RADIO AIR NAV | LUFTWAFFE - FUSAN 724/725 "BERNHARD" GROUND STATION

Radio Air Nav - **main page**
Radio Air Nav **sub-pages** ▼
My other pages ▼
About (impressum)
Contact

Print

Directly related pages pages: ["Bernhard" ground station locations]
[The "Bernhard/Bernhardine" Luftwaffe radio-navigation system]
[The "FuG120 "Bernhardine" airborne Hellschreiber printer system]

For other Radio Air Navigation systems: see the Radio Air Nav tabs of the menu at the top of this page.

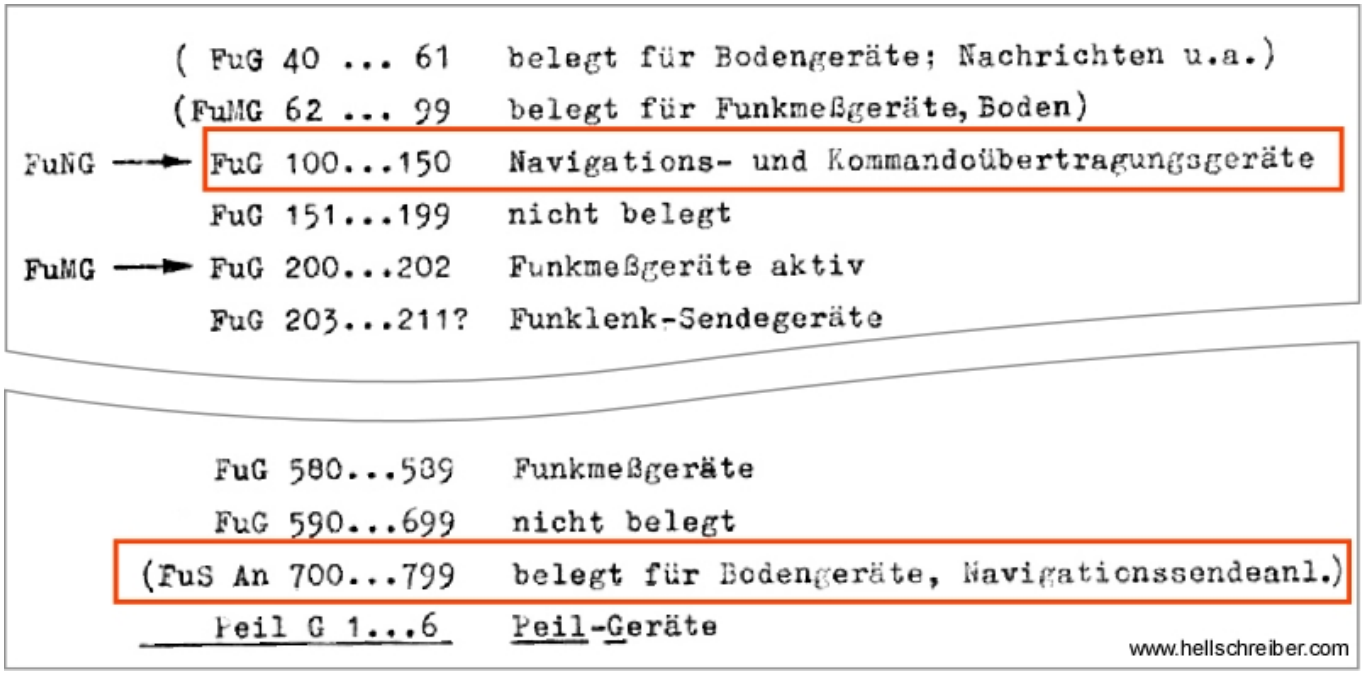
Note: the total download size of this page is about 23 MB. If you have slow internet access, please be patient...

Latest page update: June 2024 (replaced Fig. 168, expanded text around it).
Previous updates: February 2024 (added Fig. 5, Fig. 50and text); January 2023 (replaced Fig. 57 and expanded associated text); July 2022 (expanded the section on Hein, Lehman & Co); May 2022 (split the transmitter section into FuSAn 724 &725; added associated figures, added ref. 10 & 164, updated optical disk section, made separate section for transmitter modulation & spectrum); July 2020 (added ref. 265 about rail traction); February 2020 (added ref. 253B); October-November 2019 (added ref. 253A and associated text, added high-res version of ref. 15); August 2019 (split into two pages, added ref. 208C, 243).

INTRODUCTION

"Bernhard" is the German codename for the ground-station ("Stellung", "Anlage") of the "Bernhard/Bernhardine" radio-navigation system that was used by the Luftwaffe during part of WW2. The beacon ground-station is a complete radio transmitter installation - including the antennas. A complete installation is a "**Fu**nk **S**ende-**An**lage", abbreviated "FuSAn". The FuSAn developed for the "Bernhard" system was FuSAn 724. Its two transmitters had a maximum output power of 500 watt each. On-board the aircraft, the "Bernhard" beacon had a counterpart radio system ("**Fu**nk **G**erät") called "Bernhardine": the FuG 120. A FuG includes the receiver (or transmitter, as the case may be), antenna (s), and installation rack(s), power supply, control boxes, etc. At the heart of the FuG 120 was a Hellschreiber-printer. It printed the bearing data transmitted by the selected "Bernhard" beacon.

The numbers 724 and 120 are entries in a multi-category running numbering system. The range FuSAn 700-799 was reserved for "Bodengeräte, Navigationssendeanlagen" (ground equipment, navigation transmitter stations) and FuG 100-150 for "Navigations- und Kommandoübertragungsgeräte" (navigation & command-uplink equipment). Ref. 2, 185.



	(FuG 40 ... 61	belegt für Bodengeräte; Nachrichten u.a.)
	(FuMG 62 ... 99	belegt für Funkmeßgeräte, Boden)
FuNG →	FuG 100...150	Navigations- und Kommandoübertragungsgeräte
	FuG 151...199	nicht belegt
FuMG →	FuG 200...202	Funkmeßgeräte aktiv
	FuG 203...211?	Funklenk-Sendegeräte
	FuG 580...539	Funkmeßgeräte
	FuG 590...699	nicht belegt
	(FuS An 700...799	belegt für Bodengeräte, Navigationssendeanl.)
	Peil G 1...6	Peil-Geräte

www.hellschreiber.com

Table-1: FuG120 and FuSAn724/725 within the equipment numbering system
(source: ref. 2D)

Note that over a dozen different fixed and mobile FuSAn types were developed for various radar and radio-navigation systems of the Luftwaffe, primarily by Telefunken, Lorenz, and the DVL (**D**eutsche **V**ersuchsanstalt für **L**uftfahrt), ref. 141.

The "Bernhard" FuSAn comprised a large rotating antenna system (ca. 25 x 35 meter). The main sub-systems of this rotating navigation beacon are (see Figure 1):

- The rotating upper structure ("Gerüst"), consisting of:
    - a large antenna system that comprises three antenna arrays,
    - a cabin ("mitdrehender Geräteraum" = co-rotating equipment room) with the two transmitters,
    - a small square block near each of the four corners of the cabin.
- A large concrete ring, with
    - a circular rail track, and
    - four electric locomotives for rotating the upper structure.
- A small round central-support and equipment building ("feststehender Geräteraum" - stationary equipment room) in the middle of the ring.
- A remote antenna mast and receiver, for monitoring the signals transmitted by the beacon.
- Sources of electrical power.

The Telefunken company had gained good experience with the steel construction of the Large and Small "Knickebein" beacon systems, with their large antenna arrays, rotable on a circular track with central support. This gave them confidence for applying the same approach to the continuously rotating Bernhard system. Ref. 181 (p. 71, §3; 1942).

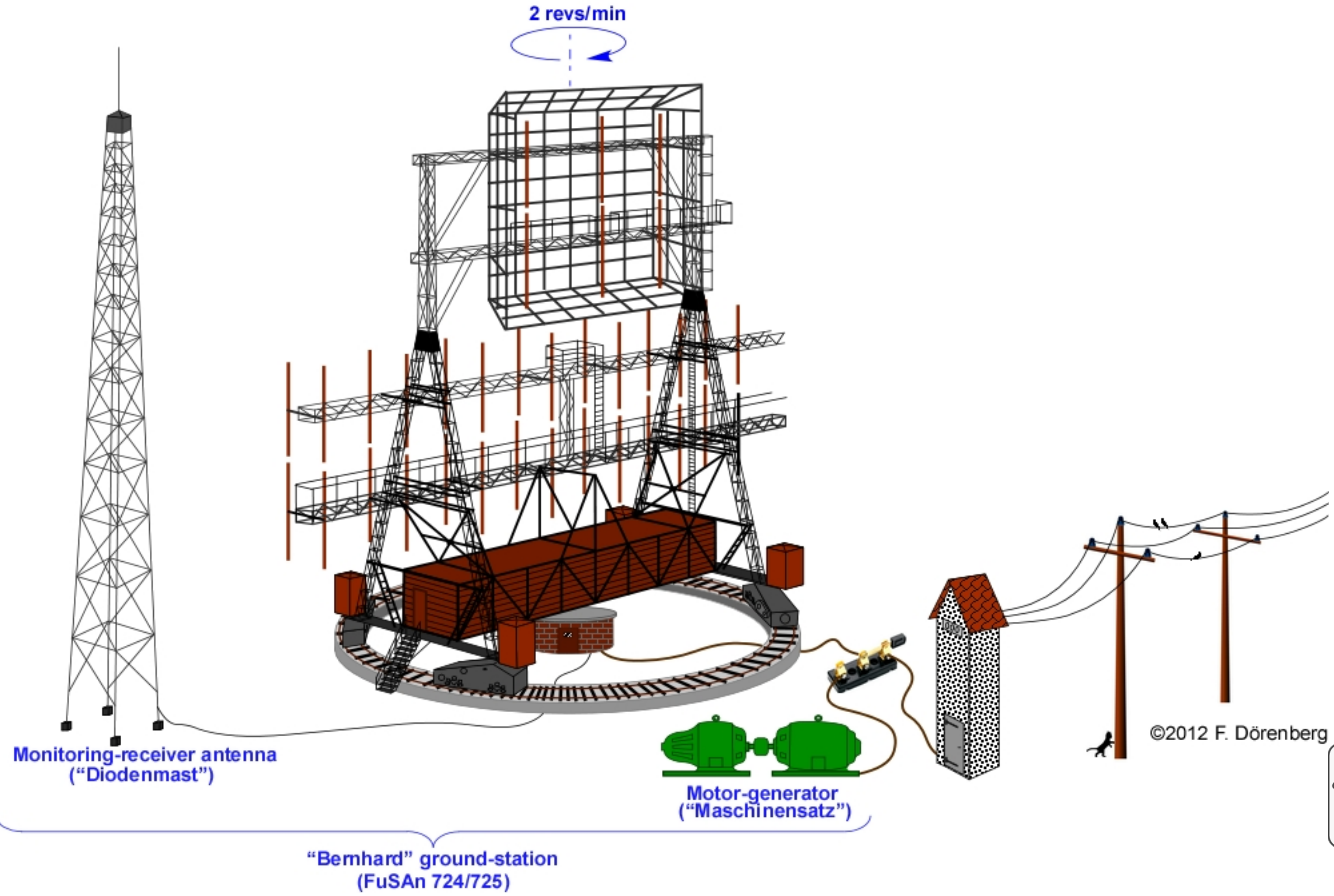


Fig. 1: The "Bernhard" ground-station of the "Bernhard/Bernhardine" radio-navigation system

(click here to get full size)

Basic characteristics of the "Bernhard/Bernhardine" system are:

Frequency: 30 - 33.1 MHz.

Transmitter power: 2 × 500 watt (FuSAn 724)

The available literature often refers to "Bernhard" as FuSAn 724/725. The 725-version was intended to have more powerful transmitters: 5000 W each. However, there is no evidence that these transmitters ever entered into service, were even developed or were available off-the-shelf. Ref. 20 and 2C4 state that they were planned only. The exact reasons for the power increase is unknown, but would typically be extended range and improved immunity against interference and jamming.

The wiring list of the "Bernhard" station contains several items with two gauge specifications: one for the 500 W transmitters, an a much heavier gauge for **4**000 W transmitters (i.e., not **5**000 W, see cables nr. 6-8, 33, 34, in ref. 189).

Antenna system dimensions: ≈28 x 35 m (HxW, 92x115 ft).

Antenna system track diameter: 22.5 m (≈74 ft).

The specified average track radius (mid-point between the inner and outer rail) was 10.55 m.

The track was laid on top of a concrete ring width a width of 1.5 m, hence an outer diameter of 22.6 m.

Antenna system weight: 120 metric tons (265000 lbs), ref. 2C4. Only ref. 183 (p. 19) states 120 metric tons as the weight of the "Gerüst", i.e., of the super-structure without the locomotives. Some literature states the weight as 102 tons (ca. 256000 lbs), which may be a typographical error, or 100 tons (ref. 20) - without being specific about what is included in the weight.

Antenna rotational speed: 12 degrees per second (2 revolutions per minute, see the "rotational speed" section below).

This means that the small locomotives that turned this enormous antenna installation, moved at a respectable linear speed of about 8 km per hour (5 mph).

The speed had to very accurate: to within ±0.2-0.3 % of the nominal speed (ref. 181, p. 80). Note that by design, the printer in the aircraft can not work with a beacon that turns at a different speed.

System accuracy: initially ±1°, then improved to ±0.5°, finally reduced to ±4° by using a single-trace (= simpler) printer system, a single transmitter, and a single antenna system; the latter was under development towards the end of the war, see the FuG 120 k section.

Operational range: 150-500 km (80-270 nm), depending on aircraft altitude with respect to the "Bernhard" antenna (p. 22 in ref. 15).

THE CONCRETE RING AND CIRCULAR RAIL TRACK

The base of the entire rotating "Bernhard" superstructure is a large concrete ring. On top of the ring lies a circular rail track, for the four locomotives that actually rotated the system. The superstructure (= equipment cabin + antenna systems) is basically a large turntable. Standard width of the ring is 1.5 m (5 ft), as measured at several of the still-existing rings. The specified diameter of the center of the circular rail track (= midway between the two rails) was 2x10.55 = 21.1 m (ref. 193). Hence, the outside diameter of the ring was about 21.1 + 1.5 = 22.6 m.

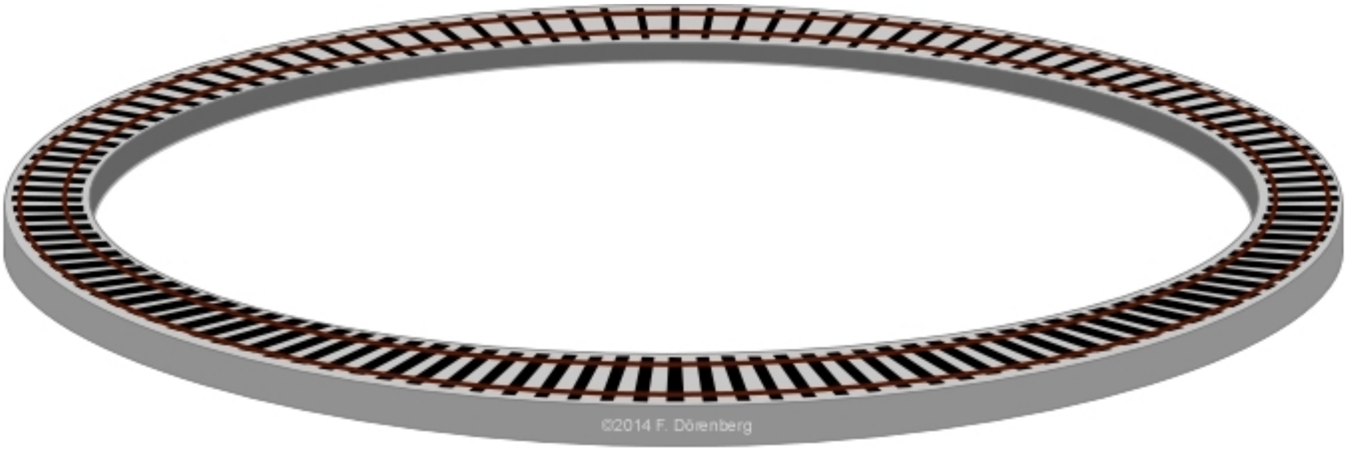


Fig.2: Concrete ring with the circular rail track

Fig. 3: Satellite image of the "Bernhard" site at Arcachon/France - overhead view (ca. 2013)
(source: http://www.geoportail.gouv.fr/)

A rail track comprises two main elements:

- The track structure:
    - Steel rails
    - A rail fastening system. This typically takes the form of ties (crossties; *UK*: sleeper, *D*: Querschwelle), and fasteners to fix the rails to the ties. Their purpose is to maintain the correct distance between the rails (= gauge), hold the rails upright, and transfer the loads from the rails to the underlying track bed and ground. Fasteners take the form of rail anchors, tie-plates, base-plates, sole-plates, rail-chairs (*D*: "Schienenstuhl"), bolts and nuts.
- The track bed or foundation: typically layers of ballast, sub-ballast, and subgrade (layers of crushed rock, gravel, and sand) on top of the natural ground. For applications with very high loading (= large "weight on wheels"), the track bed may be "ballastless": a continuous slab of reinforced concrete on top of a subgrade. The latter is the case for the "Bernhard" track. This has a major advantage compared to the traditional track structure: no need for regular heavy maintenance to restore the desired track geometry and smoothness (e.g., by tamping the ballast and associated re-aligning of the rails).

The next Figure shows the curved "Bernhard" rails, fastened to I-beam ties (UK: "sleepers") with standard clamps. This Figure also shows a "rail gauge rod" (a.k.a. "gauge tie rod" and "gauge tie bar") between the rails. There were 80 such "Spurstangen", evenly distributed between the 120 cross-ties. A rail gauge rod is a member bar that is specially designed to join two steel rails at the rail bottom. Their purpose is to protect the rails from tilting, and to hold the track to gauge (= keep the gauge constant around the track). A distinction is made between single-ended and double-end rods, depending on one or both ends being adjustable. Here, a simple steel rod is used, with both ends threaded.

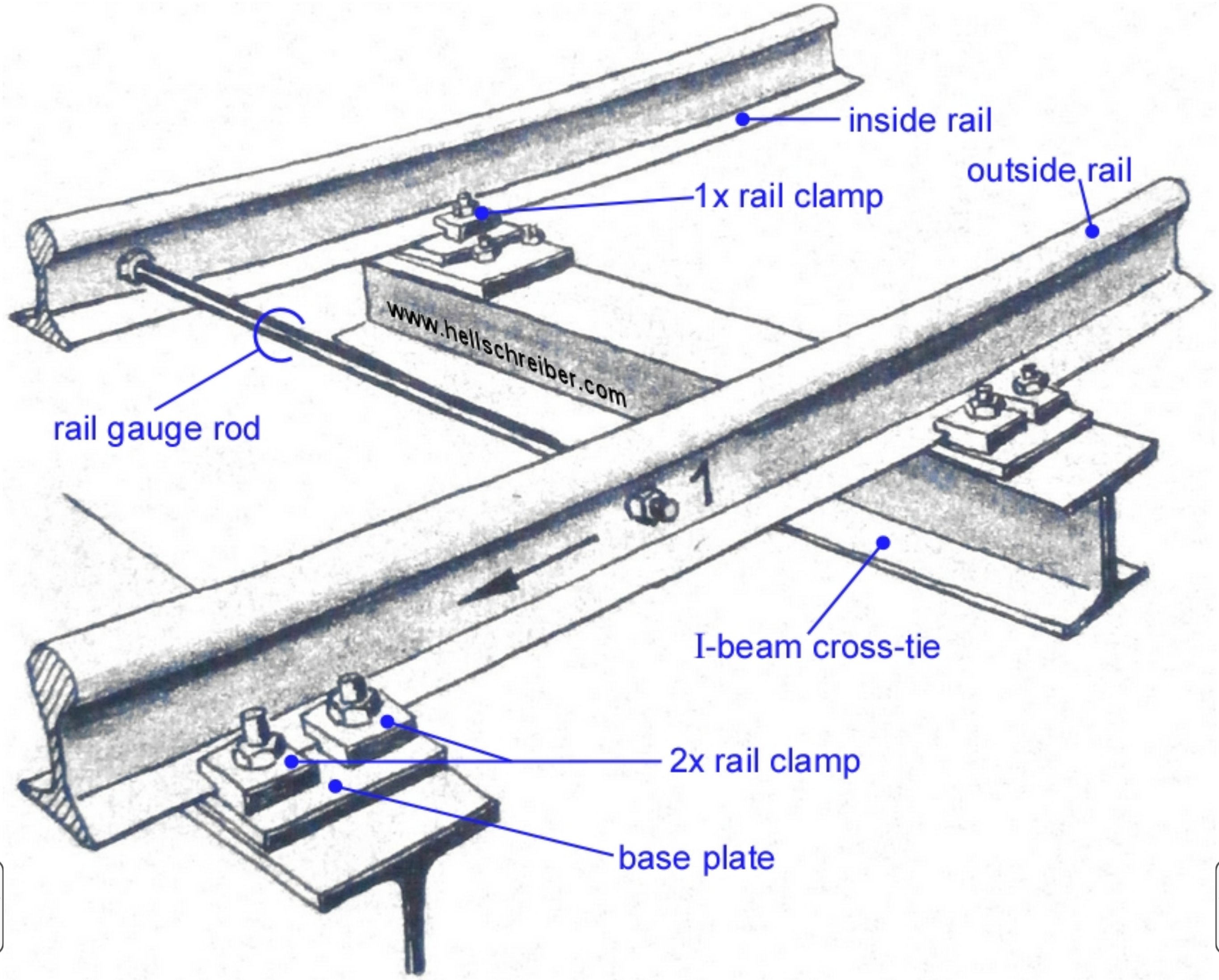


Fig. 4: The "Bernhard" track
(source "Bernhard" track image: adapted from Fig. 1 in ref. 193)

The standard rail profile ("Regelprofil") of the *Deutsche Reichsbahn* (and of its successor, the *Deutsche Bundesbahn*, until 1963) was *Schiene 49* (S49), where "49" refers to its weight in kg/m. It was, and still is, also used for narrow gauge tracks, tramway and subway tracks. It would have made sense to use a readily available national standard profile for the "Bernhard" track. A section of rail found near the ring of Be-0 confirms that profile S49 was used:

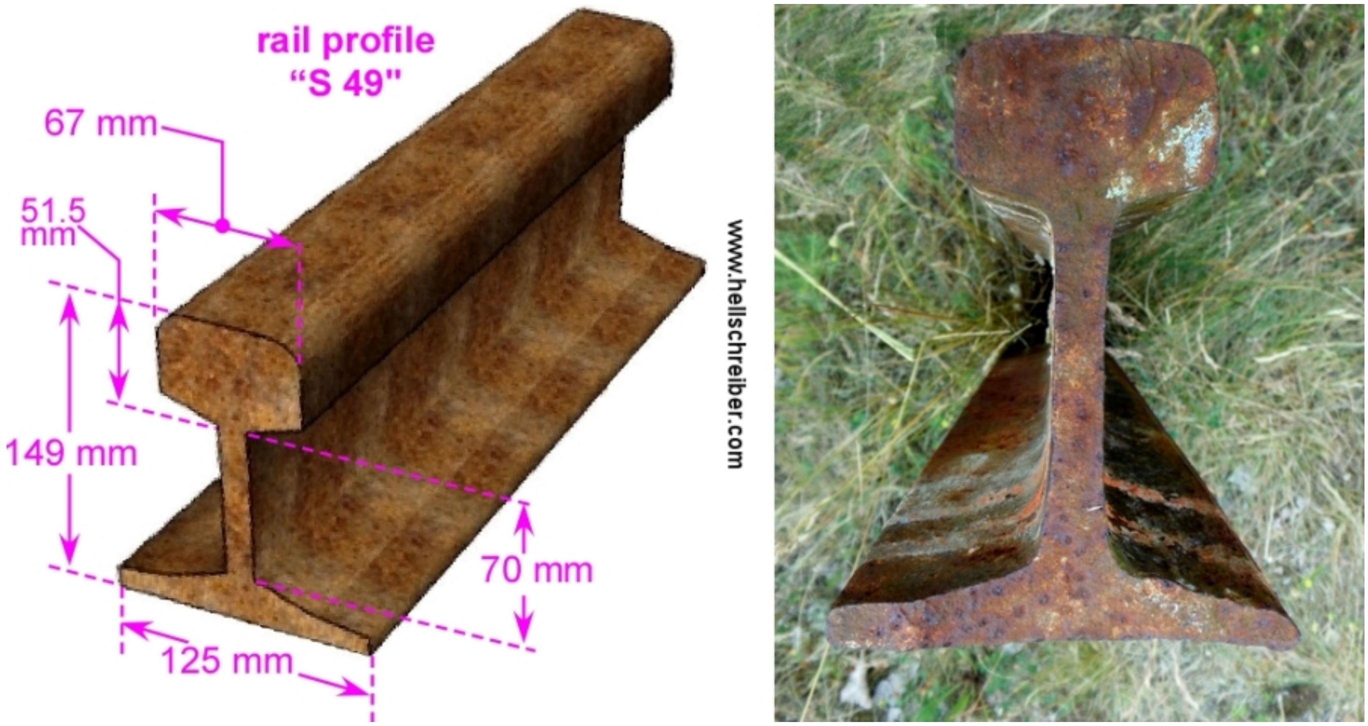


Fig. 5: Dimensions of Deutsche Reichsbahn standard rail profile S49 and a section of "Bernhard" rail

(source profile dimensions: de.wikipedia.org; source rail segment: ©2014 A. Ladenthin/H. Bergmann; used with permisison;)

The "Bernhard" track is "narrow gauge": the distance between the rail-heads is less than local standard gauge.Standard gauge in Germany is 1435 mm (= 56½ inches). It is the same as in North America, most of Europe and the Middle East, in China and Australia. For this standard gauge, narrow gauge is defined as 500-1435 mm (18-56½ inch). To ensure the accuracy of the "Bernhard/Bernhardine" system, stable and accurate rotation of the antenna system was required. This translated to very tight tolerances for the rail track. They were specified by Telefunken (Dept. V/Mo in Berlin-Zehlendorf) and the *Hein, Lehmann & Co.* company - Telefunken's standard manufacturer of the antenna installations.

Per the 1942 adjustment and verification instructions for the "Bernhard" rail track, the nominal dimensions and tolerances are as follows (ref. 193, see Fig. 5 below):

Gauge ("Spurweite") is the distance between the inside of the rail heads). Here: 842 mm, with an acceptable tolerance of ±1 mm (= 5/128 inch).

On-center distance between the rail heads: 900 mm (≈ 3 ft), with an acceptable tolerance of ±1 mm.

The top of the inside rail is higher than the outside rail by 24 mm (nearly 1 inch). Allowed tolerance: ±1 mm.

The top of the rails must be at the same height, all the way around the track. This is verified for 20 evenly distributed points around inside rail of the track, the first point being the one at which the height difference between inside and outside rail is checked. The height of these 20 points must be within ±2 mm (= 5/64 inch) of each other.

Average radius of the track (mid-point between inside and outside rail): 10548 mm (10.55 m = 34 ft 7 inch). Allowable tolerance: ±15 mm (0.6 inch).

There is a large ball bearing at the center of the roof of the round building in the middle of the concrete ring. The top flange of the ball bearing raceway must be higher than inside rail by 1297 mm (= 4 ft 3 inch). Allowable tolerance: ±30 mm (1.2 inch). This is not an extremely critical dimension: it was compensated when installing the locomotives, by placing shims between superstructure frame and the ball-joint ("Kugelzapfen") on top of the locomotives.

After installing the rails, all specified dimensions had to be checked against the associated tolerances. All measured values were recorded on a special form, and sent to department V/Mo of Telefunken in Berlin-Zehlendorf. This enabled determining trends during regular re-verification. For some measurements, a reference point had to be defined. It had to be marked clearly and permanently. Ref. 193.

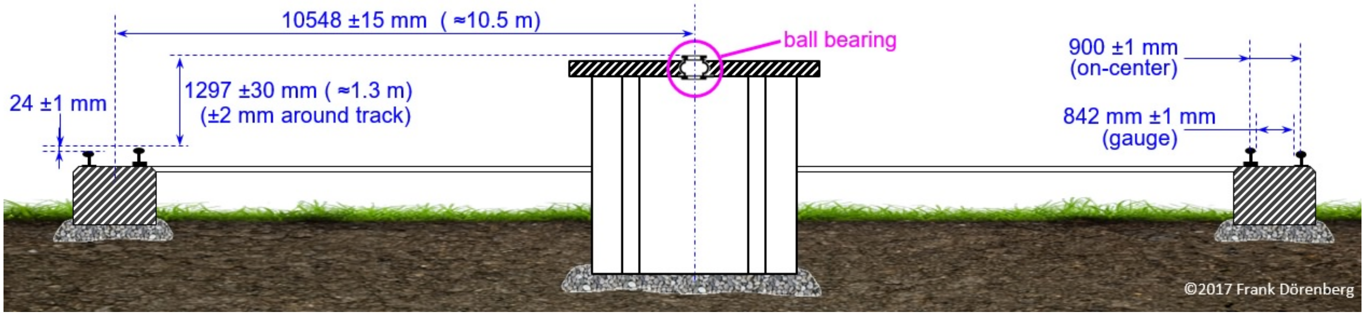


Fig. 6: cross section with nominal dimensions and tolerances
(source of dimensions and tolerances: ref. 193)

The documented "Bernhard" installations have at least six different fastening systems. In all cases, the rails are fixed in place either with 120 ties, or with 120 sets of anchors in the concrete.

A: the concrete ring has 120 pairs of rectangular vertical holes, with a square dimple half way between them. Example: Be-15 Szymbark/Bytów. Possibly, pre-fab ties were used that had a rectangular vertical post at both ends, and those ends were inserted into the vertical holes. The purpose of the dimples is unknown.

B: the concrete ring has 120 pairs of rectangular vertical holes, but there is only a dimple for every third pair of those holes. Example: Be-14 Aidlingen/Venusberg. There, the holes measure about 11x22 cm and are about 50 cm deep; the dimples are 17x17 cm. A pair of steel rods is anchored in the bottom of each rectangular hole. The part of the rods that sticks out above the ring is threaded (M20). The holes are not placed very accurately. However, as the upper part of the steel rods can be moved around, this is not an issue when installing the rail fasteners.

C: the concrete ring has 120 pairs of rectangular vertical holes, but there are no dimples. There are no steel rods anchored in the holes. Examples: Be-12 Nevid/Plzň, and Be-16 Sonnenberg/Hornstein.

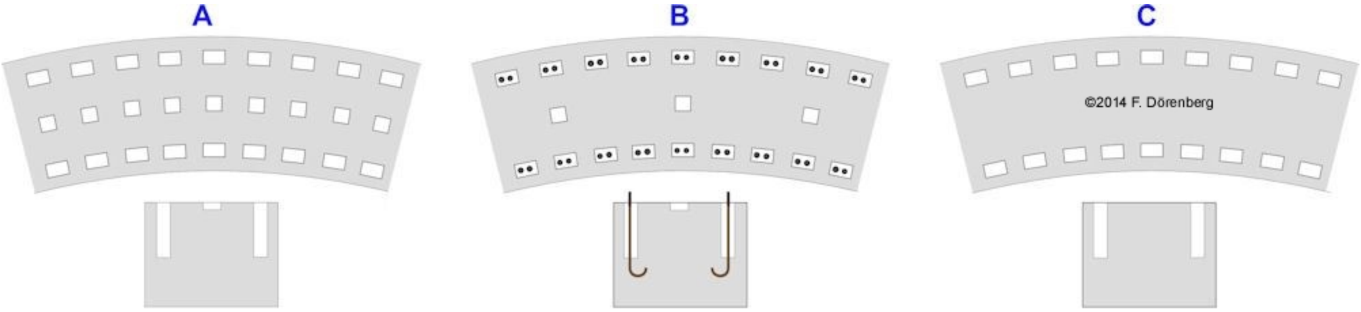


Fig. 7: The various forms of rail fastening and associated features in the concrete ring

D: the concrete ring has no holes, but there are 120 sets of 2+2 threaded rods sticking out where there are vertical holes in versions A-C. This requires more accurate placement of the rods than in cases A-C. Examples: Be-4 La Pernelle, Be-11 Trzebnica/Trebnitz.

E: the ties are sections of I-beam that are embedded into the top of the concrete ring; 2+2 vertical bolts are welded onto each end of the I-beams. Variations:

Concrete ring with a flat top. Examples: Be-10 Hundborg, Be-3 Le-Bois-Julien, Be-6 Marlemont, Be-2 Mt.-St.-Michel-de-Brasparts, Be-7 Arcachon. At Archachon, the I-beams are 15½ cm wide and 17 cm tall (= standard I-beam per DIN 1025), and are embedded in a concrete layer that was poured separately.

Concrete ring with a rounded top. Example: Be-8 Schoorl/Bergen, where the ties are 1.3 meter long and the bolts are placed at 13 and 27 cm from each end of the ties; here too, the ties have the standard width and height per DIN 1025. Rounding the concrete top must have required additional effort. It is unclear why it was done.

F: two sets of 120 ties, one set is narrower than the ties at all other sites. Example: Be-0 Trebbin which was also a "Bernhard" test site. The narrow ties have a width of 7 cm, and may have been from an initial version of the track. However, both sets of ties are embedded into the same layer of concrete, i.e., both sets were already installed when the concrete of the top layer was poured. The bolts on the narrow ties appear to have been removed with a grinding tool, suggesting that they predate the wide ties.

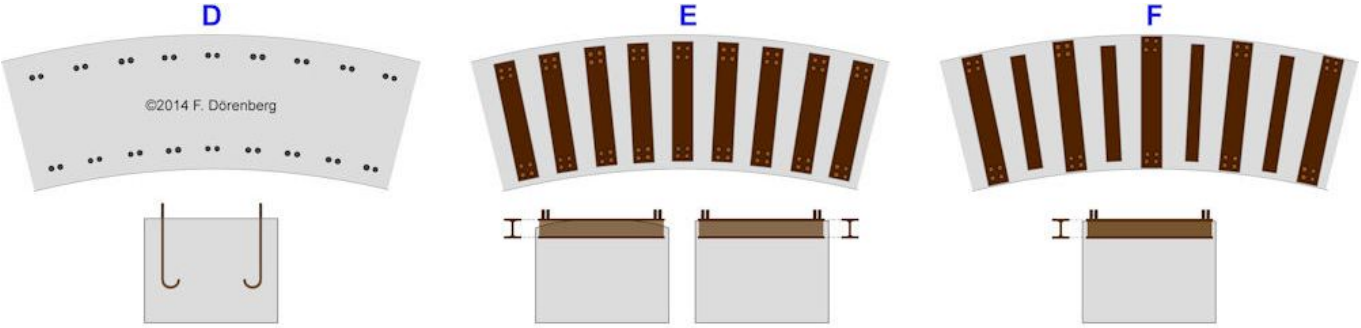


Fig. 8: The various forms of rail fastening and associated features in the concrete ring

Fig. 9: Pairs of threaded rods

I visited the remains of the "Bernhard" ring of Buke in April of 2015. This ring was destroyed by the British after the war, exposing the cross-section of the concrete. It suggests that the concrete was cast with as many as six distinct parts, see the photo below. The top layer is about 7 cm (≈3 inch) thick.

Fig. 10: Cross-section of the ring at Buke

A number of the "Bernhard" rings have rail-ties (sections of I-beam) that are embedded into a separate layer of concrete on top of the ring:

Fig. 11: Top layer of concrete, with embedded I-beam rail-tie at Arcachon

The on-center inside rail of the track has a radius of 10.55 - 0.45 = 10.1 meter. For the outside rail, this is 10.1 + 0.9 = 11 meters. This is very small for a rail track, and causes a large difference (≈4.3 %) in the speed between the inside and outside wheels of the locomotive bogies. This "slippage" causes problems with normal bogies (*US*: trucks) that have rigid axles, with wheels that cannot turn independently. It also causes problems with traction, required locomotive tractive effort, and wear of the wheel flanges and the rails. One way to solve this, is to use wheels with a smaller diameter (here: 4.3%) on the *inside* rail of the track. In turn, this requires that the inside rail be raised slightly (here: 2.4 cm):

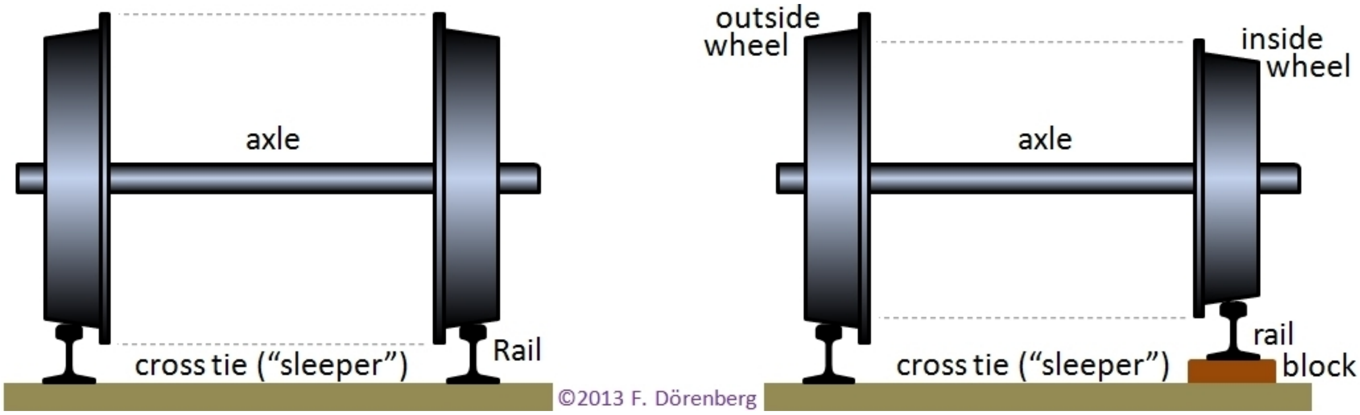


Fig. 12: Raising the inside rail with a block on the ties

The "Bernhard" installations at, e.g., Be-3 Le-Bois-Julien, Be-6 Marlemont, and Be-10 Hundborg, had a block on all ties. At Be-5 Mt.-St.-Michel-Mt.-Mercure, there is only a block on every fourth tie.

Fig. 13: A block on the inside end of all ties of Be-6 at Marlemont
(source: unknown)

Fig. 14: A block on the mounting plate on the inside end of all ties of Be-10 at Hundborg
(source: Hundborg Lokalhistoriske Arkiv; used with permission)

A jig was used to check the gauge and the height difference between the inside and the outside rail. Gauge and height verification is repeated at each of the 80 rail gauge rods:

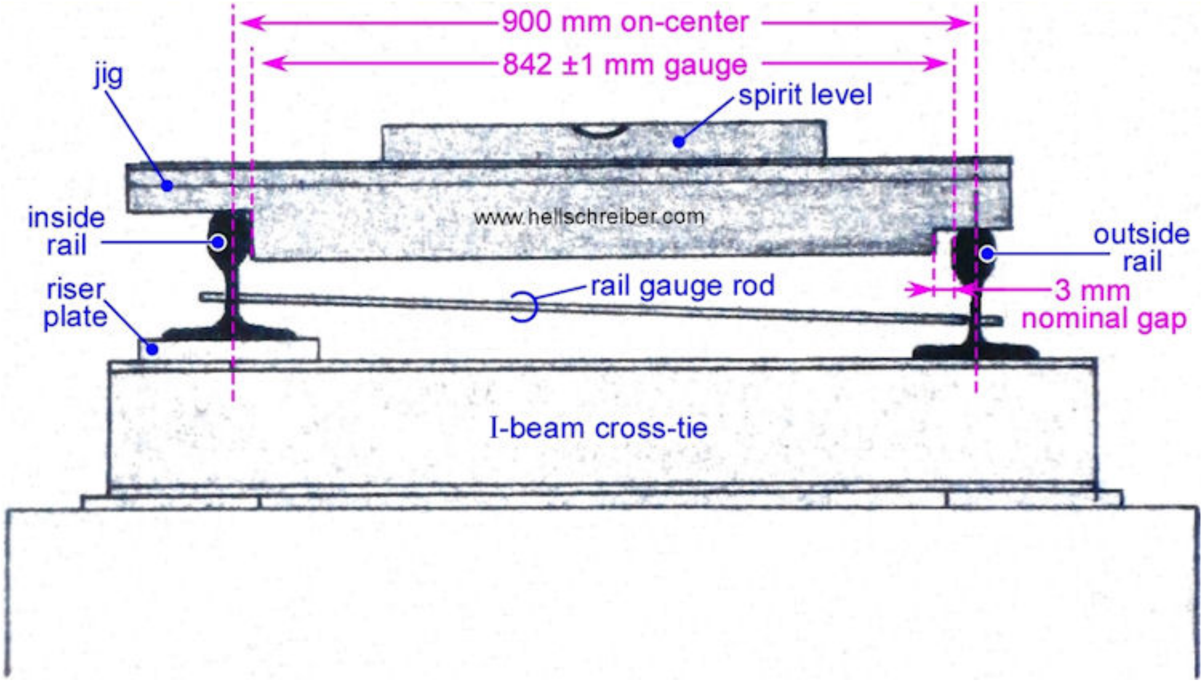


Fig. 15: Measuring the gauge and the height difference between inside & outside rail height
(source: adapted from Fig. 2 in ref. 193)

The bottom of the jig has a notch at each end. A spirit level (a.k.a. mason's level; *D*: "Wasserwaage", *F*: "niveau à bulle") is placed on top of the jig. The notches are sized such that for nominal dimensions, the spirit level shows "horizontal" and the gap between the jig and the rail heads is 3 mm. The latter gap is verified with calibrated shims. The shims are also used to raise the jig on the side of the inside or the outside rail, until the spirit level shows "horizontal":

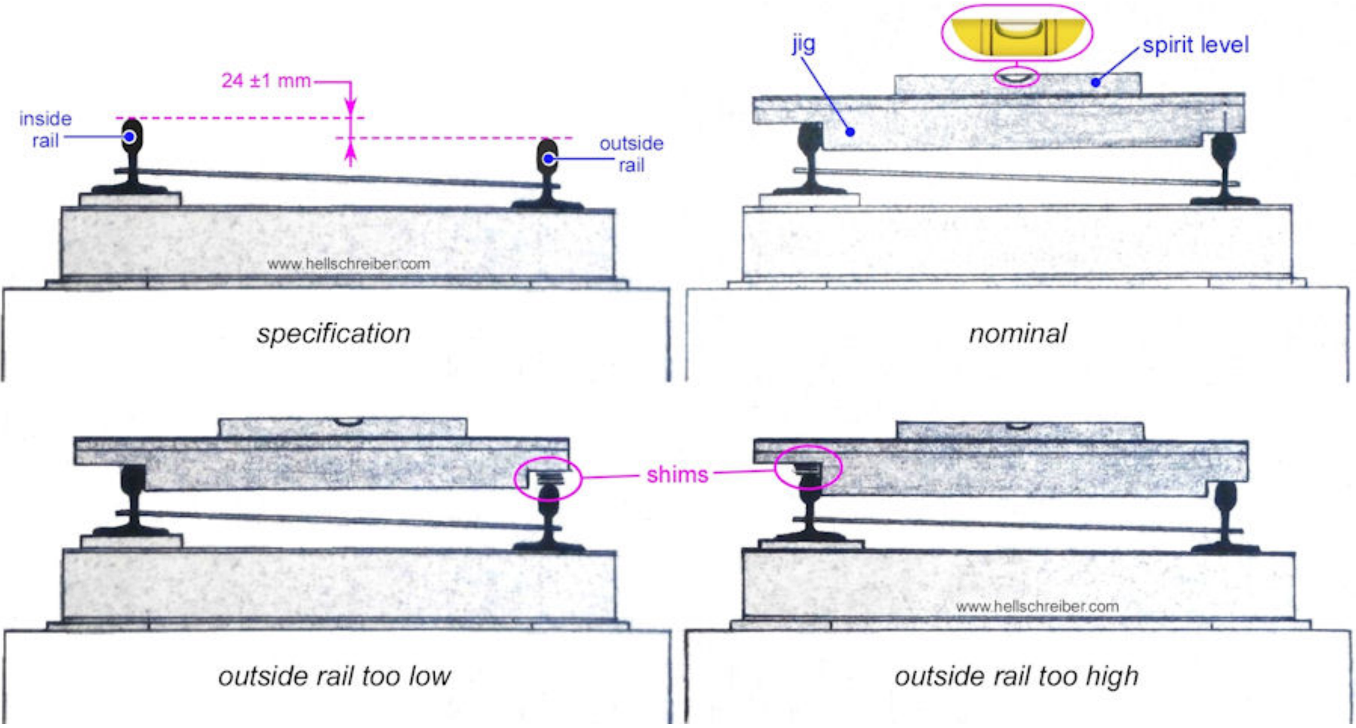


Fig. 16: Measuring the height difference between inside & outside rail height
(source: adapted from Fig. 4 in ref. 193)

Generally, the aim is for trains to run without *any* contact between the flange of the wheels and the rail head. Such contact causes stress on the frame of the bogie, and wear on the wheels and rails. This is why wheel treads normally have a conical shape that widens towards the flange of the wheel. On a circular track with a very small radius, it may be necessary to align the bogie axles radially with the curvature of the track. I.e., the axles always point at the center of the circular track, perpendicular to the rails. No information is available about the bogie design of the Bernhard locomotives. So it is unknown if this approach was actually used. Note that the wheel-pairs of the Small Knickebein rotable beacon - a predecessor of the Bernhard beacon - *were* angled. See here on the Knickebein page. The track diameter of the Small Knickebein was about 50% larger than that of the Bernhard!

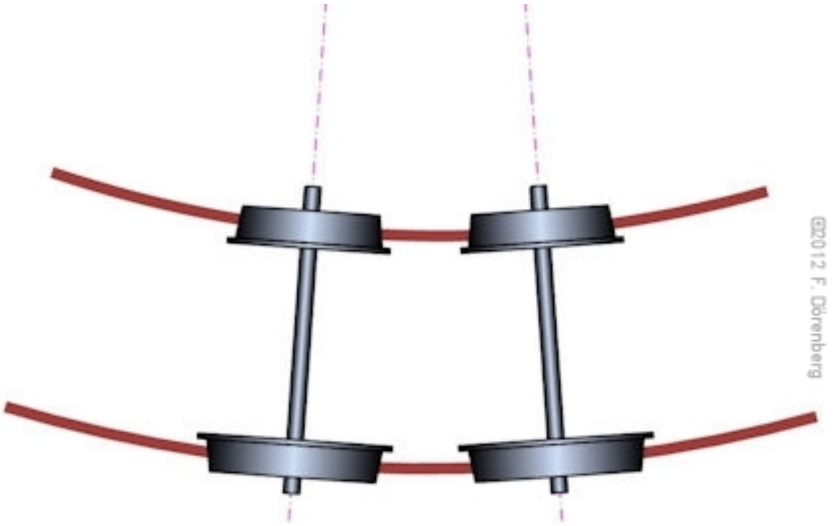


Fig. 17: Bogie axles angled towards the center of the circular track

The relative height of points around the track, and the relative height of the top of the round building is verified with a two-tube water level (*D*: "Schlauchwaage", *F*: "niveau à eau"). This level works on the principle of "communicating vessels". It consists of a sufficiently long flexible tube that is filled with water. There is a glass tube at both ends of the tube. The tubes have an adjustable scale. First, a reference point ("datum", *D*: "Normalpunkt") is chosen. As many points around the track must be measured, it is most convenient to use a reference point at the round building in the middle of the circular track. This will also be used to measure the height of the building. A two meter long surveyor's pole is pounded into the soil, and against the overhanging roof of the round building. With a sprit level, the height of the top of the ball bearing in the roof is marked on the pole:

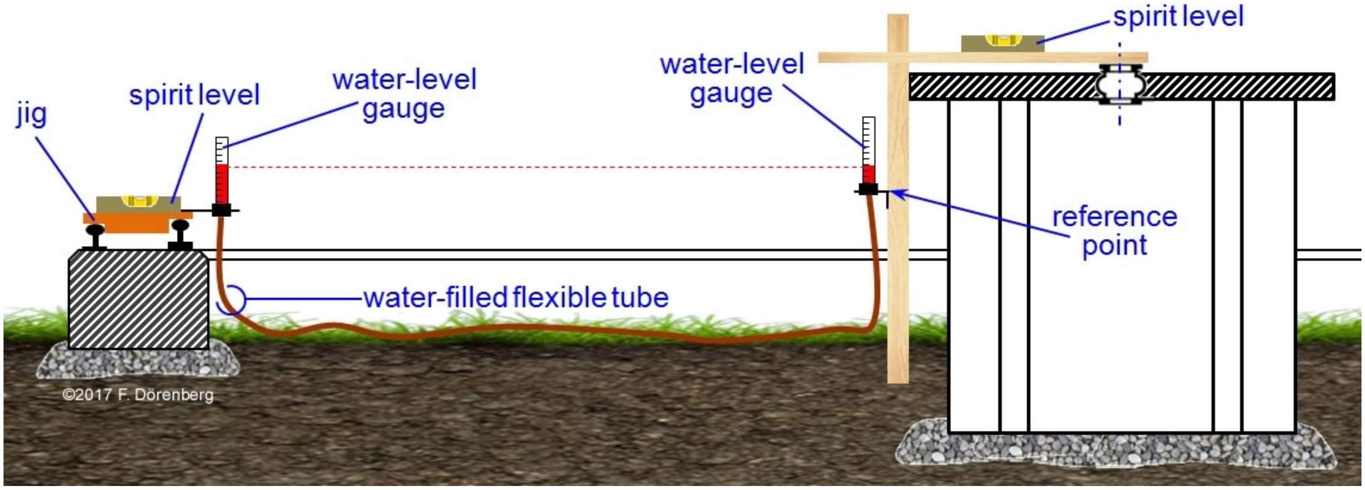


Fig. 18: Measuring relative height around the track and of the top of the round building
(source: adapted from Fig. 6 in ref. 193)

With a two-tube water level, the height of the top of the inside rail is measured at rail gauge rod number 1. This height is also marked on the pole. The relative height between top of the rail and ball bearing flange can now be determined with a ruler. The height of the inside rail is then measured at every fourth rail gauge rod (i.e., at 20 points in total).

Obviously the circular rail track was not transported to the "Bernhard" sites in one piece. Rather, they were delivered as sections of curved rail. It is unknown which type of rail joints were used:

- Conventional joints with a small expansion gap (*D*: "Stoßlücke"). The rail sections are connected with so-called "fishplate" joint-bars (*D*: "Schienenlasche") and bolts through the rail. The "fishing" is the vertical web between rail head and rail base. The gaps cause the familiar clickety-clack noise when the train wheels bump over them. There is a tie underneath both of the joining rail ends. None of the "Bernhard" tracks have pairs of ties that are placed right next to each other. So it is unlikely that this type of joint was used.
- Expansion joints (a.k.a. "breather switch", "adjustment switch", *D*: "Dehnungsfuge", "Schienenauszug"). The ends of the mating rail sections are tapered diagonally, and are not bolted together with fishplates. This type of joint allows for smoother transitions (= reduced noise and vibration) than conventional joints.
- Fusion-welded seamless joints. The welding is done on-site with the "Thermit" process that is described below. The result is a *continuous welded rail* (CWR, *D*: "durchgehen geschweißtes Gleis", "lückenloses Gleis"). Such rails need very solid anchoring, in order to to avoid warping of the tracks due to thermal contraction/expansion (e.g., "sun kink").
    - The "Bernhard" track has a length of π x track diameter = π x 21.5 ≈ 67.5 m. The expansion of steel rails is ca. 12 mm per °C per km. Concrete has a expansion coefficient of 10 mm per °C per km. Assuming a very moderate summer-winter difference in rail temperature of 50 °C, the relative expansion would have been ca. 6.8 mm (≈1/4 inch). Note that this is a steady-state value, as steel and concrete have different thermal inertia.
    - For CWR, the *Deutsche Bahn* installs a heavy concrete rail-tie every 60 cm. To minimize expansion/contraction forces, the rails are installed when the

temperature is around 20 °C. The ties of the "Bernhard" track are spaced by... 60 cm!

Fig. 19: Three standard types of rail joints
(left-to-right: conventional joint, expansion joint, seamless joint)

The "Thermit" process was discovered by the German chemist Hans Goldschmidt around 1890. He was a student of the German chemist Prof. Robert Bunsen (yes, of the famous "Bunsen burner" - actually the "Bunsen & Desaga" burner). Goldschmidt patented the process (originally intended for purifying metals) in Germany 1895, and named it "Thermit". It is a simple but intense exothermal reaction: a mixture of powdered iron oxide (commonly known as "rust") and aluminum is converted into iron and aluminum oxide, plus enough heat - over 2400 °C (4300 °F) - to fully melt the mixture in a matter of seconds! The reaction is typically started by igniting a magnesium "sparkler" stick or ribbon that is put into the mixture. Unlike blast furnace smelters, basically no external heat needs to be applied. The aluminum slugs will float on top of the melted iron. The mix normally contains additives, to obtain the desired steel alloy. The process can be used for welding large steel parts, such as shafts, cables, pipes, and rails. It can also be used for casting of parts, and for under water welding. The first commercial welding application were tramway rail projects in Essen/Germany in 1899 and Berlin in 1901. The *deutsche Reichsbahn* followed in 1928. The process was patented in the USA in 1928, by the *Metal & Thermit Company* (named *Goldschmidt Detinning Company* until the first world war). Ever since the 1920s, it is the standard process world-wide for welding rail tracks. The intense pyrotechnic process has also found military applications (grenades, incendiary devices, etc.). The aluminothermic Thermit rail-welding process is as follows:

The ends of two rail sections that are to be welded, are brought together with 2-3 cm spacing (1 inch) and are aligned.

The gap is clamped with a two-part ceramic shell that has the same shape as the cross-section of the rail. This is needed to avoid the molten steel from running off. The sides of the clamp are sealed with special molding sand.

The ends of the two rail sections are pre-heated to ca. 1000 °C with a blow torch.

A ceramic "funnel" pot is placed on top of the molding clamp, and is filled with Thermit-mixture.

The mixture is ignited with magnesium ribbon, and then boils. The entire process only takes about 25 sec.

After cooling off, the pot, clamp, and slugs are removed.

The weld is ground, to get a smooth rail head.

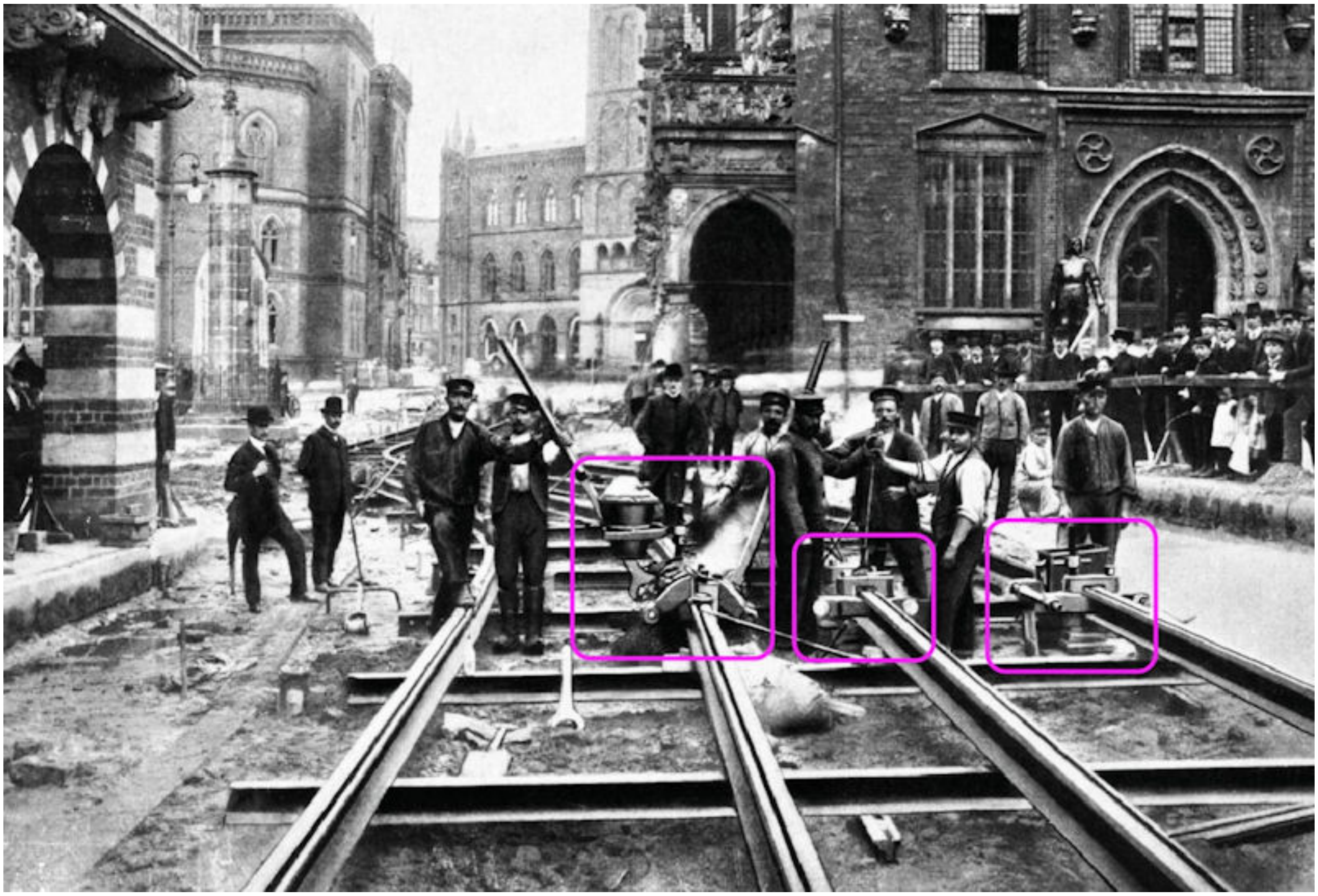


Fig. 20: Thermit-welding of tramway tracks in the city center of Bremen/Germany around 1900
(source unknown)

Rails that are dirty (grease, decomposing leaves (finally explained in 2020, see ref. 265), rain, snow, and ice) significantly reduce traction of locomotives. Traction heavily depends on the adhesion coefficient ***μ*** between the steel wheels and the steel rails (ref. 158):

μ ≈ 30% for clean, dry rails.
μ ≈ 20% for rails that are clean but wet or icy, and for greasy rails.
μ ≈ 5-10% for rails covered with (decomposing) plant leaves.

This is why the final version of the "Bernhard" stations had a track-cover that moved with the rotating installation (p. 20 in ref. 183). Not only to maintain traction and avoid disturbance of the constant speed ("Gleichlauf"), but also to avoid accidents.

Based on available photos, such a cover was installed at least at the "Bernhard" stations Be-4 at La Pernelle (though not yet in March of 1943), Be-8 at Schoorl/Bergen, Be-9 at Bredstedt, and Be-10 Hundborg. The "Bernhard" station Be-0 at Trebbin did not have such a cover.

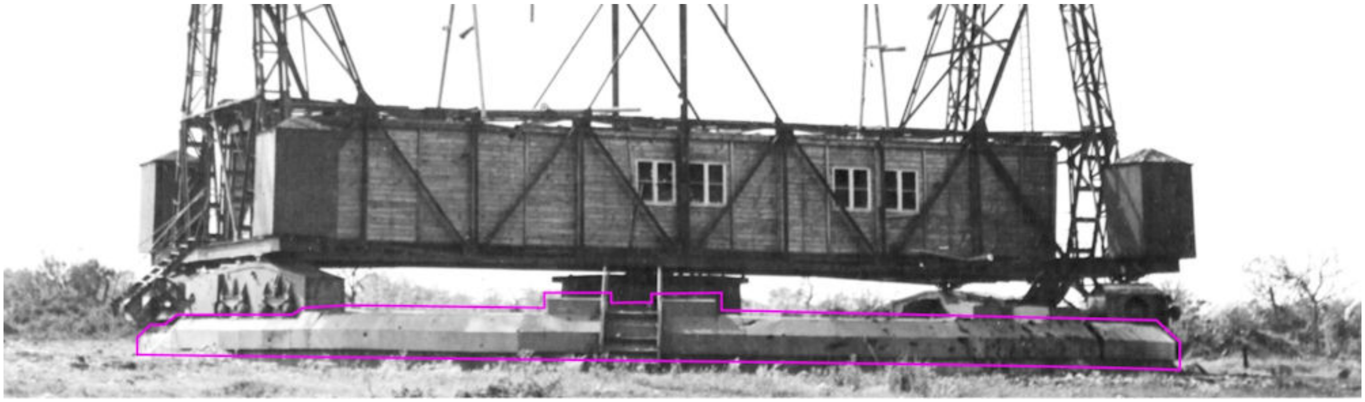


Fig. 21: A steel track-cover moves with the rotating platform
(station Be-4 at La Pernelle, France, July 1944)

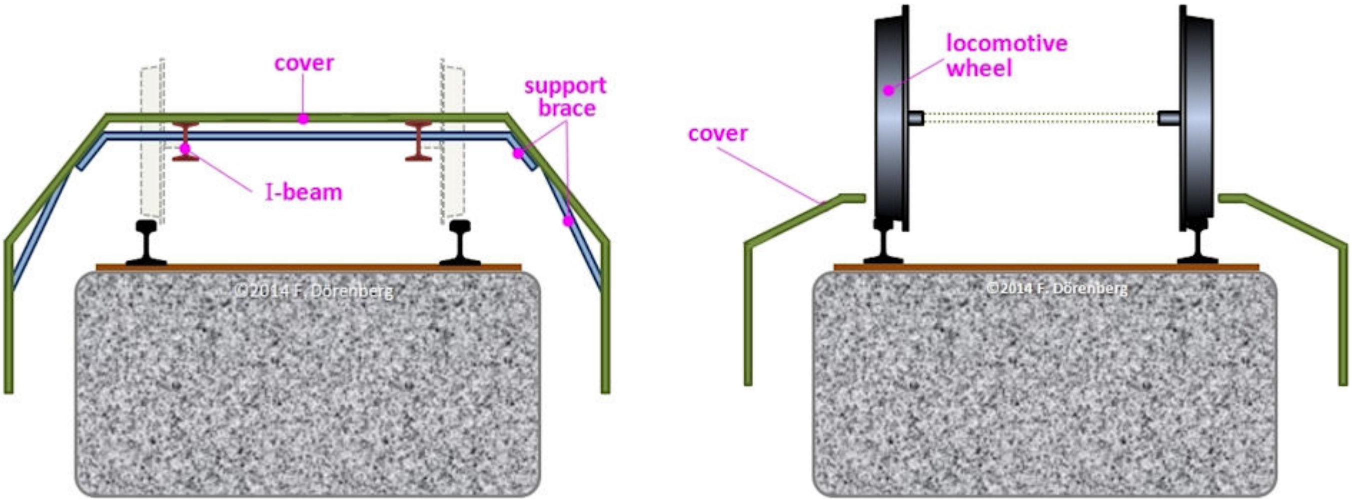


Fig. 22: Cross-section of the track cover - made of sheet metal and support braces

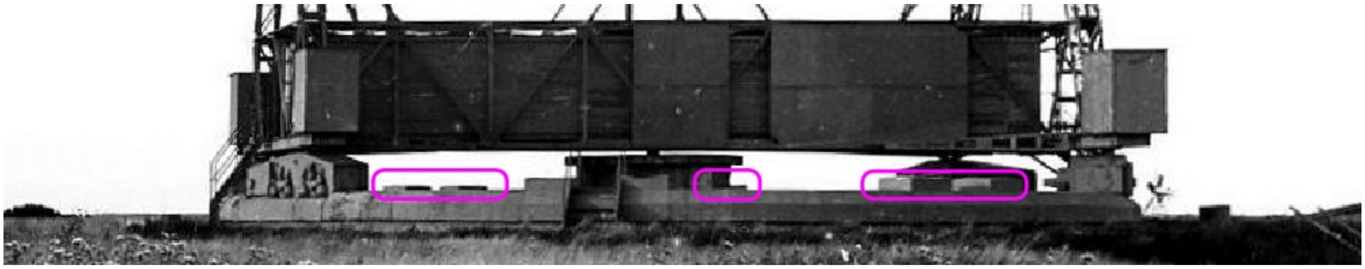


Fig. 23: The cover has a "box" around each pair of support wheels
(Station Be-10 at Hundborg/Denmark)

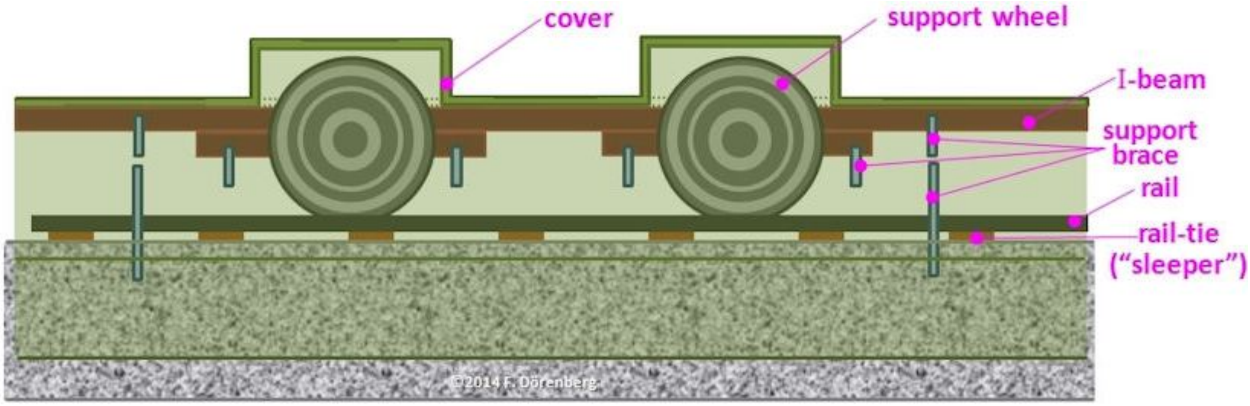


Fig. 24: Side-view of the track cover - "box" around each pair of support wheels

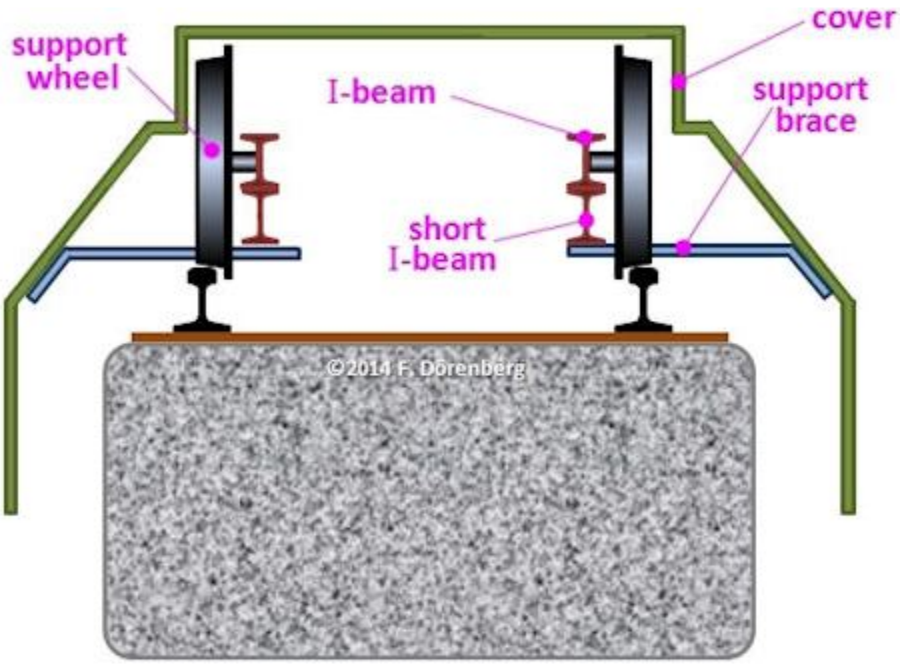


Fig. 25: Cross-section of the track cover - "box" around each pair of support wheels

The small round building below the rotating cabin contained electronic equipment. Operators had to get to an from that building, even when the station was rotating. So they had to cross the rail track. To facilitate this, two sets of stairs were integrated into the moving rail cover, placed at opposite sides of cabin (p. 20 item 6 in ref. 183, though some photo material suggest only one such set of stairs...).

