Some hardly known aspects of the GHG, the U-boat's group listening apparatus

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Introduction

It is surprising that so little has been published in the last fifty years about sonar devices utilized by German U-boats, although sonar systems were of the utmost importance to them, as they were also for the Allies. Probably various forms of 'Secrecy Acts' and/or company policy requirements were the cause of the lack of the adequate post war publications.

This paper will briefly focus on some aspects of Germany's passive sonar developments, as far as the end of the hostilities of the past World War. (The 'Gruppenhorchgeräte' here after referred to as GHG or group listening apparatus, was not only utilized by submarines, but was fitted into all sorts of other vessels as well)

During this century there were, on the whole, great advances in technology between 1920 and 1945. Sophisticated technology is (nearly) never the result of one man's mind, but rather the culmination of sequences of scientific work, often from different disciplines, and the course of the sonar history is certainly no exception. Although most fundamental sonar inventions took place in the US and France, several important aspects were brought to maturity firstly in both Britain and Germany.

Some early retrospective aspects

The first scientific sonar research was undertaken in Switzerland in 1826, by Colladon and Sturm in the Lake of Geneva. Using an underwater bell, they observed how sound travelled, over a distance of 14 km, and computed a velocity of 1435 m/s.

Since the eighteen eighties, several western countries have been researching underwater acoustics in some way or another, but the signal losses between the membranes and the ears were a significant disadvantage, because the ears were the only available receiving devices. Therefore, relatively little practical progress could be made.

In 1902 Gray and Mundy designed, in the US, the first water tight underwater microphones, or hydrophones as these are called, which proved to be a revolutionary improvement. Initially, this was registered as patent No. DE162600, owned by the Submarine Signal Company, of Boston. The German company: 'Norddeutsche Maschinen- und Armaturenfabrik' of Bremen, obtained a licence, in 1905, to use the US patents and sold their products in Germany, Holland, Belgium and Russia, later on the market was to extended the monarchy of Austrian-Hungary and also the Scandinavian countries as well.

About 1908, the 'Kaiserliche Marine' (Navy of the Emperor or Imperial Navy) contacted the Neufeldt & Kuhnke company to ask if it were possible to construct a competitive underwater telegraphy apparatus, to counter the rather too expensive products of the Submarine Signal Company.

Hecht constructed a 'water siren' able to produce sufficient sound energy, equal to several hundred watts, at a frequency of 1000 Hz. In 1910 the torpedo research establishment of the German Navy, TVK (Torpedoversuchskommando) could, with such an apparatus, clearly receive underwater Morse signals, from a distance up to 100 km (approx. 54 nautical miles). This was, in those days, quite a sensation. (Rössler, 1991 9-12)
The 'Kaiserliche Marine', as well as its successor 'Kriegsmarine', called such devices
UT - Anlage = Underwater sound Telegraphy apparatus.

In 1912 British Intelligence informed the Admiralty about German U-boats fitted with underwater signalling apparatus, enabling them to communicate underwater in Morse Code. (Hackmann, 1984 45)

After the catastrophe of the Titanic on 15 th April 1912, there was a requirement for all kinds of listening and/or early warning apparatus. This was hampered by the lack, as yet, of adequate technology in the form of electronic receivers and amplifiers.
Hülsmeyer in Germany patented his 'Telemobiloskop' (D.R.P. 165546 and 169145, issued in 30.4.1904 and 11.11.1904). In 1904, he constructed the world's first, radar like, apparatus able to detect obstacles, by receiving the reflection of electro magnetic waves, from conducting objects. His 1904 demonstrations, held during a naval conference in the harbour of Rotterdam, could not induce the ship owners to equip their vessels with his newly invented early warning devices, although detection up to 3 km was clearly demonstrated. The step by step introduction of Marconi's Wireless systems, on board their ships, was already more or less budgeted for. No company was interested in Hülsmeyer's patents, not even Telefunken, so the world had to wait for more than thirty years before radar could be developed into a practical apparatus. (Trenkle, 1986 21-22)

Consequently, naval establishments all over the world were focusing, in the first place, on the use of sound for signalling, locating objects and, for measuring of distance.

The TVK discovered, in 1913, that the microphones (hydrophones) used for the UT-apparatus, could also intercept all sorts of sound and noise, such as that generated by power engines and caused by propellers. It soon became obvious that special microphones had to be designed because the standard types were only sensitive for frequencies of the order of 1000 Hz.
The German U-boat establishment VKU (Versuchskommando der U-Boote) started, in 1914, to research into the construction of new types of carbon microphones, but it took quite some time until adequate, depth charge proof, hydrophones became available.
Some boats were equipped soon after, on both starboard and port sides with two groups of six hydrophones. Each group was divided into three sections of two microphones, each section utilized one microphone most sensitive at 700 Hz and the second one peaked at a lower

frequency. By comparing the microphone (hydrophone) outputs, it became possible to discriminate the sound direction, ie coming from right or left, front or aft.
According to Hackmann, the German- and the Royal Navy as well, preferred the use of microphones (hydrophones) peaked on a particular frequency, whereas the US Navy preferred a non resonant microphone response, '*the latter had a longer range, but did not reproduce sounds so faithfully, which could cause identification problems'*. (Hackmann, 1984 56)
All systems were subject to interference by the noise generated by electrical generators and other rotating devices, inside the submarine. The first step taken by the Germans to reduce this noise used a variable resistor parallel to the earphone circuit, a crude but quite common method used, in those days, to quantify the strength of a wireless signal. A special
potentiometer was fitted with a 270 degree scale and was calibrated in ohms. The parallel resistance had to be reduced until the sound, in the headphone(s), had vanished. The signal strength was, for instance, considered as being 150 ohms. The value of the parallel resistance could indicate the increase or decrease of the sonic signal strength and allowed an
approximate distance estimation, as well.
To reduce the man made noise picked up by the hydrophones, 1050 Hz band pass filters were inserted between the microphones and the earphones circuits.
The next step was to increase the system sensitivity, by adapting the valve amplifier used for the wireless station. Ships could now be observed up to 20 - 25 nautical miles, but greater attention had to be given to the reduction of man-made noise, from inside the submarine so as not to negate the improvements.

A real improvement was the construction of the 'binaural sound phase compensation' apparatus, by v. Hornborstel and Wertheimer.

