Chapter 7 - Direction Finding 1918-1930

In 1926 DSD Capt J F Somerville, lecturing at Greenwich, said:-

"With regard to DF, no results that can be regarded as really successful were achieved in the Grand Fleet until 1918, when the difficulties experienced in correcting the large errors which had hitherto existed were overcome, and in ships of the QE class at any rate it was possible to obtain bearings with considerable accuracy. At the present moment all capital ships, with the exception of the Iron Duke and a certain number of cruisers, are fitted with Bellini-Tosi* but the growing use of short waves makes it improbable that we can continue to use this system in the future, as it is only suitable for wavelengths of 450 m and above. We propose instead to use a rotating coil placed up in the high angle position forward, with a small office built just underneath the high angle control. This is to be tried out experimentally on "QE" and one of the "Royal Sovereign" class."

The QRs for June and Sept 1922 and M144 of April '22 (Archives 9 and 10) give summaries on DF techniques at that date.

"The problems of DF are twofold; firstly those that depend upon the instruments and the peculiarities of the system which is employed. Secondly those that depend on the way in which the waves are propagated and their direction distorted. But the analysis of many bearings taken at all hours of day and night has shown that df by wireless can, under good conditions, give reliable results. The second factor cannot be treated experimentally without a solution of the first. At present, therefore, effort is concentrated on the improvement of instruments, including aerials. The provision of DF sets suitable for steel ships is therefore the first consideration.

There is no hesitation then in pronouncing in favour of the Bellini-Tosi system with large triangular loops. This is the only type which employs an aerial system comparable in size with the metal structures which abound in ships, loops enclosing about 2500 sq ft, and this is the secret of its superiority. Experiments with 'frame coils' have shown that the curve of errors usually takes an irregular form unless the emplacement is an exceptionally open one. The important advantages of the B-T system are:-

a. No heavy structure to rotate.

b. Great range.

c. The possibility of automatic correction for errors due to the ship, which for this system, properly installed, are always quadrantal.

Should the aerials be tuned or aperiodic? At a land station where the two aerials can be made large and identical, and where watch is often kept on one wavelength only, tuned aerials have important advantages. But in a ship the aerials cannot be made identical; tuned aerials need variable inserted resistance to balance the unequal pick-up at various wavelengths. This is so delicate and liability to error so great that tuned aerials have been abandoned in ship work.

* See p 30.

Next what is the best method of taking a reading; on a maximum or minimum? The ideal would be a maximum so sharp that it could be ascertained to ½ degree. At present no means of getting anything like this precision is known. The next alternative is to read the position of zero signal. Research into the factors which influence the sharpness of a zero is therefore of the very first importance. Hence to find the position of minimum sound with an imperfect zero, one finds two positions where the signal has equal strength and takes the mean. Hence a simple mechanical means of moving quickly the search coil from one position to the second is best inasmuch as it is possible to choose the amount of movement to suit the signal strength. An imperfect woolly zero is nearly always a sign that the bearing is not reliable; the magnetic field inside the goniometer is then not stationary but rotating. Providing all ordinary precautions have been taken this implies that the field in the region of the aerials is a rotating one, and caused by two magnetic fields in different directions which are not in phase. If they happen to be in phase a wrong bearing results. These subsidiary fields are due to the currents induced in neighbouring conductors by the main wave. Of these conductors the funnels are the most important.

The metal structures of a ship can be replaced for their effect on the DF aerials, by two loops and one vertical aerial. One loop lies in the central plane of the ship and the other athwartships. The aerial is at a point on the central line, and has the effect that the minima are most indefinite when the wave is incident on the beam and for short wavelengths; the deviations are not quadrantal and vary with wavelength. The deviations due to the two subsidiary loops are quadrantal and independent of wavelength.