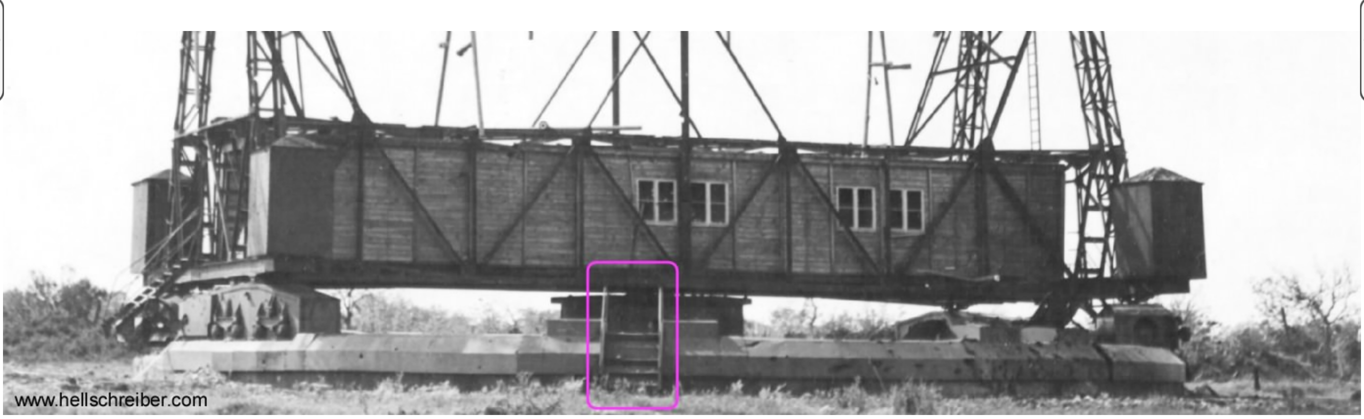


Fig. 26: One of the two sets of stairs for crossing the covered track
(Station Be-4 at La Pernelle/France)

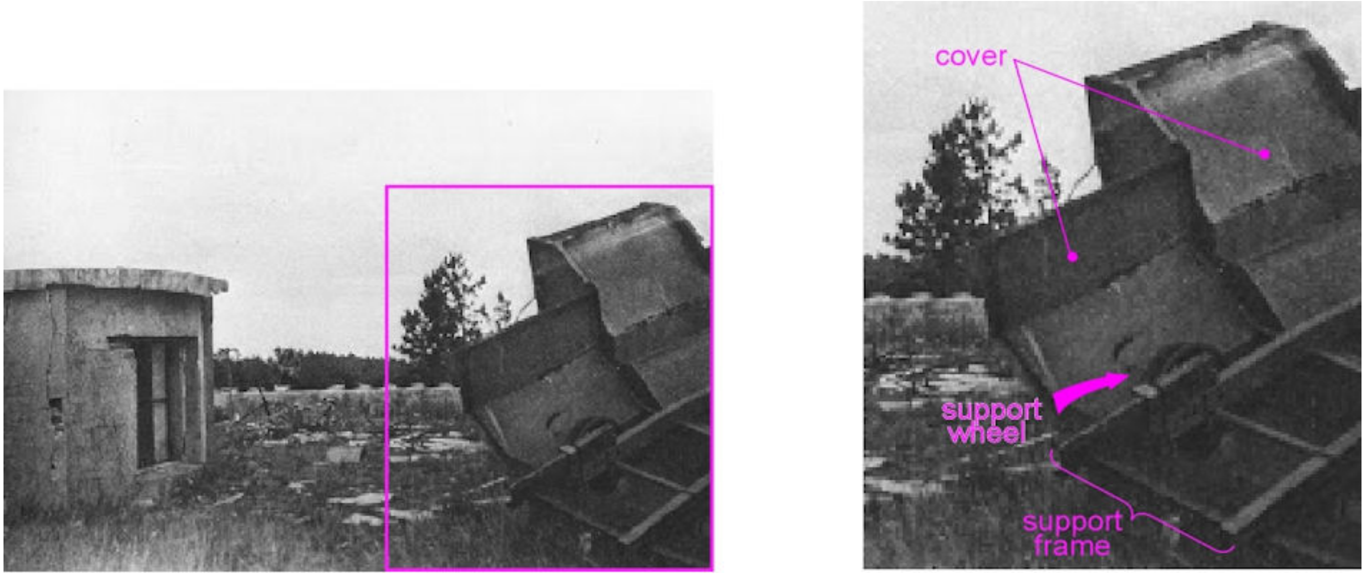


Fig. 27: The destroyed "Bernhard" Be-8 at Bergen/Schoorl - upside-down section of track cover
(source: ref. 127)

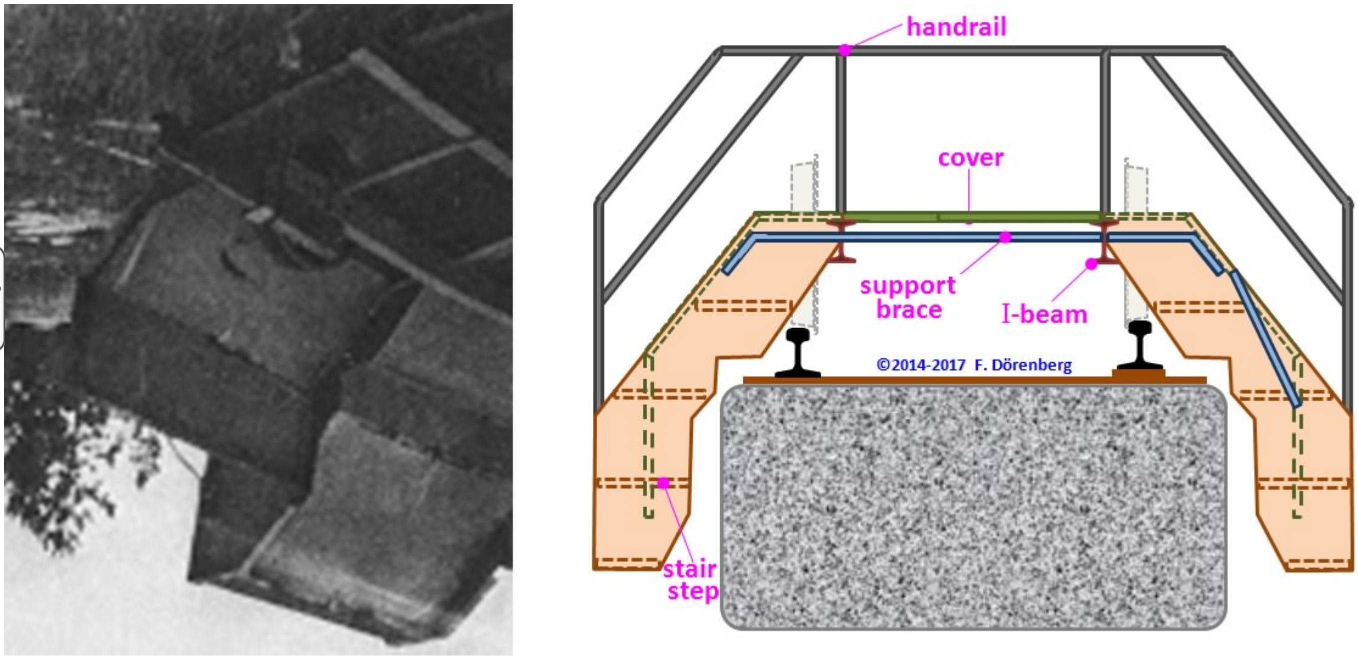


Fig. 28: Staircase section of the track cover
(photo - turned right-side-up: ref. 127)

The wooden cabin on the turntable has an entry door at each end. Stairs are attached to the turntable, to get in and out of the cabin, while rotating or stationary (p. 20 item 4 in ref. 183).

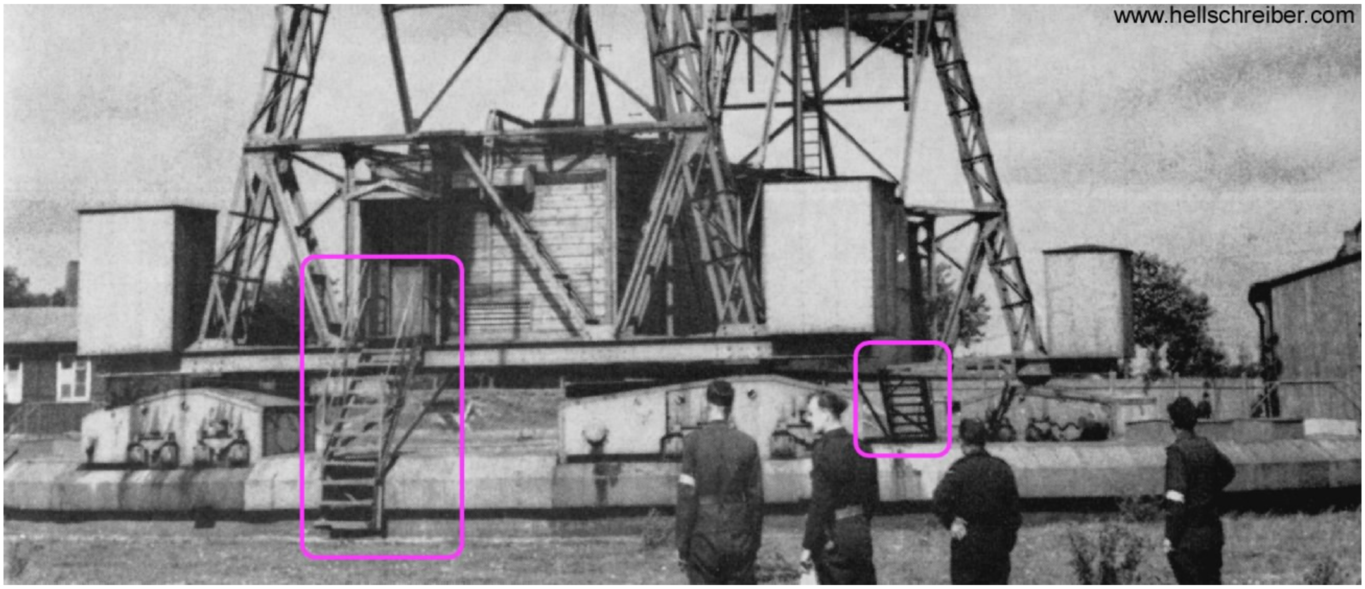


Fig. 29: The stairs attached to the turntable, providing access to both ends of the cabin
(Station Be-9 at Bredstedt)

THE ROUND CENTRAL-SUPPORT BUILDING

At the center of the concrete ring of the "Bernhard" beacon, there is round brick building with a flat concrete roof:

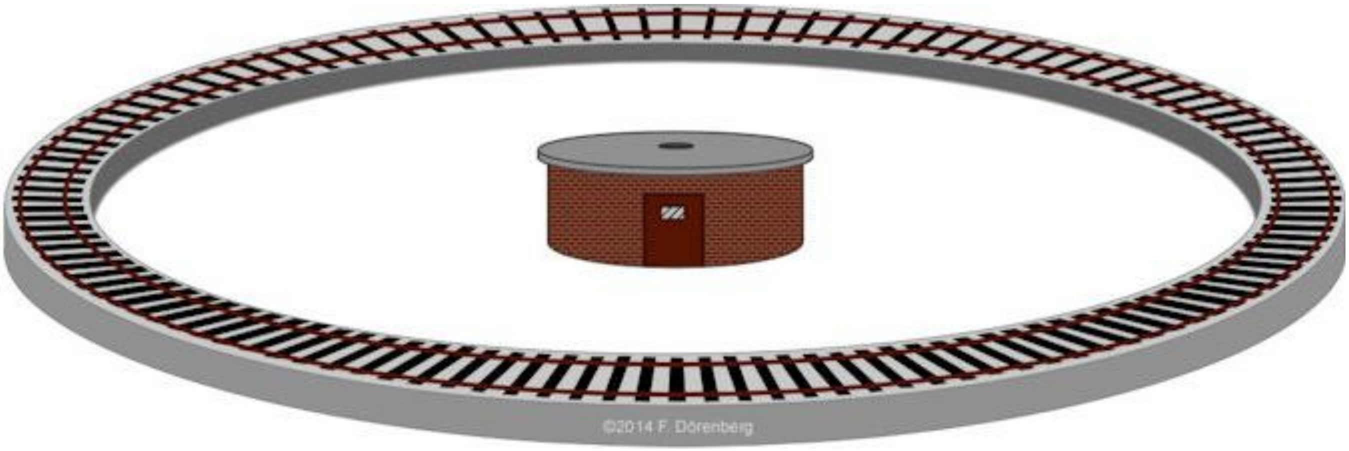


Fig. 30: Concrete ring with central- support building

Fig. 31: Left-to-right - the round building of Be-7 at Arcachon, Be-14 at Aidlingen, and Be-3 at Le-Bois-Julien
(photo Le-Bois-Julien: ©2006 T. Oliviers, used with permission)

Fig. 32: The round building of Be-8 at Bergen/Schoorl (left), and Be-12 at Nevid/Plzeň
(sources: photo Be-8: ref. 127; Be-12: © Jacek Durych, used with permission)

This small building has two functions:

Central support for the heavy rotating superstructure (= cabin and antenna systems) of the beacon.

Stationary equipment room (*D*: "feststehender Geräteraum").

EQUIPMENT ROOM

The following items were installed in this equipment room below the rotating superstructure (see Figure 33):

A 15-ring slip-ring assembly, suspended from the ceiling of the equipment room. Slip-rings allow electrical lines to traverse continuously rotating mechanical joints. The rotor of the assembly was driven by a shaft that descended through the ceiling of the equipment room (see Fig. 43) and rotated with the superstructure. The slip-rings passed electrical power and signals between the stationary equipment room and the rotating cabin above it.

Optical encoder disk assembly, suspended from the slip-ring assembly and driven by the shaft of that assembly.

Three audio tone modulators:

a constant 1800 Hz audio tone for the pointer beam transmitter

2600 Hz audio tone pulses, representing the compass scale in Hellschreiber format, for the compass scale transmitter.

2600 Hz audio tone pulses, representing the command-message text string in Hellschreiber format, for the compass scale transmitter (when replacing transmission of the compass scale with the command-message).

Two Hellschreiber printers (the same HS 120 printers as used in the aircraft), for printing:

the signals transmitted by the beacon, as received by a remote receiver.

the command-message text string, to verify it before actually transmitting it (only installed at a few beacons).

A patch board and associated patch cord, for composing the up to 10 characters of the command-message (only installed at a few beacons).

A power distribution and control panel. The panel also indicated the exact rotational speed of the optical disk (and, hence, of the beacon), as measured by a tachometer track on that disk.

A switch for selecting the forward/reverse rotational direction of the beacon.

An emergency shutdown button.

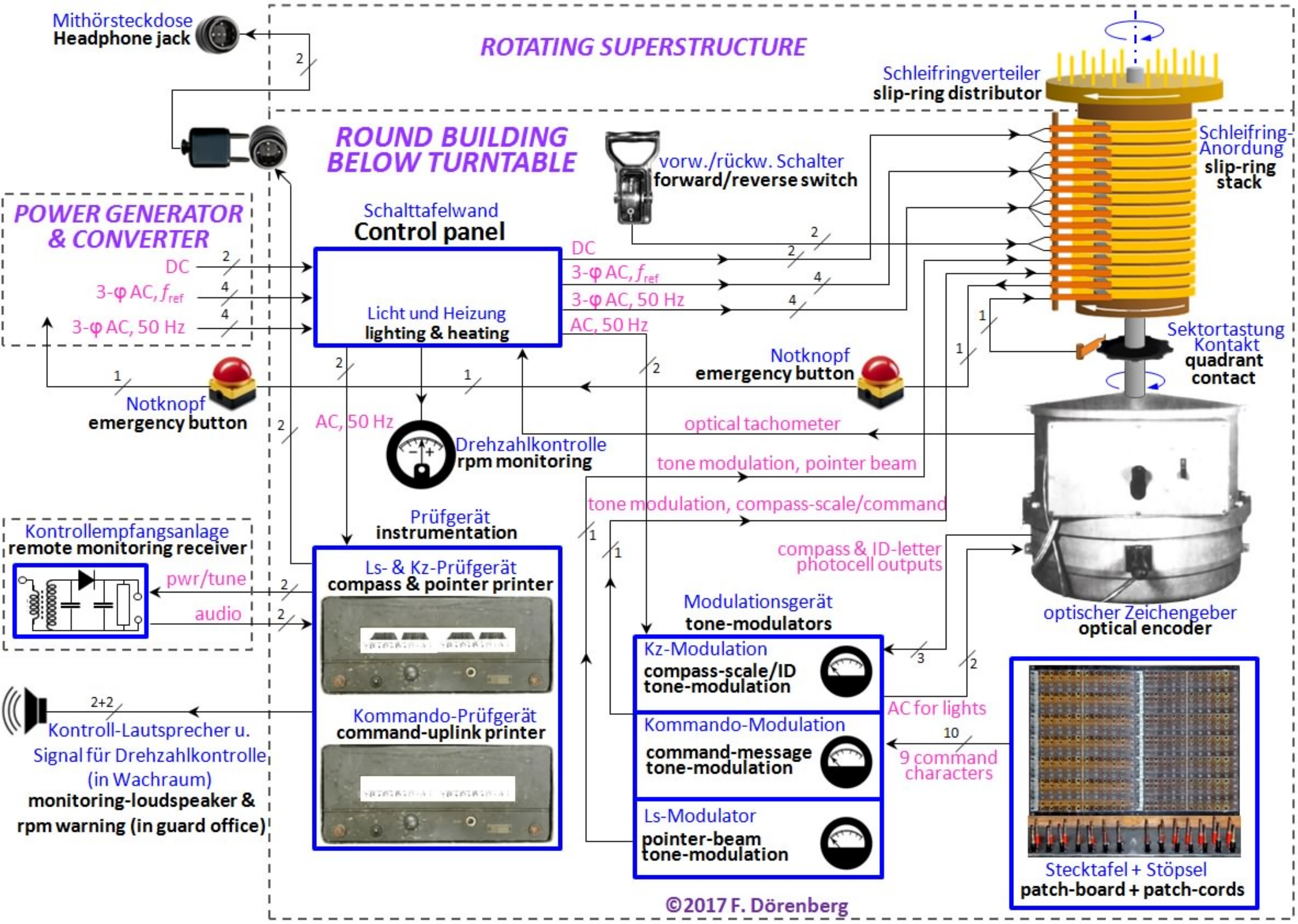


Fig. 33: The round building below the rotating superstructure - equipment and interconnections

(source: derived from ref. 189 and 190)

The photo below is the only one that I have of the inside of the equipment room:

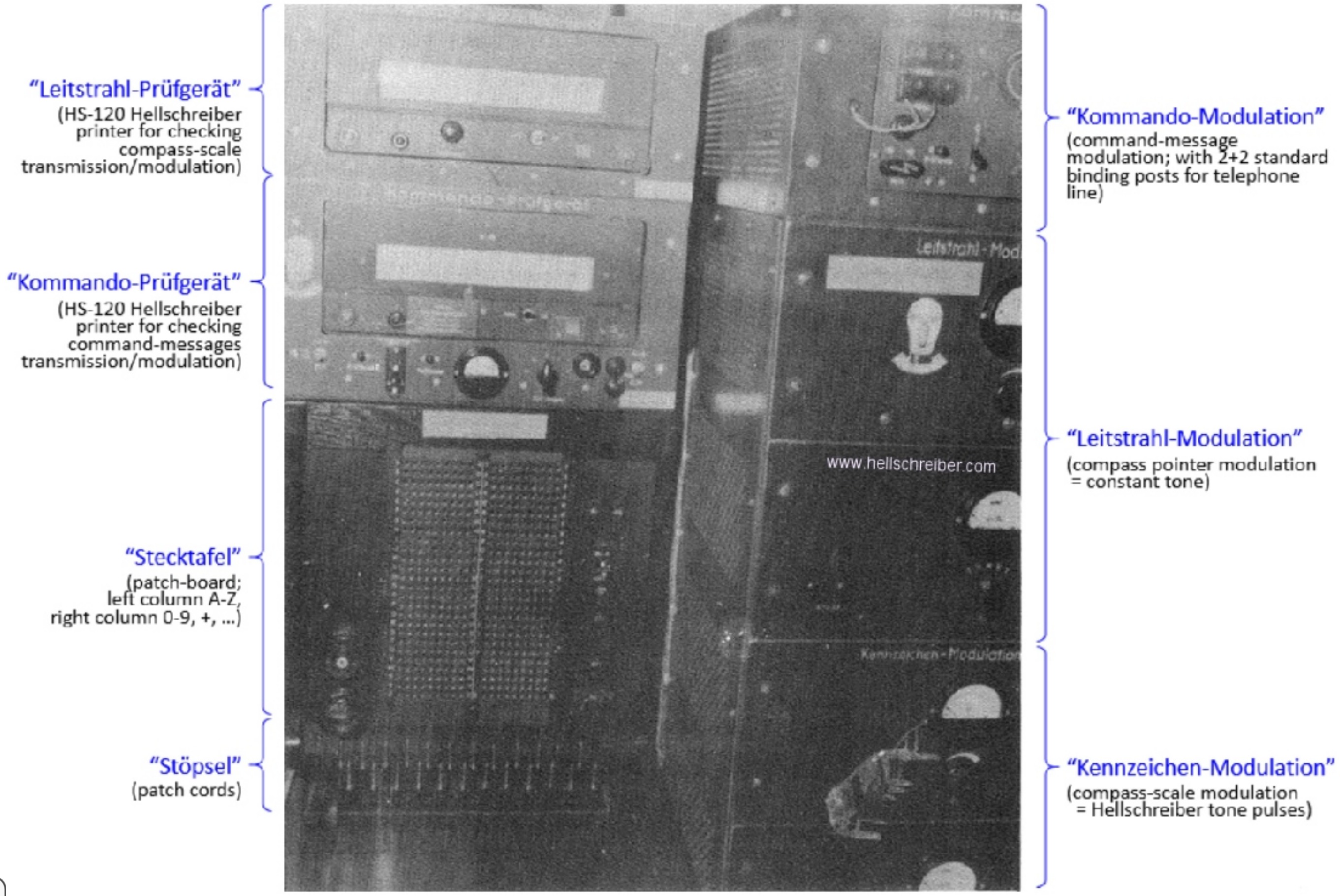


Fig. 34: Equipment inside the round brick equipment room of the Bernhard installation at Hundborg

(source: Figure 30 in ref. 93A)

The 15-ring slip-ring assembly passed the following electrical power to the rotating cabin:

DC, for the DC motors in the four locomotives. The associated fuses had a rating of 160 A / 500 V (ref. 189).

3-phase AC, constant frequency. Used for the synchronous AC motor in locomotive nr. 4. The associated fuses were rated at 80 A / 500 V.

3-phase AC, nominally 50 Hz (directly from the public power grid or a local backup generator). Used for the power supplies of the two transmitters, as well as general lighting and heating.

The slip-ring assembly passed the following other signals to and from the rotating cabin:

Constant-tone audio modulation for the pointer beam transmitter.

Hellschreiber tone-pulse audio modulation for the compass scale transmitter.

Quadrant-keying ("Sektortastung") to both of the transmitters, by a switch contact that is actuated by a notched disk on the shaft of the slip-ring assembly. Most likely, this was (or could be) used to not transmit during the entire 360° rotation, but only in a specific limited directional range. This could be used to avoid detection of transmissions by Allied monitoring stations, e.g., in Britain. Beacons operating this way were referred to as "Sektorfunkfeuer" (p. 16 in ref. 181).

Switch closure of the emergency shutdown button on the superstructure.

No photos are available of the slip-ring assembly. As an example, the photo below shows the slip-ring assembly of German "Panther" and "Tiger" tanks of the same era. Their slip-rings have a diameter of 12 cm (≈5 inch). There are four brass rings for electrical power (12 & 24 volt, 50 amps) and seven rings for communication and lighting.

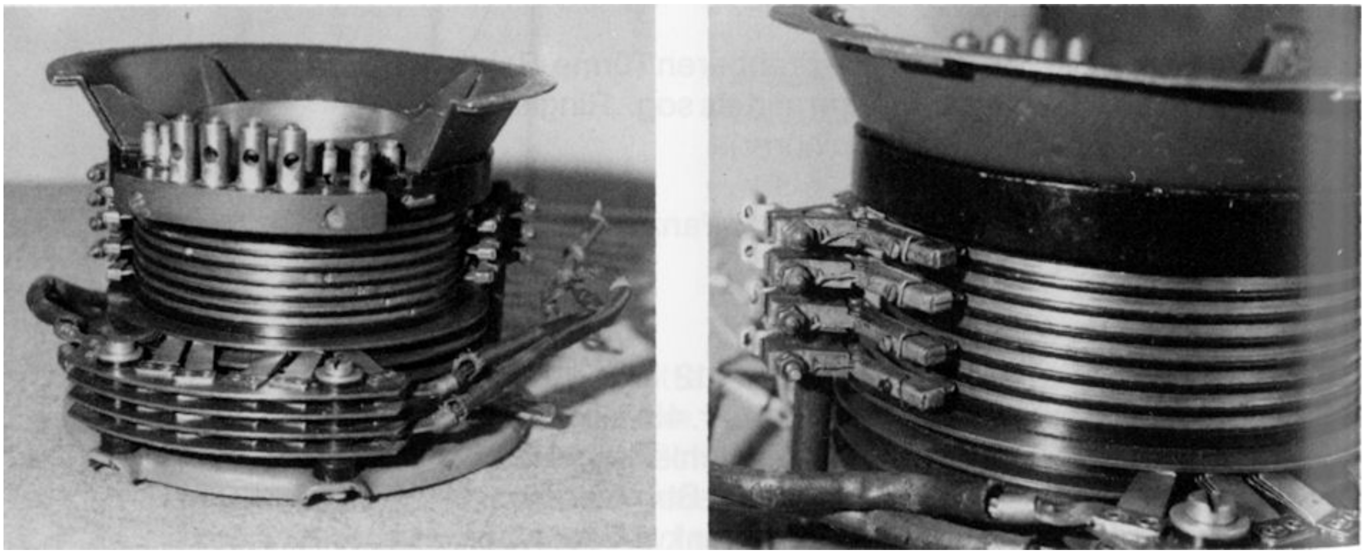


Fig. 35 The slip-ring stack assembly of Panzer V "Panther" and VI "Tiger" tanks
(source: ref. 145A)

The standard "Bernhard" equipment included a full set of 52 spare tubes (valves), per sheet 19 & 20 in ref. 189 (pdf pp. 22, 23):

For the modulators and transmitter-keying units:

10x RV12P2000, 1x RG12D60, 1x AZ12, 6x RV275, 4x RV335, 4x RG62, all made by Telefunken.

1x STV100/25Z and 1x STV280/80 made by Stabilovolt.

For the measurement/monitoring equipment:

3x RV12P2000, 6x LV1, 6x RG12D60, 1x RGN4004, 3x RV275, 2x RV335, 2x RG62, all made by Telefunken.

4x STV150/15 and 1x STV280/80, made by Stabilovolt.

CONSTRUCTION

The walls of the building are made of brick. There are four windows of 1.2x1.2 m (4x4 ft), and a door. Whatever equipment was installed inside this building, it must have fitted through the door or a window. Floor-to-ceiling height inside the building is about 3 m (10 ft), so the floor is well below the base of the concrete ring. This is why there is a small trench and steps that lead down to the door.

The three diagrams below show the cross-section (with measured dimensions) of the concrete ring and round building of the "Bernhard" installation at Aidlingen/Venusberg, Arcachon, and Hundborg:

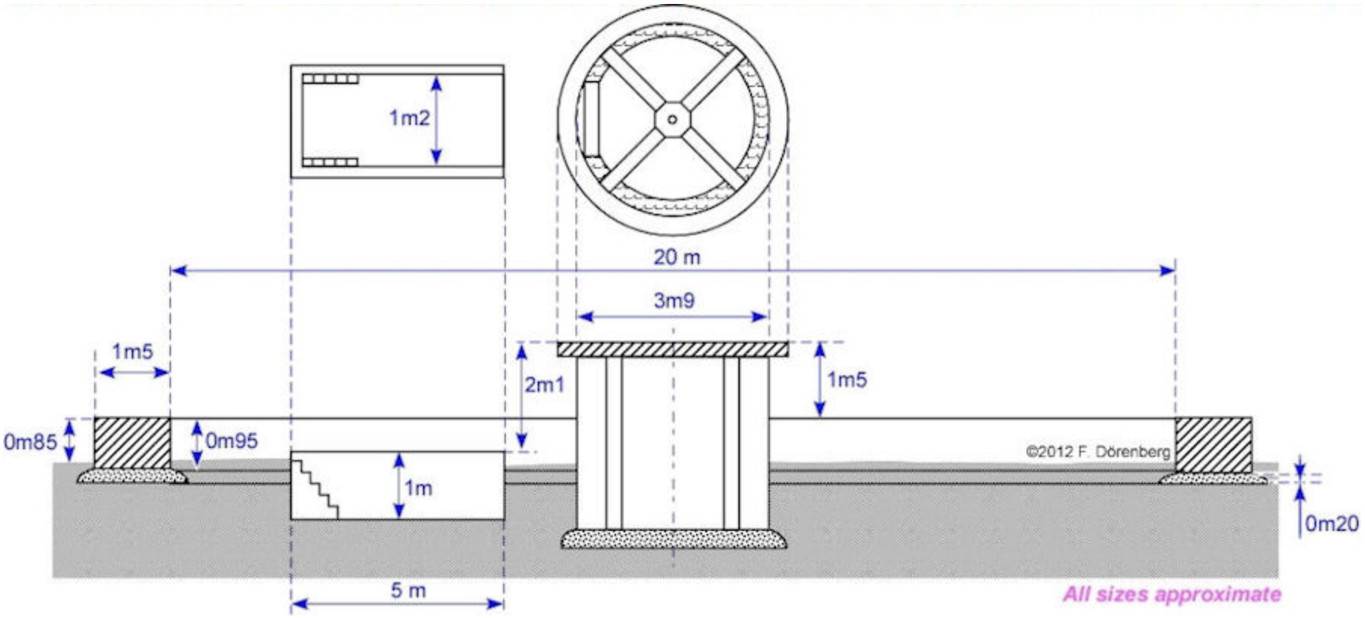


Fig. 36: Cross-section of the installation at ***Aidlingen/Venusberg***
(based on the measurements that I took in June of 2012)

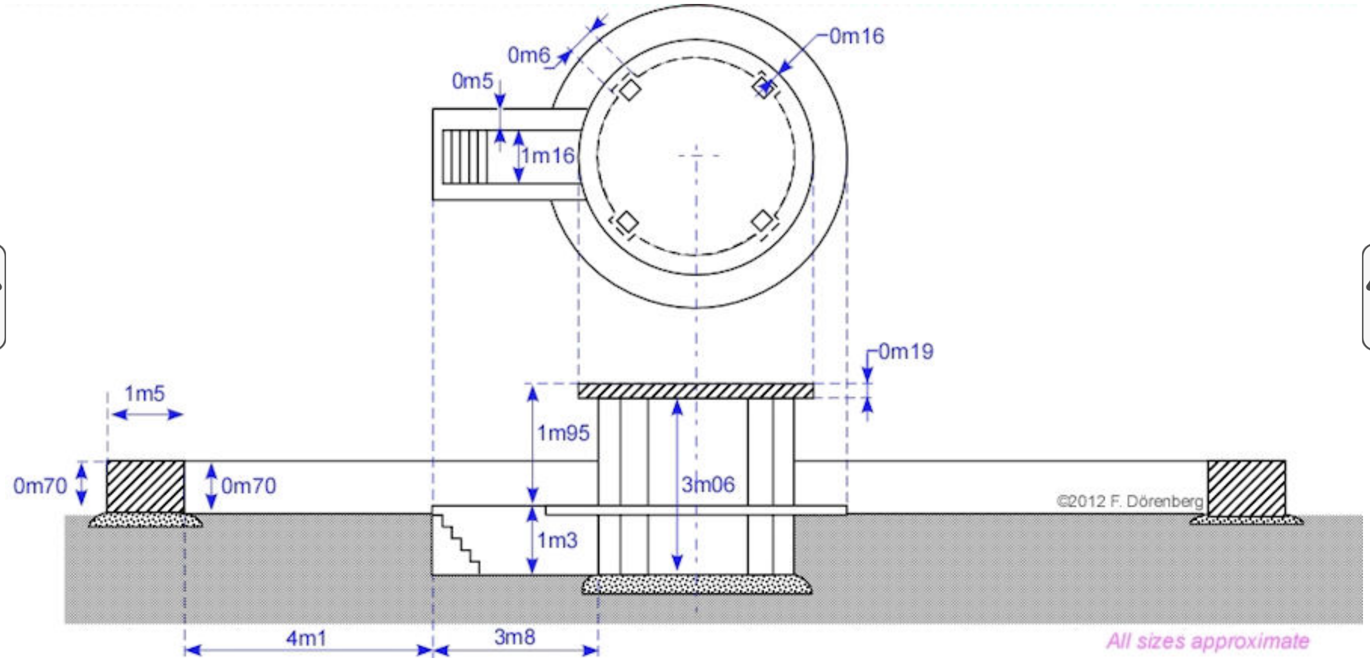


Fig. 37: Cross-section of the installation at ***Arcachon***
(based on the measurements that I took in July of 2012)

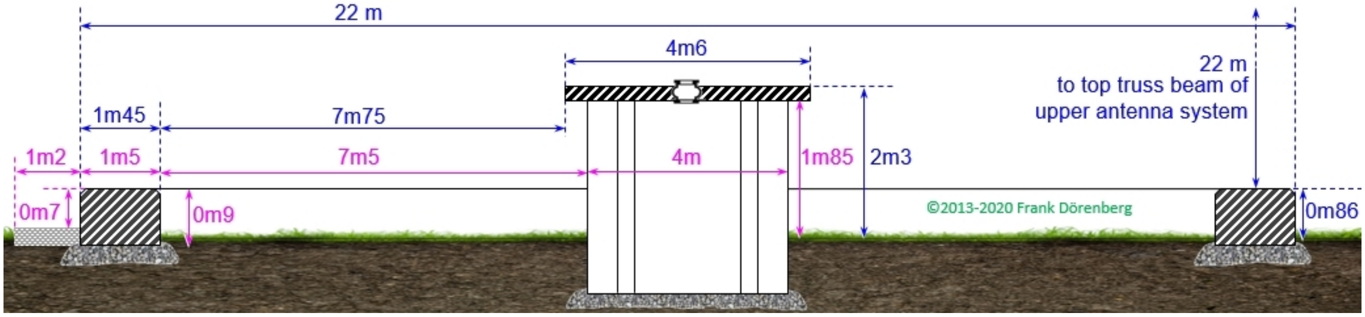


Fig. 38: Cross-section of the Bernhard ring on Gåsbjerg hill at ***Hundborg***
(based on ref. 115)

The concrete roof of the round building is supported by four columns, made of massive steel I-beams (H-beams, *D*: "Doppel T Träger"): the flanges are 30 cm (1 ft) wide and 24 mm (1") thick! The web of the beams is 32 cm (12½ inch) wide and 15 mm (0.6 inch) thick. So these columns have a cross-section of 30x37 cm. The columns are spaced evenly in the round wall. The roof-joists are made of the same heavy I-beams. Why would such a solid, heavy construction be necessary? The rotating superstructure weighed 120 metric tons (265 thousand lbs). Assuming the weight was distributed evenly between the four locomotives and the central support, the roof had to carry 120 / 5 = 24 metric tons (53 thousand lbs) statically!

The following diagrams show more details of the steel structure:

4 large steel I-beam columns, with end-plates. The flange of these vertical I-beams is 30 cm (1 ft) wide, and the height of the beams is 37 cm (1 ft 3")

4 large steel I-beam joists, with a joist-to-column brace and a triangular filler plate. The brace is a heavy steel plate (3 cm thick), as wide as the flanges of the columns and the joists. The joist and brace are mounted to the column with 8 bolts. The brace prevents the structure from racking (= sideways swaying of the tops of the columns). The brace is mounted to the column at a 50° angle.

4 steel doubler-plates, to better transfer vertical forces on the joist to the column, and to distribute any bending force to both flanges of the columns. The doubler-plate is mounted onto the end-plate of the column with 8 bolts, and to the joist with eight bolts.

2 identical steel octagonal plates, to interconnect the four joists. Each joist is mounted to the two octagonal plates with 6 bolts. The plates have hole at the center.

4 small steel plates that form the sides of a box that is placed between the octagonal plates. The corners of the box are butted up against the web of the joists, but do not appear to be welded to them. The function of the box is unclear - possibly to prevent the center of the top octagonal plate from being pushed down, possibly they where used to pre-assemble the two octagonal plates.

4 small steel I-beams, connecting the joists above the braces. This makes the structure torsionally stiff. I found no sign that the columns are interconnected at the bottom.

Numerous steel concrete reinforcement rods/bars ("rebar"), placed radially inside the concrete of the roof. The ends of the rods are curled back.

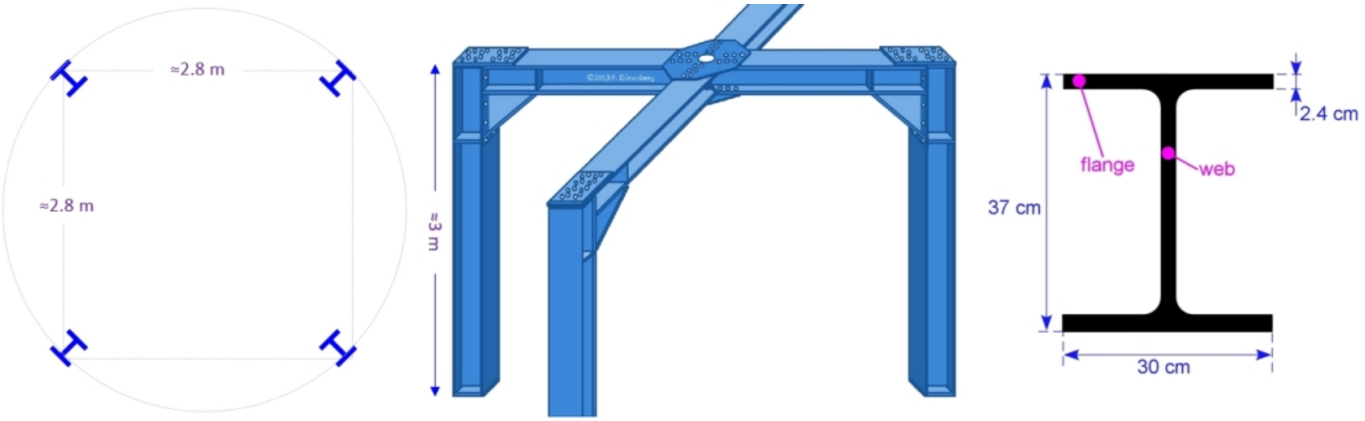


Fig. 39: The major elements of the massive steel support structure of the round building
(based on my measurements of the "Bernhard" Be-14 ground station)

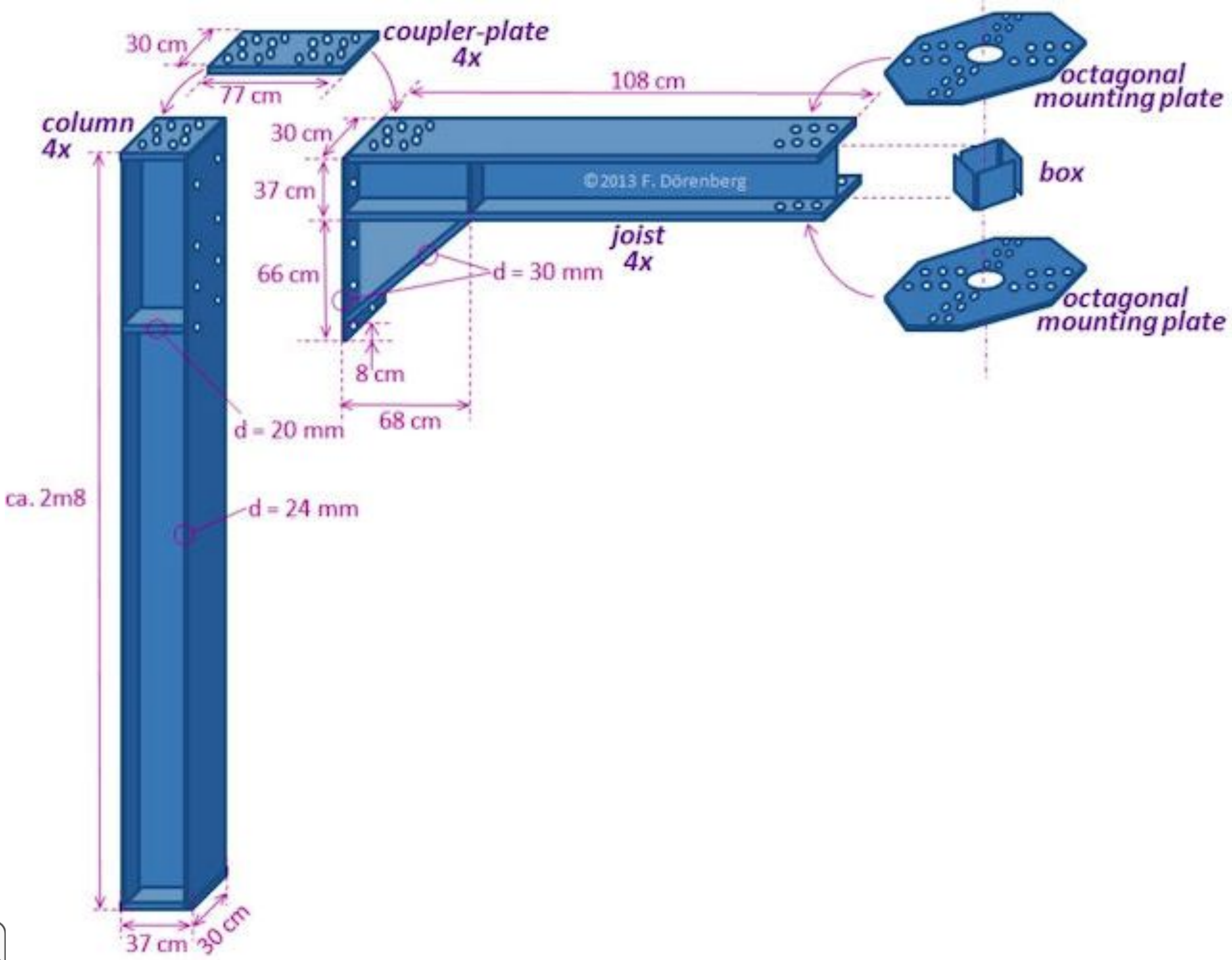


Fig. 40: Dimensions of the steel "skeleton" of the round building
(based on my measurements of the "Bernhard" Be-14 ground station)

A doubler-plate reinforces the joint of each joist and the associated column:

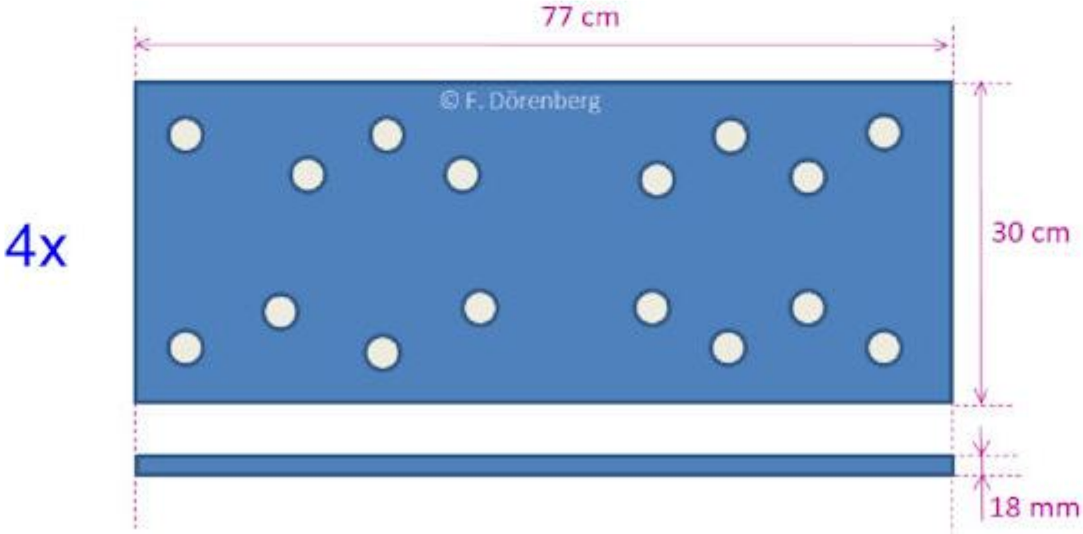


Fig. 41: Dimensions of the column-to-joist doubler plate
(based on my measurements of the "Bernhard" Be-14 ground station)

Fig. 42: Details of the steel support structure of the "Bernhard" Be-14 ground station

Two heavy octagonal plates interconnect the four large I-beams joists at the center of the roof. One plate on top, one from below. There are two brackets on the bottom plate, for suspending equipment. The space between the brackets is about 55 cm (22 inch).

Fig. 43: The octagonal mounting plate against the ceiling - with mounting brackets to suspend equipment

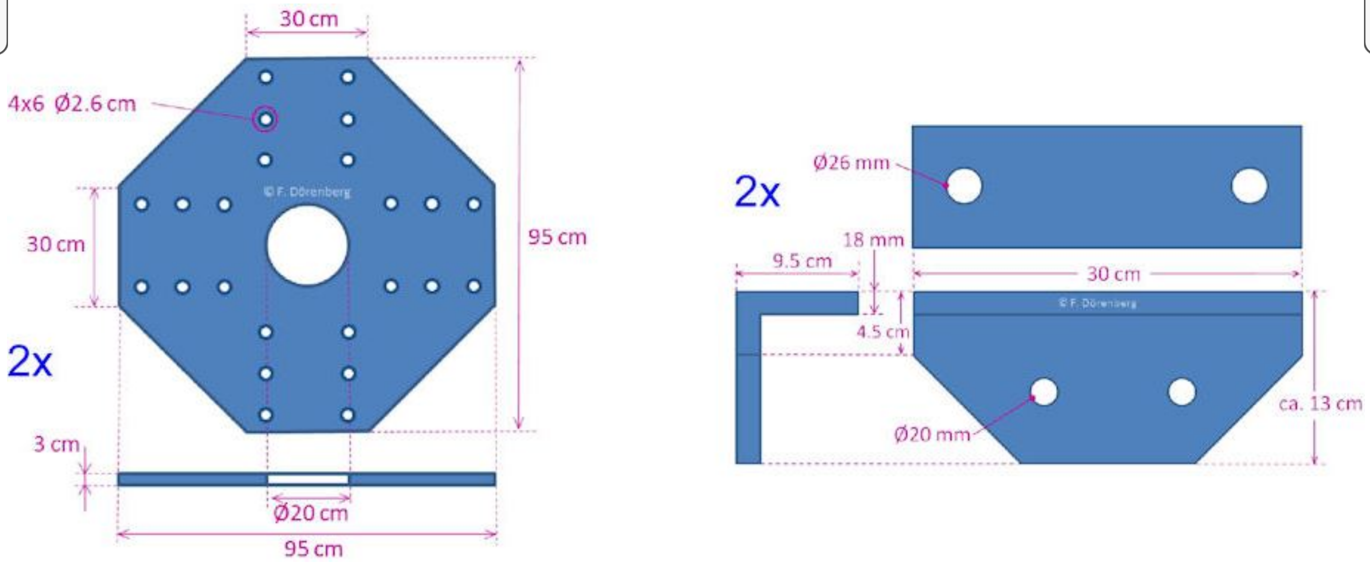


Fig 44A: Dimensions of the octagonal mounting plates and associated brackets
(based on my measurements of the "Bernhard" Be-14 ground station)

Four smaller I-beams make the top of the structure torsionally stiffer, by bracing the four main joists:

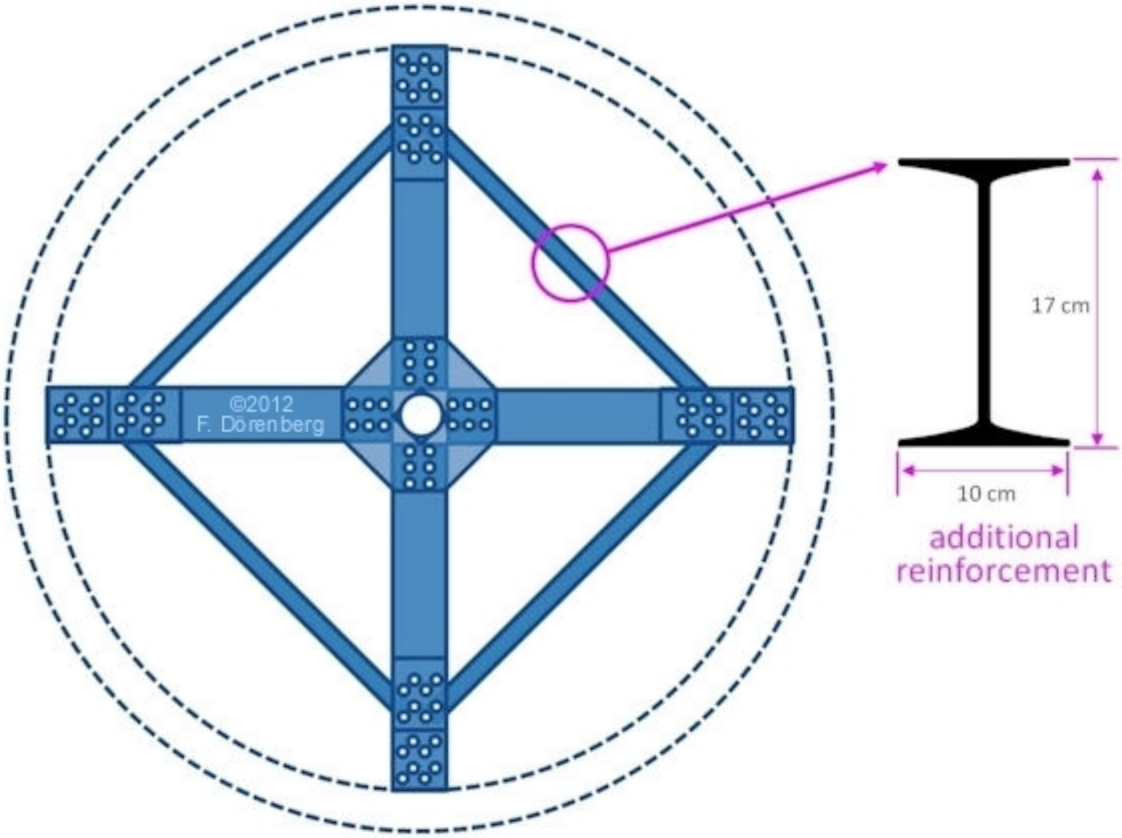


Fig. 44B: Top view of the steel support structure
(based on my measurements of the "Bernhard" Be-14 ground station)

The next photo shows the remains of the steel structure (upside down), after removing the walls and collapsing the roof:

Fig. 45A: The remains of the steel structure of Be-12, after destruction of the building in 2015

(source: © jdvlavicka)

Fig. 45B: The remains of the steel structure at Be-12, after destruction of the building in 2015

(source: © jdvlavicka)

The baseline for the "Bernhard" ground station was the experience gained during 1939-1941 with the ring and the antenna system of the "Knickebein" rotatable beam system. It operated in the same 30-33 MHz frequency range as the "Bernhard/Bernhardine" system. At the center of the "Small Knickebein" ring, there also was a central support structure: a concrete block measuring 1.4 x 1.4 m, with a rotatable steel pivot on top:

Fig. 46B: The concrete central support block with pivot of "Small Knickebein" station Kn-13

(compare with Fig. 39 above; source photo of I-beam remnant & spacing measurements: ref. 230Q1)

...**except for the last Small Knickebein that was built**: Kn-13. It did not have a concrete block, but an I-beam structure with four corner-columns. It had to be rigid and hold the above pivot construction, to keep the rotatable antenna structure centered on the rail track. So, it must have had crossing joists - just like the "skeleton" of the "Berhard" central support, but significantly smaller and with a much lighter construction:

Fig. 46B: Remnant of a vertical I-beam of the central support structure of "Small Knickebein" station Kn-13

(compare to Fig. 39 & 45A/B above; source photo of I-beam remnant & spacing measurements: ref. 230Q1)

A very large ball bearing was installed at the center of the roof:

Fig. 47: The round building with the raceway of a large ball bearing in the middle of the roof

(Be-12 at Nevid/Plzeň; source: © Jacek Durych, used with permission)

It had an outer diameter of about 40 cm (≈16 inch). The ball bearing held a cylindrical tube, that rotated with the antenna system and the cabin. The bottom of this tube has a flange, for connecting to equipment that rotated with the tube. The tube had a diameter of about 14 cm (5½ inch).

Fig. 48: Tubular shaft descending through the roof of Be-6 at Marlemont and Be-10 at Hundborg

(source Hundborg photo: www.gyges.dk, used with permission; note the original wiring)

A small turntable is installed on top of the ball bearing, and the tube is attached to it from below:

Fig. 49: small turntable on top of the shaft
(Be-6 at Marlemont; note the large mounting bolts inserted into the turntable from below)

THE CABIN

Below the antenna installation, and rotating with it, is a steel truss bridge. The rectangular bottom frame of the bridge is made of heavy I-beams. It is supported by the four locomotives and by the round building at the center of the concrete ring. The upper frame of the bridge was suspended from the large lattice truss-joist of the lower antenna system.

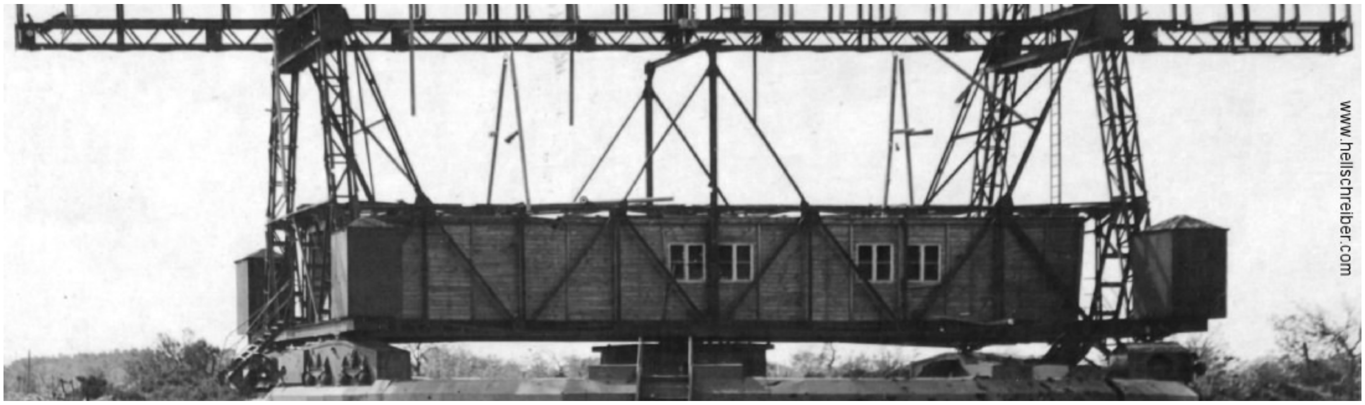


Figure 51: Cabin of Be-4 at La Pernelle/France

Inside the bridge is a long "co-rotating" wooden cabin ("mitdrehendes Holzhaus"). It measured about 20x4x3m (LxWxH, ≈66x13x10 ft), based on p. 20 in ref. 183, as confirmed by photometric analysis of available photos. Its length is close to the inside diameter of the ring (≈20.5 m). The cabin was made of heavy wooden planks. There is a entrance door and set of stairs at both ends of the cabin.

Ca. 1943, Telefunken contracted its standard antenna structure supplier, *Hein, Lehmann & Co.*, to provide "Panzerung von Holzhäusern" for 12 "Bernhard" stations (purchase order nr.

253/33163, ref. 177C). That is, for sheet-metal protection of the wooden cabin. "Panzerholz" is plywood that is covered with sheet metal armoring on one side or on both sides. The price was 4167 *Reichsmark* per BE-station. Based on general inflation data, this is equivalent to ca. US$21,900 or €20,250 (early 2017, ref. 177). The metal protection was only installed at five stations (Be-2, Be-3, Be-4, Be-8, and Be-10), before the course of the war intervened. The protective panels probably took the form of large panels that could be slid in front of the cabin windows, see Fig. 91 below. The wooden part of the panels involved *Fa. Rostock* in Trebbin (ref. 176A). This company operated three owned or leased sawmills in Trebbin (close to Be-0) since the early 1930s, and supplied wooden construction materials for a number of "radar" installations and other Wehrmacht constructions.

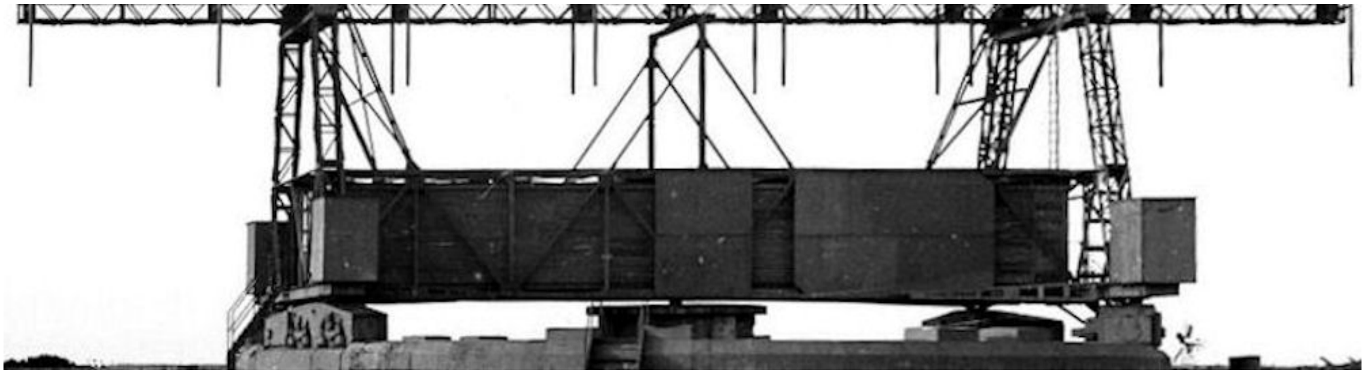


Fig. 52: The cabin at Be-10 Hundborg/Denmark - with protective siding panels

At some "Bernhard" sites, these sliding covers are on the *outside* of the bridge frame that suspends the cabin from the truss-joist. At other sites, these panels slide between the cabin and that frame.

The cabin contained the two transmitters, AC/DC electrical power distribution and controls for the locomotive motors, and for cabin heating & lighting. See the "Electrical & signal distribution" section. Ref. 13 (p. 4.09) suggests that the cabin was divided into three sections. The section on the right (looking at the front of the antenna system) contained the transmitter equipment. This is confirmed by the layout diagram of the Be-0 station. The center section housed the controls for the four electric locomotives. The section on the left was a workspace. A plaque at La Pernelle (Be-4) states that it had one or more beds in it.

The photo below shows the power distribution and control panel ("Schaltwandtafel") inside the rotating cabin of Be-10 at Hundborg. The spoked handwheel in the lower right-hand corner (sheet 15/20 in ref. 189) belongs to the circuitry for bringing the locomotives up to speed from standstill, and for slowing down to standstill ("Kontroller und Anlaßwiderstand"). Also see the "Electrical & signal distribution" section.

Fig. 53: German engineer describing controls in the cabin of Be-10 at Bredstedt to a member of the RAF-ADW

(source: Australian War Memorial photo SUK14636, public domain; ca. August 1945)

THE FOUR CORNER-BLOCKS

At each of the four corners of the cabin, there is a "block" or square silo of about 1½x1½x2 m (WxDxH; ≈5x5x6½ ft). They are mounted on a cantilever, away form the main cabin and above the rear bogie of the locomotive underneath. There are no openings for ventilation in the walls or the roof. No conduits appear to emanate from the bottom. From the available photos it is clear that there are no windows, and it appears that there is no door. Whatever was in there, apparently did not require access! So it was not electrical or mechanical equipment, nor a container with brake sand for the locomotives (for which there would have been a tube descending in front of the powered wheels).

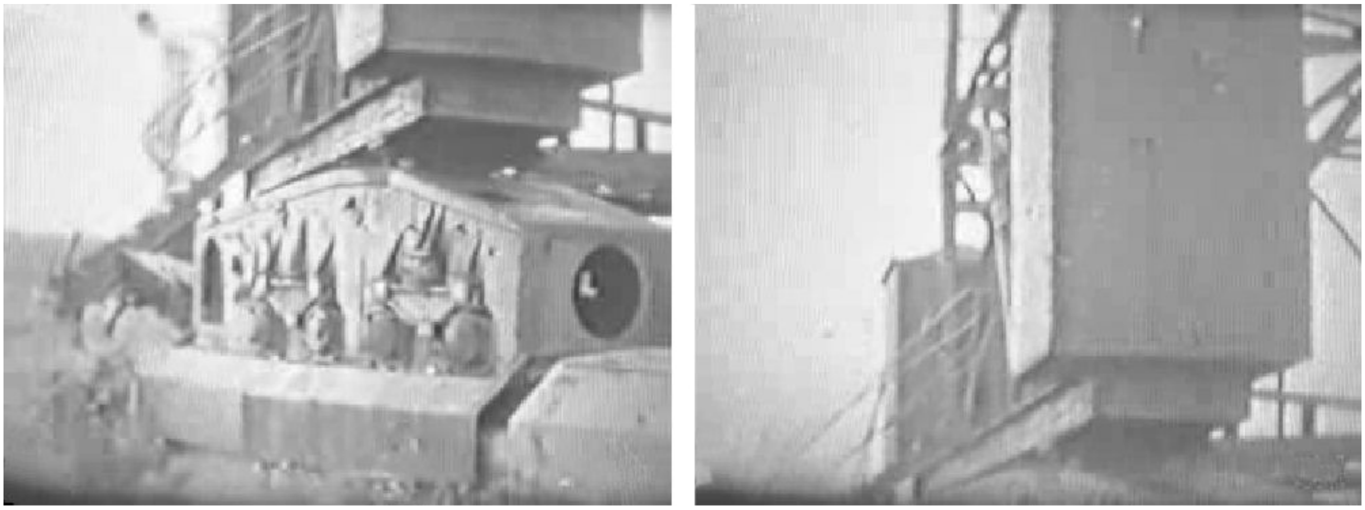


Fig. 54: One of the cantilevered corner sheds in a 1946 film clip of Be-4 at La Pernelle)
(source: Cinémathèque de Normandie)

The next photo shows that the blocks were empty at some point in time (probably during construction, as the photo dates from March 1943):

Figure 55: Low-altitude oblique RAF aerial photo of the La Pernelle site
(source: ref. 172A; photo by G.R. Crankenthorp, taken on 3 March 1943)

Most likely, they contained dead weight (e.g., stone, sand, concrete, lead), to get more weight on the traction wheels of the locomotives - even though the entire structure carried by the locomotives was already quite heavy by itself. However, the blocks must have had considerable weight: a triangular stabilizing arm was installed between the cantilever supporting each block, and the bottom frame of the bridge:

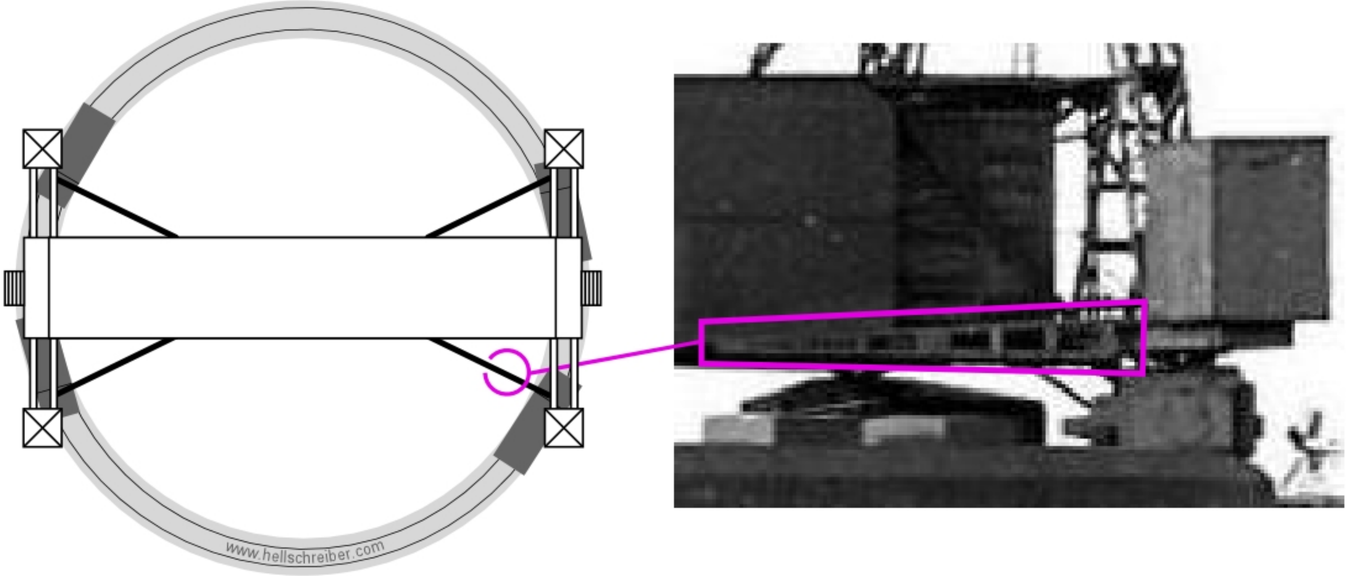


Figure 56: One of the four stabilizing arms of the turntable at Be-10 in Hundborg

At some sites, these blocks have a flat roof (e.g., Be-9 at Bredstedt, Be-10 at Hundborg). At other sites, the four-sided roof is pointed (e.g., Be-4 at La Pernelle, Be-7 at Arcachon).

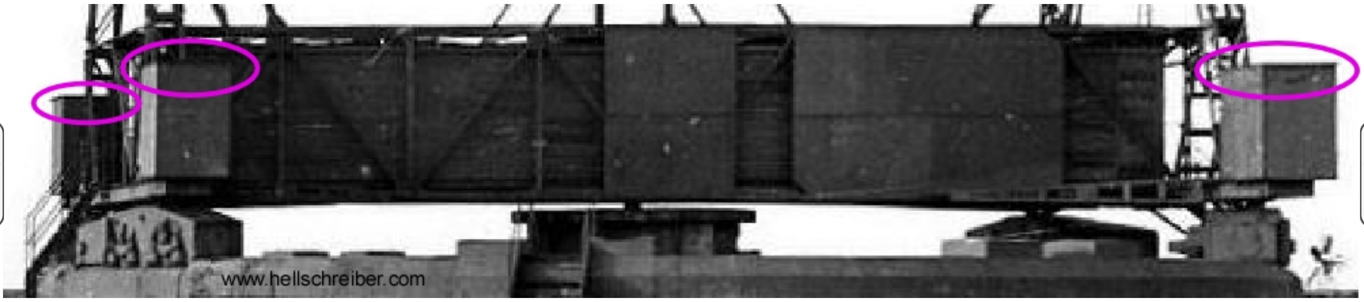


Figure 57: Corner-sheds with a flat roof (Be-10 at Hundborg/Denmark)

Figure 58: Corner-sheds with a pointed roof (Be-4 at La Pernelle/France)

Unlike the main cabin, the walls are not made of wooden planks - they apear to have been made of sheet metal:

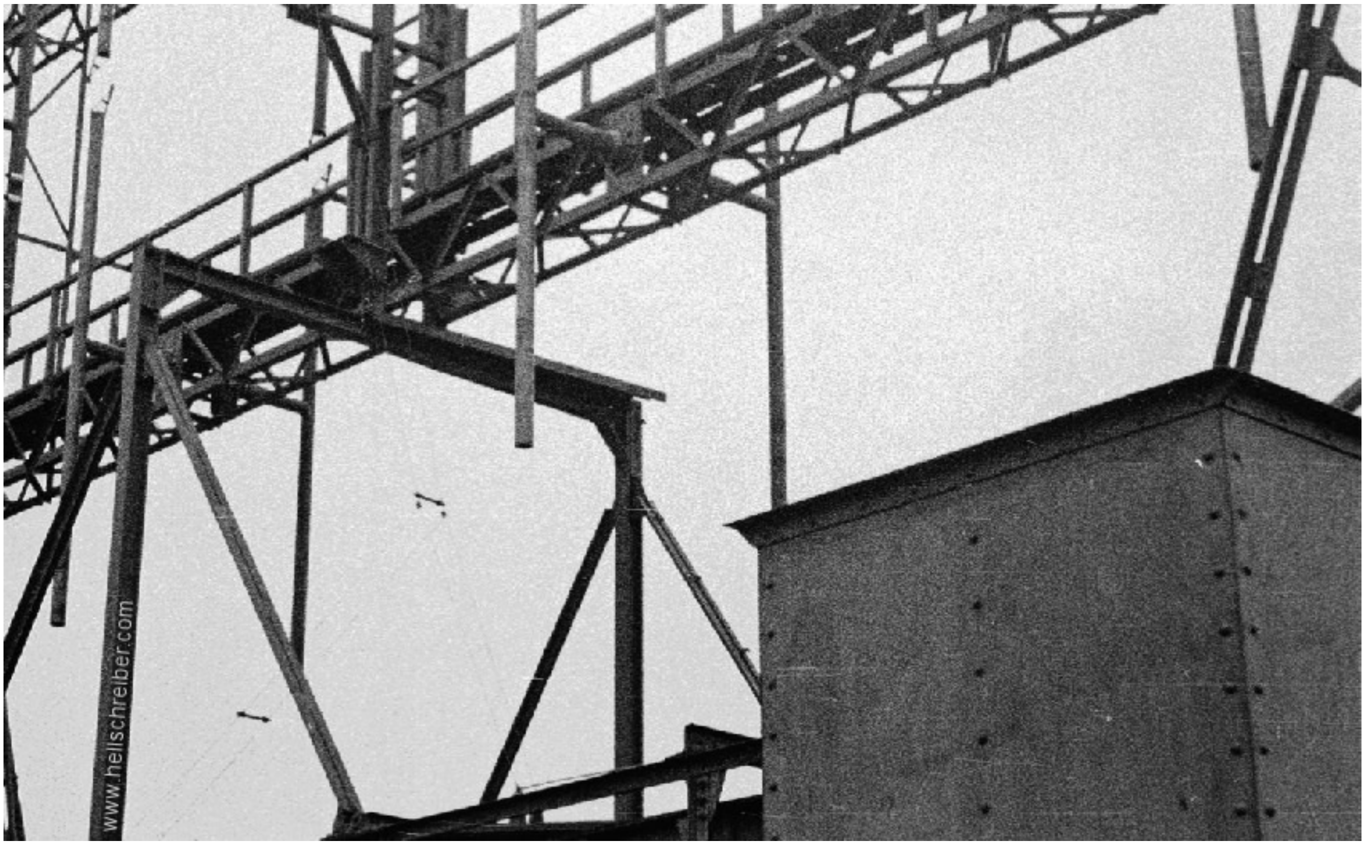


Figure 59: Corner-block of Be-9 at Bredsted/Germany - note the construction details
(unedited photo taken May 1945 by Flt. Lt. Herbert Bennet, RAF Mobile Signals Units of No. 72 Signals Wing; © David Bennet; used with permission)

In available post-war photos of "Bernhard" installations (La Pernelle, Arcachon), the main cabin is completely stripped of its materials - but not the four corner-blocks! Either the material was hard to remove and carry away, not valuable enough, or not usable for some other reason.