(Consider figure on the next page)

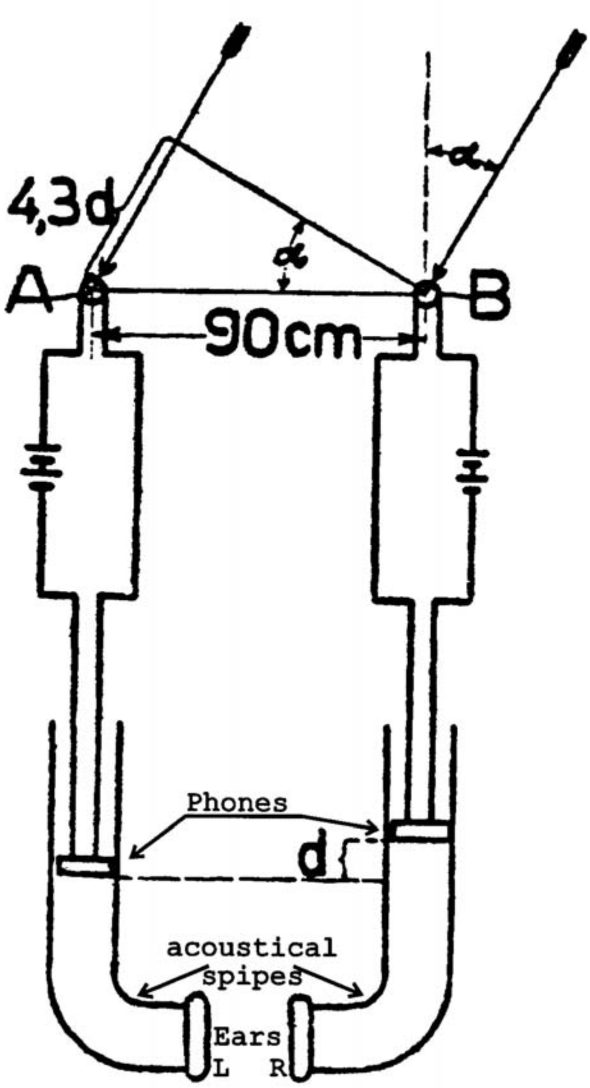

Figure. 1: Binaural sonic phase compensation

The principle of this device is quite easily understood, whereby the phase comparison took place, very effectively, in the operator's head. This kind of phase comparison system creates a stereophonic sound image in the brain and can be highly sensitive and effective.
The space between the two microphones (hydrophones) was, according to Rössler, approx. 4 times wider than between the output of the phones inside the air pipes between the ears, to keep the travelling time of sound, for both media, approximately equal. (the velocity of sound in free air, at 20° C, is approx. 344 m/s, and in seawater 1465 m/s (see after), hence resulting in a time ratio of approx. 1 : 4.25) It is evident that only one phone had to be adjusted.
This apparatus could be rotated on its base and made accurate sonic bearings more adequately than did previous systems. These devices were produced in 1918 and production continued until 1925, according to Rössler, at the Atlas Werke, the successor to the 'Norddeutsche Maschinen- und Armaturenfabrik'; the same company still formally holding the production licence of the

American: 'Submarine Signal Co.', during the entire WW I. (Rössler, 1991 14-17) Hence, artifacts of the latter company were used during the hostilities on either side of the North Sea as well.

Developments during the 'inter bellum'

To understand this complex subject, we first have to consider and define the sonic frequency and/or wave length relationship used by the German Navy, for passive sonar systems.

The typical velocity of sound waves, in seawater, can be quoted as 1465 m/s. The corresponding wave length is defined by: $\lambda = c/f$ (c is the velocity in a medium, f the frequency, λ the wave length) The audible sonic frequencies mostly used were approximately between: 100 Hz and 7000 Hz, equal to wave lengths between: 14,65 m and 21 cm.
It can be seen therefore that a hydrophone base will never, for the lowest frequencies, cover one full λ but, for the upper frequency spectrums, several wave lengths are covered. It is realistic to estimate that the spacing between the hydrophones was, for the upper frequency spectrums, often more than one wave length. For German underwater listening systems the wave length ratio to be handled was approx. 1 : 70.
Subsequently, much attention (see later) had to be focused on the appearance of unwelcome frequency (λ) dependent sidelobes. (Stenzel, 1929 175-179) (Stenzel, 1939, 34-37)

Sonic (sonar) technology improved radically after Brillié's publication (France 1922) and this has proved to be of significant importance, ever since. (Brillié, 1922 398)
Brillé placed, in the surface of a ship's prow, a group of 18 hydrophones and linked their membrane outputs, by acoustical pipes of equal length, onto a funnel. This funnel was constructed like a miniature projection of the ship's prow, so as to counter the velocity difference of sound waves, in sea water and in free air. (≈ 4.25: 1)
The observer, or operator, had to maximize the sound output, coming out of this funnel, by moving its open end in such a way that the angle (bearing) of the travelling sound waves, in both media, was equalized.
Perhaps not yet a practical apparatus, but it's fundamental significance was evident as it showed that sound waves, divided in to several elements, could be recombined effectively, when all the sound components were brought into a correct time and phase relation.

A significant improvement was F.A. Fischer's so called: 'Streifenkompensator' or strip line compensator, patented in Germany under No. 529 458 dated 22.11.1929. Though electrical delay lines were already quite common in those days, his invention was to link each delay line section onto a conducting strip line.
(cf one of Fischer's papers: '*Mitteilungen aus dem Laboratorium der Electroacoustic G.m.b.H*' of Kiel, thus he worked at the research centre of the Elac company. (Fischer, 1932, 147))

In Germany, according to Stenzel, these electrical phase or time delaying circuits were known as: 'Wagnerschen Siebketten' designed by K.W. Wagner. (Stenzel, 1929 174) However, according to

Hackmann and Holt, it was invented by Pierce at Harvard in the US. (Hackmann, 1984 191, 193) (Holt, 1947 680) and this was supported by Rössler. But, according to the latter, it was Pierce who first proposed to utilize electrical time delaying circuits for time compensating purposes. (Rössler, 1991 21)

