THE DECCA NAVIGATOR AS AN AID TO HYDROGRAPHIC SURVEY

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INTRODUCTION.

In the following paper a method is described of assessing the accuracy of position-fixing provided by a given chain of DECCA Navigator Stations. Some notes are included on the practical techniques adopted in Survey work, with particular reference to the procedures for the correction of Random and Systematic errors in the DECCA observations. The paper is prefaced by a short outline of the principles and characteristics of the System.

BASIC PRINCIPLES.

The Hyperbolic Patterns.

The underlying principle of the DECCA System consists in the generation by fixed radio transmitting stations of a set of stable standing-wave patterns. These patterns form co-ordinates in terms of which a radio receiver carried by the user provides continuous indication of its position. The geographical positions of the ground stations being known, the data given by the receiver are directly convertible into co-ordinates of latitude and longitude. The conversion is effected by means of a map or chart overprinted with the system co-ordinates.

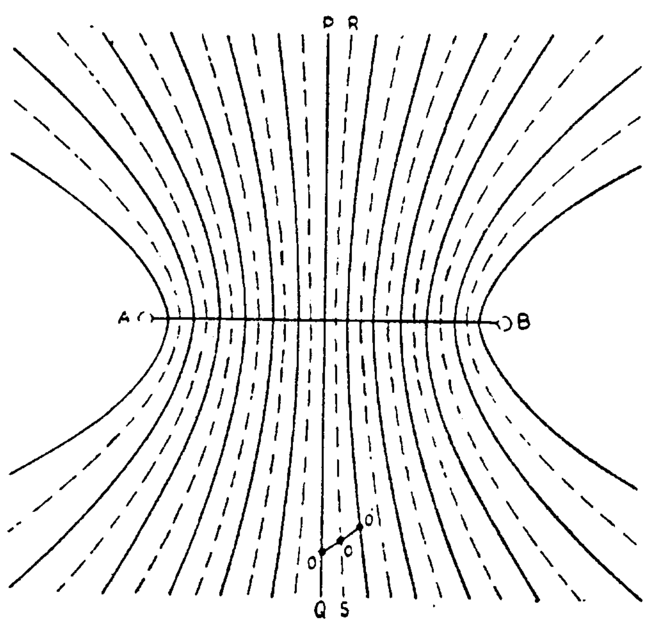


FIGURE 1*a*.
Set of hyperbolic position lines generated by synchronised transmissions from Stations A & B.

The DECCA co-ordinates are hyperbolic in form ; a given family of hyperbolae comprises the loci of points of equal path-difference as between radio signals reaching the observer from a pair of ground stations, the speed of propagation of electro-magnetic waves being assumed to have a certain constant value. The transmitters radiate pure continuous-wave signals and the hyperbolae are lines of equal phase difference, closely analogous to the standing waves of an optical interference pattern. In Fig. 1*a*, points A and B represent two such transmitting stations. We assume that they are radiating signals of equal and constant frequency and that the transmissions are rigidly locked in phase. If PQ is the right bisector of AB it follows that at any point on PQ the signals from A and B will be in phase since they have travelled equal distances at the same velocity. In other words a phase-comparison meter would read O^{o} when placed at point *O* or at any point along the hyperbola PQ. Suppose an observer with such an instrument moves from point *O* along the shortest route towards B : his distance from A will at the same time increase and he will eventually arrive at a point O' at which the signals from A and B are exactly out of phase. This out of phase condition will exist everywhere along the hyperbola RS. Continuing towards B, the path from A will again lengthen until at *O''* the phase difference will be 360^{o} degrees or one whole cycle ; *O''* is a point on the adjacent in-phase hyperbola to that containing *O*, and in passing from *O* to *O''* the observer is said to have traversed one complete "Lane". On the base line AB, the width of a Lane or the distance between any adjacent hyperbolae of equal phase-difference value is equal to half a wavelength.

The needle of the phase meter will now have made one complete rotation. If the observer continued in the same direction as before, the meter needle would continue to rotate, reading zero at each in-phase line and indicating each measurable fraction of phase difference over the whole cycle. In returning to point *O* the needle would turn in the opposite sense through the same number of revolutions as it made on the outward journey.

Position Lines and Fixing.

A single pair of stations produces a pattern which, being dependent on the distance AB and on the frequency used, can occupy calculable and highly stable positions on the earth's surface. From the point of view of an observer carrying a phase comparison device, therefore, the pattern constitutes a set of navigational position lines taking the form of a family of hyperbolae focussed on the two transmitters. The observer makes use of the position lines by reference to a map on which selected hyperbolae of agreed phase-difference value are drawn. In practice these are generally lines of zero phase difference, although fractional values may conveniently be shown in addition on large scale charts.

To enable the observer to fix his geographical position with reference to the ground station, two sets of position lines are required. These are provided by a second interference pattern generated by Station *C* (Fig. 1*b*) in conjunction with the common "Master" Station *A*. The receiving and phase-comparison apparatus is duplicated to work with the two sets of co-ordinates and the observer fixes his position at any instant by transferring the reading of the two phase meters to a map on which numbered lanes of the two patterns are printed. Stations *B* and *C* are referred to as "Slaves".

