

Abstract

HF/DF An Allied Weapon against German U-Boats 1939-1945

Radio communication influenced WW II much more than was realised by the early post war historians and by the general public. For example, after 1974 ULTRA became common knowledge yet, even today, some aspects still remain secret. Likewise, though HF/DF (huff-duff) was known about, the understanding of its technology remains limited. It is quite likely that this is due to the strict secrecy practised by the British authorities. It even happened that, in the 1960's, after Derek Wellman offered BBC TV a play concerning his experience as a wartime huff-duff operator, a call came advising him that "this subject is not of interest to the British people"!!

The aim of this paper is to explain, briefly, some aspects of HF/DF so as to create a greater understanding of its technology and the circumstances surrounding its use. After all, it could be associated either directly or indirectly with the sinking of an estimated 24 % of all U-Boats lost during WW II.

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HF/DF an Allied weapon against German U-boats 1939 - 1945

Introduction

During the First World War the German U-boats played an important role. The main aim of the U-boat High Command was to cut off the Allied life line. The fact that the United States gave up their initial relatively neutral stance and joined the Allies has to be ascribed above all to the so-called unrestricted U-boat war fought by the Germans.

As one knows, the British were able (very cleverly) to persuade the USA to come into the war before the end of 1917. Though this is not the place to examine in detail how this came about!

The First World War showed how vulnerable the supply lines between the USA and Great Britain are. In the Second World War there too was a moment when the shipping losses became unbearable and the cancellation of convoys across the Atlantic was a distinct possibility as the shipyards could no longer make good the losses of tonnage. Building a ship just takes longer than its torpedoing.

The course of history is rarely determined by one factor or cause alone and that was naturally no different in the two world wars. Nonetheless, individual events or circumstances sometimes exercise a great influence on the way things work out.

Some aspects of "Direction Finding", a well known technology

Famous names appear when we look back into the historical sequence of inventions which lead to the design of modern direction finding apparatus. In my opinion, one of the most important was the invention, by E. Bellini and A. Tosi, in 1907 of the radiogoniometer, which became known as Bellini - Tosi or the so-called B-T goniometer. After about 1915, i.e. after the sensitivity of receivers became more adequate, B-T became very popular and has been widely used since. (Keen, p. 156 - 201, et al.)

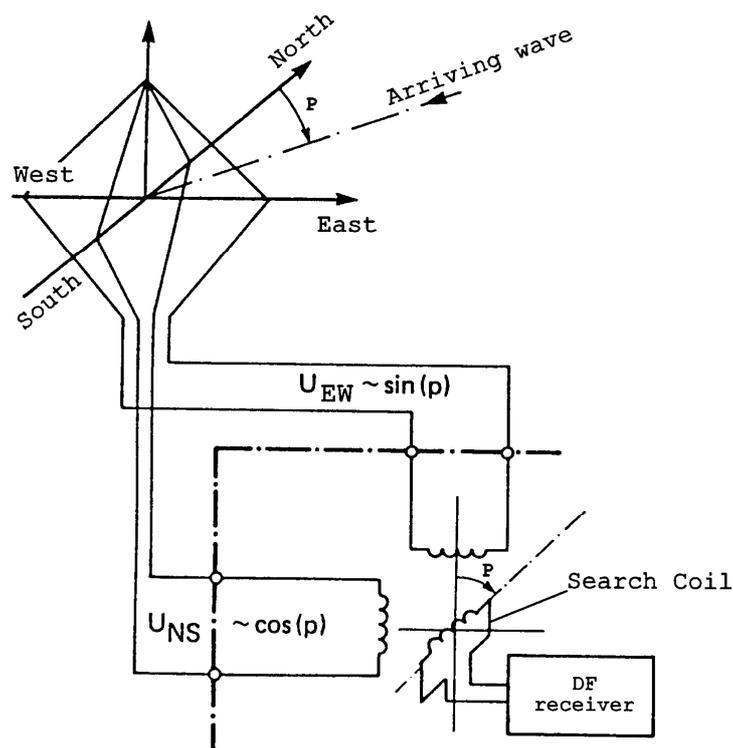


Figure 1: The goniometer principle of Bellini-Tosi

It can easily be understood from this line drawing that two wire loop aeriels are fed onto two field coils. These coils are mounted so as to be at right angles. It is known that the induced magnetic field lines do not then (theoretically) affect each other.

Their real invention was to introduce a search coil, which acts as a magnetic flux pick-up device. It is evident that when a particular E.M. (Electro Magnetic) wave induces an electrical current in one or both loops this subsequently results in an electrical current in the goniometer circuit. It can be understood that this produces a magnetic flux pattern which is due to the arriving E.M. wave. With shore based DF antennas the search coil zero setting was usually related to the direction of an antenna loop which picked up the maximum field strength from a specified source or direction. Shore based antennas were (are), quite often lined up North-South and East-West. For ship board antennas relationship tended to refer to Fore - Aft and Port - Starboard.

It can be proved that only the magnetic field component H of an E.M. wave can induce an antenna loop current when its perimeter is $< \frac{1}{4} \lambda$ (wave length). Sense antennas commonly function on the electrical or E field component of E.M. waves.

As we know each antenna loop in fig. 1 is delivering its appropriate current onto its connected field coil, hence the magnetic field distribution is equivalent to that of the induced loop currents. Although I am not going to prove it here, we can easily explain this principle by assuming that an incident E.M. wave reaches the antenna system under an angle of 45 degrees parallel to the horizontal plane, and this subsequently results in equal currents in both loop circuits. If we bring the cylindrical axis of the search coil parallel to that of one of the field coils, only half of the induced antenna power can be picked up by it. Only when the cylindrical axis of the search coil is brought into line with the arriving E.M. wave (hence in our assumption the bearing angle $P = 45^\circ$) can the optimal power transfer occur. What happens if we rotate the search coil through 180° ? Again a flux (signal) maximum will be picked up. Hence it is impossible, by means of such B-T goniometer only, to determine from which direction the arriving E.M. wave is approaching, is it from 45° or 225° ? Therefore a sense antenna has to be incorporated and its signal will create, by vector summation, a cardioid radiation pattern (which I do not intend to discuss further).

We will look briefly at the origin of B-T vector summation.

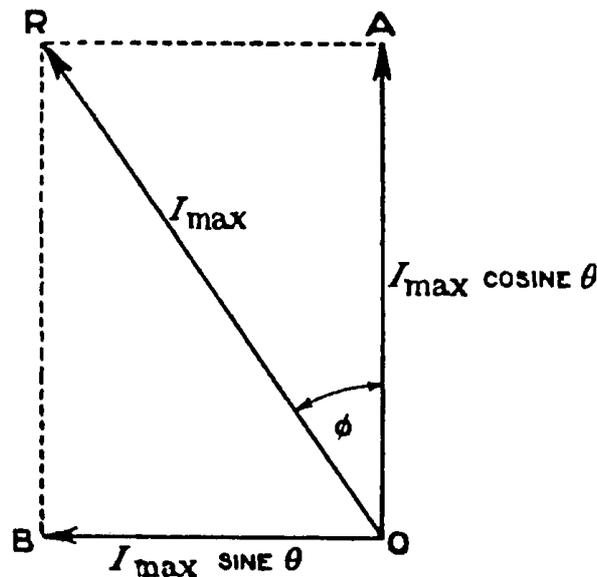


Figure 2: Vector summation of the induced antenna currents and the resulting pointer

The line (or pointer) OR can easily be determined by the well known Pythagoras' theorem.

$$OR^2 = OA^2 + OB^2 \quad (1)$$

The resultant flux is thus proportional to:

$$I_{\max} = \sqrt{I_{\max}^2 (\cos^2 \theta + \sin^2 \theta)} . \quad (2)$$

We can assume that:

$$\tan \phi = \frac{I_{\max} \sin \Theta}{I_{\max} \cos \Theta} = \tan \Theta . \quad (3)$$

For this explanation we will ignore the coupling deviations (errors) of this goniometer type, because these are of a systematical order and do not influence the fundamentals of DF by means of a B-T goniometer.