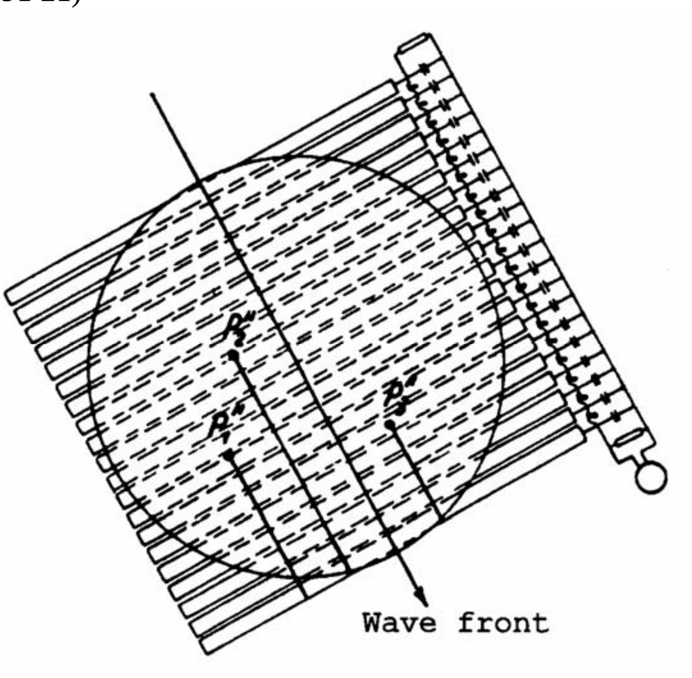

Fig. 2: The principle of Fischer’s strip-line-compensator

This illustration is very easy to understand, the output of the hydrophones was fed onto their corresponding rotor contacts and these contacts were, as in Brillié's invention, a scaled projection of the configuration of hydrophones (membranes) mounted in or on the boat's hull. Though, not visible, in Figure 2 the delay line was divided into 100- or sometimes even up to 160 strip line sections, in order to increase the system accuracy.
The reduction ratio is: c_k : c (c_k the signal velocity in the compensating delay line, c is the velocity of sound in seawater) The scaled ratio is not limited any more, as in Brillié's apparatus, to approx. 4.25 : 1, but is defined by the electrical value of the delay lines used. Hence, the reduction of the scaled ratio, allowed the use of an expanded hydrophone base, in conjunction with a more handsome compensator apparatus. Due to the limited space inside a submarine, this was a real necessity but, it still left a bulky device nonetheless.

The arrow in Figure 2 indicates the direction of the (eg sound or sonic) wave front and its delayed appearance at each membrane. It is obvious, that the membrane P_2 is reached first and the membrane P_3 will be touched last, by the advancing wave front. It can be seen therefore, that the longest time delay occurs with P_2, less with P_1 and least of all with P_3. The remaining delay line sections, up to the earphone circuit, cause no change of information at all.
Fischer's invention could, theoretically, be used for receiving and/or transmitting purposes as well. When, for instance, a generator source is connected in place of the earphones, the array will now radiate in the reverse direction.

The technological optimum was reached after the introduction of Carpentier's 'Cylindrical Compensator apparatus', patented in France. (No. 816 789 dated 20 April 1936) However, the description of this very complicated and outstanding device will be not be discussed in this paper.

Introduction, and some theoretical aspects, of the group array compensation
We will rely briefly on Stenzel's theoretical explanations, from his book *'Leitfaden zur Berechnung von Schallvorgängen*' published in 1939, as well as on his 1929 and 1950 papers. His 1939 publication was of significant importance and was reprinted in 1944, (including the original German copyright information!), as a facsimile: *'Published and distributed in the Public Interest by Authority of the Alien Property Custodian under License No. A-491'* , by: J.W. Edwards, Ann Arbor, Michigan, U.S.A.

Let us assume that a sound ray will points at a membrane (eg hydrophone) *F*, in the X-Y plane.

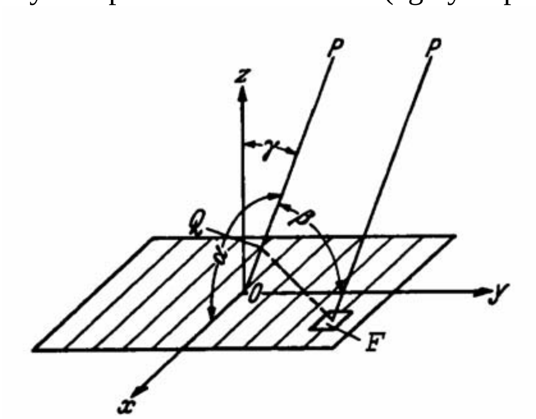

Fig. 3: Sound ray pointing at F

The angle α, β and γ represents the direction of the straight line pointing at *F*, for the coordinates x, y. Without entering into the proof, we consider for a single membrane, the directing factor is defined by $\Re = 1$, for the angle $\alpha = 90°$ and $\beta = 90°$. Firstly, this conclusion makes sense, because the optimal energy transfer takes place when a wave reaches the membrane parallel to the Z axis. Secondly, the directing (beaming) factor (Richtfaktor) contains no amplitude information. To simplify this explanation, we figure a = 1. ('a' is the amplitude)

We assume, the GHG, group listening array was symmetrically placed as in Figure 4 on a straight line at the abscissa Y. Although, in practice, the hydrophones were often placed on a, more or less, half open elliptic, or arc.
We presume all elements (membranes) will have equal sensitively (group array technology is, generally, theoretically valid for RF applications as well).

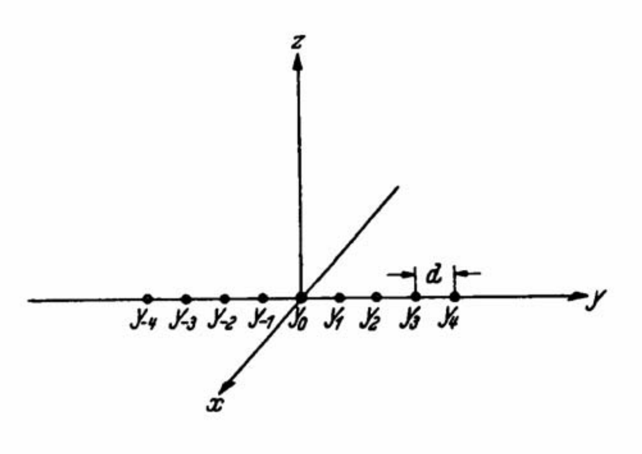

Fig. 4: Array of membranes, grouped on a straight line

The (uncompensated) aperture, is explained by the quotient of d/λ. ($\alpha = 90°$, $\beta = 90°$) The total length of an array, placed on a straight line, is defined by the product of: n.d. ('n' is the number of membranes)

According to Stenzel, it can be proved (Stenzel, 1939 7-15) that, for equal frequency as well as array (base) length, the radiation pattern gets sharper when $n_2 < n_1$. Hence, for a particular frequency, an array, utilizing less membranes, will display a smaller aperture, compared to the inverse situation.