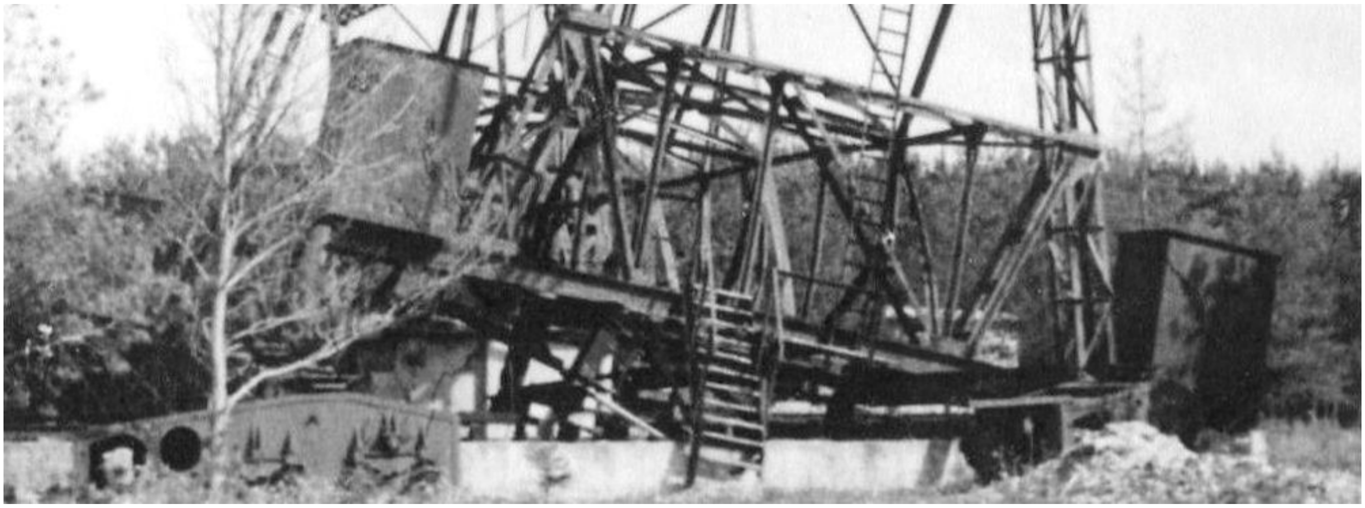


Fig. 60: Post-war photo of Be-7 at Arcachon - installation dismantled and stripped, except for the corner sheds

Fig. 61: Post-war photo of Be-4 at La Pernelle - installation dismantled and stripped, except for the corner sheds
(source: unknown)

The photo below (a post-war postcard) shows the site of Be-2 at Mont-St.-Michel-de-Brasparts. The installation was dismantled in 1946, but the (solid!) corner blocks were abandoned inside the concrete ring:

Fig. 62: Postcard of the Bernhard site Be-2 at Mont-Saint-Michel-de-Brasparts (late 1940s / early 1950s?)
(source: unknown)

No such blocks have been found at the "Bernhard" sites were there still are visible remains these days.

THE LOCOMOTIVE SYSTEM

The superstructure of the "Bernhard" (i.e., the antenna system and bridge with cabin) was rotated by four electrically powered locomotives on the circular rail track. Each locomotive had two bogies (*US*: trucks). The photos below shows that each bogie had two axle-boxes with leaf-spring suspension. Such axle-boxes typically have greased sliding bearings (a.k.a., journal bearings, not ball bearings). Each of the locomotives had 2 x (2+2) = 8 wheels, so the four locomotives had 32 wheels in total. The weight of the superstructure was carried by the four locomotives and the round central support building below it. Let's assume that the weight was evenly distributed among the four locomotives. So, the combined locomotives carried 4/5 x 120 = 96 metric tons. Hence, each wheel carried a weight of 96 / 32 = 3 metric tons. This is well below the standard railway limit of at least 11 tons/wheel, for the load at which both the rail head and full-size train wheels are damaged (about 6 tons/wheel for standard tramway ("Sraßenbahn") wheels).

Fig. 63 Each locomotive has two bogies (Be-10 at Hundborg) - 32 wheels in total

(source: www.gyges.dk, used with permission)

Based on photometric analysis, the locomotives measured about 4x1.2 m (LxH, 13x4 ft). The wheels on the outside rail had a diameter of about 60 cm (24 inch), the ones on the inside rail about 55 cm (22 inch). This is based on the diameters of the inside and outside circular rail track being about 4.3% different, and the wheels on the inside rail having a diameter that is 2 x 2.4 = 4.8 cm smaller than the wheels on the outside rail. The wheels have about half the size of a standard rail wagon wheel, which is about the size of a tramway wheel.

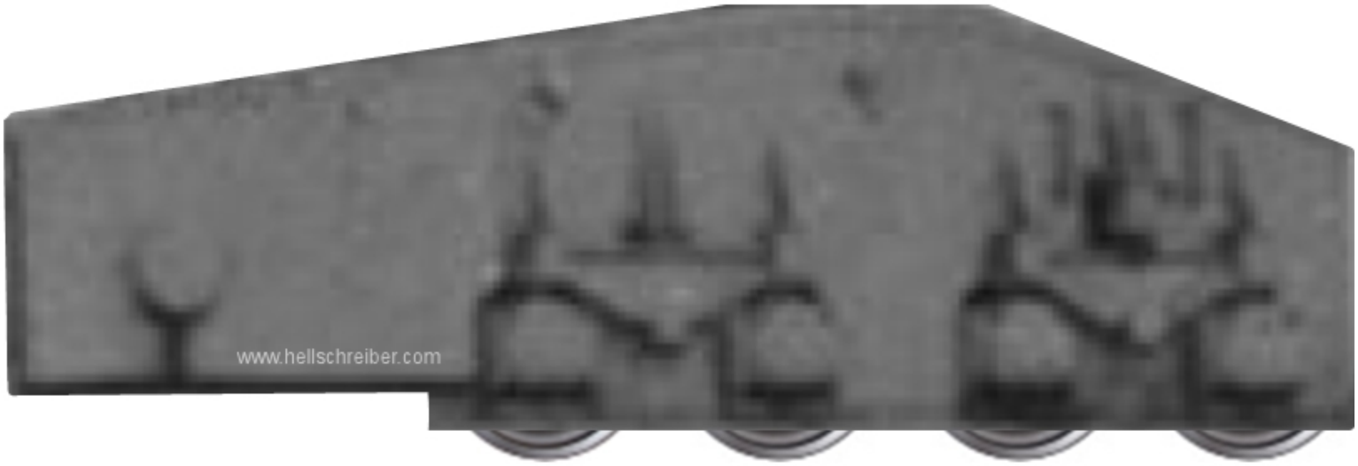


Fig. 64: The side of the locomotive on the outside of the track - direction of motion is to the left

The next photos show that the locomotives had large access holes, normally covered with a rectangular cover plate. The right-hand photo shows that the locomotives had external down-gearing between one of the two motors and the forward bogie. The down-gearing ratio is small: about 1.6:1. The gearing is covered, so it is not sure if it was a chain or a belt. The width of the cover box suggests a belt.

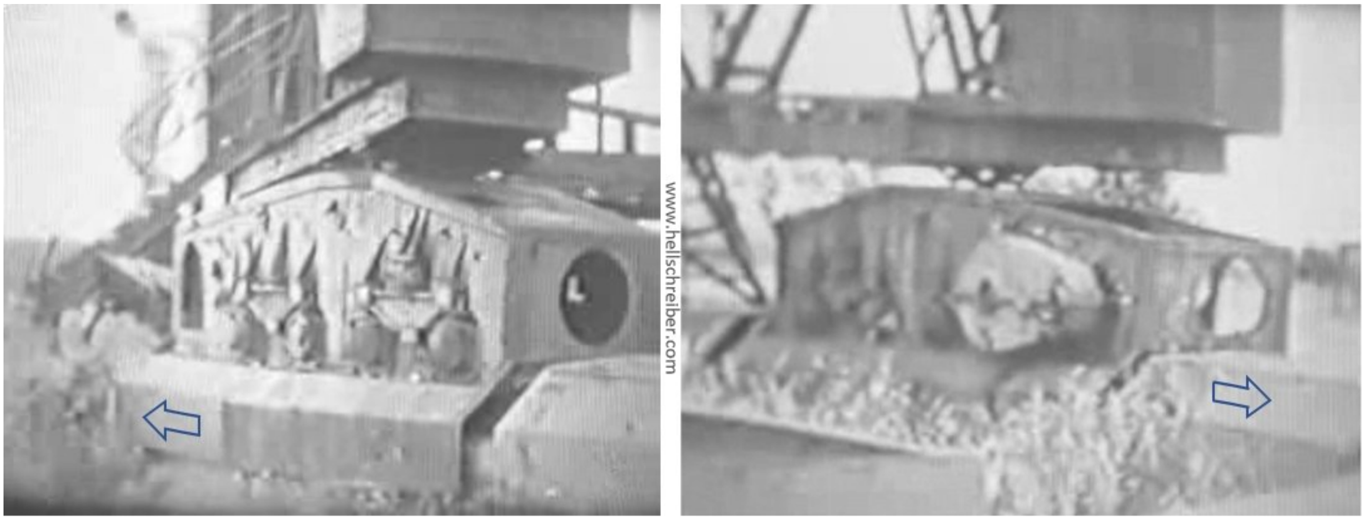


Fig. 65: Close-up of two of the locomotives in a 1946 film clip of Be-4 at La Pernelle)
(source: Cinémathèque de Normandie)

The photos in Fig. 65 and 66 show that the locomotives supported the weight of the superstructure at the point halfway between the front and rear bogies - which makes sense for weight distribution. There was ball socket ("Kugelpfanne") at this point on top of the locomotive (p. 8 in ref. 193). The socket held a large downward-pointing ball-stud ("Kugelzapfen") that was mounted underneath the I-beam frame of the superstructure. Between the superstructure and the locomotives, there are only conduits for electrical power cables to the motors (and a tachometer signal, but only at locomotive nr. 4, see Fig. 67).

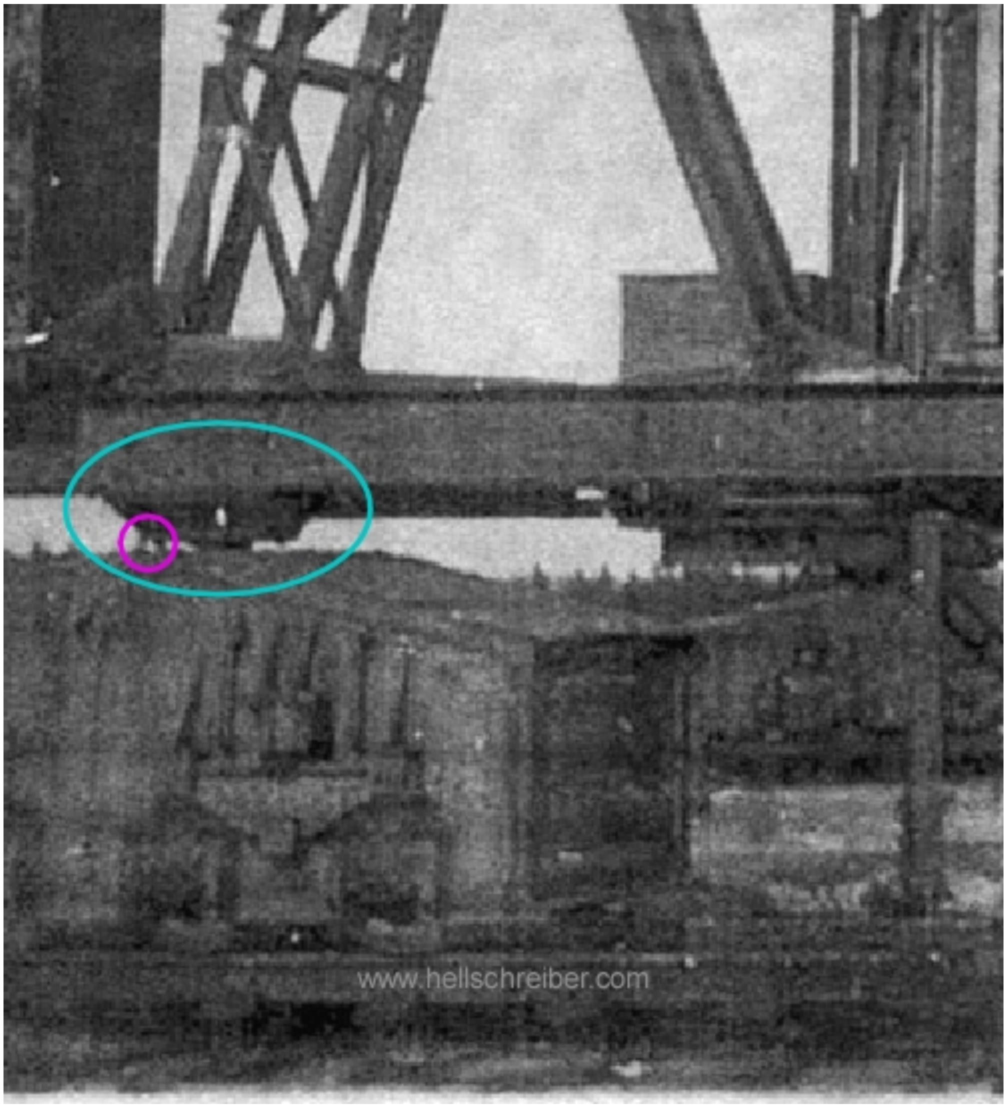


Fig. 66: Ball joint on a locomotive of Be-12 at Nevid and electrical conduits to the motors (magenta circle)
(source: brdy.org)

As stated above, each locomotive had two double bogies. Each locomotive had two motors. Per ref. 10 (§7), each motor drove two wheels of a bogie. Presumably, this means that each bogie had one motor, and this motor only drove one axle of that bogie. Dividing motor power evenly between both axles of a bogie might have optimized traction, but would have complicated the construction.

Three of the locomotives had two DC motors. The fourth locomotive had one DC motor and one synchronous AC motor:

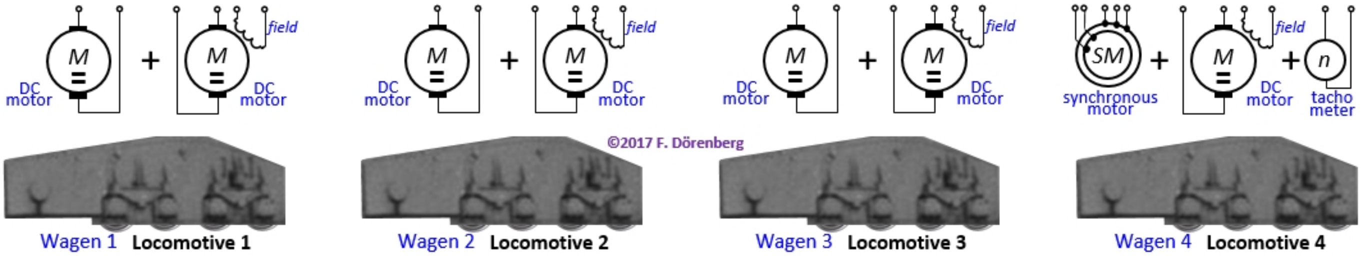


Fig. 67: Motorization of the four locomotives

(source: derived from ref. 10, 189, 190)

There were three motor types used in the locomotives (ref. 10 (§7), ref. 190):

"Hauptantrieb": **main drive**, 220 volt DC-motors. Only locomotives nr. 1-3 had such a motor. They were used to smoothly accelerate the rotation from standstill to close to the nominal speed, and provide the majority of the drive power that was required during normal operation.

Per ref. 189, the specified gauge of the wiring to each of the motors was 25 mm^2 (≈ 5.6 mm Ø, equivalent to about AWG 3). The gauge between the control panel and the variable starter resistance was 95 mm^2. I.e., a diameter of 11 mm (AWG 3/0-4/0). Note that aluminum wiring was specified for all cables. Aluminium has 61% of the conductivity of copper.

Input fuses were rated 160 A / 500 V.

"Synchronantrieb": **synchronous drive**, 3-phase 380 volt AC 50 Hz synchronous motor drive. Only locomotive nr. 4 had such a motor. It was used to accurately maintain the nominal rotational speed - without an electrical or electromechanical control system! This motor was engaged once the DC main drive motors had brought the system to within 90-95% of the nominal speed. At that point, the synchronous motor would capture and lock on to the nominal speed, i.e., the excitation frequency of the 3-phase power (which is why that frequency had to be accurate).

The wire gauge for the 3-phase AC was 16 mm^2 (≈ 4.5 mm Ø, equivalent to AWG 5). Modern 4-conductor insulated aluminium cable of this gauge has a current rating of 50 amps (e.g., cable type NAYY-J). The wiring for the DC field excitation was 2.5 mm^2 (≈ 1.8 mm Ø, ≈ AWG 13). Modern 2-conductor cable of this gauge has a current rating of about 18 amps.

The associated fuses were rated 80 A / 500 V and 6 A / 500 V respectively.

"Nebenantrieb": **auxiliary drive** DC-motors, with a separately controlled field winding (a.k.a. "separately excited DC-motor"). All four locomotives had such a motor. The rotation direction of these motors was reversible. These motors were disengaged during normal operation. they were only used for positioning the system during tests and calibration/adjustment. These motors were significantly down-geared, to be able to (very) slowly rotate the system.

Per ref. 189, the specified gauge of the wiring to each motor's field winding was 2.5 mm^2 (≈ 1.8 mm Ø, ≈ AWG 13), and 6 mm^2 (≈ 2.8 mm Ø, ≈ AWG 9-10) to each armature winding.

The two input fuses were rated 35 A / 500 V.

At the nominal speed of the system (2 rpm), the locomotive wheels had to turn at about 72 rpm:

The diameter of the outer rail track was 21.95 m. Hence, the length of the outside track was close to 69 m.

The diameter of the outside wheels of the locomotive was about 60 cm = 0.6 m. Hence, the circumference of those wheels was close to 1.88 m.

I.e., the wheels made about 35.8 revs per revolution of the system.

As the system turned at 2 rpm (30 sec/rev), the wheels (= axles of the locomotive bogies) turned at about 71.6 rpm.

So, the synchronous drive motor definitely required some down-gearing. Its speed was fixed: it was determined by the 50 Hz electrical power and the (integer) number of rotor pole pairs. A direct drive would have required a prohibitively large number of rotor pole pairs: 50 Hz x 60 sec/min / 71.6 rpm ≈ 42. Most likely, the auxiliary drive motors also required down-gearing. The gearings would have been integrated with drive axles of the locomotive bogies. Note that Fig. 114 above shows external gearing, but only with a small gear ratio. It is unknown which drive it was part of.

LOCOMOTIVE POWER

How powerful did the locomotives actually have to be? Let's do a simplistic reasonableness check, using the definition of "horsepower". On a level (= horizontal) track, the required locomotive horsepower $\mathbf{HP_{loc}}$ is (ref. 156, 157):

$$\mathbf{HP_{loc}} = \mathbf{W} \times \mathbf{T} \times \mathbf{S} / 375$$

where

W = total gross train weight in tons (1000 lbs)
T = total Train Resistance (a.k.a. Starting Resistance) per ton. A standard value used in the railway industry is 8 lbs/ton. Modern rail systems have a lower resistance.
S = speed in mph
375 is a constant that assumes that no HP is used for driving accessories (gearing, compressor, alternator, ...)

Converting this to metric units, we get:

$$\mathbf{HP_{loc}} = \mathbf{W} \times \mathbf{T} \times \mathbf{S} / 271$$

where

W = total gross train weight in metric tons (1000 kg)
T = total Train Resistance per metric ton = 8 kg/ton
S = speed in km/h = mph / 1.609

Total weight of the rotating superstructure was 120 metric tons, distributed among the four locomotives and the central support at the center of the concrete ring. The locomotives carried 4/5 x 120 = 96 metric tons. Wind load would increase this value. The specified diameter of the center of the circular rail track (= midway between the two rails) was 2x10.55 = 21.1 m (ref. 193). Hence, the track length was π x 21.1 ≈ 66.3 m. This means that at 2 rpm = 120 rph, the small locomotives moved at a respectable speed of 120 x 66.3 = 8 km per hour (5 mph). Hence, the required total locomotive horse power is 96 x 8 x 8 / 271 = 22.7 HP *at the traction wheels*. There is down-gearing between the motor and the driven wheels. Let's assume a reasonable transmission efficiency of 85%. For the required total *motor* horsepower we now get:

$$\mathbf{HP_{motor\text{-}total}} = \mathbf{HP_{loc}} / 0.85 = 22.7 / 0.85 = 26.7 \text{ HP}$$

The "Bernhard" system used *four* locomotives. So, the required motor horsepower *per locomotive* would be:

$$\mathbf{HP_{motor}} = \mathbf{HP_{motor\text{-}total}} / 4 = 26.7 / 4 \approx 6.7 \text{ HP}$$

Note that locomotive motors did not have to drive accessory loads such as generators and blowers. Hence, *traction horsepower* = *brake horsepower*. The above derivation does not take into account a requirements to accelerate to the nominal speed *within a certain amount of time*!

The *rolling resistance* of a railway vehicle (which is a science all by itself) is the sum of all forces acting through the wheels and the axles, that oppose motion of that vehicle. There are many sources of rolling resistance. Some vary only with weight (e.g., journal bearing resistance, rolling friction, track resistance), some are linearly proportional to speed (e.g., wheel-flange contact, wheel-rail interface, lateral and vertical movement), some depend on the square of the speed (e.g., aerodynamic), and some on the fourth time-derivative of displacement. Examples:

> Bearing friction.
>
> Elastic deformation of the wheel-tread and of the rail, in the wheel-rail contact area. Note that the contact surface between a wheel and the rail is a very small elliptical area, called the "contact patch". It is typically only about 15 mm (0.6 inch) across! The weight of the wheel and the load that it carries, makes a "dent" in the surface of the rail head. This dent moves with the wheel, and is like a very small bow wave. So, trains actually always go uphill, even if the track is perfectly horizontal!
>
> Losses due to *wheel creep* (during accelerations and decelerations, the elastic deformations cause the actual wheel displacement to be be different from its rolling distance).
>
> Losses due to grinding of wheel flanges against the rail head, and "hunting" (horizontal back-and-forth waving movement of the bogies on the track).
>
> Wheel noise (vibration and resonances in the wheels).
>
> Suspension "jounce" (the fourth time-derivative of displacement), due to impacts on rail joints (if any), and associated rebounds. Bumps and bounces convert horizontal momentum into vertical momentum; the associated energy is dissipated in the suspension.
>
> Track deformation (Rayleigh waves).
>
> Aerodynamic drag that acts on exposed wheels and on the body of the locomotive. At low speed, this is normally quite small, if not negligible. However, in the case of "Bernhard", there is also drag of the large antenna system due to system movement and wind load. The antenna system is symmetrical with respect to the vertical axis of rotation. So there is a "push & pull" effect, depending on whether the movement is upwind or downwind. Wind will change the apparent weight on the locomotives.
>
> Curve resistance, due to the radius of the curvature of the track. Note that regular "1 meter" gauge track typically has a <u>minimum</u> curve radius of 45 - 60 meters, about 4 - 6 times that of the circular "Bernhard" track! Without special measures, the curve resistance would have been quite high!
>
> > The "Bernhard" track had a gauge ("Spurweite", distance between the inside of the rail heads) of 842 mm. The on-center distance between the rail heads was 900 mm (≈ 3 ft). Ref. 193.

In *normal* rail applications, total resistance at low speed (less than about 15 km/h, ≈10 mph) is dominated by friction of the axle bearings (ref. 159). Note that a train with steel wheels on steel rails has a friction factor that is about 80% lower than that of a truck (*UK*: lorry) with rubber tires on pavement! Also note that the central load-bearing support below the rotating superstructure had a large ball bearing (diameter ≈40 cm ≈16 inch). Clearly, it too caused some rotational resistance.

DC MOTOR DRIVE

Electrically powered rail vehicles (electric and diesel-electric train locomotives, streetcars/ tramways, subways) traditionally used DC traction motors. This remained the case until well after the advent of solid-state power electronics, in particular gate turn-off (GTO) thyristors, in the early 1960s. DC traction motors where primarily of the series-wound brushed type. I.e., with a commutator, and the field windings in series with the motor's armature windings. Note that *brushless* DC-motors only date back to the late 1950s, ref. 160.

Series DC-motors can produce their highest torque at low speed: as much as 3-8 times the full-load torque at nominal speed. This is ideal for traction applications. For a given field flux, DC motor speed is determined by the armature *voltage*, whereas the delivered torque is driven by the armature *current*.

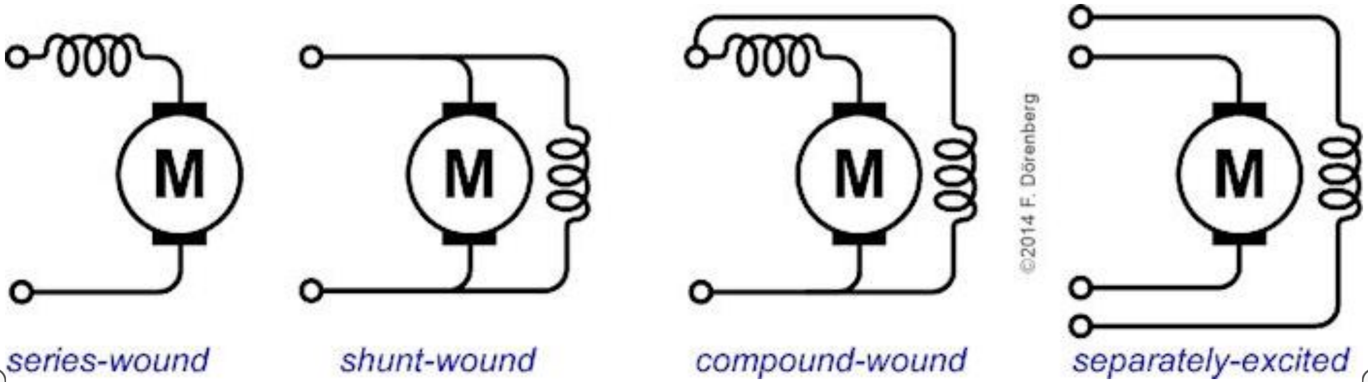


Fig. 68: Basic types of wound Direct Current (DC) motors - classified by placement of the field winding

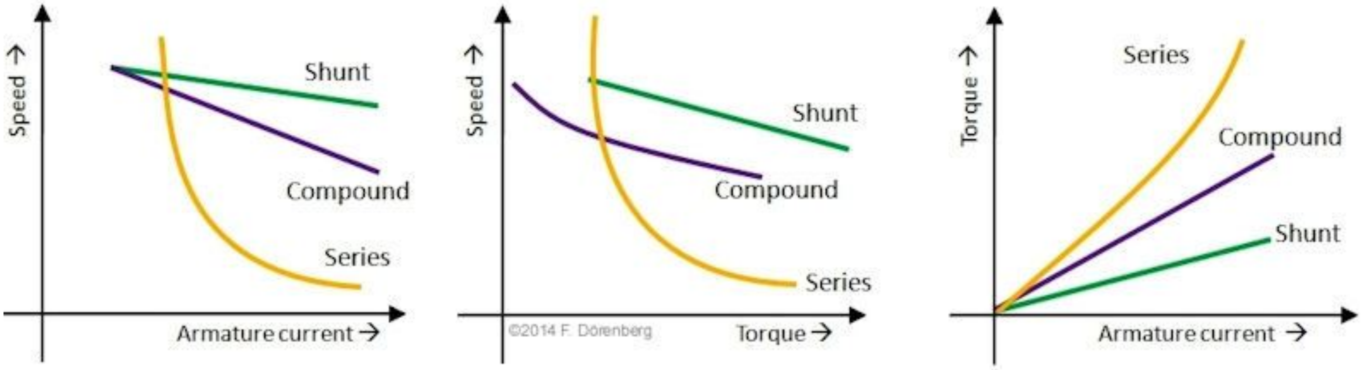


Fig. 69: Basic characteristics of series, shunt, and compound DC motors

As stated above, the speed of a DC motor depends on the voltage across the motor's armature and the field flux. Standard methods to vary the armature voltage of a series motor are:

An adjustable resistance placed in series with the motor's armature.
Ward-Leonard drive system.
Rectified adjustable AC-voltage (ref. 161, 163G).

There are *many* other flavors of motor speed control (variable AC frequency, Pulse Width Modulation, ...). They are generally beyond the scope of this discussion, and of the technology available at the time.

The **adjustable series-resistance** method (e.g., rheostat) has a major disadvantage: poor speed regulation (= speed is highly load-dependent). There are also very high losses (= heat dissipation) in the series resistance at low speed. That is, during speed-up from, and slow-down to stand-still. Some speed-control methods for series DC-motors are illustrated in Figure 70 and 71.

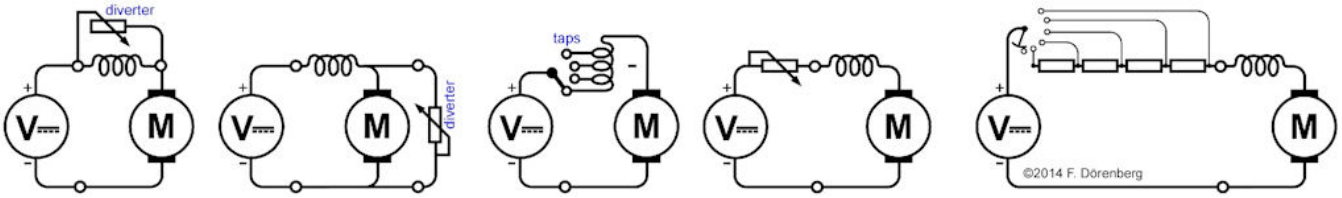


Fig. 70: Speed control of a series DC-motor via field or armature diverter, tapped field-winding, variable series resistance

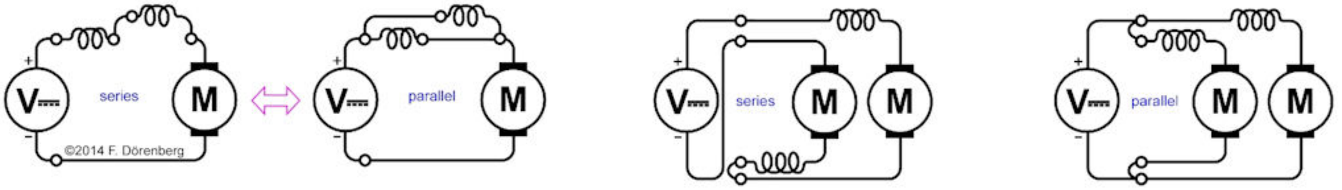


Fig. 71: Speed control of a series DC-motor via series-parallel reconfiguration of split field-winding and multiple motors

The **Ward-Leonard Drive System** (*D:* "Leonardsatz", "Ward-Leonard-Umformer", "Leonard Doppel-Umformer") is basically an electro-mechanical way of generating a variable DC-voltage to control the speed of a DC-motor. Ref. 162A-162G. It was invented by Harry Ward Leonard in 1892. For about 75 years, there were few practical alternatives to this system - until the advent of solid-state power-electronics such as thyristors in the 1960s. Worldwide, this was the normal way to provide smooth, step-less control of the speed of high-power DC-motors, from zero to full speed. It has been - and still is - used in many applications, such as cannon/gun- and turret-aiming, elevators, rolling mills, cranes, hoists, mining (colliery) winders, diesel-electric propulsion of locomotives and of special ships, strip-mining shovels, and heavy radar antennas. German WW2 radar antenna systems with a Ward-Leonard drive include the "Wassermann S" (FuMG 42; see figure 2 in ref. 162G; 36-60 m tall / 4 m diameter column, weight up to 60 tons) and the AEG-Telefunken "Würzburg Riese" (FuSE 65) with its large dish antenna (7.5 m diameter, 9.5 tons; ref. 162F). Allied radar system also used Ward-Leonard drives. E.g., the 20 ton antenna of the British "Marconi Type 7" was rotated with a 15 HP DC-motor, controlled with a Ward-Leonard set comprising a 24 HP 3-phase motor, a main DC-generator, and a small DC exciter generator. Ref. 162H.

The Ward-Leonard Drive System consists of a Ward-Leonard Drive Unit and a shunt-wound DC motor. The Drive Unit consists of a motor-generator. The motor (referred to as the "prime mover") has a near-constant speed. This can be a 3-phase or single-phase synchronous AC motor, or a combustion engine (diesel, gasoline/petrol) with a speed governor. The output shaft of the motor is coupled (direct-drive) to the input shaft of a DC-generator. The output voltage of this DC-generator is connected to the armature of the DC-motor that drives the load. The DC-motor need not be located near the motor-generator. The shunt-field of the DC-motor is connected to a constant voltage source; hence, the motor's excitation field (flux per motor-pole) is constant, and the torque only depends on the armature current - independent of the motor speed. The shunt-field of the DC-generator is connected to that same constant-voltage source, though via a rheostat (large variable resistor).

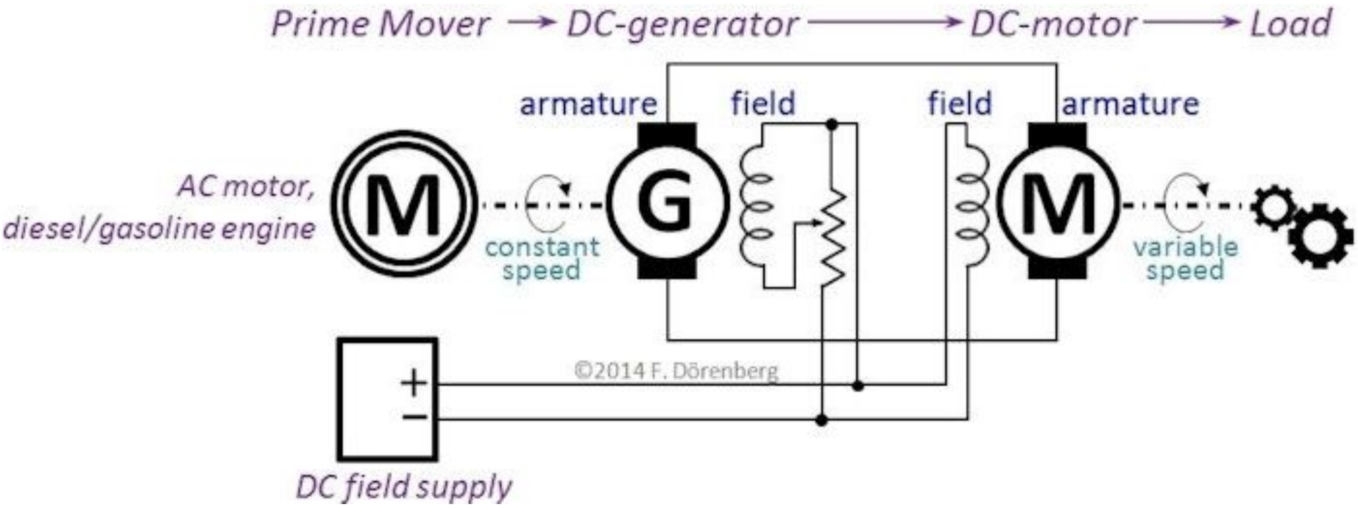


Fig. 72: Ward-Leonard Drive System

The generator's output voltage is varied by changing the generator's field current with the rheostat. In turn, this changes the DC-motor's armature voltage, and hence its speed. The constant voltage source may be a rectified AC voltage (if the prime mover is an AC-motor). It can also be generated with a small DC exciter-generator ("selbsterregter Erregergenerator"), that is also driven by the prime mover, and has its shunt-field connected to its own armature (hence, "self-excited").

The Ward-Leonard drive unit is an electro-mechanical multi-kilowatt amplifier: a small change in the input current (generator field) results in a large change at the output (generator armature voltage and current). However, in its basic form, it is an open-loop control system: the rotational speed of the load is not measured and fed back in order to adjust the generator's field current. Hence, that speed is not regulated with the high precision required in the "Bernhard" application. Note that it *is* possible to expand the basic Ward-Leonard system with such a feedback loop.

Another drawback is that both the AC-motor (or the engine) and the DC-generator must be dimensioned for the full and peak power of the load-driving DC-motor(s) and system inefficiencies.

System efficiency is driven by the product of the efficiency of the three machines (AC-motor, DC-generator. DC-motor), and typically lower than that of rheostat control and field control methods. A single Ward Leonard drive unit can control multiple load-sharing DC motors in parallel ("group control"). Variations of the Ward-Leonard drive system are electro-mechanical amplifiers such as the Metadyne (1930s) and the Amplidyne (1940s).

As elegant and effective as the Ward-Leonard drive system may be, it was *not* what was used in the "Bernhard" to provide a variable DC-voltage to the locomotive drive system! The DC motors were regulated with series rheostat for speed up from standstill and down to standstill.

SYNCHRONOUS AC MOTORS

There are two basic types of AC motors: ***a****synchronous* motors and *synchronous* motors. Both have two main parts: a stator and a rotor. In a 3-phase motor (synchronous or asynchronous), the stator basically consists of triple pairs of formed coils of wire. Each coil is mounted in the slots of a laminated steel core. The coil pairs are spaced evenly around the stator. See Fig. 73. The two coils of each pair are connected in series.

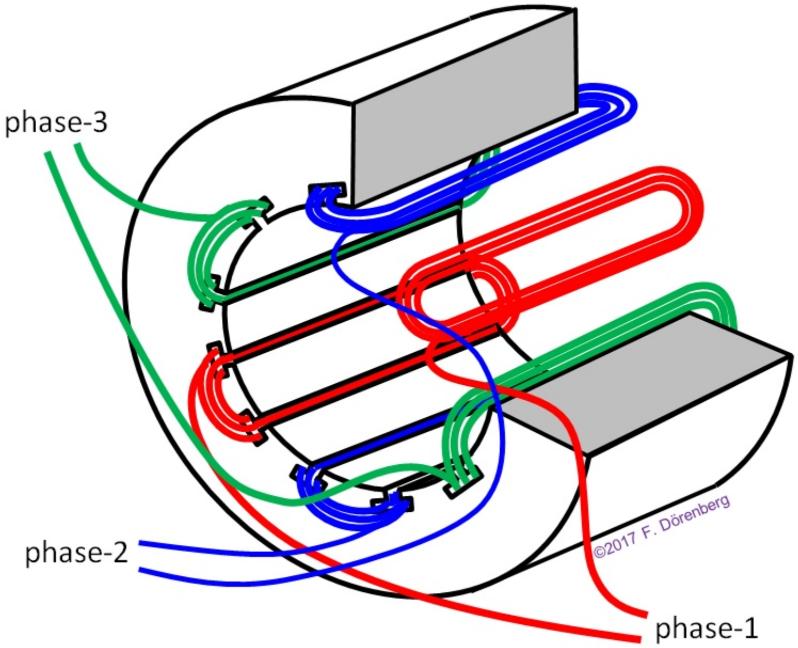
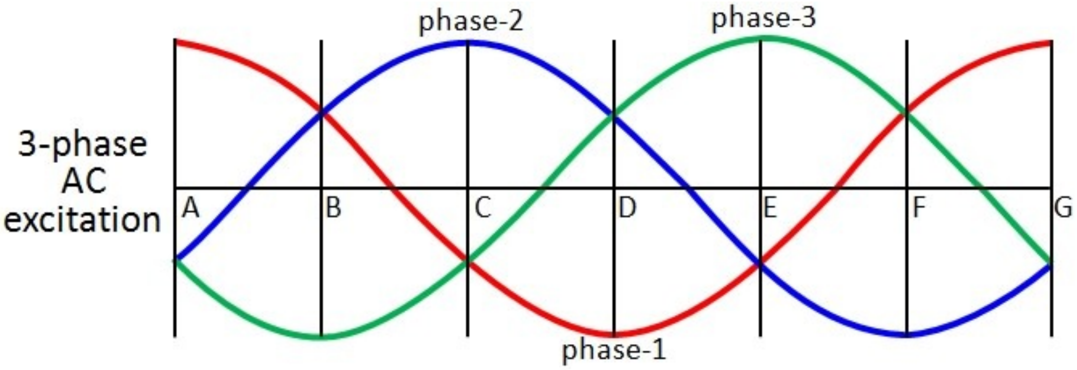


Fig. 73: Simplified cut-away view of the stator of a 3-phase AC motor (synchronous or asynchronous)

Each stator coil-pair is energized by one phase of the 3-phase AC electrical power. Each energized coil-pair forms a pair of magnetic poles. The resulting magnetic field extends into the air gap between the stator and rotor, and into the rotor. The magnetic field strength and polarity of each pole-pair changes cyclically, as the AC excitation is sinusoidal. When all three phases are connected, the stator generates a rotating magnetic field (RMF). This field has a constant amplitude, and rotates with the same speed as the 3-phase excitation. E.g., for an excitation frequency of 50 Hz = 50 cycles/sec, the RMF rotates at 50/sec x 60 sec/min = 3000 rpm, and at 3600 rpm for 60 Hz excitation.



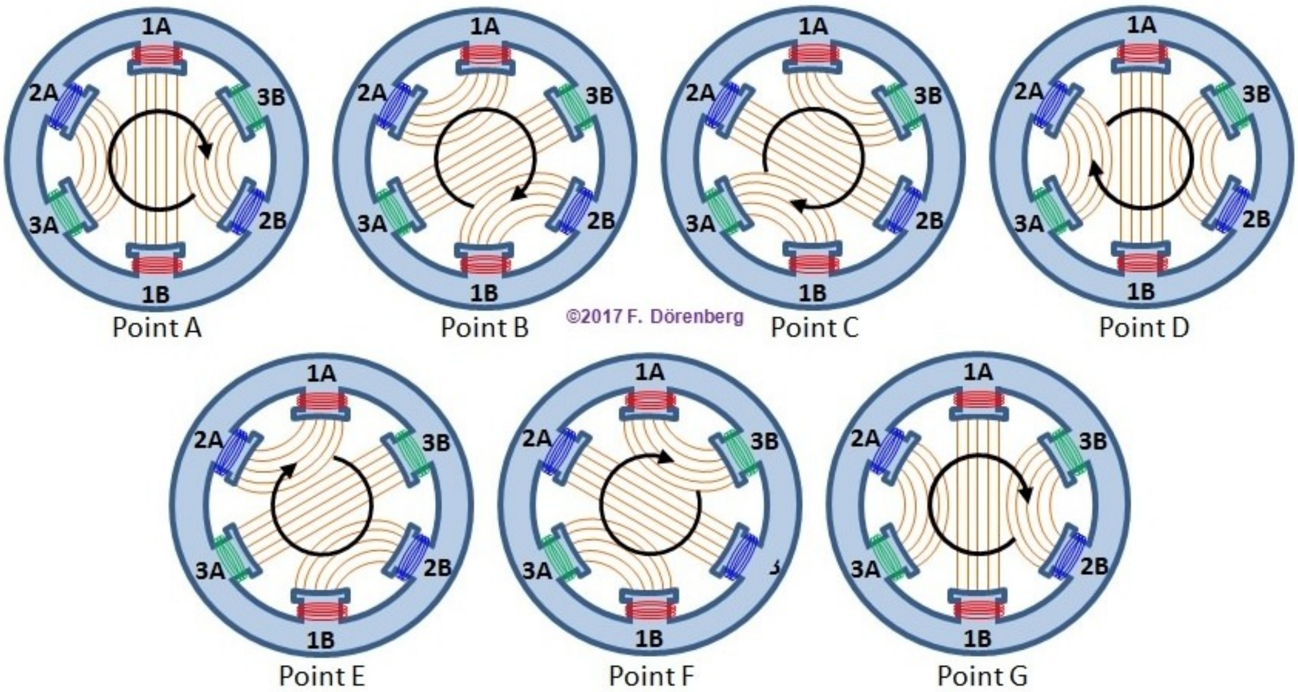


Fig. 74: Concept of how RMF is generated by a 3-phase stator when excited with 3-phase AC power

We all know that *unlike* magnetic poles (North-South) attract each other, and *like* magnetic poles (North-North, South-South) repel each other. The motor's rotor can turn freely inside the stator. Let's take a rotor that consists of one or more magnetic pole-pairs. The stator generates a rotating magnetic field, so the magnetic rotor poles will try to remain aligned with that field: the rotor turns. There are several ways to make a stator pole-pair, see Fig. 74:

A permanent magnet (bar magnet).

A coil with the ends short-circuited. By itself, such a coil does not generate a magnetic field. However, if a varying magnetic flux is induced in this coil, a current will circulate in the coil. The direction of this current is such that it opposes its cause (Lenz's Law). The cause is the varying induced flux. With the RMF of the stator, the induced flux in the rotor winding only varies if the rotor does *not* turn at the same speed as that RMF. This induced varying flux, combined with the induced current, generates an electro-magnetic force (EMF, Faraday's Law) that acts on the coil conductors. The *magnitude* of the torque (= rotating force) is proportional to the relative rotational speed of the rotor, compared to the synchronous speed (= the speed of the RMF). The speed difference is called "slip". The *direction* of the torque is such that torque is reduced (remember: Lenz' Law): in other words, such that the speed difference is reduced.

Important: there is no rotational force if the rotor turns at the synchronous speed! Hence, the rotor never turns at the synchronous speed, but always slower. The amount of slip depends on the mechanical load that is driven by the motor. The heavier the load, the larger the slip (= lower motor speed). If the load varies, the speed varies. An AC motor with such a rotor is called an ***a**synchronous* motor. As it works on the principle of induction, it is also called an *induction* motor. Low-power asynchronous motors can have a slip of 5-10%, whereas asynchronous motors with a higher power rating have approx. 2-5% slip.

The rotor coils can be implemented as actual coiled wires (in which case the rotor windings are typically made accessible via slip rings), or simply be implemented as so-called "squirrel cage" (two parallel metal rings with a number of evenly spaced metal bars between them, often at a skew angle).

A coil that is energized by a DC voltage. This is equivalent to a permanent magnet. As the rotor has to turn, the DC power is supplied via slip rings. When the rotor is at standstill or at low speed, the alternating polarity of the stator's rotating magnetic field (RMF) sweeps by the poles of the rotor relatively fast. Each rotor pole is cyclically briefly pulled into one direction (without producing sufficient starting-torque), and than briefly in the opposite direction. The rotor may vibrate but will not turn!

Important: a motor with such a stator is inherently not self-starting! The motor needs a supplemental drive mechanism (e.g., a starter winding incorporated into the motor, or another motor) to first be accelerated to 90-95% of the synchronous speed (i.e., < 5-10% slip) - *without* energizing the rotor. At that point, the rotor is energized and automatically pulls into synchronism (a.k.a. "in step") with the RMF: the rotor poles are locked to the RMF and the rotor turns at synchronous speed. This is great for a constant speed drive application: no need for a closed-loop speed control system! For obvious reasons, a motor with such a rotor is called a *synchronous* motor.

Important: a synchronous motor turns at the exact synchronous speed, from no-load to full-load!

Contrary to the asynchronous motor, the motor torque is generated as a result of the physical *angle* between the stator and rotor. This phase angle is called the *load angle*, *coupling angle*, or *torque angle*. An increase in mechanical load causes this angle to also increase - but synchronous speed is maintained! If the mechanical load ever exceeds the motor's maximum torque, the rotor completely loses synchronism (drops "out of step") with the stator's RMF, and the motor comes to rest. The same happens if the rotor supply voltage or the stator supply voltage is reduced excessively.

For a constant load, the motor's EM torque is equal to the load torque and the torque angle is a non-zero constant. A sudden change in load will upset this steady state. The locking between the rotor and the RMF is not rigid! A sudden increase in load causes a temporary slow down of the rotor, which simultaneously increases the torque angle and the EM torque. This accelerates the rotor back to the synchronous speed. As the rotor reaches synchronous speed again, the torque angle is larger than needed and the rotor speed overshoots the synchronous speed. This reduces the torque angle, and the EMF torque drops simultaneously. The rotor decelerates and the rotor speed now undershoots the synchronous speed, etc. I.e., the rotor speed oscillates around the sync speed. This phenomenon is known as "hunting" and "phase swinging". Under certain conditions, these oscillation may diverge (= exponentially increase in amplitude), even to destructive levels. The oscillation can be reduced by adding damping windings (a.k.a. amortisseur windings) to the rotor, and by large load inertia (e.g., a heavy flywheel, such as the rotating structure of the Bernhard system).

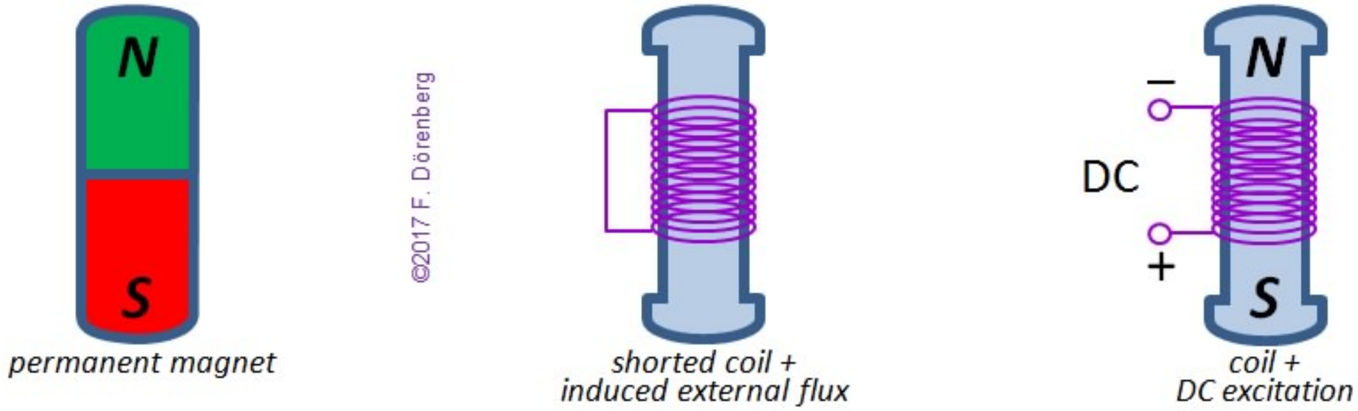


Fig. 75: Possible configurations for a pole pair of an AC motor

The following graphs show the torque-versus-speed characteristics of an asynchronous and a synchronous AC motor:

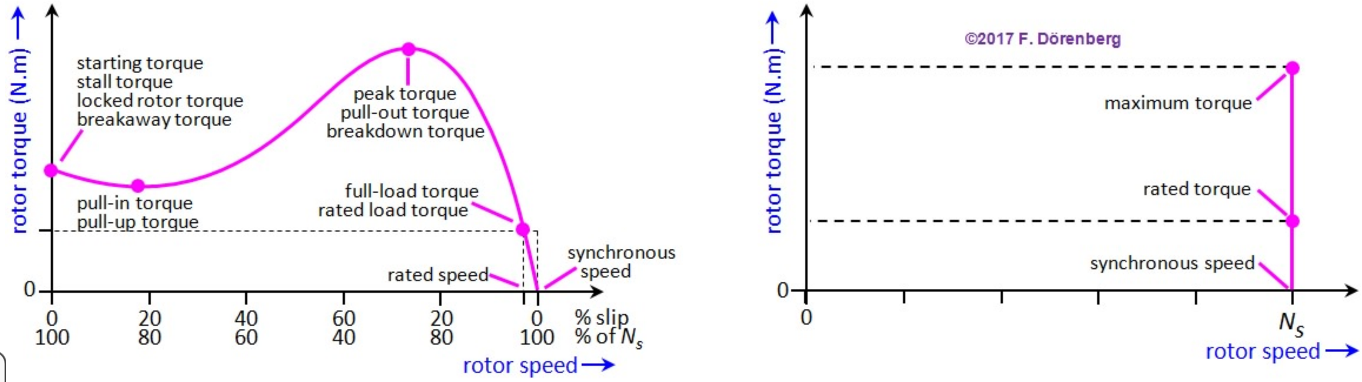


Fig. 76: Torque-vs-speed characteristic of a typ. asynchronous AC motor (left) and of a synchronous AC motor

The synchronous rotor speed of an AC motor is clearly proportional to the RMF that is generated by the stator, i.e., to the frequency of the AC excitation of the stator. However, it also *inversely* proportional to the number pole-pairs of the rotor. The simple formula is given in the figure below. For instance, for a 50 Hz excitation, the synchronous rotor speed N_S is 3000, 1500, 1000, and 750 rpm, for 1, 2, 3, and 4 pole-pairs, respectively. The number of pole-pairs is an integer value, so it obviously cannot be chosen as freely as an excitation frequency. Compared to asynchronous motors of equal power and speed, synchronous motors are attractive for low-speed (< 300 rpm) and ultra low-speed drive applications: their efficiency is high, their power factor can always be adjusted to 1 (via field current adjustment), and they are less costly.

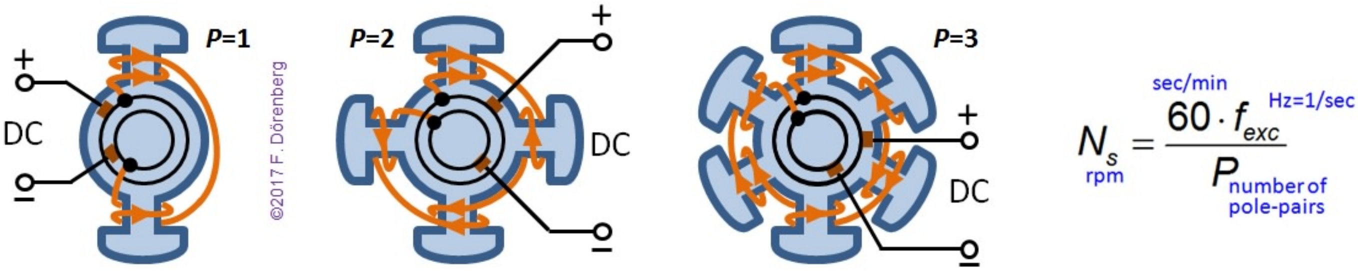


Fig. 77: Synchronous motor rotors with 1, 2, & 3 pole-pairs and slip-rings for DC power
(rotors shown with salient (= protruding) poles, typ. for low speed applications, rather than cylindrical rotor with distributed windings)

The characteristics of the synchronous motor of "Bernhard" locomotive nr. 4 are not known: neither the frequency of the 3-phase AC (other than "mid-frequency", which is typ. 400 - 2000 Hz), nor the number of rotor poles, nor the torque rating.

At least one of the locomotive motors of the Be-13 station at Buke was built by *Ziehl-Abegg Elektrizitätsgesellschaft m.b.H.*, of Berlin-Weißensee. It was a 10 kW (13.6 metric horsepower, 13.4 US hp) "low rpm" motor (ref. 99). This suggests that it may have been the synchrounous AC motor. The motors at (some) other Bernhard stations may have been built by *Siemens* (e.g., ref. 103). This was probably *Siemens-Schuckert*, who also manufactured electric locomotives.

Ziehl-Abegg is a company specialized in electric motors. It was founded in 1910 by Emil Ziehl and the Swedish investor Eduard Abegg as *Ziehl-Abegg Elektrizitäts-Gesellschaft m.b.H.* Abegg dropped out of the partnership the same year, as he could not come up with the required funds, and the patent that he brought into the deal (ref. 214) proved useless. However, Abegg's initial "A" was retained (as a solid triangle) in the the "Z-A" company logo. Ref. 154. In 1897, Emil Ziehl invented the external rotor motor ("Außenläufermotor", outrunner motor: stator inside the rotor - very compact and excellent weight balancing). In 1904, he invented electrically powered gyroscopes with gimballed suspension. Prior to 1910, Emil Ziehl had developed electric motors and tested generators at AEG, and developed gyro-compasses at ***Be****rliner* ***M****aschinenbau* ***AG*** (BEMAG, frmr. *Eisengießerei und Maschinen-Fabrik von L. Schwartzkopff*). BEMAG was a manufacturer of locomotives powered by steam, compressed air, and electricity. Ziehl-Abegg made DC-DC converters (DC-motor + generator) for Zeppelin airships and airplanes. Telefunken was a major customer. They also made electro-mechanical transverters ("Drehstrom-Gleichstrom-Umformer", i.e., AC-motor + DC-generator, as in Ward-Leonard Drive Systems) for elevators and generation of anode voltage of large transmitters, transformers for directional-gyros (e.g., *SAM-LKu4*), motor-generators such as the *U 4a*, and the motor-generator-alternator of the U 120 of the "Bernhardine" system. After the war, the production facilities were carried off to the Soviet Union. In 1947, the company restarted, this time in the south of Germany (some 70 km northeast of Stuttgart). These days, Ziehl-Abegg AG is a manufacturer of electric motors for elevators, ventilation and air-conditioning systems.

Fig. 78: Company buildings of Ziehl-Abegg Elektrizitätsgesellschaft m.b.H in Berlin-Weißensee

(source: www.ziehl-abegg.com, accessed 2023)

Fig. 79: 1912 advertizing poster, relief on outside wall of the above building - before/after 2018 restoration

(sources: poster - ref. 155, plaques - www.pomm-restaurierung.de, accessed 2023)

ZIEHL-ABEGG
El.-Ges. m. b. H.
Berlin - Weißensee
An d Industriebahn 12-18
Fernspr. 56 40 41

Fig. 80: Ziehl-Abegg postmark on an envelope (1938) and listing in 1943 Berlin phonebook

(source: www.briefmarken12.de, accessed 2017)

THE LOCOMOTIVE MOTOR CONTROL SYSTEM

The task of the locomotive motor control system is to smoothly increase the rotational speed of the "Bernhard" beacon from stand-still to exactly 2 rpm, and to accurately maintain that speed. The signals transmitted by the "Bernhard" beacon were printed aboard the aircraft with the "Bernhardine" Hellschreiber-printer. The compass-scale channel of this printer was synchronized to pulses transmitted by the beacon. As explained in the "Optical Encoder Disk" section, to make this synchronization scheme work, the allowed tolerance on the 2 rpm beacon speed was only ±0.2-0.3 % (p. 80 in ref. 181 and p. 8 & 18 in ref. 183). This small tolerance had to be met, independent of variations in the motor load (e.g., rail resistance around the circular track, wind load), and independent of amplitude and frequency variations of the 3-phase 50 Hz primary AC power. Note that towards the end of the war, the minimum frequency of the 50 Hz power grid was reduced to 43.3 Hz in the Central German block, and to 41 Hz in the Western German block (ref. 14).

One standard way to control and regulate motor speed is with a closed-loop control system. This requires tachometer feedback of the momentary speed, for comparison against the speed set-point. The amount of speed error (and possibly one or more of its time derivatives, and its integral) is then used to command the motor to speed up, or slow down. If the control system is properly configured and dimensioned (= control laws/algorithms), and it has sufficient control authority (= "power"), then the torque-vs-speed curve of such a drive system can be made to approach that of a synchronous motor (see Fig. 125 above, ref. 215). So, when constant speed is required - *as is the case here* - then why not go straight to an inherently synchronous AC motor drive and use an AC power source that has a sufficiently constant frequency? Yes, indeed, why not! Doesn't this basically just move the control system from the motor to the AC generator? Yes, indeed. But there, it is easier to implement - as we shall see.

On the one hand, the locomotive drive system must operate with 3-phase primary AC power that has varying frequency and amplitude. On the other hand, DC power (= rectified AC power) is required for several reasons. First of all, as explained in the "synchronous AC motors" section above, a synchronous motor is not self-starting. It must be brought close to synchronous speed by other means. Here: with DC traction motors. Also, the field winding of a synchronous AC motor is DC-powered. So, a 3-phase AC rectifier is required. And to complete the synchronous AC drive system, we need a "DC to fixed-frequency 3-phase AC" converter.

For low power applications, constant speed was often achieved with a "phonic motor" arrangement (ref. 235). Its concept was invented by Poul la Cour in Denmark in 1885 and patented by him in Britain in 1887. Ref. 235. It was used to synchronize telegraphy and teleprinter systems, as well as J.L. Baird's television system. In essence, it uses a stable electric oscillator to drive a synchronous AC motor. Since the 1920s, this was implented as the simple electronic audio tone generator. Its signal drives an electromagnet that is coupled to a mechanical tuning fork and continuously excites the fork. Tuning forks can only oscillate at a specific frequency. The resulting precise, constant fork vibration is captured via capacitive coupling. This signal is then amplifed to the required power level for the synchronous motor. This approach was also used in the antenna motor drive of some British 1920s rotating-beam beacons, and in the 1950's military Field Hellschreiber made by RFT.

The next diagram illustrates the three main blocks of the "Bernhard" locomotive drive system:

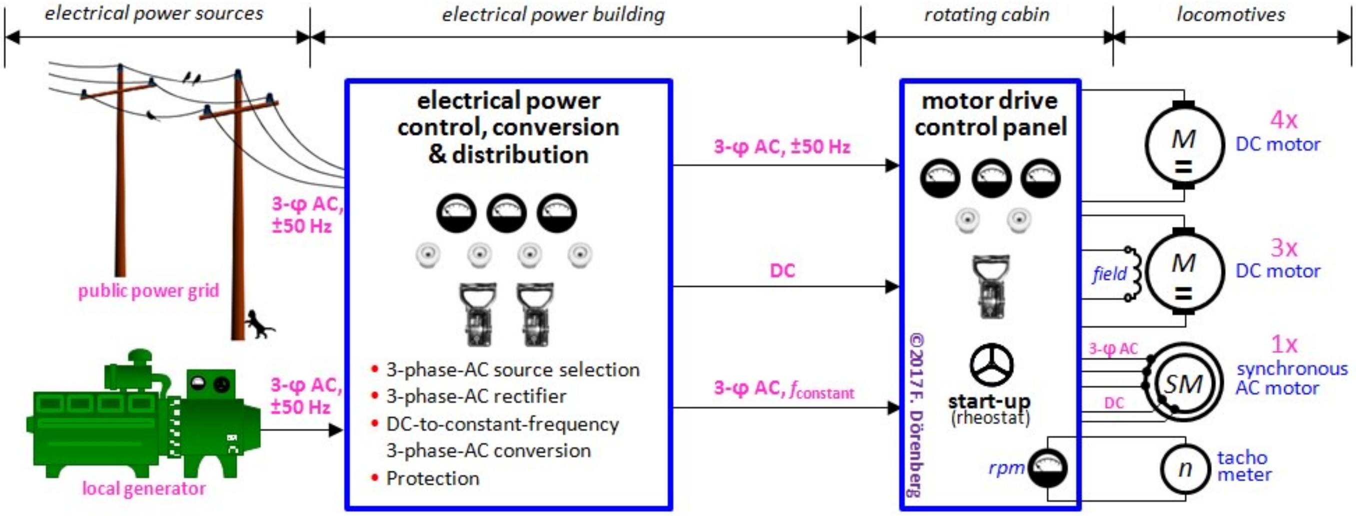


Fig. 81: Top-level block diagram of the "Bernhard" motor drive system
(source: derived from ref. 189, 190)

The "Electrical power control, conversion & distribution" block has the following functions and associated control panels:

Selection of the source of 3-phase 50 Hz (nominal) AC main power: the public power grid, or the local generator of the “Bernhard” station.

Protection against over-voltage / over-current conditions of the primary AC power, and emergency shutdown. For the latter, there was a shutdown button located in the rotating cabin, in the round building below it, and outside the concrete ring.

Conversion of the selected 3-phase 50 Hz AC power to DC power. This was done with a 6-anode Mercury Arc Rectifier described further below.

Conversion of DC power into 3-phase AC power that has a constant frequency (unlike the primary AC power). This conversion was done with an electro-mechanical DC-AC inverter; in this case, a so-called "Conz" converter as described further below.

Distribution of the AC and DC power. The selected 3-phase 50 Hz AC main power is distributed to the rectifier unit and to the rotating cabin (via a slip ring assembly in the round building below that cabin). The DC power from the rectifier unit is distributed to the DC-AC inverter and to the rotating cabin, Also see the "Electrical & signal distribution" section.

The motor drive control panel was located in the rotating cabin. It had separate controls for the three motor types (main drive DC, auxiliary drive DC with separate field winding, and synchronous AC). The block diagram in the next figure illustrates the power conversion and motor drive control functions with more detail:

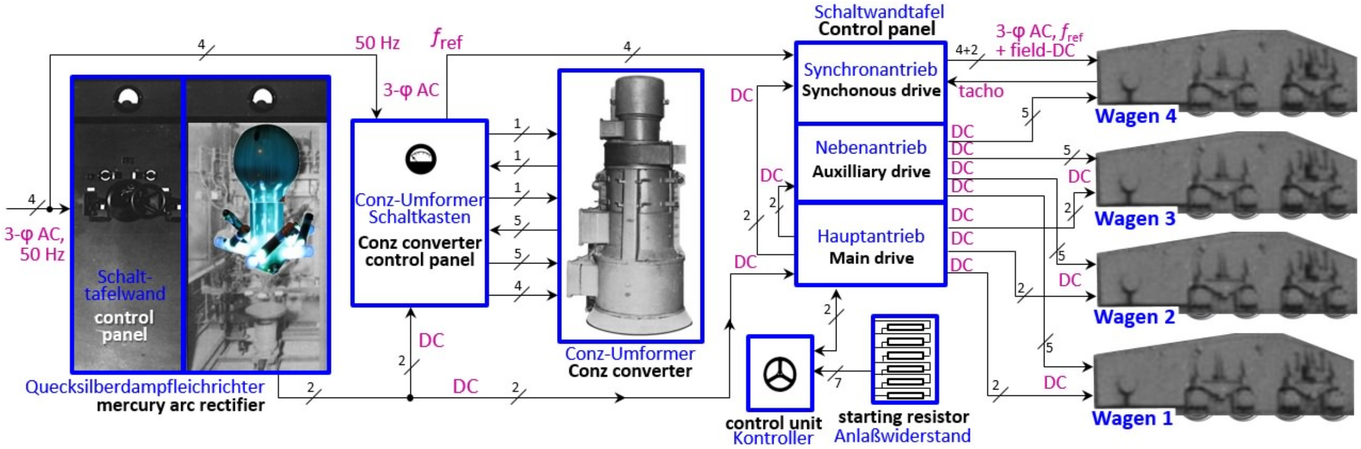


Fig. 82: Electrical power and signal interconnections of the locomotive system
(source: derived from ref. 93, 189, 190; 3-phase 380 Vac, 50 Hz from the backup Diesel generator could replace power from the publick grid)

The three main-drive DC motors were controlled via a heavy-duty variable resistor arrangement in series with the field and armature windings of each motor. The controller and resistor bank ware located in the rotating cabin (see the hand wheel on the "Main Drive" control panel in Fig. 83 below). The four auxiliary-drive DC motors had a separate field winding that was wired to the "Auxiliary Drive" control panel. The field current was also controlled with a variable resistor, but with a much lower power rating than that of the main-drive motors.

Fig. 83: German engineer showing the locomotive control panel of Be-9 at Bredstedt to a member of the RAF-ADW
(source: Australian War Memorial photo SUK14636, public domain; ca. August 1945)

Since the synchronous AC motor provided inherent accurate speed control, there was no need for a closed-loop speed control system with a speed sensor. But there *were* two speed sensors: a tachometer in locomotive nr. 4 (with the synchronous AC motor), and a tachometer track on the optical encoder disk (measurement accuracy 0.1%) in the round building below the rotating cabin and superstructure. However, they were there for speed monitoring and alerting purposes only.

MERCURY ARC RECTIFIERS

A rectifier is an electrical device that converts alternating current (AC) to direct current (DC).

The device achieves this by allowing electrical current to flow through it in one direction only. A half-wave rectifier only passes either the positive or the negative half of a full AC voltage cycle. A full-wave rectifier passes the positive half cycle directly, and the negative half cycle with inversed polarity:

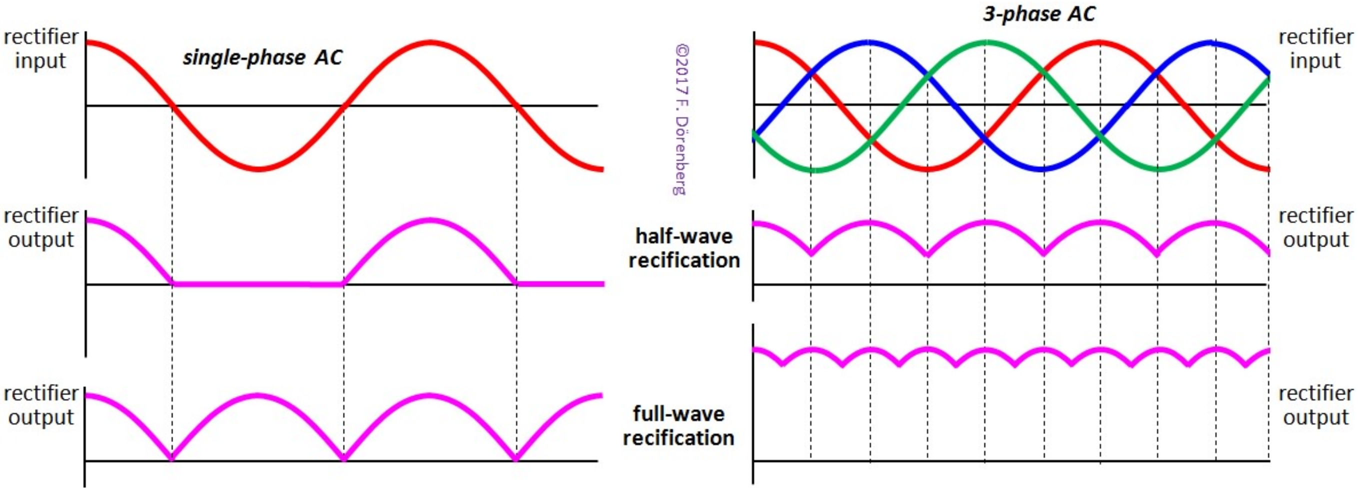


Fig. 84: Half-wave and full-wave rectification of single-phase and 3-phase sinusoidal AC voltages

*(assumes **ideal** rectifiers/diodes (no forward voltage drop, etc.), no source reactance (typ. inductive), no output smoothing, and no load)*

By 1930, the **M**ercury **A**rc **R**ectifier (MAR, a.k.a. Mercury Vapor Rectifier; *D*: "Quecksilberdampfgleichrichter", ref. 163A-163R) had become the best method for rectifying high power AC voltage in industrial applications and electrification of light and heavy railroad. The discovery of the unidirectional current-flow of an atmospheric arc between a mercury pool and a carbon electrode, goes back to 1882 (Jules-Célestin Jamin and his co-worker Georges Maneuvrier, ref. 163H). The MAR was invented around 1900. P. Cooper-Hewitt patented a glass-envelope MAR in 1902 (ref. 163J), based on his mercury vapor lamp. He marketed a metal-envelope MAR in 1908. In 1914, Irving Langmuir patented the concept of using a control-grid between the anode and the mercury-pool cathode (ref. 163K). This made it possible to arbitrarily choose the actual moment of arc initiation (= switch-on via phase angle control, instead of it being determined by the primary power), and thereby vary the DC output. MARs can also be configured as an inverter instead of a rectifier, i.e., as a DC-to-AC converter.

