Centre for German Communication and related technology

NAXOS, THE HISTORY OF A GERMAN MOBILE RADAR DIRECTION FINDER 1943-1945

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Introduction

In spite of the fact that after 1942 the Second World War became more and more unsatisfactory for Germany, interesting projects were still being initiated. One of these was a device with the code-name Naxos. Although meant as a mobile receiver for detecting enemy radars, the German Navy and Air Force actually used it also as an Early Warning device. It was often the only set that could detect the enemy early on.

Naxos could determine the direction from which transmissions of a 9 cm radar came e.g. from a H2S set on board allied bombers, although no distance information could be obtained. Because the narrow rotating radar beam illuminated the Naxos antenna for very short periods, this antenna was made to rotate at a high speed of ≈1,300 revolutions per minute (≈22 Hz). The bearing of the received radar signals was indicated on a c.r.t.

General

Almost all countries involved in World War II knew some form of radar and as this is a general term we will use the word *radar* in this article, though the Germans called it *Funkmessgerät* (Radio measuring set).

Before high power centimetre radar was introduced, performance of sets did not differ very much from country to country. Development of Chain Home in Great Britain started on a much lower frequency than was customary in Germany. The lack of transmitting valves, for high power on VHF and higher frequencies, may well have been the reason for this. The German radar sets Freya, Seetakt and the very well known Würzburg used frequencies of 125, 385 and 560 MHz respectively. The *Luftwaffe* made a lot of use of Freya and Würzburg. Freya first detected a target, measuring bearing and distance and then it was handed over to Würzburg, often used for GL (Gun Laying), Because of this it was the most dangerous radar for allied aircraft. Via a kind of analog computer; elevation, azimuth and distance were passed via a Kommandogerät (Predictor) to the *Flak* (Anti Aircraft guns) with great accuracy. The typical system error of the Würzburg radar, Fu MG 62 D, was: ≈ 30-40 m. [1], [2 page 293]

Already in 1941 the British started to investigate Würzburg. Dr. R.V. Jones was deeply involved in this investigation. After having been postponed several times the well known Bruneval raid was undertaken on 28th February 1942, a Würzburg type A (first generation) radar was captured and the main parts (but not the display unit) and a German radar operator were taken back to England. The report on the investigation shows that quite a bit of its functioning was not understood. The captured parts were already obsolete in 1942. They dated back to the first generation of Würzburg from about 1940. The investigators supposed this already, as their report shows. [3], [4]

The German army was shocked by the raid. To avoid further danger several emergency measures, for all radar systems, were taken under the so called *Wismar Aktion*: making the working frequencies variable. The problem here was the much too rigid frequency planning of the Germans, due to the systematic and rigid fixation on: one spot frequency, for every type of radar system. Among others, Dr. R.V. Jones was impressed by the frequency stability of the German radars. The reason for this lay in the German nature viz. to build everything very stable and of very high quality. In the design of Würzburg therefore every possible cause of frequency variation had been eliminated. [1]

Figure 1: A beautiful example of the first local oscillator of the early Würzburg radar types. Notice its ceramic structure.

After the Bruneval raid the British also realized how much this German tendency to thoroughness was a factor in their favour.

Development of radar in Germany

In most countries development of what later was to be called "Radar" started about 1933-1935 and relatively short waves for that time were often used. The German firm Pintsch had already experimented on a wavelength of 13.5 cm. It was realized that such short waves made beaming the signal easier and more effective. Radio valves formed the crucial problem. Magnetrons (not the cavity type) existed already, but were unstable and produced un-sufficient power.

Boot and Randall in England in 1940 developed the first high power magnetron that made radar on 9.8 cm feasible. Because the pulse power was so high a radar receiver with relatively poor sensitivity could be used.

As the burden of war became ever heavier Germany started rationalizing. A *"Führer Befehl"* was issued, which decreed that every project, not guaranteed to be ready for the front within six months, had to be abolished. Dr. Runge, head of radar development at Telefunken, saw no use for centimetre waves in radar, as objects would reflect the narrow beam of radio waves like a mirror would; the reflected energy would also be a narrow beam and the amount energy coming back in the direction of the radar set was considered to be too small to be useful. So the decision to terminate development of centimetre radar was easily taken.

At the end of November 1942 both, the *DMW* (***D**ezi-**m**eter**w**ellen*, UHF) and the *CMW* (**C***enti**m**eter**w**ellen,* SHF) laboratories were closed. General Martini tried to get the labs reopened, but the *Reichs Luftfahrt Ministerium (RLM,* Ministry of Aviation) persisted and decided on 15th January 1943 that the decision was irrevocable.