Consider for example (see Fig 5), two different arrays operating at equal λ, but set up as follows:- system one, $n_1 = 18$, $d_1 = \lambda/6$ and for the second system, $n_2 = 3$, $d_2 = \lambda$. Because $n_1.d_1/\lambda_1 = n_2.d_2/\lambda_2 = 3$, both arrays will still retain equal aperture, nevertheless, the array length ratio is slimmed down to 17 : 12 (Stenzel, 1939 15).

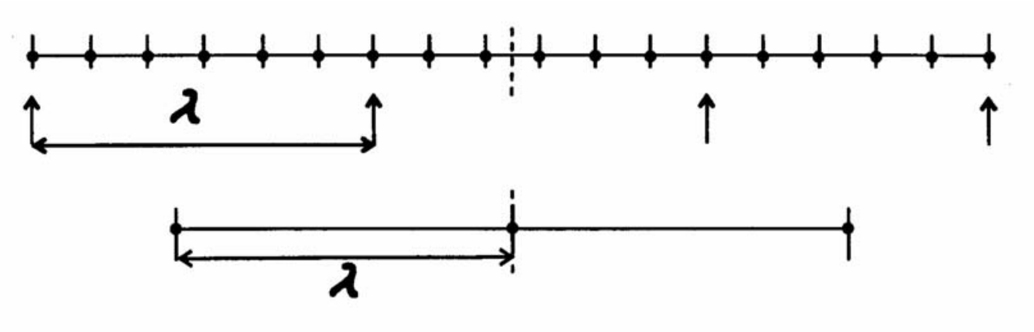

Fig. 5: Two arrays for n = 18 and n = 3, with equal aperture

On the other hand, the sensitivity parameters could be enhanced by increasing the numbers of hydrophones used. An impeding factor was, and perhaps still is, the relatively wide sonic frequency range over which operation takes place. The sonic (audible) frequencies used by the German Navy influenced the quotient of: n.d/λ and resulted in a change in aperture and overall radiation pattern, owing to the wave length ratio > 1 : 70.

To determine the bearing of a noise- or sonic source, we have to rotate the hydrophone array until the received signal reaches it's maximum value. When the array is integrated in or at the hull of a vessel, this is a quite impractical procedure.

Fischer's 'Streifenkompensator' or strip line compensator apparatus, could beat this technical challenge, but many problems still had to be taken into account.

Time delay circuits had to conduct, information electrically, without changing its contents, thus no aberration of the signal phase and/or its amplitude was permissable. To prevent signal loss in the compensator circuit, L and C's ladder networks, or low pass filters, were employed. The time

delay, for this type of configuration, is defined by:- $\tau = \sqrt{L.C}$, which holds true, as long as the frequency spectrum used is kept (significantly) below the maximum frequency, defined by:

$f_{max.} = (\pi\sqrt{L.C})^{-1}$. (L self inductance in Henries, C capacitance in Farads)

The German Navy standardized the time delay, for most of their GHG apparatus, at 17 μs per compensator section or segment, equal to 2.5 cm sonic wave displacement in sea water. Subsequently, this figure had to be multiplied by the numbers of compensator strip lines utilized. When hundred strips were utilized, we got a maximum of: 100 x 2.5 cm = 2.5 m base length. (or 160 x 2,5 = 4 m) (After 1943, an improved compensator type, utilizing only 40 strip lines, came into production, to equip the type XXI U-boat, thus economizing and restricting the application of raw materials.) (Rössler, 1991 53-54)
We cannot accurately calculate the dimensions of the employed arrays, because the mounting of the hydrophones was determined by the specific construction details of the surface of the boat's hull, as well as its main construction. (see later)

Beaming towards a sonic signal
The beaming factor, of a hydrophone (microphone) array, is defined by $\Re$, and when compensation is employed by $\Re_k$. (Stenzel 1939, 32-33)
We assume, at a X-Y plane, as in Figure 2, three membranes are projected at its coordinates: (x_1 , y_1), (x_2 , y_2), (x_3 , y_3). (To simplify this explanation, we will assume the use of three membranes only) The natural beaming factor is obtained from the equation

$$\Re = \frac{1}{3}\sum_{n=1}^{3} e^{ik(x_n \cos\alpha + y_n \cos\beta)} \qquad (1)$$

α and β, represent the angles used in Figure 3. The equation from the resulting artificial beaming factor $\Re_k$ and its corresponding optimal bearing, at a compensated plane, is determined by φ and ψ is (see Fig 6)

$$\Re_k = \frac{1}{3}\sum_{n=1}^{3} e^{ik[x_n(\cos\alpha - \cos\varphi) + y_n(\cos\beta - \cos\psi)]} \quad (2)$$

If we rotate the (scaled) array projection (c_k), (see below in Figure 6) at its centre 0, the signal amplitude reaches its maximum value, when the bearing of the arriving (sound) wave front and that of the compensator are becoming more or less equal.

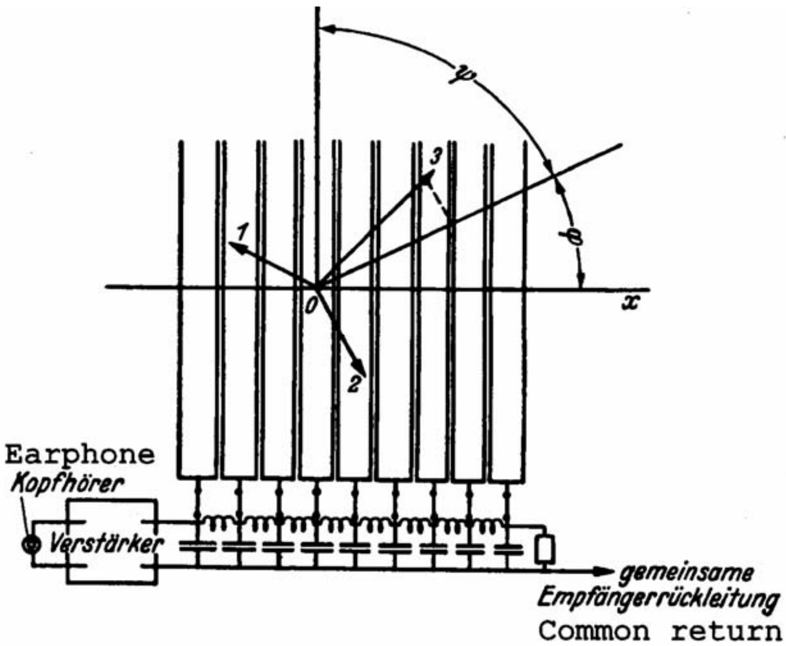

Fig. 6: Compensator, utilizing the scaled projection of three membranes (1,2,3)