The mass of structures which surround the DF aerials can be seen in Fig 3 showing "Antrim's" main aerials, p 93. The office is situated between the two foremost funnels; thus for waves incident on the beam there is great lack of symmetry. This soon showed itself by giving poor zeros on shorter waves (600 m) incident on either beam. It was proved that this was not due to unequal aerial loops. To balance disturbing factors one against the other, by choosing the position which gives the greatest symmetry with respect to the principal masses of metal both for waves incident along the centre line and on the beam, is the most satisfactory method of eliminating errors.[27]

Ordinary aerials are among the most important of interfering conductors since they are designed to resonate and may therefore have large currents induced in the often greater than those induced in the loop itself. The currents induced in the loops for equal main aerial amps are greater the shorter the wavelength. This means that the coupling is mainly electrostatic; if it had been electromagnetic the current would have been constant with wavelength. At 1000 m the ratio of the subsidiary current to the main current with the main aerial detuned so that its impedance is about equal to that of the loop, is about 1/12. Thus the main aerial should work on a considerably different wavelength from that in use for DF; its impedance should be three or four times that of the DF loop. DF trials were also made during the "Antrim" cruise previously mentioned, p 93. Regarding sensitivity it was not possible to hear Paris spark at Sierra Leone, but there was no difficulty in receiving Leafield (arc) on 8750 m, Long Island on 16500 and Glace Bay on 7850 m. One detecting valve, and two note magnifiers to sharpen the zero, is a suitable combination for 600 m work in the English Channel, where many stations can be heard. Then it is possible to fix position at almost any time within two miles by cross bearings. During the daytime errors on long waves were only occasional and small; as a general rule the accuracy on distant stations is ±2° by day. Only at great distances from land are observations of distant stations of any value in navigation except as checks. At night bearings should not be relied on.

(27) C E Horton 'Correction of Direction Finders for Deviation due to the Metalwork of a ship' JIEE V 69 p 63 1931: and Wireless Section V 6 p 107 '31. Also Wireless DF in Steel Ships JIEE v 61 p 104 1923.

The ideal conditions for using DF are:-

a. a transmitting station on the coast,

b. no high land intercepting the wave,

c. short range, say 30 miles, over sea.

The radio-goniometer. It is first necessary to ensure no mutual coupling between the loops themselves: to correct for residual mutual a small variable mutual inductance should be inserted between the aerials and so connected to make the total mutual zero.

In the goniometer the requirements for accuracy are not provided unless:-

a. Each aerial current alone gives a uniform magnetic field.

b. The two fields are strictly at right angles inside the goniometer.

c. The search coil is contained wholly within the uniform part of the field due to the two primary windings.

To produce the uniform fields the windings are arranged as in the Helmholtz galvanometer. Each winding consists of two halves connected in series and spaced apart by the radius of either." (See Fig 24 of M144.)

Experiments in Sense Finding. "Many suggestions have been made to remove the ambiguity of 180° in the reading. One of the earliest was to combine a vertical antenna with the loop effect. If its extra emf is in phase with that due to the loop and equal to it in amplitude, then the signal amplitude is proportional to $1 + \sin\alpha$, and one zero is obtained. The only difficulty resides in the phasing. No success has been obtained with any of the apparently straightforward ways of phase rotation except for long wavelengths; even here the adjustment varies with wavelength. Low frequency phase rotation by a goniometer on which the fixed coils carry equal currents in quadrature giving a rotating field, so that the search coil output varies in phase through 360° as it is rotated, is quite practicable. In series with one fixed coil are a capacitor C and resistance R_2, the fixed coils each having inductance L and resistance R_1, fig 25 of M144. The conditions for quadrature currents equal in amplitude are $wL + R_1 = 1/wC$; $wL = R_1 + R_2$. This circuit is satisfactory at long waves provided time is available to make the adjustments of R_2 + C. At 600 m nothing satisfactory on these lines has been achieved.

The only alternative was to devise some circuit in which the equality of phase of the two emf's is secured automatically. After numerous trials a simple circuit was evolved in which one of the large loops is made to function as an ordinary aerial at the same time. So far good results have been obtained on spark and CW up to 10000 m. In common with all sense finders however it cannot be used for accurate bearings which must be found in the ordinary way.

DF in Submarines. Using the directional properties of the frame coils used for underwater reception, the best arrangement would consist of four coils two at each end of the conning tower in planes at right angles. Opposite parallel frames will be connected in series for long waves and in parallel for short waves and will then form one loop of a Bellini-Tose set, the other pair similarly forming the other loop. The constants of the frame coils in use have been examined; resistance and self capacity are increased by the insulating compound round the wires. The natural wavelength of a single coil was found to be as high as 1400 m and the resistance 4 ohms at 15000m up to 25 at 1600 m. Air dielectric for the wires is necessary and the coils must be kept as far as possible from lossy dielectrics such as wood.

