCURACY AND COVERAGE

3. 1. Introduction

As an aid to the general navigation of ships and aircraft, the Decca Navigator is used at all times and seasons and at distances out to the maximum of which the system is capable. The principal source of position-line and fix errors in the system is interference by the skywave signal. Errors of a fixed or systematic type are not considered below since they are in general small by comparison with those due to skywave. Most of the material in this chapter is taken from Ref. 4. *

3. 2. Propagation at frequencies in the region of 100 kHz

Decca transmitters operate in the 70-130 kHz frequency band and the energy they generate is propagated omnidirectionally, as a vertically polarised radiation from an antenna having a vertical polar diagram of cosine form. Ground observations at the ranges where the groundwave predominates are in good agreement with the amplitude and phase curves derived by Bremmer (Ref. 5)* and show that at 450 km over sea-water, for example, the amplitude is only 4 dB lower than the inverse distance value; over land of poor conductivity it is only 6 dB worse than over sea-water. These figures illustrate the good ground-level performance that this frequency band makes possible at ranges beyond the line of sight.

The energy propagated towards the ionosphere is partially reflected back to earth, the amount of reflected energy at any instant being dependent on the density and depth of the ionospheric layer at that time. At medium ranges in temperate latitudes during summer day, the reflection coefficient is very low and only about 2% is reflected from a layer having an effective height of some 70 km. During winter night, the reflection coefficient at 500 km is about 0. 25, from a fairly strong layer at a height of some 95 km.

Observations of skywave signals during any period show that their amplitudes vary in a manner approximating closely to a Rayleigh distribution. Observations have also shown that by night the r. m. s. value of the skywave is equal to the groundwave at about 800 km; however, it is possible for a lane slip (or gain) to occur at night with the Decca system, through a strong momentary burst of unwanted skywave in antiphase to the groundwave, when the r. m. s. skywave level is only some 50% of the groundwave. This ratio obtains at about 460 km in temperate latitudes.

* References are listed at the end of this chapter.

There is ample evidence to show that under night conditions, the size of the "zone of confusion", where the groundwave and skywave can be of similar amplitude, extends from about 500 km to 1300 km. Beyond 1300 km, the signal is directly under skywave control. As a matter of interest, the experimental Decca Dectra long-range navigational aid was a c. w. system that could work through this confused zone where the signals borne by the two modes of propagation are of comparable magnitude; the Dectra tracking pattern employed time-shared transmissions of the same frequency from master and slave, and because of the high correlation between the skywave signals on the two paths, each with a phase-stable groundwave signal, the phase-difference readout did not fluctuate excessively.

In parts of the world where the earth's magnetic field approaches the horizontal, the strength of the skywave propagated signal depends upon the azimuth of the transmission path and reaches maxima on paths oriented plus/minus 90º from magnetic north. This applies throughout a broad low-frequency band extending at least from 50 kHz to 200 kHz, and it affects any navigation or communication system employing frequencies within that band. In such areas the night-time range of a Decca transmitter when the receiver is to the north or south of the station is similar to that in Europe over similar terrain, but there may be some reduction in the night-time range in the east or west directions.

3. 3. <u>General effect of skywave</u>

Decca lattice charts are based on the assumption of pure groundwave transmissions. Interference between skywave and groundwave causes unwanted phase variations in the Decometer readings, which cannot be corrected because the receiver cannot differentiate between the two components and sees only the resultant phase. As shown in Fig. 3. 1. , the amount of variation depends on the amplitude and phase of the skywave and the groundwave signals; these are a function of time and season and of the position of the receiver on the earth's surface, with respect to the stations. The resultant variable errors are complex in form, since the effect of skywave has to be considered on three transmission paths for each position line (master to slave, master to receiver, slave to receiver). Since each of the skywave components varies in amplitude and phase, it is not possible to make a "skywave correction" for night operation. At any time and place, however, the probable extent of the skywave errors as seen on the Decometers can be predicted in statistical terms, as the percentage of time during which the variations would not be expected to exceed a certain value.

Skywave interference does not upset the cycle-to-cycle integration of a moving Decca receiver until it effectively controls either the master or slave resultant signals. As a general rule, this should not occur within 460 km of the master by night or within 1000 km by day. Beyond the critical range there may be loss of torque on a Decometer due to the skywave on the master or slave signals being in antiphase with the groundwave and of comparable amplitude, so causing signal cancellation. Lanes can be lost or gained if the skywave phase is changing at a time when its amplitude is greater than that of the groundwave.

3. 4. Distribution of random errors due to skywave

The analysis of many thousands of observations made at Decca monitor stations has shown that the random errors at any point in the coverage are disposed about the mean value (which is the same by day and night) in a very similar manner to the normal or Gaussian distribution. In fact, the Gaussian and the observed Decca distribution agree in that, of an infinite number of observations, 95% would be within plus or minus twice the standard deviation. Between plus and minus the standard deviation value, the Decca distribution contains 75% of observations, while the normal distribution contains 68%. This means that fewer large errors appear in the tails of the Decca distribution than in the Gaussian and the Decca distribution is therefore slightly peakier or "leptokurtic", although for statistical working a normal distribution is assumed. Experience has shown that a minimum sample of a hundred independent readings is required if the standard deviation is to be meaningful.

