Abstract

Some historical and technical aspects of radio navigation, in Germany, over the period 1907 to 1945

Radio navigation, in the broad sense, has become of the utmost importance since the end of the 1930s. Warfare, without navigation by radio signals is, today, nearly unthinkable. It is therefore useful to look back in history to get some understanding as to how, why and when, some aspects of this technology came into being.

Navigation by radio as an aid has been practised in Germany since 1907. Scheller invented the complimentary dot - dash guiding path, which can be seen as a 'landmark' for several decades of navigational aids. Some aspects of the Lorenz civil 'Blind - Approach' apparatus and several technical details of the relentless Beams over Britain will also be discussed as will the principles behind Sonne (or Consol) used for long distance navigation and some other related subjects.

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Introduction

Already in the early days of the German wireless industry, it was Telefunken (fifty-fifty shared (owned) by AEG and Siemens & Halske) and C. Lorenz (the latter hereafter to be called Lorenz), who dominated Germany's market. The latter company was owned, since May 1930, by the American ITT company and, after WW II this company was also known as: - Standard Elektrik Lorenz (SEL). Around 1990 it was finally sold to the French Alcatel company.

From the beginning of the Wireless industry, the German government was keen to keep both major companies in business, to avoid the possibility of the internal market becoming one company's monopoly.

In 1907 both companies were testing their first "Funkbaken" or radio beacons. It is not known to me who really was the first to construct such radio beacon(s) but, from the beginning, the developments engendered by the Lorenz company showed signs that indicated the likely development of their product over several decades to come.

Scheller's patented No. 201.496 [1, p. 490] of 1907, was based on the idea of creating a particular radiation pattern, caused by two identical crossed antenna loops. It is quite interesting that, according to Kramar [2, p.155], the original patent application did not yet employ crossed loops but four vertical radiators, connected in a way similar to that suggested by Adcock 10 years after!
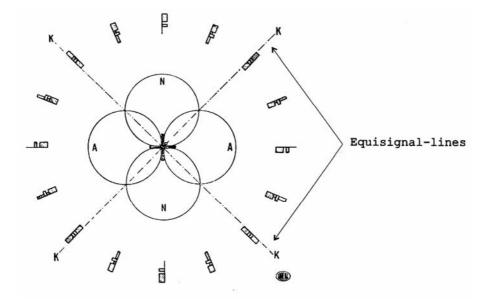
Figure 1: Scheller's virtual "A/N" path (1907) (Esau, [1, p. 348-349])

This figure shows in the centre the crossed loops and its well known radiation pattern. But his real invention was to feed both antenna loops from the same signal source, whereby each loop was switched (connected) on and off in such a manner that, each loop was fed with complimentary currents. One loop was transmitting in the rhythm of: dot - dash (**.** **-**), which stands for the Morse character A, and the other loop was transmitting in the inverse sequence dash - dot (**-** **.**), which in Morse code stands for the character N. This keying application became well known later as the 'A/N system' and formed the cornerstone of many other Lorenz applications.

It is evident, that the field strength at the equipotential-lines KK are both influenced by the crossed antenna loops, so their electromagnetic field components are identical at this virtual line. It is obvious that there will be, subsequently, only a continuous signal remaining at both crossed KK lines as long as we ignore the obligational keying clicks.

The next important step, patented by Scheller, was to let virtually rotate the radiation pattern, by the integration of a goniometer into the system. For this he had designed a special goniometer device, to avoid the distortion of the radiation pattern. According to Trenkle [3, p. 85], two special goniometers were utilised and the complimentary keying was executed in such a manner that only one single keying circuit was employed. A pair of toroid transformers (although these were called chokes then) were wired in such a manner that the two toroid cores were alternately brought in or out of saturation, by a keyed DC current. Whilst one antenna loop was radiating RF energy, the second loop was kept without current.

Subsequently this beacon, when not virtually being rotated, created, on a map, fixed A and N sectors. According to Esau, the aperture of equisignal sectors, when these were monitored acoustically, was approx. between 1° and 5°.

In 1908, Telefunken erected a different type of navigational beacon, which became known as the 'Telefunken-Kompass-Sender'. (Trenkle, [4, p. 80-81]
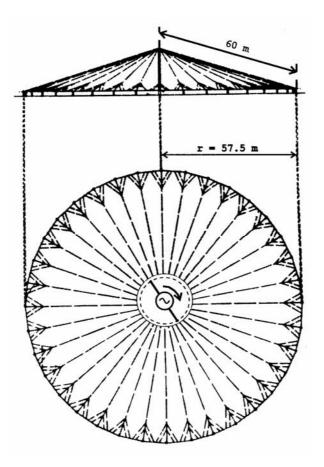

Figure 2: The antenna array of the Telefunken "Kompass-Sender"

It shows the circular construction of the antenna system. Thirty two wires were fed from the centre and were wired as for sixteen dipoles, installed as a sort of 'inverted V' or umbrella. Each antenna dipole was sequentially connected to a spark transmitter. The radiation pattern, for each dipole, was in the form of two lobes, perpendicular to the antenna wires. The shape of the lobes was influenced by the ratio between the length (l) of the dipole and the wavelength (λ) of operation. (l : λ)

The north-marker signal was generated by connecting all sixteen dipoles onto the exciter at the same time. Then, after a certain interval, during which the call sign was being transmitted in Morse as well, the virtual rotation of the radiation pattern was started. The virtual rotation of the antenna diagram was carefully synchronised, so that it became possible to utilise a specially designed watch in which only one indicator needle of double length was used. This watch had to be triggered just after the north marker had been switched off and the virtual beam rotation had been started. The watch had to be stopped at the point when the signal reached its maximum value. Though an ordinary watch (when all system parameters were taken into consideration) could manage this job too, it became evident that only one double length watch needle could been utilised because the dipoles had symmetrical radiation patterns.

The first, and necessary improvement was that, due to the relatively broad aperture of the antenna radiation pattern the antennas had to be connected to the beacon transmitter such that the minimum radiation indicated the correct bearing. Hence, the antenna (or dipole) wires were pointing straight at the direction of the receiving apparatus.

A whole range of improvements came into operation, but the basic principal was in use for about a decade.

The beacon had still one major disadvantage due to the symmetrical antenna pattern it was not always possible to determine whether a bearing was at + 180° or - 180°!!

During WW I, due to this disadvantage, the Zeppelins had to counter check their bearings by comparing two beacon stations. In western Europe, the stations Cleve and Tondern were widely used for this purpose. It was also possible, for such a moving platform, to compare and/or by control the trend of the change of the true bearing, and thus to determine its correct quadrant.

Some developments during the "interbellum"

The American Bureau of Standards experimented in 1921 with Scheller's type of beacon. Two years later the US Army set up technical trials with similar beacon devices. In 1926 a technical commission ordered the introduction of beacons, that could be used for navigation and utilised a simple wireless receiver, only. (1, p.349-350)

As we already have noticed, the early Lorenz A/N system was widely tested in the US. But, due to the devastating economical situation during the first years after Germany surrendered at the western front in 1918, it took nearly a decade before Lorenz was really commercially back on stage.

In 1928/29 an improved beacon type was erected in Eberswalde near Berlin. The utilised frequency was 385 kHz and the beacon had a radiated power of approx. 800 W. [1, p. 350-351], [4, p. 81] The first practical trials took place in co-operation with the Luft Hansa. (today known as Lufthansa)

According to Esau's paper [1], the great advantage of this Lorenz equipment was the keying method, which absolutely guaranteed that both A and N signals were, under all circumstances, completely complementary. This was in contrast to the system utilised in the US, whereby two separate transmitters were employed.