It has been found that it is necessary for accurate work to have four frames situated symmetrically round the conning tower. If 20° accuracy is acceptable two only are sufficient. Provided signals are sufficiently strong submerged bearings are as reliable as those on the surface. The quality of the zeros is good; the "antenna" action of the frames is small. The chief limit to accuracy is the disposition of the guns. Reception is better on long waves, 2000-15000 m, than on 600 m.

Short Wave DF. All the factors which may spoil zeros or render bearings inaccurate clearly become more and more important the higher the frequency. It can confidently be predicted that every kind of DF apparatus will fail on a metal ship at some wavelength sufficiently small, when the waves become comparable in length with the metal structures of the ship. At all points near the ship the magnetic field will be a rotating one having no fixed direction. In the goniometer, if the two halves of one of the fixed coils are connected in magnetic opposition no emf ought to be induced in the search coil. At 2600 m this was so, at 600 m an appreciable current was induced; at 130 m the effect was marked. The problem of reducing the e-s forces within the goniometer has not yet been solved.

Perhaps the most important advance that has been made in SW DF is the use of earthed braided covering of the aerial wire with a break in the braid at the top of the coil. Whereas normally the antenna action of a loop is very considerable, the effect of the uniformly distributed earth round the cable is to reduce the antenna effect to a very small value, even at 130 m. This is important because the higher the frequency the more harmful are the effects of the distributed capacities to earth of the sides of the loop. It is this which makes it practically impossible to get perfect zeros with tuned loops on board ship . . .

In "Diomede" using metal covered aerials and a short wave goniometer, zeros of moderate quality were obtained on 130 m in approx the right position. The ship was not however the necessary five wavelengths from land to give the best results.

Rotating Frames. In submarines a rotating frame coil mounted on the periscope had been utilised with fair accuracy (±5°) on 1600 m in 1924. By 1927 model SGX with a rotating frame coil high up on the foremast of "Queen Elizabeth" was giving ±7° max quadrantal error from 800-3000 m, ±12° max on 450 m. On 270 and 130 m only the roughest indications of bearing were found, sometimes 40 to 50° in error with very flat minima. "At Nutbourne the frame coil consistently gave readings of excellent definition on 130 m. Thus on a ship there is a masking effect due to re-radiation from the ship. It is for waves of about the same length as the ship that the effect seems most pronounced. It is possible therefore that a DF set in a cruiser or destroyer would be effective to a shorter wavelength than in a heavy ship."

"A special DF receiver Q8X on the foretop of "QE" proved successful in taking bearings of signals on 12 to 30 m when the receiver was within range of the earthbound wave of the transmitter. Trials ashore are proceeding with other forms which are effective on both earthbound and reflected waves," (Adcock's). "It is not yet possible to say whether such a DF could be fitted on board ship. The loop was a single turn 1½ ft diameter for 12-30 m: two-turn 3 ft for 35-85 m. The receiver employed balanced quenched self oscillating detectors. (Figs 1-3 of QR Dec '27.) During trials with an aircraft transmitting on 46 m good signals were obtained with a Q8 at all distances up to 250 miles.

In general however a bearing cannot be obtained on sea or land of a distant transmitter when reception is chiefly by rays from the upper atmosphere ie with an inclined wave-front; often there is then little sign of direction with a vertical loop or frame coil. An arrangement of rotatable spaced vertical dipoles is under investigation in this connection. It is based essentially on the same principle as the Adcock system for reducing night errors on medium wavelengths. The whole of the pick-up is intended to take place in the vertical dipoles, all horizontal components being balanced out; an inclination of wave-front should then give no error of bearing."