3. 5. Accuracy of skywave error prediction

Ever since the first Decca chain became operational, variable errors due to skywave have been intensively studied in order that the performance can be predicted as realistically as possible. Early estimates of variable errors based on,»the, known transmitting antenna characteristics and ground conductivity, and on the theoretical height and strength of the reflected layer, fitted the observed results within tolerable limits, but the only sure way to establish correct parameters was to use data from actual field observations. An improvement in prediction resulted from many hours of trials and study between 1946 and 1950, when the task of breaking down field observations into their component parts was undertaken. These parts are time of day; season of year; type of conductivity in the area of observation; and the contribution of the total error on each transmission path as outlined above.

For latitudes between 45° and 60° , it was possible by 1950 to predict the error at any time or season within very small limits, over several types of ground conductivity. This was achieved by analysing tens of thousands of monitor readings taken throughout the year over the full 24 hours and examining the resultant standard deviation from hour to hour and from day to day. For analysis, the observations were grouped into periods of about seven days in order to obtain smooth results; in many instances a single night's reading would give an r. m. s. error better or worse than predicted according to the severity of the skywave on that particular night. With expanding Decca coverage in the world, these studies have continued in order to improve knowledge of low soil conductivity parameters and of the seasonal effects in other latitude bands: the variation seems to correlate roughly with the sun's zenithal distance.

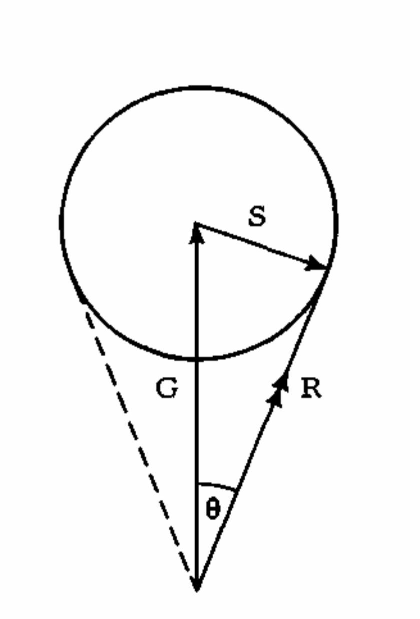
The degree of skywave interference seen in temperate latitudes is correlated with the cycle of sunspot activity which has a repetition period of approximately 11 years. The correlation does not appear to be present to any degree near the magnetic equator, probably because in that region the reflection coefficient for transmission in the east/west directions is too high for the sunspot effects to be other than secondary. In temperate latitudes sunspot activity tends to introduce an uncertainty in the error predictions, amounting to some 10% to 20% about the mean figures on which the error predictions are based, and these effects are felt mainly in winter. In general the performance of the system is at its best when sunspot activity is at a maximum. The years 1949, I960, 1971, 1982 and 1993 would be forecast as good years and this was confirmed for the first three years mentioned. Bad years would be 1944, 1954, 1965, 1976 (all confirmed as such), 1987 and 1998. Predictions are liable to an error in time of one or two years because the cycle period is not exactly equal to 11 years and is slightly variable.

3. 6. <u>Skywave errors in the position line</u>

When skywave interference is absent, the phase of the received master and slave signals can be computed at any known point, using as a datum the instantaneous phase of the signal at the respective transmitting station, and assuming that the automatic phase control at the transmitters is perfect and that the effective conductivity constants of the terrain are accurately known. In the absence of skywave interference, these signals would give the correct Decometer reading at the observation point. However, when there are skywave signals this computation would no longer be valid because the signal received at any point on any transmission frequency is the resultant of the groundwave signal of known phase and amplitude and an unknown signal reflected from the ionosphere (Fig. 3. 1).

Fig. 3. 1.

Vector diagram showing phase error θ of resultant received signal R in presence of skywave component S of random phase, interfering with groundwave G.



Consider a "red" pattern observed at some point during conditions of skywave interference and let M and R be the master and red slave stations (Fig. 3. 2). The discrepancy in the Decometer reading from the computed value at the observing point X is assumed to be due to the following phase deviations, expressed in cycles, in the transmitted signals from the datum:

S_{ml} cycles at the master frequency along the "locking" path MR

b_r cycles at the slave frequency along the path RX

a_m cycles at the master frequency along the path MX

The deviation of S_{ml}, cycles suffered by the master signal travelling from M to R is multiplied by 4 at the slave control receiver to raise it to the comparison frequency and is then effectively divided by 3 to give the datum phase for the slave transmission; thus, due to skywave on the locking path, the slave transmission at the slave station is subject to a phase deviation of $4/3\ S_{ml}$ cycles. This signal now travels to the point X and suffers a further phase deviation at the red transmission frequency of b_r cycles. The red signal arriving at X is therefore subject to a phase deviation from the datum of cycles.

The master signal also travels to X along the path MX and suffers a phase deviation from the datum of a_m cycles. Hence when multiplied up in the receiver at X to the comparison frequency, the deviation of θ_R the red Decometer reading from its computed value is given by ($b_r + 4/3\ S_{ml}$) cycles.