MARs are a form of cold-cathode gas discharge tube. The rectifier consists of a glass or stainless steel vessel. The vessel is evacuated, or filled with inert gas. There is a pool of liquid mercury at the bottom of the vessel. This is the cathode. The vessel has one or more upward arms with a graphite anode. Clearly, a MAR is a *static* rectifier, as opposed to the mechanical rotary converters that preceded the MAR.

Full-wave rectification of a single-phase AC voltage requires two anodes. See Figure 135. For rectifying 3-phase AC power, the MAR must have a multiple of three anodes.

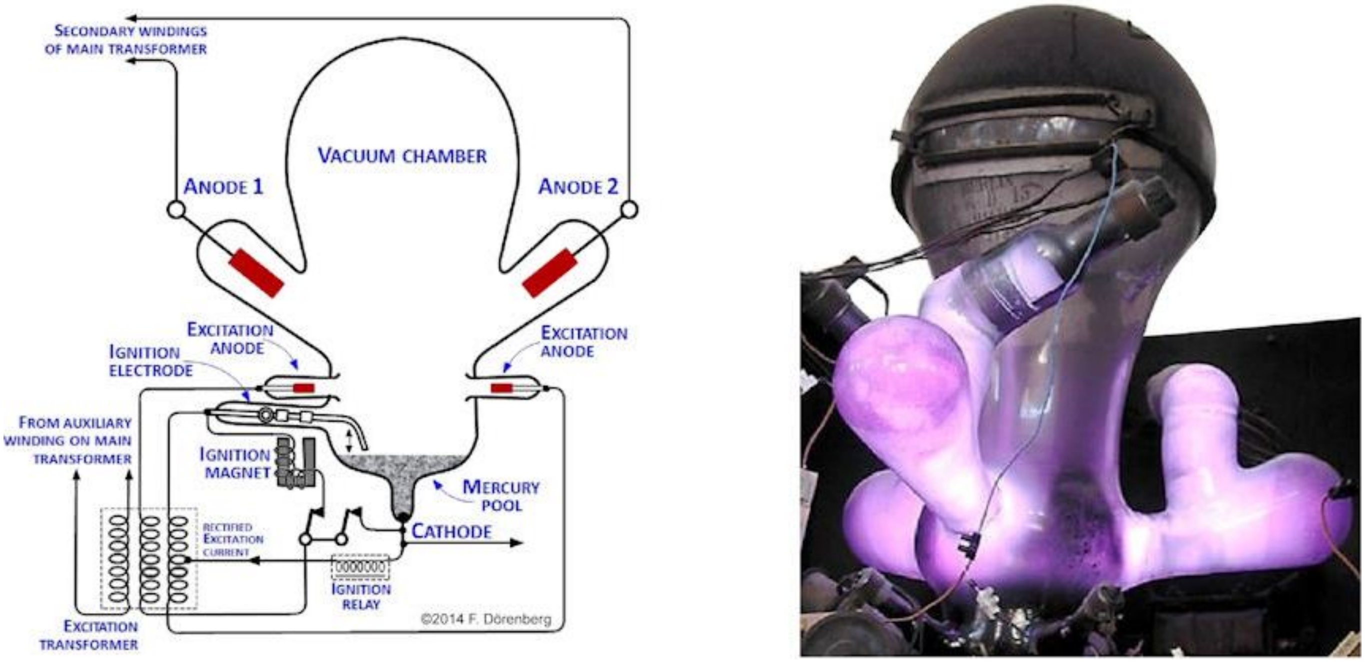


Fig. 85: left: Simplified principle diagram with a 2-anode MAR (left) and an active 3-anode MAR

Like a fluorescent lamp, a MAR must be started. Conduction is initiated by dipping the starting (igniting) electrode into the mercury pool, passing a high current, and retracting the electrode. This locally heats up the mercury (the "cathode spot" or "emission spot") and vaporizes it. This starts abundant emission of electrons by the mercury cathode. The mercury vapor is ionized by the stream of electrons that flows to the anode, and causes plasma discharge (arc) between the anode and the cathode. The mercury ions emit both visible blue-violet light, and a large amount of ultra-violet radiation. The light may have another color when the vessel is filled with an inert gas, e.g., pink as in Fig. 85 (probably argon). Evaporated mercury condenses on the cool wall of the vessel (hence the large bulbous form), and returns to the mercury pool at the bottom of the device. The plasma discharge stops as soon as the anode voltage drops below a certain level, or anode current is interrupted. Hence, for rectification of an AC voltage, ignition must be synchronized with that voltage. Alternatively, excitation electrodes may be used to maintain the plasma. The anode material does not emit electrons, so electrons can only flow from the cathode to the anode. I.e., current can only flow from the anode to the cathode. The ripple on the DC output current is smoothed with a series-inductance ("choke coil").

The heat of the mercury vapor must dissipate through the glass envelope in order to condense. To help keep the glass envelope cool enough, an electric fan is typically installed below the MAR (as clearly visible in Fig. 138 and the the right-hand photo of Fig. 90 below).

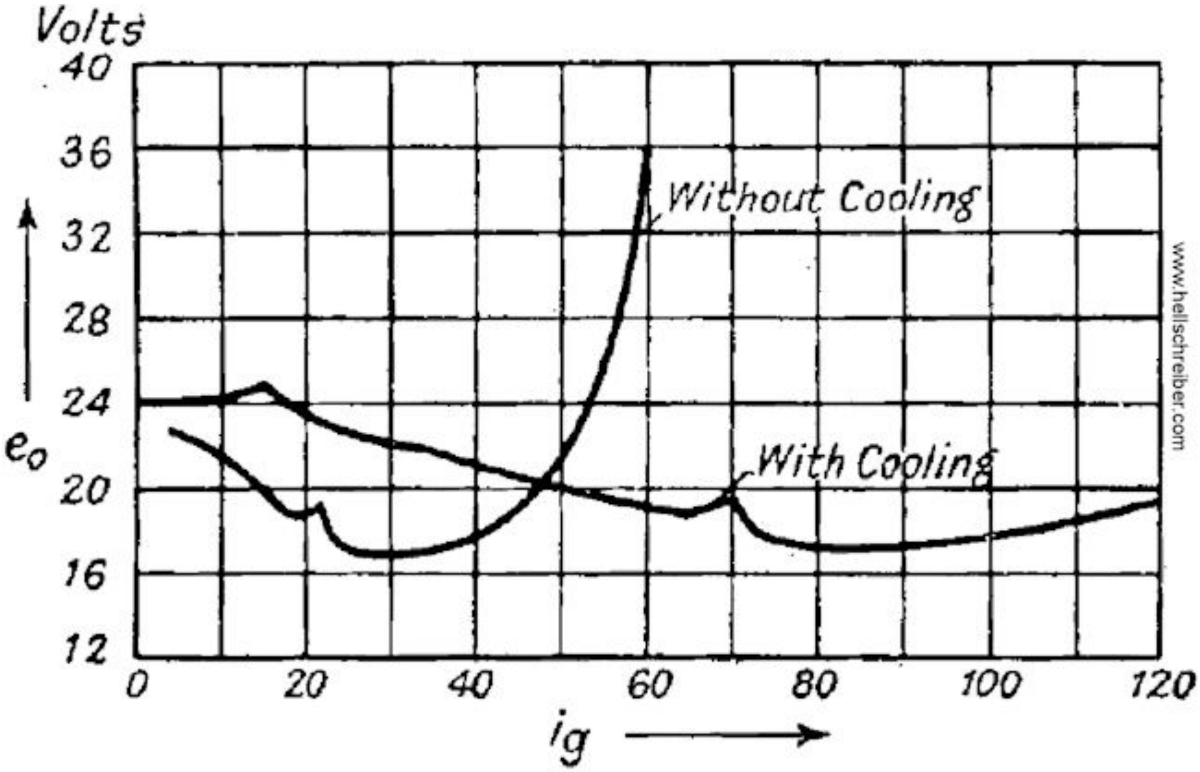


Fig. 86: Effect of cooling on voltage vs. current curve (= losses & efficiency) of a glass MAR

(source: Fig. 66 in ref. 192)

For operating temperatures below 10 °C (50 °F), special measures must be taken to protect the MAR against damage from instable operation, and the attached transformers against current surges. This may be done with surge diverters and cathode heating. Ref. 161. Note that mercury freezes around -39 °C (-39 °F).

The MAR anodes are connected to AC power via a transformer. Each phase of the secondary side of this transformer has an inductance: inductance of the secondary winding itself, and transformed inductance of the primary transformer windings and the AC power line. Inductance prevents current (here: anode current) from varying instantly. Hence, when one anode becomes conductive and its current is building up, the current of the adjoining previously conductive anode anode is still dying down: for a short time, *both* anode arcs are active simultaneously! This cyclic "overlap" phenomenon effectively short-circuits the main transformer's secondary phases that are associated with these anodes. For rectifier circuits, the "overlap angle" (a.k.a. commutating angle) is the commutation time interval when when both devices conduct. This causes the rectifier's DC output wave to temporarily drop to the average of the overlapping sinusoidal transformer phase voltages, which significantly distorts the ripple (Fig. 25, 29, 33, 37 in ref. 163C).

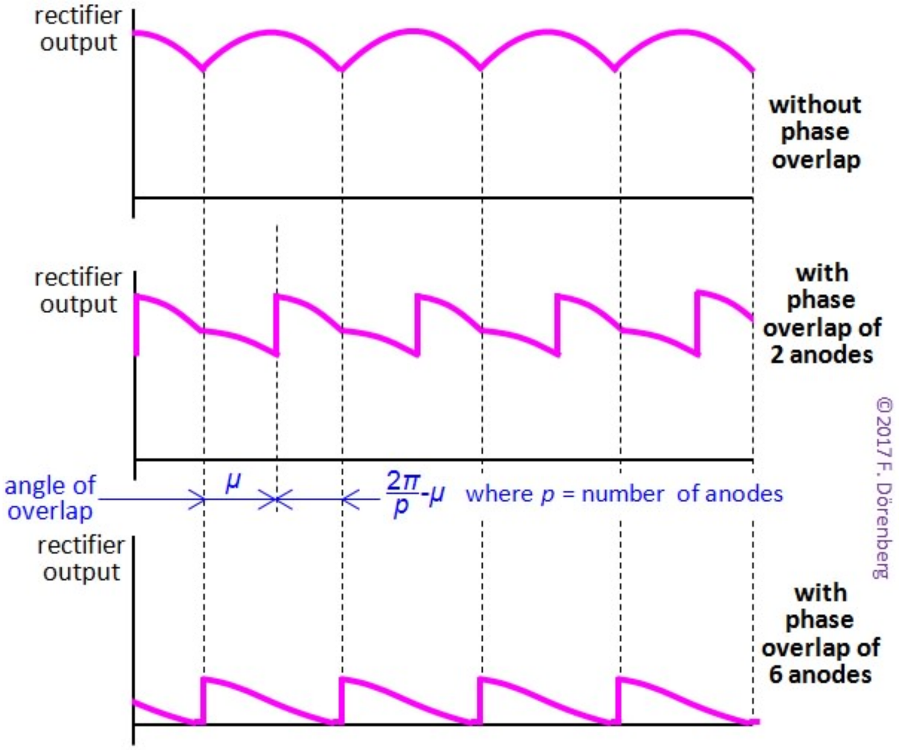


Fig. 87: The effect of phase-overlap on the DC voltage wave
(overlap due to source reactance or load; source: Fig. 25 & 29 in ref. 163C)

The voltage drop during the overlap period is proportional to the output current, and is also a function of the number of anodes and of the transformer inductance. As load current is increased, the operating time (duty cycle) of each rectifier phase is increased, and more phases will overlap. In case of a short-circuit load, the significant voltage drop across the rectifier arcs and resistive losses in the transformer (and other parts of the rectifier circuit) prevent full-time overlap of all phases.

MARs can be constructed for hundreds of kilovolts and tens of thousands of amps. They have been used, and sometimes still are (!), as rectifiers for locomotives, radio transmitters, control of industrial motors, welding equipment, aluminum smelters, high-voltage DC power transmission, etc. Glass-bulb MAR designs are typically limited to 250 kW (500 volt, 500 amps). For higher power levels, a steel-tank version was developed around 1908. *Siemens-Schuckert* developed a compact double-wall water-cooled tank rectifier around 1920. Through the 1960s, high power (up to gigawatts, ref. 163L) high-voltage DC (HVDC) transmission line systems were designed with MAR rectifiers and inverters. MAR technology was succeeded by ignitrons and thyratrons (ref. 163F, 163S), and then solid-state Gate Turn-Off devices (GTOs, e.g., thyristors), ref. 163Q.

In May of 2015, I obtained the black & white photo shown below. It shows the large 6-anode MAR of the Be-10 "Bernhard" at Hundborg/Denmark. The MAR does not appear to have control-grid electrodes. It was installed in a typical MAR-cubicle, 2 m tall (≈ 6.7 ft). The required primary transformers were located in the adjacent MAR-control cabinet. Likewise, the choke-coil, though the DC-motors may have had enough inductance so as not to require such a DC-current smoothing coil.

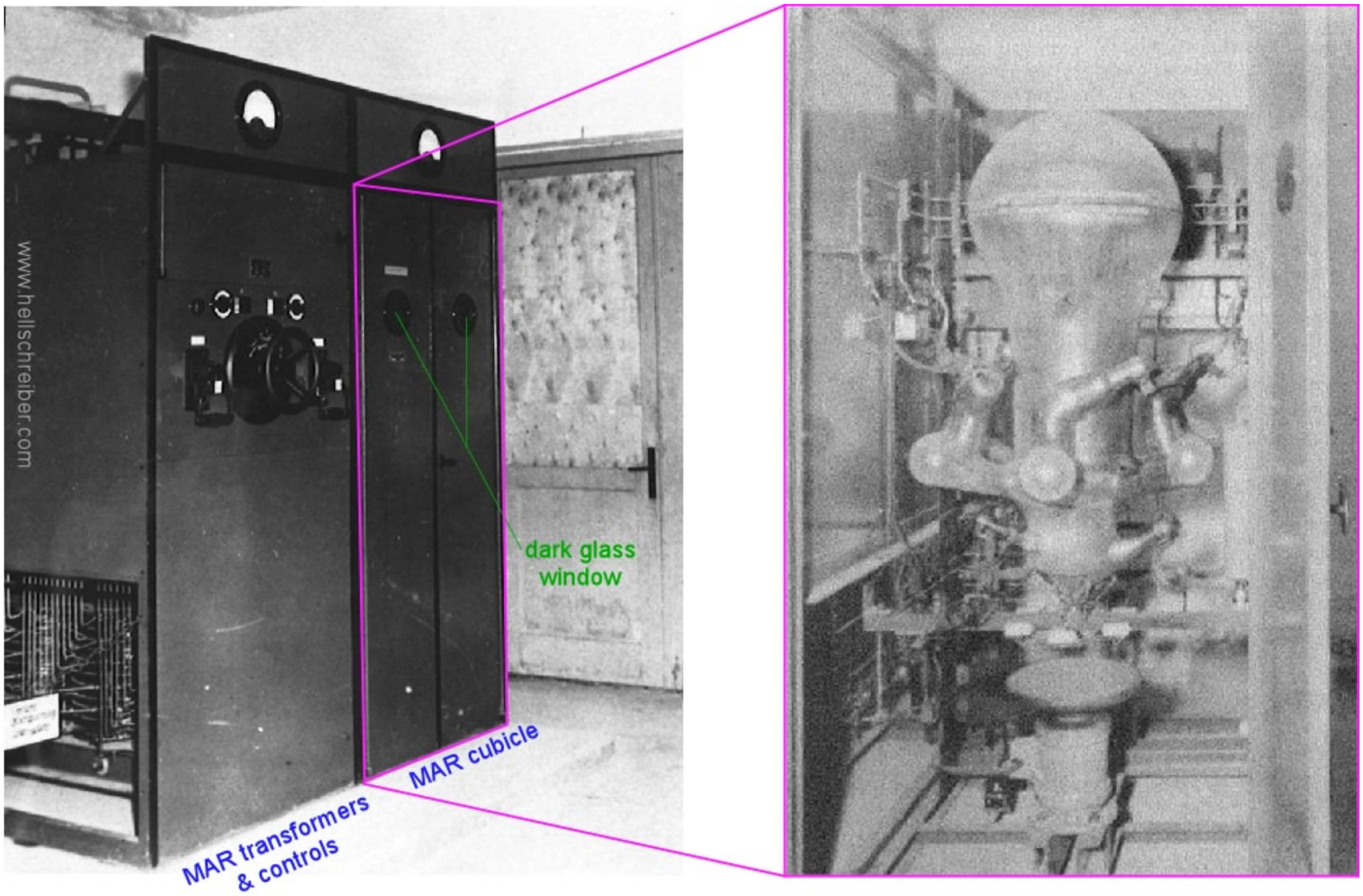


Fig. 88: The rectifier system of Be-10 at Hundborg/Denmark

(sources: (left) ref. 223; (right) Fig. 31 in ref. 93; the thick "disk" below the MAR is actually the spinning cooling fan)

The "Bernhard" MAR was made by the *Gleichrichter Gesellschaft m.b.H* company in Berlin, manufacturer of rectifiers since 1919. They were acquired by the Swiss company *Brown-Boveri & Cie.* (BBC) in 1921 (ref. 191). *BBC* became *ABB* (ASEA Brown Boveri), after a merger between *BBC* and *ASEA AB* of Sweden in 1988. The "Bernhard" MAR was a model **S 18 T** "Glasgleichrichterkolben" (glass bulb rectifier; pdf page 20 in ref. 189). The complete rectifier cubicle with all the equipment and controls was model **DRA 300A / 220 V**, also of the *Gleichrichter G.m.b.H.* (pdf page 20 in ref. 189). The model designator suggests that the MAR had a rating of 330 amps DC at 220 volt AC. The cubicle included the standard cooling fan as well as a bulb heater. The circuitry around this MAR included 17 fuses! Standard equipment of each "Bernhard" station included one spare MAR (pdf page 21 in ref.189).

Fig. 89: Label of a BBC MAR-cubicle with a MAR built by Gleichrichter G.m.b.H. in Berlin
(source: H.-T. Schmidt homepage; MAR for 220 volt 3-phase AC @ 75 amps, 100/140 volt DC @ 150 amps, 140/165 volt DC @ 65 amps)

Other German MAR manufacturers of the era included *Siemens-Schuckert Werke*, several German subsidiaries of *BBC*, and the AEG company ***A***_pparate-Werke Berlin-_***T***_reptow_ (AT) that was founded in 1928. A 6-anode MAR with a height of 90 cm (3 ft, about the size of the "Bernhard"-MAR) can typically handle as much as 350 amps at 650 volts. The photo on the left in Fig. 140 below shows a small MAR, rated for only 220 volt / 100 amps (22 kW), together with its transformers. This MAR was manufactured in the 1950s by ***E***_lektro-_***A***_pparate-_***W***_erke J.W. Stalin_ in Berlin-Treptow. This was the post-war continuation of AEG-AT in the Soviet-occupied part of Germany. The 6-anode MAR in the photo on the right is about 60 cm (2 ft) tall. It is part an elevator (lift) system in a defunct very large WW2 air-raid shelter 140 ft (43 m) below Belsize Park in London (ref. 243). This MAR is still operational in modern days (at least through the year 2014). The cubicle is similar to the "Bernhard" cubicle in Fig. 138.

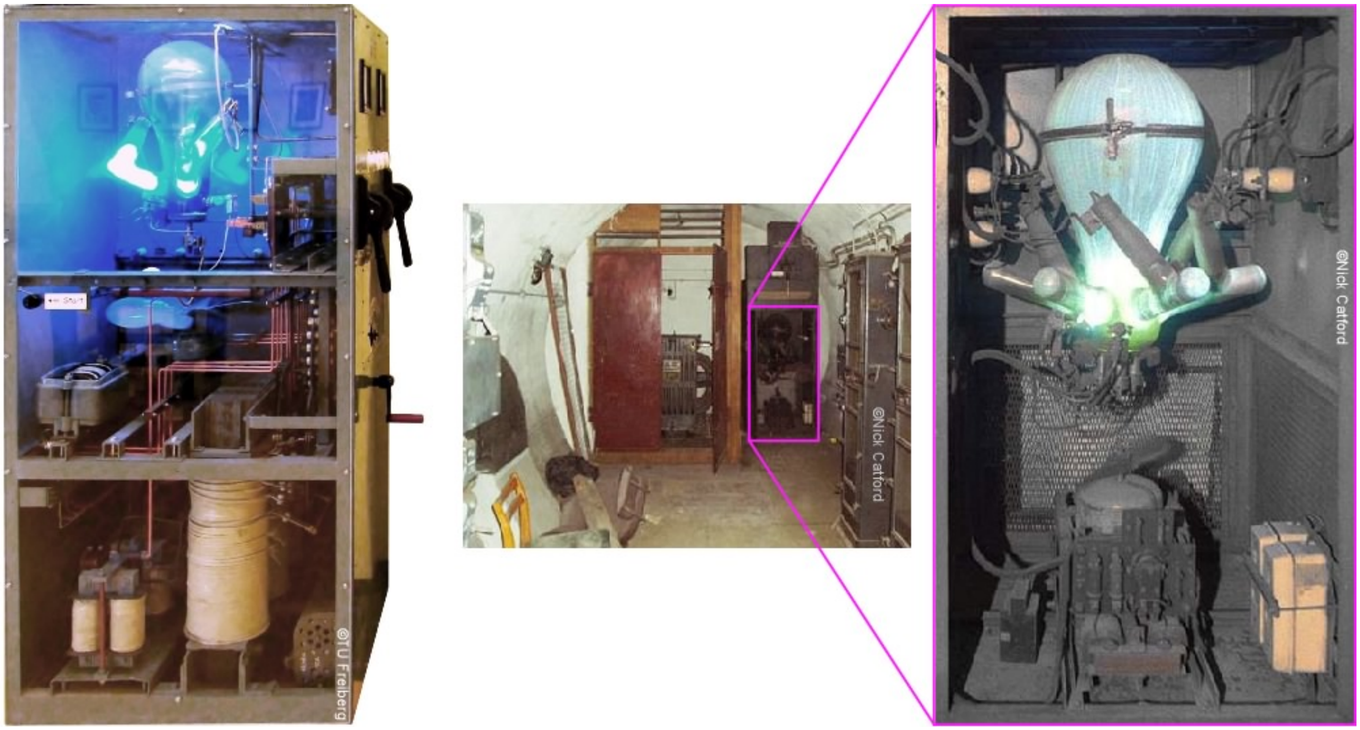


Fig. 90: Example of MAR cubicles (left: 1950s, right: 1936)

(sources: Technische Universität Bergakademie Freiberg (left); ©2000 Nick Catford Subterranea Brittanica (ref. 243); both used with permission)

The "Bernhard" MAR shown in Figure 88 has *six* anodes. For obvious reasons, these multi-arm MARs are sometimes referred to as "Krakengleichrichter" ("octopus-rectifiers"). Compared to a 3-arm MAR, a 6-arm MAR reduces the ripple in the rectified voltage. It also requires a more complicated main-transformer connection to AC power, e.g., a delta/double-star or star/double-star configuration. See pp. 18-24 in ref. 163B. Six-anodes is typically sufficient. Having more anodes does reduce the output ripple (which has a lowest harmonic frequency of six times the 50 or 60 Hz main power). However, the reduction when going from 6-phase to 12-phase rectification is less than half the reduction when going from 3-phase to 6-phase (Fig. 35 in ref. 163C for no-load conditions). Also, cost increases rapidly without increasing rectifier output, and the already low power factor (due to an undesirably large phase angle between AC supply voltage & current) is further reduced.

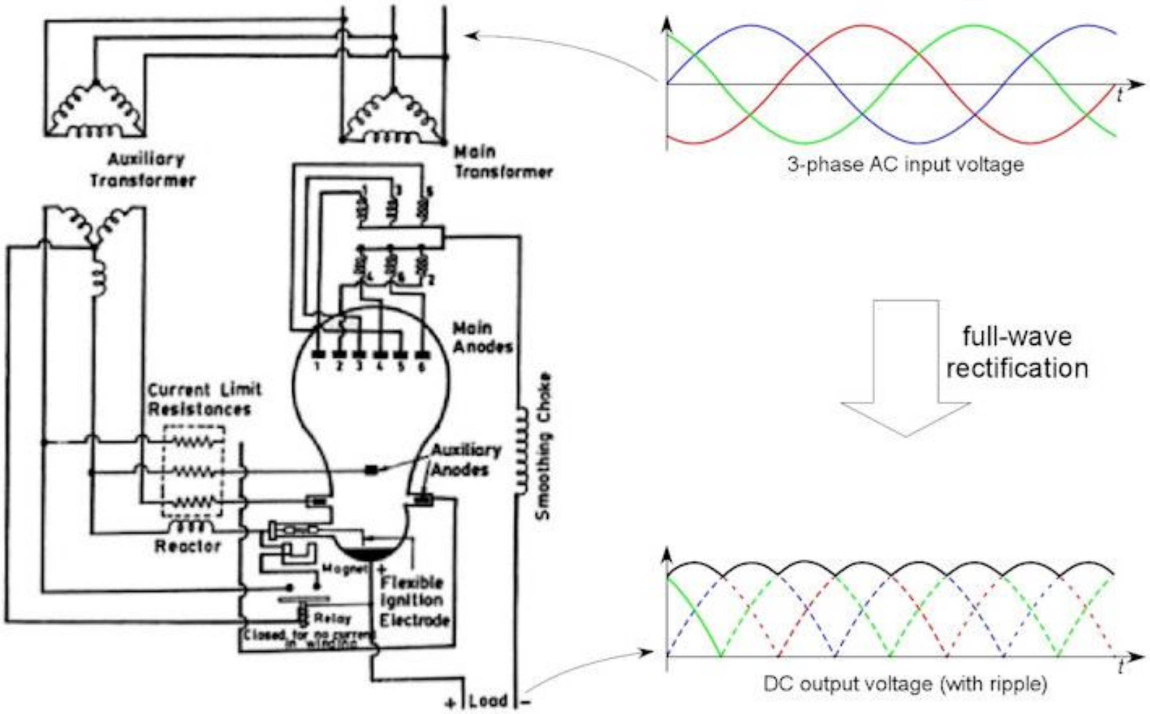
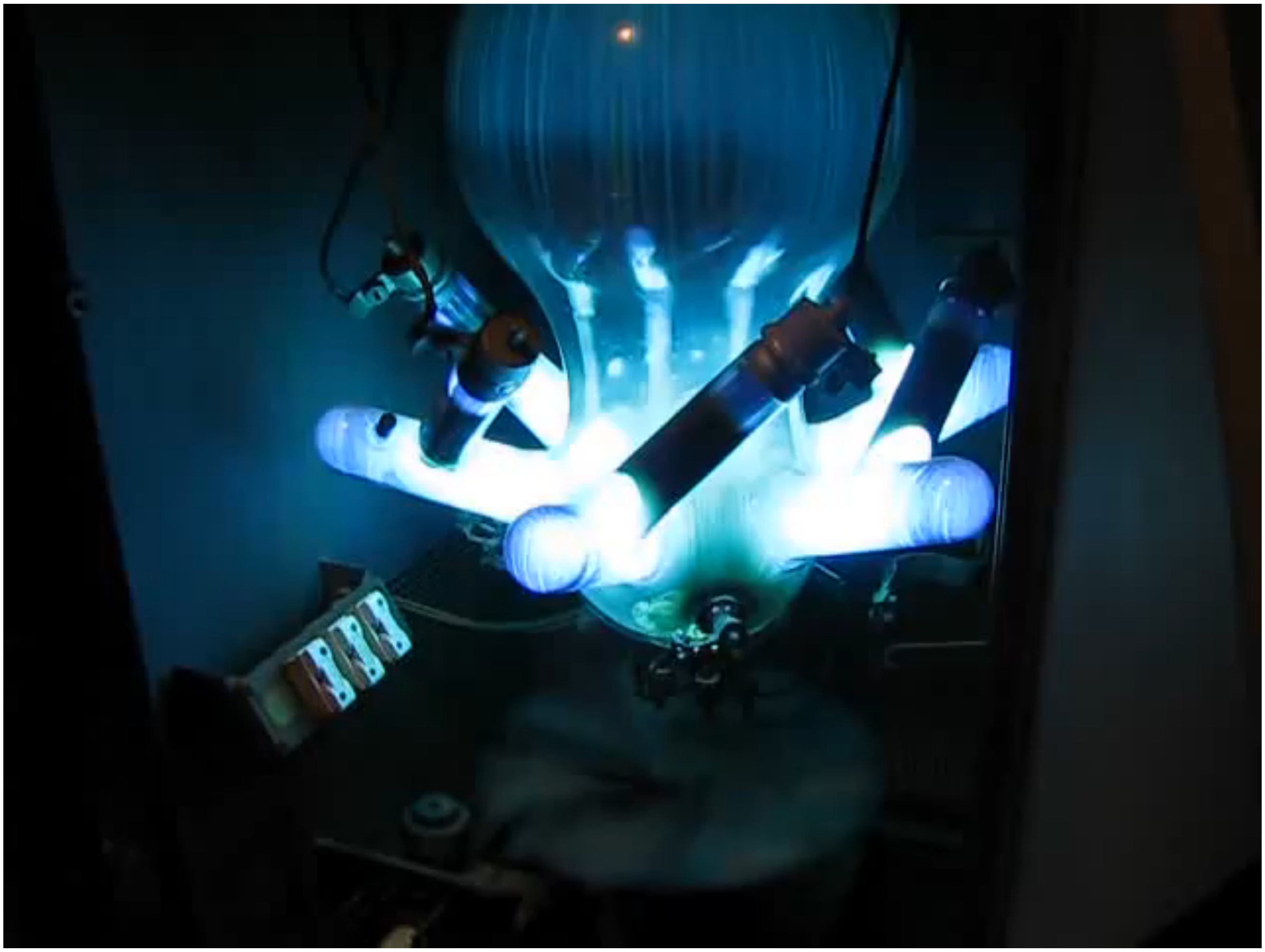


Fig. 91: A 6-anode Mercury Arc Rectifier with delta/double-star main-transformer connection to 3-phase AC power
(source: Figure 7.41 in ref. 163E)

When the motor voltage is reduced to slow down the motors (e.g., to brake to standstill), the large inertia of the "Bernhard" turntable will reverse the load torque of the motors. However, current can only flow through the MAR in one direction - it is a rectifier/diode. So, regenerative braking (= using the motor as a generator and feeding the generated electricity back to a power grid) is not an option, and the motor cannot exert a braking torque. As a result, the armature voltage will increase to undesirably high levels. This is typically handled by switching-in a large dummy-load resistors across the armature of the motors, and dissipating the generated power as heat.

Here is a 36 sec video clip of a 6-anode MAR in action (WARNING - MAR systems are very loud!):



A six-anode Mercury Arc Rectifier in action
Source: *YouTube*; one of four MARs of the 300 kW, 600 volt DC power supply system of the tramway network in Melbourne/Australia. MARs made by Hewittic Electric Co. Ltd. (frmr. Westinghouse Cooper-Hewitt Co Ltd., estd. 1906) in Walton-on-Thames/England, installed in 1936, operational until 2019! Ref. 163T.

THE "CONZ" DC-AC POWER INVERTER

As stated above, a synchronous AC motor was used for obtaining and maintaining the required accurate locomotive speed. The frequency of the 3-phase AC power from the public power grid and the local backup generator was not sufficiently accurate. Hence, the fluctuating primary AC power had to be converted to constant-frequency 3-phase AC. Before the days of solid-state power electronics (1960s), the required power conversion was done by electro-mechanical means: an electric motor, an AC generator, and a closed-loop control system. The motor, generally referred to as the "prime mover", could be AC or DC. In the "Bernhard" system, a special DC-to-3-phase-AC inverter (*D*: "Umformer für Gleichstrom-Drehstrom") was used: a model **NGJV So, 5/2 T** built by the **Conz** company (sheet 16 in ref. 189). It was located in power generator building near the "Bernhard" beacon. The associated control panel had the following fuses: two for 350 V, 160 A, and three for 500 V, 35 A (per sheet 20 of ref. 189).

The **Conz Elektricitäts-Gesellschaft mbH** company was founded in 1887 by Gustav Conz. It was originally located in the Spaldingstraße in the southern German city of Ulm. The company moved to Hamburg in 1890, and acquired a plot of land in Hamburg/Altona-Bahrenfeld (Gasstraße 6-10) in 1911. An office building and two factory building were constructed here in 1912. Ref. 207. In 1962, Conz became a wholly-owned subsidiary of *Deutsche Maschinenbau-Aktiengesellschaft* (DEMAG) in Duisburg. The Hamburg plant was closed in 1995.

CONZ ELEKTRICITÄTS-GESELLSCHAFT
mit beschränkter Haftung
ALTONA-BAHRENFELD
SPEZIALFABRIK
Elektr. Maschinen und Apparate
[345]

Fig. 92: advertizing of the Conz company from 1924
(source: Elektrotechnische Zeitung (ETZ), Nr. 16, 17 April 1924)

CONZ
Elektromaschinenbau
CONZ ELEKTRICITÄTS-GESELLSCHAFT M. B. H., HAMBURG-BAHRENFELD

ELEKTRO-MASCHINENBAU
50
CONZ

50 jährige Erfahrung im Bau von Motoren, Generatoren und Umformern, in Serien als auch im Einzelbau hergestellt, gibt den

CONZ ELEKTROMOTOREN

ihre Überlegenheit und Anpassungsfähigkeit an jeden Betriebszweck und ihre besonderen Gütemerkmale.

CONZ ELEKTRICITÄTS-GESELLSCHAFT M.B.H. ALTONA-BAHRENFELD

Fig. 93: advertizing of the Conz company from 1937 & 1940

A standard AC-generator has a field winding that is fed with DC power, and an armature winding that outputs the generated AC power. That is: a "singly-fed" generator. However, at the heart of a Conz converter is a high-power "doubly-fed AC generator" (*D*: "Doppeltgespeister Drehstromgenerator"). This is also called a "doubly-fed induction generator (DFIG) and "slip-ring generator" (*D*: "Schleifringläufergenerator"). Note: "doubly-fed" is somewhat of a misnomer, as it does not mean that the machine has two separate power inputs. Just that it has two sets of 3-phase connections. A DFIG is similar to the singly-fed generator, in that the stator outputs the generated AC power. However, now the rotor is excited with 3-phase AC power at variable frequency. The frequency of this AC excitation power is continuously adjusted to compensate for changes in the speed of the prime mover. The result is regulated 3-phase AC power (*D*: "geregelter Drehstrom") with a constant frequency. In modern times, DFIGs are widely used for large wind turbines, as solid-state inverters required for megawatt-scale wind turbines are larger and more expensive.

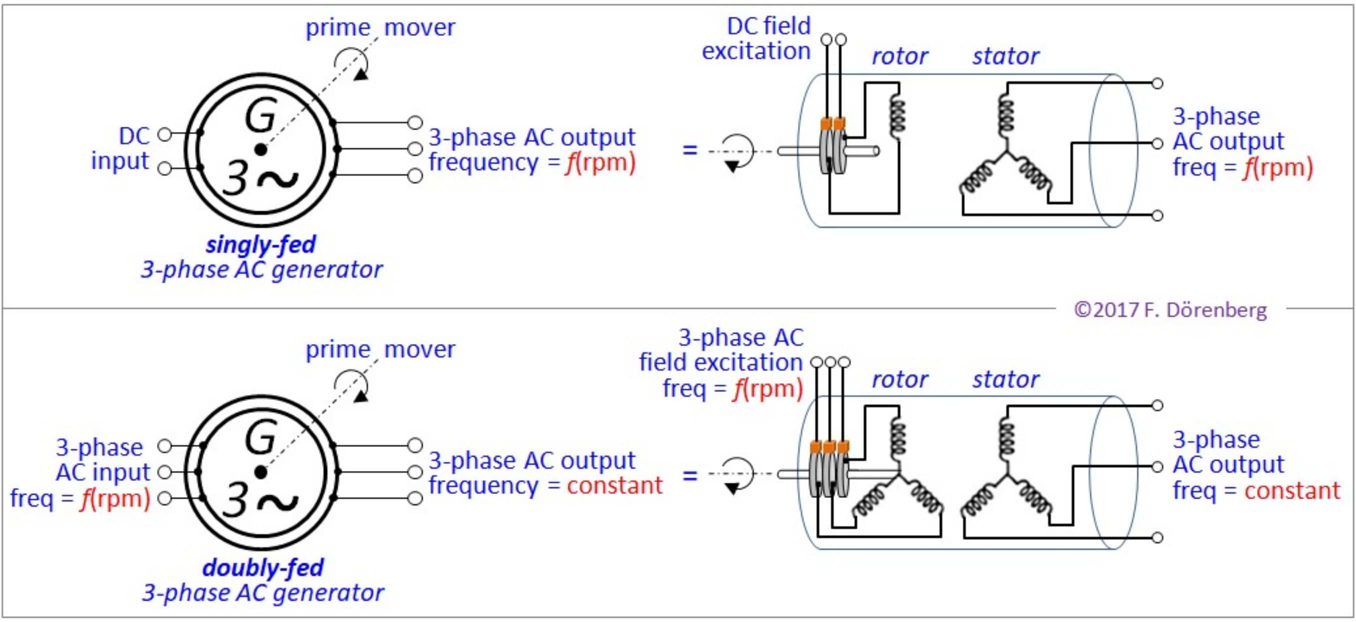


Fig. 94: singly-fed DC and doubly-fed 3-phase AC power generator
(the stator windings and DFIG rotor windings are shown in the standard WYE (a.k.a. "Y", "star") configuration rather than Delta ("Δ"))

The next figure shows the principle diagram of the AC-AC Conz generator, as patented in 1937:

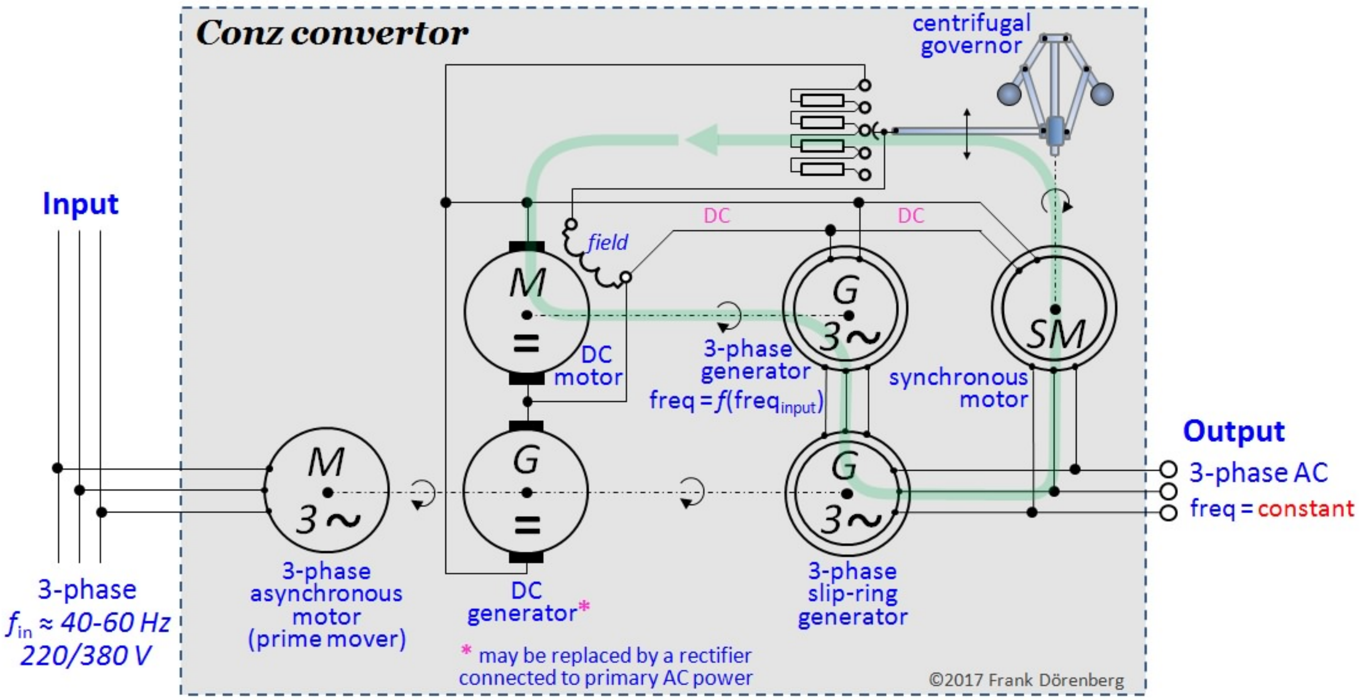


Fig. 95: Conz convertor - variable-to-fixed frequency AC-AC converter

(source: adapted from the 1937 Hans Gross / Conz patent nr. 692583; see ref. 188 for a list of related patents)

The green overlay in the figure above, shows the control loop for keeping the output frequency of the DFIG constant - independent of variations of the frequency and voltage of the primary AC power and of the output load: the 3-phase AC output power drives a synchronous AC motor. This motor is small (low power) compared to the DFIG and the primary mover. It drives a centrifugal governor. Based on the rpm, the governor adjusts a variable resistance. The resistance is placed in series with the field of a small DC motor, so as to change its speed. The DC motor drives a small 3-phase AC generator that excites the DFIG. Note that it is also possible to reverse the rotational direction of the three phases of the output. The efficiency of a Conz generator is higher than Ward-Leonard converter, especially under partial load or no load (idling).

The Conz generator configuration above uses an AC motor as prime mover, and a DC generator. This configuration can be simplified if a high-power DC source is available. This is the case in the "Bernhard" system, for powering the DC motors in the four locomotives. The DC-to-AC converter configuration is also mentioned in the Conz patent. So, a DC motor was used as prime mover, and the small DC generator was eliminated:

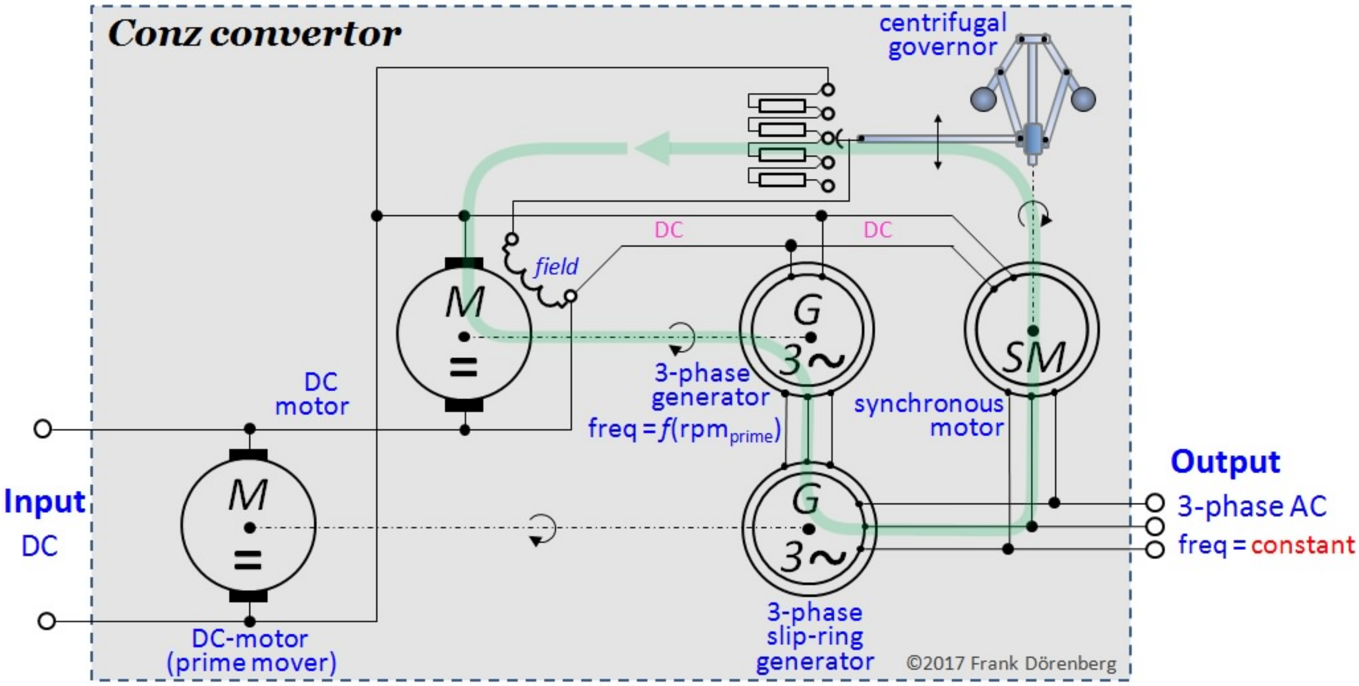


Fig. 96: Conz generator - DC-AC configuration as probably used in the "Bernhard" motor drive

(source: adapted from the 1937 Hans Gross / Conz patent nr. 69258; see ref. 188 for a list of related patents)

The output frequency of the "Bernhard" Conz-generator is not known. However, the title of the related 1937 *Reichs* patent is "Frequenzwandlergruppe zur Erzeugung konstanter Mittelfrequenz", i.e., "Frequency converter for generation of constant mid-frequency". In modern times, 400 - 2000 Hz mid-frequency AC is used in high-power application such as resistance welding. Ref. 10 (1946) states that the the "Bernhard" Conz-generator generated 50 Hz power. Ref. 290A also suggests this.

The photo below was taken in the power supply bunker or barrack of Be-10 at Hundborg/ Denmark. The Conz converter is on the right and is about 2 m tall. It is installed upright, probably due to the centrifugal governor. The cabinets on the left house the MAR rectifier and associated circuitry and controls.

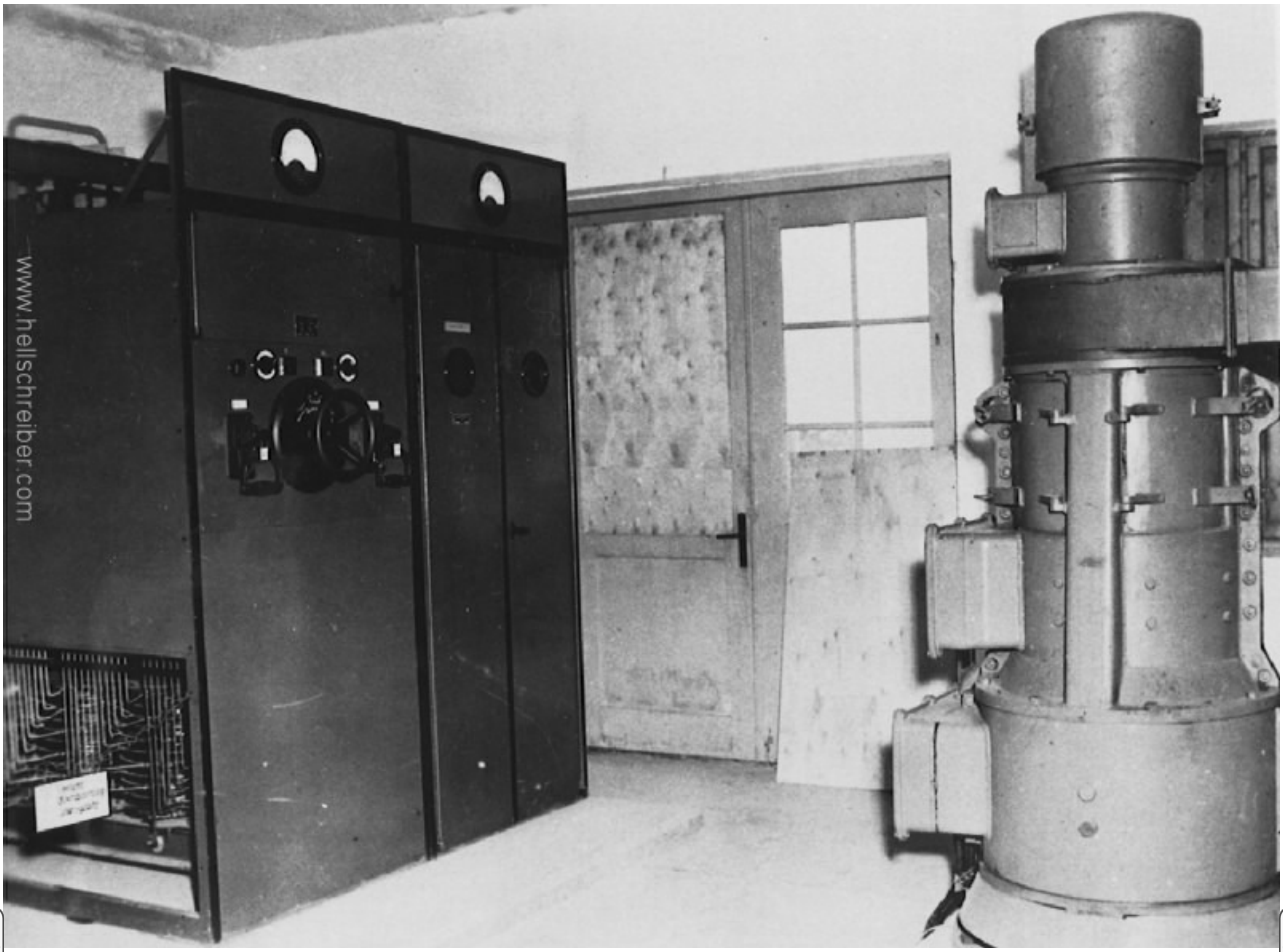


Fig. 97: The Be-10 Hundborg installation - cabinets with the MAR and its controls, and the "Conz" generator

(photo courtesy Mike Dean, US National Archives & Records Adm. (NARA) image nr. 111 SC 269041; US gov't = no ©)

ROTATIONAL SPEED

The official German Bernhard/Bernhardine system description documents (ref. 181, 183, Blatt 8 & 10 in 198A) clearly state that the Bernhard-beacon rotated once every 30 sec, i.e., at 2 rpm. The specified diameter of the center of the circular rail track (= midway between the two rails) was 2x10.55 = 21.1 m (ref. 193). Hence, the track length was 66.28 m. This means that at 2 rpm = 120 rph, the small locomotives that turned this enormous antenna installation, moved at a respectable speed of 8 km per hour (5 mph). As described in the "Locomotive system" section below, the rotational speed of the system was determined by a single synchronous 3-phase AC motor in one of the four locomotives. The 3-phase AC power was provided by a DC-AC inverter that had a fixed reference frequency. Hence this motor could only turn at the reference speed, and the speed was monitored very accurately. The rotational speed of the beacon was kept constant to within -0.2 to +0.3% ! See p. 80 in ref. 181 and p. 8 & 18 in ref. 183.

The official German system descriptions and the manual of the FuG 120 "Bernhardine" printer system also state the same 2 rpm speed (top of Section B on p. 5 in ref. 15, sheet 8 & 10 of ref. 198A; also §3 in ref. 10). Moreover, the "Bernhardine" printers were simply not compatible with antenna rotational speeds that deviated more than a couple of percent from that nominal speed! As with other types of synchronized teleprinter systems, the motor of the Bernhardine-printer had to turn 1-2% faster than nominal system speed (p. 18 in ref. 183).

There are some persistent statements (e.g., ref. 5A) that the "Bernhard" beacons rotated with a period other than 30 sec. Some of the sources for these statements are the following:

> The French resistance explicitly reported in 1943 that this station Be-3 at Le-Bois-Julien rotated once per minute (p. 62 in ref. 91).
>
> A British 10 cm [= 300 MHz] radar station at Fairlight (on the East Sussex coast, east of Hastings, 87 km [54 miles] northwest of Be-3 at Le-Bois-Julien) concluded that the station appeared to rotate once a minute (ref. 173B, December 1943). Likewise, extensive radar measurements early-June 1944 also concluded that the rotation period was 52-60 sec (ref. 173A).
>
> Luftwaffe POWs in the UK reported 1 rpm for the Bernhard system in general (§10, 18, 19 in ref. 6C)
>
> A 1946 US air force survey of German electronics development, stating that "... information is printed once per minute" (ref. 93). This may have been based on war-time "intelligence" from other sources.
>
> A "reliable informant" who saw the Be-6 station at Marlemont/France station in operation, reported to the British that he was told [correctly] that it rotated with a speed of 8 km/h. Based on the wrong British photometric assumption that the Bernhard-ring had a diameter of 82 ft [25 m], a rotational period of 36 sec. was estimated. Ref. 173E. For the actual diameter of 71 ft [21.5 m], the correct period of 30 sec. would have been obtained.
>
> Ref. 225 and 226A state that the system rotated at 1 rpm with and the beam was received by aircraft during 10 sec per rev.
>
> Ref. 175B (RAF 192 Squadron) mentions that the beam was received by aircraft during 5-10 sec per minute. This may suggest 1 rpm. Note that typical reception time was actually 3-5 sec per rev, so 5-10 sec / minute could be 1 or 2 rpm...

The 1936 Lohmann/Telefunken patent 767528 states that the limiting factors for the upper limit of the antenna's rotational speed, are the printing speed of the Hellschreiber and the required pixel resolution of the printed information. Given the large size and weight of the antenna system, there are obviously also mechanical considerations for the upper speed limit. The patent proposes to resolve this, by quadrupling the number of antenna beams, spaced at 90º intervals. Each optical encoder disk would simply have four "light source plus photocell" pairs (two pairs shown in the diagram above), that could be adjusted to account for angular offsets between the beam centerlines.

THE ANTENNA SYSTEM

The "Bernhard" ground station is the rotating radio-navigation beacon of the "Bernhard/ Bernhardine" system. This means that its transmission is *not* simultaneously in all directions (i.e., omni-directional), but it sweeps the horizon with its directional radio beams. Secondly, it is a 2-channel transmission: one channel is used to transmit the momentary azimuth value of the beam-direction. This is done in Hellschreiber-format. The second channel is used to transmit a signal that disappears ("null") when the associated beam is pointing straight at the antenna of the navigation-radio receiver in the aircraft.

So, how is this all done? Clearly, we need two antenna sub-systems: one for each transmission channel. The antenna sub-system for the azimuth-data must create a single-beam radiation pattern. The antenna sub-system for the pointer-channel must create a twin-beam radiation pattern, with a sharp null between the two beams. That is, two narrow beams, that point slightly to the left and right of the centerline of the single-beam. To get the sweeping effect, the two antenna systems must be aligned (pointing in the same direction), and be continuously rotated together.

Let's look at the actual antenna systems to see how all of this was implemented. Figure 55 below shows three development stages of the antenna system of the initial UHF Bernhard system. It operated at a frequency of 300 MHz, which is equivalent to a wavelength of 1 meter. The fourth development form (1940) used a parabolic antenna with an aperture of 6 λ (ref. 3, 181), which translates to a beamwidth of almost 10°. This antenna is shown in the far right photo in the next figure.

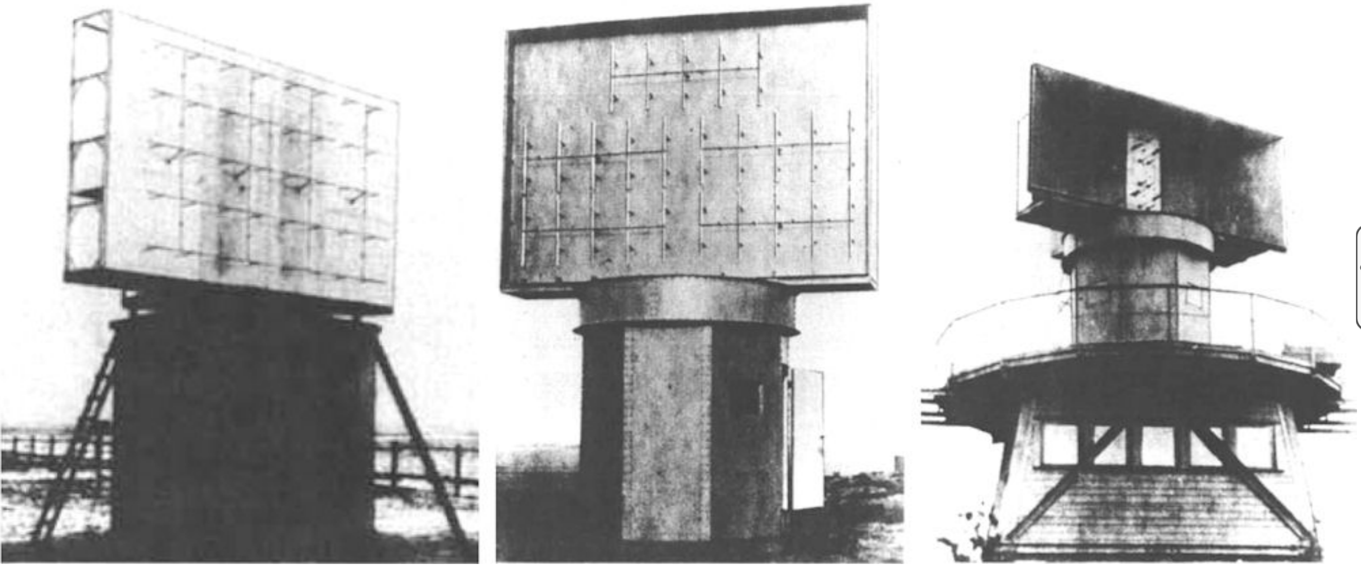


Fig. 98: Three antenna systems developed for the UHF-version of "Bernhard"
(left: 1935 (twin-beam only), center: 1936 , right: 1940; source: ref. 2B)

The antenna system in the center photo of Figure 98 most clearly shows the arrangement of a large number of vertically-oriented antenna elements:

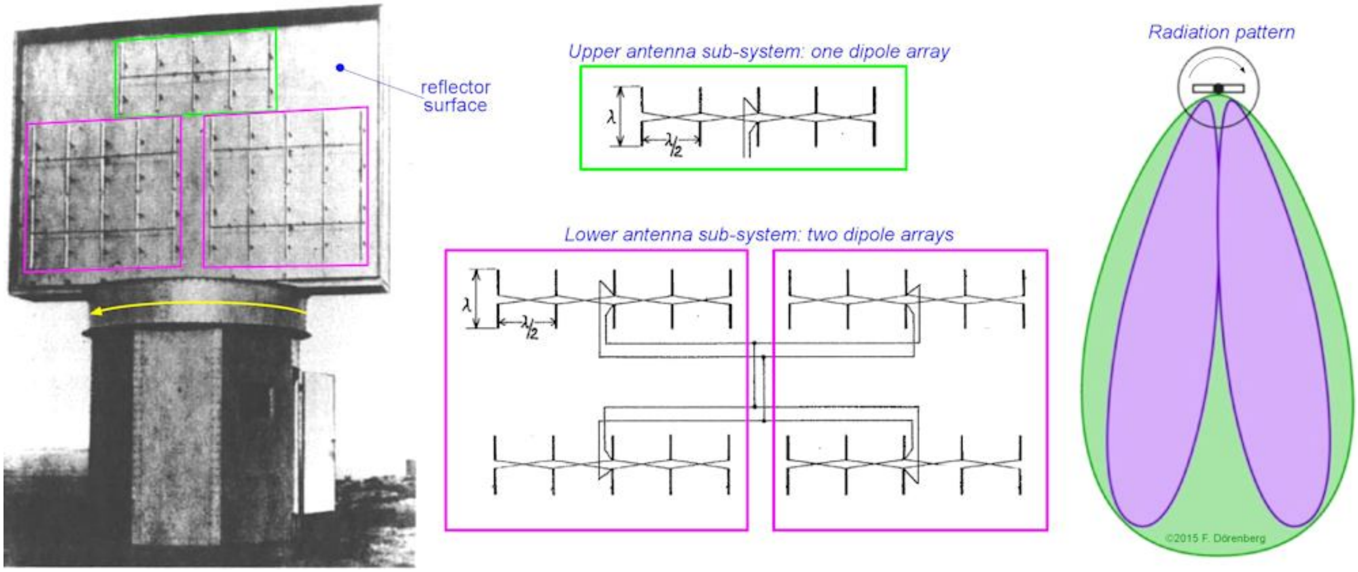


Fig. 99: The three antenna sub-systems and the resulting radiation pattern (top view)
(dipole arrays diagram: adapted from Reichspatent [767532](767532))

The antenna sub-system at the top (see the green box in the above Figure) shows a group of five identical, parallel antennas that are interconnected. These antennas are simple dipoles. As the name suggest, a dipole has two identical "poles", typically straight metal rods or wires. The two halves of the dipole are connected to the transmitter via a 2-wire feedline. The next figure illustrates the radiation pattern of a single, vertically oriented dipole antenna in free-space (i.e., sufficiently far from other objects and ground). It is a doughnut-shaped omni-directional pattern - which is *not* what we want!

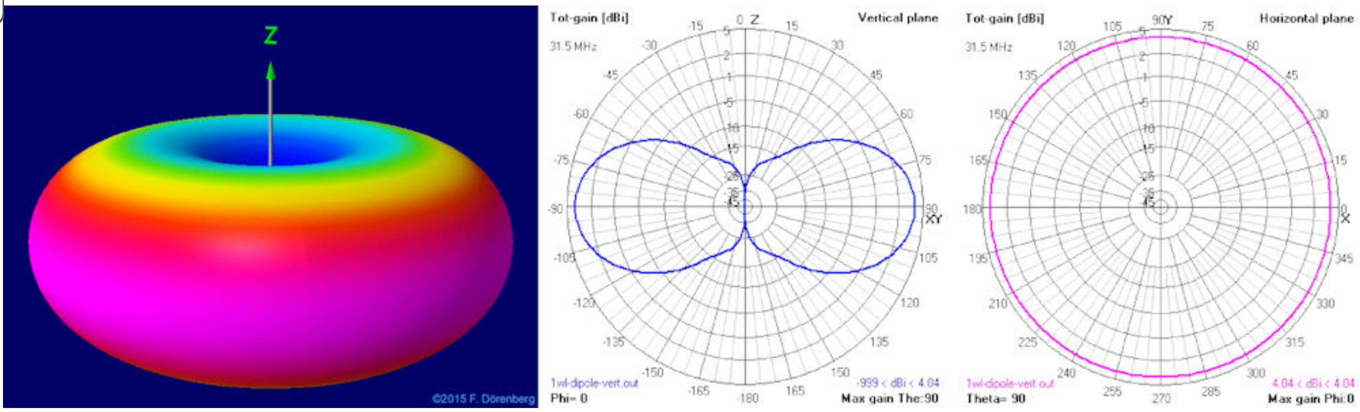


Fig. 100: The omni-directional radiation pattern of a single vertical dipole antenna in free-space
(left: 3D pattern of the strength of the radiated signal; center: vertical cross-section of the pattern, right: top view)

So how do we get a directional beam-pattern? This requires that we concentrate the transmitted energy in the *desired* direction(s), and radiate less energy in all other directions. This can be done in at least three ways (ref. 139K1):

- By placing a reflector surface behind the (dipole) radiator.
- By using a "longwire" antenna (such as a Rhombus antenna), with a radiator length of several wavelengths. This is not very practical for a rotary antenna system that

operates at a wavelength of ca. 10 m.

By combining the radiation pattern of multiple dipoles.

or a combination thereof.

Let's keep it simple and use several identical dipoles that are placed in parallel, and arranged on a straight line (= linear). As all dipoles lie in the same plane, this is called a **planar array**. Let's use the same spacing (= equi-distant) between adjacent dipoles: a **linear array**. We feed all dipoles of this array with the same radio-frequency current (= same amplitude and same phase). I.e., a uniform distribution of the dipole excitation. The in-phase (co-phase) feeding makes the array concentrate the radiated energy in the direction that is perpendicular (= broadside) to the plane that is made up by the parallel dipoles. We now have a **uniform linear broadside array**. The actual pattern depends on the distance between the dipoles. The next two Figures show this dependency for an array of 3 and of 4 parallel dipoles, respectively. This is beginning to look like what we want!

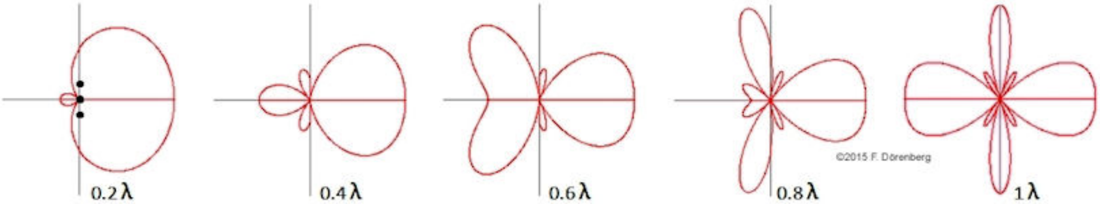


Fig. 101: Top view of radiation patterns of a uniform 3-dipole broad-side array (dipoles spaced by 0.2 - 1 λ)

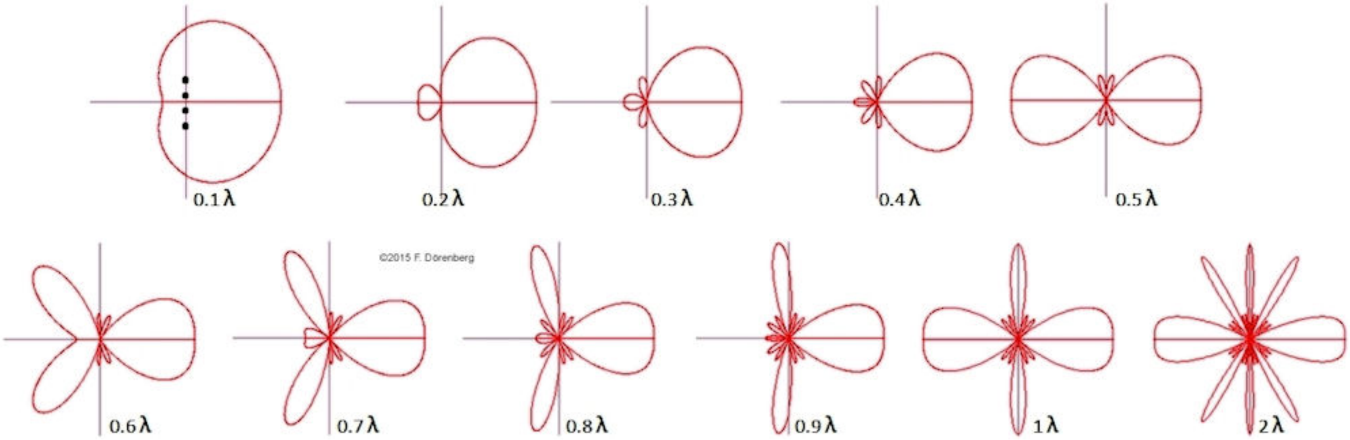


Fig. 102: Top-view radiation patterns of a uniform 4-dipole broad-side array (dipoles spaced by 0.1 - 2 λ)

We can make several general observations:

The direction with maximum radiation intensity, is independent of the number of parallel dipoles and their spacing.

For spacing larger than 0.1 λ, all patterns have one or more clear side-lobes, in addition to the "forward" radiation of the main beam. This is not desirable.

For spacing equal to, or larger than, half a wavelength (0.5 λ), some side-lobes become very significant and approach the strength of the main beam. These are called *grating lobes*. This is also not desirable. Note: maximum gain for a given number of dipoles is typically obtained for a spacing of 0.5 to 0.7 λ.

The main beam becomes narrower (= directivity) and stronger (= gain), as the number of dipoles and/or spacing increases. This is desirable. However, each additional dipole adds less gain than the previous addition ("law of diminishing returns"). The latter is illustrated in Figure 37 below. Also, if the number of dipoles is increased without increasing the overall size (span) of the array, then the directivity is reduced (main beam becomes wider), ref. 139J.

As, for a given number *n* of dipoles, the spacing increases, the number of (equal strength) maxima increases. Between these maxima, there are *n* - 2 smaller lobes. Ref. 139J.