Towed antenna wires, widely used by aircraft in those days, were a great disadvantage due to the fact that the antenna was forced (by drag) into a position somewhere between vertical and horizontal polarisation. Hence, both the vertical as well as the horizontal field components were picked-up by this antenna thus creating an unacceptable distortion of the bearing. The solution, to prevent this unwanted effect, was found by placing a fixed vertical antenna rod of 1.5 meter length onto the fuselage of the aircraft.

Secondly, it became obvious that, although acoustical observation of beacon signals was theoretically quite effective, there was a great need for a left / right bearing indicator. (this subject will be discussed later)

From aviation authorities around the world there was an increasing interest in 'Blind-Approach' facilities (hereafter to be called B.A.), but, for over a decade a combination of national pride combined with commercial interests prevented the development of a world wide standardised system.

The first attempt came from the American Bureau of Air Commerce around 1930 and resulted in an instrumental B.A. system by Diamond and Dunmore. The American aviation industrial complex was in those days already the largest in the world, nonetheless even at the end of the 1930s they still were not certain enough to standardize B.A. for commercial use. [Esau, 5, p. 4] Handel suggested (in the same paper) that one of the resulting advantages for Germany was that the German Aviation Authorities were (at the end of the 1930s) not therefore strictly constrained by an already developed and definitive standard system.

In my opinion one aspect too often neglected by historians has been that the early introduction of new system standards, which although very sophisticated at the time, can soon become be very outdated even so, they are kept often operational for a decade or even sometimes much longer. We can call this phenomena: *- the disadvantage of being advanced*, and nearly all nations were, and sometimes still are, suffering from this limiting effect. For example, in the US their 115 power voltage and NTSC CTV standard, and in Britain their 405 line TV norm, up until the 1960s..! Even today, all PCs (DOS computers) are victims of the 640 kB memory phenomena!

Subsequently, the aviation standards in Germany could continually improve, as previously noted, without being limited by the existence of absolute standards. But, during WW II, it became more and more evident that German industry could no longer develop new technology and were not able to cope with the demands of their authorities. Thus they were forced into a position of standstill in respect of the introduction of really new and advanced apparatus and systems design. (Bauer, [6 p. 76 - 82])

The Lorenz "Ultrakurzwellen-**L**ande**f**unk**f**euer" (LFF) or VHF, B.A. beacon

Technically there are two elements to be taken into consideration for a B.A., these are the horizontal and the vertical system components. Both of these are of great importance.
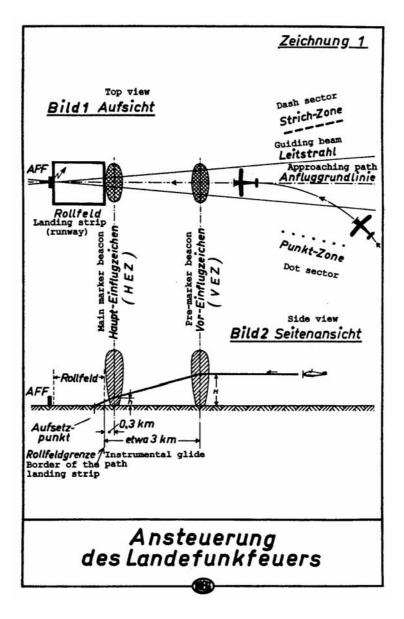

Figure 3: Lorenz instrumental B.A. system (Blindlandeanlage)

Let us consider the figure 3 drawing (Zeichnung) 1. The horizontal system component for navigation (Leitstrahl), has to indicate the true course towards the landing strip (today called runway). It is evident that, whatever the glide-path conditions may be an approaching aircraft needs to keep pointing straight onto the centre of the landing strip axis.

The Lorenz B.A. system proved to be most useful for this purpose. It was Kramar who brought this system to maturity. Let us take a brief look at what the basic elements of this system were.
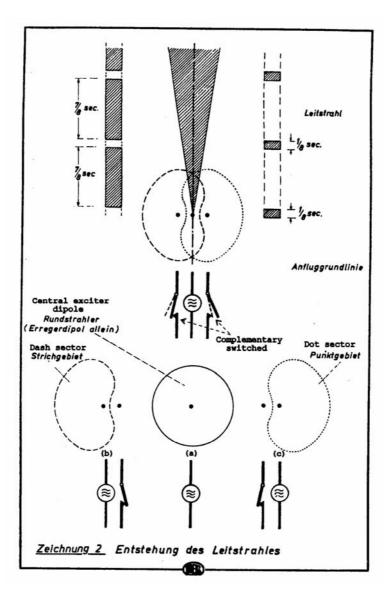
Figure 4: Beam forming of the virtual approaching path

Basically, the complementary dot - dash antenna lobe switching created an equisignal-line that was on the axis of the landing strip. Figure 4 shows the principle of such an antenna switching circuit.

First of all, let us take a look at the keying circuit: - it is obvious that both reflectors are switched on and off in a complementary fashion. Its time pattern is shown left and right from the virtual guiding path.

Figure 4a shows the omnidirectional radiation pattern, when non of the reflectors are (electrically) actuated to half wave reflectors (these were then equal to ordinary dipoles of $\lambda/2$). It is known that, generally, quarter wave conductors are not good reflectors for electromagnetic waves.
Figure 4b and c show the radiation patterns when each particular reflector is activated.

It is evident that the antenna lobes will virtually move in a particular sequence from left to right and vice versa.

As we have noticed before, this lobe switching had to occur in a complementary manner. To simplify operation a dot - dash sequence was chosen to distinguish between left and right of the centre of the virtual guiding beam path. Which side will be demodulated (either the dot or dash sector side) will depend upon the direction a plain is approaching - the Germans called this the 'green and red direction'. Until now, we have assumed that an acoustical observation would be used to determine left or right, but this would have posed difficulties, because the lobes were never operating at the same moment, due to the complementary keying. The difference of the received left - right amplitudes had to be distinguished in some alternative way. To overcome this disadvantage a left - right indicator was introduced. Its instrumental circuit reacted to different impulses from the demodulated left - right signals. As long as these were of equal value, so the antenna was pointing to the centre of the virtual guiding path and a moving coil instrument was indicating the centre, or zero, position. When the impulses were uneven in value, the meter circuit was wired in such a manner that the pilot would easily recognise what action he had to take. The left - right meter reading was most sensitive near its centre or zero position. The same instrument was combined with a second cross-meter section, that indicate the amplitude of the received signal.

Further information was, however, necessary before an aircraft could initiate its glide-path procedure.

It was Kramar who introduced a marker beacon that allowed the initiation of a controlled glide-path, as is shown in drawing (Bild) 3. (see [7], [8], [9]) The two specific beacons, for the so called pre- (VEZ) and main (HEZ) marker signals, were operated all at the same frequency of 38 MHz, with a special shaped, upwardly (vertical) directed, antenna diagram. The radiated power was limited, to avoid interference with, or between, the other adjacent beacon signals. Both marker signals (VEZ and HEZ) were picked-up by a dipole antenna that was installed parallel to the axis of the fuselage of the aircraft. Only one spot frequency was utilised so that only one receiver frequency setting had to be employed for this purpose. Each marker beacon, both the pre- and the main signal, could be recognized by its particular manner of keying and its particular modulation tone. The sensitivity of the utilised marker receiver could be kept quite limited.