Then the unforeseen happened, 3rd February 1943 a British Stirling bomber crashed south of Rotterdam (near Hardinxveld-Giesendam) in the Netherlands. On board was, according to Brandt [5], a H2S 9 cm radar, serial number 6.

The *Rotterdam Gerät* (Rotterdam set, as the Germans called this captured H2S radar set) caused all decisions regarding the termination of centimetre radar development to be cancelled. Already on 22nd February 1943, less than three weeks after the bomber crashed, the so called *Arbeitsgemeinschaft Rotterdam (AGR)* (Rotterdam working group) held its first session, the chairman was Dr. Brandt and the AGR committee were given full powers. [6], [7]

It was customary with the German Army to use the name of the place where an important object was found as code-name.

Thus the race against time could began. As a whole new territory had to be explored, activities on different fields were organized simultaneously:

1. Investigation of the *Rotterdam Gerät* (apparatus), in order to start up, as quickly as possible, the development of a German 9 cm radar system. (code-name Berlin)

2. Development of a Warning cum Homing receiver, with facility for automatic all around direction finding (code-name Naxos).

3. Development of a, shore based, superheterodyne SHF receiver (code-name Korfu and Kornax, *the last is a combination of: Korfu and Naxos*). (Blaupunkt)

4. Research on and construction of a German Cavity magnetron (LMS 10), SHF coaxial cable, special c.r.t. technology, etc.

5. Co-operation and integration of Germany's; industry, universities, as well as military organisations, to start-up, radar related, research projects.

One of the leading firms in the field of electronics in Germany - Telefunken - was put in charge as the main contractor.

Why the code name Naxos was chosen is not clear. Already 735 years B.C. on the East coast of Sicily a colony called "Naxos" existed. Also in the Aegean Sea there is a Grecian island called "Naxia", earlier "Naxos", "Strongyle" or "Dia". It was dedicated to the Grecian God Dionysos. Figure 2 shows that the Naxos antenna apparatus has a round shape (Dia). [8]

The Germans used names of islands when radar search receivers were concerned (Naxos, Korfu, Samos, Fanö, Zypern, etc.). Radar sets were often designated after towns (Würzburg, Mannheim, Berlin, etc.).

In order to avoid confusion, we will limit ourselves mainly to the development of *Anlage Naxos* (Equipment Naxos).

Figure 2: The shape of the Naxos antenna-arrangement is clearly visible. (Navy type ZM 290M, with its Perspex radome being removed)

Direction Finder Naxos

Fig. 3 shows the block diagram of the Naxos system. The main problem in developing centimetre wave equipment is that the extremely high frequencies prevent the use of standard receiving techniques. Adjustments to the radar transmitter can easily result in large frequency shifts causing loss of signal in a selective receiver or not receiving the signal in the first place. Sheer necessity or rationalization may have been the reason that for NAXOS a; wide-band, passive and un-tuned, receiver was chosen. The detector is directly connected to the antenna output. The first SHF detector diodes probably were not of very high quality, but this caused no problems, as the high power of the radar transmitters produced a respectable signal at the detector anyway. The output of this detector contained a strong component at the pulse repetition (recurrence) frequency (PRF) of the radar, received by the Naxos receiver. This component in turn was modulated by (fluctuated in turn with) 22 Hz, caused by the rotation frequency of the antenna, due to the ≈1,300 revolutions per minute. (according to [9 page 7] up to 2000 revolutions, ≈ 33 Hz). The antenna had to rotate so quickly as to ensure that several radar impulses, from the also rotating H2S antenna, were always picked up. The signal from the antenna was passed to the receiver first via the coaxial motor shaft and a capacitance coupler to the detector.

