LARGE SCALE OFFSHORE SURVEYING FOR THE OIL INDUSTRY

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The increase in engineering work on the continental shelf over the past decade has been matched by the development and wider use of electronic positioning systems designed specially for survey work rather than navigation.

This is just as well in view of the oil industry's requirement for reliable survey plans at scales of 1/5 000 or 1/10 000 at distances of 300 kilometres or more from shore, and in depths of water which may exceed 200 metres.

Part I discusses the determination of position in this context; Part II gives a brief description of the requirements of a drilling rig site survey.

PART I

The following comments result from work over the last 10 years in the North Sea. The methods employed apply equally to similar activities in many other parts of the world, except that in the North Sea there is one advantage which is unusual. Due to the shape of the North Sea, almost entirely enclosed as it is by land, and being of the order of 300 nautical miles in width, empirical work has been possible at distances of 150 miles from shore. In this work it has been necessary to compare one phase comparison system with another. It will be interesting, as soon as an opportunity occurs, to compare these positions with those obtained from satellite observations combined with acoustic doppler. Current claims for the latter systems indicate comparable errors in the determination of absolute position, in the centre of the North Sea for example, but larger errors in terms of repeatability. In the meantime, observations such as those described below are adding to our knowledge of the type of errors existing in our present work.

POSITIONING IN THE NORTH SEA

Systematic hydrocarbon exploration of the North Sea began in 1961 with an open grid of gravimetric and aeromagnetic observations. These were positioned by the present Decca Navigator navigational chains which had errors due to land path effects and chain geometry varying from one or two hundred metres to 1 ½ kilometres in the area of interest, even in daylight conditions. These errors were acceptable in this early reconnaissance stage, but the need for survey purpose designed systems for future work was already recognised.

The large scale shipborne seismic operation and an airborne reconnaissance magnetometer survey, which took place in the following year, were therefore positioned by a phase comparison system specially sited for that programme. This system, later designated "Sea Search I Chain" (figure 1), differed from the navigational chains in three main respects.

The stations were sited so that the signal transmission paths from all three transmitters to the ship's receiver, and to a lesser extent the inter-transmitter signal path, were so far as practicable entirely over sea water. This layout minimised attenuation of the signals which takes place over ground of poor conductivity and consequently increased effective range, or alternatively, increased signal to noise ratio at a given range, and reduced distortion of the transmitted pattern due to land paths.

Secondly, on average the phase comparison on the Sea Search chain is at a higher frequency than that used in the navigational chains. Consequently, lane-widths (the distance travelled at right angles to the pattern to cause one complete revolution of the pattern counters) on the baselines are narrower; in this case about 296 metres on the Green (eastern) pattern and about 444 metres on the Red (western) pattern. An additional advantage was that the Sea Search receivers were more sensitive and accurate than those available at that time for the reception of Decca Navigator main chain transmissions.

Thirdly, the baselines being 50% longer than the average navigational chain, gives enhanced geometrical conditions which, combined with the first two points, produce a remarkably accurate survey system.

In 1962, suitably trained hydrographic surveyors and adequately equipped positioning vessels were not available to carry out the full calibration programmes which have become a feature of the installation of the later systems. Having adjusted all transmitting station positions into European Datum terms, the Sea Search I chain was calibrated by monitoring the signals received at various coordinated points on the continental and United Kingdom shores of the North Sea and by an aircraft lanecount around the baseline extension. Analysis of these observations indicated the use of a speed of propagation of 299 594 km/sec. to reduce the systematic errors over the working area to a minimum. This figure was used for computations and the construction of hyperbolic lattice charts. Subsequent and more detailed observations have confirmed that this was a good figure

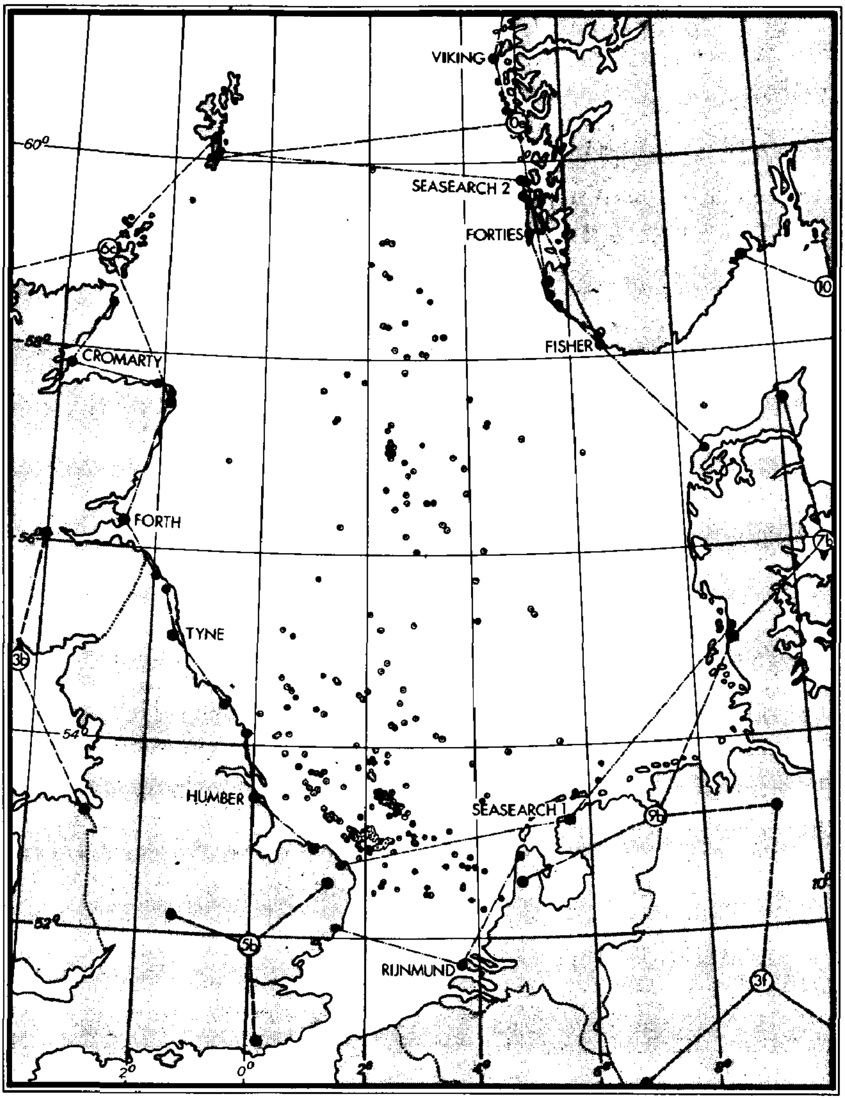

FIG. 1. — North Sea. Distribution of Decca systems coverage, and of completed exploratory wells.

for this chain. Transmitted frequencies are 168.740 kHz from the Master station, 126.555 kHz from Green slave and 112.493 kHz from Red slave. It is not claimed that this is necessarily the best general figure to use for the speed of propagation of these frequencies over sea water in any part of the world.

Seismic work has continued in each year since 1962 and the Sea Search I chain, with a lane identification facility added in 1964, remains the primary positioning aid to both exploration and development work in a large part of the southern North Sea. In addition to this aid, further Sea Search and Hi-Fix chains have since been put into operation on either a semi-permanent or 'on call' basis to meet the further requirements of the oil industry.

Now, in 1970, the number of phase comparison position lines available in the North Sea can be deduced from the pairs of transmitting stations shown in figure 1. All these chains are in operation with the exception of Sea Search II which was withdrawn in Autumn 1967, prior to the establishment of the Norwegian Vestlandet (OE) navigational and fishing chain.