It is evident that two signals had to be monitored, by the pilot, at the same time. The main approaching course could be tracked, if necessary, for several kilometres (often up to 30 km) before the glide-path procedure had to be initiated, at a point 3 km before the landing strip. The pre marker (VEZ) signal and the main marker (HEZ) signal, were than heard in the headphones and indicated visually by a flashing light (often a neon bulb) incorporated in the left-right meter indicator. The specific modulation (2A2), as well as the individual keying of the marker beacons was designed to alert the operators and so avoid misinterpretations. The pre- marker was modulated for 700 Hz and the main marker was modulated for a tone of 1700 Hz.

Finally, let us take a brief look at Fig. 3 again. All system parameters such as the dot-dash sectors and the position of the pre- and main glide-path marker beacons, are clearly shown. The aperture of the antenna lobes facing towards the landing strip are smaller than those perpendicular to the axis of the system, so as to ensure that if the aircraft was a bit off course it did not fail to pick up a marker beacon signal.

I am not suggesting that this technology was utilized in Germany only far from it this system was also adopted for use in Britain as well. Kramar also presented several papers in the US at

meetings of the I.R.E., and other places, in the 1930s. Some aspects of this technology were utilized during the famous X- and Y- beam guidance for bombers during the Blitz. However, because of their knowledge of the system made British response, to counter these threats, a much easier job!

Navigation by "Doppler-effect"

In 1935/36 the DVL, (German Aviation Research Establishment) tested the worlds first fully operational Doppler aircraft apparatus. To simplify matters we will follow the block diagram shown in this figure.
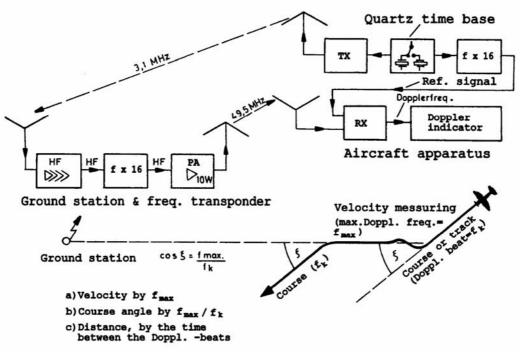

Figure 5: World's first operational aircraft Doppler-Navigation apparatus 1935/36 (DVL)

To utilize the Doppler effect, we require two different signals that have to be compared in phase and/or frequency. The reference signal here was generated in a quartz controlled time base and was send by two different routes towards the deployed Doppler indicator. The reference signal was linked (after being multiplied with the factor 16) to the front-end of the receiver in the aircraft. The second route was via the transmitter (by wireless) to a ground transponder. This transponder multiplied the RF frequency (without demodulation) sixteen times and, the signal was retransmitted after amplification, towards the aircraft. The reference, and the Doppler modulated signals, interfered somewhere at, or near, the front-end stage of the receiver and then passed through in the usual way. After demodulation the resulting signal was fed to the Indicator apparatus. This indicator used a paper strip to indicate and store the received Doppler information. It was then possible to obtain several system parameters from this information.

The Doppler frequency reached its max. value when the aircraft was flying exactly towards the ground transponder. (f_{max}). It should be noted that, if the aircraft happens to be following a circular track around the location of the ground transponder then, it is not possible to demodulate the Doppler signals.

The third option would be the true state of affairs for normal navigation when the aircraft is following a certain track or course. The demodulated Doppler frequency (beat notes) will in this case always be of a lower value than the case of direct approach to the transponder. The ratio between both values for f_{max} / f_k indicates or creates cos ξ. (see fig. 5)

It was, in my opinion only possible theoretically to evaluate situation c) (in fig. 5), to distinguish the distance between the aircraft and the ground transponder. This would have had to be managed by fast switching between the two (build in) quartz references. (Although, a triggered oscilloscope could have determined the time delay, without a second reference frequency)

The first trials were from the start very successful and indicated the significance of both the theory and technology. However it also showed that it was not very easy to handle this apparatus as a navigational aid. For instance: - the interpretation of the Doppler beat notes, when airborne, proved to be quite difficult. Due to this disadvantage, the project was put 'into cold storage'.

Although, many more projects were being initiated in Germany during the "*Interbellum*", we will turn to perhaps more familiar aspects of navigational technology!

"The X Programme"

This section of my discussion will sound more familiar, especially to those who experienced the relentless Blitz over Britain. This was an historical phase of development including the widespread adoption of civil technology for military purposes. An avalanche of publications have appeared since - see reference: - [3], [4], [10] and [11]..... .

Plendl of the DVL (German Aviation Research Establishment) in Berlin-Adlershof, had suggested to the Luftwaffe, already in 1933, that it would be possible to adopt radio navigation as a 'blind bombing aid'. The first attempts were undertaken using two commercial Lorenz B.A. apparatus. Basically, the crossing point of two antenna beams marked the pre- and/or main points, at which the bombing procedure had to be initiated.

It soon proved that the antenna aperture was approx. 5° and, hence, for long distance guidance, useless. At a distance of 100 km the beam aperture was already enlarged up to about 8 km! Subsequently, attempts were initiated to reduce the beam aperture to approx. 0,1°.
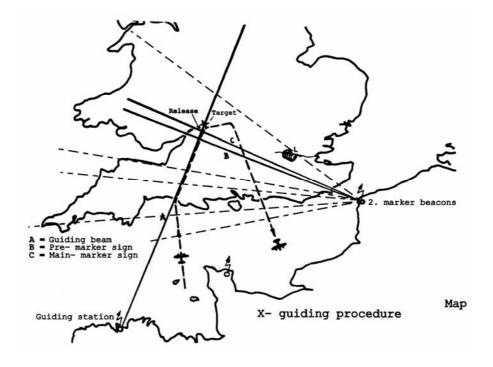
The new X- antenna arrays consist of two, 3.5 wavelength spaced vertical dipoles (D = 3.5 λ) (although sometimes other versions were utilised as well), these were fed in counter phase and created altogether fourteen (guiding) beams. Each virtual beam had an approximate separation between 2° and 4°. As we have already noted, such a beam lies, in fact, in between two maximum antenna lobes. The minimal aperture of such equisignal-line is perpendicular to the array axis and at approx. 0.05°. We have also to consider that, the beam aperture is dependent, as for all phased antenna arrays, on the ratio of the length of the antenna radiator(s) and wavelength of the signal (l : λ) as well as on the spacing of the antenna elements.

The dot-dash sectors were sequentially switched by a motor driven phase shifter. According to Trenkle [3, p. 60-62] the carrier was modulated by a sinusoidal 2000 Hz for this purpose.

Later, the deployment of antenna reflectors increased the radiated power in the forward direction and enhanced its effective range of operation. During the war, sometimes, very comprehensive antenna arrays were deployed.

To decrease the dimensions of the antenna array, the frequency band employed was increased up to 66 - 77 MHz. Precise navigation along a virtual path became possible in 1935/36; extensive trials were set up to estimate the effective range of such guidance beams. It was found that ranges up to 500 km could be achieved at flying altitudes of 6000 m. The standard altitude for German bomber aircraft, during the Battle of Britain, was at about 4000 m.

First practical trials in December 1936 proved that it was possible to get most of the dropped bombs within a square of 300 m by 300 m over a guidance range of 350 km.