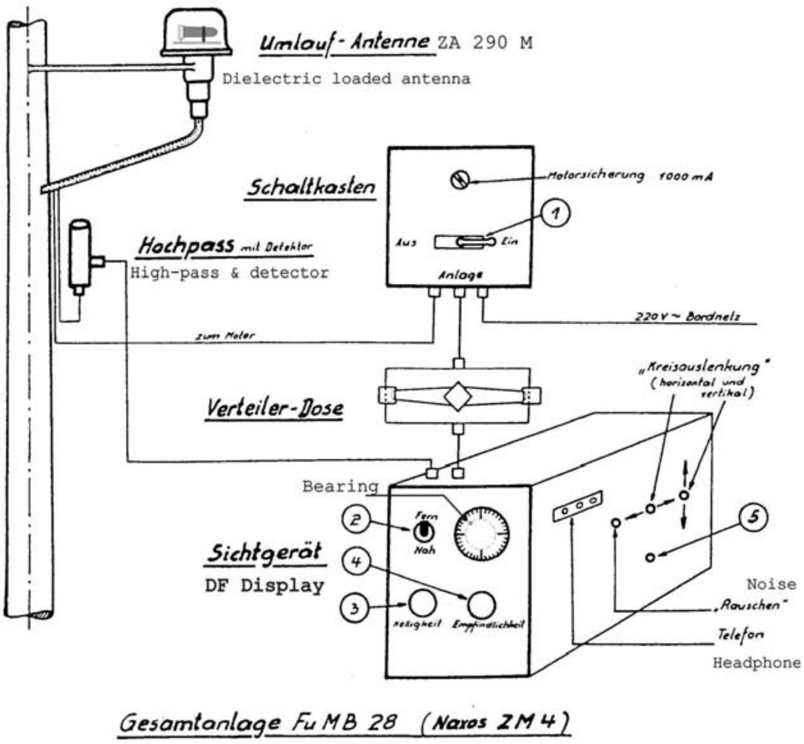

Figure 3: The Navy version of the Naxos DF system

The first model of the detector contained a high pass filter between antenna and detector, to eliminate all interference fed to it. Later it was found that omitting the filter increased the detector output voltage. The detector was followed by a, low frequency, amplifier with a gain of about 120 dB (10^6), and a frequency response that was optimized for the PRF's of the radars to be observed. The output of the amplifier directly controlled the cathode ray tube, causing either a radial deflection of the spot in the early models (fig.4 left) and after by different kinds of z-modulation (fig.4 right).

The spot traced a circle on the screen of a c.r.t., in step with the rotation of the antenna. To achieve this, a two-phase a.c. generator was coupled to the antenna shaft. The two voltages produced differed 90 degrees in phase and were directly fed to the X- and Y- deflection plates. (c.r.t. DG 7-2 Philips) (the earlier versions used a circular magnetic deflection. (c.r.t. LB 2 Telefunken)

The first experimental Naxos-Z flight took place on 11th September '43. According to Sir Bernard Lovell; the British intelligence "*obtained overwhelming evidence that the Germans were plotting it (H2S transmissions) (they had started as early as (28th November 1943), and were in fact equipping their fighters with a receiver code-named 'Naxos' to home on to the transmissions not only from H2S but also on the kindred equipment fitted to our bombers.......*". [7 page 175], [10 page 233]

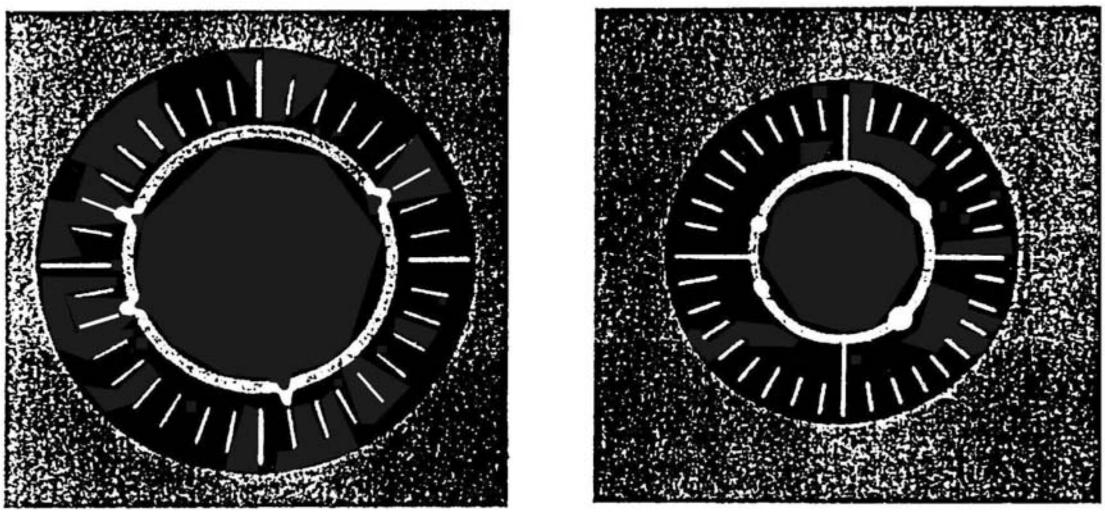

Fig 4: Naxos c.r.t. display, showing four radar signals being received from different bearings. The display at the left is of the first apparatus generation, at the right its successor.

The NAXOS Antenna

The antenna is of a very advanced design for its time, using dielectric loaded radiators. A general view of this antenna system is given in figure 2. The arrangement mounting of the two dielectric loaded radiators (also known as polyrods) are fed in phase.