The centre 0, permits a sovereign rotation of both systems, see also Figure 2, the projection points 1, 2, and 3, are synonymous to P_1 - P_3.
It doesn't matter which system is rotated, both result in an optimal magnitude of $\Re_k$, when the artificial compensated bearing is pointing at the arriving sound wave. (Stenzel, 1939 31-33)
Practically, the strip lines, mounted inside the GHG compensator housing, will be maintained, on board ships, in a horizontal position between port and starboard. The delay line represents the axis of the GHG hydrophone base and represents logically the central axis of the vessel as well. (between F = Forward and A = Aft, see also Figure 6 and Fig 11)

Finally, we take a brief look at some disturbing aspects of the radiation patterns of an array. The beaming factor (Richtfaktor) $\Re$ is, for a certain uncompensated array, always constant because no outside electrical change, of the system parameters, can occur.

However, the circumstances are totally different, when a compensated array is being utilized, the resulting aperture, and so its beaming factor, are considerably dependant on the approaching angle of the arriving sound (sonic) wave.

$$\Re_k = \frac{\sin\left[\frac{n\pi d}{\lambda}(\sin\gamma - \sin\gamma_0)\right]}{n\sin\left[\frac{\pi d}{\lambda}(\sin\gamma - \sin\gamma_0)\right]} \tag{3}$$

γ_0 is representing the direction (bearing) of the compensation plane, for maximum signal strength. (see Fig 3 and Fig 4)
Figure 7 displays the computed radiation patterns, for a straight line array as in Figure 4, when: n = 6, d = $\lambda/2$ for: 1.γ_0= 0°, 2. γ_0=45°, 3. γ_0 =60° and 4. γ_0=90°.

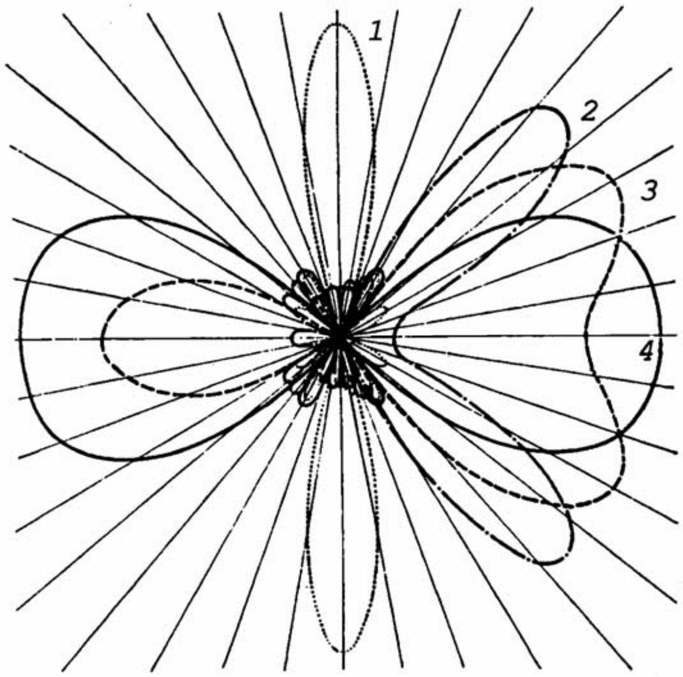

Fig. 7: Radiation patterns of a compensated array, on a straight line, for n = 6

It is apparent that for γ_0= 0° and γ_0=45° the aperture of this array is still an adequate match, but it is widening its aperture significantly for the plots 3 and 4 and this also results in an aberration of the radiation symmetry.

It becomes obvious that no reliable bearing can be obtained when sonic (sound) waves are approaching from angles tending more and more towards the Y axis. (Fig 4)
Around the centre of this graph we can recognize clearly the existence of many uncontrollable sidelobes. Although we will see later that, by suppressing the lower frequency spectra and utilizing the smaller wave lengths of the spectra, the bearing accuracy can be significantly improved.

Some aspects of Germany's wartime sonar developments

By the end of thirties, German passive sonar technology was maturing. If we consider, that more than eleven hundred submarines were built during WW II, it's impossible to cover in this paper, all the GHG related devices that had been deployed, during this dark episode. Let us consider briefly, two passive sonar devices firstly, the extensively used 2 x 24 GHG or group listening apparatus and secondly, the improved 'Balkon' or Balcony apparatus, introduced in 1943/44.

The sensitivity of passive sonar systems were (are?) primarily limited by the parameters of the hydrophones used. The German Navy were utilizing Rochelle (salt) crystals ($K\ Na\ C_4\ N_4\ O_6$) (known as Seignette-Kristall, in Germany), based on the 'piezoelectrical effect'. Most German listening devices employed broad band Rochelle crystal hydrophones, but several sophisticated sonar sets were utilizing magnetostriction transducers too. (Hackmann, 1984 295)

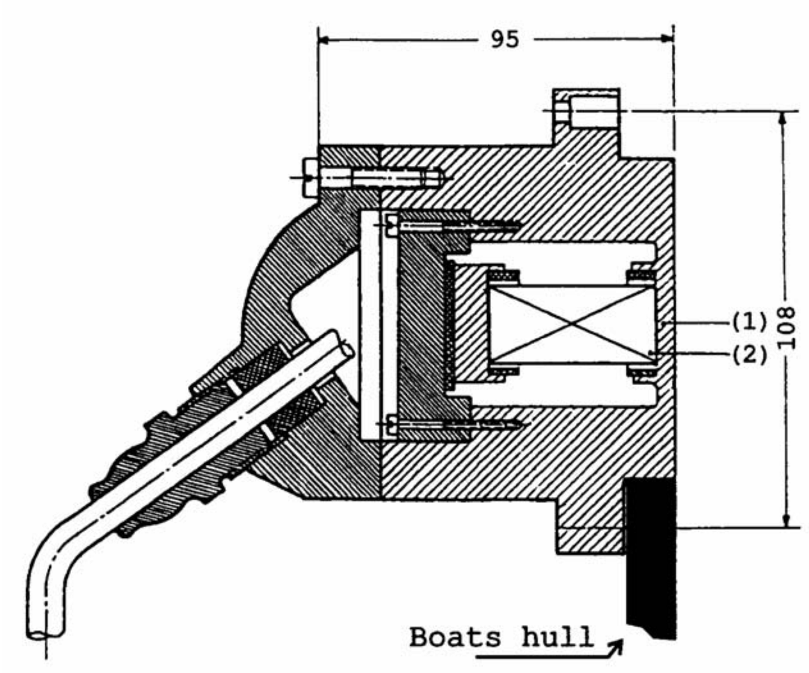

Figure 8: Cross-section of a GHG hydrophone, (1) = membrane, (2) = crystal block (Elac)

This s figure shows an exposed view of the cross section of a hydrophone produced by the Elac company, the Rochelle crystal blocks (2) were build in multi layer stages and touched the membrane (1) at its rectangular side.