Map 1 illustrates an example of a typical 'X- Beam' over Britain. The dot-dash 'Leitstrahl' path was transmitted from France, somewhere from the Breton coast. The pre- and main marker signals were transmitted from or near Calais. Although everything seems to be quite easy, as we know there was not only one main virtual beam path being radiated, but, due to the inevitable antenna lobes several equisignal-lines which had to be crossed (the dashed line on the map), before the first pre-marker ray was reached!

To start with, the pilot had to distinguish the correct beam A and had to keep on this virtual path until the marker signals B and after C were crossed, and until they passed the target. Crossing a certain equisignal-line was not the point that determined the moment of the bomb release, but the point at which a special computing 'X- Uhr' or X - Clock had to be triggered to initiate computing of the exact release moment.

As we have noticed (and will be discussed later) several inevitable side lobes and their generated equisignal-lines had to be crossed, before the chief B and C marker rays could be reached. This was done by counting the dot - dash zones being crossed.

Telefunken developed, during 1939/40, a system that became known as 'Knickebein' (crooked leg). It consist of an antenna array of, sometimes, huge dimensions. One of the first antenna apparatus was constructed on a large rotatable undercarriage and was mounted on a circular rail track, having a diameter of approx. 90 m! The vertical height was nearly 31 m. The antenna array was crooked in the centre about an angle of 165°, which explains the German word: -Knick(e), and: - bein, the latter stands for leg. The max. range, at an altitude of 6500 m, was up to 500 km. Already, in autumn '39, there were three operational stations under construction.

Again, the commercial VHF (UKW) frequency band (30 to 33.3 MHz), of the well known 'B.A. system', was being used, although, certain special military equipment was being used with it. However system components of the Lorenz system could be adopted for Knickebein as well. The first attempts still had one major disadvantage, because the system still adhered to the techniques of the X- beam apparatus! [3, p.66-68]

In the archives of the: - Foundation for German Communication and related Technology 1920 - 1945, a manual exists of a German mobile 80 kW U.K.W. (VHF) Sender, type S. 561a, equivalent to Philips type DR. 85. When AM modulation was used, the carrier output was reduced to 20 kW. The frequency range was between: 30 MHz and 34 MHz. For what purpose was this transmitter being ordered? One thing is certain:- Philips managed to delay this project until 23-3-1944, as indicated by the signed date (and modifications) on several diagrams. I believe this transmitter had been ordered in 1940 or early 1941 for deployment with offensive X- and/or Y-beams. [12]

The X- procedure never became quite successful but, its basic idea created, after the implementation of more sophisticated technology, engendered a variety of further systems.

We will not discuss here the knocking-out of the X- and Y- beams because this story has been told many times already.

"The Y Programme"

The basic principle of nearly all German 'Y' related subjects is that distance measuring, by a controlling ground station, became possible. But, it was based on Koulikoff's basic idea, patented in 1929, that it was possible to determine the distance between two wireless stations, by measuring the time delay between a periodically transmitted signal, and its instant retransmissions towards the station of origin. Today such retransmitting apparatus is called a 'transponder'. The content of the British translation was, originally, worded in the following manner: -

The distance between two wireless stations may be ascertained by causing an outgoing train of waves from the first station to be automatically retransmitted from the second station back to the first, and so on, the periodic note set up at the first station being a function of the distance separating the two.
According to the present invention, an oscillating valve is interposed between the transmitting and the receiving circuits at the first or active station, and serves to interrupt or modulate the outgoing wavelength at a definite frequency, the receiving circuit being rendered sensitive only during those intervals when the transmitter is quiescent. The distance between the local or active station and a distant or passive station is then determined by adjusting the frequency of the

oscillating valve or modulator until maximum reception of the retransmitted wave is obtained. This period corresponds to the time taken for a wave train to reach the distant station and return. A. Koulikoff, France, convention date was: - 15th December 1929, No. 302602, [13, p. 528]

It is evident, what Koulikoff was suggesting was that, by the means of the summation of two signals, the maximum output will be reached, and so measured, when there is no phase difference between these two signals. This may be achieved by the careful control of the phase of the signal source (reference). We will discuss this subject later.

The introduction of new devices, by the Luftwaffe was already underway in 1939. It was evident that more advanced systems had to be developed. Ideally only one guiding beam should be deployed, thus, no extra confusing beams or signals were radiated towards the target. The aircraft merely had to keep onto this virtual track (path) and had to follow the instructions from the controlling stations.

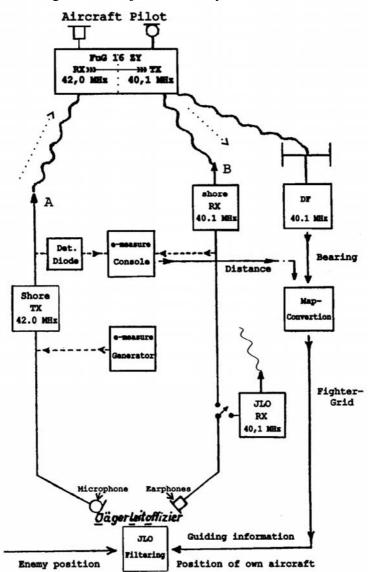To gain some understanding of this subject, we firstly take brief look at the theory.

Figure 6: Operational e-measure guidance

This drawing shows the content of a Y- system unit (although, the state of the art used since 1943 is shown). From the transmitter (TX) the modulated carrier (wave) A, is sent towards an aircraft, where this signal is then retransmitted, with an offset of - 1.9 MHz, by the wireless set FuG 16 ZY (transponder). Though, a FuG 17 E was deployed over Britain during 1940/41. The retransmitted carrier B is received by a shore station and was, after demodulation, sent on to the e-measure console. The character e - stands for the German expression:- Entfernung, meaning distance. Let us return to the signal A, a fraction of the generated energy was picked-up from the antenna circuit. The envelope of this demodulated signal was being sent to the e-measure console to act as the system reference. With the DF receiver, bearings could also be taken on the retransmitted signal (B) as well.

We have now learned about the two major system components of a 'Y' station. Firstly, the measuring of e- or distance- and secondly, the bearing- information of the aircraft. Within a certain accuracy this expressed the position of the aircraft. In the bottom of this drawing we note the filter room of the fighter control (JLO = **J**äger**leito**ffizier). The transmission of the wave A, could also be used for regular radio communication (control) as well. The measuring tone and the voice modulated signal could be received simultaneously, in the aircraft radio apparatus, without disturbing the spoken content.