The Adcock Direction Finder. "The original patent 130490 of 1919 was allowed to lapse. The essential feature is the complete absence of horizontal field pick-up, the whole of the effective emf being induced in the vertical conductors. The horizontal wires connecting the dipoles to the receiver are very near together and from the manner in which they are connected to the goniometer, one diagonal pair of dipoles connected in opposition to one fixed coil, the emf in any one wire is opposed by the almost exactly equal emf in the other wire of the pair. The total will be almost zero therefore whatever the inclination of the electric field. With the basic arrangement using centre-fed dipoles the receiver should ideally be suspended in mid-air. The arrangement which has been fitted at Nutbourne (App Mar 1928 Fig 8) has four 22 ft vertical wires in a square of 28 ft side, with a buried lead cased cable connecting the base of each wire to the central hut, the assumption being that no emf can be induced in these horizontal connections. There is no need to earth centre points of the primary windings of the goniometer: these have four turns each and so does the search coil. The receiver consists of a neutrodyned push-pull hf stage followed by an oscillating detector. A circuit with a single screened-grid valve followed by the oscillating detector has been tried but the lack of symmetry blurs the zeros. A push-pull version is being constructed to remove the need for the neutrodyne condensers which sometimes need re-adjustment with frequency changes. The diagonal of the aerial square is 39.5 ft, half a wave for 26 m, 11.5 MHz, the aerials of a pair then reinforcing each other. When the distance apart is not small compared to the wavelength an octantal correction then has to be applied to the apparent bearing.

Experience shows that the Adcock system is better than the rotating coil on short waves and is the most promising form of aerial known as yet. Trials will be carried out in a ship as soon as the improved goniometer and receiver have been tested satisfactorily at Nutbourne."

"The rotating Adcock opposed dipole pair does not require the correction mentioned above: also no goniometer is required. An experimental model has been made with two rod dipoles each 10 ft long at the ends of a rotating arm 10 ft long. The position of the zero of Nauen is well defined but fluctuates by a few degrees from time to time but is generally within 5^{o} of the true bearing. The fixed aerials are more sensitive in proportion to their size and spacing and the goniometer is quicker and lighter to work; but a correction is required for their spacing and the screening technique is more difficult. The rotating aerial is simpler, better balanced and gives better zeros but is relatively insensitive and more effort is required to rotate it. Both systems will be tried in "Concord"."

A longer wave system, 40 ft masts 150 ft side of square was also erected at Nutbourne for $\frac{1}{2}$ to 15 MHz. "The main features of short-wave DF found on the preliminary trials have been verified with the new apparatus; that is, sharp readings to 20 miles, fair zeros on the distant stations at most times and no zeros in the intermediate region eg English beam stations."

During the "Concord" trials of DF (40-60 m) between Portsmouth and Malta (Dec '28) a new system of intensity variation was used to give a known law of reduction of the local signal intensity, so that only a few microvolts were put into the aerial circuit. With increasing frequency the inverse cube law used before was not useable due to e-s coupling. Three precision goniometer like variable magnetic couplings in series, with very loose couplings were employed with 10/1 accurately known variation in each. The essential feature was the electrostatic screening placed between the fixed winding and the search coil. It was then possible to ensure a true sine law of variation with angle of the search coil. The reception was at Freshwater, "with a lavish use of copper gauze earthing, lead covered connecting cables and drastic screening for the local oscillator. The great merit of the system is the ease with which it can be verified at any moment that there is no direct pick-up from the local oscillator and that the attenuator is functioning correctly. The presence of two perfect zeros 180° apart in each goniometer ensures that the apparatus is functioning correctly. The apparatus could detect half a microvolt induced in the aerial. As a general rule 6 MHz was the best frequency day and night with 97% of messages received, and the voltage on the aerial varied between 2 and 100 microvolt during the greater part of the cruise. In the further development of the subject it will be necessary to measure the fields acting in several different directions and so determine the true direction of arrival of the wave."

"Bearing accuracies of "Concord's" transmission were also made at Nutbourne on a system of Adcock aerials 20 ft high. There were interestingly large errors, eg 25°-75°, at around 1800-2000 and 0400-0600 hrs. "First class bearings, ie very good zero, were very uncommon, but often third class bearings gave results approx correct. A small number of excessively large errors were obtained noticeably when the ship was at Malta."

"DF in a Submarine with hull and conning tower entirely submerged but the loop above the surface, at 500 kHz and below gave practically no quadrantal error, whereas it was normally 6°. Thus when the submarine is submerged the effect of the metal work is very largely if not entirely eliminated. The conductivity of the sea is sufficient to prevent any distortion of the wave by the submerged hull."

The position at 1930 was therefore that rotatable screened loops high up were beginning to supersede the Bellini-Tosi fixed-loop systems on medium waves and might do so on shorter waves if the influence of the ship below the loops, which "pulls" the bearing towards the bow or the stern (quadrantal error), and resonance of the masts, could be overcome. How this was achieved is the story of the development of HF DF told in a later chapter.