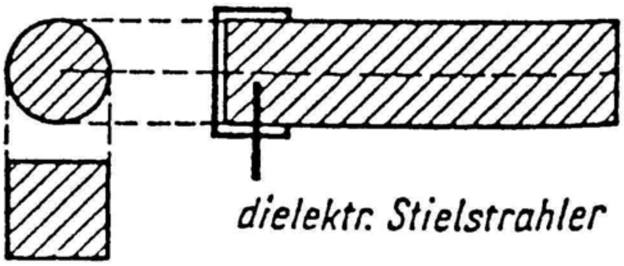

Figure 5: Priciple of the dielectric loaded antenna (polyrod radiator)

P. Mallach's first experiments, theoretical as well as empirical, with dielectric loaded radiators, were undertaken at the Heinrich Hertz Institution of Berlin, around 1939. Although earlier scientific work, at the beginning of the past century, contributed to the research in this field. Famous names like: D. Hondros and P. Debeye, had already published a paper in 1910 called: “Elektromagnetische Wellen an dielektrische Drähten”. (translated: electro magnetic waves by dielectric wires) [11], [12 Mallach page 33-39] With the exception of a lecture held in March 1943, no post war publication on the subject appeared before 1947, G.E. Mueller and W.A. Tyrell [13 page 837-851]. (This paper basically focused on the purpose of backfire radiators, whereby the polyrods were excited by wave guides) For an explanation of the Naxos antenna we will mainly rely on P. Mallach's papers, as *"the pater intellectualis"*, published in 1949-50, and H.J. Fischer's *Radartechnik* of 1958, a former East German book (DDR) [14], as well as on; H. Awender's & O. Lange's, article in FTM 1938, [15]

Polyrod, a dielectric loaded radiator

Previous research, before Mallach started his scientific work in this field, mainly focused on the excitation of E- waves in dielectric conductors (wires). But, according to Awender's & Lange's equations [15 page 9 (11)]; E-waves would have required far thicker polyrods, than for the excitation of H- waves. Besides this, as we will see later, the losses for E- waves would make practical operation on 10 cm, by polyrods, (nearly) impossible.

$$F_{max} = 0{,}2\,\lambda_0^2\,(\varepsilon_{rel} - \varepsilon_f)^{-1}$$

$$F_{min} = 0{,}087\,\lambda_0^2\,(\varepsilon_{rel} - \varepsilon_f)^{-1}$$

Polyrods in general, exciting H- waves, can only operate properly within two certain limits of λ_0, depending on: the surface square of the cross section F (cm^2) and its ϵ_{rel}. [12 page 34]
λ_0 in free space, ϵ_f is a fictive frequency dependent dielectric value, related to the surface velocity λ_{ϵ}, of the polyrod. If the difference in velocity between; λ_0 (velocity of light) and λ_ϵ (at the surface of the dielectric) is less than ≈15%, than $\epsilon_f = 1$.

The direct consequence of this equation is; the area of the cross section (F cm^2) can be decreased for increasing ϵ_{rel}.

Prof. O. Zinke quotes that pure H- waves theoretically can not be asymmetrically excited, because of this he suggested the use of a more accurate expression: HE- waves. But, according to Mallach; *"Um Irrtümer zu vermeiden, sei aber darauf hingewiesen, daß es sich dem technischen Verhalten nach um eine Welle vom H-type handelt"*. Abbreviated translation; to avoid confusion: from the technical point of view this type of wave acts similarly as normal H- waves". [12 page 33, 37]

To understand the working principle of this type of dielectric loaded radiator, we must first imagine its radiation principle for light.

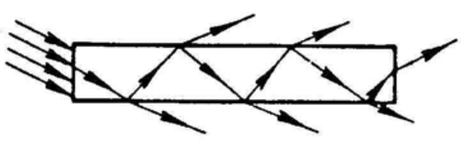

Fig 6: Light propagation and refraction through a glass rod

When light enters a glass rod under an angle (fig. 6), it propagates by multiple reflections [14 page 220]. At each reflection some light leaves the rod and refraction (bending) takes place. This also occurs when light is substituted by a SHF signal. The components of the signal leaving the rod over its length, together with their relative phases, creates the radiation pattern.