Collection of data in a particular area prior to a decision to drill may depend on a number of quite independent operations sometimes separated in time by a year or more. All this data must be compiled against a common reference system which, in the case of the North Sea, is usually the International Spheroid (European Datum).

To provide a satisfactory positioning system in these circumstances, it is essential that each pair of transmitting stations generate a pattern which remains stable on its calibrated setting day after day and year after year. To this end, each pattern is provided with one or more static monitoring receivers at which readings are regularly recorded and tabulated. These stations are sited, so far as is practicable, so that the propagation conditions between the transmitters and monitor approximate those which will be experienced by a receiver in the centre of the coverage. Additionally, information from the slave receiver readings of opposite patterns, ship's baseline extension crossing readings, ship's simultaneous inter-chain observations, and check calibration readings in conjunction with sextant, hydrodist or theodolite fixes, are all considered in the control of the transmissions.

This control is solely concerned with repeatability, or the ability to return an observer to the same position with the same pattern values at any time. But this type of operation also requires that a fix from any two readings should be capable of expression in terms of a defined geodetic system — European Datum International Spheroid geographicals for example. Apart from the usual survey problems of ensuring that all transmitting station positions are expressed in mutually consistent terms, this entails knowledge of the systematic errors of each transmitted pattern; not only within sight of shore where the ship's position can be determined within a metre or two, and hence where theoretical and observed hyperbolic coordinates can be directly compared, but also at distances of 150 or more miles from land.

In the first place, as each survey chain is set up, its systematic errors are determined accurately by observation wherever this can be done. In general, this will be within 15 kilometres of the coast in the vicinity of the 3 transmitting stations, and in some cases along the baselines as well. Methods used are the well established ones of observing the position of the ship's receiving antenna by hydrodist, theodolite, or a combination of these, computing the grid coordinates of this intersected or resected position, converting to hyperbolic pattern coordinates, and comparing these with the observed pattern readings.

In general, the patterns of survey chains are set at a value which reduces systematic errors in the area of usage to a minimum. The problem at this stage then is how best to apply the calibration data obtained up to 15 km offshore to an area which may be 100 km offshore, and where the necessary extrapolations cannot be checked in practice, because the system being used in itself provides the most accurate measurement that is readily available.

In the North Sea, phase comparison signals can be received from opposite shores and from widely differing directions. These provide observed data with which to test these extrapolations. Of the theoretical considerations which have to be applied to evaluate a systematic error at these distances offshore, it is the assumed speed of propagation which must first be suspected for most of the displacement of the fix from its true position, and land path will be more troublesome than sea path in this respect. (See Appendix I).

A multiple fix, that is the simultaneous observation of three or more patterns (not necessarily of the same chain) will provide a fix from any two position lines, and none of these fixes will occur at precisely the same point except by chance.

In the case where assumed speeds of propagation from the three transmitting stations of one chain have been wrongly assessed by nearly the same amount, the true position will lie nearly on a position line (or its extension) joining the Master station to the position. In practice, treatment of the multiple data in this way results in a satisfactorily small 'cocked hat' in the majority of cases. This position can then be used as a first trial point to examine the values of systematic errors which it imposes on each pattern. The exercise is repeated until a 'best fit' solution is found.

Finally, a 'best fit', remembering that we are trying to detect changes in systematic errors of as little as 1/100th of a lane, would be difficult to justify if the position were considered in isolation. Even at 150 miles offshore, a change in ship's position of only 10 miles might result in considerable changes in land path to one or more transmitting stations with a consequent change in systematic errors on those particular patterns. At the same time other patterns may not be affected at all.

A large quantity of data is therefore necessary.

COLLECTION OF DATA

To establish the offshore systematic errors with certainty it has been necessary to observe a network of traverses in each of which simultaneous records of all the useful Decca coordinates are made at frequent intervals.

Specially equipped Decca survey vessels (see figure 2) have undertaken a number of cruises for this specific purpose. On one cruise alone for example 4500 stations were observed, recording 9 or more patterns at each station.

Typically, the equipment on board these vessels includes 3 Hi-Fix receivers, 2 Sea Search receivers and 2 Mark XII Decca Main Chain receivers; a total of 16 dials to be read simultaneously. Even three observers could not undertake this task optically and manually by the verbal 'standby...Fix' procedure, without introducing personal and time

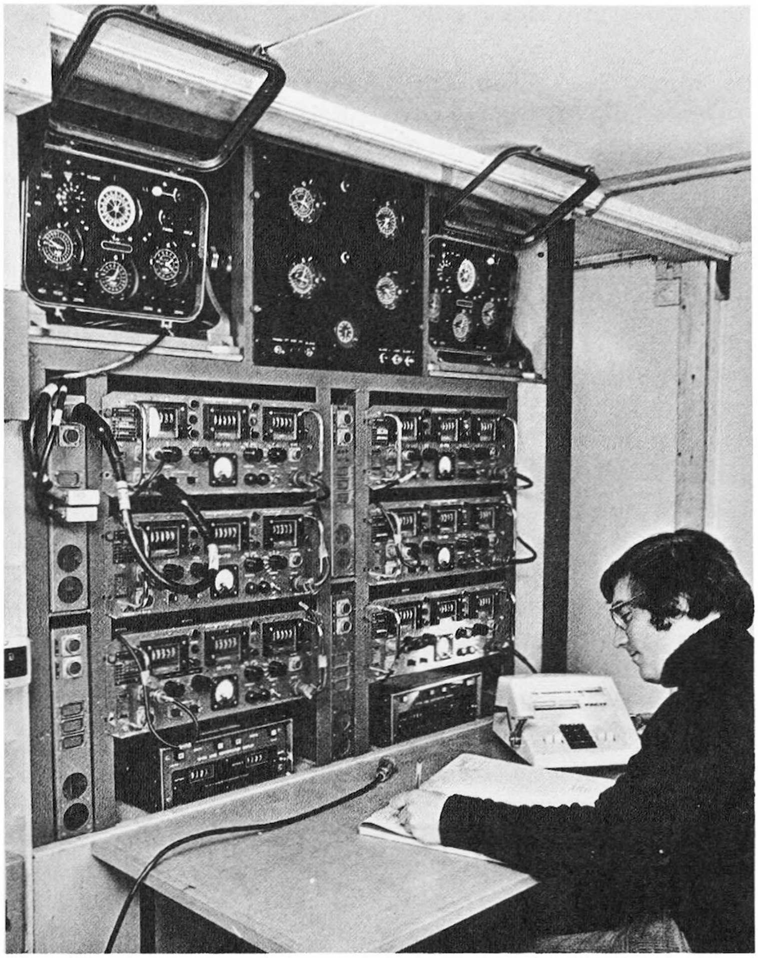

FIG. 2. — Receiver bank in the Operations room of a North Sea Decca survey vessel showing 2 Mk XII main chain receivers, 2 pairs of Sea Search decometers with one lane identification indicator (top centre panel), 3 high frequency and 3 low frequency Hi-Fix receivers, and 2 Hi-Fix Lane Identification displays.

delay reading errors larger than the smallest systematic errors we hope to detect. Recourse therefore had to be made to photo recording on 35 mm film. Photographic recording, though accurate, is being largely replaced by data acquired on punched paper or magnetic tape, due to the latter's greater facility and flexibility in processing.

TREATMENT OF DATA

In the analysis of results care must be taken to avoid any procedures which would tend to propagate or accumulate poor estimations into adjoining areas.