Returning for a moment to the observer moving across a single pattern, it is clear that if the phase meter were provided with a geared indicator the latter could be arranged to count the lanes progressively, showing a change of one Lane for each full rotation of the phase meter pointer. Such an arrangement is provided in the phase meters of Decometers driven by the DECCA receiver. At the start of a journey the pointers are set by

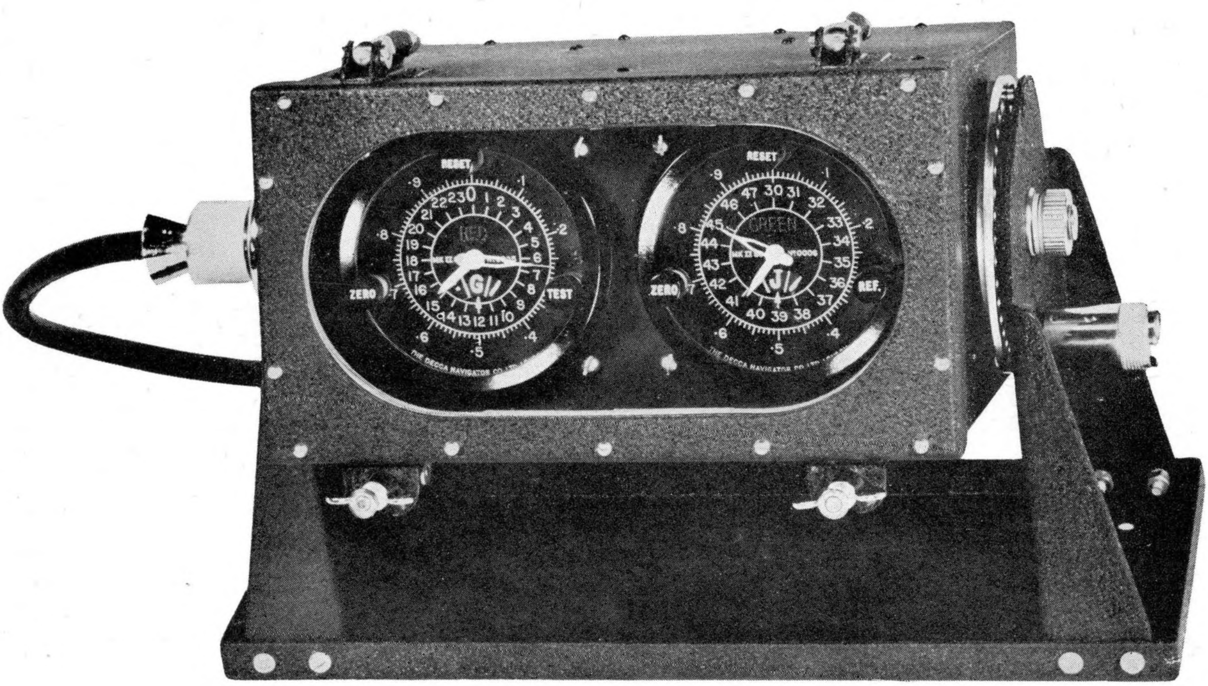


FIG. 2

A pair of survey Decometers.
The Decca co-ordinates indicated are Red G. 15.268, Green J. 40.820.

hand to indicate the Lane number at the start point (found from the map) and thereafter they record the number of the Lanes crossed and the full fixing co-ordinates of the receiver's position can be read off at will at any point on the journey. A pair of Decometers is illustrated in Fig. 2. The small split pointer corresponds to the phase meter needle discussed above

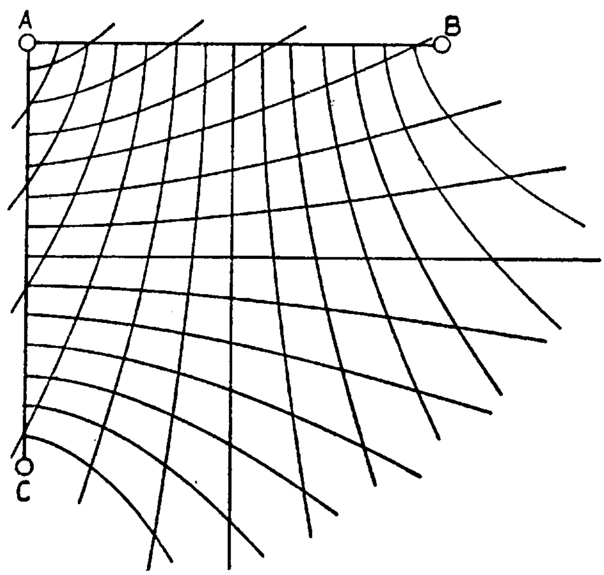


FIGURE 1*b*.
Hyperbolic grid generated by slave stations B, C, locked to Master A.

and divides each Lane into hundredths ; another pointer indicates Lanes within recurring groups or Zones, the Zones themselves being counted by a further geared dial. The Zone letters and Lane numbers of the meter scales correspond with those on the map and each pattern is shown in a distinctive colour — Red. Green and Purple.

The Survey Equipment.

The position-fixing equipment installed in survey aircraft, ships or vehicles consists essentially of two or more Decometer display meters, one for each hyperbolic pattern, driven by a radio receiving set. Since the only transmitters involved are the fixed stations ashore, there is no limit to the number of users. The receiving set contains three or more channels with fixed tuning, one tuned to the Master and one to each Slave. If a pair of transmitters were actually to radiate the same frequency, the receiver could not discriminate between them and it would be impossible to feed the Master and Slave signals separately into the phase-comparison device ; in practice each transmitter of a pair radiates a different frequency, so related that there is a common harmonic. The harmonic is generated in the receiver but, being common to the two signals, fulfils the condition shown in Fig. 1a. The phase-comparison frequencies are in the order of 300 Kc/s or 1000 metres. The lane width on the baselines is therefore about 500 metres and each division of the Decometer fractional scale represents a distance of about 5 metres along a baseline between Master and Slave.

The Master and Slave Stations are simple continuous-wave transmitters. Each Slave has a locking receiver which picks up the Master signal and compares the phase of the common harmonic with that of the Slave transmission, automatically maintaining the correct phase relationship. The

Greenland and Swedish hydrographic chains have two slaves, a third (Purple) being necessary only in cases where 360 degrees coverage around the Chain is required. The English and Danish Navigational Chains are three-slave systems.

Characteristics of the Transmitted Signals.