The HF/DF type FH 3 utilised the manually controlled B-T goniometer in conjunction with the Navy type B 21 B receiver. This latter system proved to be the backbone of huff-duff against the U-boat threat, on board most escort vessels. For instance, even during the zenith of the Battle of the Atlantic (during the early days of May 1943) of seven escorting convoy ships of ONS 5 only HMS Duncan was equipped with a FH 4. (ADM 237/113, and Bauer, p. 150) Not until the second half of 1944 did the FH 3 apparatus become surpassed by its famous successor the FH 4, which will be introduced hereafter.

Watson-Watt and Herd designed for the Radio Research Board in 1926 their twin channel receiver, which was originally designed to detect the direction of thunderstorms and consequently was not required to be, for this purpose, very sensitive. This type of direction finder became well known as: - Watson-Watt, or Twin Path C.R.D.F., receiver system.

It is fairly clear that the twin channel indicator in figure 3 has some similarity with Bellini-Tosi's invention. The field coils are replaced by the X and Y deflection plates of a CRT. The indication of the E.M. wave direction (bearing) now appeared automatically, when appropriate deflection voltage were induced between the appropriate deflection plates. In some way we can understand that according to Keen (p. 159) this apparatus was described as an "Electrostatic Radiogoniometer".

The major advantage of this invention is its instant bearing indication, without any man made delay. In other words, the search coil was "quasi replaced" by an electronic beam which painted a Lissajous figure on the indicator screen of a CRT, and whose amplitude was proportional to the resulting vector pointer after summation of the two field components. Only when an E.M. wave is exactly in line with one loop, and thus causes only one deflection to be fed with electrical energy, no vector summation occurs. Therefore one sees only a straight vertical- or horizontal-line on the CRT.

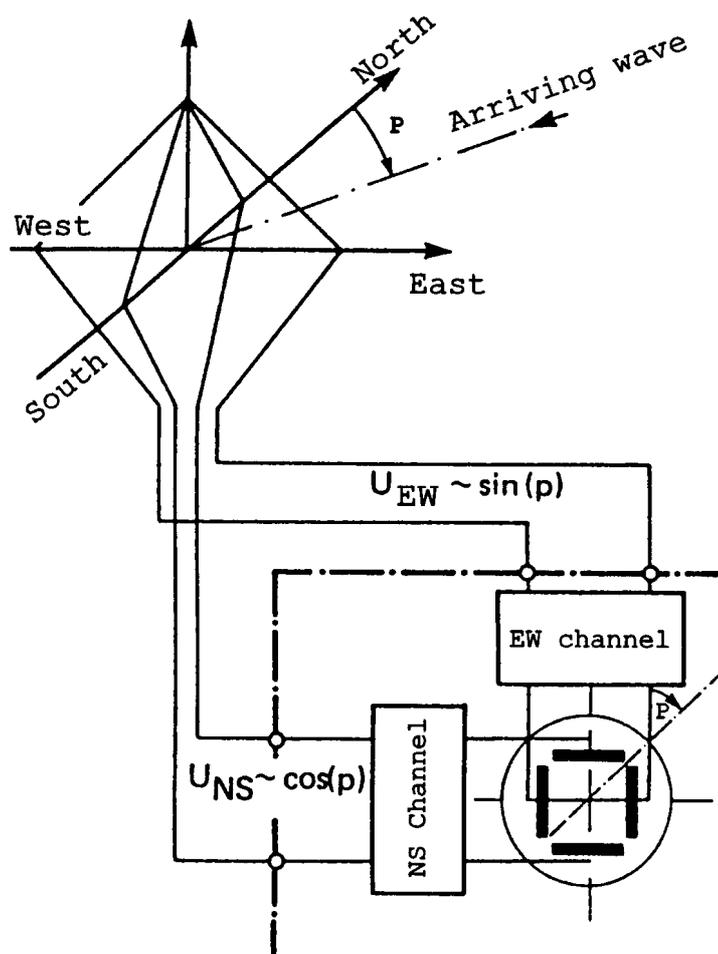


Figure 3: Twin channel DF apparatus, based on Watson-Watt's principle

As we have noticed the original Watson-Watt DF system was only able to respond on to signals which were generating sufficient deflection voltages (several volts). Though the sensitivity of CRTs in general are measured in V/mm deflection, it soon became evident that the sensitivity of such an apparatus and its response to low level signals had to be enhanced by means of implementing selective amplifier stages in each channel.

Although this all sounds quite simple, it soon proved to be rather difficult to control the amplification factor and its accompanying signal phase for both receiver channels.

If we assume that no phase error occurs, then the voltages which are finally fed onto the deflection plates of the CRT are determined by:

$$\begin{aligned} U_y &= A \cdot V_y \cdot \cos(p) \cdot \sin(\omega t) \\ U_x &= A \cdot V_x \cdot \sin(p) \cdot \sin(\omega t). \end{aligned} \quad (4)$$

U = the momental voltage between the deflection plates, A = max. signal voltage at each receiver channel, $V_x = V_y$ = amplification figure for both receiver channels, p = the angle of the E.M. wave in the horizontal plane in respect to the zero degree reference.

If we look at the circuit shown in fig. 3, it can be seen that - although the real E.M. wave did not change its direction (p) of arriving, a rotation of the painted trace will occur in the

direction of the deflection plates which may be fed with increasing voltage as, for example, due to a mismatch between the amplification factor V of one of the receiver channels. To avoid bearing errors it is evident that it is very important to exert sufficient control to ensure equal amplification figures for both channels.

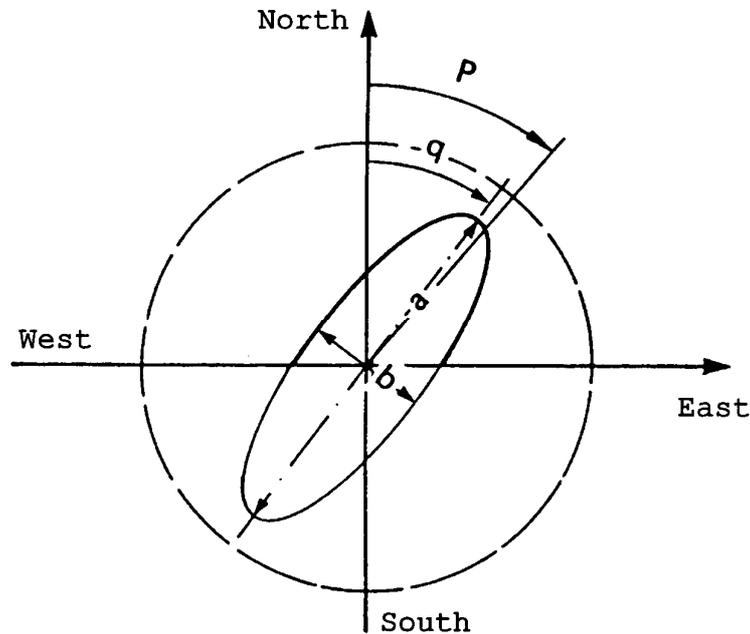


Figure 4: Ellipsoid is causing bearing errors due to deviation from the true axis of rotation (Blurring)

As long as the signals are in phase the bearing angle 'p' can be determined by the equation:

$$p = \arctan (U_x / U_y) = \arctan \left[\frac{\sin (p)}{\cos (p)} \right], \quad (5)$$

hence the (arctan) of the bearing angle can thus be understood to be directly proportional to the ratio of the deflection plate voltages U_x and U_y .

This all assumes that both the E.M. wave arriving at the antenna and the signal delay in each of the two receiver channels have no mutual phase shift. But this supposition hardly occurs in practice where, in fact, all sorts of disturbing phase shifts will result in producing an effect which became known as "blurring". This can result - as shown in figure 4 - in a displacement of the long axis 'a' of the ellipsoid from the angle $p \rightarrow q$.