In any one part of the North Sea there will be a key pair of patterns, not necessarily of the same chain which, because of their angle of cut, lane width, good sea path and range, will provide a stronger fix than any other combination of two patterns which can be received at that point. In the sense used here, the strongest fix refers to the two pattern readings which, with a given change in value, say ± 5/100ths of a lane on both, will produce a smaller diamond of error than any other pair of patterns changed to the same extent.

Series of simultaneous observations in the first instance are analysed by giving all the weight to the two patterns of this 'strongest fix', and examining the systematic errors imposed on the other patterns by this assumption.

Take for example a series of observations recorded in position 53°45′ North 1°00′ East. Here, as can be seen from figure 1, Humber Pattern I and Humber Pattern II provide the strongest fix. The southern (Red) pattern of the Sea Search I chain is also a 'good' pattern, but a change of 5/100ths of a lane on each of the Humber patterns produces an equivalent change in Sea Search I Red of less than 1/100ths of a lane. In this instance the two Humber pattern observed values would be corrected for systematic errors from extrapolations or interpolations of existing data, these corrected pattern values would be converted to geographicals, and these geographicals converted back into computed values of all the other observed patterns for evaluation of the error (Computed – Observed) in each case.

Suppose that these observations had been part of an inter-chain comparison traverse carried in an easterly direction from this position. At some point along this traverse, at about Longitude 2°30′ East there will no longer be any justification for retaining the two Humber patterns as the 'strongest fix'. A combination of Sea Search Red and one of the Humber patterns now gives an equally strong fix, and must therefore be given equal weight in arriving at a first trial point. Already this may require slight revision of the values arrived at to the westward. It will be seen that the adjustment becomes complex when dealing with as many as nine different patterns over a wide area.

Throughout the North Sea there are dozens of areas in each of which a different pair combination provides the strongest fix. Confidence in the overall result can only be achieved when transition from one area to another, and from there by any route to known calibration points near shore, can be shown by observation to accord within certain limits with predictions for *all* patterns. These limits are now considered to be ± 5/100ths of a lane in all rig drilling areas.

This treatment, and the large amount of data, require a quantity of calculation which could not be handled in sufficient depth without the aid of a computer. Appendix II gives an actual example of one set of observations, selected at random from a correlation cruise along the Norwegian/Scottish median line in June 1967. At that time no systematic errors had been assigned in this area to the two Forth Hi-Fix chain patterns except for those established within 15 km of shore. It is of passing interest to note the small errors resulting from this Hi-Fix tie across the North Sea.

Figure 3 shows a portion of a systematic error diagram, in this case that of Pattern I of the Norwegian Fisher Hi-Fix chain. Errors are shown, in hundredths of a lane, in the sense Computed minus Observed (C−O). An error of −10/100ths is represented by (10) and +10/100ths by 10. It will be noted that errors are consistently −6 except in two small areas. One of these is close inshore off the Master station, and the other in approximate position 57°30′N, 4°00′ E.

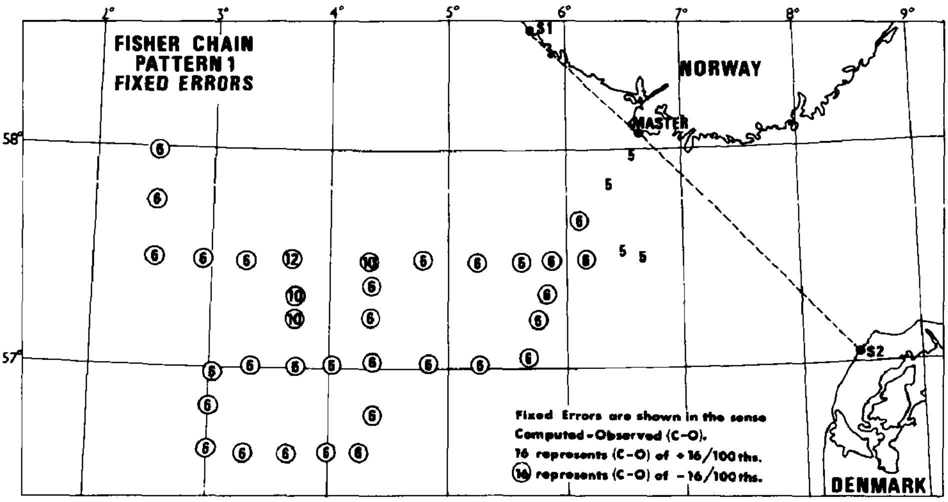

FIG. 3. — Part of the systematic (fixed) error diagram of Fisher Chain Pattern I. One of these diagrams is prepared for each pattern and is corrected or augmented as required by new data.

The change in error on approaching shore in the vicinity of the Master station is to be expected, due to the intervention of land path in the transmission path between the ship and Slave 1. This has the effect of slowing down the average speed of propagation in this path, and consequently increasing the phase of the received slave signal.

In a hyperbolic chain, the observed lane number is formed from

$$F\left(\frac{dm}{V_1}+\frac{dms}{V_2}-\frac{ds}{V_3}\right)$$

where F = frequency in kHz;
V_1, V_2, V_3 = actual mean speeds of propagation over the three transmission paths Master/receiver, Master/Slave and Slave/receiver respectively in kilometres per second;
dm = true distance in metres Master aerial/receiver aerial;
dms = true distance in metres Master aerial/Slave transmitter aerial;
ds = true distance in metres Slave transmitter aerial/receiver aerial.

This particular land path therefore will decrease the observed reading and consequently increase the error Computed minus Observed (C−O).

The small anomaly evident in and around position 57°30′N, 4°00′E cannot be explained in this way, at least not by examining land paths on a map of the scale of figure 1, but there is a large amount of evidence to indicate its existence. The results of less than one in a 100 of the observations in this area are shown in figure 3, but this anomaly appears consistently amongst the observations within about 5 miles of this position. Assumption of a value of -6 here imposes values on some of the other patterns which immediately upset the 'best fit'. Appendix II further illustrates this point.

Presentation of the data in this way tempts one to resort to a small degree of "smoothing". This is not done except for rejection of "wild" readings for two reasons. Firstly these localised small anomalies do exist, usually associated with bearing rather than area, and secondly, the accepted errors for all patterns must bear a direct relationship, from the computed patterns, through the application of (C−O) errors with sign reversed, back to the simultaneously observed pattern readings which provided the original data.

RIG POSITIONING

Since the order of cost of maintaining an offshore drilling rig in operation is $ 20 000 per day entire exploration programmes must be organised around the efficient use of such units. Hence every possible check must be applied to prevent delays and mistakes in positioning.

Instructions for the initial survey task, which may be received by cable, telephone or letter, must first be examined for mistakes or possible sources of misunderstanding. A typical operation will require a pattern of buoys to be laid in a precise geographic position together with a large scale survey (say 1/10 000) of the surrounding area.

Details of the survey will vary in each case, but every rig positioning operation will have this in common — a seismic record will have been examined, and a part of a feature shown on it will have been selected as a drilling site. The time interval between the seismic and large scale surveys may be a few days only, or it may be a few years. It is then the surveyor's job, not only physically to mark at sea the position given in his instructions within certain probable limits of error, but also, whenever possible, to examine the positioning data giving rise to the location specified. The end object is not to drill at a certain Latitude and Longitude, but at the intended part of a given seismic feature.

This being so, receipt of survey instructions will immediately raise a number of queries : —

> Is the quoted Latitude and Longitude related to a certain spheroid and datum ? Typically, in the North Sea, an ambiguity of over 400 feet arises from this cause alone.