$$\theta_r = 4_{a_m} - 3(b_r + \frac{4}{3} S_{ml})$$

$$= 4_{a_m} - 3b_r - 4S_{ml} \quad \text{Cycles or "lanes"....... (1.0)}$$

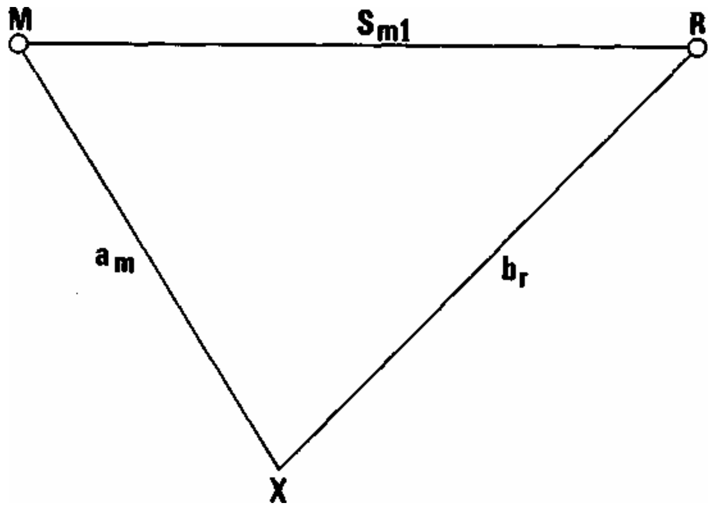


Fig. 3. 2. Phase deviations on transmission paths from master station M and slave station R generating "red" position-line.

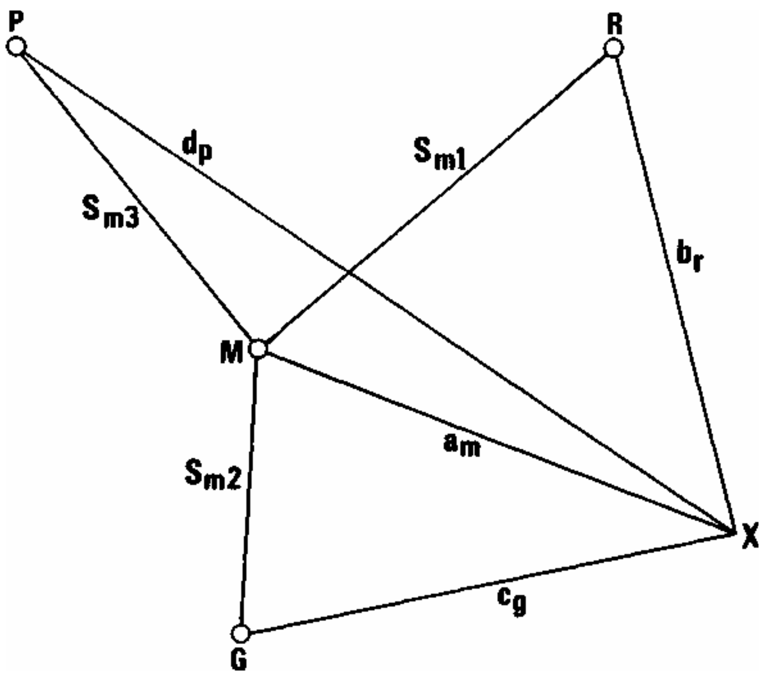


Fig. 3. 3. Phase deviations on transmission paths for red, green and purple position-lines.

Suppose we now take a very large number of random observations of θ_R. If we square the deviations, divide by the number of readings and σ_R the square root of the result, we obtain the standard deviation such that

$$\sigma_R^2 = \frac{\theta_{R1}^2 + \theta_{R2}^2 + \theta_{R3}^2 + \ldots\ldots\ \theta_{RN}^2}{N} = \frac{\Sigma_1^N\ \theta_R^2}{N}$$

where θR, θR2 .... θRN observed values of Decometer deviations due to skywave and N is the number of observations. Therefore, inserting the various deviations, we can write:

$$\sigma_R^2 = \Sigma_1^N \frac{(4\,a_m - 3\,b_r - 4\,S_{ml})^2}{N}$$

$$= \frac{16\,\Sigma_1^N a_m^2}{N} + \frac{9\,\Sigma_1^N b_r^2}{N} + \frac{16\,\Sigma_1^N S_{ml}^2}{N} - \frac{12\,\Sigma_1^N a_m b_r}{N}$$

$$- \frac{16\,\Sigma_1^N a_m S_{ml}}{N} + \frac{12\,\Sigma_1^N b_r S_{ml}}{N}$$

Now consider any cross-product term of the form $\frac{\Sigma_1^N a_m b_r}{N}$

The terms a and b represent independent, uncorrelated phase errors, each of which is randomly distributed about a mean of zero. Thus, if a large number of random readings are concerned in the cross-products a and b_r, the cross-product term will tend to be zero if the sample of readings is large enough. We can therefore say that:

$$\sigma_R^2 = \frac{16\,\Sigma_1^N a_m^2}{N} + \frac{9\,\Sigma_1^N b_r^2}{N} + \frac{16\,\Sigma_1^N S_{ml,}^2}{N} \quad \text{or}$$

$$\sigma_R^2 = 16\,\sigma_{a_m}^2 + 9\,\sigma_{b_r}^2 + 16\,\sigma_{S_{ml}}^2 \quad \ldots\ldots\ldots\ldots\ (2.0)$$

It will be seen that if a large number of red Decometer readings are taken at a certain observation point tinder skywave conditions, a mean deviation of zero would be expected on the theory assumed, and that the variance (i. e. the square of the standard deviation) of the distribution of Decometer errors caused by skywave can be expressed in terms of the variance of the distributions of instantaneous phase discrepancies in the transmitted signals along the three paths concerned.