Many position-finding systems involve the transmission of very high radio frequencies (wavelengths from a few metres to a few centimetres). In general such transmissions tend to limit the working range to a distance roughly equal to the optical horizon as viewed from the transmitting site ; high ground between the transmitter and the receiver, or the earth itself, may cast a radio "shadow" in which the signals cannot be received unless the transmitting or receiving aerials, or both, are at a certain minimum height. Consequently it is necessary to site a shortwave aerial on a high tower or a hill in order to extend the coverage of the system to ships and distant aircraft.

As the wavelength is increased, the behaviour of signals propagated over the earth's surface undergoes a marked change. At wavelengths of thousands of metres, intervening terrain does not give rise to shadows and ground-wave signals can be received at distances of 1000 km. or more from a transmitter. The strength of the received signal becomes substantially independent of the heights of the transmitting and receiving aerials above the ground. With the development of the DECCA phase-comparison technique of measurement it became possible to employ radiated frequencies (130-70 kcs, 2300-4300 metres wavelength) which have these relatively favourable ground-wave propagation characteristics.

ACCURACY.

From the hyperbolic form of the DECCA co-ordinate patterns it follows that the accuracy of the System is dependent on several factors including range and bearing with respect to the transmitting stations. For theoretical purposes it is convenient to consider errors in two categories : first, those inherent in the nature of the System, i. e. those which would occur if the chain of stations were sited on ideal ground, and secondly terrain errors. Subject to certain reservations, these may be classed respectively as random and systematic in character.

Random Errors.

Random errors are caused by the sum total of a number of varying factors in the transmitter phase lock, the receivers, and the transmission paths between. They will cause a variable displacement of the position lines about the true computed position, of amplitude dependent on the statistical "spread" or Standard Deviation of the frequency distribution of such errors, and if this distribution is known the expectation of an error of any given magnitude can be predicted. It has been found that the "Gaussian" or Normal Distribution gives the best general fit to such errors, but the Standard Deviation, though sensibly constant in daylight throughout the area likely to be used for survey, depends on the operating conditions as will be seen below.

The Standard Deviation of the patterns is not wholly independent of range. During summer daylight in England the increase with range is very small, a representative overall figure being about .01 Lane plus $.007r$ where r is the range from the midpoint of the baseline in hundreds of miles. In midwinter daylight the figure is nearer .01 plus $.02r$. The increased Standard Deviation with range is largely due to the effect of skywave interference, in which the process of phase comparison of signals travelling over the earth's surface is modified by the reception of another pair of signals reflected from an ionospheric layer. Although it cannot be neglected, the skywave factor is in general less important in survey work than in general navigation ; the majority of Survey operations take place during the hours of daylight when skywave interference is least, and the accuracy requirements tend to limit the working ranges to distances over which the groundwave signal strength remains large compared with the reflected wave by day.

A combination of the effects of these random movements in the two position lines giving a fix and of the angle of cut between them will result in a spread of a number of DECCA plots around the true geographical position and a simple criterion is neccessary to describe the likely degree of uncertainty of a single DECCA fix taken at this position. The Americans in their researches into the accuracy of the Loran System have found a distance known as "The Root Mean Square Error" which can be described as the radius of a circle which, symmetrically drawn on the fix distribution, includes approximately 65 % of the plots. This distance can be predicted from the various factors mentioned above and is, therefore, a theoretical figure against which the likelihood of error of a single DECCA fix at a given point can be estimated.

The "Root Mean Square Error" is given by the formula :

$$d_{rms} = \sigma \frac{2}{L} \operatorname{cosec}^2 \frac{\gamma L}{2} \operatorname{cosec}^2 \beta + 2\, r\, \sigma_L\, \sigma_M \operatorname{cosec} \frac{\gamma L}{2} \operatorname{cosec} \frac{\gamma M}{2}$$

$$\operatorname{cosec}^2 \beta \cos \beta + \sigma_M^2 \operatorname{cosec}^2 \frac{\gamma M}{2} \operatorname{cosec}^2 \beta \qquad (1)$$

where

σ_L, σ_M = Standard deviations in the "L" and "M" DECCA co-ordinate at the point in question expressed as equivalent apparent shifts in linear units on the base lines.

γ_L, γ_M = Angles subtended by the base lines giving rise to the "L" and "M". Co-ordinates at the point in question.

β = Angle of cut between the lattice lines of constant "L" and constant "M" at the point.

r = Correlation coefficient between the deviations of the "L" and "M". Co-ordinates from their mean (true) value.

Assuming therefore that these factors can be determined and a circle of radius to d_{rms} drawn with centre at the point in question, then of a very large number of DECCA fixes taken at the position, 65 % would lie within this circle. Alternatively the chance of a single DECCA plot falling outside this circle would be 35 % or in other words the odds against it falling outside this circle would be two to one. This probability level is the one most frequently used to estimate DECCA errors for Survey purposes, but it is worth noting that the distance error corresponding to a 95 % level is given by $2.2 \times d_{rms}$.

Estimates of the Standard Deviation and Correlation Coefficient have been made on the basis of results observed on operational chains. Over the area in which a DECCA Chain is likely to be used for Survey purposes the correlation coefficient by daylight is in general a small positive quantity and can be taken to be zero with negligible effect of the values of d_{rms}.

2.—

A simple approximation to the *O* values for substitution in the formula is obtained by assuming that all patterns have the same Standard Deviation in "mean lanes". A mean lane is defined as the width of a lane corresponding to a fictitious comparison frequency of 300 kc/sec i. e. the width of a "mean lane" on the base-line is 500 metres. In computing the d_{rms} contours shown in Fig. 3, a Standard Deviation of .02 mean lanes has been assumed. This figure is conservative and has been validated by a very large number of observations made on the English Navigational Chain. If therefore the variations in Decometer readings due to random variations are converted to apparent shifts of the lattice lines on the base-line, then the resultant equivalent shifts are distributed normally with mean Zero and Standard Deviation 10 metres on all patterns.