When phase shift between the two signals occur, we can assume that the angle 'q' is determined by the equation:

$$q = \frac{1}{2} \cdot \arctan \left[\frac{2 \cdot U_x \cdot U_y \cdot \cos(\varphi)}{U_y^2 - U_x^2} \right] \quad (6)$$

and that only for the diagonals $+45^\circ$ or -45° the angle $p = q$.

Hence not only the bearing accuracy is reduced due to the difficulty of determining a true bearing-pointer but additionally a bearing error is introduced due to the unpredictable rotation of the diagonal axis angle 'p' to the angle 'q'. (Grabau, p. 116)

HF/DF designed in Britain

We shall not discuss the background history of HF/DF, as this has been described by several others e.g.: P.G. Redgment, and in the US, by Kathleen Broome Williams, *et al.*

DF on shortwave was already well known and widely used by shore DF stations before WW II. The main problem is to overcome the distinct shortcomings of antenna loops (aerials), which caused more or less severe bearing deviations (errors) especially on board ships. The best antenna system for DF on shortwave proved to be the well known Adcock antenna, although this antenna type has some disadvantages when it is used for DF of ground waves. Adcock antennas need a very strictly controlled linear antenna site (plain and flat *instrata* with uniform conductivity), which can hardly be obtained on board ships due to discontinuities which are caused by the superstructure of ships. Due to this hampering antenna behaviour the *opinio communis* was that accurate DF on shortwave could never be made fully operational on board ships of any kind.

One of the main DF problems which is faced on board ships is caused by the more or less erratic behaviour of fields re-radiated originated by the superstructure of ships, for instance, by ship masts - the bridge and pipes - (which proved to be excellent re-radiators when these are excited by E.M. waves in respect to $n \cdot \frac{1}{4} \lambda$) etc.. The relatively high Q-factor of these re-radiators can often cause an equal or even higher signal input at the front-end of a DF receiver than that which is induced, in the antenna system, by the arriving E.M. wave! As we have seen before, this could cause severe bearing errors which could reach 20° or more. This phenomenon was well known in those days, but the question arose as to how could this be countered and/or controlled? It soon proved that a DF antenna positioned (mounted) at the top of the tallest mast in the ship was the most favourable site. [IEE Proceeding, p. 798]

In my opinion it was the Polish engineer Struszynski - working at ASE - who was the "*pater intellectualis*" of a team which solved this problem.

Both the PS and FA loop can clearly be noticed, in figure 5 on the next page, on top of the central chamber. Struszynski designed, among other things, the particular coupling transformers which linked the symmetrical coaxial antenna cables either on to the B-T goniometer of the FH 3 or on to the front-end of the FH 4 receiver. These RF transformers have a very low stray field effect and are electrostatically shielded so as to prevent capacitive coupling (stray pick-up) between the primary and secondary windings. It is evident that these transformers were matched to the terminating impedance of the antenna circuits. Each set of transformers had individually to be matched for equal electrical parameters. Separating the

direct antenna loop currents from the front-end of the receiver, as well as the careful symmetrical wiring of the coaxial cable circuit, enhanced the common mode rejection of the system up to about 100 dB at 1 MHz. It can be seen that energy induced in a symmetrical coaxial cable by a stray field will be picked up by both conductors at the same time thus cancelling out any effects at the secondary circuit of the transformer. (IEE p.825) Even the radio hut and all its entering cables had to be electrically shielded and filtered so as to prevent any stray fields from being picked up by the receiver itself.

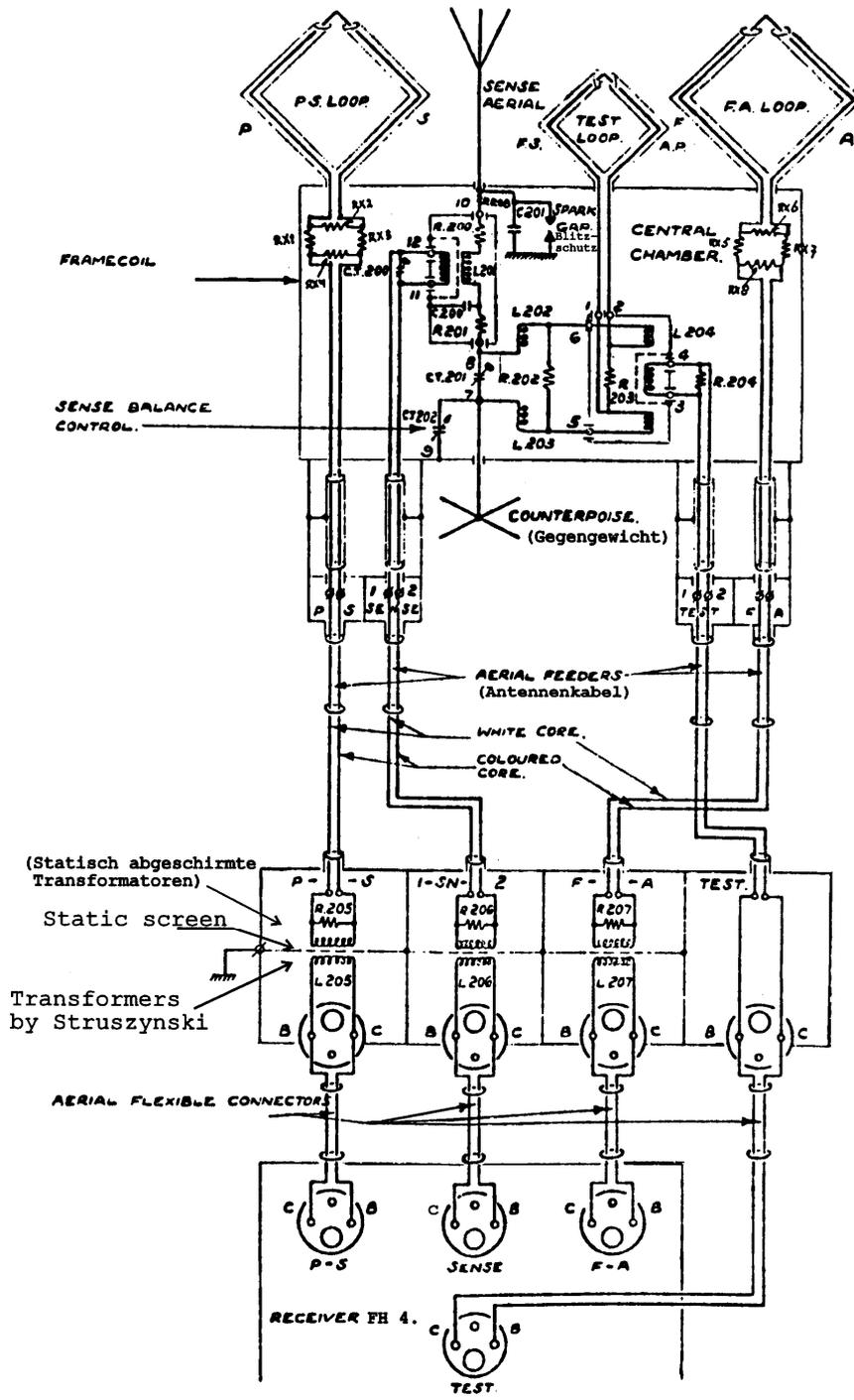


Figure 5: The FH 4 antenna circuit

The coaxial cables (so-called: twin-core feeder cables) used in these DF systems had to be all from the same production lot (same cable reel) and their mutual difference in cable length had to be kept within a maximum of 1 inch, so as to prevent unacceptable phase errors!

As we have noticed, the re-radiation field of the resonating antenna mast could be of severe proportions and such fields would be picked-up by the sense aerial too! Struszynski's team again solved this problem by balancing - for RF - the sense aerial circuit against the mounting mast by means of an adjustable electronic bridge circuit. (Redgment, p. 239)

"The antenna"

The RN sailors called this antenna the "birdcage", though how it worked electrically was kept a secret for many years. This secrecy was aided by it's very complex construction.