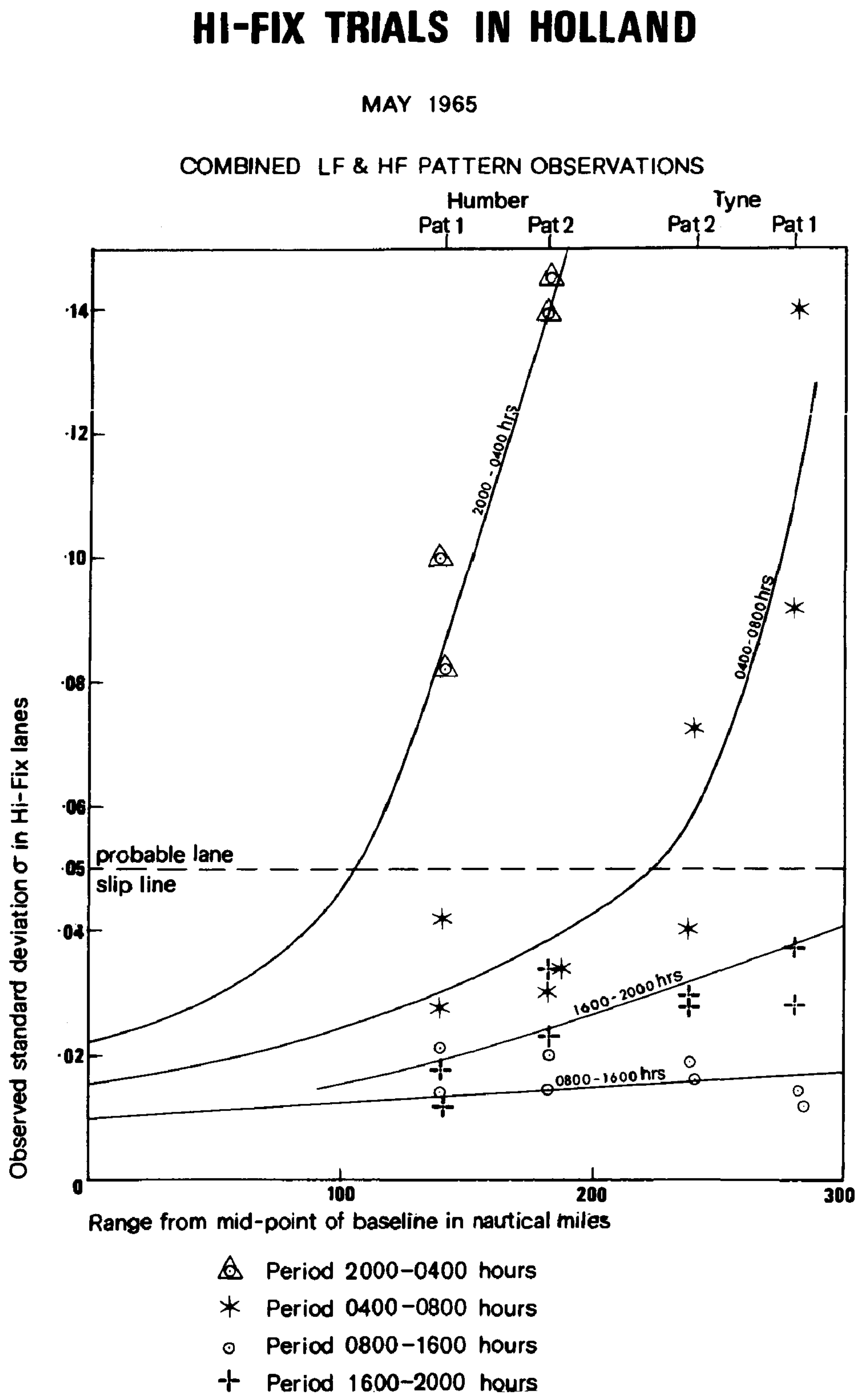

FIG. 4. — Variation of standard deviation of a Hi-Fix receiver phase reading with range.

Has due allowance been made for the separation and bearing between ship's navigation antenna position and the effective point of measurement of the seismic data ? The distance can vary from nil to over 2000 feet depending on technique.

Have systematic errors of the positioning system been applied ?

What was the effect of the random errors applicable to the time, season and ranges of the original positioning data ? (See diagrams 4, 5 and 6).

Most seismic programmes are shot whilst employing "back-up" positioning systems. For example Humber Hi-Fix may be used as the primary system, backed up by Sea Search I and English Decca Chain. In this case has all the available data been examined to check against mistakes, and to ensure that the strongest fix has in fact been used ?

All the above queries can be answered quite simply once the necessary organisation has been set up. It is always important that the surveyor responsible for locating the rig should have access to the original seismic vessel positioning log sheet; this will relate time and date to seismic line number, shot point number, ship's heading, lay back, feathering angle, positioning systems, pattern readings, etc.

Broadly one is attempting to recover a seismic feature in terms of the original positional data derived from the navigational aid used. It is therefore preferable if the original navigational aid is available to assist.

Figure 4 shows the effect of skywave on observed standard deviations

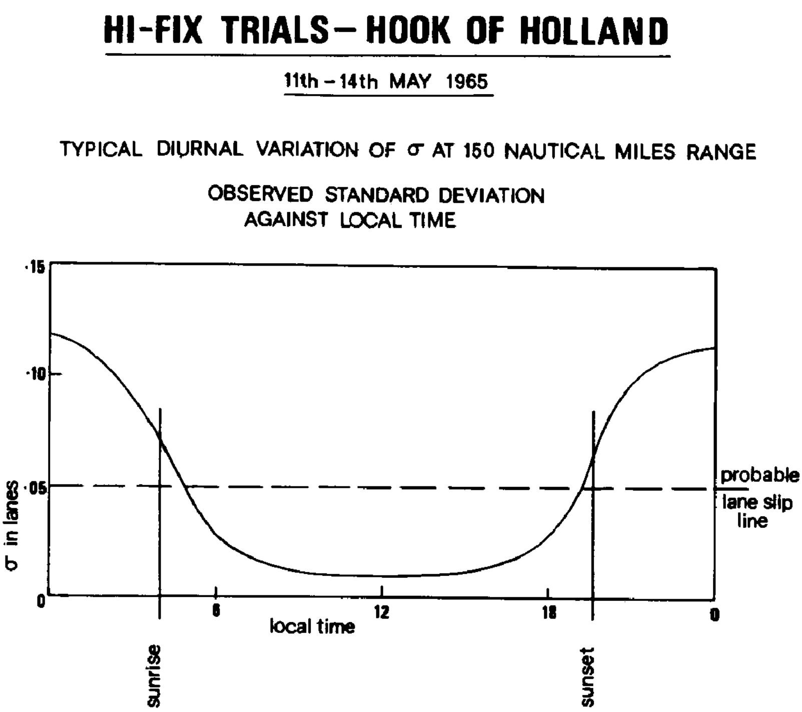

FIG. 5. — Typical diurnal variation curve of standard deviation.

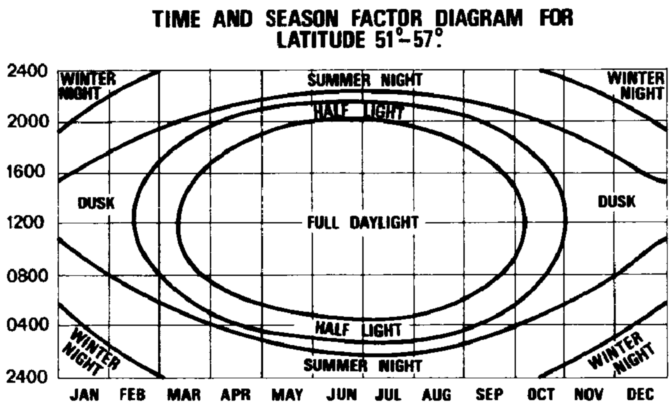

FIG. 6. — Planning guide to the times and seasons of best propagation conditions.