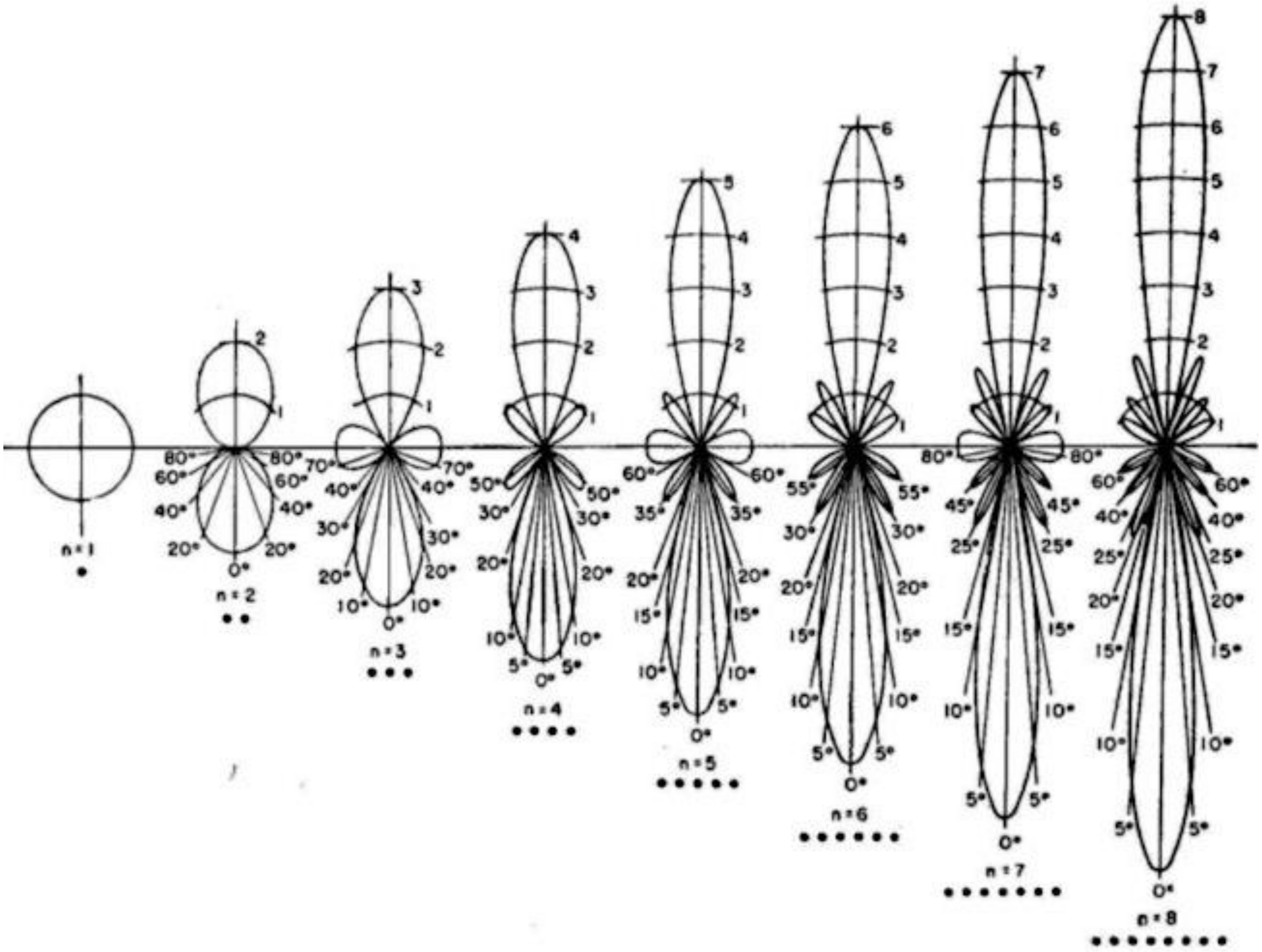


Fig. 103 The radiation pattern of uniform broadside arrays of 1-8 parallel dipoles (spacing < 0.5 λ)

(source: Figure 3.46 in ref. 139A)

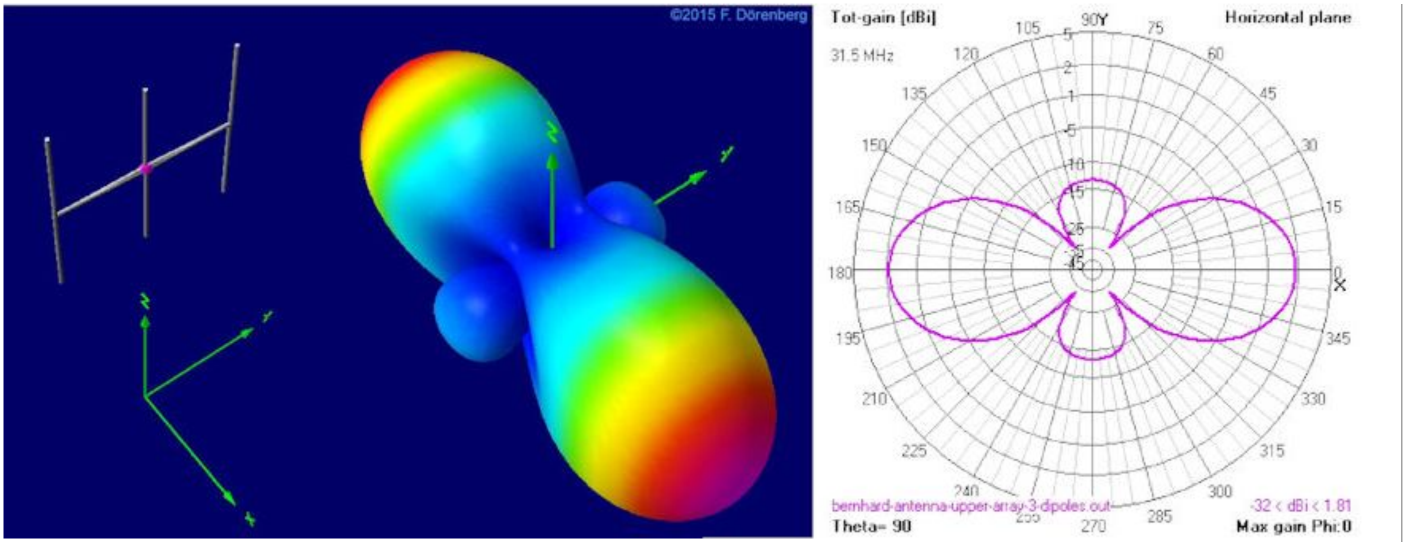


Fig. 104: Radiation pattern of uniform broadside array of 3 parallel dipoles (spacing = 0.5 λ) - without reflector screen or dipoles

(left: array configuration; center: 3D radiation pattern; right: top view of the radiation pattern; my 4NEC2 model is here)

How get can we reduce, or even eliminate, the side-lobes and rear-lobe? There are several techniques, with varying degrees of complexity. The basic parameters that we can adjust, are amplitude and phase of the dipole current, spacing between the dipoles, and the use of reflectors (ref. 139A-139H):

> One way is to *not* feed all dipoles with the same current amplitude. That is, *non*-uniform excitation instead of uniform. Instead, use amplitudes that taper off towards the dipoles at both ends of the array. This is called current "grading" or "tapering". The amplitude coefficients should be equal to those of a binomial series. For dipole spacing less than 0.5 λ, this eliminates all side-lobes. Current-grading coefficients may also take the form of a Fourier-series distribution, Power-of-Cosine distribution, Taylor-series distribution, etc. However, such distributions significantly complicate the system for feeding the dipoles. Also, the uniform distribution of the "Bernhard" arrays produces the highest directivity (see p. 518 in ref. 139H), though the first side-lobe is at best only about 13 dB down from the main-lobe.
>
> Side-lobes can be reduced by putting a reflector surface behind (and parallel to) the plane of the dipoles. This is what we see in the three "Bernhard" antenna systems shown in Figure 55 above. For UHF frequencies (λ ≤ 1 m), constructing such a conductive "mirror" surface is easy. Likewise for small VHF arrays (2-3 dipoles). Reflectors are typically placed at a distance of 0.25 λ from the dipoles (1939 Telefunken/Lohmann patent 767531, lines 114-116; also p. 18 in ref. 138).
>
> > For true broadband operation (i.e., a bandwidth of at least ±10% about the center frequency, whereas "Bernhard" is "only" ±5%), a reflector distance of 0.34 λ actually provides much less variation in feedpoint impedance, with that impedance closer to being purely resistive (ref. 139K2).
> >
> > Instead of a solid metal surface, as wire mesh may be used, as long as the size of the openings is less than 0.1 λ. Instead of a mesh, it is also possible to use a sufficiently dense "curtain" of un-tuned wires that are parallel to the dipoles.
> >
> > To get the desired effect, the planar surface or mesh may have to be extended around the array. I.e., the array is placed inside a shallow metal box or wire basket, that is open in the broadside / forward direction of the array.

Instead of a reflector surface or mesh, a reflector-dipole can be placed behind (and parallel with) each primary dipole, e.g., at a distance of 0.25 λ (e.g., p. 18 in ref. 138). The reflector-dipoles may be *passive* ("parasitic"). In this case, they are not connected to the transmitter, but receive radiation from the other dipoles and re-radiate it. The reflector-dipoles may also be *actively* powered by the transmitter. The result of the latter method is illustrated in Figure 105 below.

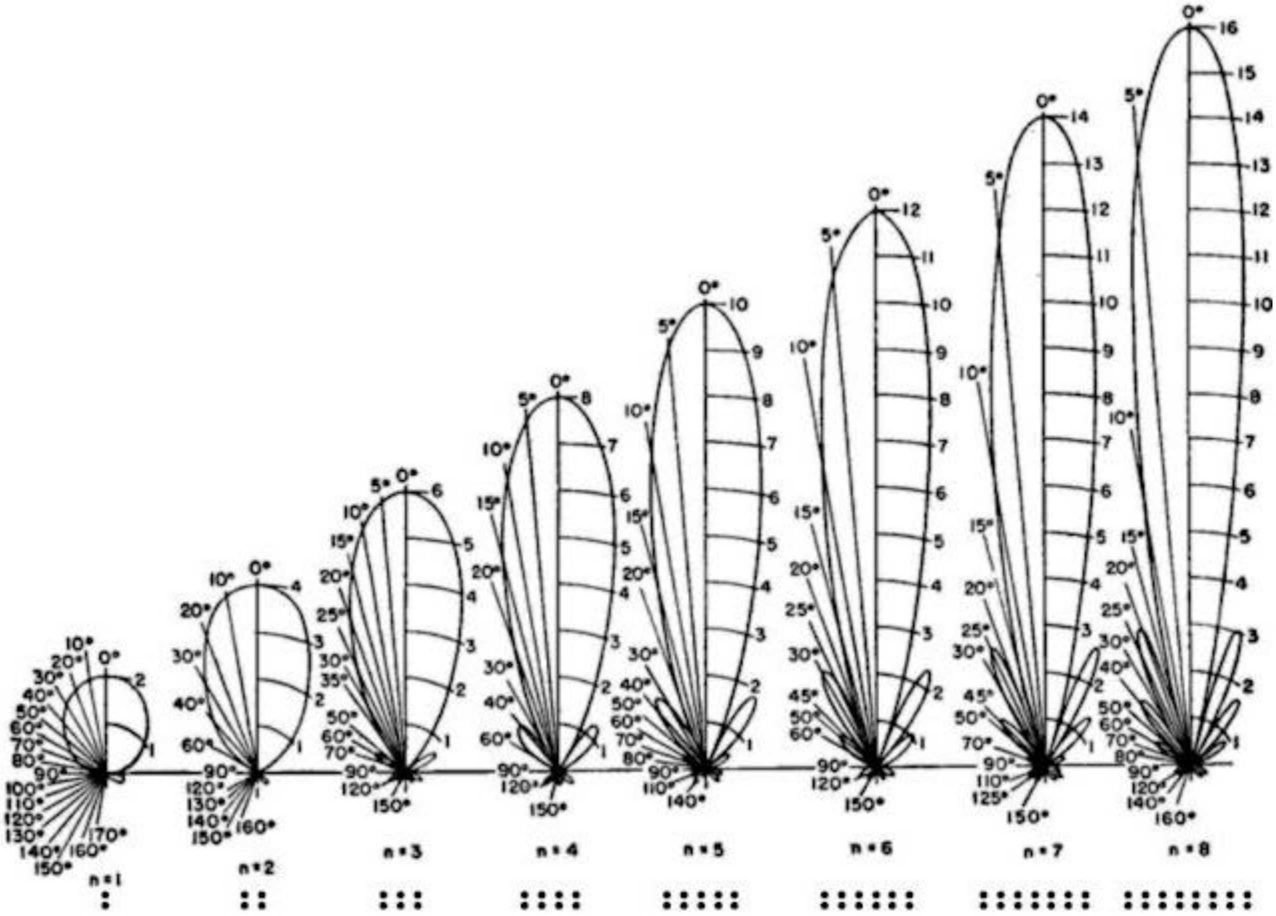


Fig. 105: The radiation pattern of uniform broadside arrays with identical array placed 0.25 λ behind it, fed with 90° phase difference

(source: Figure 3.42 in ref. 139A)

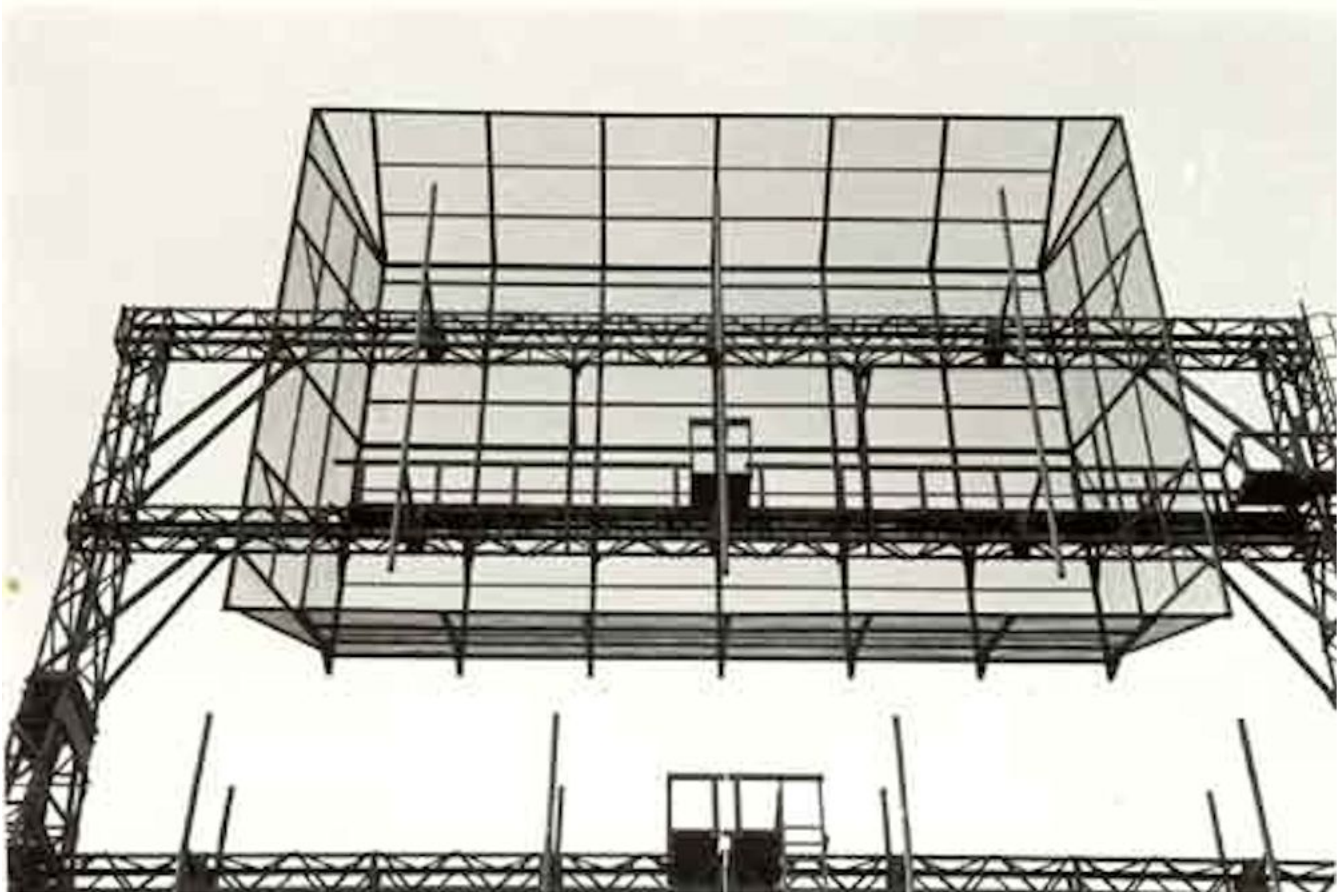


Fig. 106: Close-up of the upper antenna system of the "Bernhard" beacon
(sources: Museums Center Hanstholm, Hanstholmregistreringen; used with permission)

Figure 107 shows my simulation of the effect of placing a reflector mesh-screen (0.1 λ mesh openings) at 0.25 λ behind the 3-dipole array: a significant reduction (14.4 dB) of the side-lobes, compared to Fig. 61 above. In the actual "Bernhard" antenna system, there is a mesh-screen above, below, and to the sides of the array. I.e., a mesh cage that is open in the forward direction. This further reduces the side-lobes. I did not expand my simulation model this way.

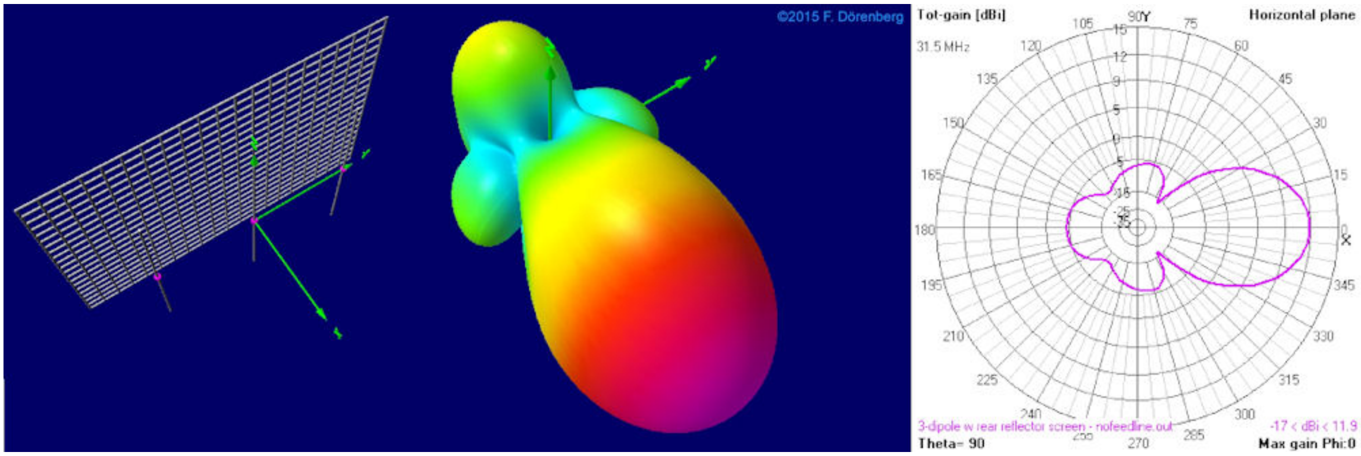
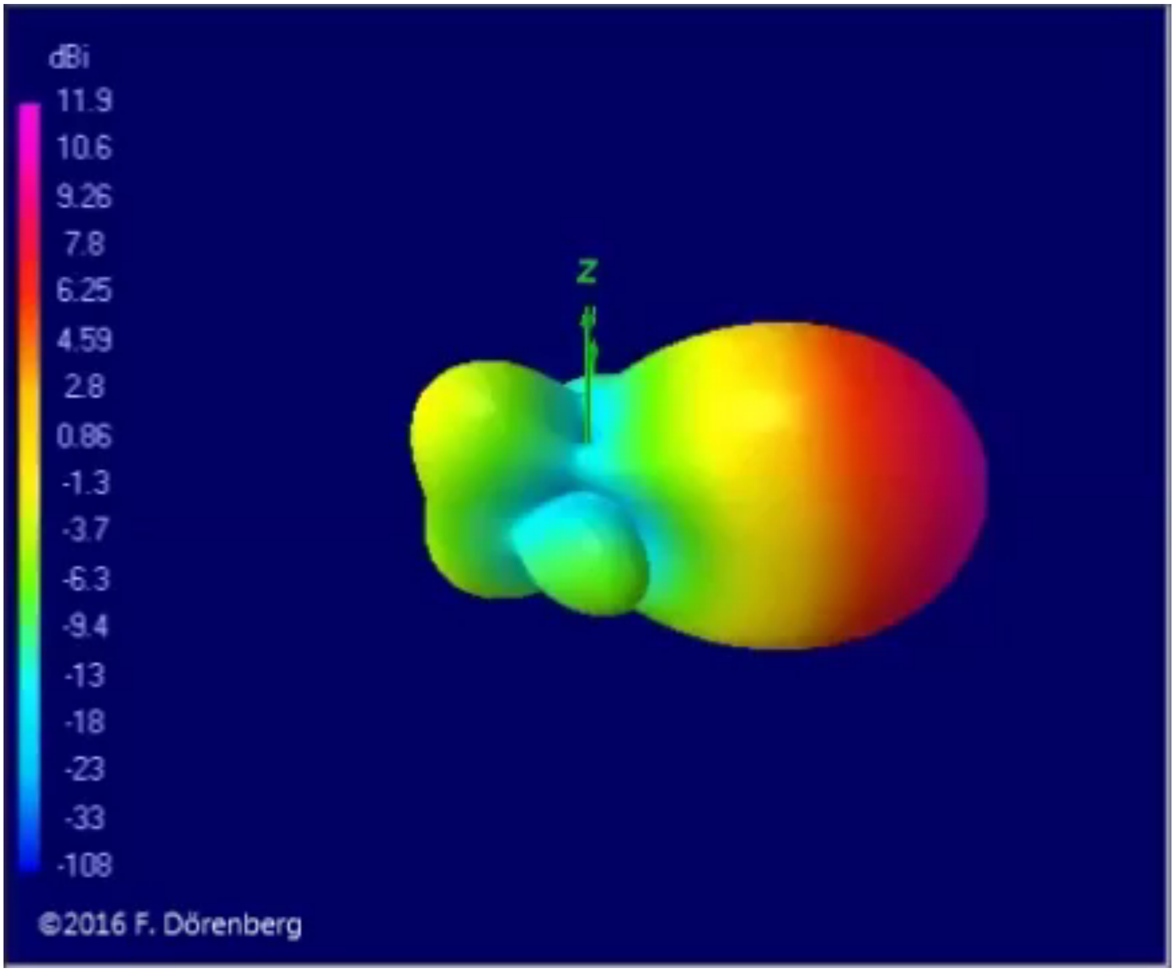


Fig. 107: Radiation pattern of 3-dipole broadside array with a reflector screen (not a cage)
(left: array configuration; center: 3D radiation pattern; right: top view of the radiation pattern; my 4NEC2 model is here)



Radiation pattern of the 3-dipole array with reflector screen - rotating at 2 rpm
(©2016 F. Dörenberg; simulation in free-space, i.e., effect of the earth's surface not taken into account)

So, now we basically know how to create a single-beam pattern with acceptably small side-lobes. But how do we get the required twin-beam pattern? How about using two separate broadside uniform arrays that are placed side-by-side? Then we "just" have to create a small angular difference between the two main beams. This can be done both mechanically and electrically. The mechanical approach was used in the small version of the "Knickebein" beacon system. The left-hand and right-hand dipole arrays are clearly placed at an angle, and the two beams cross-over in front of the antenna system. See Figure 108. Looking down onto the antenna system, the two sides form a shallow "V". Hence the name "Knickebein" ("crooked leg" = "dog leg").

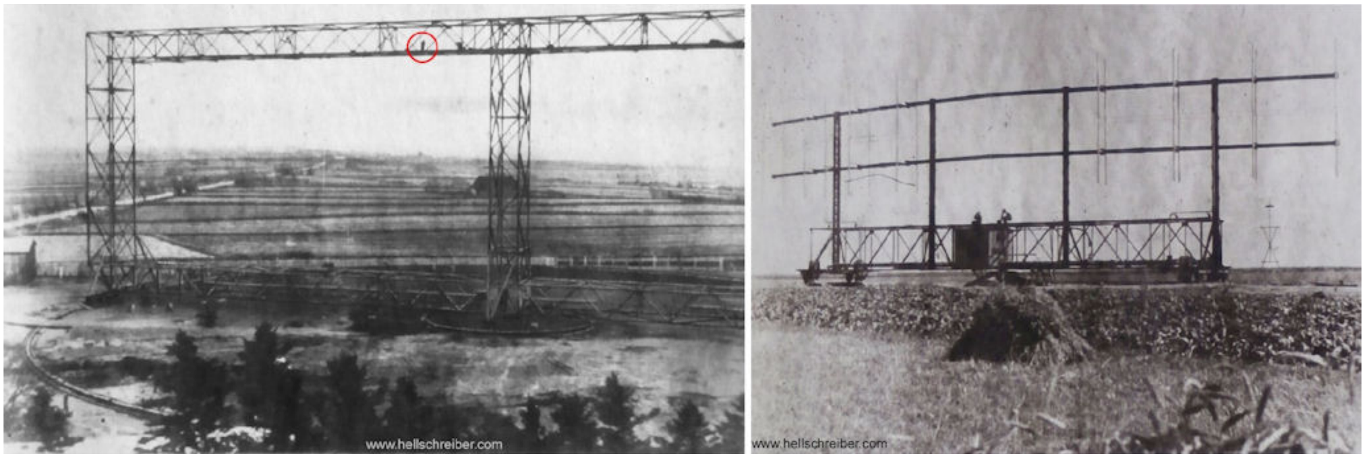


__Fig. 108: Knickebein ground-station - large (left) and small (right)__
(source: Fig. 36 & 37 in ref. 181; red circle shows size of a man)

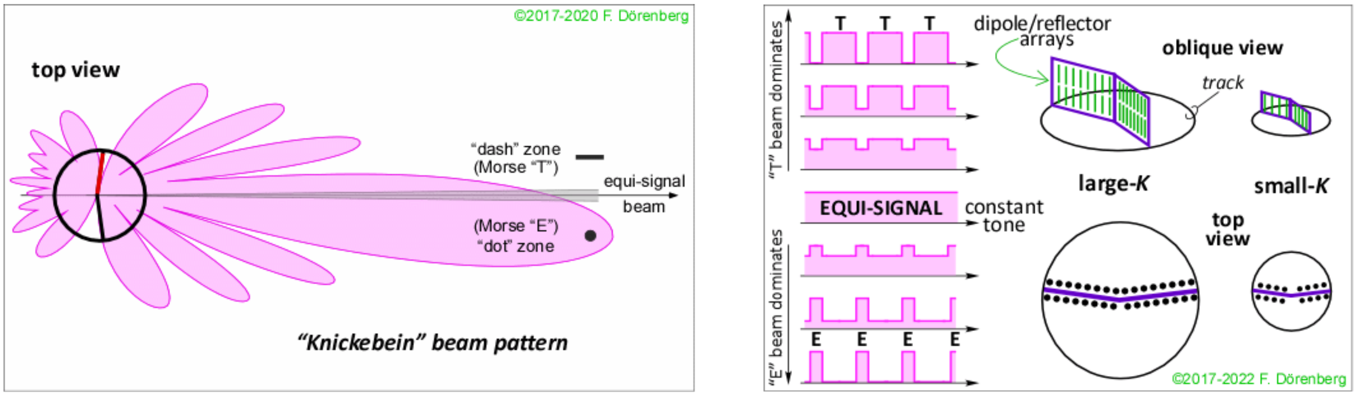


__Fig. 109: The alternating "E" (dot) and "T" (dash) beams of the Knickebein beacon__

The main beam of a *single* broadside-array can be pointed electrically in a direction other than perpendicular. This called "beam slewing" or "electronic beam steering" (see Section 3.14 / pp. 271 in ref. 139A). Here, the dipole-current in the dipoles of one half of the array, is given a phase-angle difference with respect to the dipoles in the other half of the array. The size of the phase-offset determines the amount of beam-slew or beam-tilt.

To get a twin-beam pattern, one could use two such split-arrays and put them side-by-side. However, this is unnecessarily complicated for what we are trying to achieve! All we need to do, is put two *uniform linear broadside arrays* side-by-side, and simply feed them in an anti-phase manner (180° phase difference between the two arrays). See p. 72 in ref. 137A. The resulting radiation pattern has two main-beams, symmetrically with respect to the normal (perpendicular) direction, with a small angle and a sharp, deep null between the two beam directions. See Figure 110 for a 4+4 dipole array configuration. Other than the rear-lobes, this is what we want!

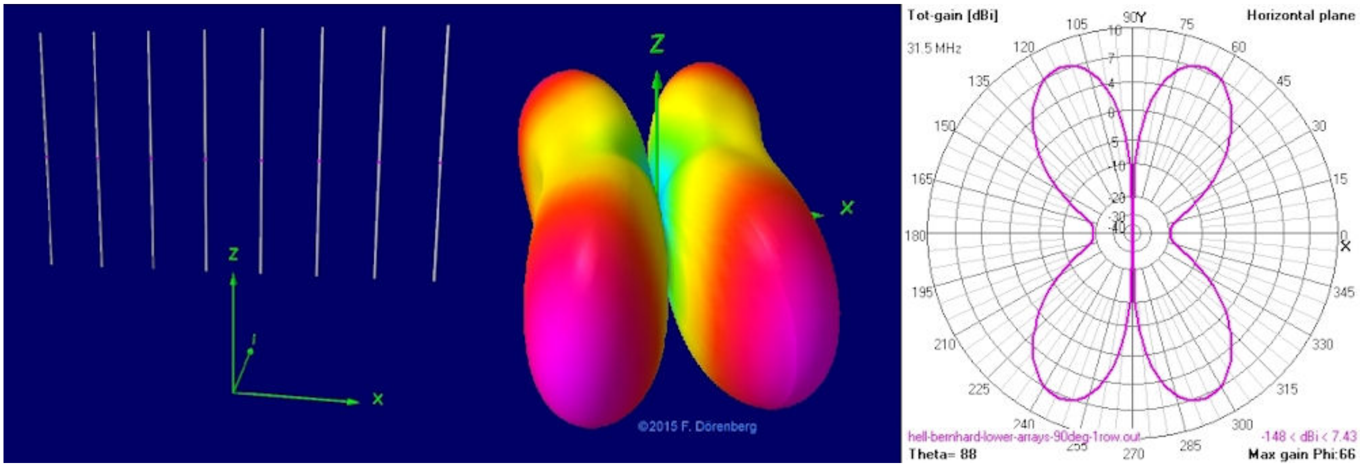


Fig. 110: Radiation pattern of two side-by-side arrays that are fed anti-phase (without reflector screen or dipoles)

(left: array configuration; center: 3D radiation pattern; right: top view of the radiation pattern; my 4NEC2 model is here)

Before discussing the VHF-version of "Bernhard", there are two aspects of the UHF antenna system that need to be mentioned:

The configuration of the twin-beam dipole array.
Feeding a rotating antenna system from stationary transmitters.

The twin-beam **U**HF antenna system comprised two side-by-side arrays (see the magenta boxes in Figure 99 above). The photo shows that each array actually comprised two sub-arrays of five dipoles each. These sub-arrays are placed one above the other (a so-called "stacked" array). This was either done as part of side-lobe suppression (see Section 3.16 (p. 276) in ref. 139A), or to increase gain. However, the latter is less likely. The system used two identical transmitters (i.e., same output power). The power of one of these transmitters was split in two, for the two halves of the twin-beam array. Increasing the gain of the twin-beams would increase the operational range of the beacon, but it would not make sense for the twin-beam system to have a significantly larger (or smaller) range than the single-beam system above it.

The **V**HF "Bernhard" system operated at frequencies in the 30-33.1 MHz band, instead of 300 MHz. That is, a nominal wavelength of about 10 m instead of 1 m. This basically means that the antenna system of the VHF "Bernhard" is about ten times as big as its UHF predecessor. Figure 68 below shows the large antenna system. It measured about 35x25 m (WxH, ≈82x115 ft). We recognize the upper dipole array (green box) for the single-beam transmission, above the two side-by-side arrays (magenta boxes) for the twin-beam transmission.

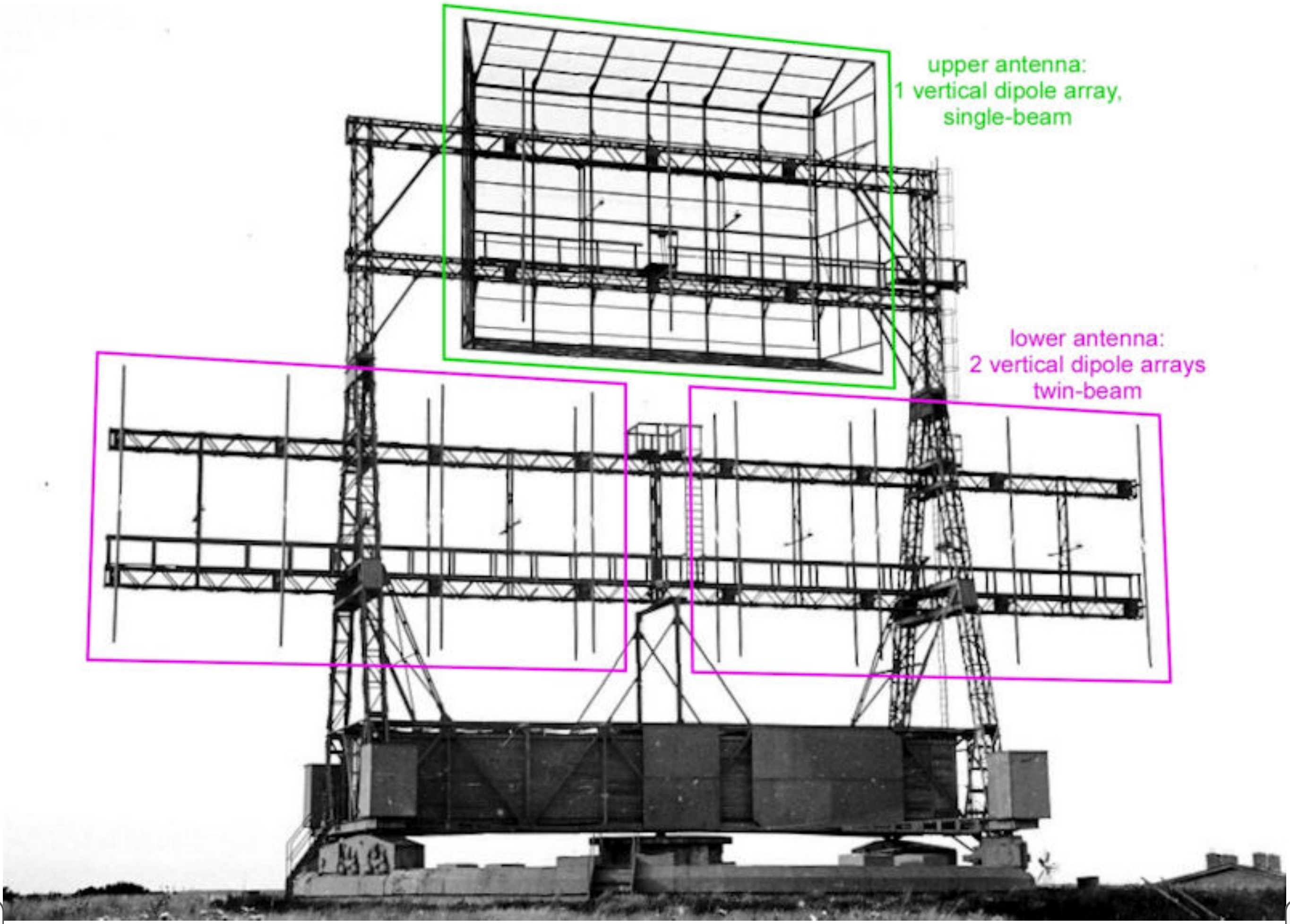


Fig. 111: The two antenna sub-systems of the Be-10 "Bernhard" station at Thisted/ Denmark

Note that the dipole-array configurations are not the same as those of the UHF "Bernhard" system:

The single-beam array now comprises *three* parallel dipoles instead of five. Clearly, having used arrays of five dipoles would have made the entire antenna system much larger. Also, the single-beam has to be at least as wide as the combined twin-beams.

There is no solid reflector surface behind the top-array. Instead, there is a wire-mesh reflector behind and around the array. Obviously the mesh is much lighter, and also has less wind resistance. It is placed at a distance of 0.25 λ from the dipoles (p. 19 in ref. 183; note that in ref. 183 and some similar German literature of the era, "dipole" refers to a dipole-leg, i.e., only half (= one pole) of a complete dipole antenna).

The twin-beam array now comprises two side-by-side sub-arrays of *four* dipoles each, instead of five. These two sub-arrays are fed in an anti-phase manner: 180° phase difference between the two arrays.

There is no reflector *surface* behind the bottom-array. Instead, there are reflector-*dipoles*. They are placed at 0.25 λ behind the primary dipoles. The reflector-dipoles are "active", i.e., powered by the transmitter. Active reflectors are more effective for side-lobe reduction than passive/parasitic reflector dipoles or rods (see p. 71 in ref. 137A). The phase angle of the excitation of the reflector-dipoles leads that of the main dipoles in front of them by 90°.

There are two different configurations of reflector-dipoles, see Figure 112A/B:

A reflector-dipole behind each primary dipole (Figure 112A).

A reflector-dipole only behind the two primary dipoles of each sub-array that are closest to the centerline of the antenna system (Figure 111 and 112B).

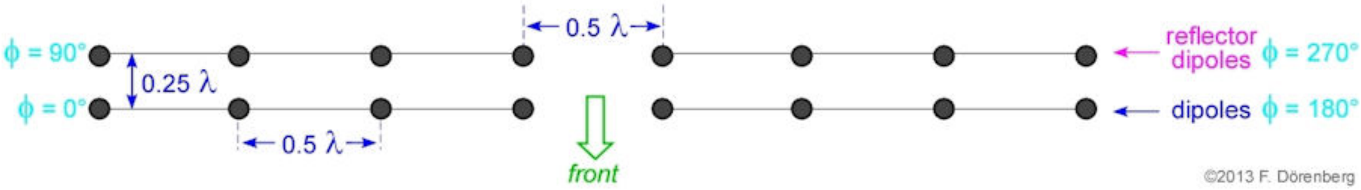


Fig. 112A: Top view of the 2x(4+4) array configuration of the twin-beam antenna

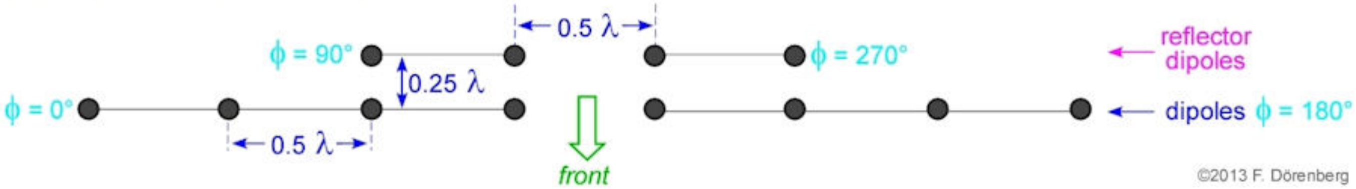


Fig. 112B: Top view of the 2x(4+2) array configuration of the twin-beam antenna

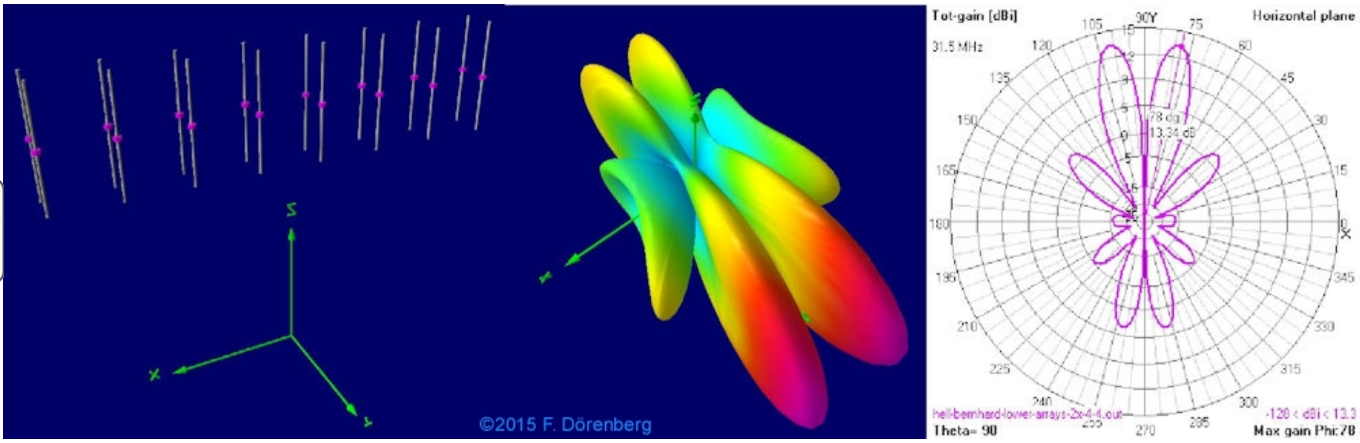
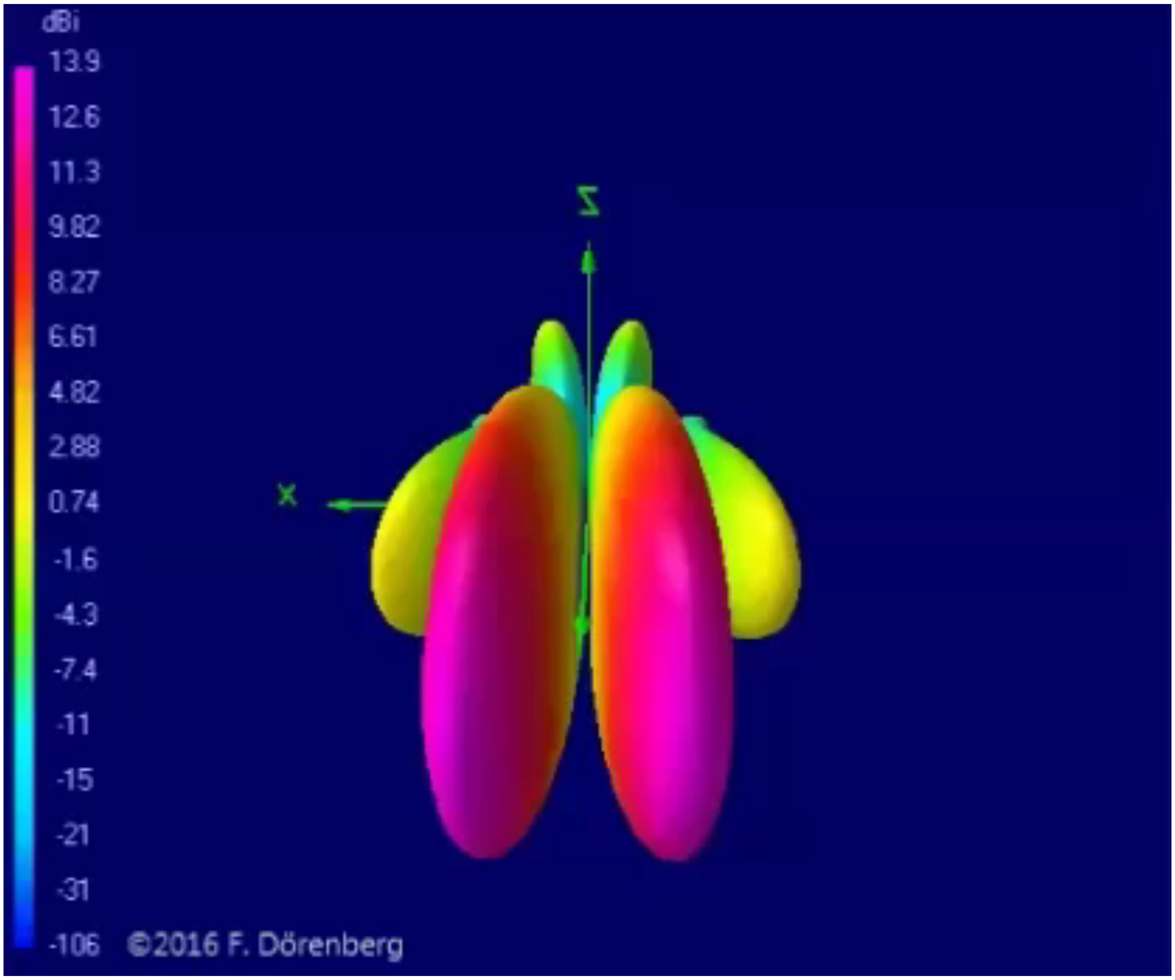


Fig. 113: Radiation pattern of two side-by-side arrays that are fed anti-phase (with active reflector dipoles at 0.25 λ)

(left: array configuration; center: 3D radiation pattern; right: top view of the radiation pattern; my 4NEC2 model is here)



Animation of the radiation pattern of the 2x(4+4) arrays - rotating at ≈2 rpm
(©2016 F. Dörenberg; simulation in free-space, i.e., effect of the earth's surface not taken into account)

Below are illustrations of the radiation pattern of the "Bernhard" antenna system. They are from pre-WW2 Telefunken/Lohmann patents, and therefore relate to the early UHF-version of "Bernhard". However, they are similar to the final VHF-version of "Bernhard" (see p. 95 in ref. 3). Note that the pattern has significant side-lobes and rear-lobes. This is confirmed by the official manual of the FuG 120 "Bernhardine" bearing-printer system that was used in the aircraft (p. 6 in ref. 15).

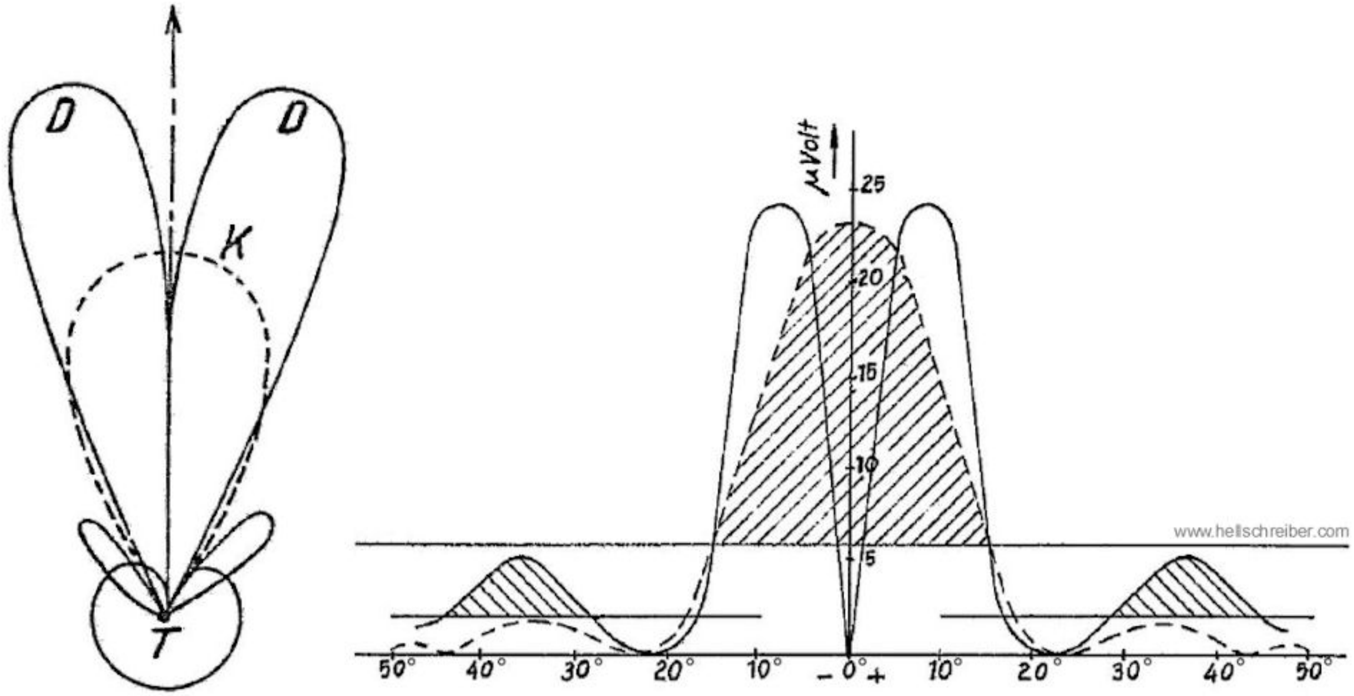


Fig. 114: Single-beam and twin-beam radiation patterns of the UHF "Bernhard" antenna system

(left: Figure 2 in the 1936 patent 767354; right: Figure 1 in 1938 patent 767523)

In the Cartesian plot (right-hand plot in the Figure above), the side lobes of the twin-beam curve are roughly a factor 24.4 : 5.2 = 4.7 below the main lobes. This voltage attenuation factor is equivalent to a power attenuation of about 10•log(4.7)^2 = 13.4 dB. This is consistent with the maximum theoretical value of about 13 dB for arrays with a uniform current distribution (see p. 518 in ref. 139H).

My simulation model generates very similar patterns:

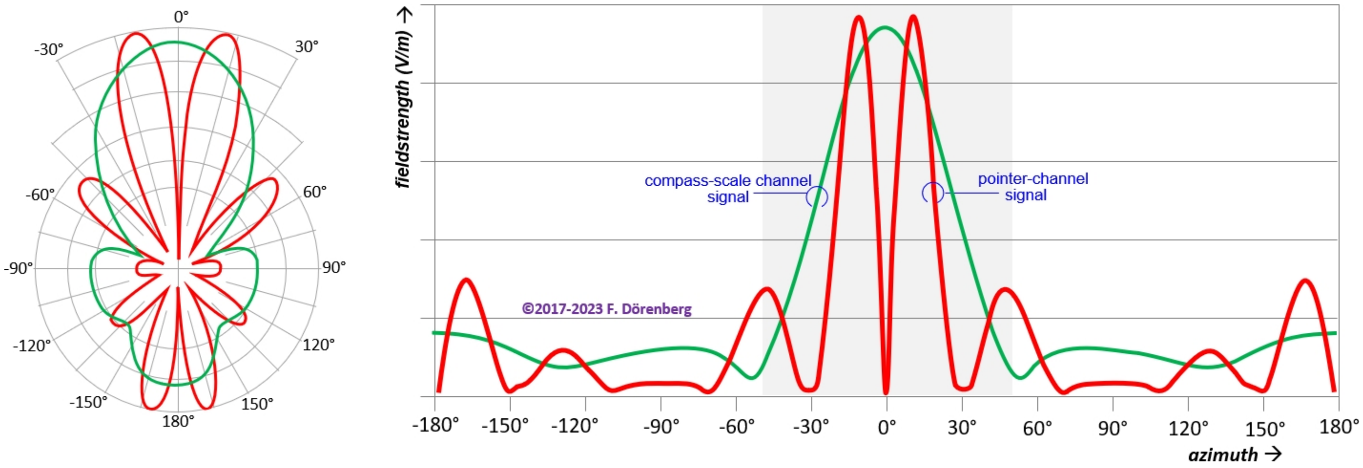


Fig. 115: Cartesian plot of the radiation pattern, based on my antenna simulation model for the 2x(4+4) arrays

(both curves converted from power gains; the grayed area corresponds to the -50° to +50° range of the plot in Fig. 47 and 48 above)

Based on available photos, the 2x(4+**4**) dipole array configuration was used at the "Bernhard" installation of Trebbin (Be-0), Mt.-St.-Michel-de-Brasparts (Be-2), and La Pernelle (Be-4). The

2x(4+**2**) configuration was used at the installation of Bredsted (Be-9), Thisted (Be-10), and Arcachon (Be-7). This suggests that the latter configuration may have been introduced with station Be-8 in Schoorl (constructed 1942/43). Why remove the outermost reflector-dipoles (other than to save material)? Figure 73 shows the difference in the 3D radiation pattern of the two configurations. *Without* the outermost reflector dipoles, there are more (and slightly stronger) rear-lobes. However, this may not necessarily have had a negative impacted on the performance of the "Bernhard/Bernhardine" system, based on the time-constants of the automatic receiver-gain control of the SV 120 printer-amplifier in the aircraft.

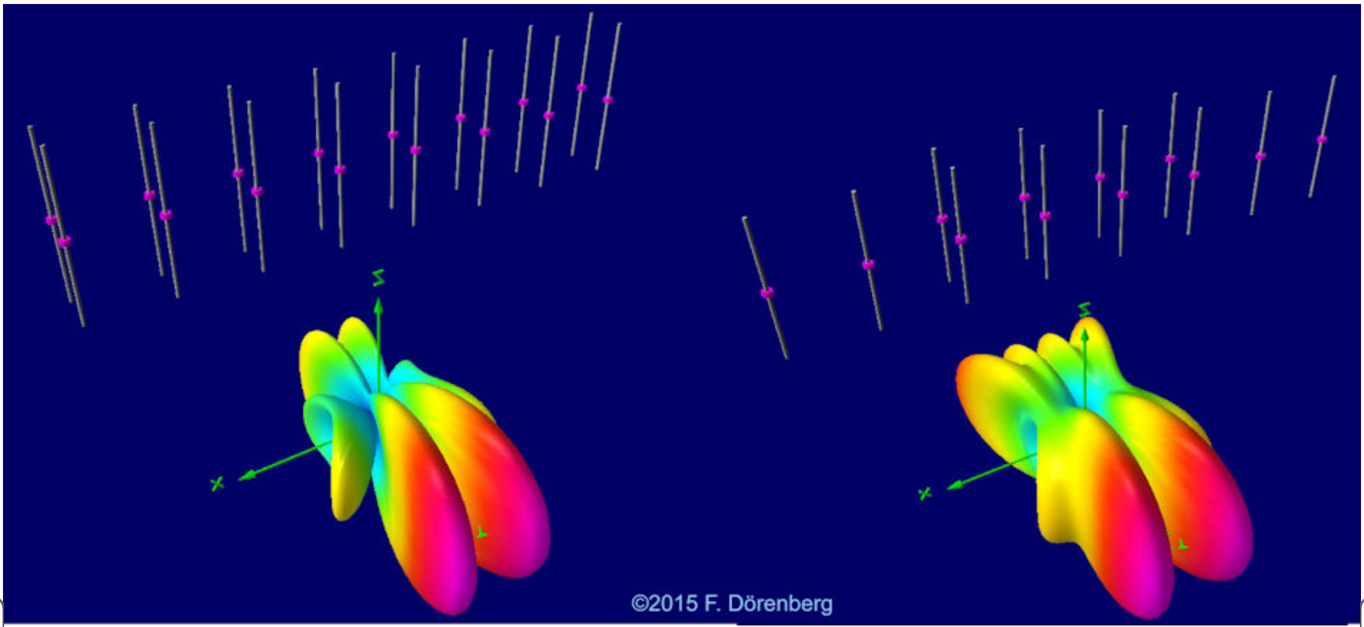


Fig. 116: Radiation pattern of the 2x(4+4) array configuration (left) and of the 2x(4+2) configuration

(My 4NEC2 models for these two configurations are here and here)

Note that the colorful radiation patterns illustrated above, were generated with modern computer-based simulation tools. Clearly, such tools were not available before and during World War 2 - the days of mechanical analog calculators, notably the slide rule (*D*: "Rechenschieber"). However, radiation patterns and other characteristics of directional antenna systems (incl. arrays with reflectors) were well understood in those days, and were indeed calculated (ref. 253A (dated 1938), 253B), albeit in a very time consuming manner.

The next figure shows a 1944 Cartesian plot of pointer-beam of the VHF "Bernhard" - it corresponds to my simulation of the 2x(4+2) dipole configuration:

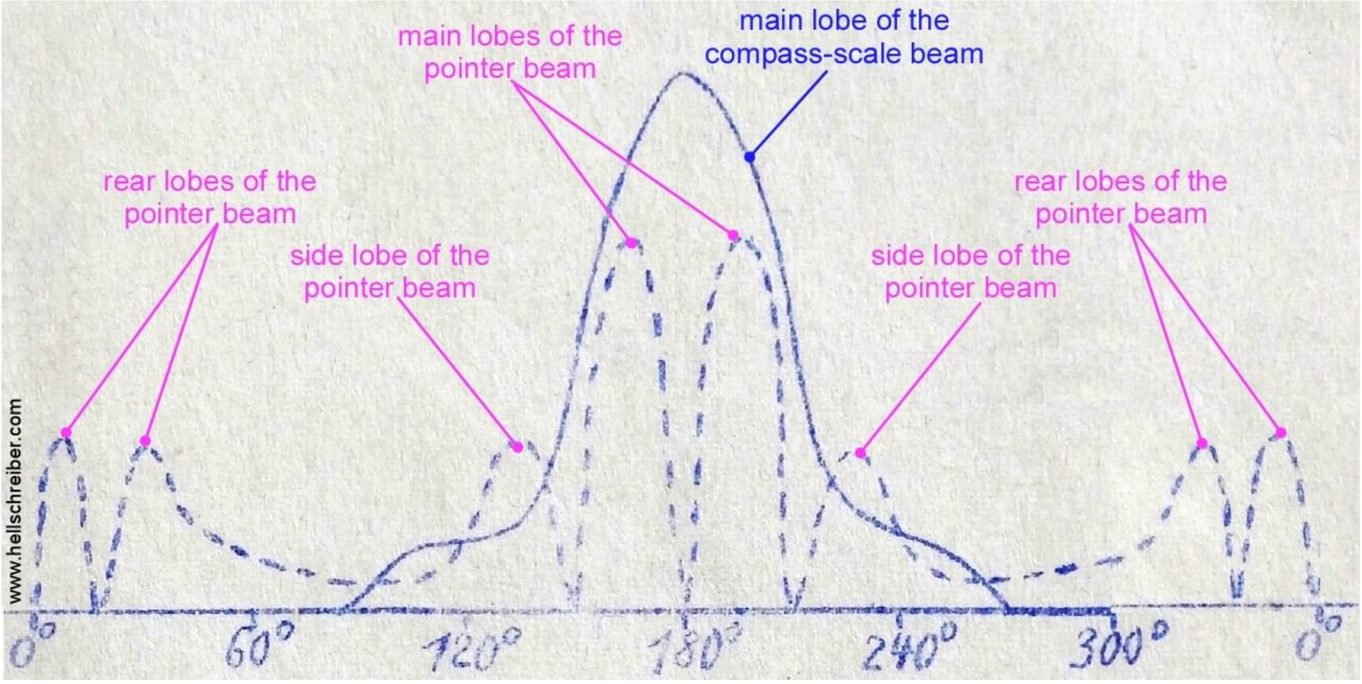


Fig. 117: Cartesian plot of the radiation pattern of the VHF "Bernhard" antenna system
(source: adapted from Fig. 1 in ref. 201, 1944)

Transmitter power output (TPO) is the radio-frequency (RF) power that the transmitter produces at its output. This is not the same as the effective radiated power (ERP) of the antenna system. ERP is basically the product of transmitter output power, losses in the feedline system (and radiation by that system) including splitters & connectors, and gain of the antenna system *in the direction of maximum gain*. ERP is referenced to the same TPO being input to a single dipole. The "Bernhard" dipole arrays concentrate the RF energy into the main lobes of the radiation pattern. This provides a gain with respect to a omni-directional reference antenna. Based on my simulations of the antenna arrays, the main lobes of the twin-beam pattern had a gain of 13.81 dB**i**. That is: 13.81 dB compared to an **i**sotropic radiator. ERP is referenced to a **d**ipole, which has a gain of 2.15 dB**i**. Hence, the twin-beams had an estimated gain of 13.81 - 2.15 = 11.66 dB**d**. With a 500 watt "Bernhard" FuSAn 724 transmitter, this would have resulted in an ERP of 7.3 kW - far from the unrealistic 5 MW (= 500 W + 40 dB) that is sometimes suggested in literature. FuSAn 725 was intended to increase the beacon's range by increasing the transmitter power by a factor of ten = 10 dB: from 500 W to 5 kW. Note: a 10-fold increase of transmitter power implies a range increase of SQRT(10) ≈ 3x. Of course, the power increase can also be used to increase immunity to enemy interference (e.g., jamming).

The next Figure illustrates the length, thickness, and spacing of the dipoles, as well as the spacing between the dipoles and the reflector-cage. The size of the two men in the photo can be used as a reference. Note that the VHF "Bernhard" operated at a frequency of 31.55 MHz ±1.55 MHz. Hence, the nominal wavelength λ is 9.5 m.

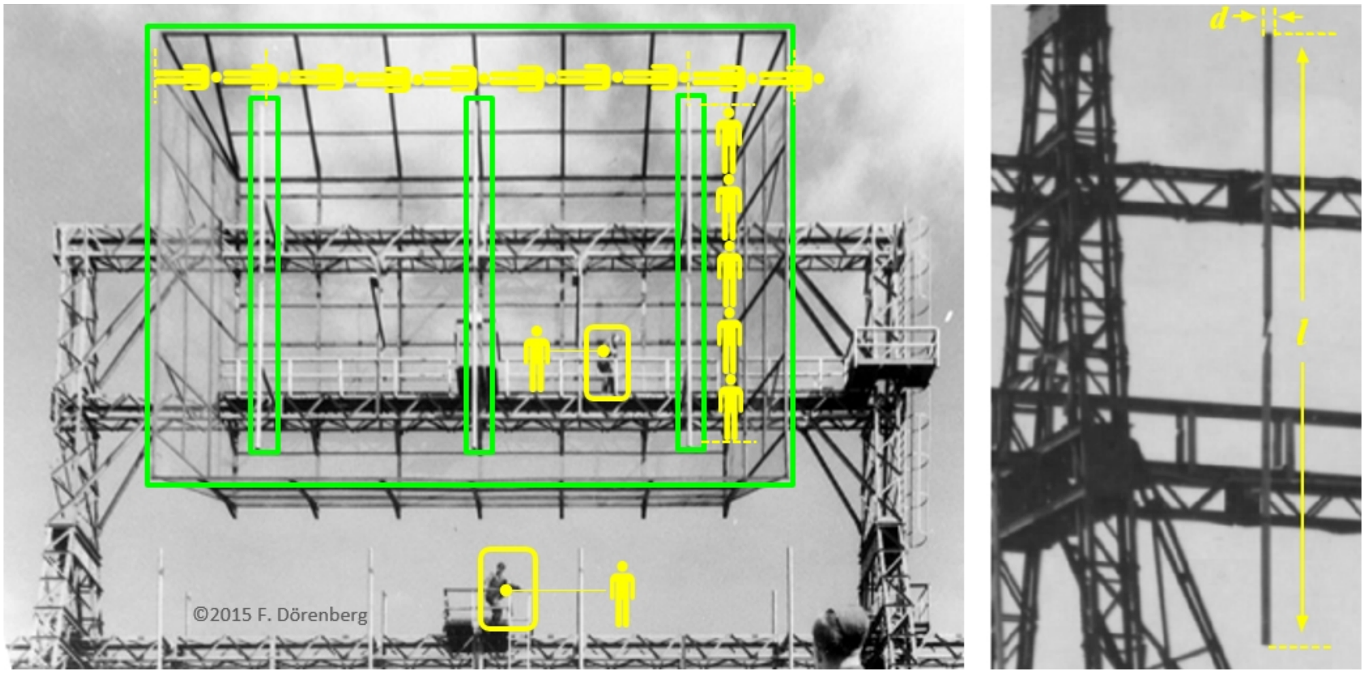


Fig. 118: Dimensions and spacing of the dipoles and the wire-mesh reflector cage

The table below shows the dipole and spacing dimensions for three different assumptions regarding the height of the men in the photo above:

©2015 F. Dörenberg

Man height	Dipole length	Dipole thickness *	Dipole spacing	Reflector spacing
1.6 m	0.85 λ (8 m)	8.5 cm	0.5 λ (4.8 m)	0.25 λ (2.4 m)
1.7 m	0.89 λ (8.5 m)	9.2 cm	0.54 λ (5.1 m)	0.27 λ (2.55 m)
1.8 m	0.95 λ (9 m)	9.5 cm	0.57 λ (5.4 m)	0.28 λ (2.7 m)

*based on length/thickness ratio of 95, as in hi-res US army photo of Be-7/La Pernelle

Table-2: Estimated dipole and spacing dimensions, based on photogrammetric analysis

I have run antenna simulations for about 30 different combinations of parameters in Table-2, for the array of 2x(4+4) dipoles. A table with the results is here. General conclusions are consistent with antenna theory:

When the dipole length is *de*creased, gain of the main beams decreases (not desirable), the front-to-back ratio decreases (not desirable), and the strength of the first left & right side-lobe increases relative to the two main beams (not desirable)

The gain of the two main beams is relatively insensitive to spacing between the front dipoles and the reflector dipoles.

The strength of the first side-lobes left & right of the two main beams, is relatively insensitive to the variation of the parameters. The relative strength is -9 to -12 dB.

The strength of the other side- and rear-lobes *is* sensitive to spacing between the front dipoles and the reflector dipoles, and to the dipole diameter.

The width of the two main beams is relatively insensitive to array dimensions, other than the number of dipoles. The beam-width is 10°-12°.

The angle between the two main beams is relatively insensitive to array dimensions, other than the number of dipoles. The angle is 20°-24°.

The total number of pattern-lobes increases when lateral spacing between the dipoles is increased. For the evaluated configurations, this even number varied from 10 to 16.

As in the **U**HF "Bernhard" system, the dipoles are "full-wavelength": they have a nominal tip-to-tip length of 1 λ. Note that this appears to be contrary to the original 1936 Telefunken/Lohmann *Reichspatent* nr. 767531 and 767532, in which all dipoles are referred to as "half-wave" (½ λ). However, literature of the era generally referred to the length of a dipole *leg*, instead of the overall dipole length.

Anyway: why use dipoles 1 λ dipoles instead of ½ λ dipoles?

The radiation pattern of a 1 λ dipole has slightly more gain and slightly narrower beams than that of a ½ λ dipole.

1 λ dipoles are more suitable for broad(er)band operation than antenna systems with ½ λ dipoles: for the same relative thickness, a full-wavelength dipole has bandwidth that is about 1.3x larger than that of a half-wave dipole (see Section 4.3 in ref. 135).

A 1 λ dipole may be harder to properly match to a modern solid-state transmitter via a 50 Ω coax cable than ½ λ dipole (at resonance), but that is not a real argument against 1 λ dipoles when using a transmitter with tube amplifiers in combination with an open-wire feedline.

The mid-point of each "leg" of a 1 λ dipole in principle has (near) zero voltage. This makes it a convenient point for attaching the dipole to a support structure. This is discussed further below. The neutral point of a ½ λ dipole is the feedpoint, which is not convenient for attachment.

Implementing a uniform array is easier with 1 λ dipoles. They have high feedpoint impedance. Therefore, they are *voltage*-fed instead of *current*-fed. A feed-system for supplying all dipoles of an array with same amplitude and phase, is easier with voltage than with current. The dipoles need to be fed *in-phase* (= co-phase). That is, the phase difference between all dipoles within a sub-array must be 0° = *n* x 360°, where *n* is an integer number. Half of the 360° is simply obtained by having a feedline length of ½ λ = 180° between adjacent dipoles. Obviously, this is easy to do: just space the dipoles ½ λ (with a small adjustment for the velocity factor of the feedline wire). A tuned ½ λ section of feedline also has the advantage that it does not act as an impedance transformer: the impedance at one end, is transferred 1:1 to the other end. In the Bernhard antenna arrays, the feedline between adjacent dipoles is a balanced open-wire transmission line (TL). I.e., two parallel wires that are suspended in the air. The second half of the required 360° is simply obtained by connecting the top element of the *even* dipoles and the bottom element of the odd dipoles to the same feedline wire, and vice versa. I.e., switching polarity at each dipole. The latter switch-over can be implemented two ways, see Figure 53:

By crossing the feedline wires between dipoles. This (standard) approach is illustrated in the 1936 Telefunken/Lohmann *Reichspatent* nr. 767531 and 767532, However, with this method, the feedline wires are not perfectly parallel. This may disturb the characteristic impedance Z_0 of the feedline.

Without crossing the feedline wires between the dipoles. Instead, the cross-over is made at the feedpoint of every other dipole (see p. 72 in ref. 137A).

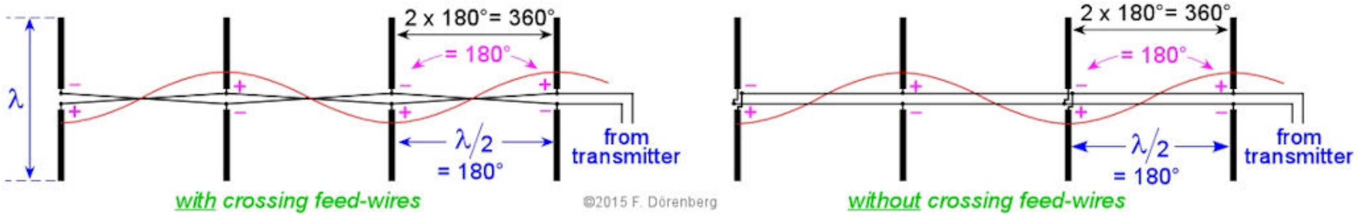


Fig. 119: In-phase voltage feeding of a uniform array of 1λ dipoles

The top and bottom antenna array are each connected to a separate transmitter in the large equipment cabin that rotates with the antenna system. The conduit was attached to the steel trusses of the antenna support structure. This feedline connection ("Energieleitung") consisted of a shielded two-wire transmission line (a.k.a. shielded two-wire TL, shielded balanced TL, shielded pair; *D*: "(ab)geschirmte symmetrische Bandleitung", "(ab)geschirmte Zweidrahtleitung", "(ab)geschirmte symmetrische Doppelleitung", "zweiadriges abgeschirmtes Kabel"), see p. 110 and 111 in ref. 181. This is basically two parallel wires in metal tubing or braiding, with a dielectric material between the wires and a round or oblong metal conduit. See Fig. 120. In modern times, we refer to this cable type as "twinax".