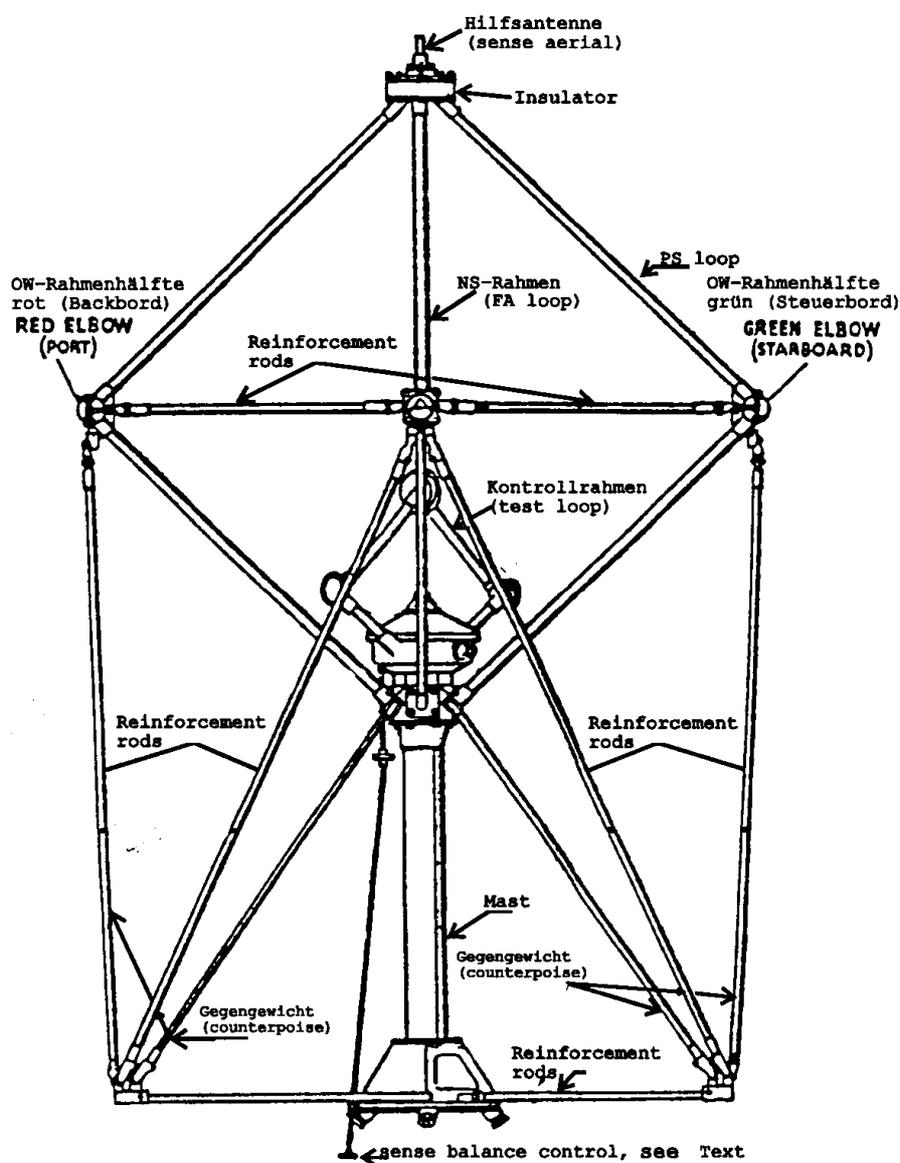


Figure 6: The FH 4 antenna in detail

The previous line drawing shows its well known antenna profile. Even with explanation this figure is not easy to understand and gives no immediate clue as to how smart the design was.

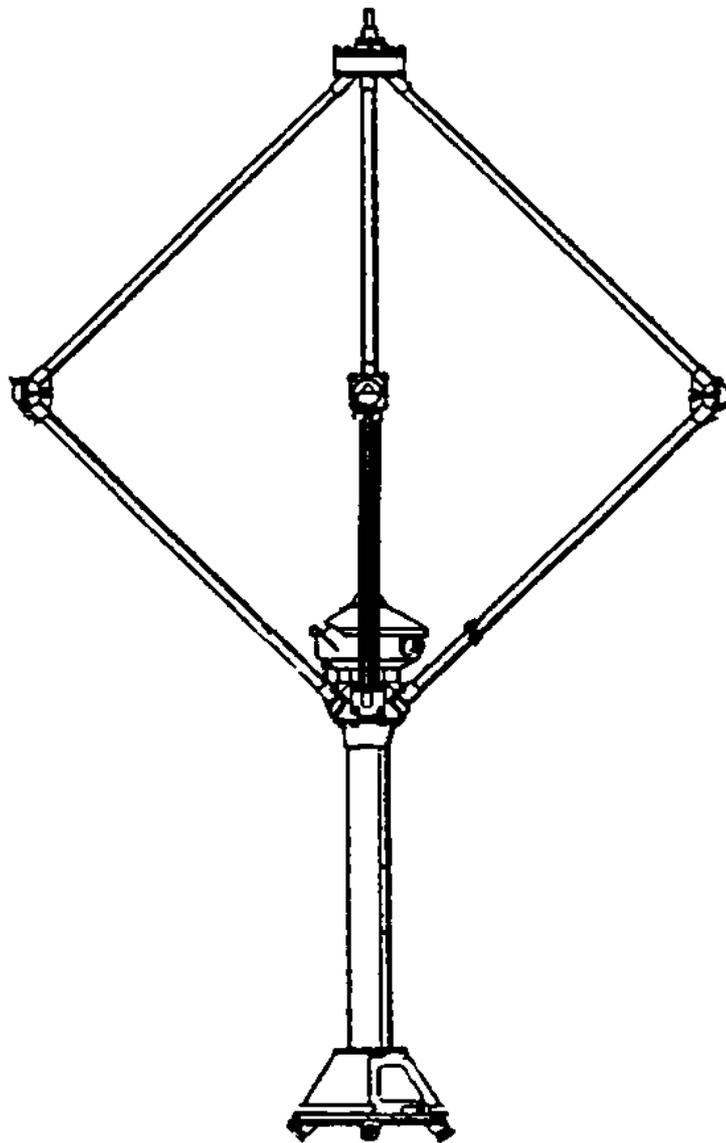


Figure 7: The PS loop

The line drawing above shows the broadside view of the PS antenna loop and the edge-on view of the FA loop.

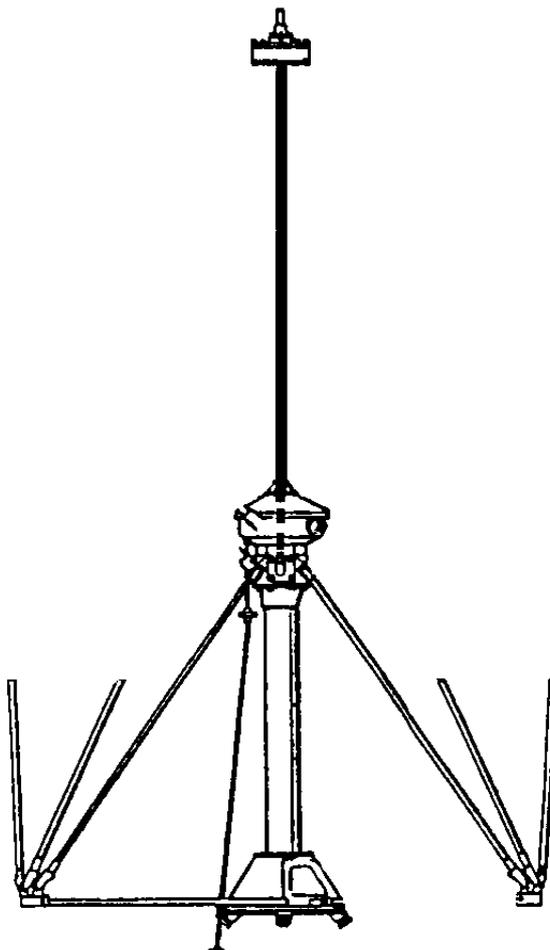


Figure 8: The sense antenna

Shown here is the sense aerial on top of the central chamber (see fig. 6), the aerial is facing upwards. Downwards we see the counterpoise, which provides an artificial ground. To extend the counterpoise the rods are folded upwards as well. I am not sure whether they also serve the additional purpose of screening off the re-radiated fields which are arriving from lower elevations.