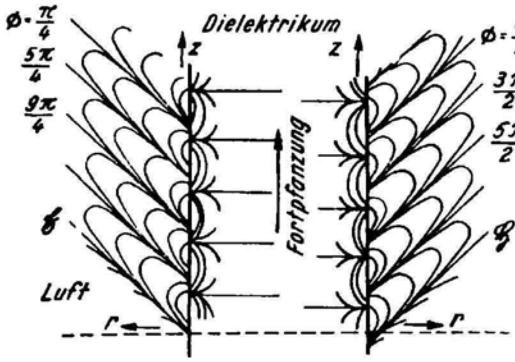

Figure 7 Asymmetric field lines of the side waves, at meridian level. (Hondros)

Hondros' 1910 paper, expressed the asymmetry, due to the ¼ λ phase difference between the E- and H- fields, inside a dielectric conductor. We have to consider his empirical work using far longer wavelengths (75-60 cm) and water as dielectric, where the E- and H -waves, both, still could be operational. [11],[15 page 7].

When a dielectric rod is placed on one side of an exciter (see fig.5) its radiation pattern is determined by the exciter (such as its polarization) - the length/diameter ratio of the polyrod, in relation to the wavelength - and the dielectric value. For the Naxos antenna polystyrene was used, with ϵ = 2.5. (equal to the 1941 - 1944 experiments, according to the "backfire antennas" at the Bell labs) [13 page 847, 848, 850])

To understand the interaction between some of these dimensions, we refer to Mallach's paper. Fig. 8 shows the apertures at -6 dB, for several parameters: F, L/λ_0. [12 page 34]

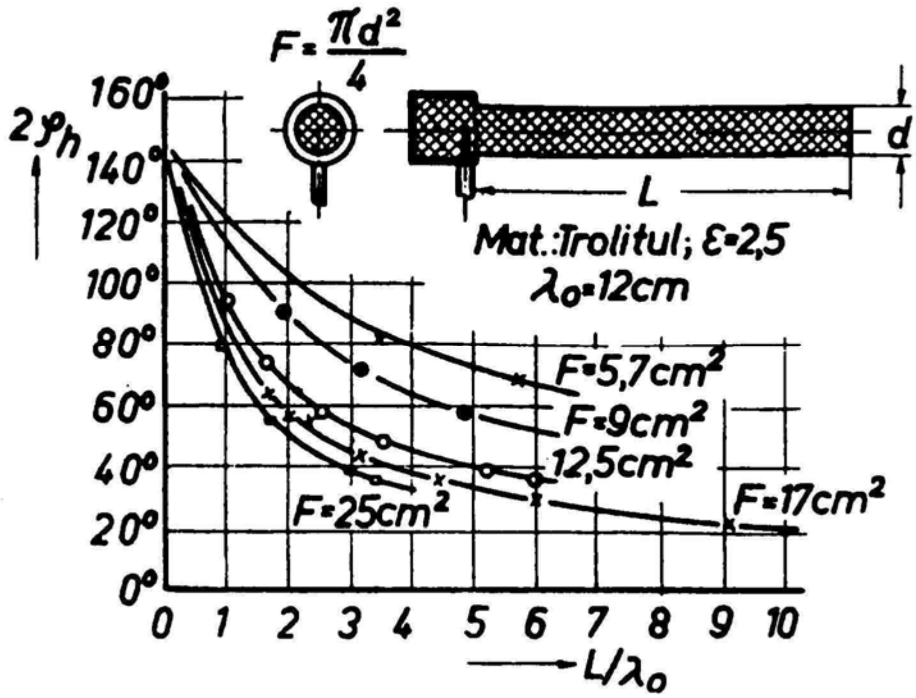

Figure 8: φh is the horizontal aperture in relation to the ratio L/λo and area F [12 page 34]

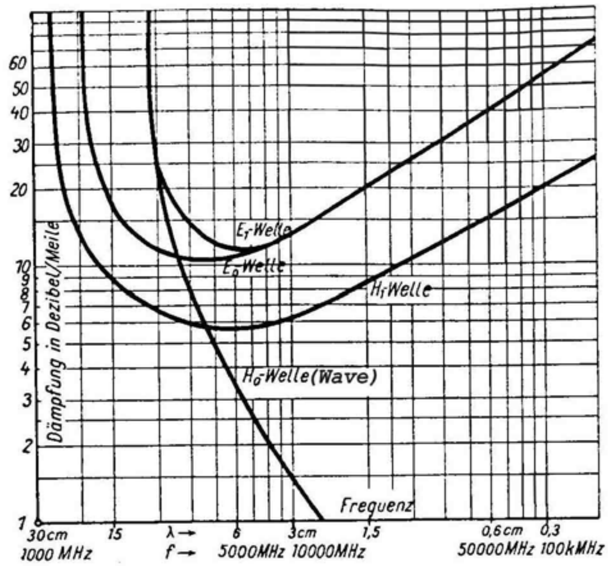

Figure 9: Losses as function of frequency for electric- and magnetic fields, in a dielectric medium

A logical question is; will the losses in the dielectric, at 3,000 MHz (the H2S frequency band), be so high as to prevent proper operation of the antenna? Fig.9, taken from Fischer's book [14 page 220], indicates the contrary. This diagram and the subject of dielectric wires, were already published in the mid thirties in USA [16], as well as by Awender & Lange [15 page 51]. The graph shows the losses in decibels per mile as a function of frequency, for E- and H- waves of different modes. The 9 cm magnetic H_0- waves are near the minimum loss and it is remarkable that its loss tends towards zero, with increasing frequency.