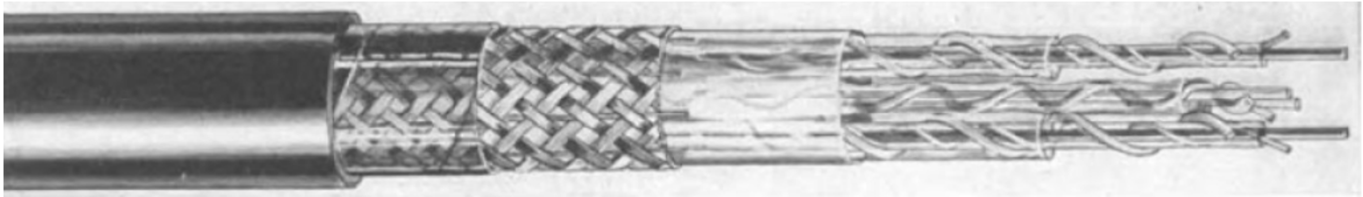


Fig. 120: "symmetrische Hochfrequenzleiting mit Abschirmung" - shielded balanced transmission line

(source: Fig. 28 in ref. 197)

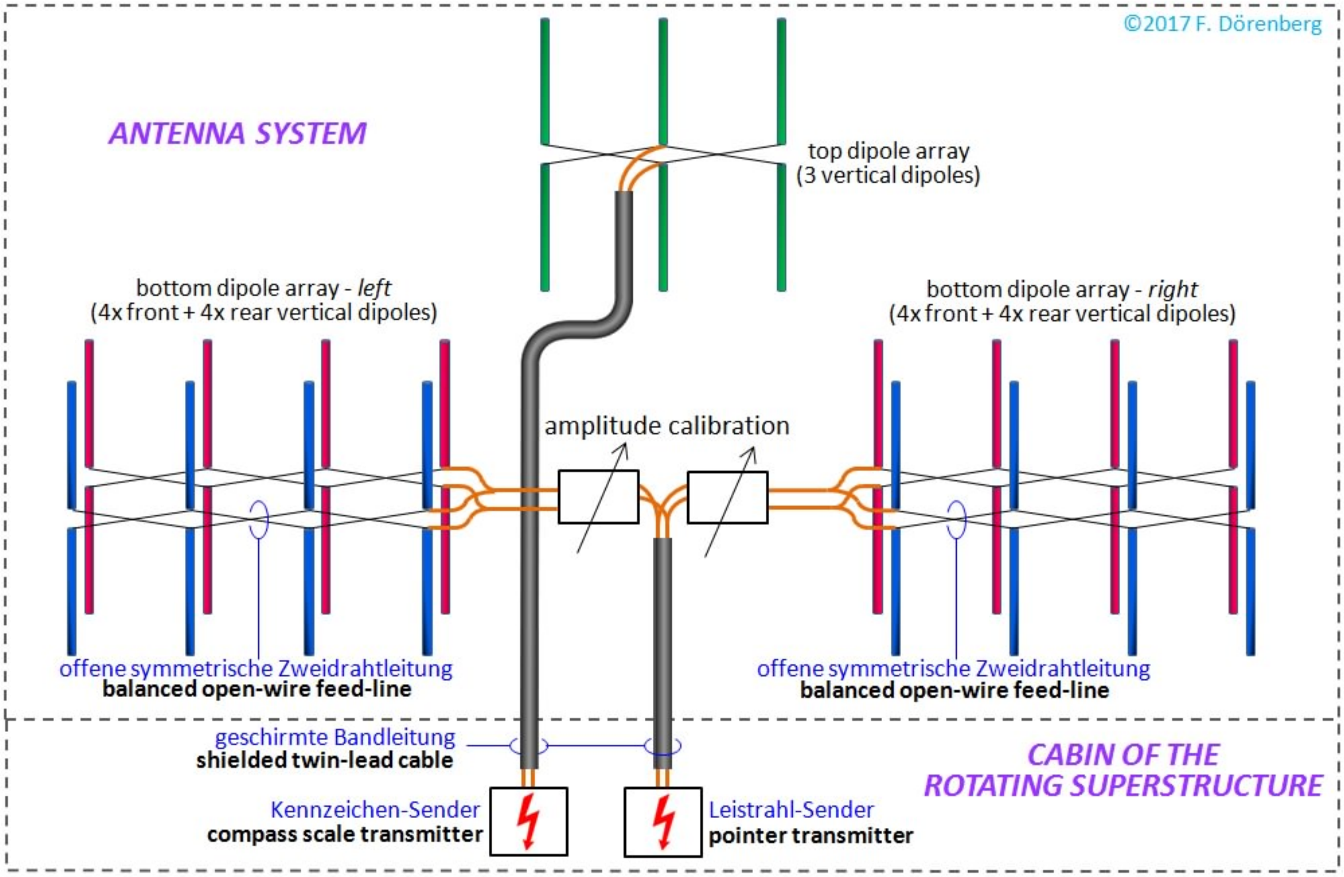


Fig. 121: Antenna system interconnections
(source: derived from ref. 181)

The null-direction of the bottom array must calibrated ("Nullverstellung", see cable item 56 in ref. 189) so as to be exactly aligned with the centerline of the beam of the top array. This null-direction is not only affected by the accuracy of the construction of the antenna system, but also by the phase and amplitude equality between left-hand and right-hand sub-arrays of the bottom antenna. As shown in Figure 121 above, there was a means to adjust the amplitude of the signal fed to the left-hand and to the right-hand sub-array. It was located at the transition from the shielded 2-wire cables from the transmitters, and the open-wire line from there to the dipoles. Note that there was no means to adjust the phase. Per ref. 181 (p. 111), the amplitude adjustment was mechanical, and the amplitude adjustment did not cause a phase shift. This suggests that the amplitude adjustment was implemented by selecting a tap of a transformer. The 1935 Telefunken/Runge/Krügel/Grammelsdorff patent nr. 737102 proposes using a fixed-location remote receiver to check the direction of the beam-null, as measuring and balancing antenna feed-currents does not guarantee its correctness. Antenna feed-currents could then be adjusted with variable capacitors across the feed-lines or adjustment of the coupling at the transmitter or the feed-point.

The following photo shows two antenna cables emanating from the bottom of a hexagonal box that is mounted to the right of the top of the door, and a ventilation screen below it, at floor level. This suggests that the transmitters were located in the cabin section behind it. This is consistent with the layout drawing of Bernhard station Be-0 at Trebbin.

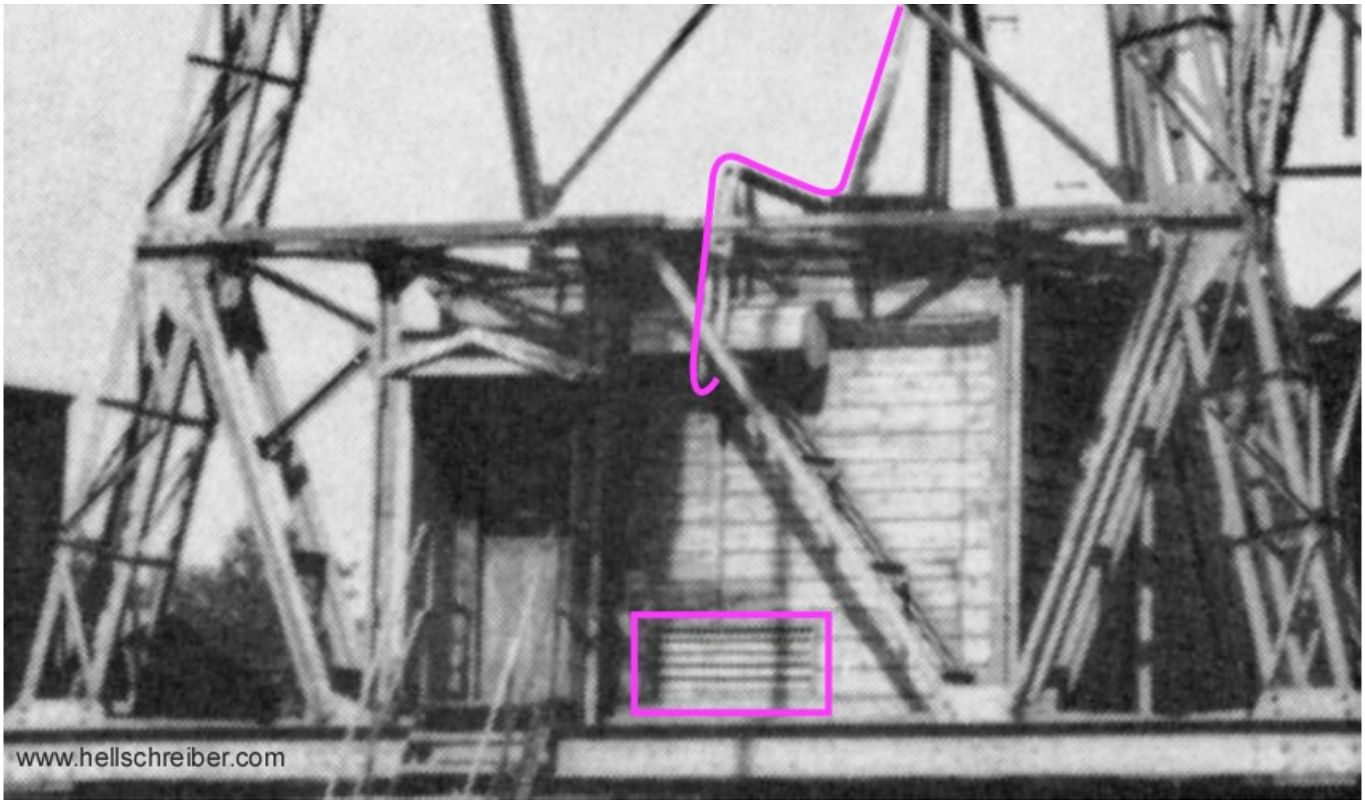


Fig. 122: The entrance end of the cabin at Bredsted - antenna feedline and ventilation panel highlighted

(source: Australian War Memorial photo SUK14634; also part of photo on page 5 in ref. 5)

The following two photos show more details of the routing of the twin-lead cable and the associated open-wire feeedline of the lower dipole array (the barely visible feedline wires have been highlighted)

Fig. 123: Routing of the twin-lead cable (pink) and open-wire feedline (yellow) for the bottom dipoles at Bredsted

(unedited photo taken May 1945 by Flt. Lt. Herbert Bennet, RAF Mobile Signals Units of No. 72 Signals Wing; © David Bennet; used with permission)

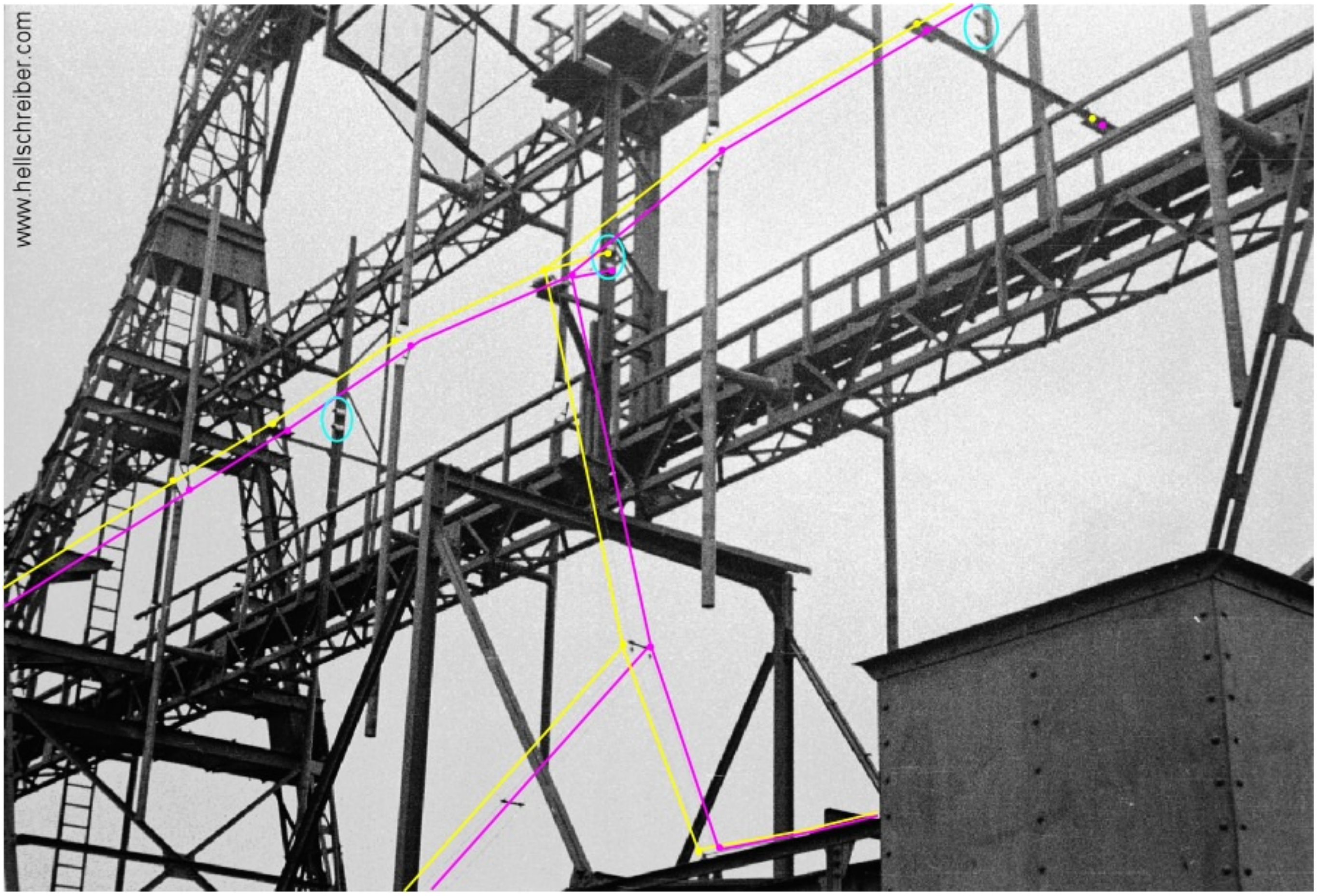


Fig. 124: Antenna feedline routing from transmitter at Bredsted
(unedited photo taken May 1945 by Flt. Lt. Herbert Bennet, RAF Mobile Signals Units of No. 72 Signals Wing; © David Bennet; used with permission)

It is unclear why there is a downward split in the open-wire feedline before it reaches the level of the dipole feed-points. At the center of the photo, the open-wire feedline splits into separate open-wire feedline for the left and right front dipole sub-arrays. Note that at that split point, the open-wire feedlines are also connected to two porcelain insulators that are located slighly above and behind the split point (but on the front side of the trusses between the front and rear dipoles). Additional insulator pairs are also visible (marked with blue circles), but no wiring is visible. Their purpose is unclear...

Available documentation does not mention the spacing between the dipole feedline wires and the diameter of those wires. It can also not be determined accurately enough from the photos. Hence, the characteristic impedance of the feedline cannot be calculated. However, it was probably at least several 100 Ω. As shown in Figure 121 above, the feedline from the transmitter was attached to the end of each 4-dipole sub-array. The 3-dipole top array was fed at the center dipole. This provided a sufficiently broadband feed system for the "Bernhard" operating frequency range of 31.5 MHz +/- 5%. See Fig. 2 in ref. 139K3. Note that open-wire feed-lines do have some disadvantages (ref. 139K4):

The wires always radiate to some extent, which may affect the radiation pattern of the antenna system

Snow and rime accretions affects the impedance characteristics

Depending on their placement, capacitance between insulators (see Fig. 125 below) affects the impedance characteristics.

Obviously, thick dipole radiators have a large cross-section. At the dipole feedpoint, these large cross-sections would be facing each other and form a significant capacitance. This is undesirable. Furthermore, the large cross-section of the radiators must be connected to the feedline wires. The feedline wires have a much smaller diameter, typically no more than several mm. A large step-transition in conductor diameter is also undesirable in antenna systems. A standard solution is to give the feedpoint-end of the dipole radiators a pointed shape, like the tip of a sharp pencil. See p. 70/71 in ref. 135. This is illustrated in Figure 125. As explained just above Fig. 119, the "Bernhard" antenna configuration required that adjacent dipoles be connected to opposite feedline wires. With flat or conical feedpoint tips, this requires crossing the two feedline wires between adjacent dipoles. This is impossible while at the same time maintaining a constant spacing between the two feedlines. Varying wire spacing causes undesirable disturbance of the feedline impedance, and may even cause arcing where the wires come close to each other. The pointed tip concept can also be adapted to implement the alternating connection to the feedline wires - without having to cross those wires between adjacent dipoles:

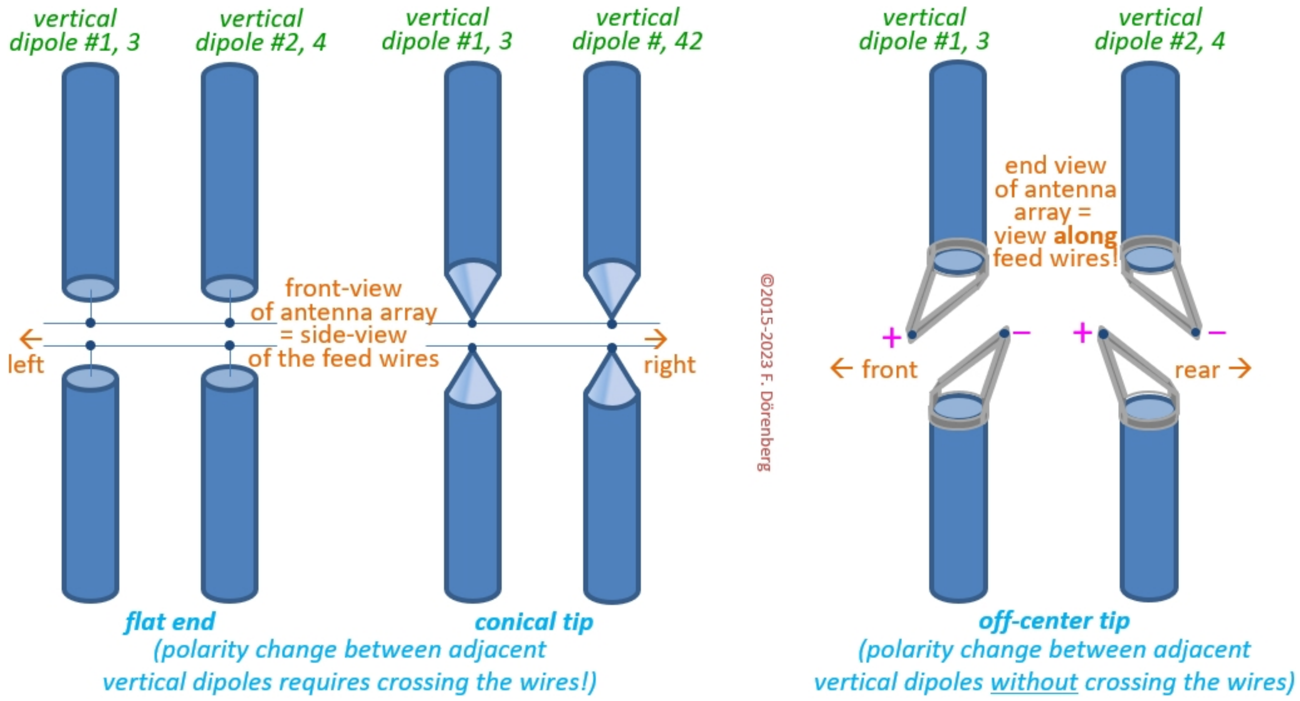


Fig. 125: Flat, conical, and off-center feedpoint-ends of dipole radiators

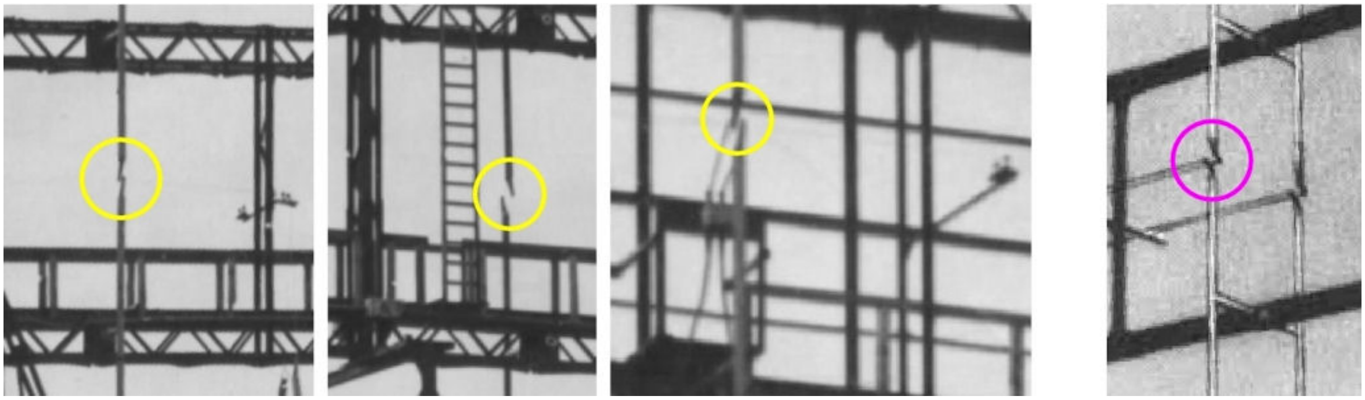


Fig. 126: Pointed radiator-feedpoint tips of several "Bernhard" installations and of a small "Knickebein" (far right)

The feedpoint tips appear to have been made of metal strips, attached to the end of the dipole tube, and are pinched (or folded over) to form a point. The point is actually angled away from the tube, as the distance between the feedline wires is larger than the tube diameter.

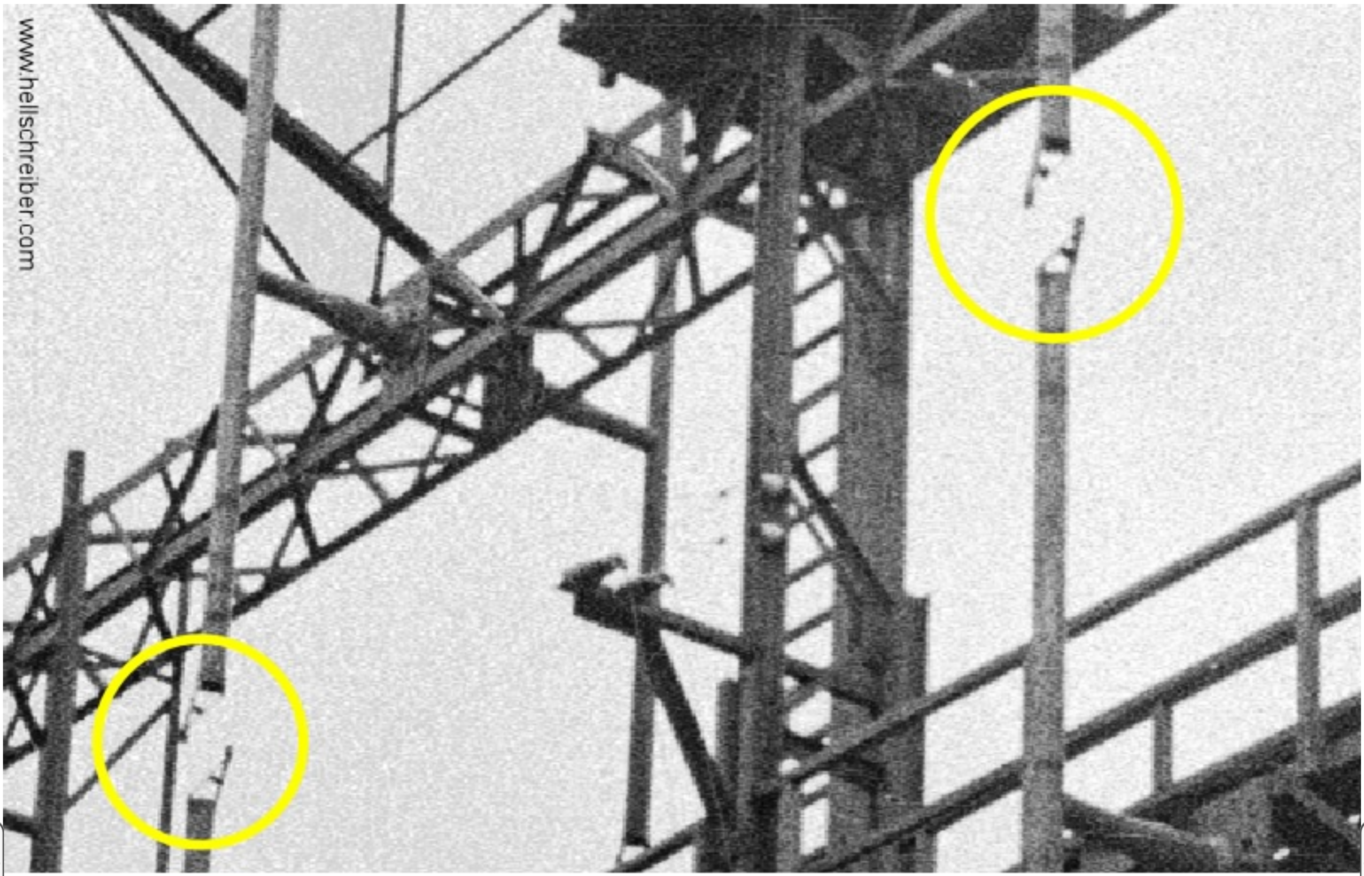


Fig. 127: Close-up of pointed dipole feedpoint-tips of Be-9 at Bredsted/Germany.
(unedited photo taken May 1945 by Flt. Lt. Herbert Bennet, RAF Mobile Signals Units of No. 72 Signals Wing; © David Bennet; used with permission)

Note that the above pointed tips are a direct copy of those used on the tubular dipoles of the ca. 1939 *Small Knickebein* beacon system! See here on the Knickebein page..

The dipole radiators were made of large diameter tubing (note: "tube" is specified by outside diameter, "pipe" by inside diameter). Ref. 13. A solid rod would have been much heavier, cost a lot more material, and not perform any better as an antenna: only the "skin" radiates. It is unknown what material they were made of: steel, copper, brass,... Copper would have had less losses, but steel pipe would have been much more easily available, stronger, and could easily be welded to an attachment arm.

The next Figure shows the standard textbook diagram of the sinusoidal distribution of current and voltage along the radiators of a full-wave dipole. The curves are only valid for "vanishingly thin" radiators!

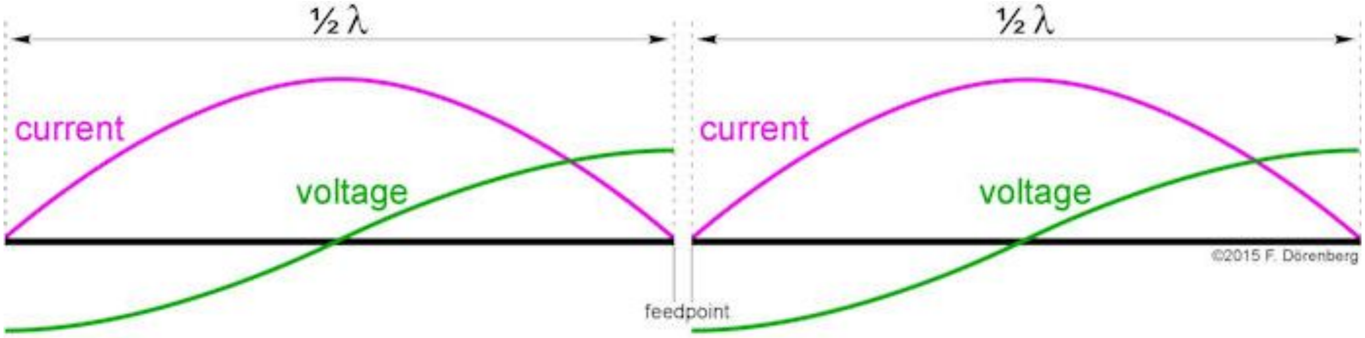


Fig. 128 current & voltage distribution of a very thin full-wave dipole in free-space
(note: only valid in free space (far enough away from ground and objects), and for very thin radiators)

When the radiators have a diameter that is *not* infinitesimally small, the current distribution is no longer purely sinusoidal - see Figure 129 below. The current at the feedpoint and tips becomes significant, due to charge concentration and displacement current. This explains the reduction in feedpoint resistance when the diameter of the radiators is increased (i.e., the λ/d ratio is decreased).

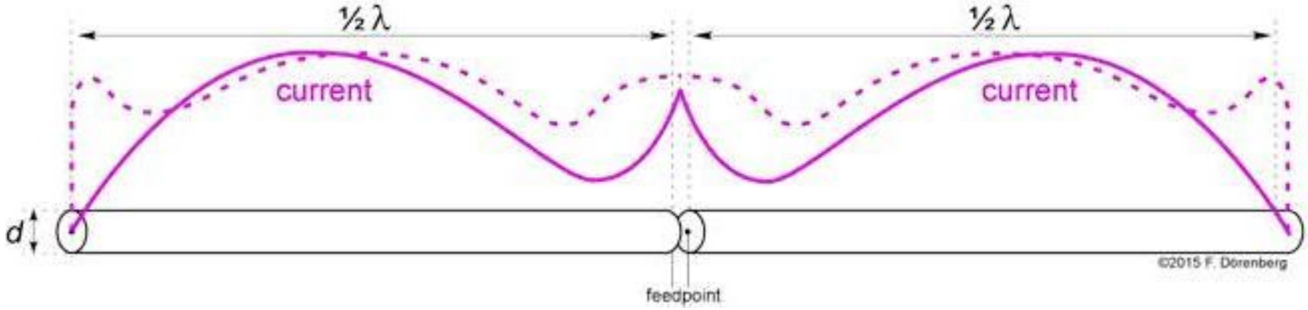


Fig. 129: Current distribution of a thick full-wave dipole in free-space
(dashed line: Fig. 4.9 in ref. 135; solid line: my 4NEC2 model)

The feedpoint resistance and resonance length of a dipole depend on the ratio of the wavelength λ, and the diameter of the dipole radiators. The diagram below shows this dependence for a single dipole. For the same relative thickness, a full-wavelength dipole has bandwidth that is about 1.3x larger than that of a half-wave dipole (see Section 4.3 in ref. 135). Note that each "Bernhard" system operated at a fixed frequency in the range of 31.5 MHz ±5%. It was obviously highly desirable to be able to use the same dipoles at all "Bernhard" installations. This required a relatively broadband antenna system, which was facilitated by using full-wave dipoles.

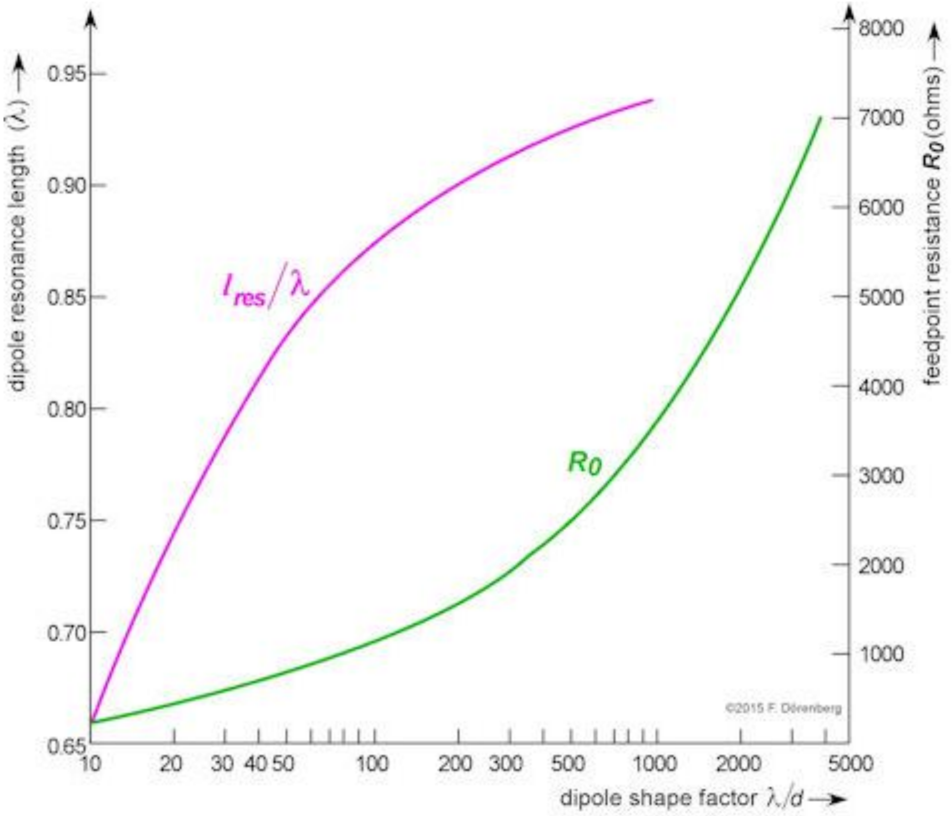


Fig. 130: Feedpoint resistance and resonance length as function of the diameter of the dipole radiator
(source: figure 4.7 in ref. 135)

Photogrammetric analysis of the available photos suggests that the "Bernhard" dipole radiators were quite thick: a diameter of about 10 cm (4 inch) for a wavelength of about 9.5 m. I.e., a ratio λ/d ≈ 100. Based on this λ/d ratio and the graph above, the dipoles should have a length of ≈0.87 λ, not 1 λ. This is consistent with the photogrammetric estimate of the actual dipole length. The bandwidth of a dipole not only depends on its length, but also on its diameter. A dipole has a feedpoint impedance that consists of resistance and reactance. The resistance is relatively insensitive to the dipole diameter, but the reactance (capacitive or inductive) is not! The thinner the dipole, the more the reactance changes for a given frequency change away from resonance. In other words: the smaller the bandwidth. So: thicker is better!

The voltage distribution of a 1 λ. is shown in Figure 127 above. The voltage is zero at a distance of ¼ λ from the feedpoint. That is: at the mid-point of each dipole radiator "leg". This means that this "neutral" point can be connected to ground, without affecting the performance of the antenna. This makes it a convenient point for attaching a dipole leg to the structure of the antenna system, without needing some form of insulation. However, this applies only to a single dipole in free-space. In a *real* dipole, the voltage and current distribution are somewhat distorted due to coupling with nearby objects (in particular other dipoles in the antenna system and the support structure) and ground (esp. with vertically oriented dipoles). Assuming that the same dipole length was used at all "Bernhard" stations, the position of the neutral point would also depend on the operating frequency of the particular station (one of 32 channel-frequencies in the 30-33.1 MHz range). From the available photos of "Bernhard" installations, it cannot be determined whether or not an insulated attachment was used. There is another advantage of attaching the dipole legs at their mid-point: the high-voltage parts of the antenna (the feedpoint and the tips) can be kept away from the antenna support structure. Hence, the effect of loading by stray capacitance (= loss and pattern distortion) between the dipoles and the structure is minimized.

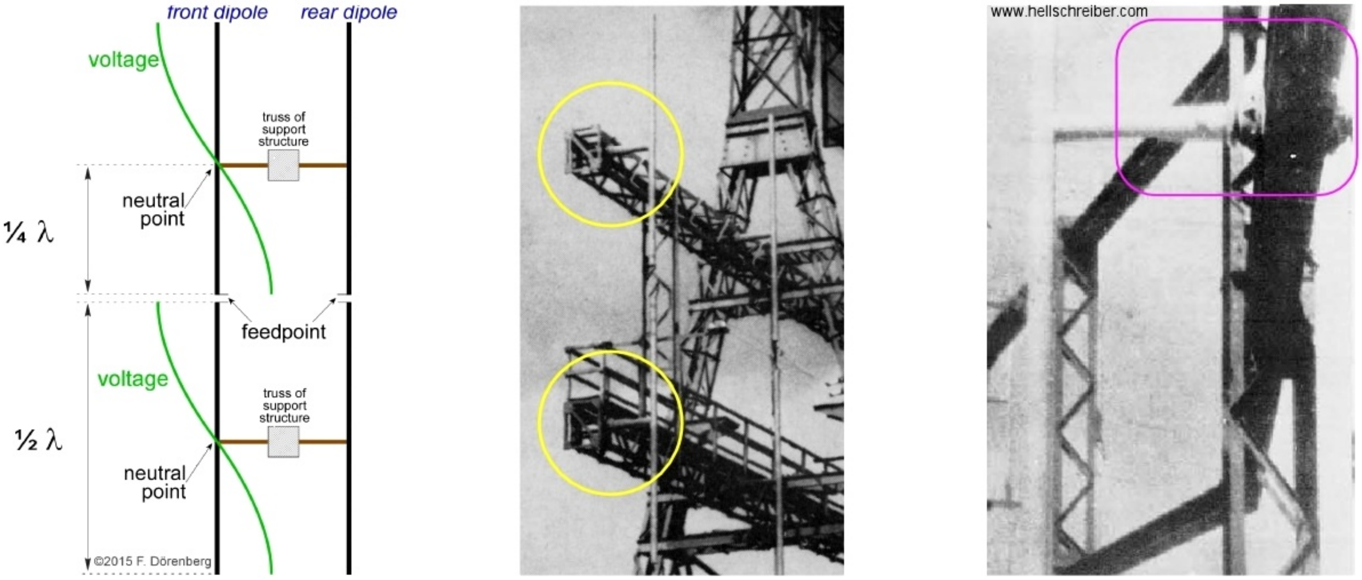


Fig. 131: Attachment of dipole neutral-points to the support structure of the antenna system

(side view of the antenna array; center: Be-9 at Bredstedt, ref. 5; right: similar dipole attachment used in the small "Knickebein", ref. 13)

The same neutral-point attachment method was used in several dipole-array antenna systems, such as that of the FuG200 "Hohentwiel" ship-detection radar (ref. 136, multiple arrays of four 1λ dipoles with passive reflector dipoles, operating at around 550 MHz, i.e., λ = 55 cm), the DMG-3 microwave link (ref. 138), and the small "Knickebein" beacons.

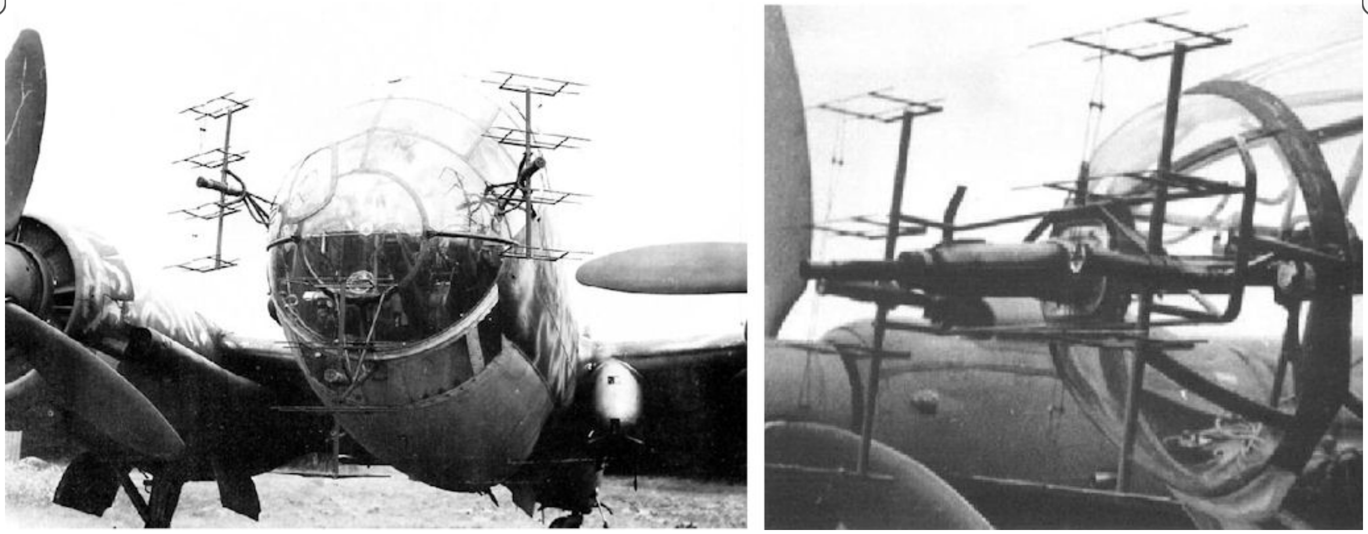


Fig. 132: Junkers Ju 188 with 4 arrays of 4 driven + 4 passive dipoles of the FuG 200 "Hohentwiel" radar

(right-hand image clearly shows crossed-over feedline wires between the dipoles)

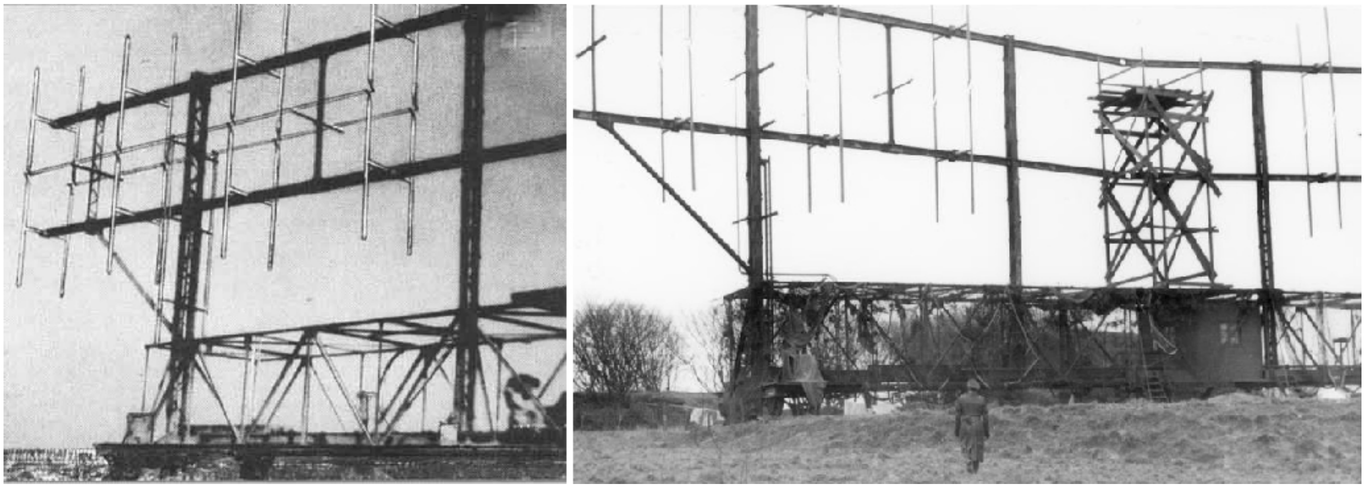


Fig. 133: Antenna sub-systems of a small "Knickebein" beacon - 2x(4+4) driven full-wave dipoles

(source left-hand photo: ref. 2A; right-hand: France 1941, Bundesarchiv Bild 101I-228-0322-04)

HEIN, LEHMANN & CO

The Bernhard antenna systems were built by the ***Hein, Lehmann & Co., Eisenkonstruktionen, Brücken- und Signalbau*** company (HL Co.). They were the standard antenna construction subcontractor of the Telefunken company, in particular of the Telefunken radio communication & navigation department ("Abt. Funknachrichten und Navigation"). The *HL* company was founded in 1878 in Berlin-Reinickendorf by businessman Max Hein and engineer Anton Lehmann. It was founded as a factory of corrugated iron sheet (regular "Wellblech" and load-carrying "Trägerwellblech"). It added production of railway signalling systems in 1885, and incorporated in 1888 as *Hein, Lehmann und Co. Aktiengesellschaft*. They relocated to Düsseldorf-Oberblik in 1889. Over the years, they expanded into steel constructions such as hangars for "Zeppelin" dirigibles, large bridges, and large antenna systems. Ref. 140. The company had an antenna construction department ("Abt. Funkbau"). They did design the construction of antenna masts and antenna turntables, but probably not the antennas as such. Ref. 177A. The antenna related activites of *HL Co.* resumed in 1946 in Berlin-Tempelhof and resided their until 1956. A small part of *HL Co.* is still in the metal products industry to this day.

Brückenbau 1946/47

Behrend. H., Pkw. Berliner Str. 88
Beton- u. Monierbau A.-G., Friedn. Maybachstr. 11—15
Hirsch, E. J., Chlb. Nürnberger Straße 23
Lehmann & Co., Tplhf. Gottlieb-Dunkel-Str. 20—22
Schallhorn, F., Schbg. Frobenstr.22

Funkturmbauten

1949

Hein. Lehmann & Co. K. G.
Eisenkonstruktionen Brücken- und Signalbau.
Berlin-Tempelhof
Gottlieb-Dunkel-Straße 20—22
Telefon: 75 01 41

Funkturmbauten*

1954

Hein, Lehmann & Co.
K.G.
Eisenkonstruktionen · Brücken- und Signalbau
Berlin-Tempelhof
Gottlieb-Dunkel-Straße 20—22
Telefon 75 01 41

Funkturmbauten

1956

Hein, Lehmann & Co.
K.G.
Eisenkonstruktionen · Brücken- und Signalbau
Berlin-Tempelhof
Gottlieb-Dunkel-Straße 20—22
Telefon 75 01 41

Fig. 134. Hein, Lehmann & Co. appears in the Berliner Stadtadressbuch / Branchen Adressbuch of 1946-1956

(source: Berlin Address Directories 1799-1970)

As mentioned, *HL* constructed and installed (very) large antenna masts and towers ("Funkmaste, Funktürme"). One example is the famous *Funkturm* radio broadcast tower in Berlin-Charlottenburg. It was designed in 1924 by *HL* (except for the observation & restaurant decks, designed by H. Straumer) and consruction finished in 1926. It was used for VHF TV broadcasts starting in 1929. It still standing tall (147 m) to this date. *HL* presented the *Messegesellschaft Berlin* a bill for 203660 *Reichsmark* on 25 June 1926 (Kom.Nr. 431/24). This is equivalent to about €1.7 million in 2022 (ref. 177A/177B). Many other large antennas for shortwave and longwave transmitters were built by *HL* around the world, e.g., at Nauen/Germany ("Großfunkstation", 1906, 200 m tall), Pennant Hills/Sidney/Australia (1911, 120 m), Kootwijk/The Netherlands (1919, 1929; 210-266 m), Bandung/Indonesia, Annapolis/MD/USA (1919; US Navy), and Lahti/Finland (1927, 150 m tall). Also the huge antennas of the gigantic 1 megawatt Goliath VLF transmitter station of the *Kriegsmarine* and the antenna system of the Large Knickebein rotable radio beacons.

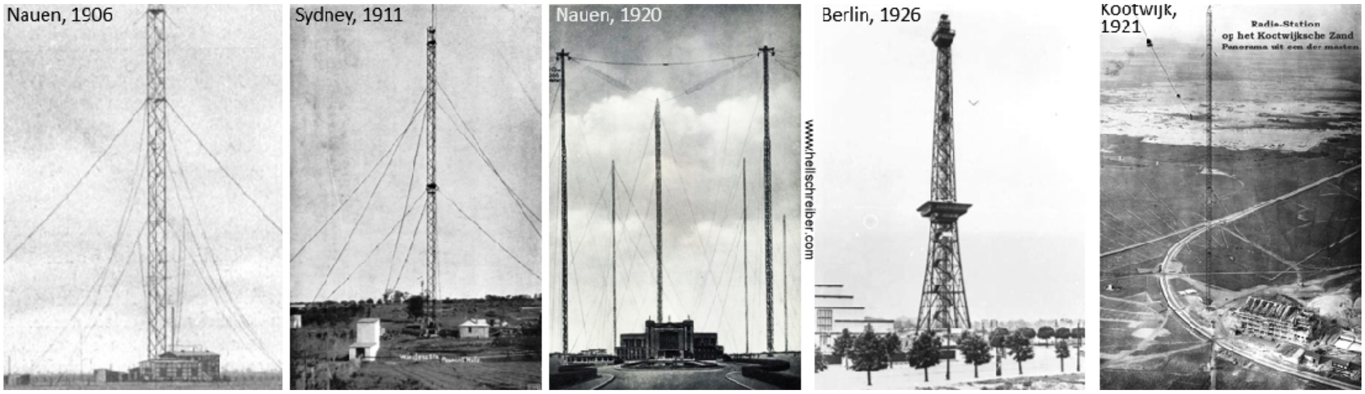


Fig. 135: Some examples of the large broadcast antenna towers built by Hein, Lehmann & Co.

On 31 July 1941, Telefunken placed an order for 12 "Bernhard" antenna systems (purchase order nr. 253/12129). They cost 60810 *Reichsmark* (RM) each, excluding *in situ* installation (ref. 177A-177C). This is equivalent to roughly US$380,000 and €352.000. These prices are estimated for the end of 2016, based on general inflation data (ref. 178A-178C). Note that Consumer Price Index (CPI) inflation data does not necessarily apply to specific products (such as antenna masts, electronics) or services. At some point in time, the antenna manufacturer reduced the price by 5.7%.

The final assembly and installation at the Bernhard-sites was billed separately. For Be-2 through Be-7 (France, 1942), Be-8 (The Netherlands, 1942), and Be-12 (Czechoslovakia, 1944), *Hein, Lehmann & Co.* charged an installation cost that ranged from 20300 RM to 31000 RM. This is estimated to be equivalent to about US$113,700 – US$173,600 or €105.400 – €160.900 (again, at the end of 2016).

Telefunken also placed an order for antenna systems for stations Be-13 through Be-22 (purchase order nr. 253/40567). The antenna system of Be-13 (Buke/Germany) was delivered and installed. The antenna system of Be-15 (Szymbark/Poland) was delivered to the station site, but never installed. The antenna systems for Be-14 (Aidlingen/Germany) and Be-16 (Hornstein/Austria) were manufactured, but never delivered. Manufacturing of the antennas for Be-17 through Be-22 was only about 50% completed by the end of the war. So, a total of 23 "Bernhard" stations was planned (Be-0 - Be-22)!

In 1941, Telefunken also placed an order for six “Diode masts” (steel lattice masts for the remote monitoring antenna), for 2020 RM each. This is estimated to be equivalent to about US$12,600 or €11.700 (end of 2016).

Furthermore, Telefunken ordered "Panzerung von Holzhäusern" for 12 Be-stations, at a cost of 4167 RM each (purchase order nr. 253/33163). That is, sheet-metal protection for the wooden cabin below the Bernhard's antenna system. "Panzerholz" is plywood that is covered with sheet metal armoring on one side or on both sides. The order was probably placed in 1943. Based on that, the estimated equivalent 2016 cost is US$21,900 or €20,250 each. The metal protection was only installed at five stations (Be-2, Be-3, Be4, Be-8, and Be-10). Possibly it took the form of large panels that could be slid in front of the cabin windows.

The antenna structure of the "Bernhard" station Be-4 at La Pernelle/France is reported as having grey-black camouflage colors (ref. 128).

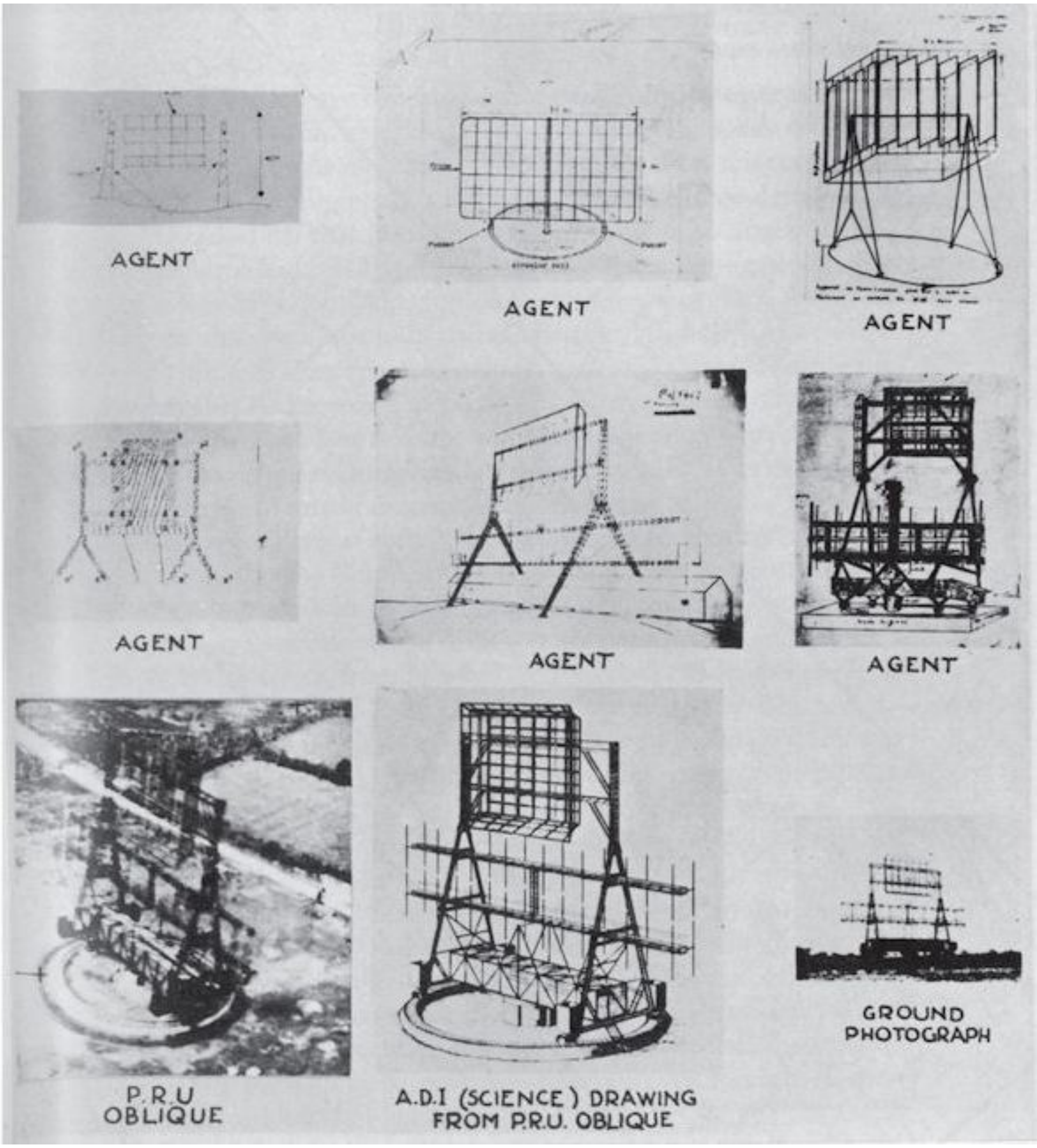


Fig. 136: British intelligence compiled by RAF Photographic Reconnaissance Units (P.R.U.) and "agents"

(source: plate 15 in ref. 230D, reproduced in ref. 91, 92)

In the figure above, "agent" typically refers to a member of the resistance movement in various countries, such as Yves Rocard in France, who provided the far right drawing in the center row, and other information (ref. 91, 92).

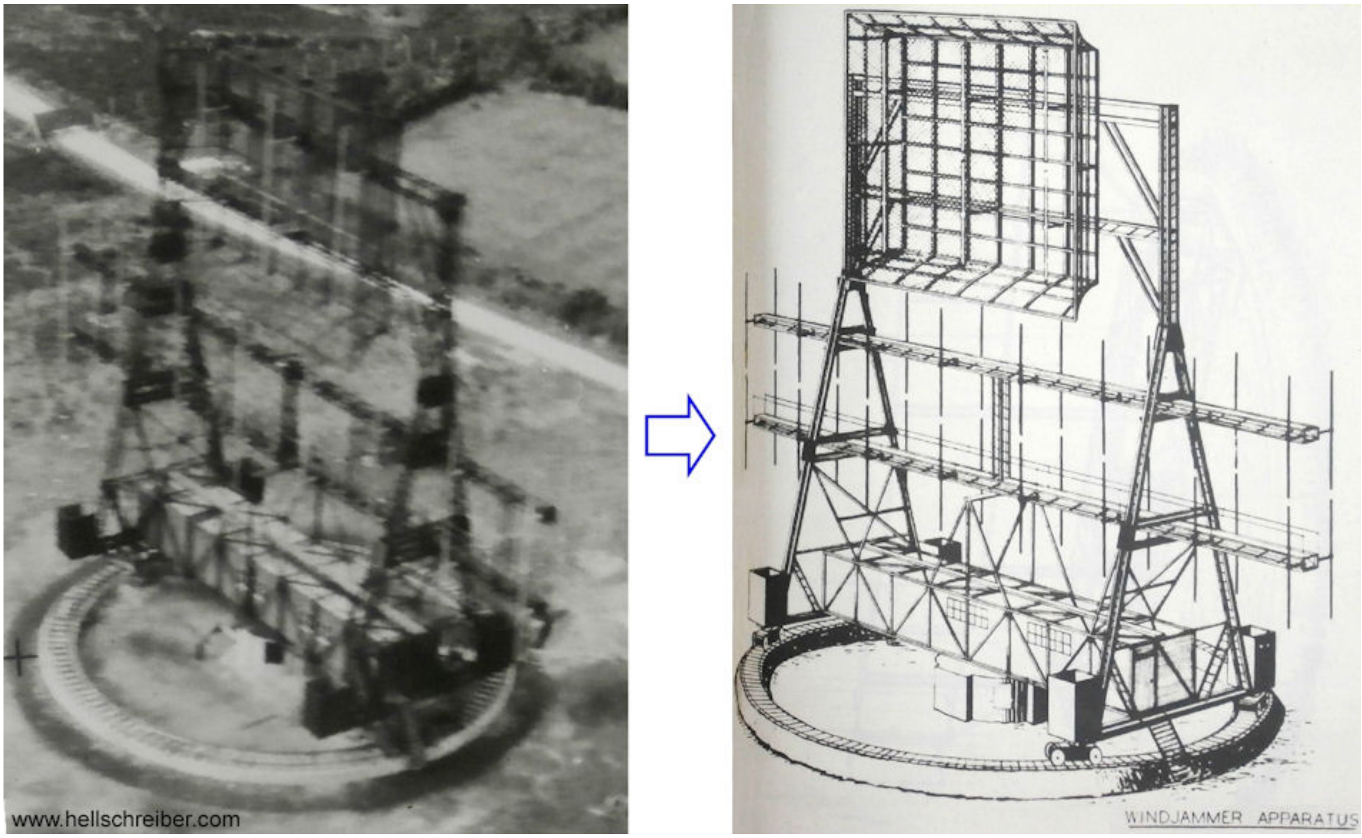


Fig. 137: RAF oblique aerial photo (3-March-1943) of "Bernhard" station at La Pernelle and drawing derived by A.D.I. Science
(source: ref. 172A)

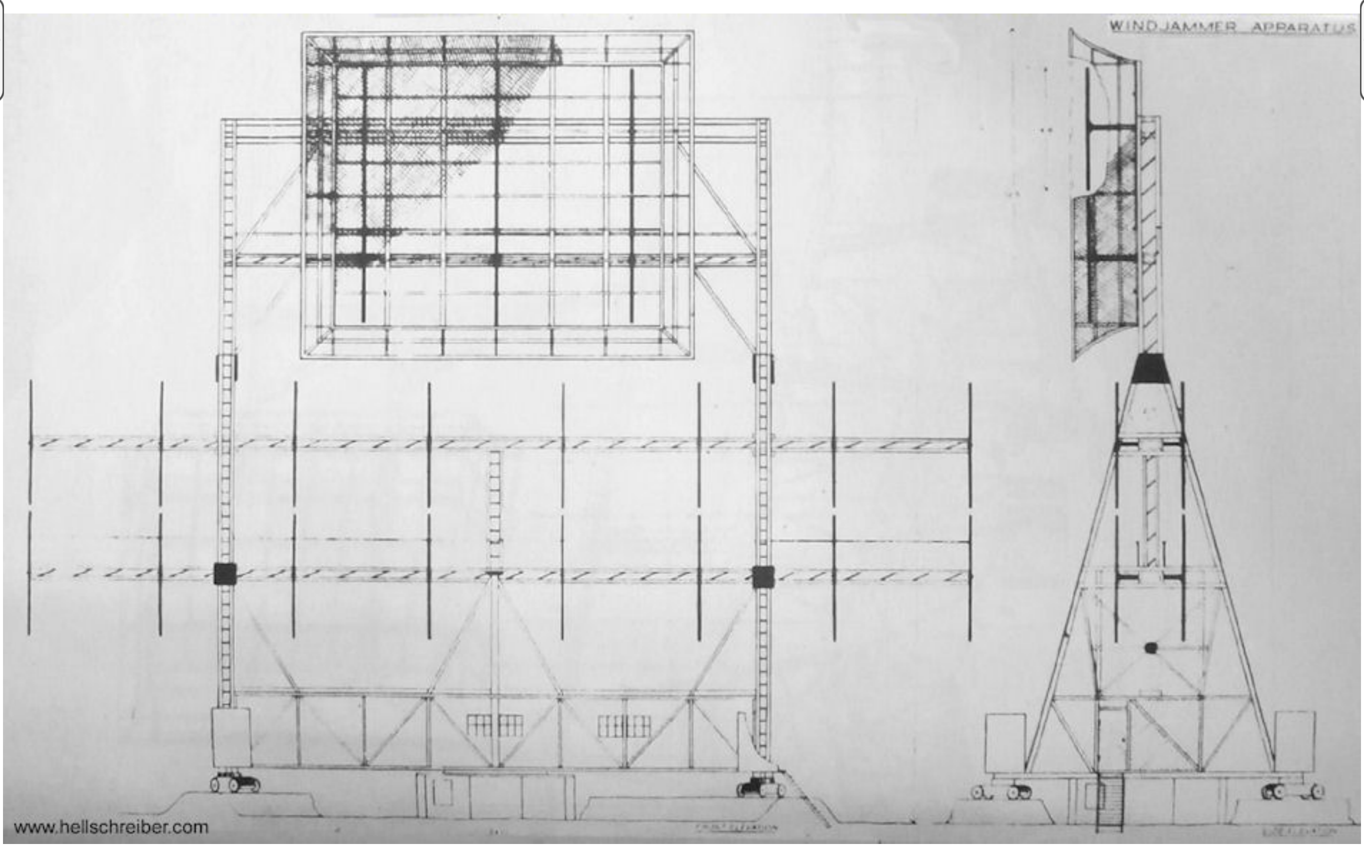
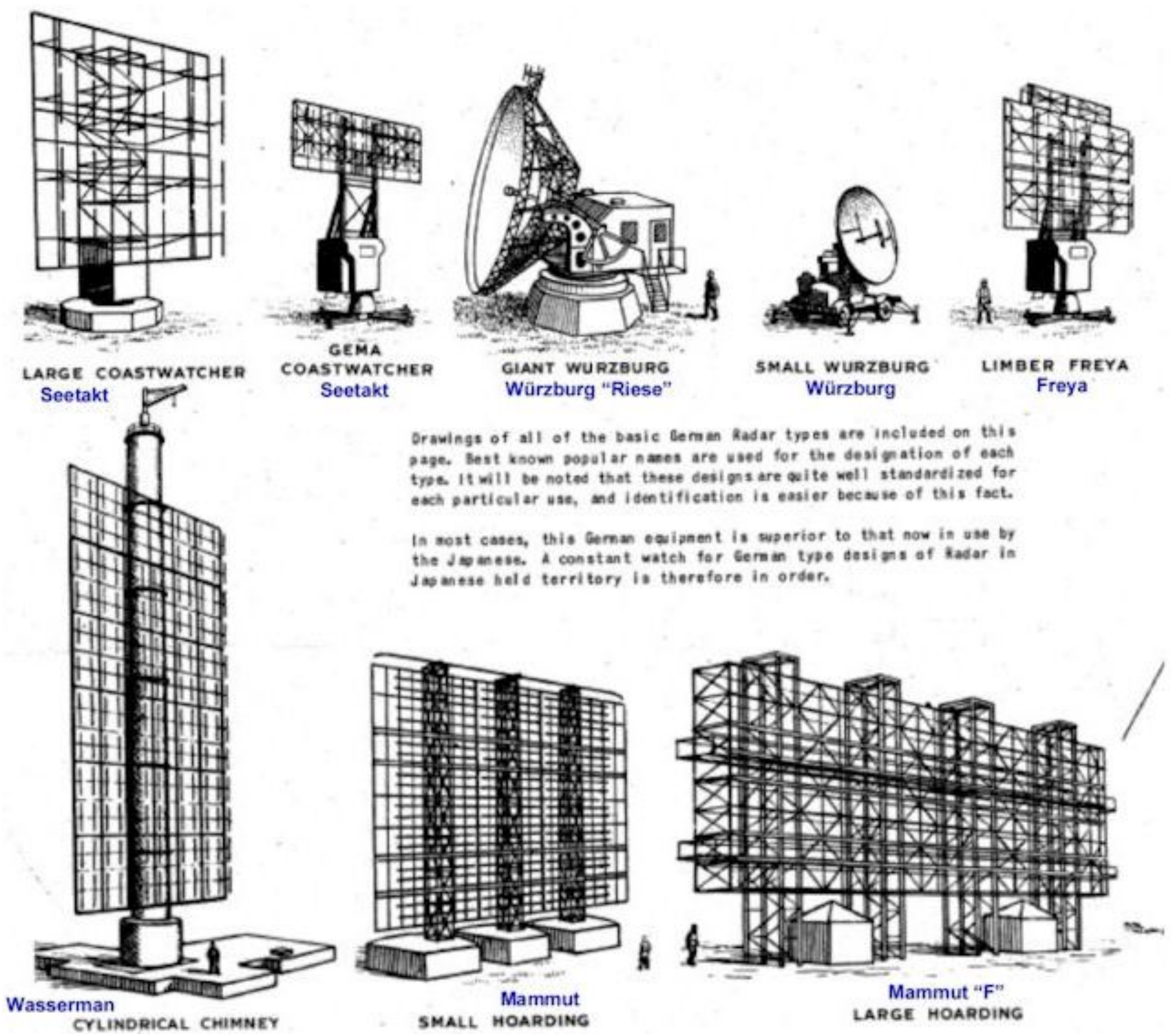


Fig. 138: ADI Science drawing derived from aerial photos by RAF P.R.U.
(source: ref. 172A)

Not surprisingly, given its size and shape, the Bernhard ground station was easily mistaken for a German radar installation of the era:



Drawings of all of the basic German Radar types are included on this page. Best known popular names are used for the designation of each type. It will be noted that these designs are quite well standardized for each particular use, and identification is easier because of this fact.

In most cases, this German equipment is superior to that now in use by the Japanese. A constant watch for German type designs of Radar in Japanese held territory is therefore in order.

Fig. 139: The "Bernhard" antenna system was easily (and often) mistaken for a German radar installation

(source: Figure 26b in ref. 34, p. I-30 in ref. 13)

MODULATION AND FREQUENCY SPECTRUM OF THE "BERNHARD" TRANSMITTERS

The AM transmitter for the twin-lobe beam was modulated with a constant 1800 Hz tone (emission-type designator A2N). Ref. 15, p. 81 in ref. 181. Hence, the spectrum of the transmitted signal consisted of the carrier frequency, and a sideband line at 1800 Hz distance on both sides of this carrier. See Figure 140. For a discussion of AM modulation, associated spectra, and demodulation, see ref. 211.

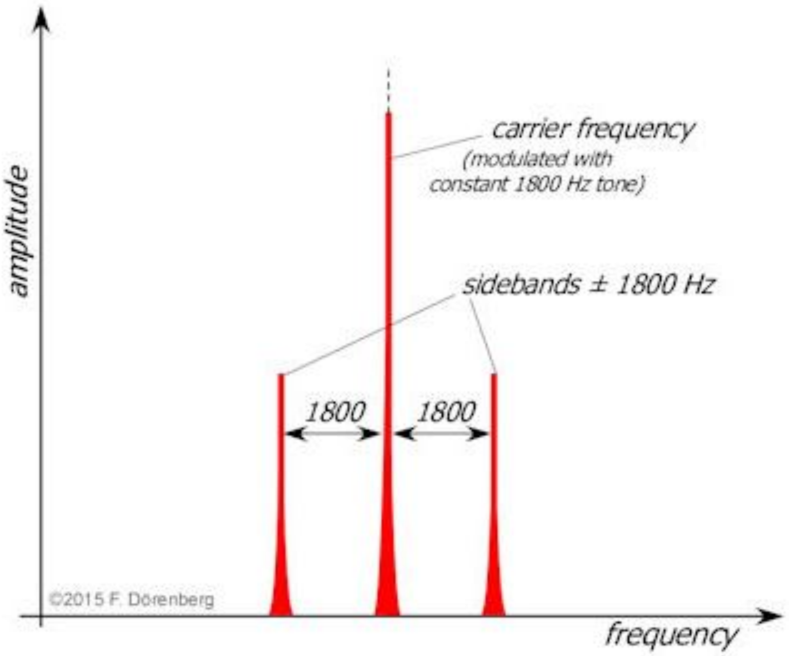


Fig. 140: RF-spectrum of an AM transmitter modulated with a constant 1800 Hz tone

The carrier for the mono-beam was modulated with a 2600 Hz tone. Hence, the spectrum of the transmitted AM signal consisted of the carrier (10 kHz away from the other carrier), and a sideband at 2600 Hz on both sides of that carrier. This is similar to the spectrum of a carrier that is modulated with a constant 1800 Hz tone. However, the 2600 Hz signal was not a constant tone! It was keyed on/off with the pixel-pulses in Hellschreiber-format, to represent the symbology of the compass-rose scale that was to be transmitted. I.e., On-Off Keying (OOK) modulation, which is the simplest form of Amplitude Shift Keying modulation (ASK, emission-type designator A2A).