(Please proceed on the next page)

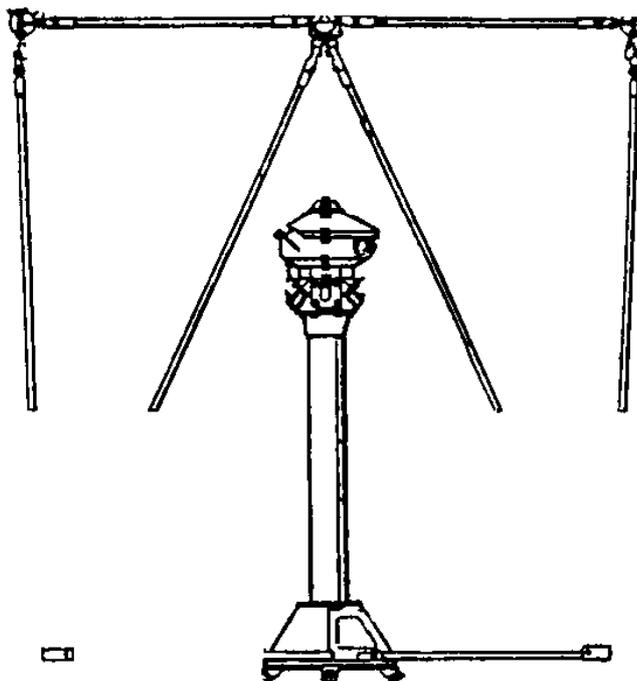


Figure 9: The reinforcement rods

It is evident that the previously shown extended counterpoise could not be kept structurally stable. Therefore, reinforcement rods were introduced to stiffen this complex antenna construction. For stable and precise operation this was a real must, certainly when one realises the nature of the environmental conditions in which it had to perform!

Watson-Watt type DF receiver

The early design of the "twin-channel" receiver type R.L.135 and R.L.66A had already been done by the Plessey Co. Ltd. in 1940; though it took quite some time before the first operational FH 4 apparatus became available for the RN in 1943. The early type used a set of 5 interchangeable coil boxes, which were stored in a (hanging) box to the left and right of the receiver and which covered a frequency range between 1- 25 MHz. Its successor FH 4 Mark IV was equipped with switched coils which covered 4 frequencies ranges between 1 - 24 MHz. (manual FH 4, chapter 2, p. 8, Bauer, p. 101 - 109, 133 -139).

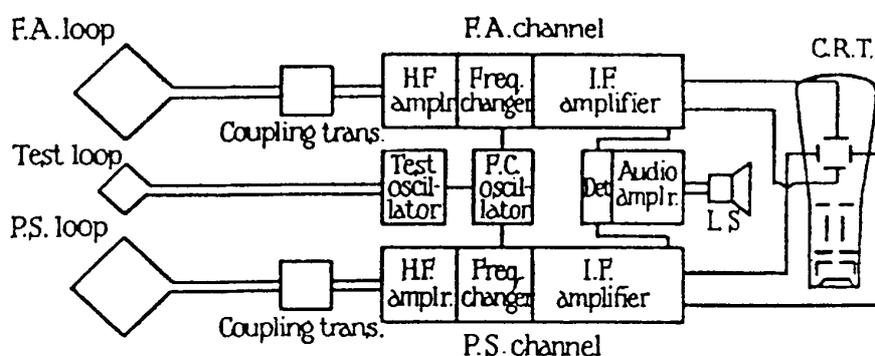


Figure 10: Blockdiagram of the FH 4 receiver

This blockdiagram explains the principle of the twin-channel HF/DF type FH 4. As we will see hereafter, the FA and PS channels were "carbon copies" to ensure that signal delay for both channels was kept (theoretically) equal. Only one local oscillator needed to be utilised, whose signal was fed to both mixers simultaneously.

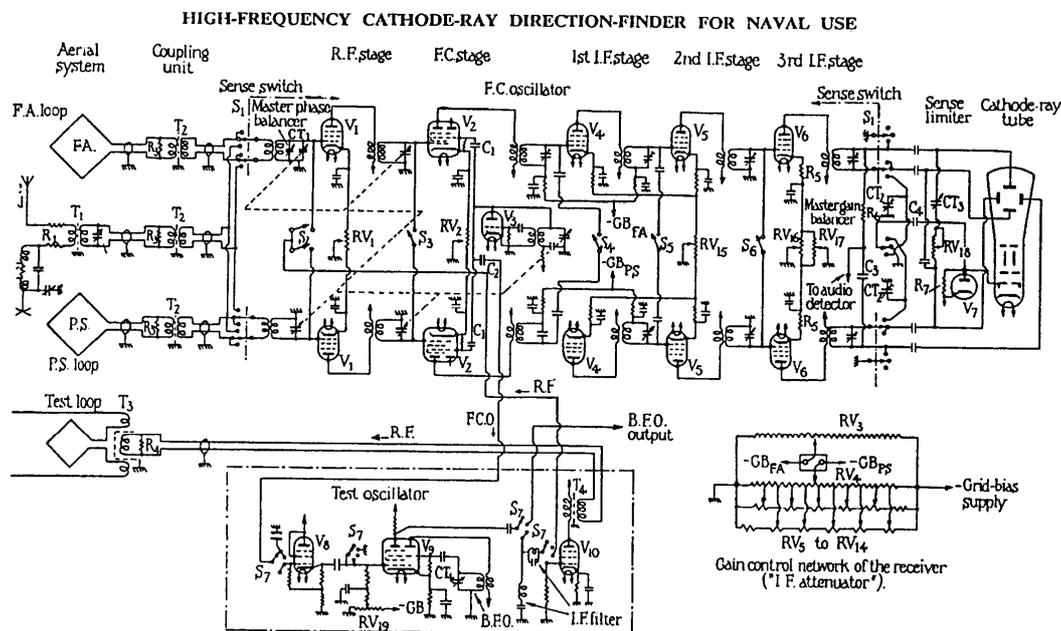


Figure 11: Principle diagram of the FH 4 receiver

Shown here is the basic circuit diagram of the FH 4, which we will discuss briefly. Let us first focus on the main FA and PS receiver channels. The two loops are linked via the transformers T₂ (designed by Struszynski) on to the input bandfilter at the front-end of the receiver, followed by the RF amplifier stage V₁ to the mixer (Frequency Changer) valve V₂. The common local oscillator (F.C. oscillator) is generated by valve V₃ and fed simultaneously to the mixers V₂. After passing three IF stages V₄ - V₆ both signals are fed to the CRT deflection plates. The bearing display is similar to that shown in figure 3.

We have seen, already, that a B-T goniometer itself always indicates a bearing which could be at + or - 180°. This ambiguity can be solved by the introduction of a third (sense) signal which phase-quadrature is relative - positive or negative - with respect to the fields induced in the antenna loop.

It is obvious that it had to be amplified equally as both loop signals, and that any time delay deviation of the signal phase had to be prevented. Inevitably, a third equal receiver channel had to be incorporated in the receiver to accommodate the sense signal. But this could hardly be managed in the available room left in the receiver. In my opinion a smart, though "poor man's", solution was chosen to overcome this limitation.