All types of insulators can be used as dielectric conductors, when: tg $\delta \leq 50. 10^{-4}$, for λ_0.

Zahn [17], and Schiever [18], as well as, Southworth [15], had already proved experimentally that "skin effect" could not occur for dielectric material. (Referring to some publications; [12, page 33-39], [15].

Ceramic materials were also tried, but found to be too brittle and therefore unsuitable for the intended application.

The exciter in the Naxos antenna is a quarter wave rod, similar as in fig. 5. The counterpoise for the rod has the form of a metal cap, that also acts as a reflector. Mallach found empirically that the level of the side lobes, in the radiation pattern, could be varied by the shape of the dielectric rod. Experimentally he determined for the Naxos antenna, a tapering rod with $(D_{max}/D_{min}) = 1.25$. The tapering, and the spherical end, also helps to match the radiator to the free field.

The wide bandwidth is also remarkable of such dielectric loaded antennae, Mallach found that when using a dielectric with $\epsilon = 1.6$ the radiation pattern remained suitable over a frequency ratio of 1 : 2.7. The bandwidth decreases with increasing dielectric value, but even for $\epsilon = 16$ the max/min frequency ratio is still 1 : 1.6.

Dielectric antenna theory is too diverse a subject to be covered here more extensively.

For many years I have tried in vain to obtain more information on the actual operation of the antenna. Finally a friend introduced me to the *Christiaan Huygens Laboratorium* of Noordwijk in The Netherlands. The antenna experts there were also interested in the World War II Naxos antenna and they measured its horizontal radiation pattern between 2.5 and 3.5 GHz. Figure 10 shows 3,210 MHz (9,34 cm), the main lobe is along the axis of the array and it is assumed this is the frequency for which the antenna was designed. The main lobe is about 20 degrees wide. There are two sidelobes at about -37 dB. The handbook for NAXOS quotes the vertical aperture at about 50 degrees, due to the antenna mounting disk.

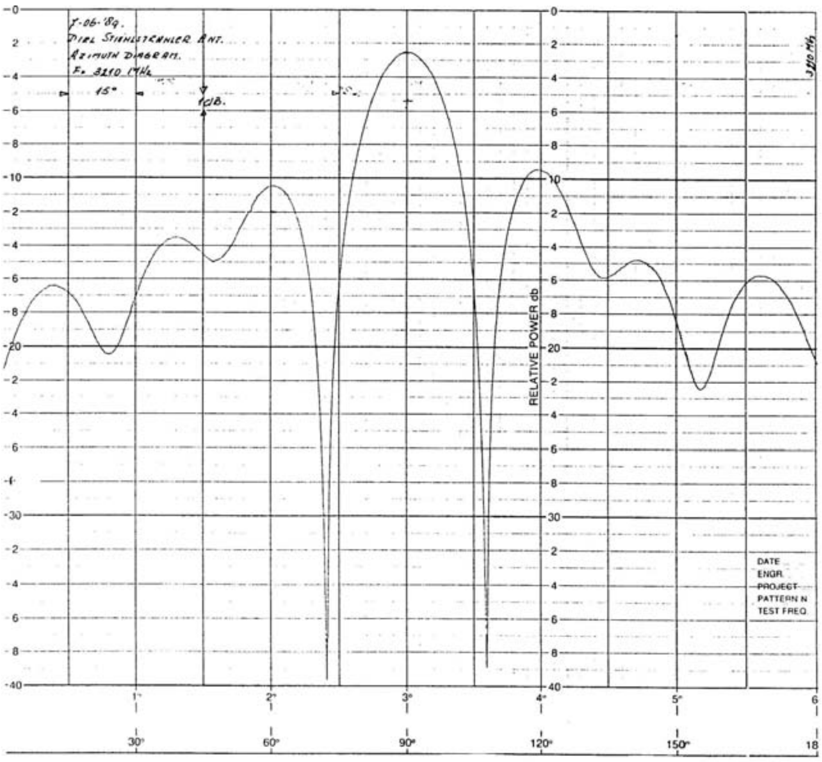

Figure 10: Radiation pattern of the Naxos antenna at the design frequency 3210 MHz