If a monitor receiver is established at a known point in the pattern (as described below) and the observed changes in readings at this point are used to correct the readings of the Red and Green Decometers used in the survey work, it has been found that the resulting Standard Deviations of pattern errors can be reduced to as little as 0.01 mean lanes, equivalent to a standard error shift of only 5 metres on the base-line.

For normal operations it will be seen that the factors in the formula reduce to :

$$\sigma_L = \sigma_M = 10 \text{ metres}$$

$$r = 0$$

$$d_{rms} = 10 \operatorname{cosec} \beta \sqrt{\operatorname{cosec}^2 \frac{\gamma L}{2} + \operatorname{coesc}^2 \frac{\gamma M}{2}} \text{ mètres} \qquad (2)$$

and the Root Mean Square Error is a function only of the angles subtended by the base-line at the point of observation. This formula is the one used to compute the various accuracy contours shown in Fig. 3 after appropriate conversion of linear units from metres to feet. The computation can be greatly simplified by a graphical method which enables the contours of constant d_{rms} to be directly drawn.

Contours of Random Error.

A family of contours, based on an assumed unit Standard Deviation in Mean Lanes, forms the basic accuracy diagram for a station layout. A study of a number of these diagrams for various layouts shows the way in which station siting can be adapted to the accuracy requirements of a given area. A typical set of contours for two-slave chains of various base angles is shown on Fig. 3. For convenience the base-lines AB, AC are assumed to be equal in length. It is important to note that, in general, for unit Standard Deviation postulated, the area within any given contour remains constant in units of baseline-length squared. In other words, the diagram is true for any scale : if the area within the contour is 100 square miles for base-lines of 100 miles, it will contain 100 square Km. for 100-Km. base-lines. Hence it is desirable to make the base-lines as long as possible, within the limit imposed by the increase of Standard Deviation with range.

The generalisation that the random error diagrams are independent of scale needs some qualification in that they are drawn for a Standard Deviation figure that is assumed to be independent of range : as has been stated, pattern stability is to some extent a function of the lengths of the transmission paths. A base-line length of 40-50 miles is probably best if the utmost of which the System is capable is required, but where large areas are to be surveyed

BASELINES AT 60°

A - MASTER STATION
B } SLAVE STATIONS
C }

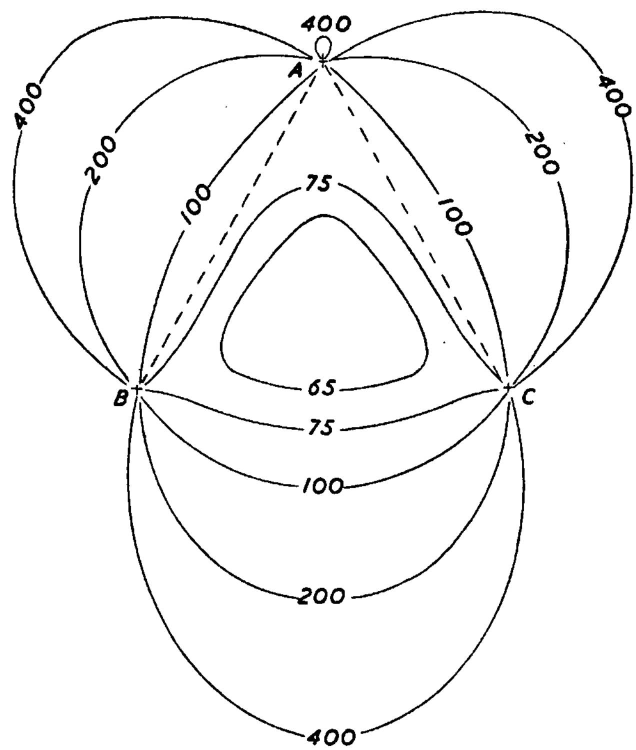


FIG. 3a.

DAYLIGHT RANDOM ERROR CONTOURS IN FEET FOR BASELINES AT 60° AND STANDARD DEVIATION OF ·02 MEAN LANES.

ERROR FIGURES ARE HALVED FOR A STANDARD DEVIATION OF ·01

NOTE:- THE SCALE OF THIS DRAWING IS DETERMINED BY THE BASELINE LENGTH SELECTED.

BASELINES AT 120°

NOTE: THE ADDITION OF A THIRD SLAVE AT D GIVES ALL-ROUND COVERAGE.

A-MASTER STATION.
B, C } SLAVE STATIONS.