One very small correction has to be made to equation (2. 0) to account for the fact that the automatic phase lock at the slave transmitter is not entirely free from variation. Such variations will however be independent of the skywave deviations; in cases where the baseline length and/or the terrain conductivity are such that excessive skywave interference could occur on the locking path, phase locking under night conditions is maintained by means of rubidium frequency standards forming highly stable signal sources at the master and the slave station concerned. The small locking variation can therefore be taken to contribute only another variance term to equation (2. 0) which analysis of actual observations has shown to amount to about (0. 012) . Therefore:

$$\sigma_R^2 = 16\ \sigma_{a_m}^2 + 9\ \sigma_{b_r}^2 + 16\ \sigma_{S_{m1}}^2 + (0.012)^2 \ldots\ldots. (3.0)$$

The above equation represents the sum total of errors expected from a series of random observations at a fixed point. (When rubidium standards are in use the locking term 16 CT S_mi disappears. If daily corrections are applied to the slave phasing, to counter oscillator drift, the value $(0.012)^2$ should be modified to $(0.02)^2$ in the formula). If, however, we can determine how σa_m, σb_r, σS_{ml}, vary with the length of the transmission path we can evaluate σ_R. Moreover, knowing the type of frequency distribution that θ_R is likely to follow, we can estimate σ_R from the likelihood of any particular error θ_R arising due to skywave.

By the same reasoning, the counterparts of equations (1. 0), (2. 0) and (3. 0) above can be written for the errors in the green and purple position lines. (Fig. 3. 3). Thus the instantaneous deviation θ_G of the green Decometer may be written as:

$$\theta_G = 3\ a_m - 2\ \left(\frac{3\ S_{m2}}{2} + c_g\right)$$

$$= 3\ a_m - 3\ S_{m2} - 2\ c_g \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.1)$$

$$\sigma_G^2 = 9\,\sigma_{a_m}^2 + 9\,\sigma_{S_{m2}}^2 + 4\,\sigma_{c_g}^2 \quad \ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

$$\sigma_G^2 = 9\,\sigma_{a_m}^2 + 9\,\sigma_{S_{m2}}^2 + 4\,\sigma_{c_g}^2 + (0.009)^2 \quad \ldots\ldots \quad (3.1)$$

The last equation includes the contribution due to imperfection in the "green" section of the equipment, derived as before from analysis of observed results. Similarly the instantaneous deviation of the purple Decometer may be written as:

$$\theta_P = 5\,a_m - 6\left(\frac{5\,S_{m3}}{6} + d_p\right)$$

$$= 5\,a_m - 5\,S_{m3} - 6\,d_p$$

$$\sigma_P^2 = 25\,\sigma_{a_m}^2 + 25\,\sigma_{S_{m3}}^2 + 36\,\sigma_{d_p}^2$$

$$\sigma_P^2 = 25\,\sigma_{a_m}^2 + 25\,\sigma_{S_{m3}}^2 + 36\,\sigma_{d_p}^2 + (0.015)^2 \quad \ldots\ldots \quad (3.2)$$

Again, the last equation includes a contribution arising in the corresponding part of the equipment.

To provide examples of practical data on position-line accuracy, figures are given in Table 3. 1 for insertion in the formulae.

To convert the values in Table 3. 1 to their equivalents for other periods of time, the following general rules apply. For summer day operation, divide the figures shown by 8; for winter day, divide by 2; for winter night multiply by 1. 5. The position line accuracies are obtained by multiplying the error expressed in Decca lanes, obtained from the formulae, by the width of one lane on the baseline of the pattern concerned, and then further multiplying by the "lane expansion factor" (see Chapter 2). Typical resultant standard deviations in lanes and units of distance are shown in Table 3. 2.

Table 3. 1

STANDARD DEVIATION (σ_T) IN TRANSMITTED CYCLES

for insertion in formulae (3. 0), (3. 1), (3. 2), for summer night conditions in temperate latitudes.

Range (km)	σ_T in transmitted cycles for good soil and sea water			
	a_m S_{m1} S_{m2} S_{m3}	b_r	c_g	d_p
100	.0041	.0041	.0041	.0050
200	.0100	.0100	.0100	.0118
300	.0187	.0187	.0187	.0224
400	.0335	.0335	.0335	.0400
500	.0532	.0532	.0532	.0632
Range (km)	σ_T in transmitted cycles for poor soil			
100	.0044	.0053	.0053	.0053
200	.0106	.0053	.0053	.0125
300	.0224	.0266	.0266	.0266
400	.0400	.0472	.0472	.0472
500	.0707	.0845	.0845	.0845

Table 3. 2

TYPICAL "RED" POSITION LINE ACCURACIES (σ) IN LANES AND METRES

in the front cover of a 160 km baseline chain, 68% probability level

Range (km)	Summer day		Winter day		Summer night		Winter night	
	lane	m	lane	m	lane	m	lane	m
100	.010	7	.014	12	.028	22	.040	30
200	.013	18	.028	40	.056	76	.080	100
300	.015	30	.047	90	.095	170	.140	240
400	.020	55	.080	200	.160	400	.240	550
500	.030	100	.120	380	.250	750	.350	1050

To present the high order of accuracy of a Decca jposition line in terms of azimuth, the distance errors can be converted into bearing errors as in Table 3. 3. This can be useful when comparing Decca with other systems.

Table 3. 3

TYPICAL RED POSITION LINE ACCURACIES AS AN ERROR (a) OF BEARING

in degrees, in the front cover of a 160 km baseline Decca chain, 68% probability level.