(σ) of the Humber Hi-Fix chain observed at a range of 150 nautical miles. Figure 5 shows how the standard deviation varies with range as well as with time of day. These diagrams being based on a small sample, must be treated with caution, although they show close agreement with expectations and results derived from previous trials. Figure 5 indicates a standard deviation of less than 0.02 lane at a range of 300 nautical miles from the furthest slave during summer daylight conditions. The duration of summer daylight conditions at various times of the year in Latitude 54° N is shown in figure 6.

The importance of considering data of this sort in practice is shown by an example.

A seismic vessel operating in the area 52°45′N, 02°20′E used Sea Search I as her primary positioning system, recording English Chain (5B) additionally as a back-up. Examination of the original log sheet showed that the required shot point had been recorded at 1800 on an October evening. During summer daylight conditions, the two patterns of Sea Search would have provided the strongest recorded fix in this position, despite the long range of over 260 nautical miles of the Sea Search Green slave transmitter. At the time, date and range of this recording however, effects of skywave must be suspected. On examination of the first differences of the recordings of the vessel's progression at three minute intervals, Sea Search Green readings show irregularity which is not present in either the Sea Search Red readings, or the 5B Green (southern slave) readings.

Further, the position derived from Sea Search Red and Green readings, after applying systematic error corrections, is displaced by about 600 feet from the position derived from the same Sea Search Red coordinates combined with the relevant 5B Green corrected reading.

In these circumstances it was the latter position which was selected for marking and subsequent drilling.

After these checks have been carried out, the positioning vessel will usually complete the rig site survey and buoy the location a few days before the drilling rig moves in. Pattern counter readings are checked for lane errors at all stages and the operation is treated as a closed traverse from and to at least one tie point; this may be the ebb or flood position of a buoy or it may be a production platform.

Rig positioning has become an all the year round activity. In high latitudes in mid-winter at ranges of 150 miles offshore larger standard deviations have to be expected as compared with summer conditions. At the same time, in certain parts of the North Sea, the key pair of pattern readings may be nominally ten times more accurate than the next best pair combination available. In these circumstances, to assist the surveyor with his on site checks, and now as a matter of routine on all rig positioning operations as a final check against mistakes, the following technique is employed.

The surveyor records a series of simultaneous readings of all available patterns in the location area; for example there may be seven of them. Results are radioed to the operational headquarters at Great Yarmouth, where a small digital computer has been programmed for the conversion of Decca to geographical coordinates and the reverse computations. With this information, and knowledge of the expected systematic errors for the area, a full inter-chain analysis is possible. The subsequent report, radioed back to the surveyor in the positioning vessel, will emphasise any individual reading which does not settle well into the predicted correlation. The aim eventually is to provide each positioning vessel with its own computer for this purpose. The same analysis can be achieved by providing the surveyor with a large scale plot of the location on which all patterns have been scribed. This is not always possible in practice because of the short notice inherent in this type of operation, and because of the complexity of a plan showing so many patterns.

An oil rig under tow must be one of the most awkward types of craft afloat. As often as not, the surveyor sees the pattern of buoys which he has so carefully laid in position being swept away by the rig's towing hawsers. The final movement of the rig into location is then assisted by frequent R/T messages from the positioning vessel giving range and bearing to go. This final stage of the tow is a difficult manœuvre for the tugs, which have to maintain the rig in position by stemming wind and tide whilst anchors of 40 tons apiece are laid, or whilst legs are slowly lowered to the sea bed. It is hardly surprising that the final location is sometimes one or two hundred feet from the intended position.

Once the rig is secured, the positioning vessel will observe the final coordinates. The rig itself forms a large radio antenna; the received signals are partially reradiated causing a local distortion of the true transmissions. Errors from this cause are avoided by circling the rig at a distance of not less than 1500 feet and observing a system of equal subtended angles to the derrick head, combined with simultaneous readings of the positioning counters.

On completion of drilling, the well may be capped off at sea bed. This operation leaves nothing above the sea bed except about ten feet of conductor pipe, which may be unmarked by buoyage or acoustic pingers. Placing of divers for well head recovery, sometimes in depths exceeding 250 feet and more than 130 miles from shore, is then a satisfying proof of the methods employed. It is a test not only of repeatability but also in some cases of determination of absolute position. Some wells near the Norwegian/Scottish median line for example were originally positioned on the old Sea Search II chain; recovery was required after this particular chain had been closed down. Each of these operations has been successfully completed by marker buoy laying and by identification of the well on the echo sounder trace following a direct pass over it. The second line of search, which would employ a high resolution side scan, has not been required.

PART II

RIG SITE SURVEYS

Before positioning a rig the operator will require certain information about the new location. Only rarely will this be available in sufficient detail from existing references. He will need to have knowledge of depth, topography, tidal range, tidal streams, predicted storm wave heights, quality of the sea bed and of the sub-sea bed.

These surveys, certainly in the case of the North Sea, have proved to be more than a reasonable precaution carried out as a matter of routine. Of about 240 site surveys completed in this area, more than 5% have yielded evidence of unsuitable location. In these cases alternative sites have had to be selected.

The reasons for rejecting certain proposed locations have been various, and have included each one of the following :

(a) *Depth too great*

Despite the fact that British Admiralty charts still depend on information from 19th century lead and line surveys over most of the North Sea, general depths have proved to be in agreement with those shown on the published charts. But the chart may be on a scale of 1/700 000 whereas the detail required by a site survey dictates a scale of 1/10 000 or larger. This extra detail has been, on occasion, the cause for rejection of a proposed location where the published chart may have indicated depths just within the capability of the jack-up rig. Alternatively, depths found on survey have been used to specify the length by which to construct extensions to the legs.

(b) *Gradients*

Again, the scale of the published chart is insufficient to assess the gradient of a proposed site, for use of a jack-up rig. For this purpose close sounding at a scale of not smaller than 1/10 000, and careful contouring are required. Contour intervals will depend on the topography, but an interval of as little as 2 feet is the aim. The use of narrow beam echo sounders significantly improves the result.

(c) *Boulder clay*

This glacial drift material is quite commonly found in the North Sea, both on and under the sea bed. It can be expected mainly north of 52° North, which was the southerly limit of the zone of deposition of the last glaciation. Figure 7 is a copy of part of a diver's sketch which shows quite dramatically what positive features these are; they can be massive objects weighing many hundreds of tons.