The signal outputs of the hydrophone groups were, for either starboard and port, linked onto twenty four pre-amplifiers. The hydrophones manufactured by the Elac company supplied more signal output, compared to competitive types, such as those produced by the Atlas company. These were loaded by a special transformer, I suppose to increase the common mode rejection, so as to avoid any sorts of hum. (see below Fig 11)

Hydrophones are very sensitive and are easily subject to interfering sound from both inside (eg by: man made noise, powering, generators etc.) and outside exterior of the vessel.
External sources of interference, could include propeller, cavitation, and water flow obstruction noise and these noises had to be strictly avoided. There is thus a need for meticulous system design.
After due consideration of all facts, some few mounting sites were left available, the difficulty being to fit the hydrophone arrays at the most favourable location, yet integrated with the hull and the submarine structure.

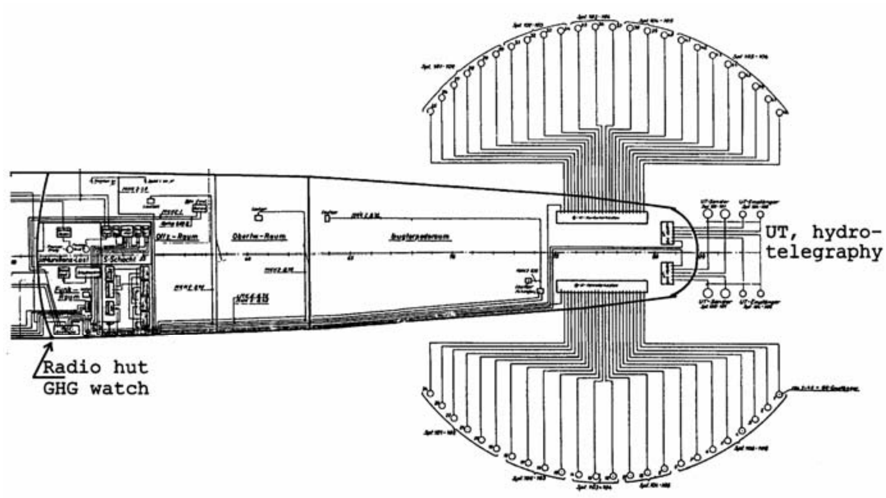

Fig 9: Schematic wiring of the GHG system

This figure displays the wiring of a GHG group listening apparatus and is fairly self explanatory. The UT transducers (underwater telegraphy) are visible on the right, but this device was rarely used, to avoid proving sonic signals for other vessels to lock on to!

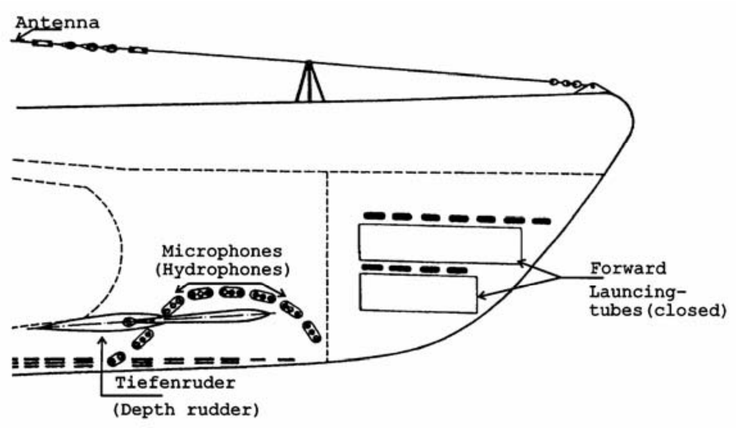

Figure 10: The place of integration of the 24 starboard hydrophones into the boat's hull (Type IX-C)

This figure shows the location with respect to the boat's hull and, an interesting detail is that the hydrophones were, as for this IX-C type, sometimes utilized in groups of three, but many other varieties placement were also employed.

Theoretically, the optimal curve on which the hydrophones had to be placed was a down wards open half arc, but this curve was often distorted due to the constraints from the construction limitations of the boat's frame.

It is interesting to note that the sonar equipment used for the movie 'Das Boot', displayed during thrilling scenes, for instance, when the submarine had to wait carefully for propeller noise (caused by hunting British destroyers) incorporated a *'contradictio in terminis'*. The attendant operator was sitting in front of a, more or less, authentic GHG compensator apparatus but, the displayed hydrophone device was a fake and was not in keeping with the GHG system used. Although more or less interchangeable with the 'KDB' (Kristall-Drehbasis), a rotatable hydrophone device was used here to give greater effect and audience awareness!