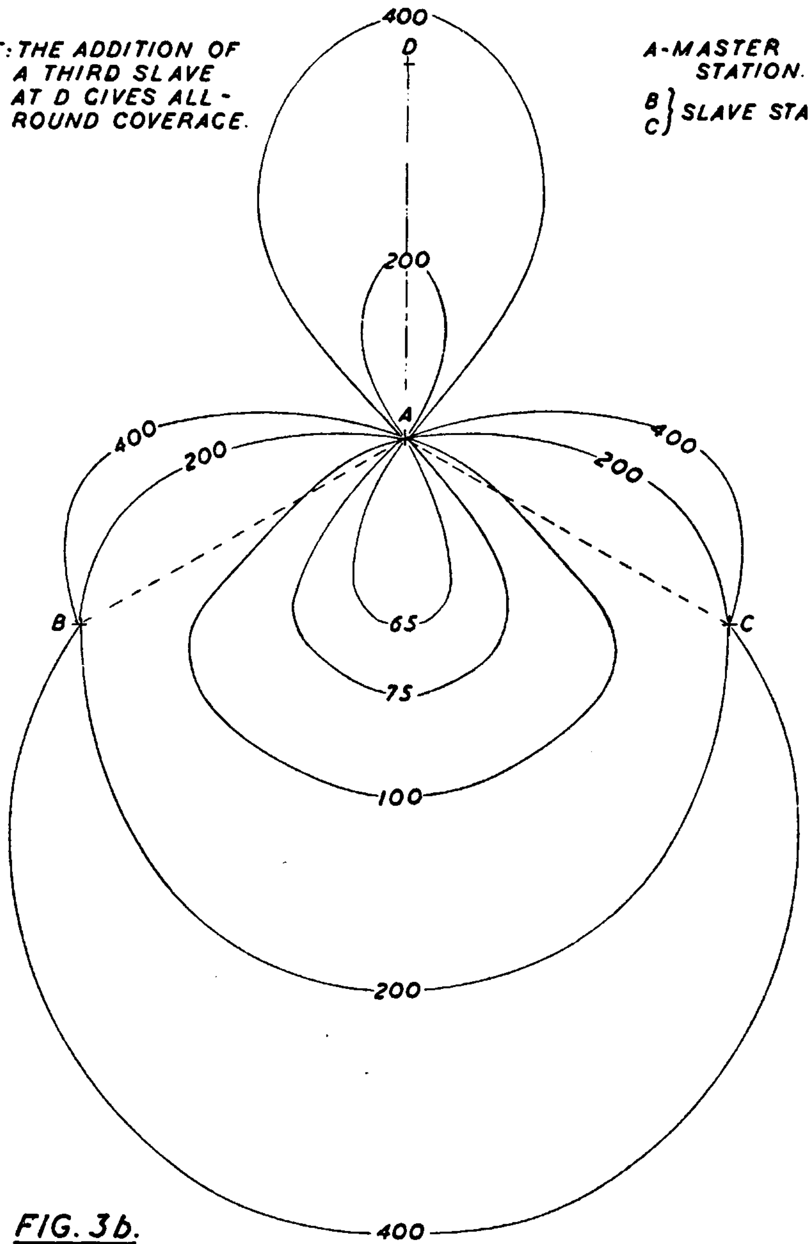


FIG. 3b.

DAYLIGHT RANDOM ERROR CONTOURS IN FEET FOR BASELINES AT 120° AND STANDARD DEVIATION OF ·02 MEAN LANES.

ERROR FIGURES ARE HALVED FOR STANDARD DEVIATION OF ·01

NOTE: THE SCALE OF THIS DRAWING IS DETERMINED BY THE BASELINE LENGTH SELECTED.

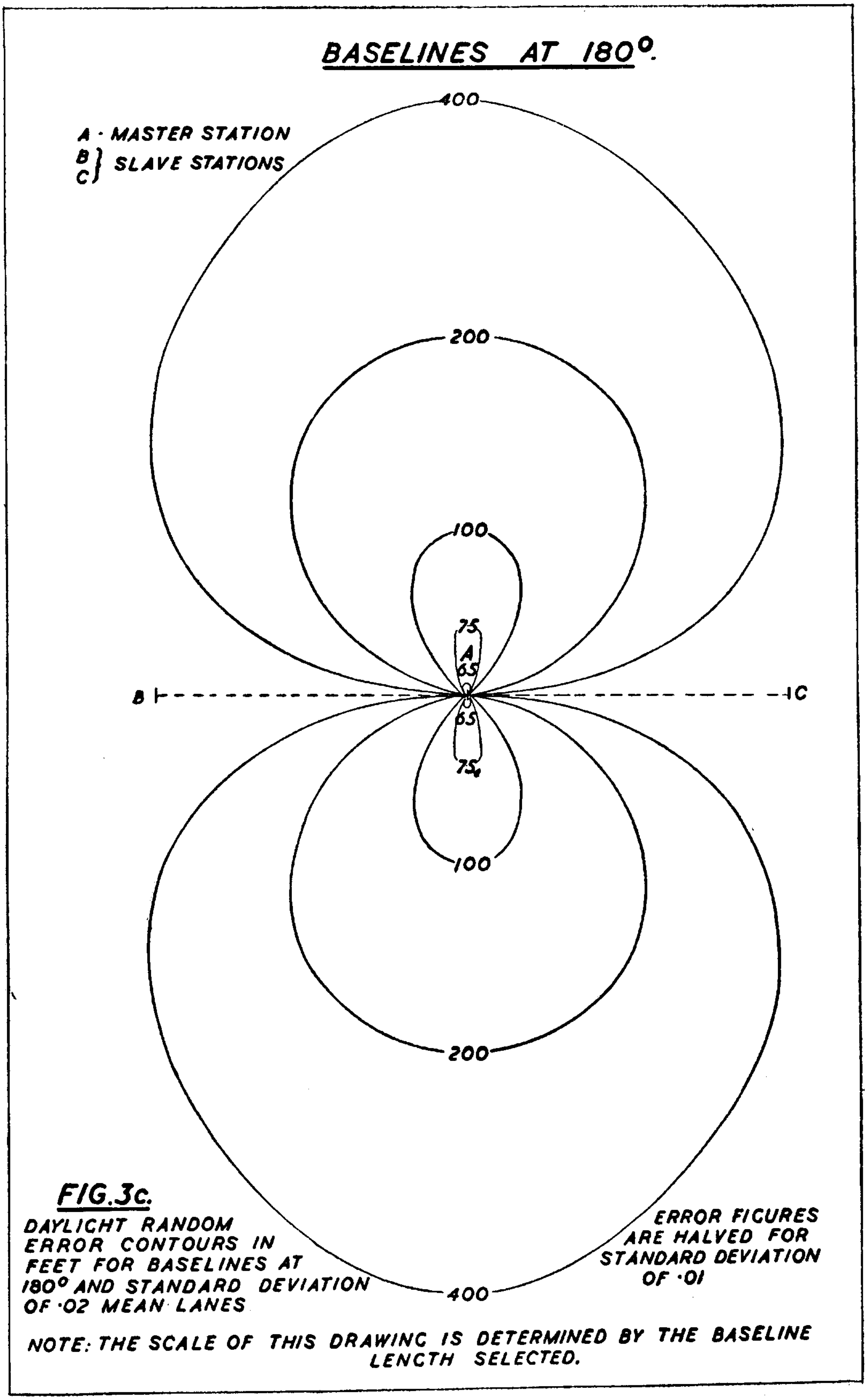


FIG.3c.