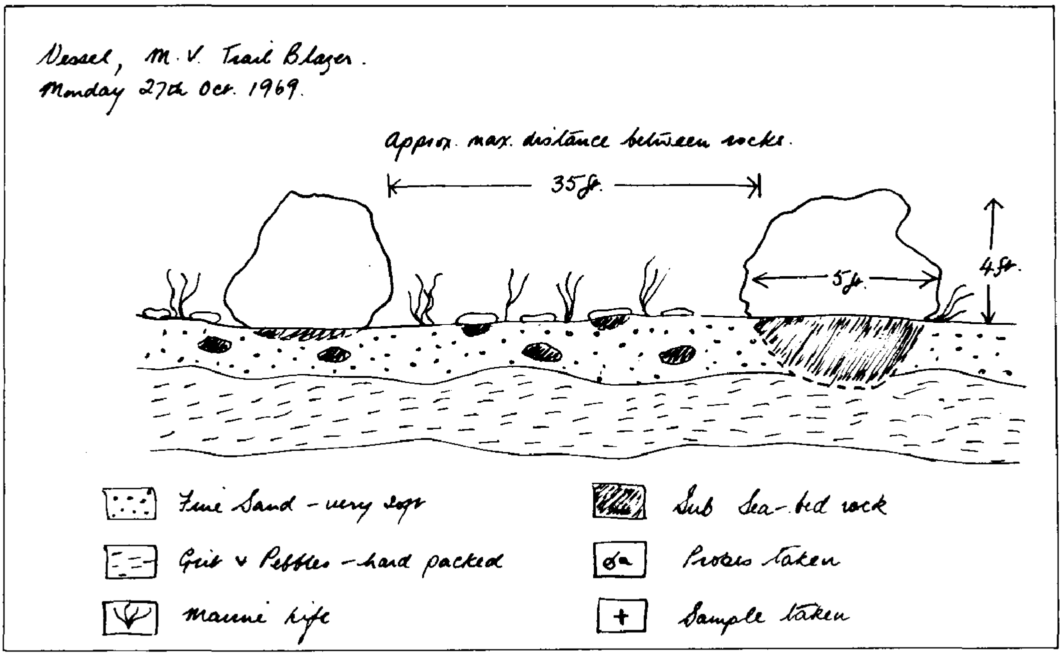

FIG. 7. — Diver's sketch of the appearance of the sea bed in approximate position 53°30′N 02°12′E.

The presence of boulders on the sea-bed can be positively determined by the use of high resolution side scan, whereas an echo sounder might miss them entirely. Identification of such features under the sea-bed, important for leg penetration of jack-ups and for burial of pipelines, is not so easy. High resolution boomers or bottom penetration sounders, however, will usually detect the presence of boulders of more than 3 feet in diameter.

(d) *Drowned river valleys*

These may be glacial melt water features, or the result of a raised water level. In either case the valley may be filled by fine sediment so that its existence is not apparent by echo sounding. Figure 8 shows a high resolution boomer record of one such feature; in this case in approximate position 54° N 02° E.

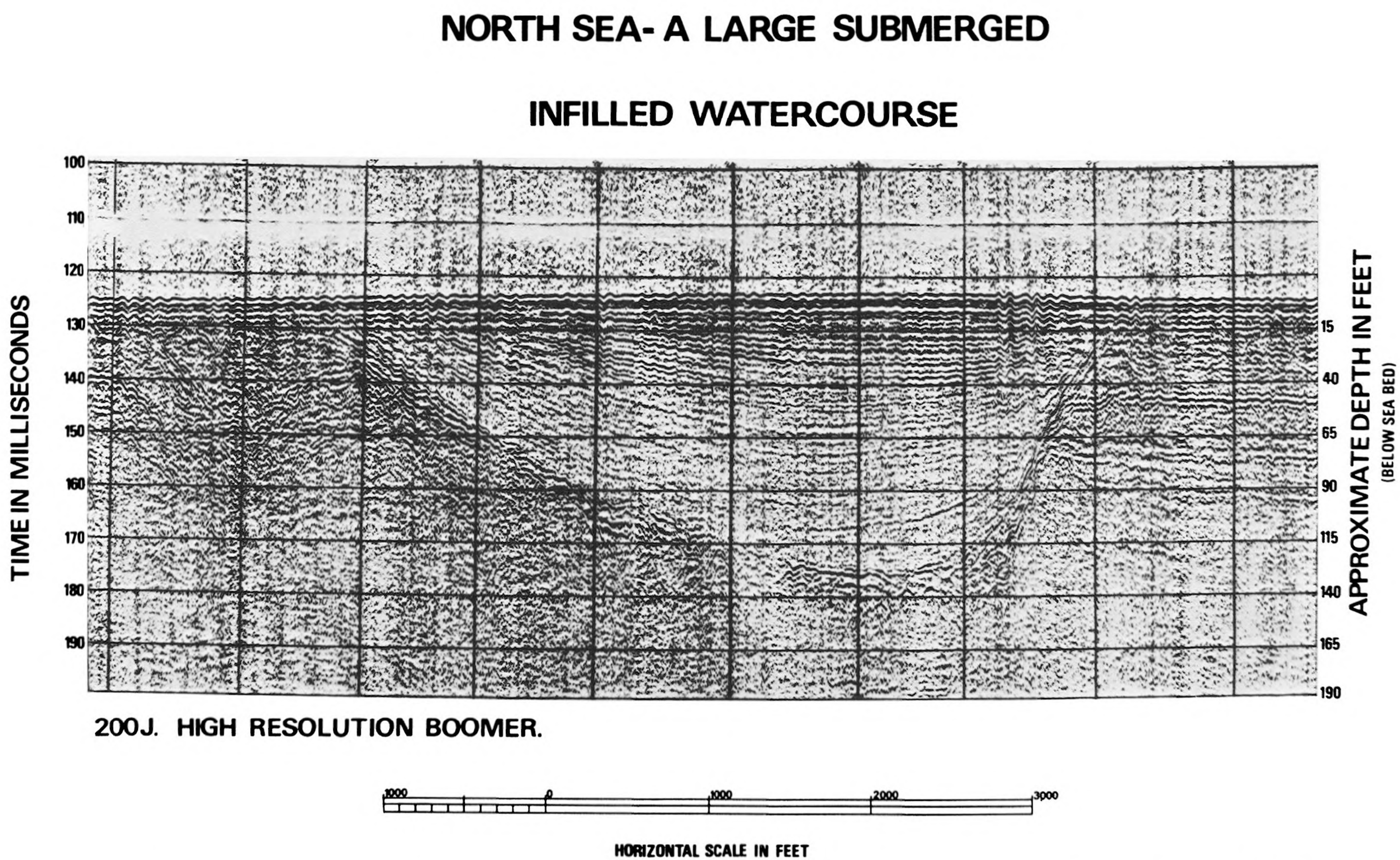

FIG. 8. — A high resolution boomer record of a drowned and infilled river valley in approximate position 54° N 02° E.
Reproduced by courtesy of EG&G Geophysical Ltd. and The Decca Navigator Co., Ltd.

(e) *Sand waves*

Sand waves are localised but frequently encountered features of the sea-bed of the southern North Sea. Small formations do not interfere with rig operations, but amplitudes of over 50 feet exist in places and have to be avoided by jack-ups.

These areas can be detected and charted from the data given by a combination of echo sounding and side scanning. The transition from sand waves to a comparatively featureless sea-bed can sometimes be remarkably sudden, showing up on the sidescan record as a well defined line.