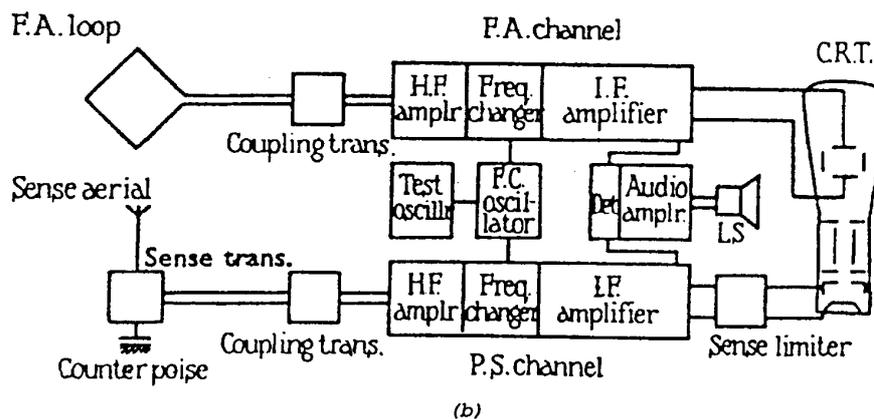


Figure 12: Blockdiagram of the FH 4, used in sense mode

The sense signal was fed to one of the receiver channels after the accompanying loop signal was disconnected. At the same time the accompanying IF output which is connected with the deflection plates of the CRT is disconnected from it and these plates are now electrically connected to ground. The IF signal is then fed, via the sense limiter, to the Wehnelt cylinder, so as to control the beam current of the CRT in such a manner that, without signal, its beam current was cut-off (blocking) and only when a sufficient signal was received could a trace be observed on the CRT screen.

Let us look, on the next page, at the principle involved (disregard phase difference between the signals).

1. the FA loop and its radiation pattern in respect to an arriving E.M. wave.
2. the typical circular radiation pattern of a sense aerial
3. the CRT; its Y deflection system is fed by the accompanying output of the IF strip and the X deflection plates are connected to ground.
- 4- 5. the upper sinusoid is representing the output of the IF strip. The lower sinusoid is received by the sense channel and fed in an appropriate manner onto the Wehnelt cylinder. The time span which coincides with the positive half cycle ($0^\circ - 180^\circ$) of the sense signal is used to de-block the Wehnelt cylinder of the CRT. (often called "control grid", which is, in technical means, not correctly)

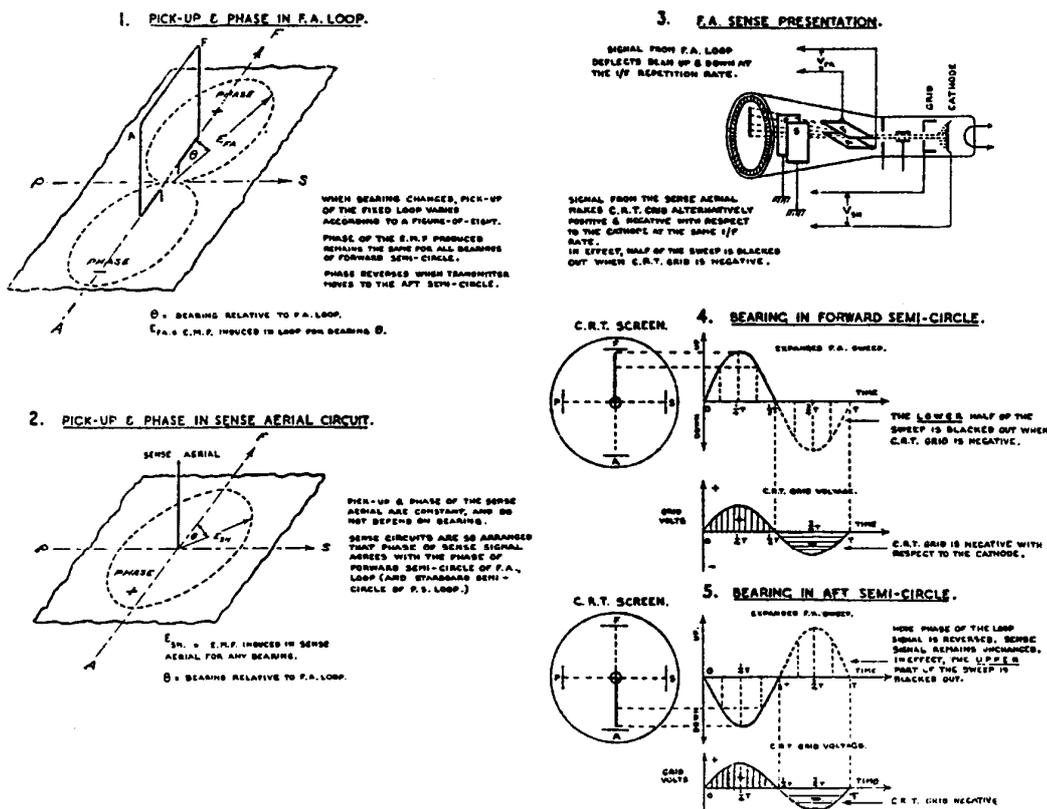


Figure 13: Principle of sense direction finding

Hence by this means it is possible to determine from which two quadrants an E.M. wave is arriving.

We have already seen that the amplification factor and the delay time of the signal phase for both receiver channels has to be strictly controlled.

To facilitate this control special requirements were introduced to speed up the operation. A special signal source (test oscillator = T.O.) was designed which always generated the exact frequency to which the receiver (RX) was tuned.

We remember the simple equation:

$$f_{LO} - f_{RX} = f_{IF} \tag{7}$$

This IF signal can be made audible as a CW signal by means of a so-called BFO (beat frequency oscillator), whose pitch operates up to 5 kHz either side of the IF frequency. If this BFO is tuned exactly at 450 kHz, which is the IF frequency of the FH 4, we easily can reproduce the RX frequency on which the receiver is tuned by the equation: -

$$f_{LO} - f_{BFO} = f_{RX} \tag{8}$$

hence

$$f_{test} = f_{RX} \cdot \quad (9)$$

Let us refer back to figure 11 and concentrate first on the test oscillator section.

In the centre of it we notice that the mixer valve V_9 has a multiple function. The triode section is used as a BFO generator, whose signal is fed onto the detector stage so as to interfere in a regular manner with the IF signal. A certain amount of energy is picked up from the local oscillator valve V_3 via C_2 , which is then followed by a separator stage V_8 and fed onto the mixer section of valve V_9 . Let us assume that the test signal is activated by the appropriate settings of switch 7. The BFO signal is then disconnected from the IF stage and fed - via IF rejection filters - onto V_{10} which amplifies and probably also separates the test loop circuit from this mixer stage. If the BFO setting is adjusted correctly the test oscillator frequency will always be exactly identical to that to which the receiver is tuned.

A third signal is generated in the test oscillator unit. This RF signal was used to ensure that the receiver channels could be adjusted properly for their mutual amplification factor as well as for mutual signal phase.

To carry out this alignment, the first step was to switch on the so-called comparator mode (S_2 - S_3). Both receiver channels were thus connected onto the same signal source. When amplification and signal phase were matched properly, a straight line was observed between 45° and 225° , which is in Navy terms equal to 45° and 135° . When, for instance, the phase tuning is incorrect an ellipsoid is shown with all its implications as we have already discussed. After this foregoing alignment (set up) the test loop was switched on. (S_2 and S_3 are opened again)

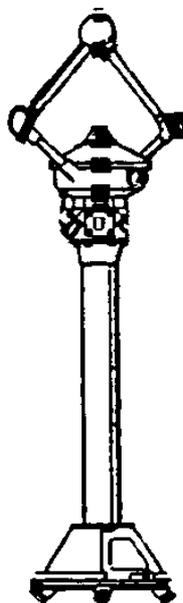


Figure 14: Test loop of the FH 4 antenna

Shown is here the test loop, which is mounted in the central axis of the DF antenna. Generally speaking, if we see somewhere a "Birdcage" antenna without a test loop it is certainly in used with a FH 3 installation. Only when a test loop is utilised is the receiver concerned an FH 4 apparatus. I do not know if its successor the FH 5 used such a test facility as well because,