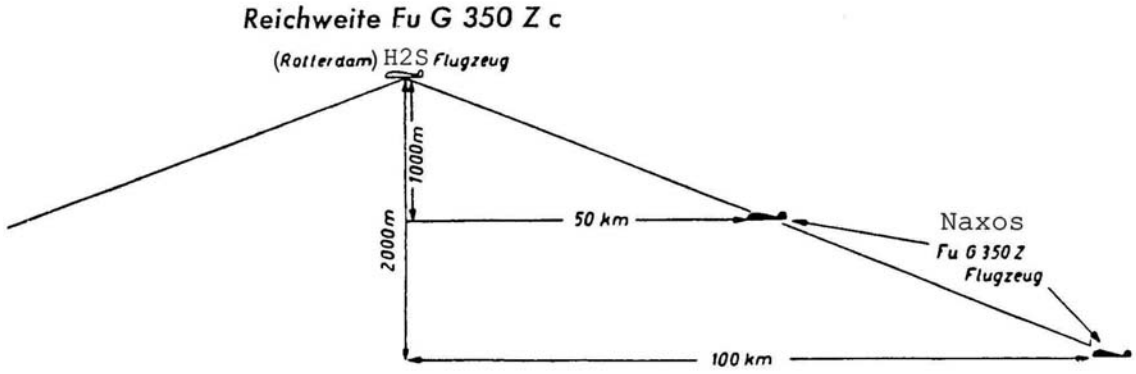

Fig. 11 shows the horizontal as well as vertical interception range of the Naxos system.

Figure 2 shows that the antenna consists of two radiators, side by side, at a distance of 1.5 wavelengths between centres. The total length of the dielectric rods are 2 λ. (in the free air ≈ 1.8 λ) The feed system for the two radiators shows an interesting feature. As seen in fig. 5 (consider also fig 2) the exciters are quarter wave rods, protruding sideways into the dielectric. The exciters are at the ends of each coaxial feedline, What would happen if the feedline to the receiver were connected midway between the two radiators is easier to understand by considering the use of the antenna as a radiator. Currents of equal phase would reach both exciters, but looking at the array from the front, the currents would run in opposite directions (to the left in one and to the right in the other). This of course is not what is desired: radiation from the two elements of the array should be in phase. Therefore the coaxial line to the receiver is connected to the exciters a quarter wave off-centre, so introducing a 180 degree phase shift (¼λ longer to one side and a ¼λ shorter to the opposite) This of course can be correct for one frequency only and is the reason for the squint when the frequency departs from the nominal value.

At a special request, of the well known German historian and author Fritz Trenkle, the antenna was also tested by the *Christiaan Huygens Laboratorium* in the 3 cm radar band. (X-band) Trenkle would like to know, whether NAXOS could have been used for radar detection in this band, in the last phase of WW II. It was found that the antenna indeed could have been used as such, but, due to the greater distance in wavelengths between the two elements a large number of side lobes appeared which were also strongly frequency dependent (interferometer principle). Although such an array would be unacceptable to the antenna experts, nevertheless Trenkle was pleased with this result, because it proved that the Naxos system could have been used, in someway, as an interception device in the 3 cm X-band, be it with limitations. It is likely that an experienced operator, in spite of the broad response of the display, could have estimated the bearing of X-band radar signals. In this respect NAXOS can be considered as a primitive Early Warning system for X-band. In the 1944-45 phase of the war, every possibility was put to use by the German Air Force and Navy, there simply being no other choice.

The Naxos antenna displayed at the Science Museum

The Naxos antenna (Luftwaffe version) owned by the Science Museum in London, confronts me with a peculiar problem as the dielectric radiators (polyrods) are made of laminated "perspex or plexiglas". Neither Mallach's paper, nor the original Army handbook, mention the use of this type of dielectric material. (The original German brand name is: Plexiglas). According to German information, only "Trolitul" or polystyrene, as the best workable material, was used, as can be observed in the photographs 1 and 2. [12], [19], [20], [9], [13]

Several publications, like David Prichard's: The Radar War, [21 page 174] use this confusing information, because it often refers to the SM source.

Let us, hypothetically, reconstruct the circumstances.

1. This artefact had been captured with broken or even without any dielectric radiators at all. (see next point)
2. The original radiators had been removed, for example to study, this or other, dielectric material, and or the integrated ¼ λ radiator, and afterwards replaced it by a perspex dummy.
3. The Germans did produce this device, for what ever reason. (most improbable)

An original manual [9 page 7] confirms my opinion: *Als Richtantenne werden zwei konische Stäbe aus dielektrischen Stoff (Trolitul) ....*
(Free translation: As DF antenna two conical rods are used, made of the dielectric material Polystyrene...)
As we know; Trolitul is equivalent to Polystyrene and perspex is an acrylic material.