Range (km)	Summer day	Winter day	Summer night	Winter night
100	.004°	.007°	.013°	.018°
200	.005°	.011°	.022°	.029°
300	.006°	.017°	.032°	.045°
400	.008°	.028°	.057°	.078°
500	.011°	.043°	.085°	.119°

3. 7. Sky wave errors in position fixing

It is shown above how the position line accuracy of a single Decca pattern can be calculated in terms of lanes and units of distance or bearing. It now remains to consider the probable accuracy of a position fix obtained by the intersection of two position lines, each of which is subject to variable skywave errors.

If a very large number of independent Decca readings are taken at any specific point, the fixes plotted on a lattice chart will be elliptically distributed around a mean position. Assuming that all systematic errors have been removed, this mean position will be the true geographical fix. For that particular point, it would then be possible to state that, by night for example, the worst error to be expected for 95% of the time in the least accurate direction (i. e. along the major axis of the error ellipse) would be X metres and the worst error to be expected for the same probability in the most accurate direction (the minor axis) would be Y metres. In addition, the bearing of the two axes from true north could be given. However, without making any actual observations, we can predict the dimensions and direction of this ellipse to reasonable accuracy, knowing only the accuracies of the two position lines, their angle of cut, and the correlation factor K.

The correlation factor contributes to the size and shape of the error ellipse and represents (as stated in Chapter 2) the correlation between the errors in the two position lines due to the common master transmission path involved. The correlation tends to make the patterns read high or low at the same time and its effect is to make the error ellipse longer and thinner. In the hypothetical case of K = 1, the ellipse would flatten into a straight line. The factor K is computed for the respective pairs of position lines- as follows: -

$$K_{rg} = \frac{12\ \sigma_{a_m}^2}{\sigma_R\ \sigma_G}$$ correlation factor between Red and Green pattern errors .... (4.0)

$$K_{rp} = \frac{20\ \sigma_{a_m}^2}{\sigma_R\ \sigma_P}$$ correlation factor between Red and Purple pattern errors .... (4.1)

$$K_{gp} = \frac{15\ \sigma_{a_m}^2}{\sigma_G\ \sigma_P}$$ correlation factor between Green and Purple pattern errors .... (4.2)

The relationship between fix accuracy, position line accuracy, correlation factor and angle of cut is shown in Fig. 3. 4, which amounts to a re-drawn version of the earlier Fig. 2. 2, with special reference to the correlation factor. The ellipse which fits into this "diamond of error" built up from the standard error on each position line, contains approximately 40% of the fixes. To obtain the 95% error in the worst and best directions, the major and minor axes of the a ellipse are multiplied by 2. 45. In practice, variable errors can be depicted by a method which ignores the direction of the error, using the d. rms criterion which was evolved for the Loran A system and is described in Chapter 2 (para. 2. 2). Practical examples of the r. m. s. error and also of the comparison between d. rms and the length of the major and minor axes of the error ellipse, are shown in Table 3. 4, together with typical values of the correlation factor.

It will be seen by comparing the. error ellipse with the d. rms that the latter is a fair criterion of accuracy, but is very pessimistic in the direction of the minor axis of the ellipse; it does, however, offer a practical method for the prediction of chain accuracy contours. To determine the accuracy in relation to specific routes, reference would be made to the error ellipse to show the errors along and across track. The major axis of the ellipse tends to point towards the master station and the probable direction and magnitude of the worst error can therefore be deduced from the d. rms figure to a reasonable order of approximation.

Table 3. 4 TYPICAL,

NIGHT-TIME RESULTS

obtained up the line of shoot of the front cover of a Decca chain having a baseline of 160 km (temperate latitudes)

Range (km) from master station	95% d. rms (metres)	95% error ellipse major axis	minor axis	Ratio major to minor axis	Correlation factor K
180	250	300	100	3 : 1	.40
320	1400	1600	200	8 : 1	.64
450	4900	5800	450	13 : 1	.72

Convenient approximations can be made to the value of the correlation factor without significantly affecting the value of the r. m. s. error; thus, for night accuracy figures a value of K = 0. 66 is normally adopted and for short ranges in daylight it is assumed that K = 0.

3. 8. Published accuracy contours

An example of a set of accuracy contours related to "times other than daylight" is shown in Fig. 3. 5(a), together with the associated table and diagram defining the time/season factor in Fig. 3. 5(b). Since ionospheric variations are directly related to solar activity, the shape of the "onion" diagram varies with latitude, as illustrated in Fig. 3. 6.

3. 9. Correlation between readings at spaced receivers

Considered as a reflector of the skywave component of the 100 kHz transmitted signal, the ionosphere is stable neither in time nor in space. Consequently, when the time-varying resultant phase of the skywave and groundwave components is observed simultaneously on two receivers some distance apart, the two sets of readings only exhibit a high correlation factor when the spacing between the receivers is less than one wavelengfh or about 3 km. Perfect correlation between the skywave variations observed on the two receivers could only be guaranteed by restricting the distance between them to a few tens of metres. As the separation is increased, the correlation rapidly falls, in a more or less unpredictable fashion. It is not, therefore, practicable, when skywave interference is present, to use the Decca Navigator in the so-called "differential" mode of operation, in which the variations observed at a fixed monitor station are communicated to users in the vicinity with the object of improving the accuracy of their position fixing.