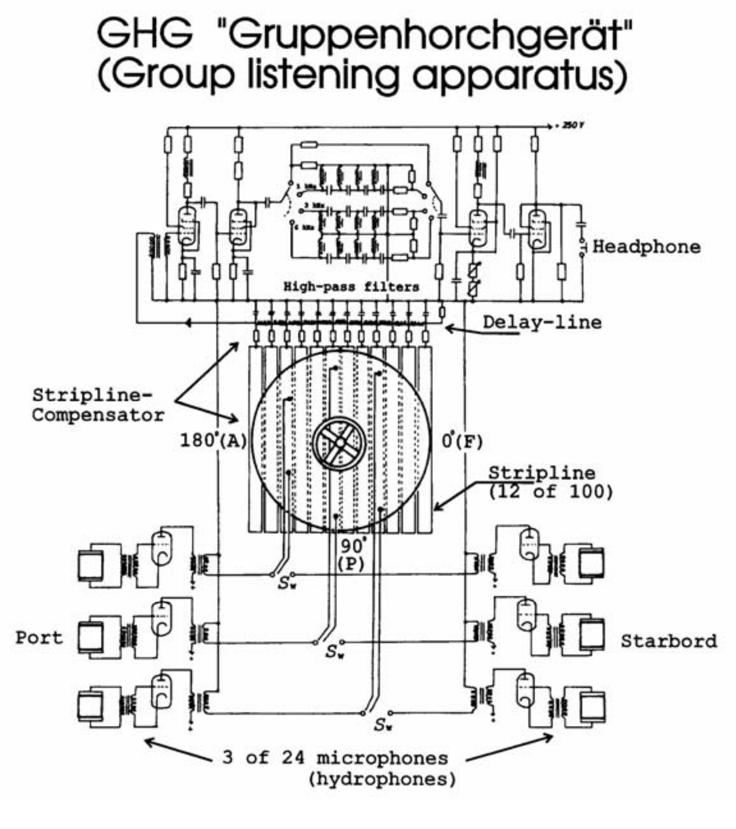

Figure 11: Schematic diagram of a standard GHG equipment

The schematic diagram is simple to understand and, we do not need to be experts to recognize this device as that produced by the Atlas company, due to the separate (loading) transformers used between the hydrophones and their associated pre-amps.

The pre-amplified sonic signals were, for all types, asymmetrically fed to the compensator unit, the unit housing being used as a common current return. This was due to the typical German application of die-casting, causing no problems at all. (Bauer, 1995 76-78)
The switch S_w changed its position at F (front) = 0° and A(aft) = 180°, to discriminate between the sonic bearings, approaching from starboard and/or port. According to F. Deters (June 1996), a former GHG operator, it was (also) possible to select manually which hydrophone group (starboard or port) was to be operated.

At the top of Figure 11 we have an outline of the four stage LF (audio) amplifier, designed for a maximum frequency response of approx. 7 kHz. It was possible to select the most effective high pass filter, at 1 kHz, 3 kHz or 6 kHz. Fritz Deters told me that 3 kHz or 6 kHz were the most frequent selections.

The British carefully investigated the capabilities of the GHG (Elac) apparatus in the captured U-570, in May 1942.
On successive selections of the high pass filters it was found that on the 6 kHz high pass-filter (utilizing the sonic spectrum between 6 kHz - 7 kHz), the bearing proved to have an accuracy of $\leq$ 1°, for 3 kHz (utilizing the spectrum between 3 kHz - 7 kHz) the accuracy was $\approx$ 1.5°, and for 1 kHz (utilizing the spectrum between 1 kHz - 7 kHz) the accuracy was $\approx$ 4°, at 500 Hz, thus bypassing the high pass filters, the accuracy was decreased to $\approx$ 8°.
Average merchant ships, cruising at 12-13 knots, produced a maximum sonic spectrum at $\approx$ 100 Hz and only 10% at 4 kHz. For destroyers cruising at 15 knots, the maximum sonic spectrum was at $\approx$ 200 Hz, but still supplying 30% of its harmonic spectrum between, 4 kHz and 8 kHz.
Thus the proportion of sonic signal level left at the higher harmonics, had to be compensated for by increasing the amplification gain.

It has been shown that the aperture is dependent on the quotient of $n.d/\lambda$ and increases for decreasing wave length but, at the same time, there is also an uncontrollable increase in size of sidelobes. (see Fig 7) (Stenzel, 1929 175-180) (Stenzel, 1939 33-51)

Thus it is evident that, careful attention had to be given to all of these confusing aspects.

The Germans generally utilized headphones, for communication purposes, with an optimal response at approx. 900 Hz. It's quite obvious that this type of listening gear is most unsuitable for wide band sonar observations and a special electro dynamic type (TAG) was introduced for this purpose. (F. Deters, May 1996)

The Balcony apparatus
We have learned that noise interference, from both inside and outside the submarine was, and today still is, a limiting factor in the use of listening systems. (Herkovitz, 1996 38-40) It became possible to counter this by reducing the speed to 'Schleichfahrt' or slink speed. The electrically powered underwater boats had to reduce their speed to a few knots only (< 3 knots). If they were submerged and powered by a Diesel engine, in combination with a 'Schnorkel', the engine(s) had to be completely switched off. Because the standard GHG system proved unable to receive sonic

information adequately, when the submarine was sailing submerged (because of the use of the schnorkel the U-boat had to steer just under the interfering water surface). To improve the interception of sonar, the boat had to steer at a minimal depth of 20 m, disregarding the use of a periscope.

It was obvious that this sort of problem introduced limitations and had to be surmounted.

At Maass's proposal, a group of hydrophones were integrated into a newly constructed hull, placed in front of the lumber keel. This modification was successfully tested in U-194 in February 1943. One of the improvements was the Balcony hydrophones were maintained at a 2.5 m lower level and thus were less vulnerable to many sorts of hampering interference.

According to Rössler, the aperture tended 60° upwards to the horizontal plane, but, in my opinion, it had to be a bit less. (Rössler, 1991 43-45)

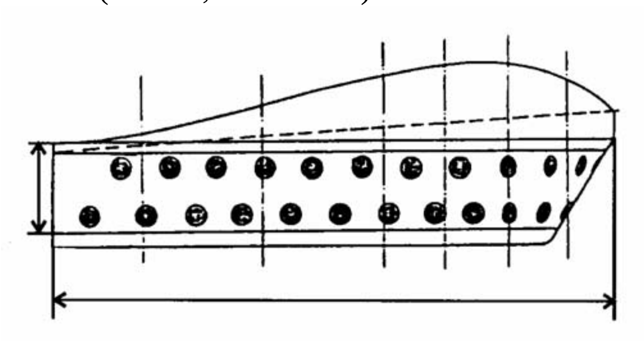

Figure 12: Balcony (Balkon) hydrophones mounted inside a special hull, in front of the keel (Type IX-C)

This new style of positioning considerably increased the forward looking capabilities of a GHG system, although, it still left a blind gap aft, between 150° and 210°.
The introduction of the Balcony apparatus brought an improvement of the interception range, compared to the near front placed GHG hydrophones, of approximately 70%. (see Fig 9)

(Consider the drawing on the next page)