To understand what type of 'e- signals' were being deployed, we take a look at fig. 7.
A 300 Hz sinusoidal tone was used as coarse measuring signal. The wavelength (λ) of a 300 Hz signal is determined by the very simple equation: $\lambda = c / f$. (c = the velocity in a medium, f = frequency) Hence, this gives a 1000 km wavelength, which has to be divided by two, because the distance between both stations has to be passed twice (vice versa). The transfer delay in the transponder (e.g. FuG 16 ZY, FuG 16 ZE, FuG 17 E...) and the ground receiver were a, more or less, constant factor and were being taken into consideration.
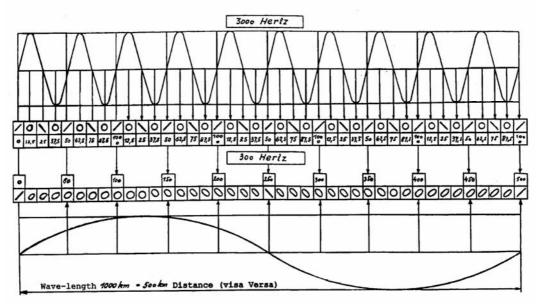

Figure 7: Signal phase – distance correlation as was used for Y- distance measuring

It is evident that, for a distance of 250 km between the two stations, the 300 Hz signal phase has rotated over 180 degrees. If, for instance, a precise location was needed, based upon the coarse measuring information, it was likely that the system accuracy was only of the order of several km. This would have been completely unacceptable, even in those days. So, a second measuring frequency of 3000 Hz could be selected, which allowed a measuring range of 50

km. (For the Y-beams deployed over Britain, the more precise value was obtained using 7500 Hz)

The demodulated reference signal, originating from the transmitter, was fed, via a cable, into the e- measuring console and passed through a calibrated tuneable time delay circuit. This device delayed the reference signal and was fed after to the deflection plates of a CRT (Cathode Ray Tube). The other deflection plate circuit was supplied with the received signal. On the CRT a Lissajous figure was painted (there were different types of comparison displays being deployed). This procedure permitted the comparison of both signal phases. (some examples are roughly illustrated in the middle sections of fig. 7) There were two different e-measuring console types deployed, one was produced by Siemens and the other by the Greatz company.

This explanation does not pretend to be comprehensive, as a great number and variety came into service during the war period.

The Y-facility allowed the (night) fighters, as well as other aircraft, to be guided (by wireless communication) onto the Allied bomber stream. But, the Y- procedure also made it possible for a pilot, having left his operational area, to obtain his position on the map from ground control. For example a night fighter might take off during the late evening from, for instance, Munich airport. It could have been quite likely that he would have to refuel near Berlin or Hamburg, his Y- apparatus would enable him to do so, by giving him his position on the map grid.

Following this brief example let us to return to the Y-beams, as these were being used over Britain. Already in September 1940 (raid on Portland), the first Y - beams were operational.

As we have noticed in a previous discussion: - the deployed guiding X- beams and the Lorenz approach beacons as well, were both keyed in a dot-dash sequence which sometime lead to interpretation errors. These originated due to the various virtual beams and the inevitable antenna lobes. (over the British Isles)

To counter this phenomena, a newly developed, sequentially, switched antenna pattern was put into service (although the first version still utilized a dot - dash sequence), as is shown in figure 8 (see next page). The procedure was as follows:- each antenna pattern radiates, without interruption during a certain, equal, time period. After both antenna lobes were sequentially being switched on and off, a short non radiating interval was introduced, in a ratio of: 8 : 8 : 1. This newly designed antenna array avoided the foregoing phenomena, due to a complicated switching and placement of several dipoles and its reflectors, in such a manner that: - one main lobe, or a cardioid pattern was being radiated, with only a few rudimentary side lobes left. The two main radiation patterns are visible in figure 8 clearly. The virtual path is not in the centre of the forward antenna lobe, but, at the equisignal-line, just where the electromagnetic forces both have equal field strength. Consequently, the usual acoustical left-right discrimination could not be employed any longer. A special designed receiver device (FuG 28a), based on the FuG 17 aircraft wireless set, was introduced and this device could distinguish the dash sequence, and convert its data into left-right commands for the auto pilot. The silent interval (gap) was incorporated in such a manner that it could be used to synchronize the system control. The regular left-right indicator in the cockpit could still also used for this purpose as well.
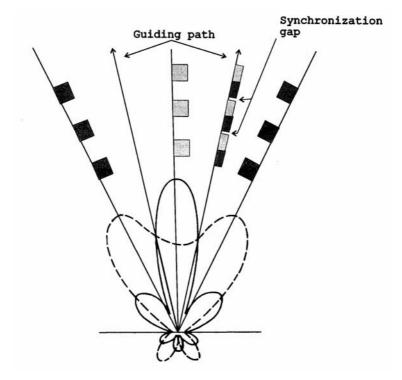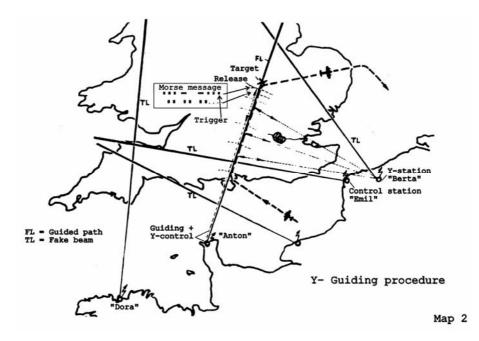
Figure 8: Dash – dash keying of the Y- beam

The main guiding beam was transmitted by the station Anton in France. The beam was pointed at (over) the future target, before the operation was commenced. If we assume that an aircraft found the (his) beam path as shown on the map, he had to steer himself in such a manner that he could keep on this virtual track (path). From this moment onwards several e-measure or Y- stations were being alerted to help control the flight. They could track the position of an aircraft by taking bearings and measuring the distance between the ground station and the plane. One of the requirements for the pilots was keep flying at a constant altitude, as well as at a constant ground speed. His course or track was monitored by one or more ground control stations. Let us assume the aircraft is arriving near to the point where the pre-phase of the dropping procedure had to be initiated. When this point was reached, the X-Uhr (or X-watch) was triggered, this was now done by the operators at the ground control station (the X-Uhr was mounted at the e-measure console). From now on, over a distance of approx. 18 km, sequentially measuring impulse trains were sent, to control the exact position on the map. From a certain point on that map, approx. 6 km before the bombing target was reached, the X-Uhr switched a contact that initiated the transmission (2A2) of several pairs of dots as: **.. .. ..** . Another section of the X-Uhr calculated the real bomb release moment and started the transmission beginning: . . . - - . . . (V B). The last received dot had to trigger the bomb release by the responsible crew member(s). The Morse message is shown inside the cadre on the map. [4, p.145 - 156]

Y- Guiding procedure

Map 2

Nearly all 'Beams' we have discussed before, had as their main purpose the guidance of an aircraft on a certain virtual path but, for general navigation, the real azimuth bearing is a requirement. Many shore station beacons, world wide, were in use for several decades, but for long distance purposes these beacons were (due to skywave errors) often quite useless.

The determination of the azimuth by wireless

From the mid 1930s onwards, several quite sophisticated beacon apparatus' were designed by, or with, the co-operation of the Lorenz company. Two names were associated with various developments namely: - Kramar and Goldmann. The latter joined the company in 1936 after leaving Siemens and Halske Central Lab. [14, p.6] In 1940 he joined the development team that worked on a project called 'Elektra' which was initiated by von Handel, who worked for the DVL as well. (see previous information).

"Elektra"

Elektra was a long wave navigational beacon that generated guiding beams similar to those being used for the VHF Lorenz B.A. systems. As we have seen before, the spacing of the antenna radiators, over several wavelengths creates, inevitably, a radiation pattern consisting of a number of antenna lobes. To understand the nature of these radiation patterns, we briefly take a look at the associated antenna theory.