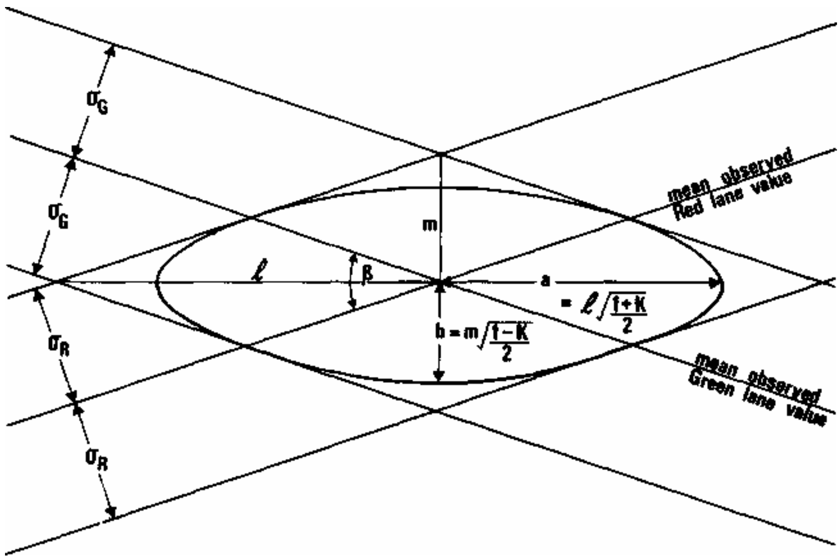
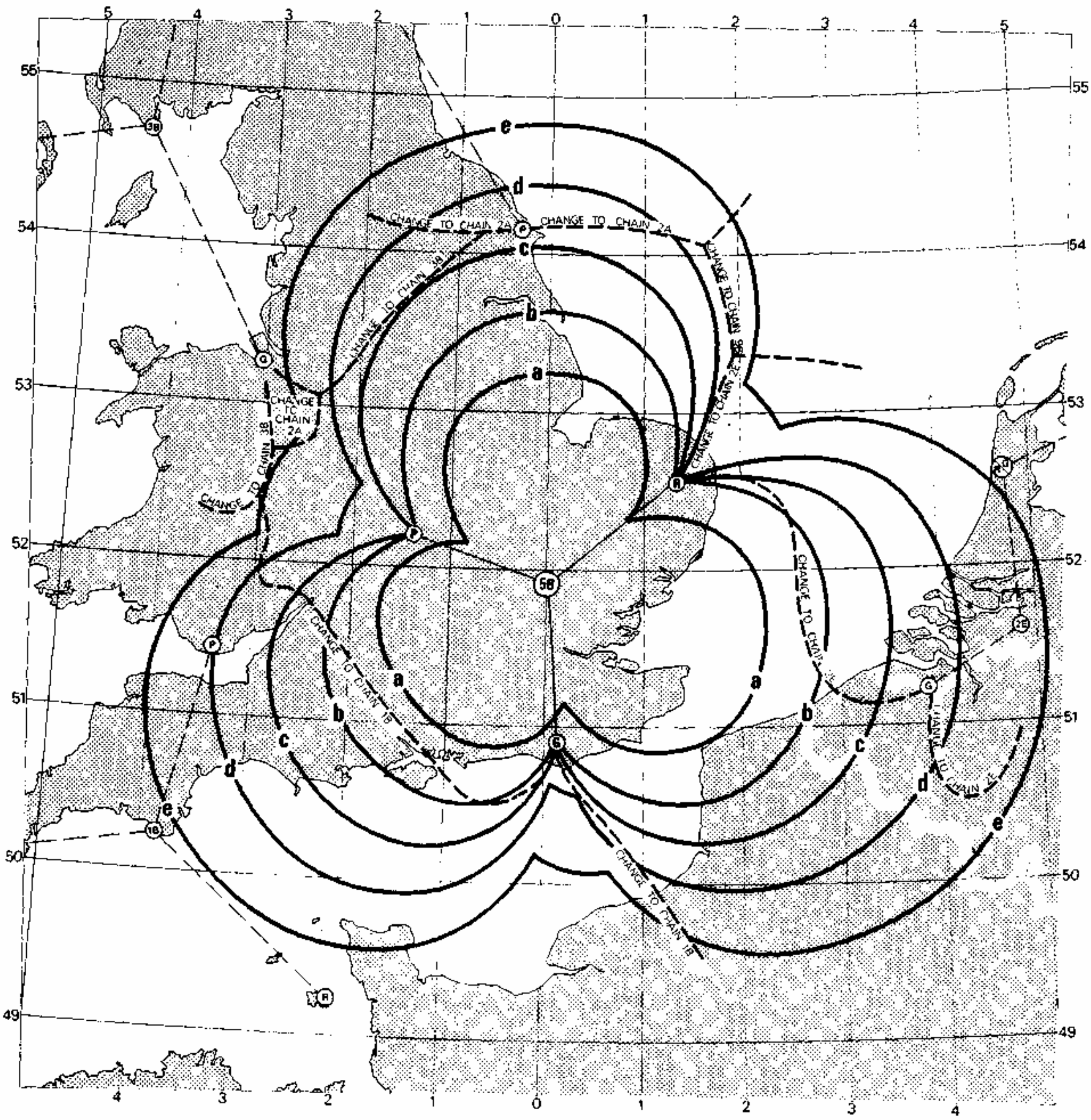


Fig. 3.4. The error diamond (semi-axes 1, m) and ellipse (semi-axes a, b) for night-time conditions, showing relationship between position line error, fix error, angle of cut p and correlation factor K.