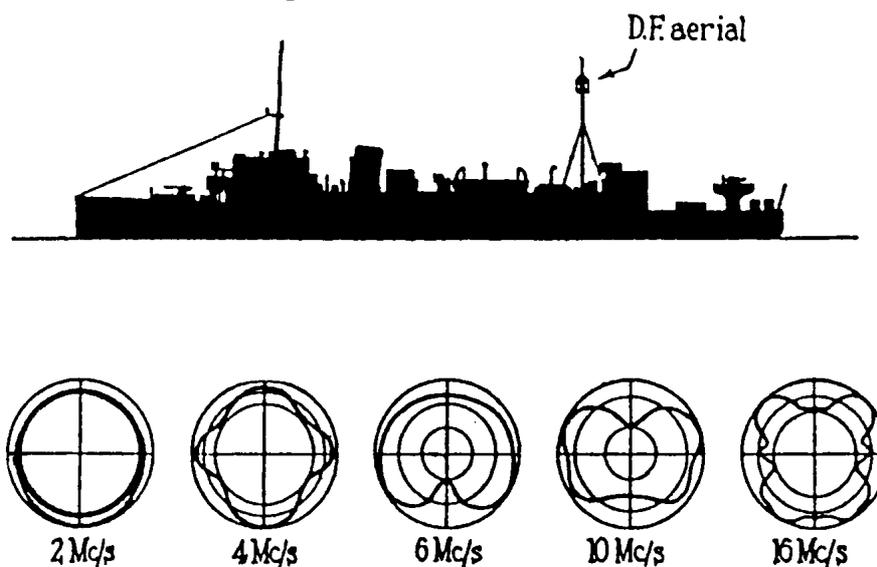
today, this information is still kept classified (some ships are still equipped with this installation).

The main function of such a test loop is to check the mutual (amplification and) signal phase of the two RF stages of the receiver which can be controlled by trimmer CT₁ (fig. 11) on the front panel (whilst, of course, watching the display on the CRT).

Up until now, we still don't exactly know what made this equipment so outstanding because, if we neglect its antenna circuit, all the rest was certainly common knowledge for the Germans also in those days. Watson-Watt type direction finders had been in wide use since the end of the 1920s.

Radiation patterns of the FH3/4 antenna

As we have already noticed, the superstructures of ships can cause all sorts of bearing deviations. We will discuss this phenomenon for some sample frequencies, though it has to be noticed that a frequency change of, for example, only 10 kHz can cause radiation patterns to be changed in an erratic manner. Due to this phenomenon, interpolation between curves is not possible and a calibration curve is needed for every frequency that is likely to be used in the operation of the installation. (IEE, p. 810)



The meridians are not necessarily true to scale.

- 2 MHz ($\lambda = 150$ m) this radiation pattern shows only minor bearing aberration.
- 4 MHz ($\lambda = 75$ m) quite some bearing errors will occur.
- 6 MHz ($\lambda = 50$ m) Aft bearings hardly can be made.
- 10 MHz ($\lambda = 30$ m) Accurate bearings can hardly be achieved.
- 16 MHz ($\lambda = 18,75$ m) Here we certainly meet bearing errors above 20° . One of the aspects which can cause these deviations is that the perimeter of the antenna loop can not be

ignored in respect to $\frac{1}{4} \lambda$, though certainly re-radiators cause the main aberration in this radiation pattern.

How then can acceptable bearings be achieved within deviation limits of between 3 to 5 degrees?

Many deviations are of a systematic nature and are widely dependant upon the superstructure of a ship. But systematic deviations lend themselves to be compensated for by means of a calibration curve and this proved to be **the** solution to this problem! The Germans call this technique "Funkbeschickung" and its technology was already widely used in the 1930s for medium and long wave DF systems.

For each possible frequency a calibration chart had to be prepared, which would hardly be managed when we realise that German U-boats on the northern (western) hemisphere used frequencies in the range 3.7 - 15 MHz. Thus, a frequency band of ≈ 11 MHz had to be covered. If we further assume that a calibration had to be made for every 20 kHz then more than 500 curves (theoretically) had to be prepared for each ship equipped with HF/DF! It has to be realised too, that the so-called "Penang" boats (also called "monsoon boats"), sailing to the Far East, were communicating on frequencies up to 24 MHz.

A calibration procedure was carried out as follows:-

Each ship had to be anchored on a buoy such that a calibration vessel could circle it with constant radius and which sent bearing signals at a distance of approximately one mile from all directions and, at the same time, all vessels had to be far enough from shore to avoid any DF aberrations resulting from land effects.

At every 5° of azimuth - "blurring" percentage, bearing deviations and the quality of sense indication had to be logged. The bearing accuracy was visually checked by optical means. Consequently, this vessel had to stop for each calibration step 71 times for one circle. Thus, if we assume that such a calibration vessel had to sail 500 times around the ship under calibration the task would seem impossible and could hardly be managed, in my opinion. ($500 \times 71 = 35500$ steps!)

But, it was the Germans themselves who made what seems to be impossible nevertheless become possible!

According to PRO document ADM 220/69 dated 3 July 1943 - which considered a list (for the calibration officers concerned) of the frequencies for which the HF/DF systems had to be calibrated for the Atlantic and Arctic areas - only 44 frequencies which were expected to be utilised! Though, we always have to consider that such details only exposure a certain *momentum*. (For more details see Bauer, p. 16 - 20)

True bearings by means of the FH 4 and its correction curves.