When one vertical radiator is fed with energy, and no other electrical elements are in the vicinity, an omnidirectional pattern will be generated, similar to that shown in figure 4 (a). When two vertical radiators are spaced for $D > \lambda$ and fed in phase from the same power source, the radiation pattern will create a main forward lobe perpendicular to the centre of the array base line. If we neglect the created lobes, and the two antenna radiators are now fed in counter phase, the maximum and the minimum patterns will have changed places. This is just what is happening for most of the antenna arrays, when these are being switched between main or split beam operation. (see later) The direction of rotation depends on the mutual phasing of the (two) radiators.
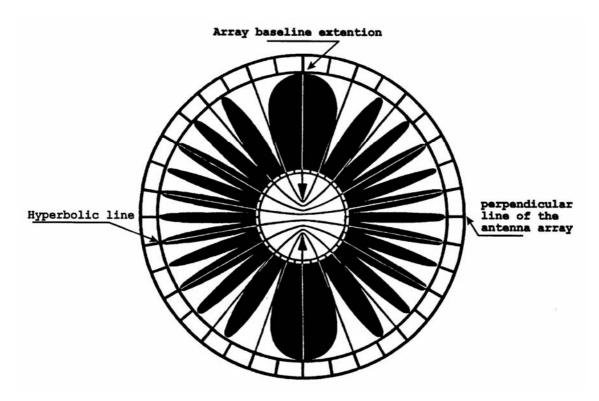
Figure 9: Radiation pattern of an antenna array of two vertical radiators, fed in phase, with a spacing of 6 wave-length, for the horizontal plain

Until now, we have only discussed the condition of being in phase or in counter phase but, in between both limits there can be a changing phase shift (rotation) and hence the virtual rotation of the concerned radiation pattern. This is just what Goldmann did, he converted the Elektra apparatus into the: - Sonne, or Consol beacon apparatus, well know to the Allies as well.

Figure 9 shows the circular (polar) radiation pattern for a 6 λ spaced pair of vertical radiators, according to Sonnenberg [15, p.4-10] the station 'Stavanger' utilized a spacing of 5.75 λ (base length of 5.4 km!), which slightly distorted the above illustrated pattern. The radiation pattern for two radiators spaced for D = 6 λ, is arrived at without entering into the proof, by the wave path difference d between two arriving electromagnetic waves in free space and distribute, at a certain point in the plot e.g. for d = 6 λ sin α the phase difference between the two arriving waves is φ = 12 π sin α.

Figure 10 on the next page, shows the principle diagram of the station 'Stavanger'. Until the 1980s, it operated with the Norwegian call sign LEC. The Germans named this station: S 1, when it was deployed as a Sonne beacon, and E 1 when it was used as an Elektra beacon. Although, I am not certain that there have not been other official German military call signs as well. [3, p. 154]
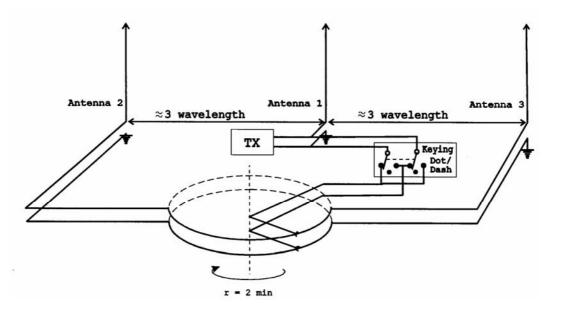
Figure 10: Simplified diagram of the Sonne or Consol apparatus

The antenna radiators 2 and 3 are similar to those we have previously noticed in figure 9 hence, their radiation pattern will be more or less similar. The motor driven phase shifter rotates for one minute from 0 to 180 degrees. After the phase shifter has reached the connections with the feeders of antenna 2, the transmission (radiation) of antenna 2 and 3 will be stopped automatically, but the motor driven phase shifter will continue its rotation (for 60 sec) until the new measuring sequence has been initiated (started).

Antenna 1 plays a crucial role, because its radiation pattern will now interfere with that of the two outside antennas 2 and 3. As we know, when two electromagnetic field components are equal and having the same phase, this results in the addition of both field components. When the phase difference between both field components is 180°, then both field components have to be subtracted (mathematically expressed by vector summation). Hence, theoretically, when at a certain point in free space two equal electromagnetic field components (waves) result in a particular field strength then, when one of the field components changed its phase by 180° vector subtraction of both field components will result in a cancellation (vanishing) of the resulting field. Thus, no signal will be observed. According to Stanner [16, p. 72] was the power ratio for the antennas was 1 : 1.7 : 1 (antenna 2 -1- 3), although, Goldmann stated, during his interrogation in May 1945, that the power ratio was: 250 : 1000 : 250 w. [14, p.8]

If we return to the purpose of Sonne or Consol apparatus, this is just what the aim of the centre antenna is. If we look at figure 9, it is feasible that the outside antennas, whatever their mutual phase difference is, will sequentially interfere in a positive or negative sense. This phenomena is due to the interference hyperboles which result in the so called 'Consol lines'. When the switched phase inverter, is 'keyed' in a dot or in a complementary dash sequence, the result is an on and off reception with the same content. If the shifter is changing its phase, this will obviously result in a transposition of the interference pattern in free space.

This type of beacon apparatus was only reliable at distance excess of approx. 40 km from the antenna base line, due to the influence of both ground and sky wave interference.
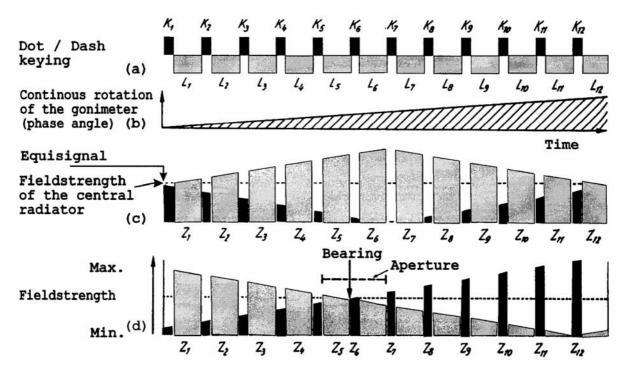
Fig. 11: Simplified dot/dash sequence of a Sonne or Consol system

This figure explains, using abridged impulse diagrams, the interaction between the variable system parameters that were deployed for both Sonne and Consol. The upper row (a) shows the sequence of the dot and dash switching or keying.
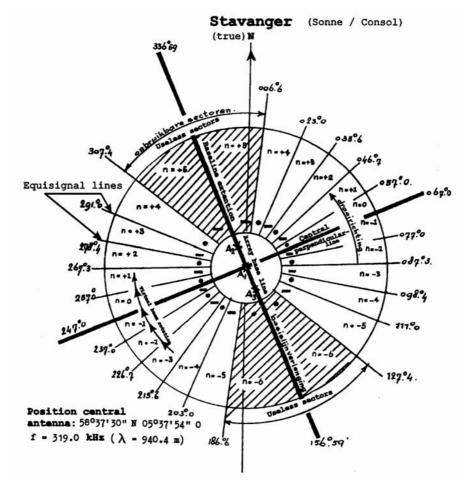Row (b) expresses the continuous rotation of the goniometer.
Row (c) starts at an important point, just where both field strengths are (becoming) equal and, as we have seen before, this would be the equisignal-line or point. Between Z_6 and Z_7 the resulting dot sequence had nearly disappeared.
The final row (d) shows, at the right edge of Z_5, the point were the rotating equipotential line marks the virtual bearing (equisignal or Consol line).

The bearing procedure was kept quite simple. A regular long wave receiver, equipped with a bfo (beat frequency oscillator), was the only instrument necessary on board an aeroplane or ship. The discrimination of the virtual bearing was fully acoustically executed. A special map was employed, which indicated at what equisignal or Consol line the particular bearing was taken.