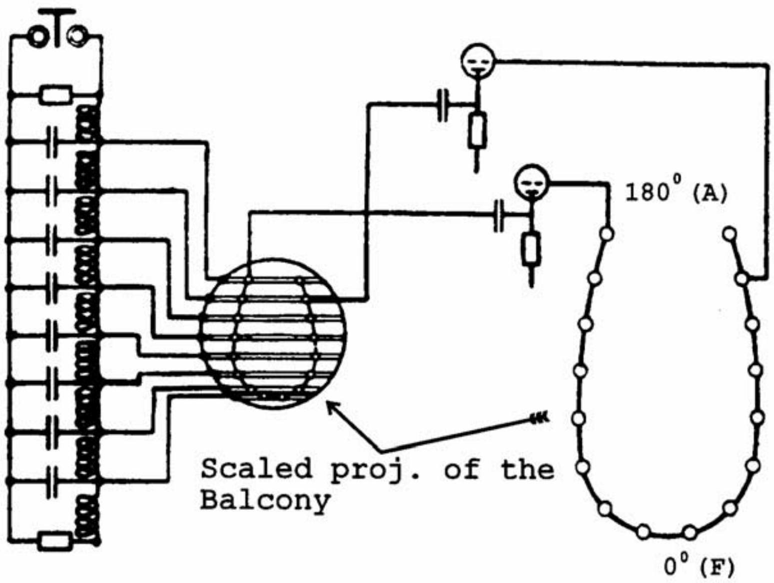

Fig. 13: Principle of the balcony GHG apparatus

This figure displays the principle of the balcony compensator apparatus. It's obvious that the indispensable group selector switch (S_w in Fig 11) had been left out here (without this device this apparatus, probably, never could have worked adequately). Although this switch did not necessarily have to be inserted into the circuit, when front bearings only were obtained, I suppose it could nonetheless, have been utilized occasionally even then. But when, for instance, bearings from > 90° or <270° were to be distinguished, a splitting of the hydrophone group, into two sections, had to occur to elucidate as to which side a particular sonic signal was originating. As it was possible that sonic signals were arriving from port and from starboard at the same moment, it would be sensible for the hydrophone array to be split permanently into two, independent sections.

Conclusion

There can be no doubt that passive sonar systems were, and still are today, of utmost importance, for submarines, to sense the presence of (and to locate) other vessels and floating objects.

Since the early days of this century, it became obvious that greater attention had to be given to noise source detection as a tactical weapon.

Initially of course, for detecting the noise caused by the engines of all sorts of vessels. It is astonishing that so little attention had been given to the reduction of these betraying sound sources. Of course, submarines became very much the exception here!

In 1913 the German Navy started, for the first time, utilizing hydrophones for passive sonar purposes, as several new techniques were invented and came into general practice. But still, for nearly a decade, the hydrophone carrier, whatever device this was, had to be rotated to determine the bearing. This made target tracking (sometimes) a quite difficult job.

It was Brillié's merit to invent a sonic compensator and he proved here that acoustic signals could be determined and fully reconstructed afterwards. Although Brillié's paper was of a more practical nature, it nevertheless triggered future research projects.
Amongst the great names, working on acoustics research were:- Fischer, Lamb, Mason, Rayleigh, Stenzel and Bouwkamp. They all paved the way for the sonic (sonar) research during the '*inter bellum'* and ever since.

Most German papers often mixed up the theory for RF- and acoustical group radiators, because their theoretical backgrounds were quite similar.
In Germany, it were primarily Fischer and Stenzel who pointed the way to the future of sonar and / or acoustical technology, although, many others were involved too.

Of great importance was the guidance and cooperation between the German Naval research establishment(s) and the German sonar industrial complex.

In 1929, Fischer connected conductible strip lines onto each section of the time delaying (compensating) ladder network, hence making it possible to obtain accurate electrical bearings from the arriving sound waves.

The German Navy mainly relied on Rochelle (Seignette) crystals, to be used for the hydrophone purposes, although more efficient materials were already known to science. Nevertheless, whatever their motivations were, this material worked quite efficiently.

Many different models (types) have been brought into service since, but the 2 x 24 GHG proved to be the backbone of all systems. The introduction, after 1943, of the improved 'Balcony' apparatus was still based on the same principles, thus this latter apparatus was effectively a modification of the former type.

Although several German manufacturers were involved into the sonar industry with their own particular apparatus design, many system components (modules) were interchangeable due to standardisation of electrical and mechanical parameters (where possible).

We have learned of the ease of determining the direction of sonic waves but, these passive sonar developments (nearly) only occurred in Germany and, rather surprisingly not in Britain, where they were usually very keen to pursue enemy beating technologies!
Despite being informed in May 1942 of U-570's outstanding GHG technology the British took no real action. Considering that the U-boat was captured in the summer of 1941, it took nearly a year before they got down to examining the GHG equipment. This typical (perhaps reluctant) attitude can be put down, in my opinion, to two major reasons:-
Firstly, the Royal Navy was concerned mainly with offensive tactics, and so was relying mostly on Asdic.
Secondly, perhaps due to the lack of vision as well as absence of support from higher authority?
We only have to compare the inverse situation, like the forward thinking concerning the implementation of Radar (RDF), into their defence strategy.

The US Navy did not introduce their outstanding sonic listening gear until 1944, although listening devices were certainly already widely used before that. (Holt, 1947 678- 679)

We have noted the abilities of U-570's GHG group listening apparatus (there were many other GHG systems utilized as well), and this also been acknowledged in a number of post war publications eg According to Hackmann: *'The GHG was undoubtedly the most important German contribution to sonar development. The German Navy relied heavily on passive sonar sets during the war, ...'* (Hackmann, 1984 295) and, according to Holt, *'The Allies probably did not realize how efficient the German listening equipment was until the summer of 1941 when the U-570 was captured by the British. They then discovered that German submarines were provided with arrays of 24 3-inch crystal microphones on each bow. .... the Germans gave their naval vessels a passive listening ability which may perhaps have surpassed that possessed by the ships of any other country'.* (Holt, 1947 678, 681)

Acknowledgement

Without several key publications, this paper could not have been written. In particular, these were:- Hackmann Willem, *Seek & Strike* and Rössler Eberhard, *Die Sonaranlagen der deutschen U-Boote.*
Of similar importance was Heinrich Stenzel's publication reprinted in the US in 1944, *Leitfaden zur Berechnung von Schallvorgangen*, as well as his papers which appeared in several German scientific magazines. (see references)
It proved to be quite difficult to get much information from former GHG operators, I suppose 'fading memories' would be one of the causes. Of great support proved to be Fritz Deters's memory and, through him it became possible to get information about his daily operational practice, whilst he was on service. He worked a while at the Atlas factory in Bremen too and, due to his special feeling for electronics, he had a clearer picture of what it was all about.

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