DAYLIGHT RANDOM ERROR CONTOURS IN FEET FOR BASELINES AT 180° AND STANDARD DEVIATION OF ·02 MEAN LANES

NOTE: THE SCALE OF THIS DRAWING IS DETERMINED BY THE BASELINE LENGTH SELECTED.

this small additional accuracy is bought at a relatively high cost in movement of stations and in extra computing work.

Systematic Errors.

The error theory developed for hyperbolic systems deals only in random errors, daylight error diagrams such as those considered above being regarded in the main as holding for chains operating under ideal conditions. In practice the performance exemplified by these diagrams may be expected to obtain where the stations are so sited that all transmission paths lie over a uniform conducting medium, e. g. a coastal hydrographic survey chain. Consideration of the design of the Master transmitter and of the phase-locking device at the Slave station makes it clear that no significant systematic error can arise in the transmitting equipment itself; in the receivers, both at the Slave station and in the field, a certain amount of drift is inevitable especially during the first hour of operation but this is taken care of by the provision of a Reference Oscillator and associated zero-setting control proper use of which reduces the drift errors to a negligible value.

Systematic errors would result from an incorrect assumption of the mean velocity in the basic computations of the lattices. There is in fact, some evidence of such errors in the English Chain, but the value of the resulting fix error is in general small and they form a definite pattern which is a function of the phasing of the stations and can be largely corrected. Local errors result mainly from difference in mean propagation speed as between the transmission paths from the observer to the Master and Slave stations of a pair. Such uncertainties must be regarded as increasing in some measure the random error of the System; but the errors in a given locality tend to have a distinctive pattern depending on the country in different parts of coverage and would, for example, contribute more to the total error in broken mountainous terrain than over flat ground of good conductivity. No satisfactory theory has so far been found to account fully for local pattern errors but the order of the deviation can be estimated from consideration of the likely conductivity of the paths over which the different transmissions pass.

The only serious effects will occur when one path lies largely over sea and the other over ground of poor conductivity. Considering two mixed land and sea paths, the error in lanes is roughly proportional to the difference in the lengths in the sea paths from the two stations; convincing support for this hypothesis has been given by the results of a series of observations at points around the English coastline. Errors of this type may properly be regarded as systematic in time and the scatter of a number of observations made at a given point is independent of the magnitude of the systematic error at that point. There is, in fact, no set of conditions variable with time which can noticeably affect ground conductivity other than a large-scale inundation to a depth of several feet. No change in systematic errors in the English Chain was detected after the heavy and widespread falls of snow in the winter of 1946.

OPERATING TECHNIQUE.

Monitoring.

In practice it is necessary to keep a check on the random fluctuations of the DECCA co-ordinates and to see that these correspond to the Standard Deviation assumed in planning the Chain and in computing the accuracy contours. This is done by setting up a Monitor receiver, which may be a normal DECCA instrument as used on survey vessels, at a point ashore or in a vessel anchored at a position of known DECCA co-ordinates.

The Monitor may be used in several ways. One method is for the operator to take readings each minute and pass the record so obtained, together with the time of reading, to the surveyors at the end of the day's working. Knowing the calculated co-ordinates of the Monitor and the times of their own observations, the surveyors can then prepare correction tables and adjust their DECCA readings for any fluctuations that may have been recorded. Alternatively the monitor can transmit radio correction figures to the surveying vessels at short intervals while the work is in progress. A further variant of this class of monitoring is the use of an automatic recording Decometer at the Monitor; this obviates the need for a human operator and produces a strip record, with time marks, of the pattern fluctuation over a period. Such a device lends itself to incorporation with an automatic tide gauge, the records from the two instruments being collected simultaneously or communicated to the vessel by a radio telemetering system.

The above monitoring methods each involve the application of corrections by the surveyor before plotting. In general it is more satisfactory for the Monitor operator to pass the pattern corrections, when he observes a change of reading, direct to the appropriate Slave transmitter where a simple manual adjustment can be made to shift the pattern by the required amount. This arrangement, which relieves the user of the work of applying corrections, has been in use on all DECCA Survey and navigational Chains. Both line and radio communications have been employed; the Swedish Hydrographic DECCA System, for example, employs a Morse monitoring procedure in which periodic groups of dots and dashes are transmitted from the Monitor to the Slave to indicate the magnitude and sign of the required correction.

The standard and tolerances of monitoring have varied considerably with different Chains. During the last two years the procedure in use on the English navigational Chain has been sufficient to maintain a daytime Standard Deviation for the whole period of approximately .02 mean lanes. For the duration of particular survey operations the standard of monitoring on the English Chain has been raised, with minute-to-minute observations and an allowed tolerance of half a hundredth of a lane, and under equivalent conditions the error values normally assigned to the accuracy contours would be halved.