An operator had to wait until the dot-dash signal sequence had vanished and no signal was being transmitted for a few seconds, followed by period with a constant (continuous) carrier. For this purpose both outside antennas 2 and 3 were switched off from the system (electrically disconnected). A few seconds before the constant signal stopped, the station call sign was transmitted. Figure 11 row (d) shows the sequence of events if we were not at an equisignal-line. A train of impulses in dot or dash sequence was received first and, after a certain period, these impulses would get weaker and weaker until no keying could be distinguished. Shortly after this, a second impulse train would begin to get louder and louder. Due to the nature of the system, the dot or dash impulses were, after passing through the equisignal-line, interchanged (see later). For the station Stavanger a total of 60 pulses of all types were transmitted. By simply counting the total dots or dashes before and after passing through the
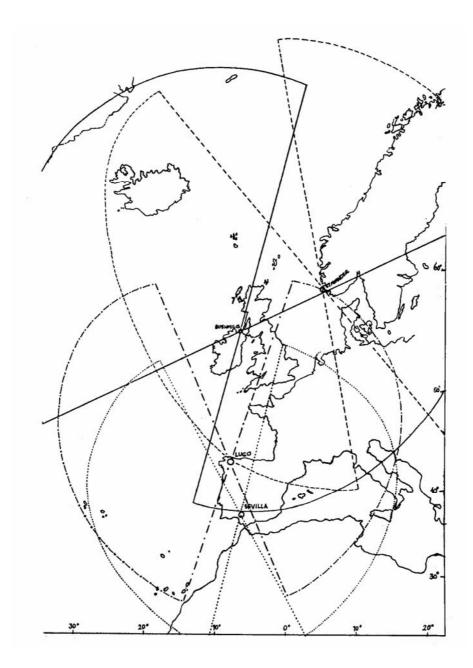
equisignal-line (Consol line), a simple calculation could be carried out with the aid of a Consol map.

Fig. 12: Dot/dash sector patterns at the start of each virtual rotation

The symbols for:- A 1 - A 3, are similar to those used in figure 10. Each dot and dash zone (sector) is separated by an equipotential- or signal-line, just before the virtual beam rotation was being initiated. This line will start its virtual rotation in the displayed direction until it reaches the next sector or zone. Some publications, dealing with this subject, suggest that the entire radiation pattern would rotate over 180°, that certainly is not true!

According to von Handel, the average accuracy of 'Elektra' was during daylight up to 0,14° and this decreased, during night time, to approx. 2.5°. [17, p. 368]. The code name 'Sonne', what stands for: - the Sun, had to express that the system only worked reliable (optimal) during daytime.

Map 3: 1000 mile range of the Sonne/Consol beacons

This map shows finally the effective range of several Sonne or Consol beacons, which were in service at the beginning of the 1950s. But, on the continent these stations had already been erected during WW II (The stations in Spain as well). According to Trenkle [3, p. 154] there were, during the War, up to 7 Elektra - and 12 Sonne stations operational.

The British copied and built, already during the War, their own Consol apparatus although they were not able to solve all the technical problems as became obvious during the interrogations held shortly after the German had surrendered. Thus, they were very keen to interrogate Dr. Goldamm about this and, of course, many other subjects as well. [14, p. 6-9]
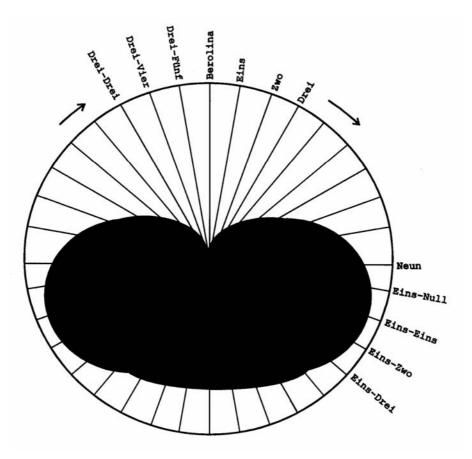
Fig. 13: Hermes or Hermion, the 'Talking Beacon'

Hermes (although it also was called Hermine) could be deployed as an avionic VHF 'Sprechdrehbake' or talking beacon, for instant navigational azimuth bearings, to be utilized by aircraft pilots. It consisted of two transmitters, one was deployed with a constantly spoken text, as follows: - one ----- two ----- three---- and so on, up to---- three-five. The north marker was identified by the call sign of the particular station, as for instance, Berolina. (Berlin) [3, p.100-102] The virtual rotation was completed in exactly 60 sec. The general picture is outlined in figure 13.

It is evident that each number group had to be multiplied by the factor ten for angle as bearing. The bearing information was radiated from a vertically polarized dipole, placed in the centre of a rectangular group of four vertically polarized dipoles. These latter dipoles were fed via a goniometer which was connected in such a manner that the radiation pattern was cardioid shaped and was modulated so as to jam the content of the spoken information. Only that sector which was in the virtual null of the cardioid was free from jamming. The rotation of the entire antenna system was coupled with an endless film sound strip, in such a manner that the cardioid null was virtually facing toward the particular direction that corresponds with the content of the spoken message. The bearing accuracy was limited to approx. 3° to 5° and its effective distance range was, depending on the flying altitude, up to approx. 250 km. This beacon could be monitored by the remote controlled B.A. receiver EBL 3 F in the aircraft. According to [14, p.21-22] this receiver (Hermine =FuG 125) had to be slightly modified (to increase the audio bandwidth) by an additional remotely controlled switch. The beacons were stationed near, or at, airports, so as to make it possible to home in on a site without the need for additional DF equipment. In my opinion this was very much an auxiliary device.

"Bernhard and Bernhardine"

In the summer of 1935, Telefunken initiated a project to develop a navigational aid called 'Bernhard'. Its purpose was to increase the achievable azimuth bearing accuracy of radio beacons, as measured from aircraft or by other platforms. This concept proved to be able to take bearings of the order of 0.1° accuracy. The frequency utilized was 300 MHz which, in those days, was a quite short wavelength (λ = 1 m). The maximum achievable transmitting power was approx. 200 w being limited by the lack of adequate high power valves although, the power gain from an effective antenna array increased the power being radiated.

In 1937, a wax printer device was introduced, to store the bearing data. Ranges between 260 km up to 340 km could be covered (depending on flying altitude) with a bearing accuracy of approx. 0.25 °. It proved that the system was not influenced by any ionospheric phenomena at all, as for instance that which occurred during twilight or sunrise.

Shortly after this, special Siemens Hell printers were employed to store the bearing data on a paper tape, and bearings were logged with an accuracy of up to 0.3°.

A disadvantage was that two receivers had to be used in the system, one to receive the correct azimuth bearing and the second to demodulate the contents of the Hell message. The actual bearing data was constantly reported in Hell characters, in much the same way as was in use on a compass rose.

Rudolf Hell invented, at the end of the 1920s, a printer device which enabled that facsimile as well as ordinary characters to be sent and then after being received, printed by means of an inked helical spindle. Every character was scanned in a particular matrix; quite often a 7 x 7 dot matrix was employed for this purpose. Nearly every character could be transmitted within such a matrix, even Chinese! This system became very popular in Russia and in China, up until the 1970s!!

Due to the disadvantage of the need for two additional receivers on an aircraft, the Bernhard system was, more or less, put into cold storage but with the proviso that if needed such apparatus could soon brought back in to service again.

In 1941 the system was adopted by the Luftwaffe, but, employing the regular B.A. frequencies between 30 - 33,3 MHz so that the ordinary EBL 3 receivers could be utilized and the system was renamed 'Berhardine'.