3. 10. <u>Use of MP for position fixing at night</u>

As indicated in Chapter 1, the hyperbolic patterns related to a comparison frequency of If which are brought into being every 20 s by the MP lane identification signals, tend to have a higher integrity at the fringe of the chain coverage by night than the fine patterns. As a result, mariners have widely adopted the practice of using the MP transmissions, in the outer part of the chain coverage, directly as a navigational aid rather than as a lane identification system. A significant improvement in accuracy can be obtained in this way at night, compared with the use of the normal patterns, as indicated in Fig. 3. 7. At the relatively long offshore distances at which this practice becomes applicable the lack of continuous lane integration and the limited data rate of 3 signals per minute can generally be accepted. The normal patterns should, of course, be used at all ranges under day conditions.



THE DECCA NAVIGATOR SYSTEM — ENGLISH CHAIN (5B)

PREDICTED COVERAGE AND ACCURACY DIAGRAM (68% PROBABILITY LEVEL) FOR TIMES OTHER THAN 'FULL DAYLIGHT'

1. See Sheet 3[a] on facing page for probable errors and time periods.
2. The time and season diagram and table are for the interpretation of the Decca accuracy contours labelled a, b, c, d or e.
3. The table gives the Variable Fixing Errors not likely to be exceeded in more than one case out of three readings.
4. Corrections to offset any known Fixed Errors are given on the following pages.

Fig. 3. 5(a) Example of published accuracy contours for 24-hour operation, to be read in conjunction with Fig. 3. 5(b).

RANDOM FIXING ERRORS AT SEA LEVEL IN NAUTICAL MILES
68% PROBABILITY LEVEL

DECCA PERIOD See Time and Season Factor Diagram below	CONTOUR a	b	c	d	e	
HALF LIGHT	<0·10	<0·10	<0·10	0·13	0·25	
DAWN/DUSK	<0·10	<0·10	0·13	0·25	0·50	
SUMMER NIGHT	<0·10	0·13	0·25	0·50	1·00	
WINTER NIGHT	0·10	0·18	0·37	0·75	1·50	

TIME AND SEASON FACTOR DIAGRAM

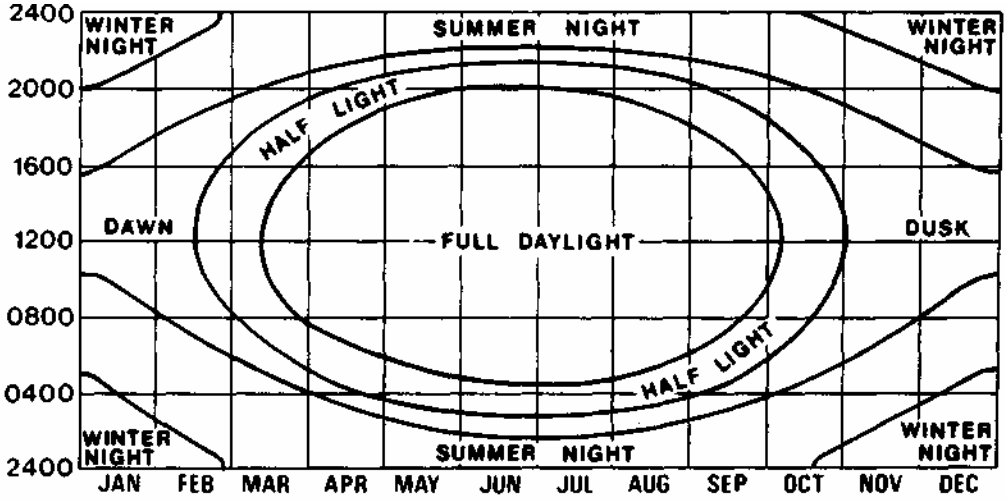


Fig. 3. 5(b) Table and "onion" time/season diagram for use with Fig. 3. 5(a). (From "The Decca Navigator Operating Instructions and Data Sheets").