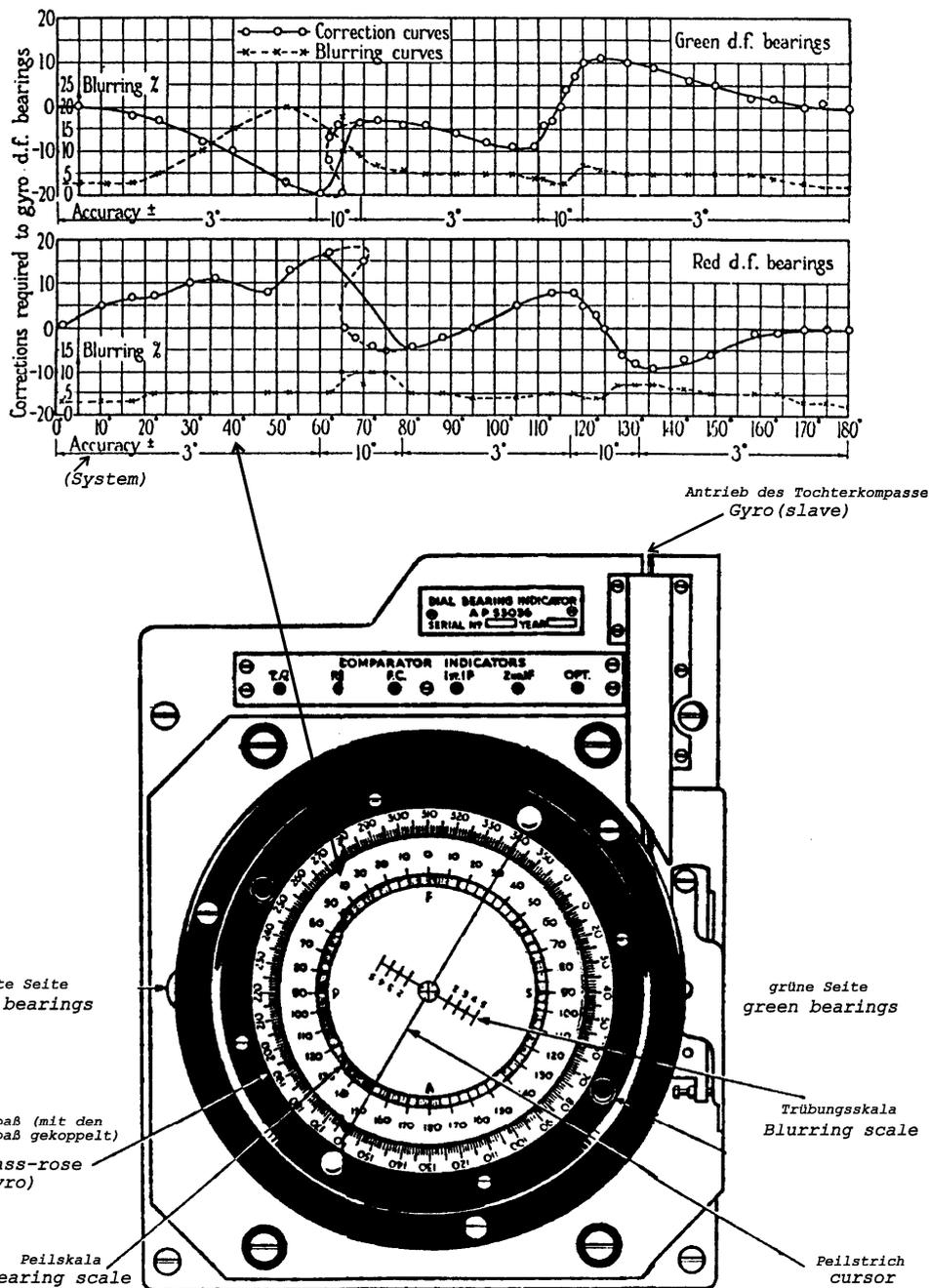


Figure 16: FH 4 bearing error compensation, by means of correction curves

Shown here are the main attributes which had to be used to assure more or less accurate bearings by means of HF/DF.

For each frequency separate bearing curves had to be prepared for Port (Red side) and for Starboard (Green side) of a ship.

Let us assume that an arriving E.M. wave induces an antenna current and a bearing trace becomes visible on the screen of a CRT. The operator had (after preceding tuning procedures) to rotate a perspex disc which covers the bearing display (CRT) so as to bring the cursor hair line along this trace (which cursor also acts as a bearing memory). We will take, as

our example, values of 30° and 150° (respectively) for the green and red curves (these equate to readings of 340° and 160° for the coincident gyro compass readings). The operator's next immediate step was to select the correct "sense" direction.

Following this, he had to refer to the calibration curves and he finds that for the Green side curve a bearing deviation correction of - 6 degrees is needed and for the Red side curve a deviation correction of - 5 degrees was required. Hence, dependant on the sense setting, the expected bearing is at: $30^\circ - 6^\circ = 24^\circ$ or at $150^\circ - 5^\circ = 145^\circ$. The blurring curves were mainly used for regular calibration purposes.

An interesting aspect is that, although severe bearing deviations occur, the average systematical accuracy still remains within reasonable limits. This phenomenon is well known in statistics and is due to the fact that not all variable deviations are possessed of the same sign, so that not all parameters are varying into the same direction.

On this occasion we have not discussed the nature of the U-boat communications and related technical topics. The contents of this paper are essentially a condensation of the five year research work covered, and published, in my book:-

"Funkpeilung als alliierte Waffe gegen deutsche U-boote 1939 - 1939"

For those who would like to study the subject of HF/DF - I strongly recommend two superb books: Wireless Direction Finding by Keen and Funkpeiltechnik by Grabau and Pfaff. (see ref.)

Conclusions

In history major technological breakthroughs hardly ever originate due to one circumstance or factor only, but almost always result from a sequence of developments which finally leads to what became known as "the particular solution". Prime examples are, for instance, the development of the atomic bomb, or centimetre radar. HF/DF is, in this respect, no exception.

In retrospective let us first look at some technical aspects of "huff-duff".

We have noticed that HF/DF had not been invented in Britain, it was a step by step scientific process which started in the early days of this century. Bellini -Tosi's goniometer proved to be of fundamental significance and it became widely used for all sorts of direction finding purposes.

We have not discussed the French - American developments which were mainly based upon Busignies work done in Paris in the late 1920s and 1930s, and which were brought to the US on behalf of ITT in late 1940. Kathleen Broome Williams' book contains much detailed information concerning this historical aspect (though, unfortunately, in technical respect here knowledge is too meagre!). Even these HF/DF apparatuses used the B-T principle, although with a spinning search coil. (Keen, p.877-880) It is interesting to note that according to Williams' book, Busignies, also designed a rotating single loop DF apparatus. (also Wireless World, p. 414 - 416)

The main problem hampering accurate DF on ships is due to the re-radiated electro magnetic fields which are caused by the superstructure. Re-radiated signals can hardly be avoided under these circumstances. It was Struszynski who solved this major handicap by the introduction of a totally new antenna design, which became known as the "birdcage" antenna.

We have noticed how the segments of this antenna were constructed and fit together. Not exactly obvious however is Struszynski's most significant invention: - the RF balancing circuit which - for radio frequencies - separates the top of the mounting ship mast from the sense antenna circuit (which is an inextricable part of the "Birdcage" antenna). Although the Americans claim that they had designed (developed?), during WW II, their own HF/DF antenna. However, I do not know if the Americans have utilised a Struszynski like "RF bridge circuit" to isolate the sense aerial from the ship mast. Though, in my opinion, the US HF/DF antenna design looks less stiff ("a nice weather artefact"). (KBW p. 46 and Henney/Markus p. 155)

We have also seen the disadvantages of Watson-Watt's direction finder design and, we have learned about its implications as well. I suppose that this was a choice made by the Royal Navy in the expectation that this type of HF/DF apparatus was the most likely to come into service quickly. Certainly for shore direction finding installations, the AH 6 (which is the shore version of the FH 4) had a great advantage over any chopped or rotating DF (goniometer) apparatus due to the lack of any forced synchronous modulation which could always interfere with the contents of an intercepted wireless signal.

I have met Dutch post war FH 4 operators and they told me that this apparatus was rather "unfriendly" to maintain, especially for those who had to align it. It utilised more than 41 tuning facilities, whose alignment had to be checked on a regular basis! According to the manual a set-up alignment could only be carried out after a warming-up period of six hours! Taking all this into consideration then, it is after all, nearly a miracle that this apparatus worked so well and did such a great job!

The introduction of calibration charts made correction of bearing errors of a systematic nature possible. We have seen that - due to the unpredictable nature of re-radiated E.M. fields caused by the superstructure of ships - a separate calibration chart had to be prepared for each frequency to be operated. This amounted to a possible provision for more than 500 available frequencies which might have had to be utilised for each ship. Under these circumstances shipborne HF/DF - as were used by the Allies - could never, tactically, have worked at all! All shipborne direction finders allowed for monitoring of only one frequency at the time, in those days. To slightly overcome this great disadvantage, the RN utilised a second communication receiver (Navy B 28 B \approx CR 100) which, at the same time, was tuned onto a different frequency which was expected to be used by the U-boat control as well. (Each HF/DF antenna could be linked - thus wired - onto one receiver only!) Each audio signal was connected onto one earphone section, so as to make monitoring of two different wireless signals at the same time possible. This mode was called: split phone operation.

It must be said that we were quite lucky that the U-boat wireless signals were nearly always tuned zero beat onto frequencies which were controlled by shore stations and these call signs were quite well known. Hence, huff-duff operators only had to monitor a limited number of frequencies.

Although we have not discussed this subject, we have to regard that for certain operations the Germans used so-called "off frequencies" which could operate randomly (from the Allied point of view) - for special services - between plus and minus 300 kHz from a particular centre frequency. Williams shows by a wartime document (p. 201) that, for example, such frequencies had to be watched by a total number of ten monitoring operators at the same time!

From an historical point of view, I think it is fair to conclude that: -
The role of allied HF/DF is generally undervalued. That this is no merely marginal phenomenon becomes clear when we notice that presumably a quarter (although some sources count this figure to be at a much lower rate) of all U-boat losses can statistically be associated with HF/DF operations during WW II. It is therefore no exaggeration to call radio direction finding a most significant weapon in the war against the U-boats and it undoubtedly influenced Allied warfare to a not inconsiderable extent.

Also, that its success owed quite a lot to wrong assessments made by the wireless organisation of the "Kriegsmarine", which kept on utilising zero beat operation for their standard U-boat wireless communications!

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