Production figures of the Naxos system

Quantification
To counter as quickly as possible the Allied H2S threat, a kind of "Crash program" was initiated.

The most logical first step was; to use, if possible, already existing modules, that could easily be converted, and integrated, into the new Naxos system, whereby the large quantity of available and obsolete, IFF modules (FuG 25) could do the job.

But soon after, several more elaborated versions became available for operation. Production figures, of the several versions, are all based on Trenkle's archive: [22]

Luftwaffe versions
FuG 350 "Naxos 1" unknown quantity. (Kleinserie)
FuG 350 R "Naxos R" unknown quantity (wenige Einbauten)
FuG 350 Z "Naxos Z" Prototype with: Target displayed as a dot. (mit Punktanzeige)
FuG 350 Za "Naxos Za" J-Scope display. On 30th July '44, 65 systems were fitted.
FuG 350 Zb "Naxos Zb" J-scope display. On 30th July '44, 118 systems were fitted.
Naxos ZP 3 not sure if equivalent to: "Naxos Z or Naxos Zc" but to be used in mobile signal truck. (Funkwagen)
FuG 350 ZR "Naxos ZR" combination of rotating- and
two separate polyrods. Probably only as prototype.

FuG 350 ZX "Naxos ZX" for 3 cm. Target displayed as a dot. (by z-modulation?) No other details.
FuG Zc "Naxos Zc" On 30th July 1944, 99 systems were operational. The estimated production schedule for August '44, was planned at 125 units. For September '44, 200 systems had to be produced (planning). On 1st January 1945, 450 systems operational. Estimated production figures thereafter; 500 systems per month.
FuG 350 ZD "Naxos ZD" combination of 9 cm and 3 cm antennas. Whereby for 3 cm only one polyrod was used. Only prototype planned.
FuG 350 ZE. "Naxos ZE" Only information to be used for 1,2-4 cm. One prototype as modification of the "Naxos ZD" version.

Navy versions:
FuMZ 6, FuMB 7, "Naxos (I)" in five freq. ranges; 1a - 1y, between 2500 MHz - 7500 MHz.
FuMB 24 "Naxos F1" "Fly" ("Fliege") prototype.
FuMZ 6 "Cuba II" Designed to resist high pressure like deep diving as well as depth charges, mounted on the conning tower, of Uboats. (Although no polyrods were used here)
ZA 280 "Naxos T = Tunis" Also knows as: FuMB 24 + FuMB 25. For 9 cm using a horizontal dipole and for 3 cm a "horn antenna". The German Navy ordered a total of: 1700 units. On 31th August '44, 270 systems were delivered by the industry. Estimated production planning; 100 systems monthly.
Fu MB 23 "Naxos ZM 1b" (2510 - 3750 MHz) Ordered hundred systems. All delivered in October '44
Fu MB ..? "Naxos ZM 3b" prototype for Uboats, but cancelled. Replaced by: ZM 4 b.
Fu MB 23 "Naxos ZMX" 7500 - 12000 MHz. One prototype of Fu MB 41.
Fu MB 28 "Naxos ZM 4b" (2500 - 3500 MHz) Antenna ZA 290 M. Ordered 1700 systems. On 31th August '44, 22 systems were delivered.

We have to consider, that not every detail listed will contain complete and/or correct information, but they are the only sources left. Fritz Trenkle started, initiated by influential Germans, his historical and technological research in the early fifties, when many young and still active persons could reproduce, more or less, accurate information. Today "fading memories" would make reconstruction impossible.

Conclusions

The Naxos system can be seen as a desperate answer to a deathly threat, after the introduction of H2S over German held territory, by the Allied Air Forces. The development of NAXOS was constantly under heavy pressure, and at the beginning, was managed as a kind of "Crash Program".

Firstly, as far as possible already existing modules had to be adopted for the Naxos system. Whereby the obsolete IFF modules (FuG 25) easily could been converted into high-gain LF amplifiers. (PRF)

Why this type of antenna construction was chosen, can't be answered with certainty. But some specific and important factors could have forced this, like; broadband operation between 2.5 and 3.5 GHz, because the Germans could never estimate what H2S frequencies were being used. The relatively low profile and the 20° horizontal- as well as the vertical aperture of ≈

50°, and or the antenna construction could rotate at a high velocity, to always ensure that several H2S impulses, were being picked-up.

What was perhaps more important; this technology was available, more or less, at hand.

Nevertheless, German "night fighters", equipped with Naxos, became a dangerous and deathly threat for Allied airplanes.

Acknowledgement

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