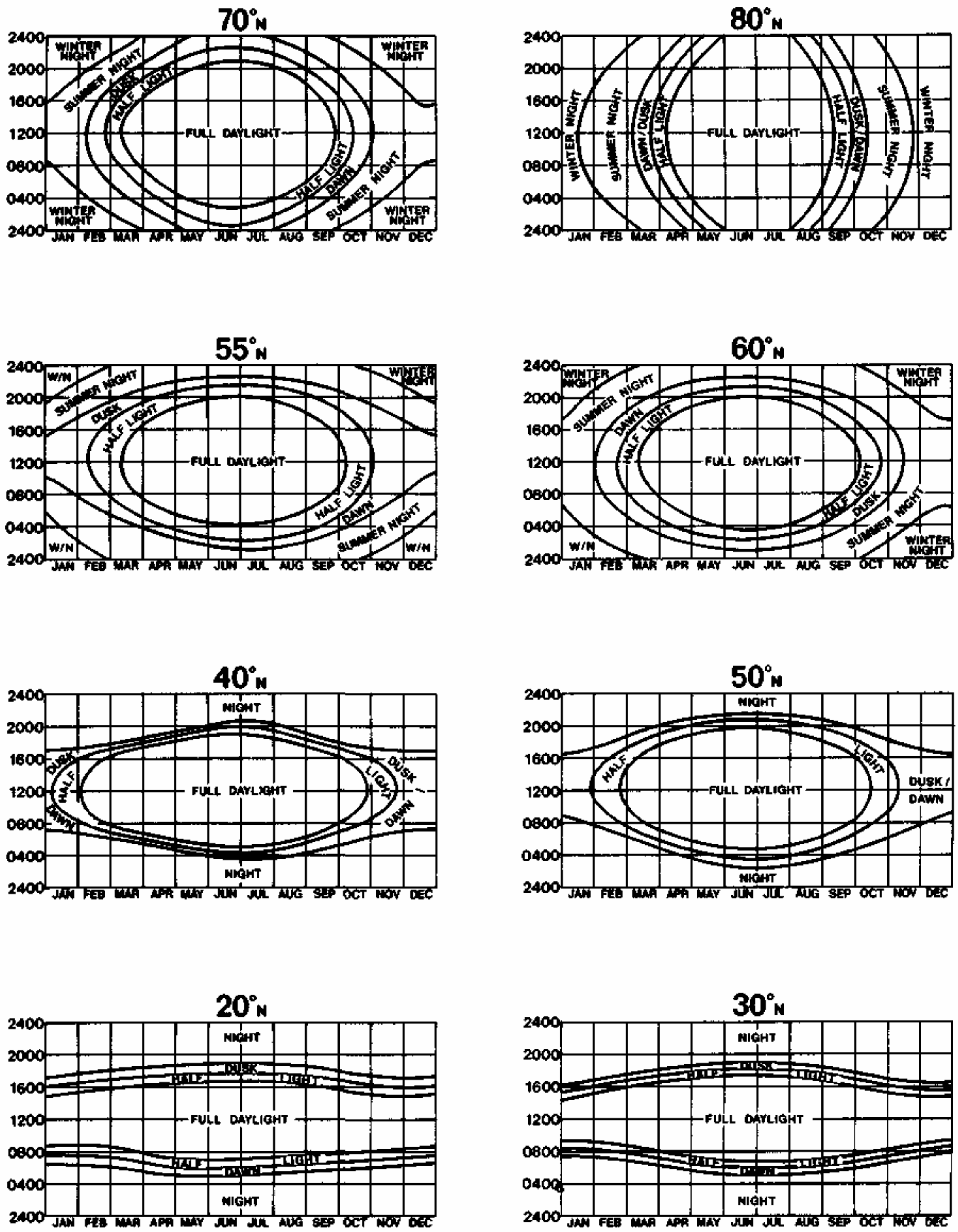


Fig. 3. 6. Variation of the shape of the onion diagram with lattitude. For the corresponding South latitudes, advance all months shown by 6 months.

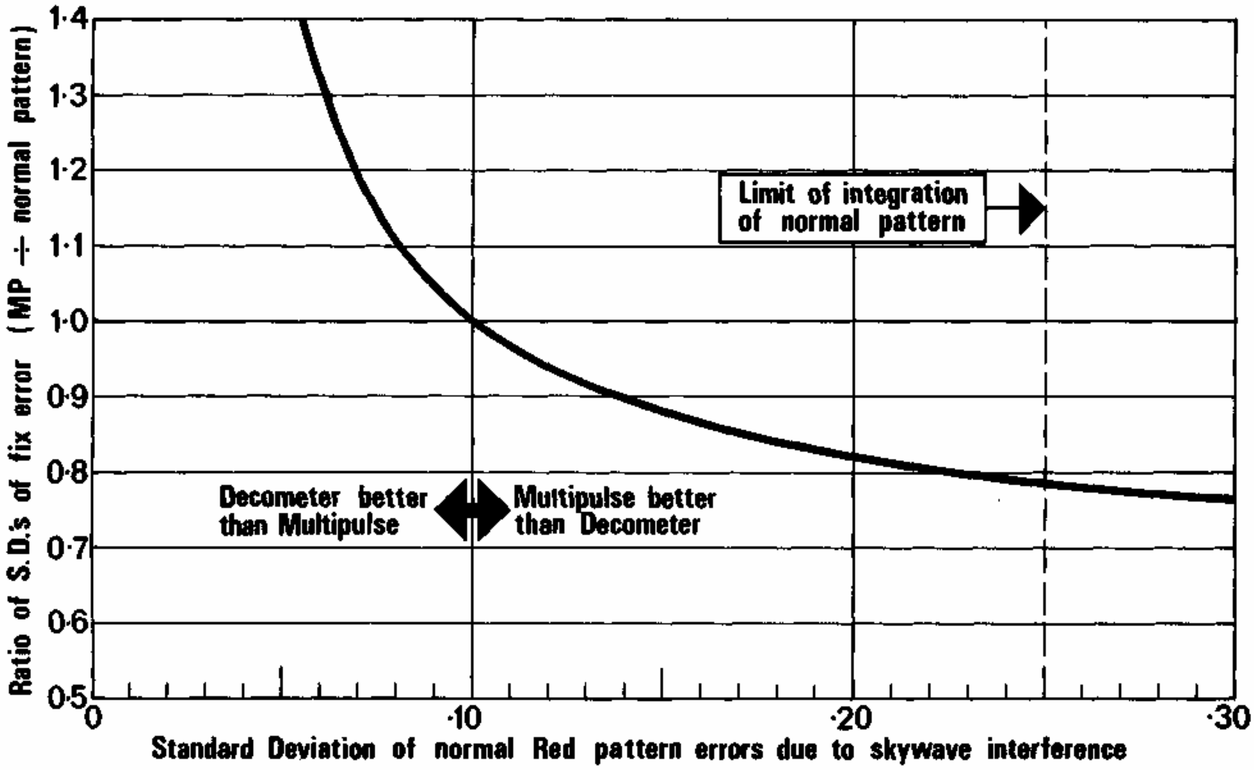


Fig. 3. 7. Comparison between normal and MP position-fixing at night.

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