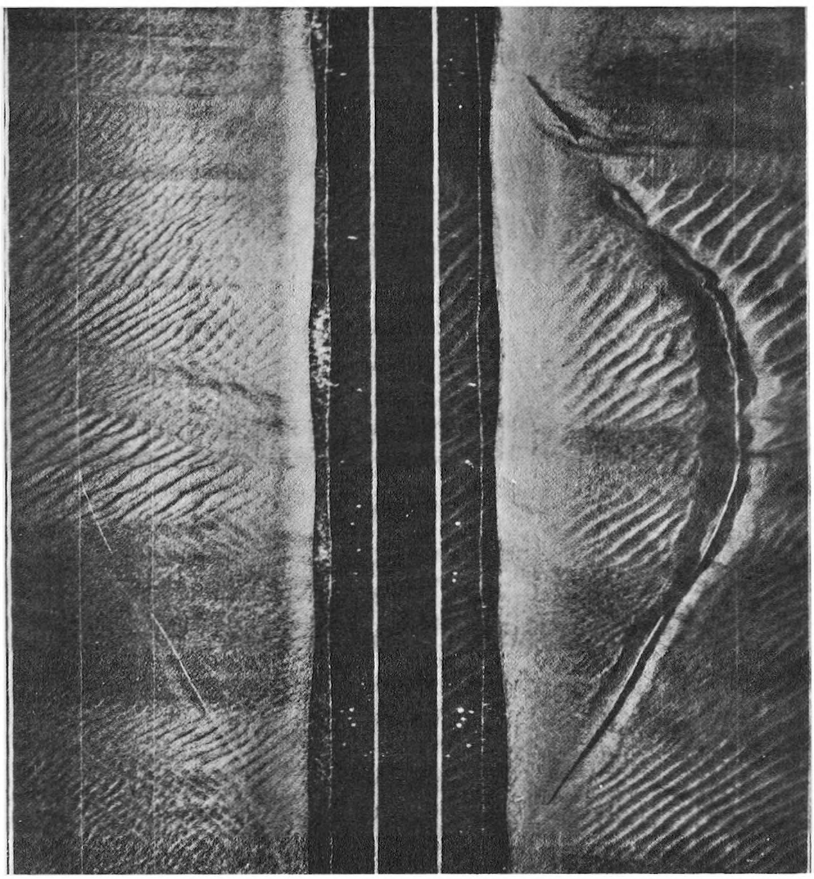

FIG. 9. — North Haisborough Sand.
A 120 Hz side scan record (250 foot range setting) of small sand waves (about 3 feet amplitude) and a partially exposed gas pipeline lying in a prepared trench.

Figure 9 shows an example of small sand waves obtained during equipment trials over the North Haisborough Sand. The instrument used in this case was a dual channel side scan operating at 120 kHz. The ship's track is represented by the double white line down the centre. The range setting is 250 feet to either side. On the starboard side can be seen a partially exposed pipeline lying in a prepared trench. Sand waves show clearly on both sides although their amplitude is only about 3 feet. The photograph is a reversal print of the original record, black for white and vice-versa, since this helps to illustrate the virtually photographic quality of the highlights and shadows.

Some of the shadows in this example are well defined. They can be used, by considering the triangle formed by the sea-bed depth below the transducer, and the slant range, to give an indication of heights of objects above the sea-bed. It is emphasised that this is an indication only, and cannot be considered a reliable method for height measurement without specially designed additional equipment. In practice, heights of interest indicated on the side scan are subsequently examined and measured by narrow beam echo sounding.

(f) *Wrecks*

Diversion of pipeline routes around wreckage has been necessary on at least one occasion in the North Sea. Detection of even small wrecks (30 ft launches or aircraft for example) within a limited area is a fairly certain matter when a suitable side scan is used in a regular search pattern. Jack-up and pipelaying operations, though, also need to guard against the possibility of old or dispersed wrecks which may be entirely covered, leaving very little sign of their existence on the surface of the sea-bed. It is mainly for this reason that magnetometers are frequently employed in preliminary surveys of this type. When towed in shallow water a fairly high background noise level can be expected; this particularly applies where the sea-bed contains a high proportion of igneous materials, but also to a lesser extent where the bottom is entirely composed of sedimentary deposits. Thus, in shallow water, no matter how sensitive the magnetometer may be, an anomaly of about 5 gamma is necessary if it is to be identified with any certainty. On this basis the approximate maximum detection range of a 100-ton vessel would be 100 metres, and the maximum detection range will be proportional to the cube root of the mass. Magnetometer searches must therefore be planned on a close grid.

ACKNOWLEDGEMENTS

I wish to thank the Survey and Systems Planning Departments of The Decca Navigator Company Limited for their suggestions and for their permission to use figures 4, 5, 6 and 10.

APPENDIX I

Effect of ground conductivity on propagation

Figure 10 shows the form of curves of phase lag over ground of various conductivities, plotted against range. They are based on theory, but beyond a range of 2 kilometres from the transmitter they have been largely confirmed by observation. Theorists can provide a speed of propagation of a 2 MHz radio wave over ground of a stated conductivity, but the difficulty in the field of course is the impracticability of measuring the mean conductivity of a given land path. Nonetheless, a clear enough pattern emerges from observed results in relation to types of terrain. Bare granite and dry coral sand for example are poor conductors (represented on the graph by 10^{-14} electro magnetic units), whereas sea water is a good one (5×10^{-11} e.m.u.).

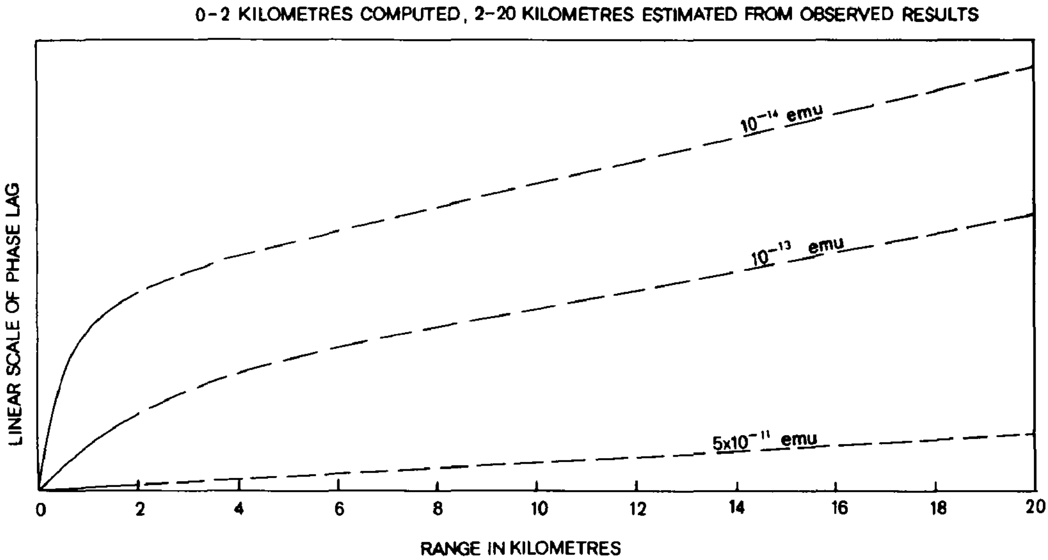

FIG. 10. — Phase lag of a 1.9 MHz radio wave relative to speed in vacuo.

It will be noted that beyond a range of 4 kilometres all three curves are virtually straight lines, representing a constant speed. Phase lag can therefore be expressed as so many hundredths of a lane per kilometre of land path relative to propagation over sea water. Over granite, and in the case of a two-range transmission which traverses the same ground in both directions, this relative phase lag can exceed 6/100ths per kilometre of land path.

Speed of propagation over sea water

If one considers 'sea water' for this purpose to include arctic, temperate and tropical conditions and partially confined bodies of water such as the Mediterranean and Red Sea, but to exclude sea ice, estuaries of large rivers, heavily silt-laden water, or very shallow water then a propagation speed of 299 650 km/sec. ± 1 part in 10 000 can be predicted.

This would be the speed recommended for use in the construction of a Hi-Fix hyperbolic lattice chart of a sea water area whenever this has to be undertaken before the results of local observations are available.

The reader will note that the linear scale of phase lag in figure 10 has not been quantified. It is hoped that this will emphasise the stress that should be placed on check observations rather than estimations of ground conductivity in order to use theoretical predictions.

Acceptance of the general shape of these theoretical curves however, will lead to a separate consideration of the land path and sea path elements making up the observed mean speed of propagation. Particular attention would be given to the first 2 kilometres of land path, since figure 10 suggests that it is here that phase lag is heaviest, particularly over ground of poor conductivity.

The mean of phase lag observed from differing bearings from the transmitter can be compensated in the calibration setting. Once the chain has been properly calibrated therefore, it is change in phase lag with bearing which must be considered and not the total value of phase lag.