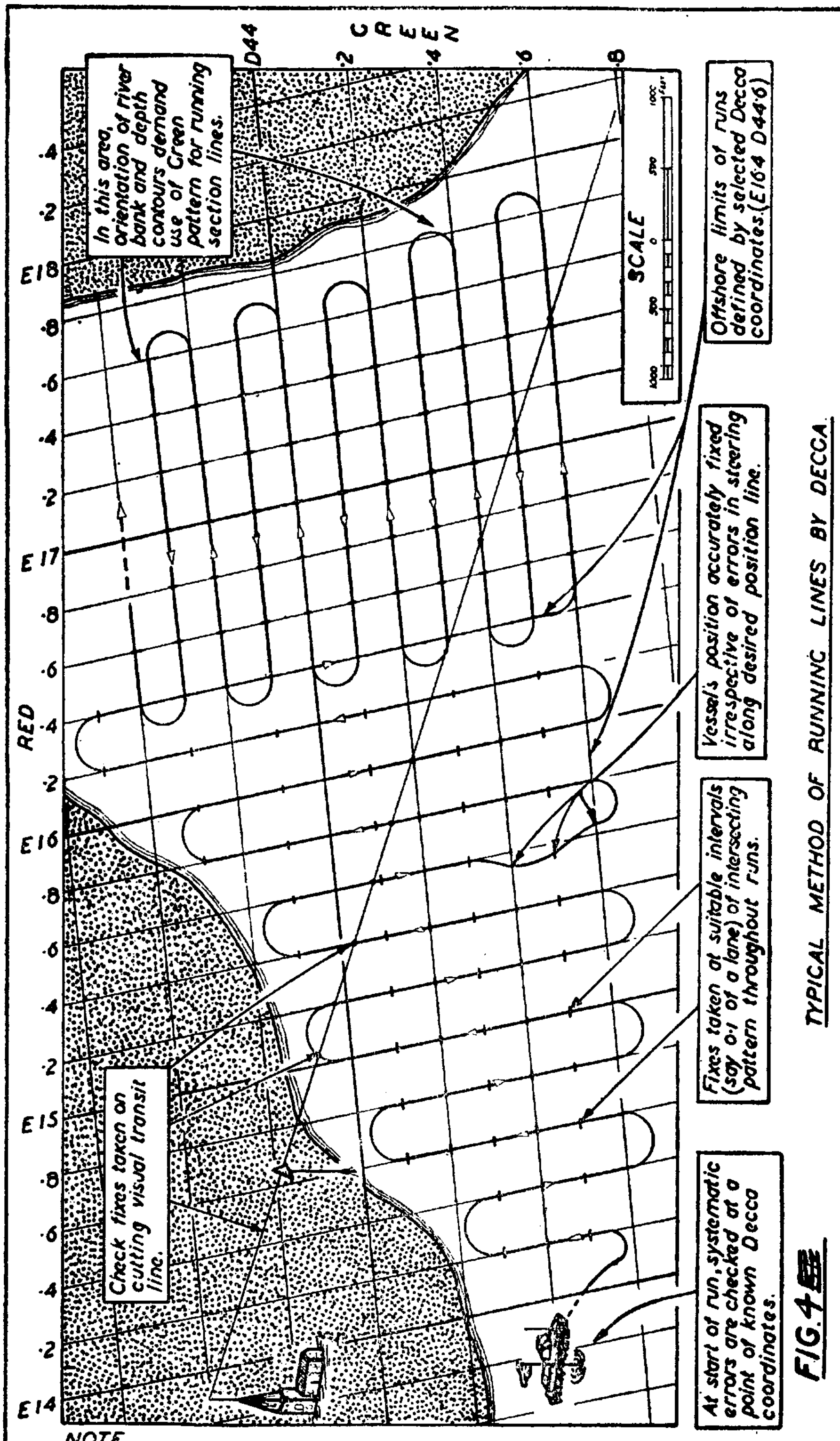
On the Red and Green patterns in daytime, there is good correlation between the fluctuations as observed on two receivers 35 miles or more apart; for this reason it is unnecessary to site the monitor close to the survey operations.

Visual Control.

From the notes on systematic error it will be clear that a chain of stations sited on the coast with a high proportion of water between the stations will in general give small errors and the overall fixing errors occurring in practice will approximate closely to the calculated d_{rms} values. Nevertheless it remains a general principle that the surveyor will combine with his DECCA observations a sufficient number of visual measurements to eliminate the effects of any systematic errors that may be present. The number of such visual observations may well be very small, amounting perhaps to a single sextant angle check at the start of a long section line or block of lines. In open water, systematic errors do not change abruptly in magnitude with the position of the vessel and in general remain sensibly constant over areas of several hundred square miles; close inshore or near the base-line extensions, where the relative amounts of land and water in the transmission paths may shift considerably with the vessel's position, surveying can still be carried out with a very low proportion of visual to DECCA observations and with little sacrifice of the advantages attaching to the use of a radio aid.

Navigation.

So far we have been considering the DECCA system purely as a means of fixing the position of a survey vessel and thus dispensing with a very



TYPICAL METHOD OF RUNNING LINES BY DECCA.

FIG.4

NOTE Arbitrary Zone letters and lane numbers are shown in this drawing.

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Drn. by G.F.KING Date 7·6·48	