The spectrum of a tone with frequency f_0 that is keyed on & off with a square wave with period $2T$, consists of a spectral line at f_0, and an infinite Fourier-series of sideband lines at odd multiples N of $1/(2T)$ on both sides of f_0. The height of the sideband lines decreases with N, via a $(1/\pi N)^2$ relationship. See the left-hand image in Figure 98. Continuously keying a tone on/off with a square wave signal is not particularly useful for conveying information. If the tone is keyed with a (quasi) random sequence of on & off pulses with duration T, then the sideband spectrum lines are "smeared" into half sine-wave envelopes. See the right-hand image in Figure 98.

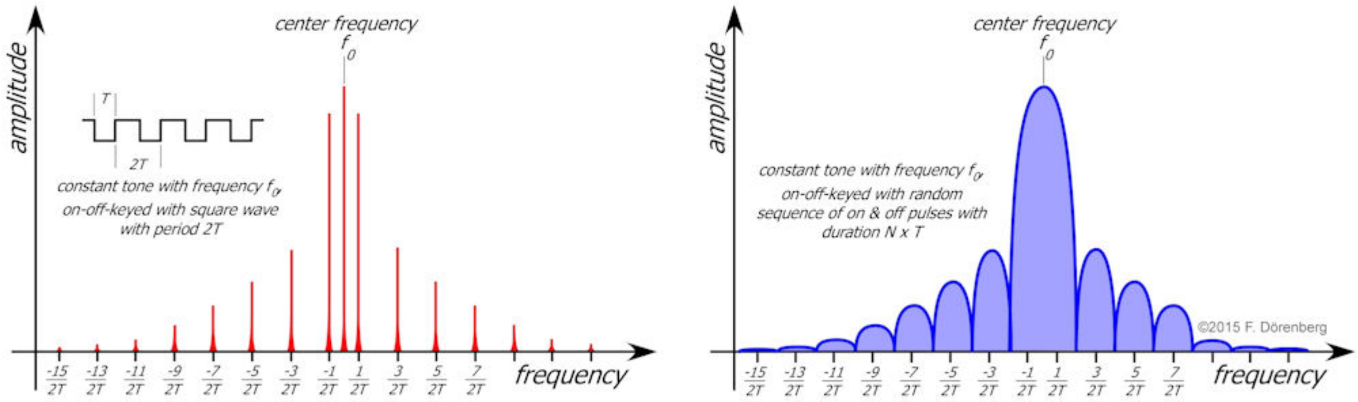


Fig. 141: spectrum of a constant tone frequency that is modulated with fixed-length on &

off pulses
(left: keying with a square wave with on & off pulses with duration T; right: keying with random sequence of such pulses)

The shortest Hellschreiber-pulses of the "Bernhard" system (one black or white pixel) had a duration *T* = 2.3 msec (p. 9 in ref. 15):

The "Bernhard" beacon rotated twice per minute.. So it had a rotational speed of 360° / 30 = 12° per second. The azimuth data was printed with a resolution of three pixel-columns per degree and 12 pixels per column (see the "Bernhardine" printer section). I.e., 432 black and white pixels per second. Hence, the shortest pulse duration was 1000/432 = 2.3 msec (p. 9, ref. 15). This implies a shortest pixel *cycle* (= 1 black pixel, followed by 1 white pixel) of 2 x 2.3 = 4.6 msec. I.e., a pixel *rate* of the 217 Hz. The tone-pulse transmitter limited the bandwidth of the sidebands with a 400 Hz filter (ref. 15). I.e., to twice the 217 Hz pixel rate. Note that in 1935, Hellschreiber manufacturer Siemens-Halske, the British *Cable & Wireless* company (actually, the Communications Division of its subsidiary *Marconi's Wireless Telegraph Company Ltd.*), and the *Reichspostzentralamt* (central office of the German national postal authority), recommended to limit the transmitted bandwidth to 1.6 times the pixel-rate (here: 217 Hz, resulting in 1.6 x 217 = 350 Hz). Ref. 28A, 29, 142. Also see the "Hellschreiber bandwidth" page. This was deemed the minimum transmission bandwidth to ensure legible printing. I.e., not necessarily high-quality printing.

The crystal-controlled carrier frequencies of the two transmitters were spaced by 10 kHz (ref. 181 (p. 81), 183, 228G). The frequencies were placed -5 kHz and +5 kHz with respect to the center of the channel bandwidth of the *EBl 3* receiver used by the FuG120 "Bernhardine" printer system in the aircraft (p. 78 in ref. 181, p. 16 in ref. 183). This receiver had 34 fixed channels in the 30-33.3 MHz band, spaced 100 kHz. The lowest 32 channels were allocated to the Bernhard/Bernhardine system. There was a +/- 1 kHz tolerance on each of the two carrier frequencies (p. 81 in ref. 181). I.e., the carrier spacing varied from 9 to 11 kHz. The nominal bandwidth of the transmitted signal was 10 kHz + 1800 Hz + 2600 Hz + 2x 217 Hz = 14834 kHz. For the given tolerance of the carrier frequencies, the bandwidth was roughly between 14 and 16 kHz. Figure 71 shows what the nominal combined RF-spectrum of the two transmitters looked like:

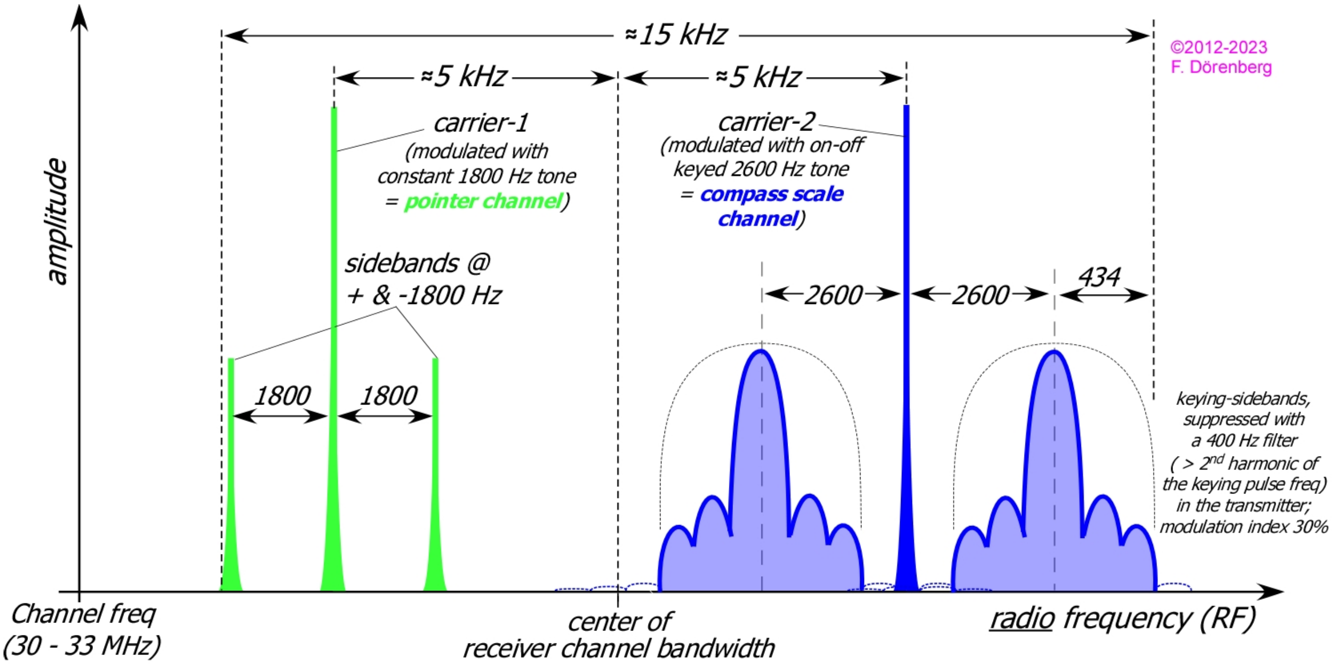


Fig. 142: Nominal RF spectrum of the combined "Bernhard" transmitter outputs
(source: frequencies taken from ref. 15 and ref. 181)

Note that this spectrum comprises two complete AM signals simultaneously. This is very (!) different from a single AM signal that is modulated with two separate baseband signals (e.g., a constant 1800 Hz tone and 2600 Hz tone-pulses), ref. 211.

It is unclear if the frequency of carrier-2 was 10 kHz above carrier-1, or vice versa. The FuG 120 manual shows it one way (Fig. 6 in ref. 15), but ref. 181 (Fig. 41) and ref. 183 (Fig. 4) show it the opposite way... The information available on the associated SG 120 tone filter also does not indicate the relative position of the constant-tone and Hellschreiber tone pulses.

The signals from the "Bernhard" beacon were received with a standard *FuBl 2* "**F**unk-**B**lind-**L**andeanlage" approach-beacon receiver system in the aircraft. It comprised an *EBL2* and an *EBL3* beacon receiver:

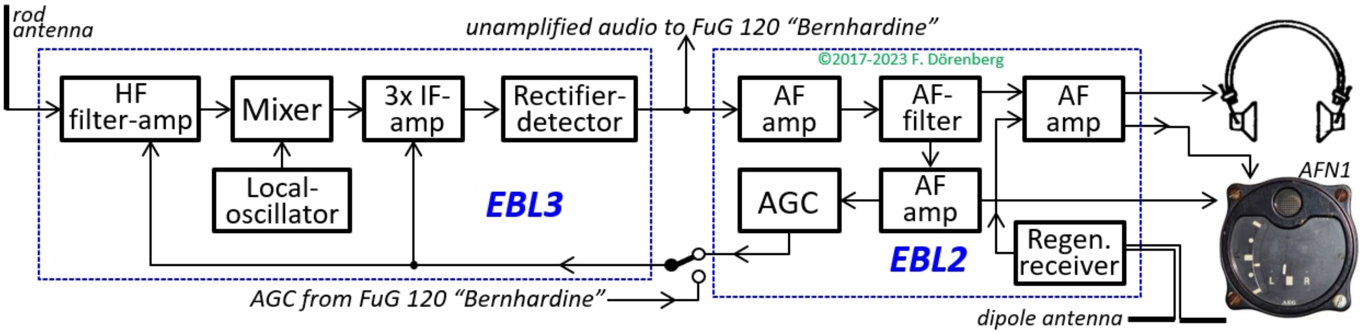


Fig. 143: Block diagram of the EBL3 and EBL2 receiver
(source: adapted from ref. 72)

The "Bernhard" signals were received with the *EBL3*. This is a superheterodyne ("superhet") AM receiver. This means that it de-modulated the amplitude modulated signals with an *asynchronous* product-detector. First, the received signals are heterodyned, i.e., multiplied (=

"mixed") with the sinusoidal signal from a local oscillator. The output signal from the mixer is then filtered, and finally passed through an envelope detector (= diode rectifier + smoothing filter + DC-blocking).

In the "Bernhard" application, the *EBL3* received two complete AM signals simultaneously. For a discussion of AM modulation and demodulation, see ref. 211. The audio output of the *EBL3* contains both the constant 1800 Hz tone from the "Bernhard" beacon's twin-lobe beam, the 2600 Hz Hellschreiber tone pulses that represent the azimuth symbology, and the 9-11 kHz (10 kHz nominal) difference between the carrier frequencies of the two transmitters, ref. 15:

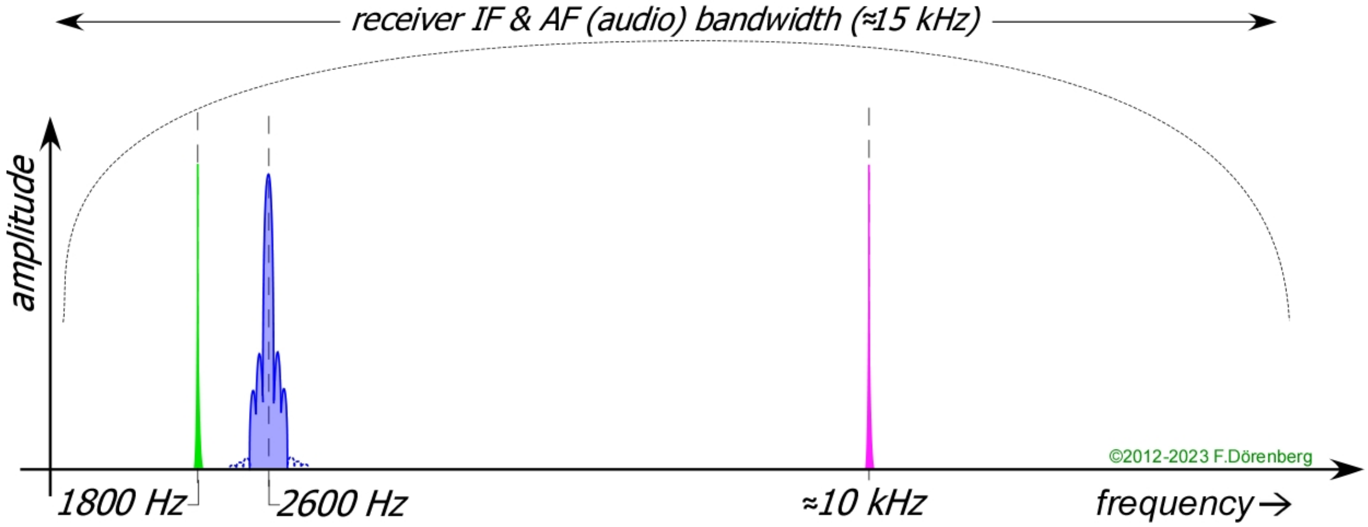
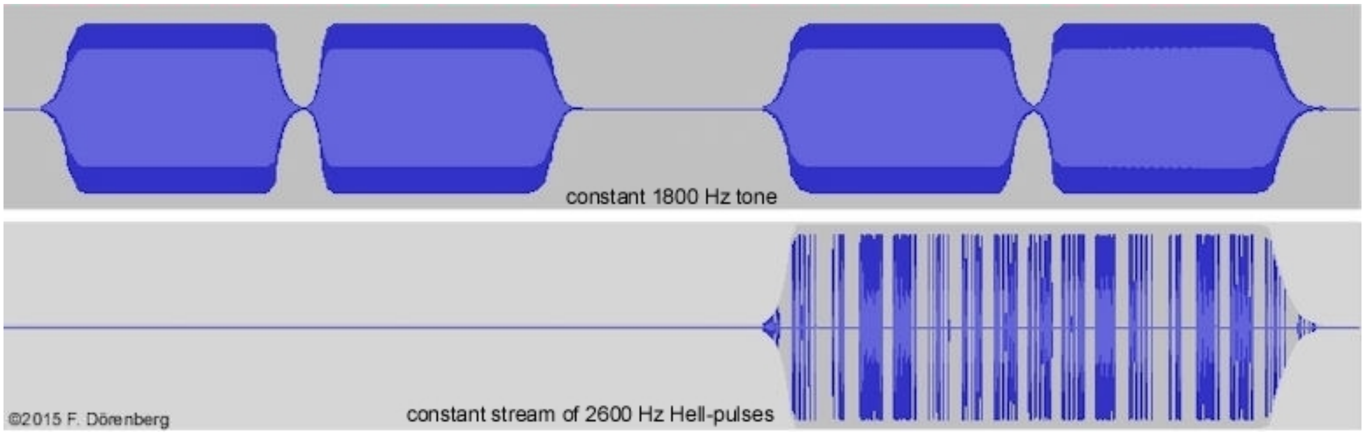


Fig. 144: Audio spectrum of the EBl 3 receiver output

The *EBL3* had an unusually large bandwidth of about 16 kHz. As derived above, the worst-case bandwidth of the "Bernhard" signal spectrum could be nearly 17 kHz. So it was very important to perform careful calibration of the *EBL3* (p. 9 in ref. 15), and precise tuning. Otherwise, either the constant tone signal or the Hellschreiber tone-pulses could end up on the upper or lower flank of the bandpass, and be significantly attenuated.

To the best of my knowledge, no original "Bernhard" audio recordings exist today. So I have simulated the sound of a transmission. The recording below comprises two beam-passages: once *without* the azimuth information in Hellschreiber-format (i.e., only the constant 1800 Hz tone), and once the constant tone plus the constant stream of 2600 Hz Hellschreiber-pulses. The simulated beam-passage duration is about 3½ seconds. Actual beam-passage duration was 3-5 sec, depending on distance from the beacon.

○ 0:00 / 0:09 ○



Simulated sound of two "Bernhard" beam-passages - without & with Hellschreiber tone pulses

Note: the second simulated beam passage also includes the 10 kHz tone. The 1800 and 2600 Hz tone signals were transmitted with two separate AM transmitters, with 10 kHz spacing between their carrier frequencies. The 10 kHz tone at the output of the radio receiver is the normal byproduct of demodulating those two simultaneous AM signals, as explained in the "Filter Unit SG 120 (Siebgerät)" description section.

THE "BERNHARD" FuSAn 724 TRANSMITTERS

The "Bernhard" beacon FuSAn 724 comprised two identical transmitters, each with an output power of 500 watt:

One connected to the upper antenna array (to the center dipole, from where it was distributed to the outer two dipoles). This transmitter is referred to as the ***K**enn**z**eichensender* ("Kz-Sender"), as it transmits the compass scale with integrated station-identifier ("Kennzeichen").

One connected to the dipole-arrays of the lower antenna. The transmitter output was split between the four sub-arrays (front-left, front-right, rear-left, rear-right). This transmitter is referred to as the ***L**eit**s**trahlsender* ("Ls-Sender", lit. guide-beam transmitter), and transmits a constant-tone signal.

This 500 watt transmitter was a standard aerodrome approach-beacon transmitter of the Lorenz company (ref 195, 196): "**A**nflugführungs**s**ender" model ***AS 4***.

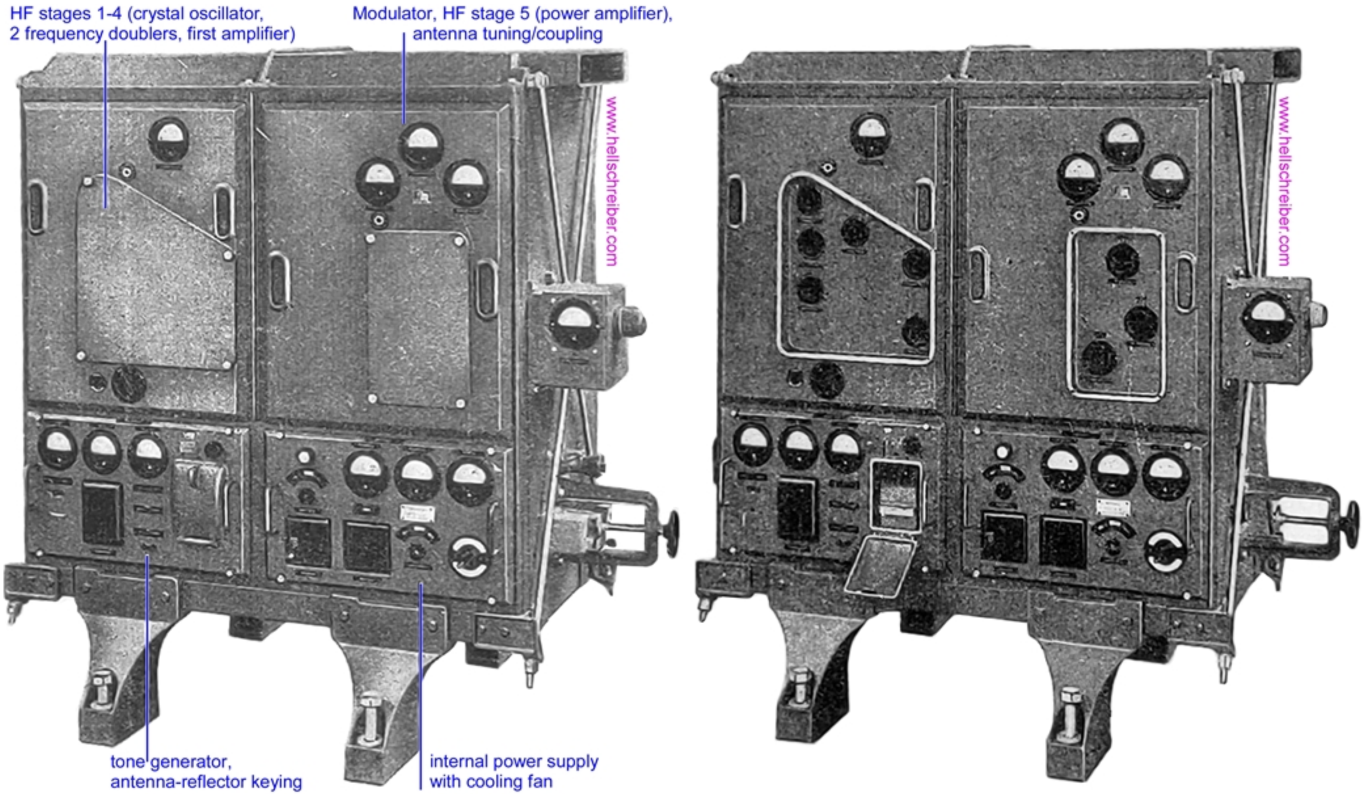


Fig. 145: The Lorenz AS 4 beacon transmitter - front view, with & without cover plates
(source: adapted from Fig. 3 & Fig. 8 in ref. 39C)

Characteristics of the **AS 4**:

Output power:

500 watt at nominal primary supply voltage (220/380 volt AC, 3-phase, 50 Hz),

300 watt for primary supply voltage 10% below nominal.

Modulation:

Amplitude modulation (AM).

Modulation index: 90% (= modulation depth = ratio of modulation signal amplitude and carrier amplitude), adjustable.

5 HF stages: crystal oscillator, first frequency multiplier (2x), second frequency multiplier (2x), first push-pull amplifier, and the final push-pull power amplifier.

Internal power supply (with forced-air cooling):

Input: 24 volt DC from the external power supply NA 500 (which also provides four anode/plate and bias voltages)

Output: 4, 8, and 23 volt DC (heater voltages for tubes/valves and oscillator crystal oven)

Built-in 1150 Hz tone generator (not used in the "Bernhard" application)

Crystal oscillator with oven (+58 °C).

Power-up time:

70 sec (time delay relay), to ensure that the cathode of each tubes is sufficiently heated to produce full electron emission, prior to applying the anode voltage.

An additional ≈3 minutes for achieving stable frequency.

The transmitter channel-frequency could be changed in 3-5 min, depending on the number of operators and their qualifications (ref. 183). This requires adjustment of five anode- and antenna-currents, and eliminating keying-clicks by adjusting the tone-pulse shape (Section III in ref. 39C).

Size: 114x121x70.6 cm (WxHxD, without the feet; 4x4x2.3 ft)

Weight: 402 kg (900 lbs)

Housing: "Silumin" die-cast. *Silumin* was an aluminium-silicon alloy of the *Metallbank und Metallurgische Gesellschaft* in Frankfurt/Main. It was marketed in the USA as "Alpax", dating back to the early 1920s.

The transmitter has two frequency-doublers after the crystal oscillator. Hence, the crystal oscillator operated at 30-33.3 / (2x2) = 7.5 - 8.33 MHz. It is unknown if the oscillator operated at (or near) the fundamental crystal resonance frequency, or at an overtone frequency (i.e., near an odd integer multiple (typ. 3, 5, or 7) of the fundamental). The crystals of the standard *AS 4* transmitter were made by the *Loewe* company (probably the *Radio Frequenz G.m.b.H* subsidiary of *Loewe-Opta*, frmr. "Radio A.G. D.S. Loewe"; ref. 221). The crystal was placed in a small enclosure with a heating element and thermostat. This is referred to as a "crystal oven". Its purpose is to keep the temperature of the crystal near the point where the slope of the crystal's frequency vs. temperature curve is zero. The *Loewe* crystal oven had a temperature setpoint of 58 °C (136 °F), ref. 39C. In the FuSAn 724, the *Loewe* crystal and oven were replaced with a module from Telefunken. First of all, the transmitter had to operate at a carrier frequency that was different from the standard *AS 4* frequencies. With the Telefunken crystal module, the carrier frequency had an accuracy of ±0.5 kHz over the normal operating conditions. I.e., around ±15 ppm ($\pm 15 \times 10^{-6}$) at 30-33.3 MHz. It is unclear if the Telefunken module was also needed to improve the frequency accuracy.

In the FuSAn 724, other modifications were made to the *AS 4* (ref. 195). For example, the *AS 4* has a built-in generator for a constant 1150 Hz tone, and a modulator stage that is tuned to that frequency. However, one of the FuSAn 724 transmitters used a constant 1800 Hz tone, and the other a keyed 2600 Hz tone. In both cases, the built-in 1150 Hz tone generator was not used. Instead, these tone signals were generated by modulators located in the small round building below the turning antenna system. Hence, several filter capacitors in the modulator stage had to be replaced. Also, the modulation index (a.k.a. modulation depth) was made easily adjustable with a potentiometer, instead of the fixed-value resistor.

Standard equipment of the "Bernhard" station included a set of spares tubes (valves) for all equipment - about 60 tubes in total (per sheet 18 & 19 in ref. 189). For the two transmitters combined, the following tubes were kitted: 2x AF7, 12x RS289, 4x RS282, 7x RS329, all made by Telefunken.

The external power supply of the *AS 4* is "**N**etz**a**nschlußgerät" model **NA 500** (ref. 39C), with the following characteristics:

Input power: separate inputs for 220 and 380 volt 50 Hz 3-phase AC ("Drehstrom"), 5 kVA.

Output power: -24, -100, +400, +1000, and +2000 volt DC; 20, 220, and 4 volt 50 Hz AC.

The input step-down transformer was connected to either 220 or 380 volt 3-phase 50 Hz AC.

The voltage of one of the three output phases of this transformer was regulated with an 8 amp "carbon pile regulator" (a.k.a. "Kohledruckregler", "Pintsch-Regler"). This is a fast electro-mechanical voltage regulator, comprising a stack of several dozen carbon discs or rings ("Kohlescheibensäule"). Ref. 208A, 208B, 208C. The resistance of the carbon stack depends on the pressure that is applied to it. This pressure is applied by an electromagnet, whose DC control-current is derived from the controlled voltage with a separate transformer-rectifier. This control-current depends on the load, as well as on the primary 3-phase voltage. This closed-loop control keeps the regulated voltage constant to within ±3% for ±10% input voltage variation. In case of over-voltage of the primary 3-phase power, the regulator mechanism reaches its extreme position. This actuates a contact that shuts down the anode voltages, after a persistence delay of about 10 sec.

The input transformer fed three separate single-phase transformers, each followed by a selenium rectifier bridge and a filter, to generate -24, +400, and +1000 volt DC. The 24 volt DC was reduced to 4, 8, and 23 volt DC in the internal power supply of the transmitter.

The -100 and +200 volt DC were generated with a similar scheme, but with two separate 3-phase transformers.

The 20 volt AC was used by a motor in the *AS 4* that continuously turned a shaft with four notched disks, associated with switching the antennas that were normally connected to the *AS 4* (but not in the "Bernhard" application)

Cooling: forced-air (fan).

Size: 183x67x50 cm (WxHxD, 6x2.2x1.6 ft).

Weight: 340 kg (752 lbs).

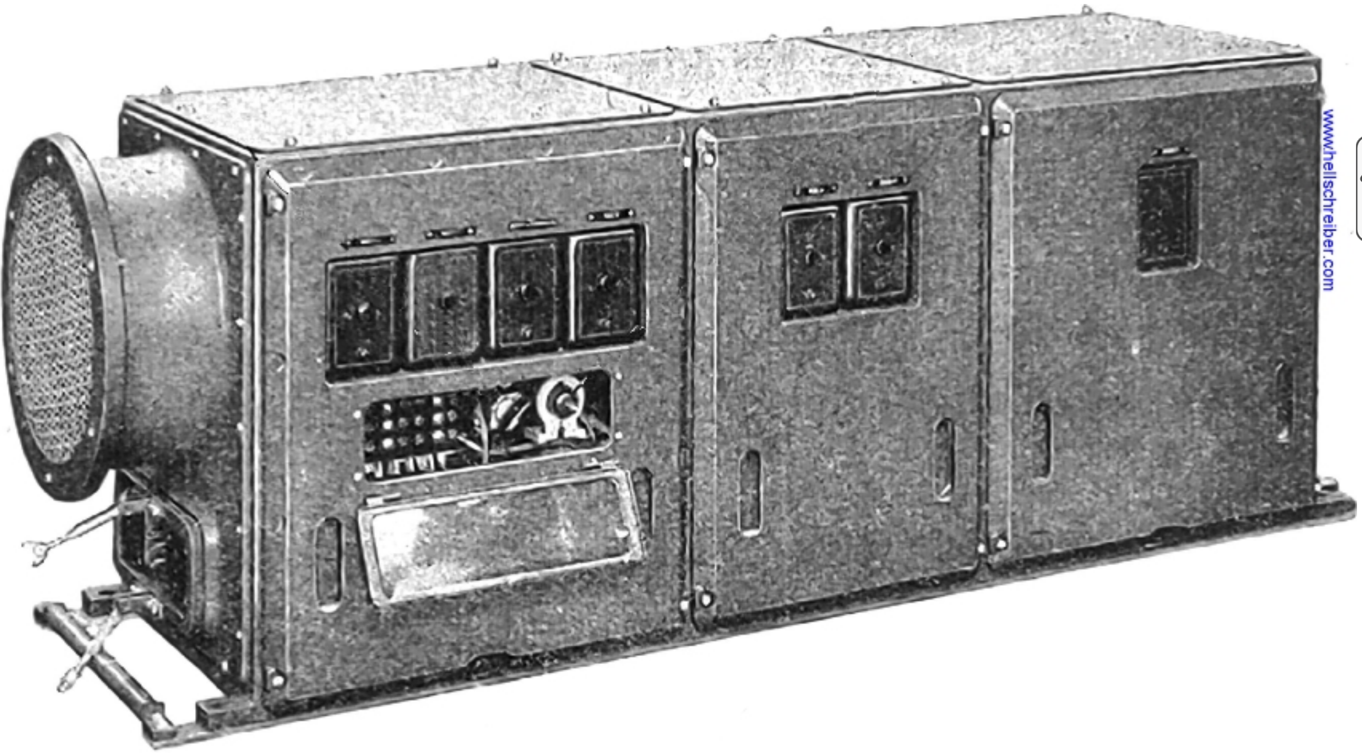


Fig. 146: The AN 500 power supply of the AS 4 beacon transmitter
(source: adapted from Fig. 7 in ref. 39C)

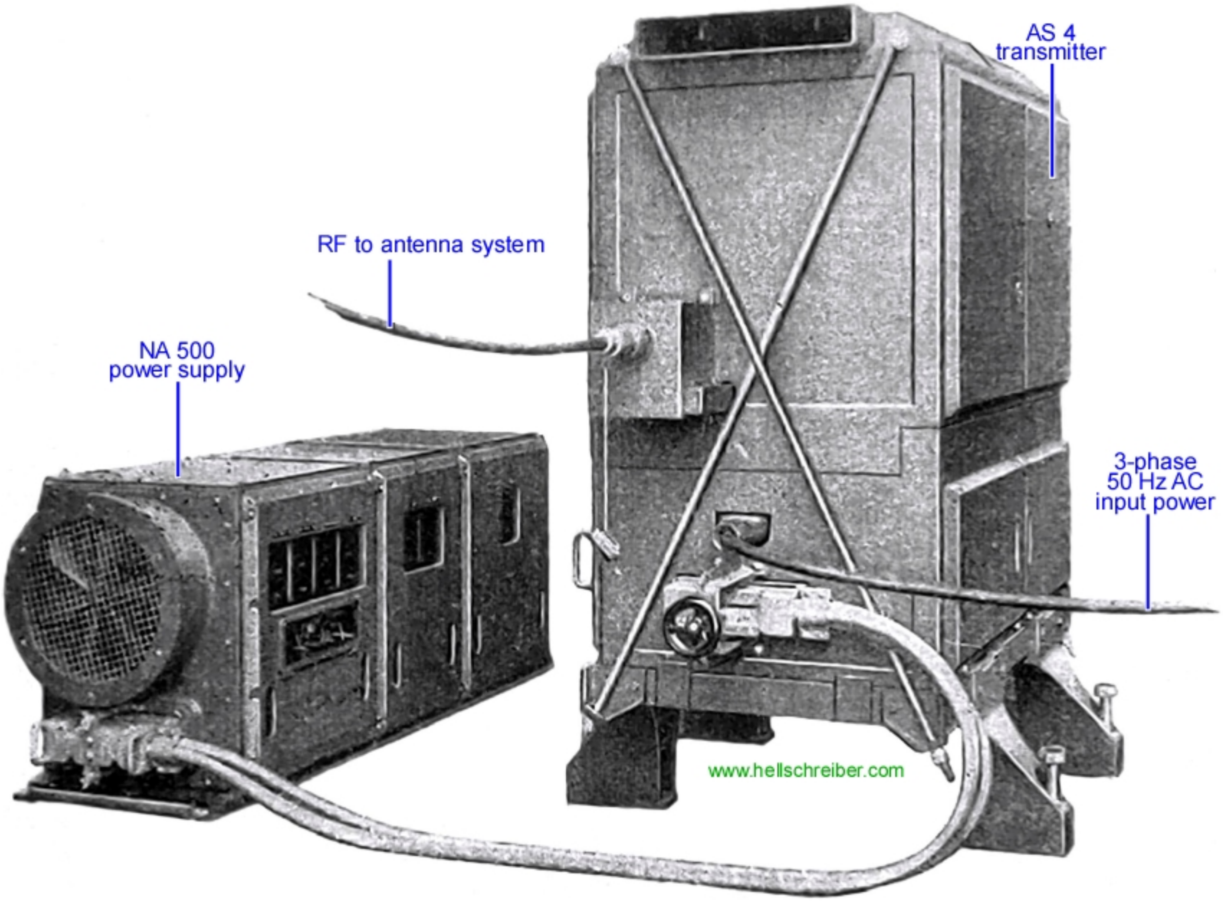


Fig. 147: The AS 4 transmitter and NA 500 power supply
(source: adapted from Fig. 4 in ref. 39C)

THE "BERNHARD" FuSAn 725 TRANSMITTERS

"Bernhard" **FuSAn 725** was the high transmitter-power version of the **FuSAn 724**. It used a **B.R.A. 30/20** shortwave beacon transmitter system ("Kurzwellen Bake Sendeanlage"), see ref. 10 (§5). Ref. 10 is a 1946 British report of the on-site inspection of two Berhard stations that were captured intact. This report states that these two stations had 5 kW transmitters. So, at least two of the Bernhard stations were FuSAn 725! One of them was Be-10 at Hundborg/Thisted in Denmark (ref. 10, Fig. 1). The second one was probably Be-9 at Bredstedt in Germany, 260 km to the south of Be-10: it too was inspected by the British "Air Disarmament Wing" (ADW). Curiously, according to ref. 164D (§6; 1944), Philips did indeed build the 20 ordered transmitters, but never delivered them... It is unclear if Be-9 and Be-10 were initially built as FuSAn 724 and then upgraded to FuSAn 725, or were already FuSAn 725 from the beginning.

Ref. 164D (§6) states that the Telefunken company integrated the *B.R.A. 30/20* system into the rotating cabin of the "Bernhard", and implies that it was a product of the *N.V. Philips' Gloeilampenfabrieken* company in Eindhoven/The Netherlands. Actually, *B.R.A. 30/20* was one of the beacon transmitter systems that was designed and made by ***N**ederlandsche* ***S**eintoestellen* ***F**abriek* (NSF, "Dutch Telegraphy Equipment Factory") in Hilversum/The Netherlands. This company was founded in 1918, as a joint venture of *Philips* (40%), *Marconi U.K.* (40%), and *Nederlandsche Telegraaf-Maatschappij Radio-Holland* ("Radio Holland" for short, 20%). The latter was founded in 1916 by several major Dutch shipowners (ref. 283, p. 46) and the *Bataafsche Petroleum Maatschappij* (a subsidiary of the *Royal Dutch Shell* oil company). *Philips* became the majority shareholder of *NSF* in 1925 by acquiring the *Radio-Holland* shares, and bought out *Marconi* in 1946. Initially, NSF produced transmitters for the Dutch Navy, Air Force, national public radio broadcast system, and overseas territories. Other NSF navigation beacon transmitter systems for aviation were the *B.R.A. 101* (ca. 1935, 3740-375 kHz longwave, loop antenna with 150 W transmitter, vertical antenna with 20 W transmitter; used in The Netherlands, Poland, Belgium, Spain), *B.R.A. 075/4* (ca. 1937; ca. 30 MHz), and the *B.R.A. 200/08* (equisignal type landing beacon, ca. 33 MHz, two 100 W transmitters, 2x2 vertical dipoles). In 1947, *NSF* was renamed *N.V. Philips' Telecommunicatie Industrie* (PTI). Ref. 283C, 283D, 283F, 223G, 223H, 229A8.

Fig. 148: logo of the NSF company in The Netherlands

The *B.R.A. 30/20* system comprised a pair of NSF model **KVC 15/L27** transmitters:

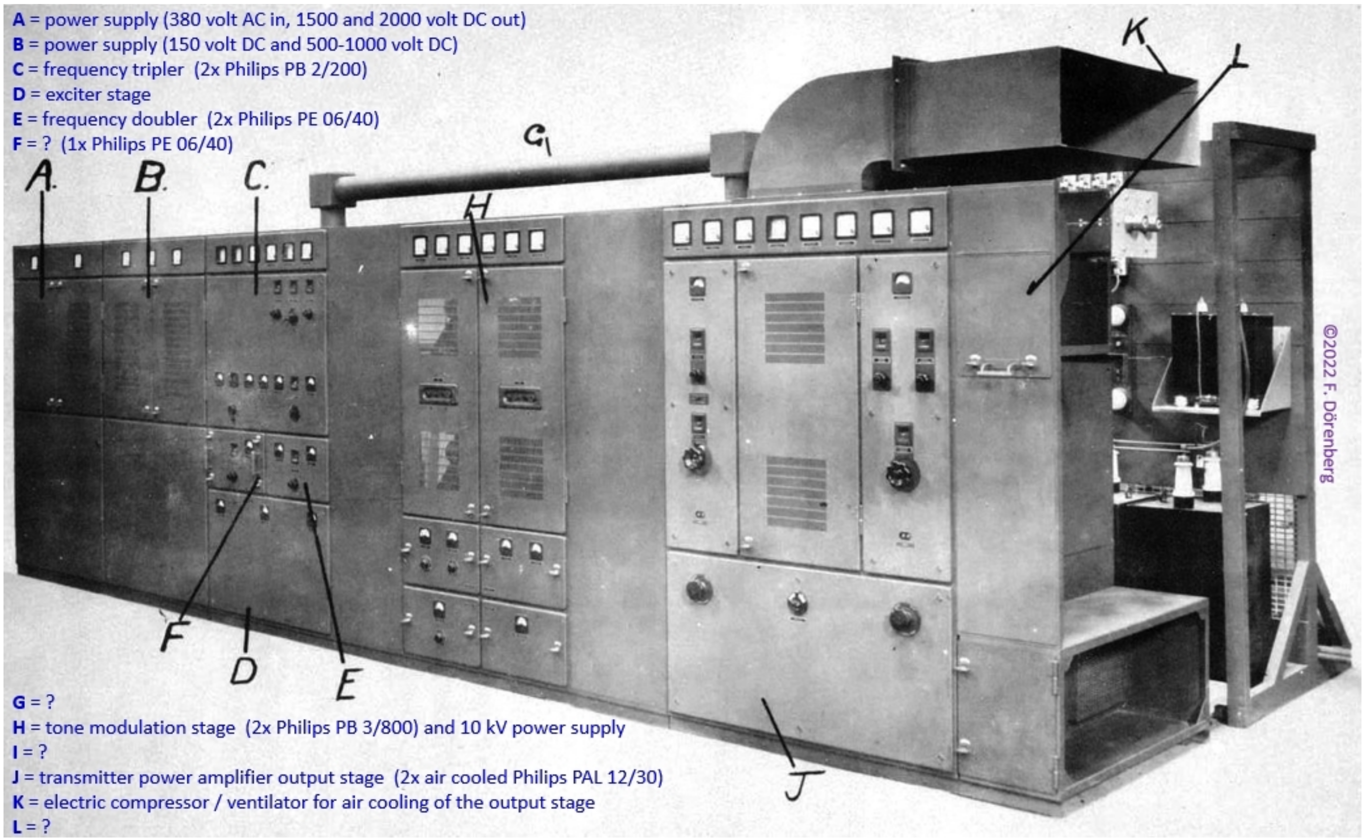


Fig. 149: One NSF model "KVC 15L/27" transmitter - half of the NSF "B.R.A. 30/20" beacon transmitter system
(source: Fig. 9 in ref. 10)

FuSAn 725 transmitted on the same fixed frequency channels in the 30-33.3 MHz band as the FuSAn 724. They were covered by the EBl3 receiver in the airplane. Transmitter "A" transmitted on a frequency that was 10 kHz higher than that of transmitter "B". Transmitter "A" was modulated with 2600 Hz, and on-off keyed with the Hellschreiber-format compass scale. Transmitter "B" transmitted a carrier that was modulated with a continuous 1800 Hz tone. See the frequency spectrum in Fig. 97 above.

The oscillator for transmitter "B" was crystal-controlled, and set to 1/6 of the output frequency. I.e., in the 5-5.6 MHz range. The oscillator of transmitter "A" was referenced to that same crystal oscillator, but offset by 10/6 kHz:

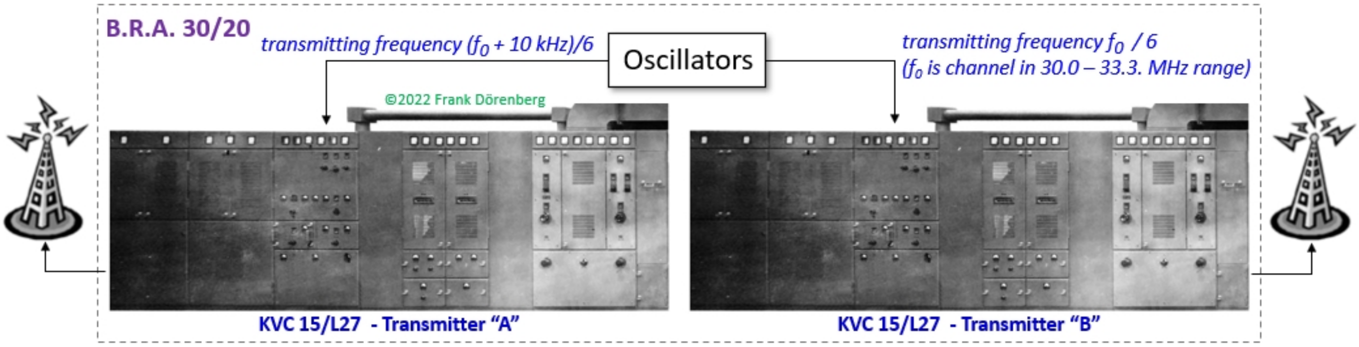


Fig. 150: Block diagram of the NSF/Philips BRA 30/20 beacon transmitter system
(source: adapted from Fig. 9 and Fig. 10 in ref. 10)

The oscilllator system is interesting - it actually comprises three oscillators that are active simultaneously:

> A crystal-driven **Master Oscillator**. This fixed-frequency Master ran at 1/6 of the standard frequency channel that was allocated to the particular Bernhard station.
>
> A tuning-fork **Offset Oscillator**, oscillating at the audible frequency of 10 kHz / 6 = 1667 Hz.
>
>> Tuning-fork oscillators were typically made for frequencies of 1-5 kHz. With accurate temperature control of ≈ ±0.1 °C, the frequency stability was about one ppm ($\pm 10^{-6}$).
>
> A variable-reactance LC **Slave Oscillator**. It tracked the "Master oscillator frequency plus the offset the tuning fork frequency", i.e., 1667 Hz higher than the Master frequency.

The alternative solution would have been to use two crystal-driven oscillators. This would have required *two* station-specific crystals. The master-slave arrangement only required *one* station-specific crystal: the slave oscillator frequency would automatically be at the correct offset. The concept of this triple oscillator system is illustrated below. Simply put: the *actual* difference between the Master and Slave frequencies is compared against their *required* difference. The resulting tracking-error amount is used to adjust the slave frequency. Note that the Slave oscillator also tracks temperature drift of the Master oscillator (and of the offset-oscillator, for that matter). The Slave oscillator tracked the Master by better than 1% (ref. 10).

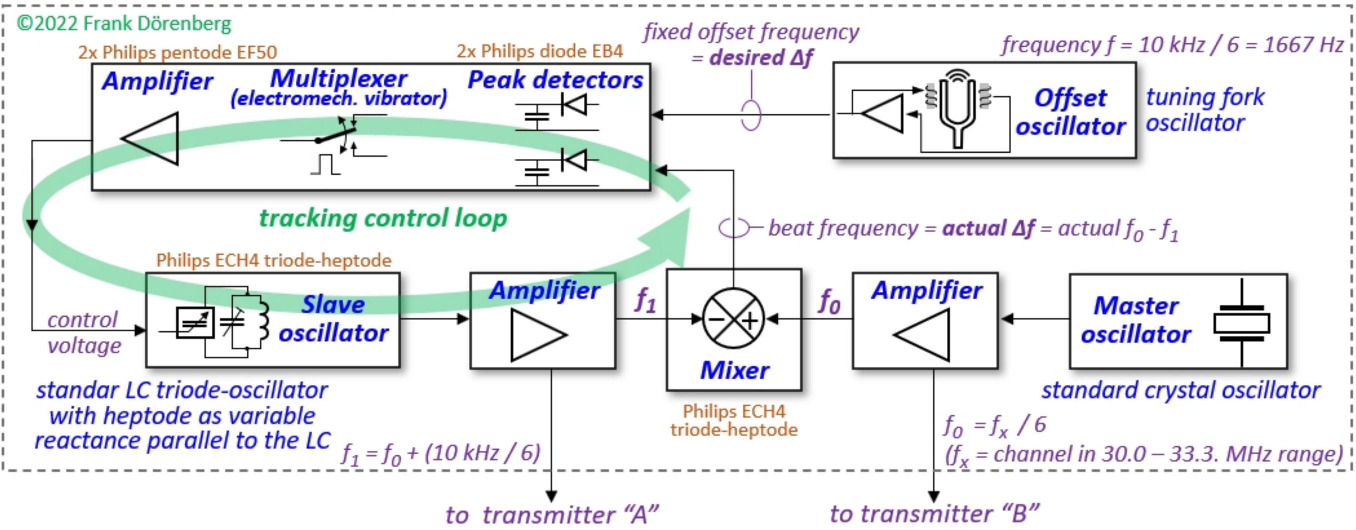


Fig. 151: Block diagram of the control loop of the Master/Slave oscillators of the NSF/ Philips BRA 30/20

(source: adapted from Fig. 10 and Fig. 11 in ref. 10)

Each *KVC 15/L27* transmitter comprised a 2x and a 3x frequency multiplier stage. The combined 6x multiplication converted the oscillator frequencies to the desired channel frequency in the 30-33.3 MHz band, with an offset of 10 kHz between them.

Most publications state that the FuSAn 725 had 5 kW transmitters. I.e., 10 times the power of the FuSAn 724 transmitters. Ref. 10 (1946) is ambiguous about the 5 kW: in it, the caption of the photo above states "5 kW", but section 5.2 states that the transmitter output stage actually delivered 4 kW - but only for transmission of a constant carrier signal of the pointer signal.

Output power of a tone-modulated signal for Hellschreiber transmission of the compass scale was less than that. Note that a **4** kW power level is actually consistent with the official wiring list of the "Bernhard" station (ref. 189)! This list contains several items (cables nr. 6-8, 33, and 34) with *two* wire gauge specifications: one for 500 W transmitters, and a much heavier gauge for **4**000 W transmitters - i.e., not **5**000 W!

A tenfold increase in Effective Radiated Power (ERP) could have increased the range of the beacon by an estimated factor of SQRT(10) ≈ 3. The increased power would also have improved interference-proofness of the Bernhardine receiver-printer system, but that was already good with the 500 W transmitters. It is unclear at which point in time the FuSAn 725 was conceived and planned. The investment in such a range increase would probably not have made much sense during the latter part of the war.

All tubes (valves) of the *KVC 15/L27* transmitters were Philips **p**entodes - hence, their type designator started with a "P":

> **PE 06/40** transmitter pentode: 12.5 V filament, 600 Va max, 25 W max anode dissipation, 11-100 W power depending on modulation type, 20 MHz max. The letter "E" indicated an indirectly-heated oxide-coated cathode.
>
> **PB 2/200** pentode: 12 V filament, max anode voltage of 2000 V, 110 W max anode dissipation, 43-400 W power depending on modulation type, 20 MHz max. The letter "B" indicated a directly-heated thoriated tungsten filament.
>
> **PB 3/800** pentode: 12 V filament, max anode voltage of 3000 V, 450 W max anode dissipation, 200-1600 W power depending on modulation type, 10 MHz max.
>
> Per ref. 10, the final power amplifier stage comprised two air-cooled **PAK 12/30** tubes in a standard push-pull configuration.
>
>> The letter "A" indicated a directly-heated tungsten ("wolfram") filament. The third letter in the transmitter tubes designator is for the cooling method. However, Philips did not use the letter "K" - only "L" for air (= the word "**l**ucht" in Dutch), "W" for water, "G" for mercury vapor, and "X" for xenon. As these tubes were actually air-cooled, it would have been an "L".
>>
>> However, none of the Philips transmitter tube handbooks list a PAL tube with "12/30" characteristics! The handbook from 1946 (ref. 283A) does list the PAL 12/**15**. It was developed in 1937. The "12" means that the maximum anode voltage was 12 kV. Per a PAL 12/15 marketing data sheet (ref. 283B), the maximum *measured* anode dissipation was 15 kW (but only 12 kW max allowed). When configured as a Class C amplifier for telegraphy, its maximum output power at 2 MHz was 14.4 kW (ref. 283A). At 50 MHz, the maximum was 14.5 kW - but only for a push-pull configuration of two such tubes. The tube had a length of 61.4 cm (≈2 ft) and a diameter of 24.5 cm (≈9½ inch).
>>
>> It is fair to assume that the PAL 12/**30** had a maximum *measured* anode dissipation of 30 kW - but signifciantly lower around 30 MHz, and for tone-modulated telegraphy (MCW). So, the B.R.A. 30/20 transmitters did not output 30 kW (despite ref. 164D suggesting so).
>>
>> If you have information about the PAL 12/30 tube, please contact me.

THE OPTICAL ENCODER DISK

As stated before, the "Bernhard" beacon continuously transmitted the momentary pointing-direction (= bearing, azimuth) of the antenna system in a pictorial format, the equivalent of a compass scale strip:

Fig. 152: Remote compass, as used in Fw190 etc.
(made by the "A. Patin & Co. G.m.b.H." company of Berlin)

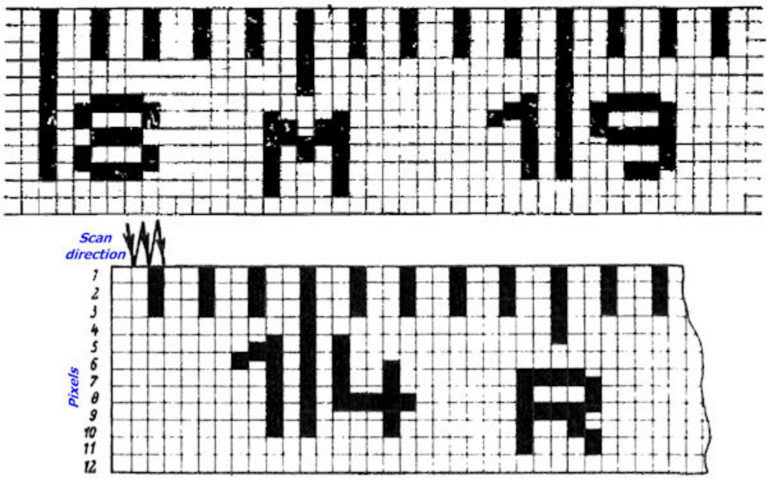


Fig. 153: Rasterized compass scale of the Bernhard system
(sources: patent 767524 (top), ref. 15 & 181 (bottom))

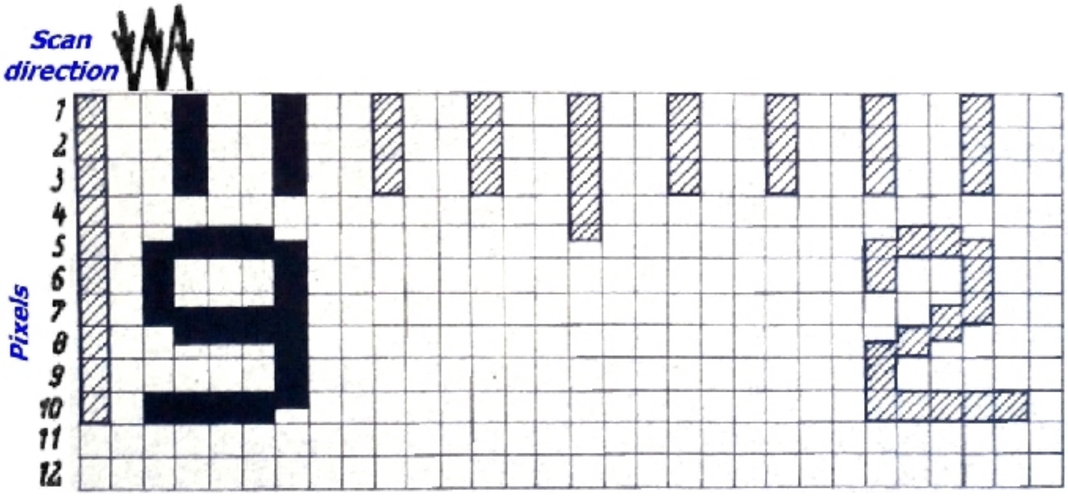


Fig. 154: Rasterized compass scale of the Bernhard system
(source: Fig. 48 in ref. 181)

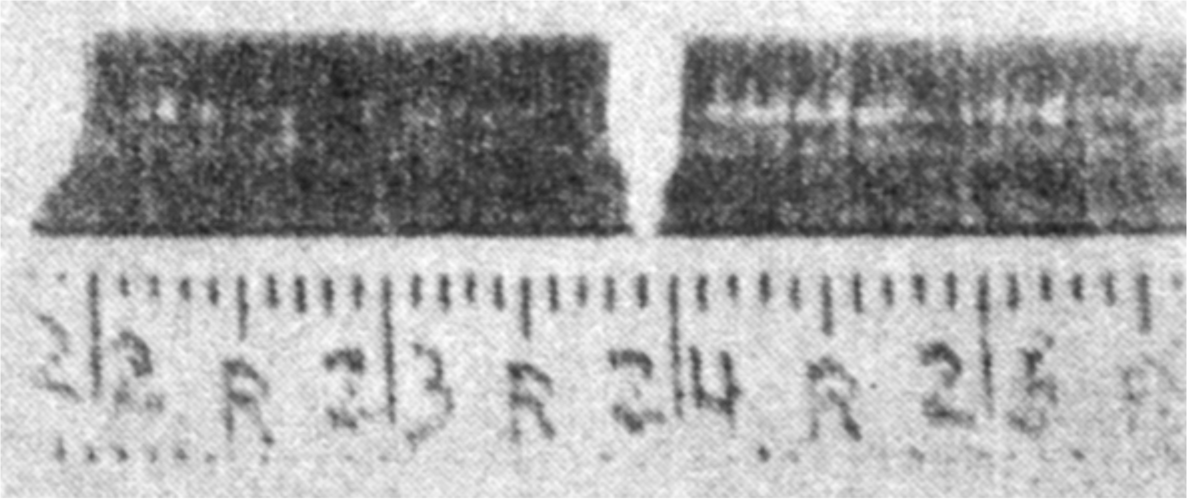


Fig. 155: Signal-strength bar graph, azimuth data and station identifier "R", as printed with a "Bernhardine" Hellschreiber

(source: ref. 2B; the strip indicates that the receiver is on bearing of 239 degrees from ground station "R")

The 360° compass-scale strip is rasterized into pixels, and continuously transmitted pixel by pixel, as the Bernhard beacon turns. Pixel columns are "scanned" and transmitted top to bottom. At the bottom of each pixel column, the pixel stream continues seamlessly at the top of the column to the right of it. Each pixel is transmitted as a tone pulse. This is known as the **Hellschreiber** transmission system, invented and patented by Rudolf Hell in 1929. See the "How it works" page. On the receiver side, the stream of received tone pulses is printed directly by a Hellschreiber printer, to recreate the compass scale strip on a paper tape.

The 1938 Telefunken patent 767524, the 1942/43 Bernhard/Bernhardine system descriptions (ref. 181 (Fig. 43 & 48), ref. 183), and the 1944 manual of the "Bernhardine" Hellschreiber printer (ref. 15) show the following pixel format (see Fig. 153 and 154 above):

- Columns of 12 pixels.
- 3 pixel-columns per degree:
  - 3 columns/deg x 360 deg = 1080 pixel-columns in total.
  - 1080 pixel-columns x 12 pixels/column = 12960 black & white pixels total.
- "Degree" tick-marks, 1 pixel wide:
  - 10-degree tick marks: 10 pixels high.
  - 5-degree tick marks: 5 pixels high.
  - 1-degree tick marks: 3 pixels high.
- Azimuth numbers: a character-matrix of 5x5 pixels (WxH, per patent 767524), 5x6 pixels per ref. 15 &181.
- Beacon identification letter (e.g., "M" and "R" in Figure 110 above): 5x5 pixels.
  - The letters "R", "M", and "W" were used by Telefunken during their 1936/37 development of the UHF Bernhard-beacon prototypes at **R**echlin, **M**ietgendorf, and on the **W**asserkuppe.
  - The letter "W" was later used by Bernhard station Be-0 near Berlin (p. 3 in ref. 244V).
  - The letter "X" was used by Bernhard station Be-9 at Bredstedt (near Leck, §21 in ref. 6C).

At first sight, Figure 153 and 154 above indeed *appear* to show a column height of 12 pixels. However, when looking closely, all alphanumeric characters clearly show "half pixels". The text of the patent and ref. 181 (p. 98) also references ½-pixels. But note that there are no single black or white ½-pixels! The smallest black or white image element ("*kleinstmögliche Bildpunktlänge*") is two ½-pixels, i.e., one "full" pixel. This not only applies *within* each column, but also at the transition from the bottom of one column to the top of the next column. With this clever scheme (part of the Rudolf Hell's patent), any image element can start at any ½-pixel boundary (for improved legibility), but the required signalling bandwidth is related to the duration of a "full" pixel. I.e., half the bandwidth that would be required if the shortest image element duration would also be a ½-pixel.

Note that the 360° compass scale shows a one- or two-digit value for every ten degrees of azimuth. That is, the numbers 1 - 36. This is also the standard for identifying the (magnetic) heading of runways at aerodromes. Note: there is no runway nr. 0, or a runway with a number larger than 36 (other than in stupid movies). The azimuth (bearing *from* the beacon) was referenced to True North (= QTE), see §10 in ref. 14 and ref. 15. These days, aeronautical radio-navigation beacons, like the runways, are referenced to Magnetic North (= QDM; exception: Canada's Northern Domestic Airspace, a polar region).

The complete compass-scale comprises 12960 "full" pixels. The Bernhard beacon makes a 360° revolution in 30 sec. Hence, 1 full pixel has a duration of 30 sec/12960 ≈ 2.3 msec ("kleinstmögliche Bildpunktlänge", p. 9 in ref. 15). The shortest pulse *cycle* (i.e., 1 black pulse + 1 white pulse) is 2 x 2.3 = 4.6 msec. This is equivalent to a maximum pixel-rate of 1000 / 4.6 = 217 Hz. As the pixels are binary (black & white), the telegraphy speed is 217 baud. This is close to the telegraphy speed of the standard Presse Hellschreiber system (225 Bd), and almost twice the speed of the military Feld-Hellschreiber system (122.5 Bd). High-quality printing of Hellschreiber pixel pulses requires that at least the second harmonic of the pixel rate be transmitted. I.e., a transmitter and channel bandwidth of at least a little over 400 Hz. This is why the "Bernhard" compass-scale transmitter has a bandwidth corner-frequency that is limited to that value (p. 9 in ref. 15).

The compass scale pixel-stream was transmitted by the "Bernhard" beacon, and was printed by the Hellschreiber printer of the FuG 120 "Bernhardine" system in the aircraft. In this particular application, the Hellschreiber printer was synchronized to the "degree" tick-marks of the pixel stream. I.e., the the "degree" tick-marks are used as synchronization pulses. The motor of the "Bernhardine" printer spindle runs a little faster than the nominal speed that is required to print the three pixel-columns that make up one degree of the compass scale in exactly 30 sec / 360° ≈ 83.33 msec. The motor runs fast by 1-2% (p. 91 in ref. 181), or 1.5% nominally (p. 18 in ref. 183). Note that "teletype" (telex) teleprinters are also synchronized to the transmitting station. They use an explicit start-bit at the beginning of each 5-bit letter code. The motor of such teleprinters typically also runs 1-2% faster than the nominal transmission speed.

The synchronization mechanism in the "Bernhardine" Hellschreiber printer uses an electro-mechanical "catch and release" mechanism, see the synchronization section of the "Bernhardine" page and Fig. 156. The printer spindle makes exactly one revolution per "degree", and has a small hook-shaped notch. The "catch" hook of the lever must be in the "catch" position, just before the notch arrives at the end of each spindle rotation. I.e., at the bottom of the third (= last) pixel column of each degree. The notch is briefly held (= spindle stops turning) until the first pixel of the "degree" tick-mark of the next "degree" column is received.

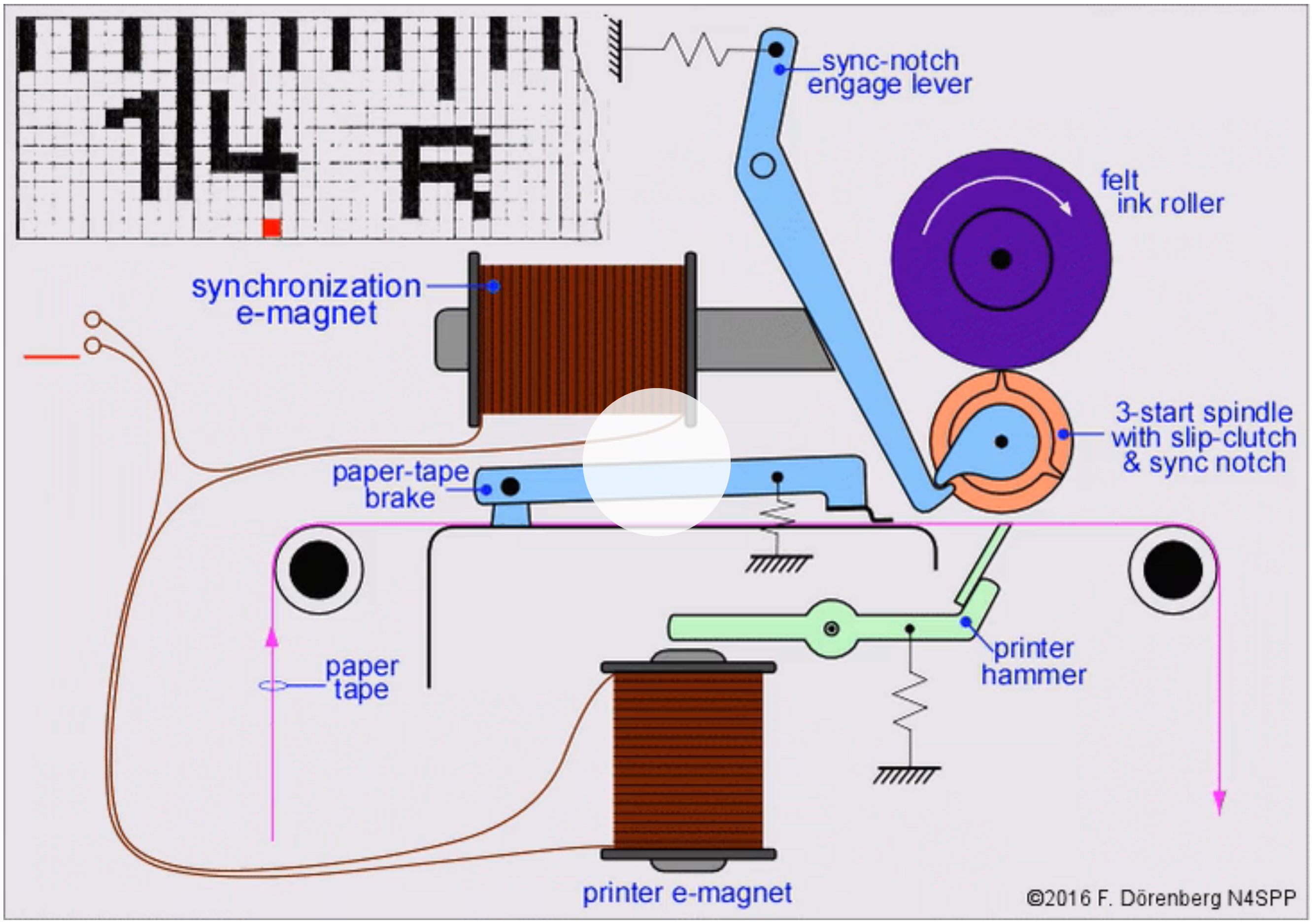


Fig. 156: Animation of a complete cycle of the synchronization process
(click to start or stop; a dynamic gif file without sound is here; source: adapted from Figure 9d in ref. 15)

To make this synchronization scheme work, at least the 1.5 pixels preceding each "degree" tick-mark (i.e., at the bottom of the preceding pixel column) must be white. This minimum pause is equal to 1.5 pixel / (3 x 12 pixels) ≈ 4% of the transmission duration of 1 degree. This is just large enough to accommodate several factors:

- Tolerances in the rotational speed of the "Bernhard" beacon: it was regulated to within ±0.2-0.3 % of exactly 2 rpm.
- Tolerances in the printer motor speed: it was regulated to within ±0.5 % with a centrifugal regulator.
- The reaction speed of the spring-loaded "catch and release" synchronization electro-magnet.
- The 2600 Hz sinusoidal modulation tone has a cycle time of 1000 / 2600 ≈ 0.38 msec. The pulse-detection circuitry that drives the electro-magnet always loses part of one tone-cycle, both at the start and at the end of each pulse.

The entire 12960 pixel sequence of the rasterized compass scale must be transmitted every 30 sec (= one revolution of the beacon). The original 1936 Telefunken patent (767354) mentions the possibility of transmitting the compass data via the principles of facsimile ("fax") or TV-video ("Bildfunk oder Fernsehprinzip"). Other early patents for rotating beacons propose using a fax system with an electro-chemical (moist impregnated paper) drum printer (1929, J. Robinson, patent nr. 562307), or a Nipkow scanning-disk (UK/US: Nipko**v**) to transmit the information as low-resolution video to an unspecified compatible imaging device (again J. Robinson's 1929 patent, and also the 1933 patent nr. 620828 of the Marconi Co.). These solutions require continuous optical scanning of a drum that has a printed compass scale strip on it. The drum rotates at exactly the same speed as the beacon, and is aligned with it. An other approach is to scan the rasterized compass scale strip only once, and record the result on a gramophone record or magnetic wire or tape recorder (Marconi's 1933 patent nr. 620828). The recording is then played continuously at the right speed, iso-synchronized (= speed & phase) to the beacon rotation. One major disadvantage of the latter approach is that gramophone records, wire and tape wear out rather quickly.

Theerfore, as suggested by the 1936 Telefunken patent (767354), the "Bernhard" pixel sequence was stored as a track at the circumference of an **optical encoder disk** ("optischer Zeichengeber", "Impulsgeberscheibe", "Kennzeichenscheibe"). The disk was mounted on the central shaft of the rotating antenna system of the "Bernhard" beacon. The pixel track passed between a light source and a photocell - no wear-causing contact! The output of the photocell was used for on/off keying of the 2600 Hz modulation tone of one of the two "Bernhard" transmitters.

The disk was made of glass (§4.2 in ref. 10, p. 62 in ref. 20, p. 79 in ref. 181). Patent 767524 proposes to implement the pixels as radial lines, engraved into a disk with a blackened surface. However, the same patent also proposes a "negative" master disk, from which a copy can be made for each beacon station. This suggests a photo-chemical process, rather than mechanical engraving. Engraving (as proposed in ref. 20, and p. 124 of ref. 2C4) would have been an extremely (and unnecessarily) laborious process, given the number of pixels and the required very high accuracy of the pixel pattern on the disk: "1/2-pixels" have an angular width of only 360° / 25920 < 0.014° = 50 arcsec (p. 91 in ref. 181)! An optical disk has important advantages (p. 98 in ref. 181):

- Reproduction of a "master" disk via a photochemical contact-print method is relatively easy and inexpensive. It is also easy to verify the quality and accuracy of the copies.
- Allows direct-drive connection to the antenna system of the rotating beacon (no gearing with inherent inaccuracies).
- The non-contact "light source plus photo cell" arrangement causes no wear of the disk, which would otherwise cause inaccuracies.
- Embodies the primary source of inaccuracy into a single, stable device. **This disk is the heart of the beacon system!**

Telefunken patents 767524 and 767354 also consider other implementations of the disk: a pixel track implemented as interconnected metal patches that are scanned with a slip contact (similar to the character drum of the Feld-Hellschreiber), or an optical pixel track with holes through the disk.