As we have noticed, two different signals had to be deployed and these were transmitted within the same audio frequency channel. A special auxiliary filter box separated the two demodulated audio signals.
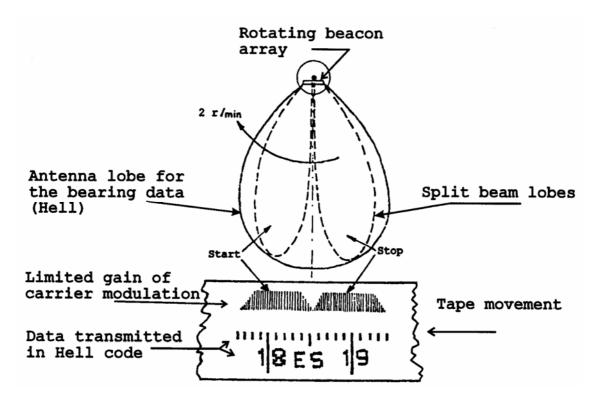
Figure 14: Bernhardine FuG 120a bearing, displayed on a paper tape, by a Hell printer device

If we look at this figure the particular system parameters are clearly visible. The two rotating beacon arrays were each fed by a separate transmitter but, mounted on the same chassis or frame. One was radiating its max. energy in the forward direction, whereas the second antenna radiated, due to its split beam operation, its bearing null.

The receiver on board an aircraft reacted first to the modulation from the split beam radiated signal which triggered the paper transport and this was kept-on by a delaying circuit (to overcome the instant stop when the bearing null was reached). At the same time, the main forward looking antenna lobe was constantly radiating (reporting) actual Hell data. This message was originated from a device that was linked to the azimuth scale of the rotating antenna array. Using an optical device coupled to a photo electric cell Hell impulses were sent to the modulator of the particular transmitter.

We have noticed that, there were two different audio frequencies being employed by the aircraft apparatus. In one case, for the split beam, a continuous sinusoidal tone modulated carrier was used. After reception its demodulated envelop was fed onto the upper Hell printer section, which operated the transport mechanism and employed a small inked, milled edged wheel, similar to those used for regular Morse printers. Beneath a certain signal level, its printing ability vanished and at this point the bearing null was indicated (as originated by the split beam operation). At the same time (secondly) the main forward antenna lobe was constantly reporting (transmitting) the corresponding Hell data. This data was sent to the lower printer section. The time interval left for an entire azimuth bearing to be taken, was between 3 and 5 seconds only.

From 1943 onwards, until the end of hostilities 2500 printer units FuG 120..., including variations were manufactured. Its average bearing accuracy was of the order of ± 0.5°.

The antenna arrays, together with all auxiliary apparatus, were mounted on a very heavy undercarriage, that moved (rotated) on a circular rail track. Its total weight was approx. up to 100 tons! This huge device rotated twice p/m. The rail track had a diameter of 19 m. To rotate a device of 100 tons, mounted on such a rail track, within 30 sec, is quite amazing. Additional information can be found in [3, p. 94 - 96] and [4, p. 83 - 87].

Finally, these Hell signals could, apparently, be activated by special command instructions, as well. This became of increasing importance after the Allies systematically jammed German ground to air communications. The very powerful 'Bernhardine' transmitters often helped to reduce the hampering effects of jamming.

Summary

Due to the number of subjects to be corralled, I have to make a very brief selection from amongst the many interesting topics. We have seen briefly, some aspects of radio aids to navigation as these were initiated, in Germany, during the first half of this century. The initial steps were taken by Scheller's invention employing interference between radiation patterns, which could create a virtual path (bordered by two complementary sectors of dots and dashes) allowing one to distinguish between left and/or right. In my opinion, this was of great significance because it paved the way for developments which have continued right up until today. ILS, was certainly based on some aspects of these early developments, initiated by the Lorenz company in 1907.

The main B.A. systems deployed in the world, were nearly all based on this Lorenz principle. It is apparent that, the fundamental idea of virtual path guiding, by keyed antenna diagrams, was due to be adopted for several other sorts of navigation applications.

In the 1930s, there was a growing support, by the aviation authorities all over world, to engender scientific research on B.A.. The latter system consist of two main system components: - firstly the guidance onto the axis of the landing strip and, secondly, the creation of a virtual glide path. Some comments on the latter subject we haven't discussed, but, according to Handel's paper [5, p. 4-21], several early B.A. glide path facilities were based upon the determination of a constant field strength, that had to be tracked during the approach procedure e.g. as initiated by the US Bureau of Air Commerce. This proved to be very difficult, due to a number of uncertainties such as the conductivity of the soil the condition of the local environment as well as the square function of the vertical radiation pattern. Subsequently, this idea was dropped. In France they followed a competitive route, which proved to be equally unsatisfactory.

It was Kramar who solved the glide path problems, in the early 1930s, by the integration of two marker beacons into the system, at 3000 m and 300 m ahead of the landing strip. These marked the two stages of the glide path procedure. Britain and the US, both adopted the Lorenz B.A. system, in the second half of the 1930s.

From May 1930, the Lorenz company was owned by ITT in the US. In my opinion this was quite significant because, as an US owned property, it could easily obtain access to their (local) market. Telefunken never became established in the avionic market although it built, in my opinion, the most sophisticated of devices. However for aviation equipment, it was almost completely overshadowed by the Lorenz company.

When the hostilities over Europe started in August 1939, the German Air Force had already adopted all sorts of guiding aids, based upon the Lorenz B.A. system. After France had surrendered, they deployed a virtual armada of guiding beams over the British Isles. Firstly, they introduced the X- beams, though, as we have noticed, these were not quite successful, due to their vulnerability to jamming signals. More notable was, perhaps, the Knickebein apparatus, but this 'X-Gerät' (and its derivates) still lacked real flexibility.

The introduction of the 'Y-beams', operating over Britain, set a technical land mark, because several entirely new system elements were employed. The introduction of dash - dash keying, in conjunction with the switching of the antenna patterns in a unconventional manner, was able to camouflage the intentions of and the recognition of such a virtual guiding path.

We have noticed that the symbol Y - was, nearly always, related to apparatus that enabled the measuring of distance between a ground station and a moving (or stationary) platform. It was based on Koulikoff's significant invention (recently I discovered, that he either must have withdrawn his patent, or that it might have been declared confidential, as no patent reference can be traced today), which has received very little recognition since.

The introduction of Sonne or Consol lasted for nearly four decades, as a navigational aid. It was used during the war by both the German Navy and Air Force. But, since more compatible aids (satellite navigation) became available, Consol were only used by relatively small ships.

Finally we have discussed two ingenious radio beacons. The very simple talking beacon 'Hermion' for coarse azimuth bearings and, the elaborate Bernhard and the later Bernhardine apparatus. The system parameters of the latter were quite sophisticated, and were widely used between 1943 and 1945 by the German Air Force.

It is nearly certain, although I can not prove it here, that several aspects of German technology were adopted by the Russians. Since the collapse of the Warsaw Pact in 1989/90, many artefacts, produced in the former Soviet Union, have become available on the market and it is apparent that many of these were influenced by German concepts. I was once able to look into a IL 66 cockpit and I was astonished that so many aviation instruments were similar in appearance to those used, by the Germans, in previous days. Also, I am certain that for nearly a decade after Germany had surrendered, France adopted several navigational aids of German origin.

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