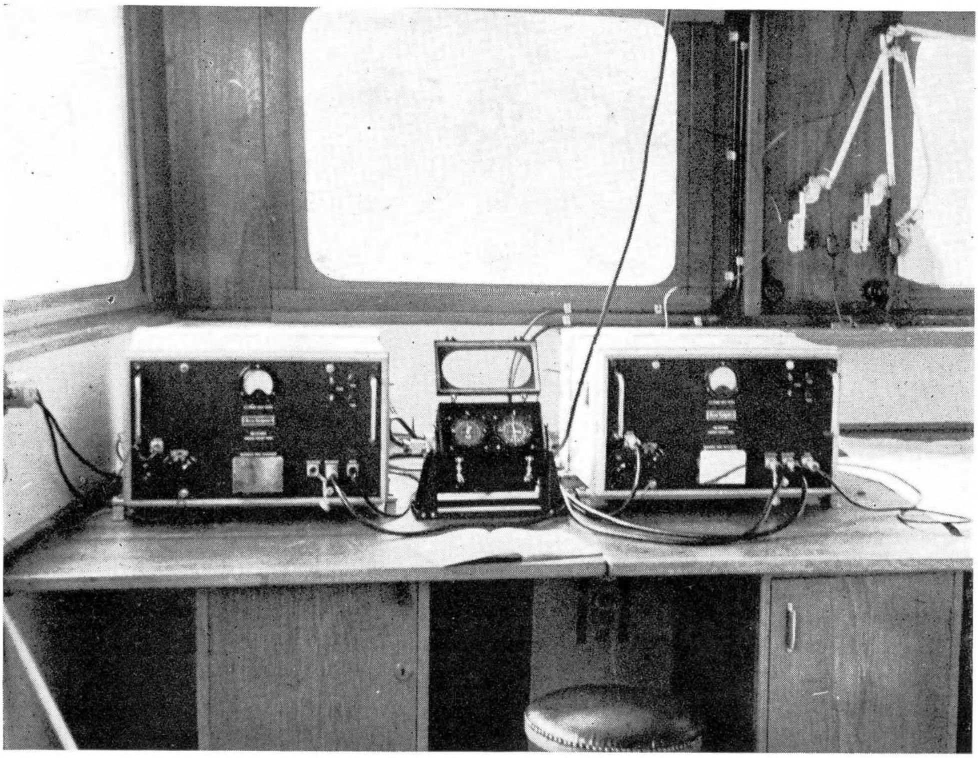

PHOTO 1

The shipborne equipment. — The *Gustaf af Klint* is fitted with two Decca Survey receivers (one operational and one standby) installed in the chart-room.

Each receiver can drive two sets of Decometers, so that Decca information is available continuously on the bridge for tracking and in the echo-sounder room for recording fixes.

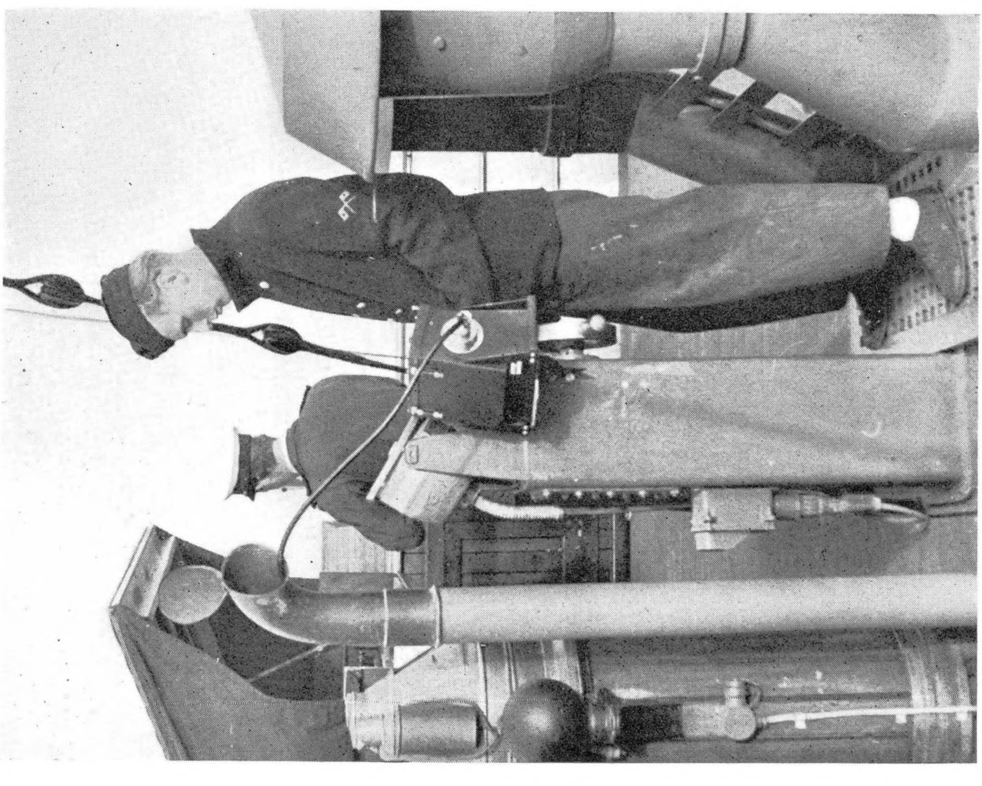

PHOTO 2.

Running section-lines.

By using one of the Decometers and the compass conjointly, section-lines can be run along selected Decca position-lines.

The photograph shows this procedure in operation on the Swedish survey vessel "*Gustaf af Klint*".

large proportion of the visual observations normally entailed. This is by no means the only advantage offered by a flexible radio system; important savings in time and effort accrue from the use of radio navigation in sailing directly at normal cruising speed to specified points, such as the ends of section lines or small areas to be re-examined, and particularly in running straight and parallel section lines.

Fig. 4 shows the method of running lines normally employed in conjunction with the DECCA system. If the track of a vessel is made to coincide with a DECCA position line the associated Decometer pointer will remain stationary; the helmsman can maintain this condition by using the fraction pointer as a course indicator to "home" the vessel along any selected whole number or fractional hyperbola. For distances of a few miles the hyperbolae can be assumed to be straight and parallel and the divergence will in any case be indicated by the DECCA charts in use. It will generally be found that one of the two patterns lies at a suitable angle to the expected line of the depth contours. Before a run the helmsman is provided with a series of fractional Decometer readings, one for each section line, selected to give the required spacing. The use of a Decometer as a left-right indicator demands but little practice on the part of a normally experienced helmsman and it has proved possible to run lines by this method in relatively heavy cross-tides. In the illustration it will be seen that homing along every 0.2 Red and 0.1 Green lattice line results in a separation between lines about 300 and 400 feet respectively. Any desired separation can be maintained depending on the sounding requirements.

Recording fixes.

The continuous presentation of the co-ordinates allows DECCA fixes to be taken at any suitable intervals along each section line. For this purpose the readings of the second Decometer, relating to the pattern intersecting the one used for tracking, are observed and logged for subsequent co-ordination with the echo-sounder charts. The readings of both Decometers are generally recorded in this way so that the position of the vessel can be accurately plotted even though there may be a momentary error in steering along the wanted line. The intervals at which DECCA fixes are taken along each line are not critical and depend entirely on the survey requirements.

Representative values at intervals of one or two tenths of the intersecting lattice are shown in the sketch.