APPENDIX II

Analysis of errors (C−O) indicated by a multiple fix

At 1107 G.M.T. on the 4th July 1968 in approximate position 57°04′ North 02°26′ E the following Decca co-ordinates were observed simultaneously :

TABLE I

Chain	Patt. I.	Patt. II	Red	Green	Purple
Forth Hi-Fix	694.26	1302.03	-	-	-
Fisher Hi-Fix	645.54	451.26	-	-	-
Forties Hi-Fix	628.33	029.98	-	-	-
Sea Search I	-	-	C 22.17	H 31.55	-
Main Chain 6C	-	-	-	H 46.99	F 69.84
Main Chain OE	-	-	A 09.84	G 40.51	F 76.79

With the aid of a chain layout sketch such as that shown in figure 1 and a protractor, the approximate conditions of the various pattern geometries can be tabulated.

The locus of a constant hyperbolic pattern value through a point is along the bisector of the bearing of the Slave and Master stations from that point.

The lane width of a hyperbolic pattern at a point is equal to the lanewidth on the baseline multiplied by the expansion factor.

$$\text{Expansion factor} = \operatorname{cosec} \frac{\theta}{2}$$

where θ is the angle subtended by the baseline at the point of observation.

Basic data for each chain will include station positions, frequencies and assumed speed of propagation. The expansion factors and local lanewidths given in table II would be, in practice, derived from this basic data.

TABLE II

Pattern	Direction	Baseline Subtends	Expansion Factor	Baseline lanewidth (metres)	Local lanewidth (metres)
Forth I (Southern)	250°	13½°	8.51	79	672
Forth II (Northern)	262°	11½°	9.98	79	788
Fisher I (Northern)	055°	14°	8.21	75.5	620
Fisher II (Southern)	075°	26½°	4.36	75.5	329
Forties II (Northern)	029°	6½°	17.64	76	1340
Forties I (Southern)	038°	12°	9.57	76	727
Sea Search I (Red) (Western)	170½°	33°	3.52	444	1563
Sea Search I Green (Eastern)	135°	37½°	3.11	296	921
'6C' Green	318½°	25°	4.62	586	2707
'6C' Purple	295°	22½°	5.13	351.5	1803
'0E' Green	355°	52°	2.28	593	1352
'0E' Purple	032°	21½°	5.36	356	1908

Before comparing the repeatability of a fix from any of these pair combinations, standard deviations must be assigned to each pattern. The surveyor will decide these for himself, based on his monitor and other records; range is obviously one factor as is shown in figure 4.

Root mean square errors of repeatability for any pair can then be compared by :

$$d_{rms} = \operatorname{cosec} \beta \sqrt{(\sigma_1^2 + \sigma_2^2)}\ (*)$$

where β is the angle of cut;

σ_1 is the 'local lanewidth' of Pattern I multiplied by the standard deviation of Pattern I which may be for example 0.03 lane.

(*) There is a further term in the full formula. This term includes the correlation between the errors of the two fixing patterns, but under Full Daylight conditions, when skywave is at a minimum, the correlation approaches zero and so the term can be ignored for all practical purposes.

TABLE III

Trial points and errors (C—O) interpolated from existing data in nearby positions.
(Figures in brackets are an estimation of the reliability of the interpolation)

Ser. No.	'Key Fix' Pattern Values	Geographicals (Int.spheroid E.D.)	Predicted systematic errors (C—O) interpolated from existing data. (1/100ths of a lane)											
			Forth		Fisher		Forties		Sea Search I		'6C'		'0E'	
			I	II	I	II	I	II	Red	Green	Green	Purple	Green	Purple
1	451.26 H31.55	57-03-53.4N 02-26-20.6E												
2	451.14 H31.60	57-03-55.1N 02-26-21.7E												
3	451.14 H31.55	57-03-54.6N 02-26-18.4E												
4	451.14 H31.65	57-03-55.5N 02-26-25.0E	?	?	− 06	− 12	+ 16	− 05	00	+ 05	− 17	− 76	− 04	− 10
5	451.19 H31.60	57-03-54.6N 02-26-22.6E			(± 04)	(± 04)	(± 06)	(± 04)	(± 02)	(± 05)	(± 03)	(± 02)	(± 02)	(± 10)(*)
6	451.19 H31.55	57-03-54.1N 02-26-19.3E												
7	451.19 H31.65	57-03-55.0N 02-26-25.9E												
8	451.09 H31.60	57-03-55.6N 02-26-20.8E												
9	451.09 H31.55	57-03-55.1N 02-26-17.4E												
10	451.09 H31.65	57-03-56.0N 02-26-24.1E												

(*) Insufficient observations in the area.
(?) Signifies no systematic error data available for this chain at the time of observation.

Similarly with σ_2.

In this case the strongest combination of position lines is given by Pattern II on the Fisher Hi-Fix chain and the Green Pattern of the Sea Search I chain. Using a standard deviation of 0.03 lane on both patterns this gives an r.m.s. error of 34 metres.

Data established from previous observations is shown on systematic error diagrams; a separate one for each pattern as shown in figure 3 for example. Those relating to Fisher Pattern II and Sea Search Green indicate, by interpolation, expected systematic errors (C – O) in this position of – 0.12 lane and + 0.05 lane respectively.

The first trial point therefore is computed from corrected observed pattern values of

	Fisher II		Sea Search Green
Observed	451.26	Observed	H 31.55
Error	– 0.12	Error	+ 0.05
	451.14		H 31.60

A computer run is then set up converting to geographicals in turn, these two patterns as observed, as predicted (i.e. 451.14 and H 31.60), and the permutations of each pattern as predicted and 5/100ths of a lane up and down from the predicted value. Each result is converted back to pattern values of the other observed patterns. Errors (C – O) which result from these trial positions are then compared with those which had been predicted from existing data.

TABLE IV

Systematic errors (C–O) imposed by acceptance of trial point geographicals (Expressed in 100ths of a lane)

Ser. No.	Forth I	Forth II	Fisher I	Fisher II	Forties I	Forties II	Sea Search I Red	Sea Search I Green	'6C' Green	'6C' Purple	'0E' Green	'0E' Purple
Predicted errors	?	?	– 06	– 12	+ 16	– 05	00	+ 05	– 17	– 76	– 04	– 10
1	+01	–16	–01	00	+02	00	+ 01	00	– 25	– 72	+08	– 06
2	–06	–02	+05	– 12	00	00	00	+ 05	– 24	– 75	+06	– 07
3	–07	–06	+08	– 12	–06	+ 03	+ 04	00	– 26	– 73	+ 10	– 09
4	–04	+01	+01	– 12	+06	–02	– 04	+ 10	– 22	– 77	+02	– 04
5	–02	–06	+01	–07	+03	–01	– 01	+ 05	– 24	– 74	+05	– 05
6	–04	–10	+04	–07	–02	+02	+ 03	00	– 26	– 72	+09	– 08
7	–01	–03	–03	–07	+09	–03	– 05	+ 10	– 22	– 76	00	– 03
8	–10	+02	+08	– 17	–03	+02	00	+ 05	– 24	– 75	+07	– 08
9	–11	–02	+ 12	– 17	–09	+04	+ 04	00	– 26	– 73	+ 11	– 10
10	–08	+06	+05	– 17	+03	–01	– 04	+ 10	– 22	– 77	+03	– 06

The 'best fit' with predictions in this case is serial number 7, with number 4 a close second.

As these two positions are at the eastern end of the selected trial points, a second approximation would now be tried with permutations of the same pair of pattern values around number 7 (451.19 and H 31.65). The final solutions would be compared with those from other observations in the area before accepting values of systematic errors for inclusion in the diagrams.