The Bernhard navigation system comprised a chain of ground stations. So the station had to be identified by its transmission. This was done by adding a station-identifier letters (callsign) between the 10-degree numbers of the transmitted compass scale, see the letters "M" and "R" in Fig. 153. The associated pixels could be implemented in several ways (patents 767524 and 767528):

- On the same disk as the compass card data, integrated with the compass data track.
- On the same disk as the compass card data, but as a separate track.
- As a dedicated track on a separate disk, mechanically aligned and synchronized with

the compass card disk. This has the advantage that the same compass card disk could be replicated for all ground stations, and the station identifier be put on a "personalized" disk. In case of a separate track (on the same disk or on a separate disk), the output of the associated photocell is simply combined (logical "OR") with the output of the photocell of the azimuth track.

Patent 767937 proposes an optical disk with multiple (e.g., 8) concentric tracks. This would enable the quick change of the station's identifier letter, and/or expansion to a 2-letter callsign, to be able to distinguish more than 26 beacons.

The actual implementation of the "Bernhard" disk is slightly different from the patents:

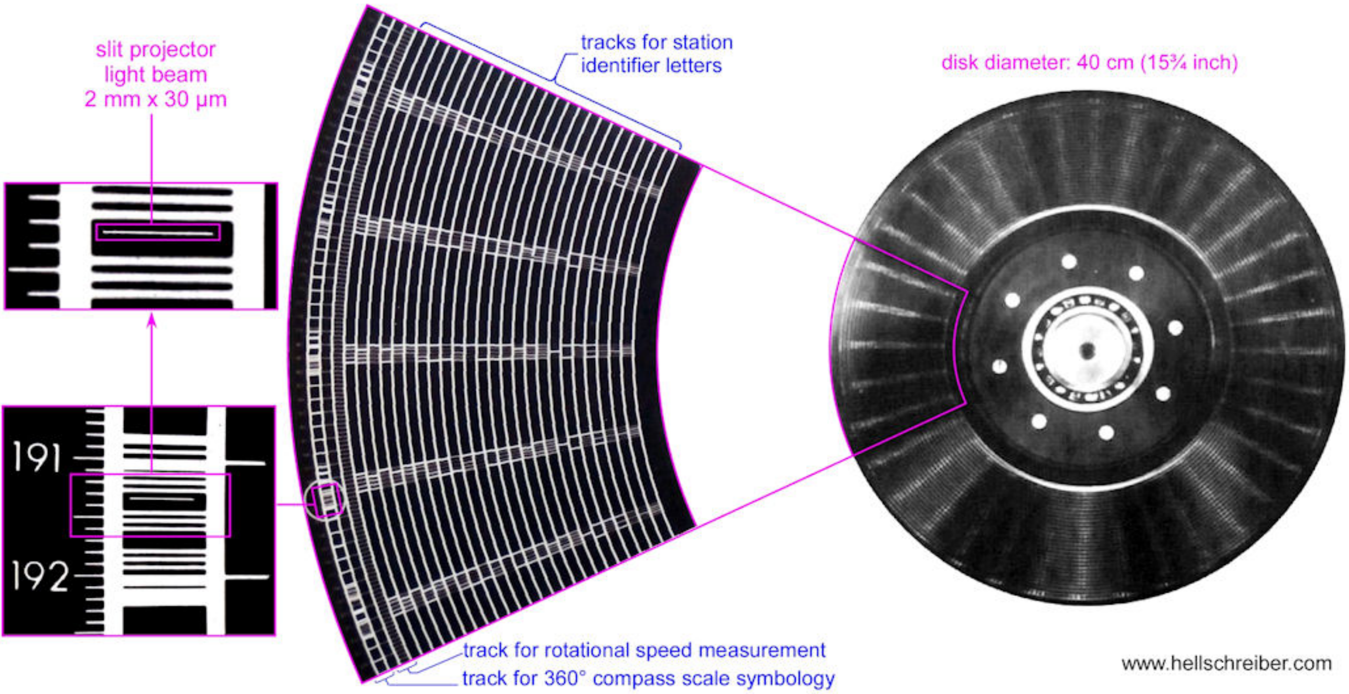


Fig. 157: The optical encoder disk of the "Bernhard" beacon
(source: adapted from Figures 45-47 in ref. 181)

This optical encoder disk has three types of track - all tracks of the disk are concentric:

Compass scale symbology,

Tachometer,

Station identifier letters. Each letter is repeated 36 times (i.e., every 10 degrees of the compass scale), evenly spaced around its track.

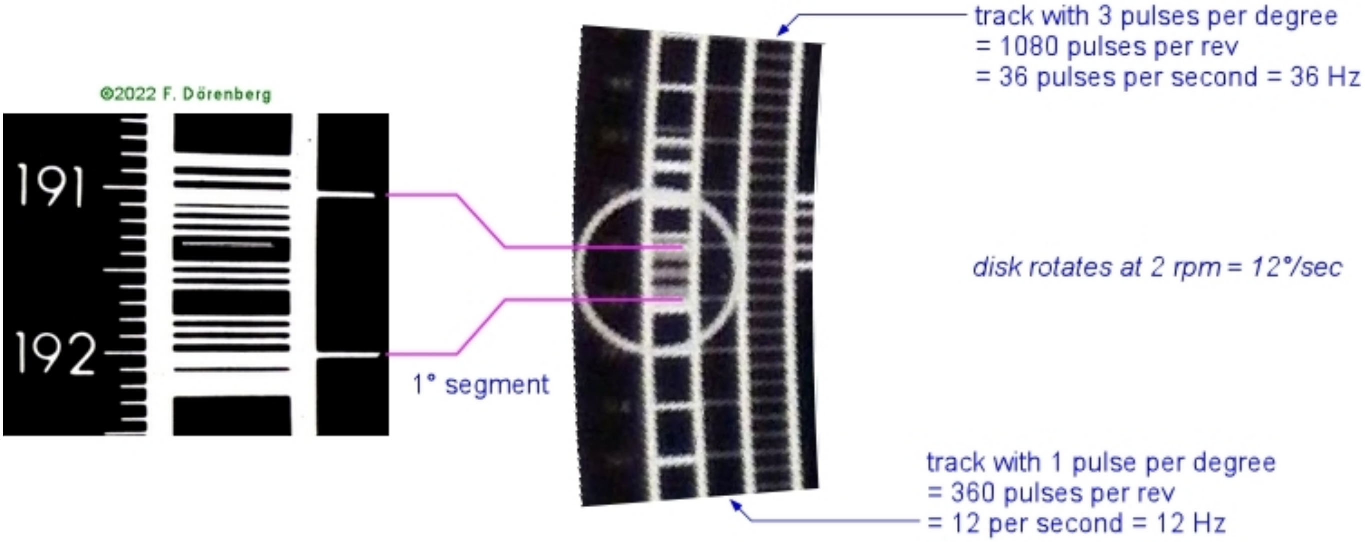


Fig. 158: Tachometer track(s) of the optical encoder disk
(source: adapted from Figures 46 & 47 in ref. 181)

The tachometer encoder track was used for monitoring the rotational speed of the beacon inside the round equipment building below the rotating cabin. Fig. 158 clearly shows two tracks that generated tachometer pulses. At the nominal 2 rpm system rotational speed, one track would have generated a 12 Hz pulse train, the other 36 Hz. The tachometer track enabled measuring the actual speed with an accuracy of ±0.1 % (p. 80 ref. 181), half the allowed system speed-error. The tachometer signal was monitored via a loudspeaker and a frequency indicator (needle instrument), and could also be viewed on an oscilloscope. Note that Fig. 158 is from an October 1942 publication. Ref. 10 (1946) states that the tachometer track (track nr. 20) had 1500 evenly spaced lines, equivalent to 50 Hz - the nominal frequency of the three-phase 380 Vac power.

Patent 767528 includes the cross-section diagram of what a 2-disk attachment might look like. One disk with the compass scale, and a second disk for the beacon's station-identifier letter ("*Funkfeuer kennzeichnender Buchstabe*"). There is a light source mounted on one side of the track of interest, and a photo cell on the opposite side of the disk:

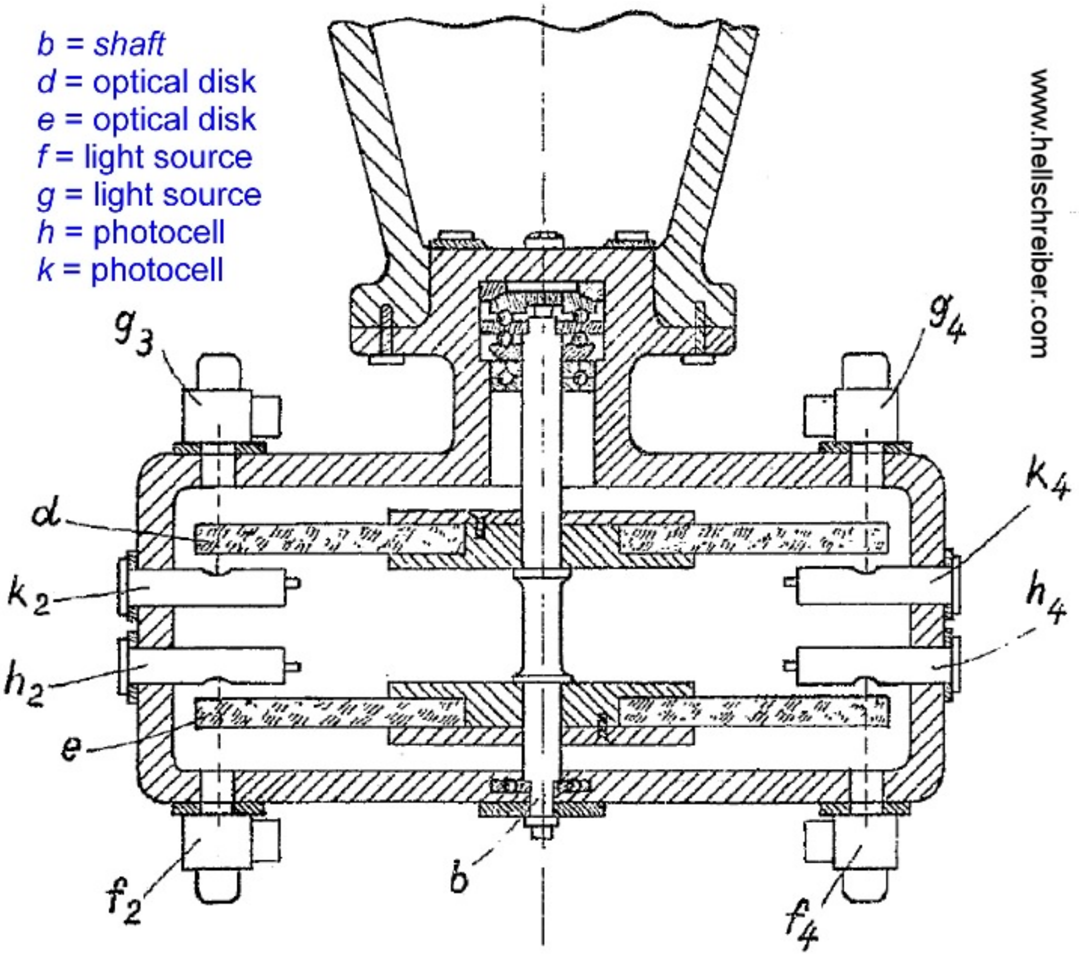


Fig. 159: Two stacked optical disks with, mounted on the shaft of the rotating antenna system

(source: Figure 4 of patent 767528)

Patent 767354 proposes that the light source be a gas discharge lamp, powered with an AC signal. This makes the output signal of the photocells also AC, which is easy to amplify. Patent 767529 discusses shaping the output signal of the photocell by amplification and clipping, to obtain rectangular keying pulses for the transmitter.

Again, the actual implementation is slightly different from the patents:

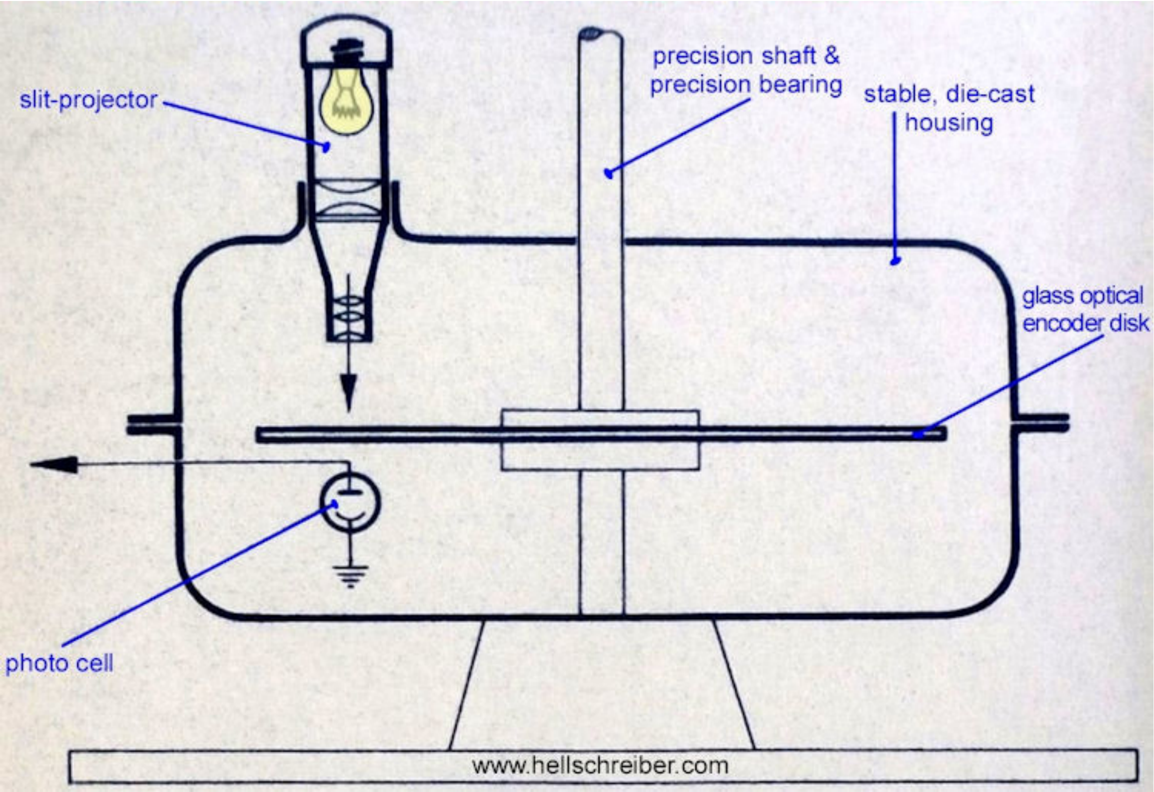


Fig. 160: Diagrammatic cross-section of the encoder disk assembly
(source: adapted from Figure 44 in ref. 181)

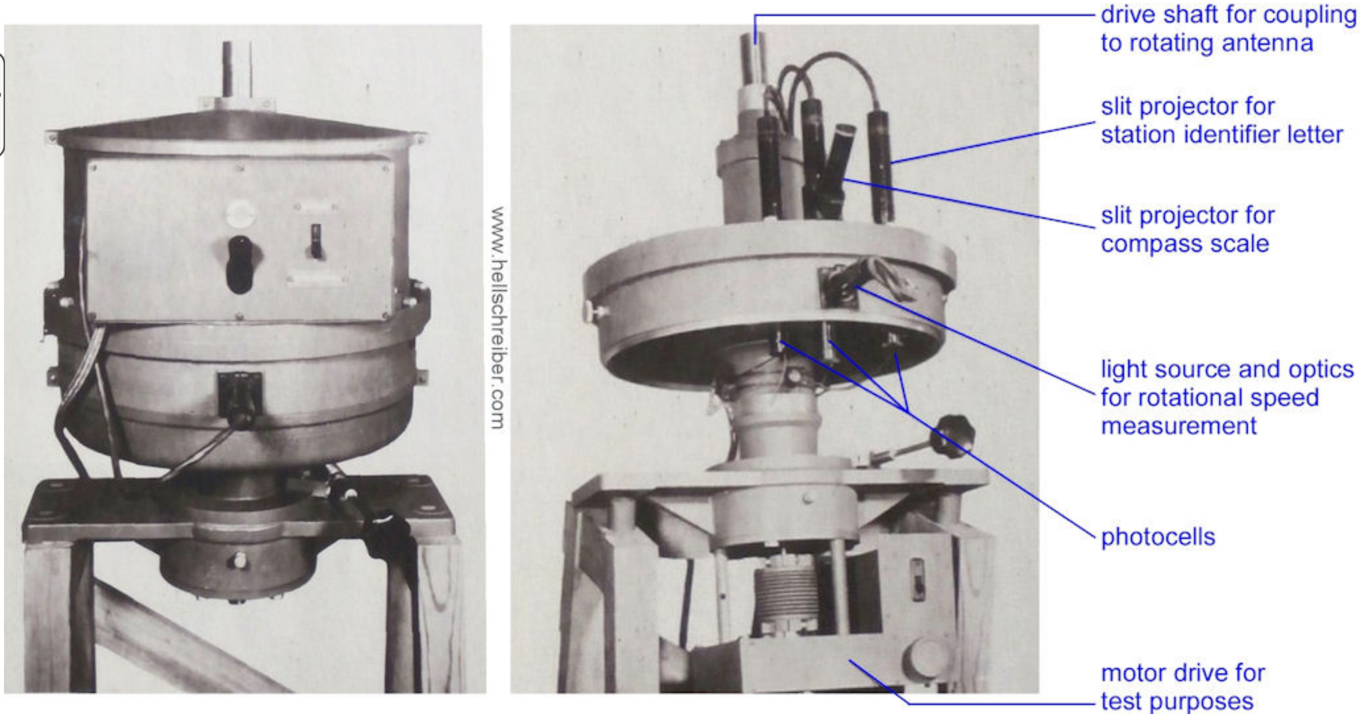


Fig. 161: The optical disk assembly of the "Bernhard" beacon (mounted on a test stand)
(source: adapted from Figures 49-50 in ref. 181)

The glass disk was very flat (no distorting and light-scattering wobbles), and very accurately coaxially aligned with the shaft. The shaft of the disk was connected to the centering spigot ("Zentrierzapfen") of the beacon's rotating superstructure, with a coupler that was torsionally stiff but axially flexible (p. 80 in ref. 181).

The light source is a so-called slit projector ("Spaltprojektor"). It comprises a high-intensity lamp, a slit diaphragm, and a lens system. This arrangement is primarily used in ophthalmic and other medical slit lamps, and dates back to the 1850s (Hermann von Helmholtz). The "Bernhard" slit projector focuses a very narrow, homogeneous, well-defined line of light onto the track of the optical disk. The line had a width of only 30 µm (1.2 thou, 1.2 mil). This is less than half the width of an average human hair (75 µm). The disk had a diameter of 40 cm (15¾ inch), ref. 181. I.e., slightly larger than an old 78 rpm phonograph record. Hence, the circumference of the compass-scale track was about π x 40 ≈ 126 cm (= 4^+ ft) for 12960 "full" pixels. I.e., a single pixel-line had a width of about 1260 / 12960 ≈ 0.097 mm = 97 µm, slightly wider than an average human hair.

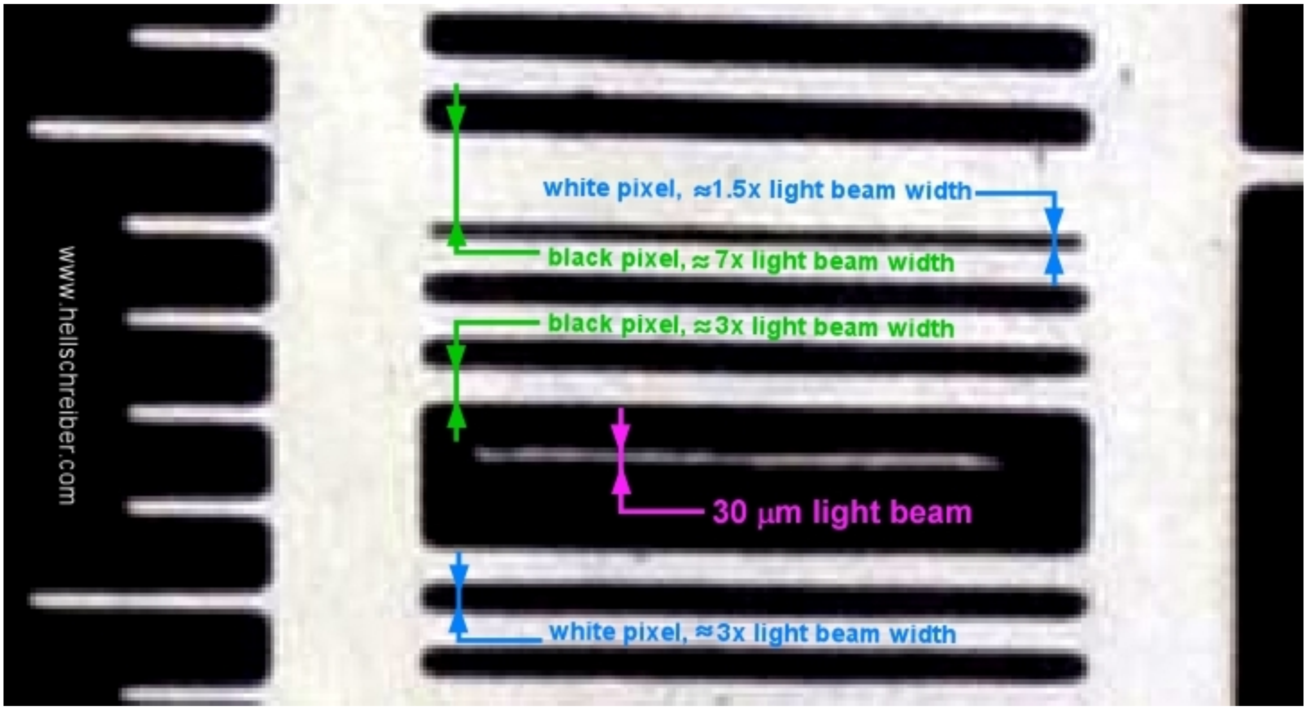


Fig. 162: Close-up of the compass scale track of the optical encoder disk
(source: adapted from Figure 47 in ref. 181)

Figure 114 above clearly shows that there were only 24 letter-tracks! However, ref. 181 (p. 100) mentions tracks for "all letters of the alphabet", and ref. 10 (1946) claims 18 letter-tracks. The duration of an individual pixel has to be independent of the distance from the letter-track to the center of the disk. All points on the disk have the same *rotational* speed. But tracks closer to the center of the disk, have a smaller track length. Hence, they have a lower *linear* speed, and the pixel-width must be proportionally smaller (so as to have the same pixel-duration in all letters). The slit-projector was placed directly above the track, so the narrow light beam had the same width at all positions. Possibly, the slit-projector and photocell for the letter-tracks could not be placed close enough to the shaft of the disk for a 25th and 26th letter. Or, the pixel lines might have been too narrow for a 25th and 26th letter. Note: in total, only 22 "Bernhard" stations were planned by the end of the war (item 12 on p. 3 in ref. 177B).

COMMAND UPLINK FEATURE

The "Bernhard/Bernhardine" system is simply a "*UKW-Richtstrahl-Drehfunkfeuer und Empfangszusatz **mit geschriebener Kommandoübertragung***". That is, a rotating VHF directional beacon system, with **printed command-uplink** capability. The latter capability was demonstrated mid-1944 (§4 in ref. 179). This led the *General der Jagdflieger* (GdJ, Adolf Galland at that time) to recognize the usefulness of the entire system, and demand its introduction on all night-fighter aircraft late July 1944. Note: *GdJ* (formerly *Inspekteur der Jagdflieger*) was not a rank, but a leading position without operational command within the *Oberkommando der Luftwaffe* (OKL, High Command of the Air Force).

Obviously, the primary purpose of a beacon is to be a navigational aid. With a single beacon, only the relative bearing (= direction) to/from that particular station can be determined (unless the beacon somehow allows the slant range (= distance) between beacon and aircraft to be determined). I.e., only a position *line* ("Standlinie") from the beacon (with known location) can be determined, and neither distance from the station, nor a position *point*. Position determination is done by combining the bearing from at least two beacons with known location. I.e., by means of conventional triangulation ("Kreuzpeilung").

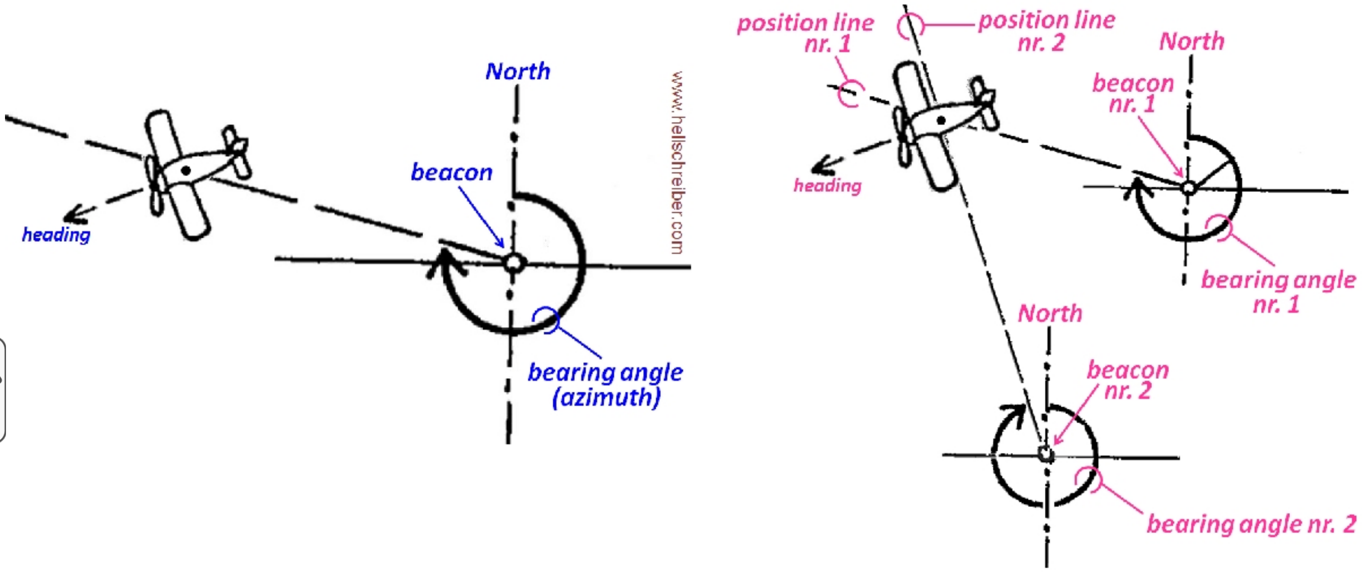


Fig. 163: Determining bearing angle with a single beacon, and position via triangulation with two beacons

(the bearing angle is measured clockwise from North)

The "Bernhard" beacons were used by fighter aircraft that were engaged in intercepting inbound enemy aircraft, primarily bombers. It was the task of regional fighter control stations ("Jägerleitstellungen", "Jägerleitstände") to guide fighter aircraft to their target. The required guidance, instructions, and information was continuously provided via HF and VHF voice radio (radio telephony, R/T). A standardized short message format was used for the broadcast stream of the so-called "Running Commentary" ("Laufende Reportage"). This was used in German fighter control systems such as "Zahme Sau" ("Tame Boar") and "Wilde Sau" ("Wild Boar"). See ref. 6B, §22-25 in ref. 6C, ref. 282A-282D. In particular, later during WW2, with increasingly frequent Allied bombing raids on Germany, the fighter control voice frequencies became saturated. On top of that, the voice frequencies were also subject to Allied jamming, as were wired-broadcast of radio signals and attacks on the wired telephone network (p. 7, 8 in ref. 282B). As a backup, the same short messages could be broadcast in spoken form via certain radio navigation beacons, and also via some Morse beacons (§59 in ref. 6B).

The 1938 Telefunken patent 767512 already addressed using the "Bernhard" beacons to broadcast the relative direction for intercepting enemy aircraft. It proposes to transmit an extra heavy tick-mark in the compass scale, see Figure 165. This could be used to indicate a target azimuth (the radial from the ground station) that is to be intercepted. The patent suggests implementation with a fixed notch (cam) on the edge of the encoder disk, and a contact that is adjustable to the desired target azimuth (Fig. 164). The notch would actuate a switch that was simply connected in parallel with the output of the photocell of the optical disk. However, this target-azimuth marker method would not have been very practical: it could only be received by aircraft that are already flying on nearly the same bearing from the beacon station as that target. Also, the command/guidance would be limited to conveying a target azimuth.

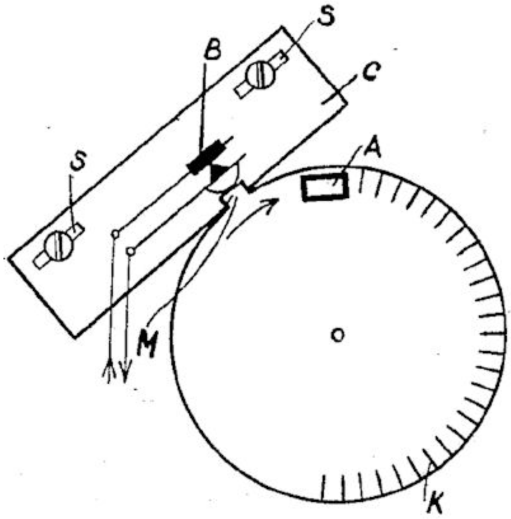


Fig. 164: Notched optical disk
(source: Figure 2 in patent [767512](767512))

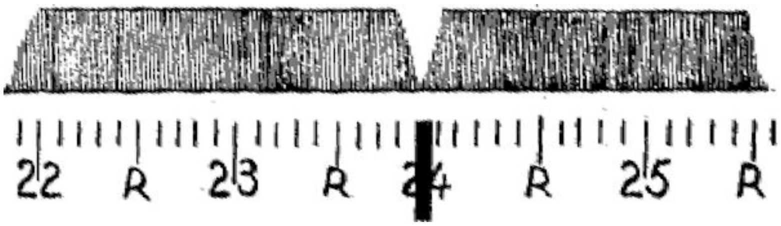


Fig. 165: Target azimuth bar superimposed on azimuth data
(source: Figure 3 in patent [767512](767512))

However, the "Bernhard" beacon already broadcasts information in textual form: the fixed numbers of the compass scale and the station identification letter. Why not use the same Hellschreiber system for transmitting short, programmable text messages? Excellent idea! But the beacon rotates, and the beam is only received during about 3^+ to 5 sec out of every 30 sec rotation (depending on distance from the beacon). At 12°/sec rotation, about a 40-60 degree section of the compass scale is printed each time. Clearly, it must be guaranteed that the complete message is printed during a single beam passage, independent of the bearing from the station on which the aircraft is flying within the operating range of the system. This limits the number of text characters that can be put into a single message.

Let's assume that transmission of the message is continuously repeated as the beacon rotates. To always guarantee that a complete message is received, not one, but two back-to-back copies of the message must fit within a single beam passage! If not, the end of one message is printed, immediately followed by the beginning of the next copy of the same message. This by itself is bad enough, but it is also not possible to determine if all characters of the message have been received. This factor of two further limits the number of text characters that can be put into a single message...

Figures 125 and 126 above show that a traditional Hellschreiber font with five pixel-columns per character is used for the compass scale. Also as standard for Hellschreiber fonts, each character has a leading and a trailing pixel-column that is blank. This is for character spacing. The compass scale has three pixel-columns per degree. Each character spans 5 + 2 = 7 pixel-columns. Hence, at least about 20 characters can be received per beam passage (also per item 9 on p. 10 (= Blatt 11) of ref. 198A). Therefore, the length of one complete message is limited to about 20 / 2 = 10 characters. To mark the beginning of each message, a delimiter symbol must be used. The start-delimiter of the next message-copy automatically marks the end of the preceding one, which allows confirmation that a complete message has been received. This leaves up to 9 characters of actual fighter guidance information. There were two types of command message (§57-64 in ref. 6B, §23-26 in ref. 6C, §17-28 in ref. 6M, p. 2 & 3 in ref. 244V):

> "Feindreportage", or "Reportage" for short, which is a so-called *running commentary* on enemy aircraft (typ. bombers).
>
> Specific instructions to either all units, or to only a specific unit, of the fighter division ("Jagddivision") to which the radio frequency was allocated. This could be orders at various levels: "Geschwaderbefehlswellen" (squadron level), "Gruppenbefehlswellen" (group level), "Divisionsführungswellen" (division level). Examples of such letters/ numbers instructions were "C" to order "return to base", "B###" for "fly to airfield nr. ###", "AGZ###" for "Target ("**A**n**g**riffs**z**iel") of the enemy bombers is airfield nr. ###", and "MOS" for "Mosquito attack in progress".
>
>> Specific instruction messages (i.e., for pursuit and intercept, or other specific navigation guidance, not "reportage" situation messages) that were sent to Luftwaffe fighter units via a Bernhard-station; "00" at the beginning of such a Bermhard message signified that it was addressed to all units of the fighter-division that was using the beacon. Messages preceded by a single "FuG 25a Kennung" letter were addressed to a specific unit of that division (§III on p. 2 of ref. 244V). The *FuG 25a* was a Luftwaffe airborne IFF-transponder system, interrogated by *Freya* or *Würzburg* ground radar. A late version of the *FuG 25a* had some limited character uplink capability. Also see §17-28 in ref. 6M.

Both types of messages had the same format as those that were transmitted via radio telegraphy transmitters (VHF, shortwave, and longwave, with fighter-division specific frequency allocations), and via radio telephony transmitters. Ref. 282A, 282B, 282C. They were also broadcast via various navigation beacons (again, fighter-division specific). The latter included a small number of specially equipped Bernhard stations.

The following format of simple coded groups of letters and numbers was used for "Reportage" broadcast via Bernhard stations (p. 275 in ref. 5B):

> The "**+**" symbol as a message start/end delimiter.
>
> The two-digit altitude (in 100s of meters) of the lead-aircraft of the enemy bomber formation.
>
> A two-character identifier of the specific box of the "*Jägergitter*" (a.k.a. "Jägernetz") air defense grid, in which the enemy lead-aircraft is currently located (e.g., "QR" for the box near the city of Mainz).
>
> The two-digit course of the bomber formation (in 10s of degrees).
>
> Two- or three-digit estimated number of bombers in the formation. Note: the size of such a formation varied from about a dozen bombers, to a stream of well over 1000 bombers that was stretched out over hundreds of km!

Depending on the message content, upto 10 message characters were sent (including the delimiter). The following hand-drawn figure from 1945 illustrates the message " +40KA27100 ".

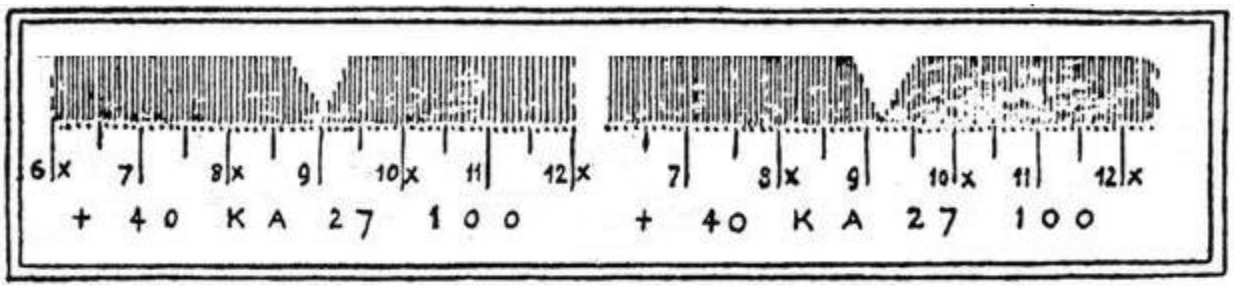


Fig. 166: Misleading British rendition of a "Bernhardine" print-out with Reportage/ Command track at the bottom
(source: ref. 6C (1945), a very similar image is used in ref. 5A)

Unfortunately, it not only (incorrectly) suggests that the station identifier in the compass scale track was sent every 20° instead of every 10°, but also (incorrectly) suggests that the messages were sent *in addition* to the compass scale (ref. 5A even actually states so!). Note that these command messages were transmitted *instead of* the compass scale, as there was simply no third printer-track. The air defence box "KA" is located south-southeast of Hannover, see Fig. 167.

Ref. 77A uses " +27K60QR18400- " as example of a typical message. However, it i stoo long: it has a length of 14 characters, compared to the 10-character example above. This is caused by the inclusion of a 1-letter Bernhard-station identifier (here "K"), a 2-digit bearing value (here: 27 = 270 deg = west of the Bernhard station), and "-" as message end delimeter. All three inclusions are wrong! The purpose of the message is to convey instructions, not to to aid navigation. The "-" is also superfluous, as it would be immediately followed by the "+" of the next transmisison of the message. Ref. 77A also states that "K" is the "transmitter code" for "Eggebeck". This is not a Bernhard station, but Luftwaffe airfield "Eggebek" (misspelled "Eggebe**c**k"), located ca. 16 km (10 miles) due east of Bernhard Be-9 at Bredstedt. Note: the air defence box "QR" is located near Frankfurt and Mainz:

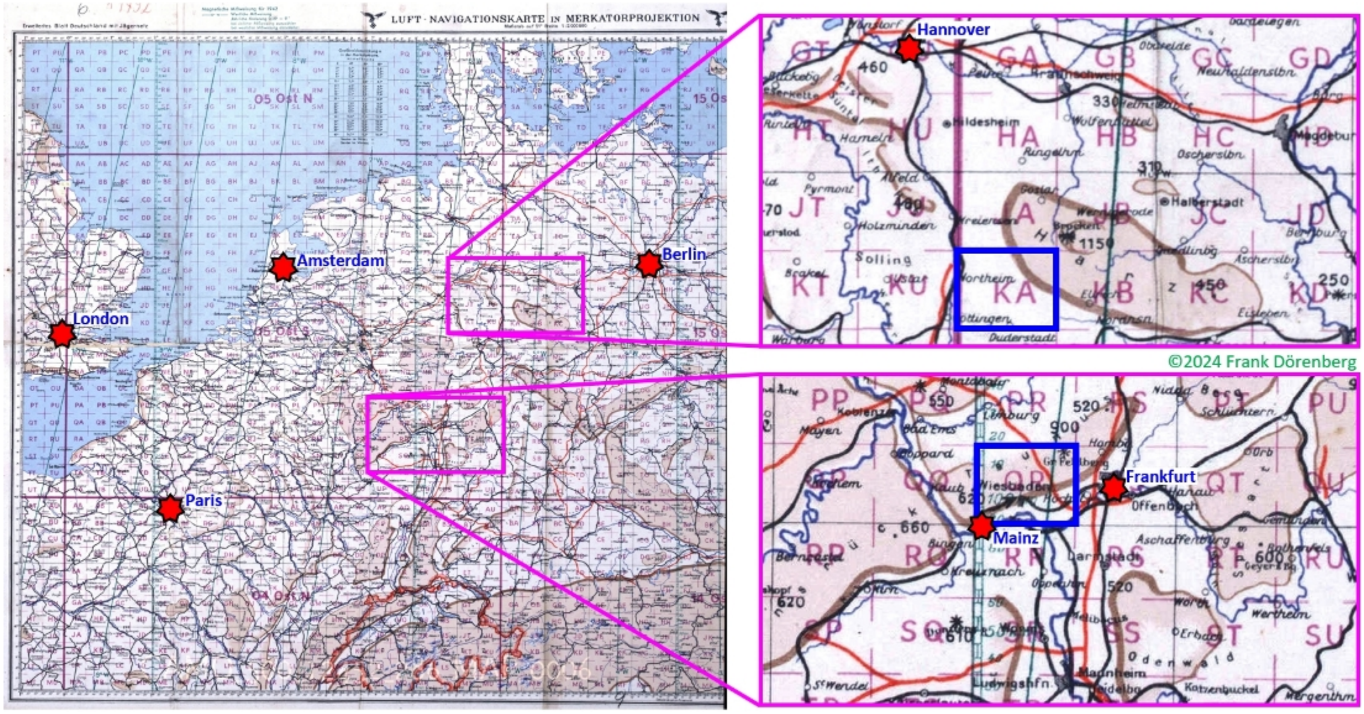


Fig. 167: grid-box "KA" and "QR" on a 1944 Jägergitter/Jägernetz" air defense grid chart
(source: adapted from ref. 244G)

In some literature, allied bomber formations are generically referred to as "bomber streams" (in Luftwaffe terminology: "Bomberströme"). However, that term only refers to a specific form of sequencing (night) bombers, used by the RAF from the end of May 1942 until the end of the war. The purpose of this tactic was to create a string of bombers (with designated altitude bands and time slots), that would pass through the narrow German (night) air defense system via a minimum number of "boxes". This defense system, established in 1940 by then-colonel Josef Kammhuber, comprised a chain of rectangular "Himmelbett" airspace control zone "boxes". The chain eventually reached from Denmark to the north of France, and was referred to by (only) the British as the "Kammhuber Line". Ref. 5, 230G. The zones had search and tracking radars (first *Freya* and *Würzburg* radar systems, later also *Würzburg Riese*) and groups of search lights (some radar controlled). Funneling all bombers through one or a few boxes, quickly overloaded the German defense capability of the boxes. Note that each box was covered by a single night fighter (with one backup fighter), that could make an estimated 6 intercepts per hour - at best.

In the compass scale format, there is one tick-mark for every degree. These tick-marks are also used to synchronize the compass scale Hell-printer to the Hell-format transmission (as explained in the "Optical Encoder Disk" section). As the same printer channel is used for the command messages, it must now also be synchronized to the command message transmission. This requires tick-marks. Here, a tick-mark is implemented at the top of every single pixel-column, instead of every third column (p. 4 (= Blatt 3) of ref. 198A). Retaining the tick-mark at the top of every third pixel-column could only have worked with a Hell-character font that is 6 pixel-columns wide (incl. blank columns for character spacing). With a tick-mark at the start of each pixel-column, there is no such limitation. Also, having more sync tick-marks than once per degree does not upset the sync mechanism: the synchronization electro-magnet of the compass scale printer-channel is activated by all black pixels, whether tick-mark or other part of the transmitted symbology.

The upper track of the "Bernhardine" printer is used to plot the signal-strength curve. The curve has a sharp V-shaped dip in the middle, which is used as a pointer for the compass scale that is normally printed below it. Clearly, the pointer-curve is not used in combination with the command messages. However, the signal-strength printer channel is not turned off, as it is linked to the automatic motor start/stop function.

The next figure illustrates what a real print-out with a command message would have looked like:

Fig. 168: re-created Bernhardine print-out with command-uplink message

As stated above, the command uplink messages were sent instead of the compass scale data from the optical encoder disk. So, somewhere, these messages were converted from a text-string input to a Hellschreiber pixel stream. This *could* have been done with a keyboard and tape-puncher, combined with a "punch tape to Hellschreiber pulse-sequence converter". This was the normal way with the "Presse Hellschreiber" system. The tape could be looped through the tape reader to repeat the message. Of course, speed and text font would have had to be adapted. However, p. 87 in ref. 2A and p. 392 in ref. 7B suggest that a different method was used to program the text character sequence: inserting jumpers ("Stöpsel") into a patch-board ("Stecktafel"). Mid-2015, I finally obtained confirmation of this, by the photo shown below (ref. 93). It was taken inside the cabin below the rotating superstructure of the Bernhard installation Be-10 at Hundborg/Denmark. The photo shows two transmitter-modulators, two monitor Hellschreiber printers (for printing signals from a nearby remote monitoring receiver and antenna), and a patch-board with patch cords. There are 9 jacks for each of up to 9 selectable characters. With some difficulty, one can see that the left-hand column is labeled A-Z, and the right-hand column 1-9, 0, +, ... So, the conversion from text strings to Hellschreiber pixel streams was done at the Bernhard station, based on telephone or teleprinter messages from the regional fighter command & control center.

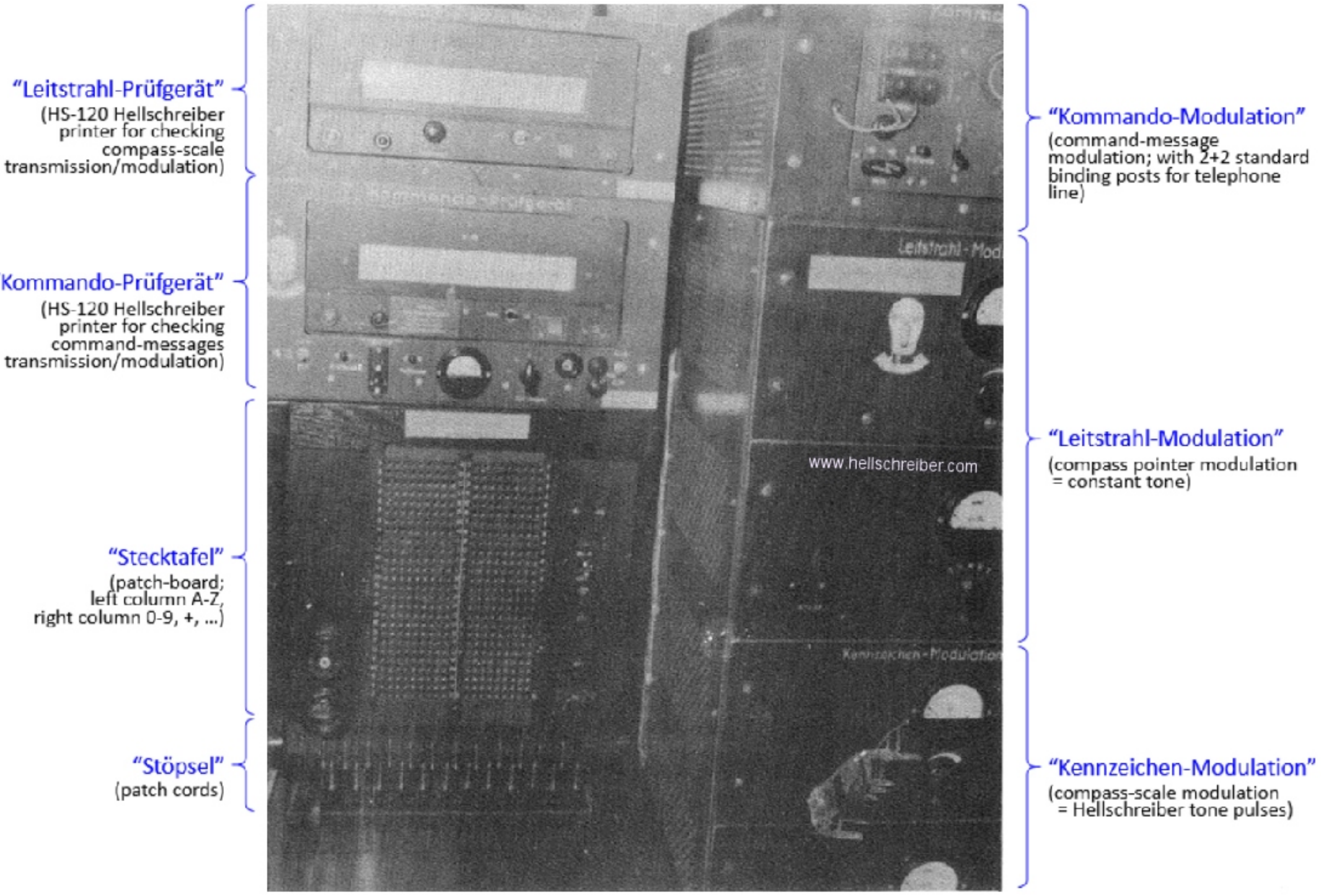


Fig. 169: Lower left-hand corner - patch-board & patch-cords for selecting command-message text string

(source: Figure 30 in ref. 93; photo taken at Be-10 Hundborg/Denmark)

The actual patch-board and patch-cords appear to be very similar to what was used during the 1930s in standard small German telephone switchboards:

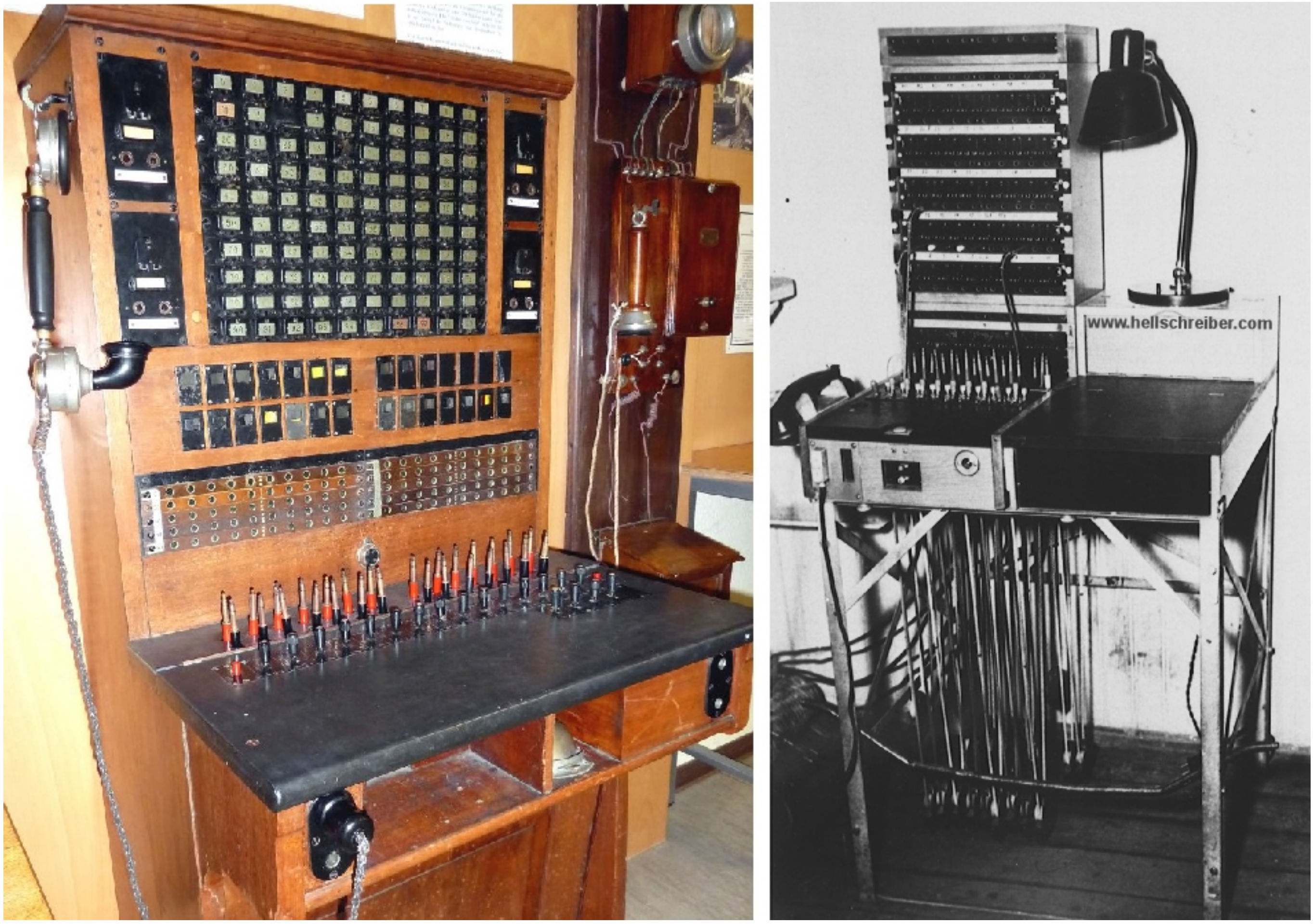


Fig. 170: Left "Klappenschrank" telephone swithboard model OB-14; right: 50-line Wehrmacht PBX

(source OB-14: Fernmeldemuseum Dresden; "OB" in "OB-14" stands for "Ortsbatterie", meaning local battery operation)

This patch-board method is similar to what was used in the mechanical Siemens-Hellschreiber-sender model 44 in the 1960s. This sender has a character-drum with 19 notched disks and associated slip-contacts: seven disks to generate the pixel sequence for the characters A - G, ten for the figures 0 - 9, and one notched disk for the character "**-**". This machine sent a string of eight characters, based on a discrete code at its inputs (representing status and self-test results from a telephone exchange system).

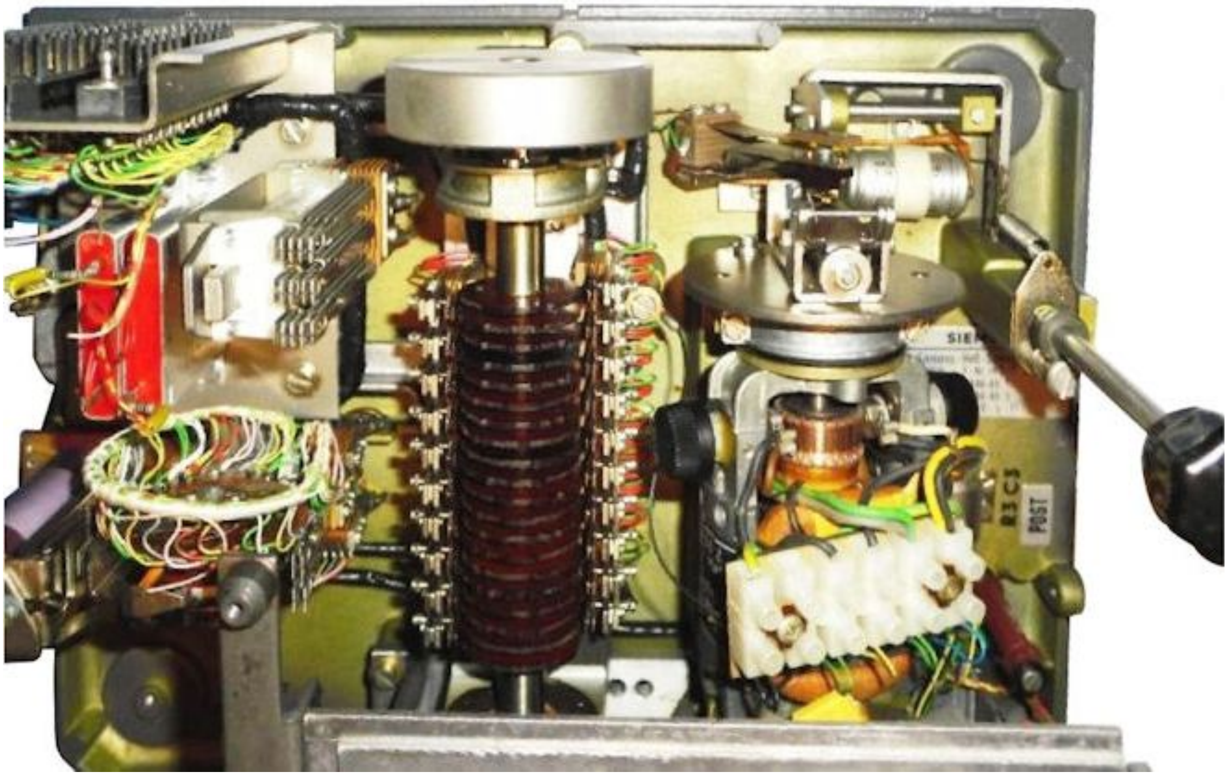
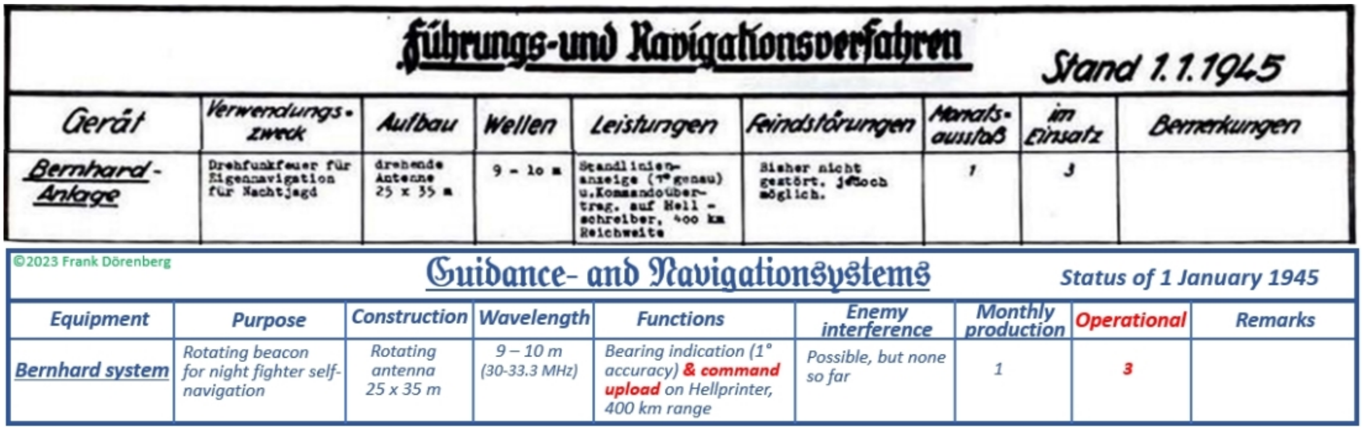


Fig. 171: The inside of a Siemens-Hell model 44E with a stack of notched character-generator disks at the center

A similar method with a stack of notched disks may have been used for generating Bernhard message strings in Hellschreiber format. When the messages had to be sent, the output of the photocell of the optical azimuth disk was simply disconnected, and the pixel stream of the text message generator was used instead.

Note that the command-uplink capability was not a standard feature of the "Bernhard" stations. Implementation of this data link system required a modification to the beacon, and was only implemented at three stations by the end of the war in Europe, including [Be-9 at Bredstedt]() in the far north of Germany, and [Be-10 at Hundborg]() in Denmark. It is unclear which



Führungs-und Navigationsverfahren Stand 1.1.1945

Gerät	Verwendungs-zweck	Aufbau	Wellen	Leistungen	Feindstörungen	Monats-ausstoß	im Einsatz	Bemerkungen
Bernhard-Anlage	Drehfunkfeuer für Eigennavigation für Nachtjagd	drehende Antenne 25 x 35 m	9 - 10 m	Standlinien-anzeige (1° genau) u.Kommandoüber-trag. auf Hell-schreiber, 400 km Reichweite	Bisher nicht gestört, jedoch möglich.	1	3	

©2023 Frank Dörenberg

Guidance- and Navigationsystems Status of 1 January 1945

Equipment	Purpose	Construction	Wavelength	Functions	Enemy interference	Monthly production	Operational	Remarks
Bernhard system	Rotating beacon for night fighter self-navigation	Rotating antenna 25 x 35 m	9 – 10 m (30-33.3 MHz)	Bearing indication (1° accuracy) **& command upload** on Hellprinter, 400 km range	Possible, but none so far	1	3	

Table-3: Early 1945, three of the Berhard stations had reportage/uplink capability
(source: adapted from p. 1 of ref. 292)

Apparently, late 1943 / early 1944, the Lorenz company also experimented with an expanded Hellschreiber-based command data-link system, referred to as "Sägezahn" ("sawtooth", ref. 2C1).

The Bernhard/Bernhardine system was the first and only operational ground-to-air data-link system of the second World War that had freely formattable messages! Since about the year 2000, the same concept has been introduced to "modern" civil aviation: *Controller-Pilot Data Link Communications* (CPDLC). In 2015, its usage became mandatory in European airspace above 28500 ft. CPDLC is for up-linking of routine (= non-time-critical) air traffic control instructions and clearances to aircraft via digital radio. Purpose: reduce the significant time that air traffic controllers spend on routine communications over VHF voice links, and help reduce miscommunications as well as "stuck microphone" issues (which block the radio channel). However, contrary to the Bernhard system, the pilot can now respond to messages, request clearances and information, and declare an emergency - all via the same system (in addition to voice radio).

ELECTRICAL-POWER AND SIGNAL DISTRIBUTION SYSTEM

This section describes the interconnections within and between the main elements of the "Bernhard" ground station:

- the rotating superstructure, comprising the
    - the antenna system, and
    - the equipment cabin
- the stationary support & equipment building below the rotating superstructure
- the electrical power distribution & conversion building
- the remote monitoring antenna mast and radio receiver.

The interconnections between the dipoles of the antenna system, and the connection between the transmitters and the antenna system are discussed in detail in the antenna system section.

The large cabin that rotates with the antenna system contains the two transmitters and the associated power supplies (motor-alternators). These power supplies are powered by regular 50 Hz 3-phase AC voltage ("Drehstrom"). The cabin also contains an electrical power distribution panel and the control panels for the four locomotives. All four locomotives are powered by DC-voltage. One of the locomotives also has a 3-phase synchronous AC motor, powered by a fixed-frequency 3-phase AC voltage ("geregelter Drehstrom"). Lighting and heating appliances in the cabin are powered by single-phase AC voltage ("Wechselstrom").

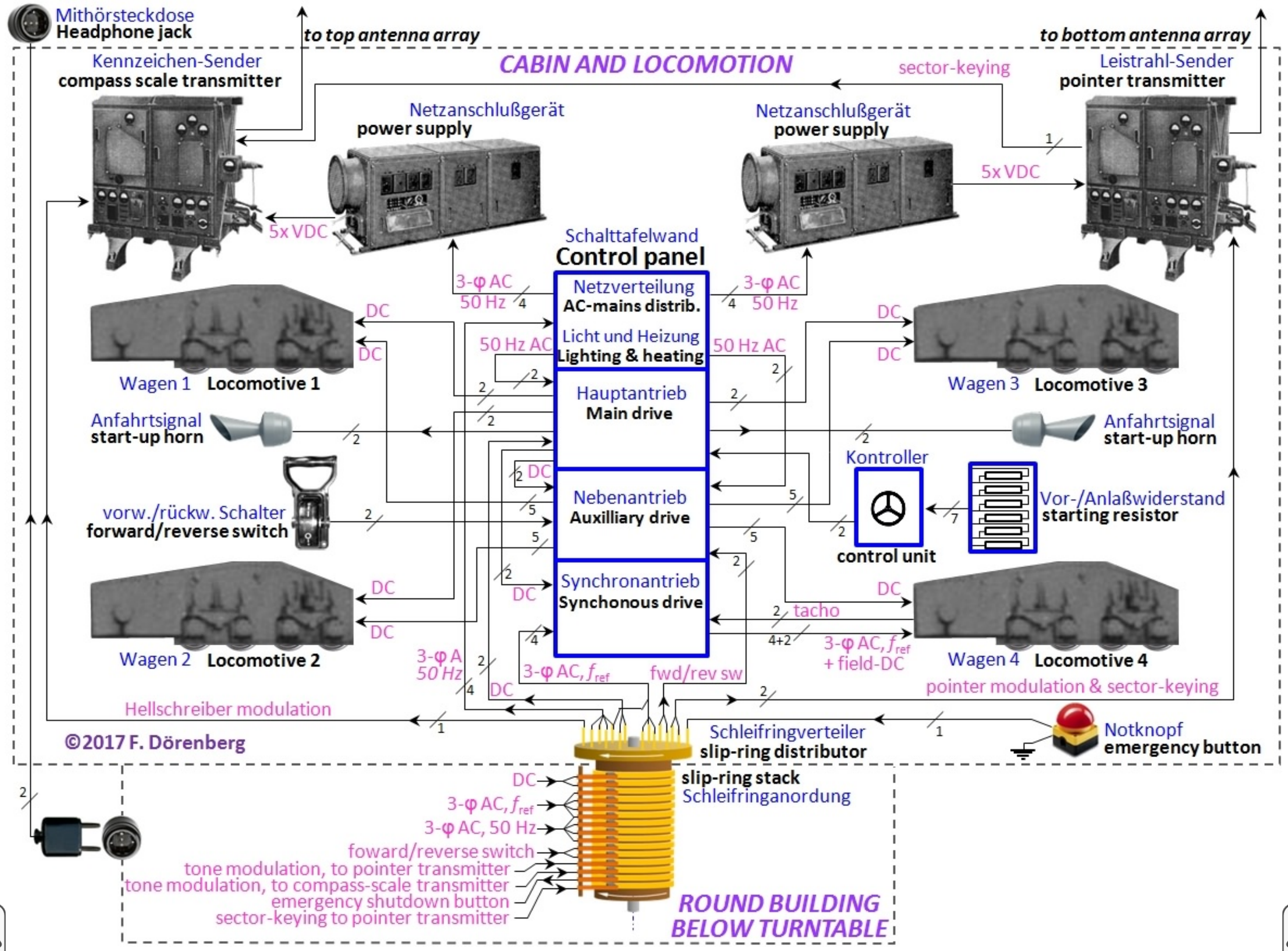


Fig. 172: Electrical power and signal interconnections of the rotating part of the system
(source: derived from ref. 189 and 190)

The AC and DC voltages and tone-modulation signals for the transmitters are transferred to the rotating cabin via a slip-ring assembly that is attached to the ceiling of the small round brick building below the rotating turntable. Slip-rings allow electrical lines to traverse continuously rotating mechanical joints. In the rotating cabin, the cables between the slipring dsitributor and the control panel were about 2 m long (ref. 189, cable item 42), so the control panel was located close to the center of the cabin.

The shaft of the slip-ring assembly is extended to the heart of the beacon installation: the optical encoder disk. The three light-projectors of the encoder disk are AC-powered. Two of the three associated photo-cells are used to key the modulation tone of the compass-scale transmitter on/off in the rhythm of the symbology to be transmitted. The third photo-cell generates a tachometer signal for monitoring the rotational speed. The signals transmitted via the two antenna arrays are received via a radio at a nearby mast, and printed with two Hellschreiber-printers (the same HS 120 printers as installed in the aircraft). All AC and DC power is passed through a power distribution & control panel to the slip-ring assembly and to local equipment.

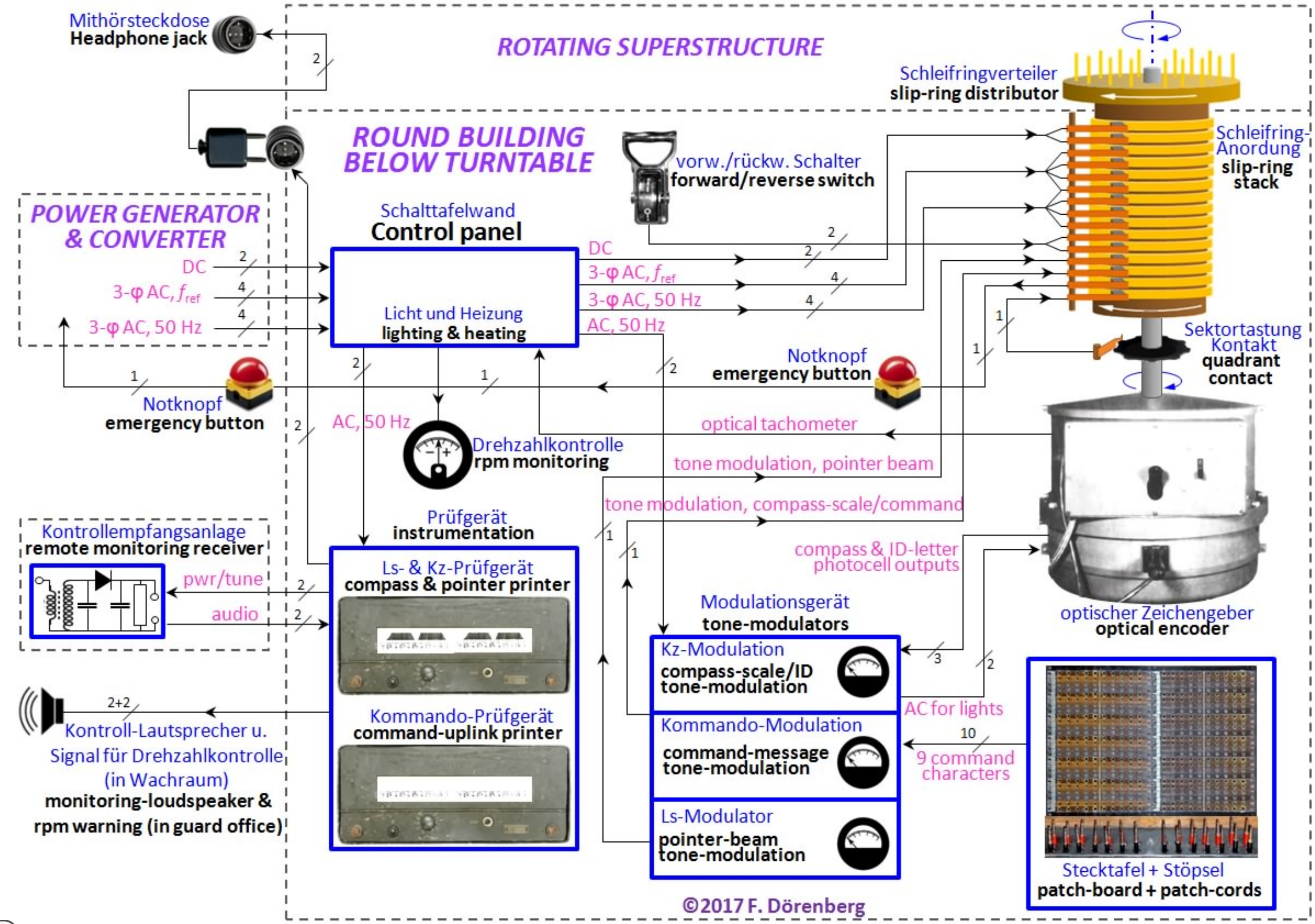


Fig. 173: Electrical power and signal interconnections of the round equipment room below the rotating superstructure

(source: derived from ref. 189 and 190; strip-chart recorder mentioned in ref. 10 not included)

The DC and two 3-phase AC voltages are provided by a nearby power generation & conversion building. This building receives 3-phase AC power from the public power grid or from a local diesel generator. The selected AC power is rectified with a mercury arc rectifier (MAR), to power the DC-motors of the locomotives. Part of the DC-power is converted to 3-phase fixed-frequency AC-power, for the synchronous AC-motor in one of the four locomotives. This DC-AC conversion is done with a Conz-converter.

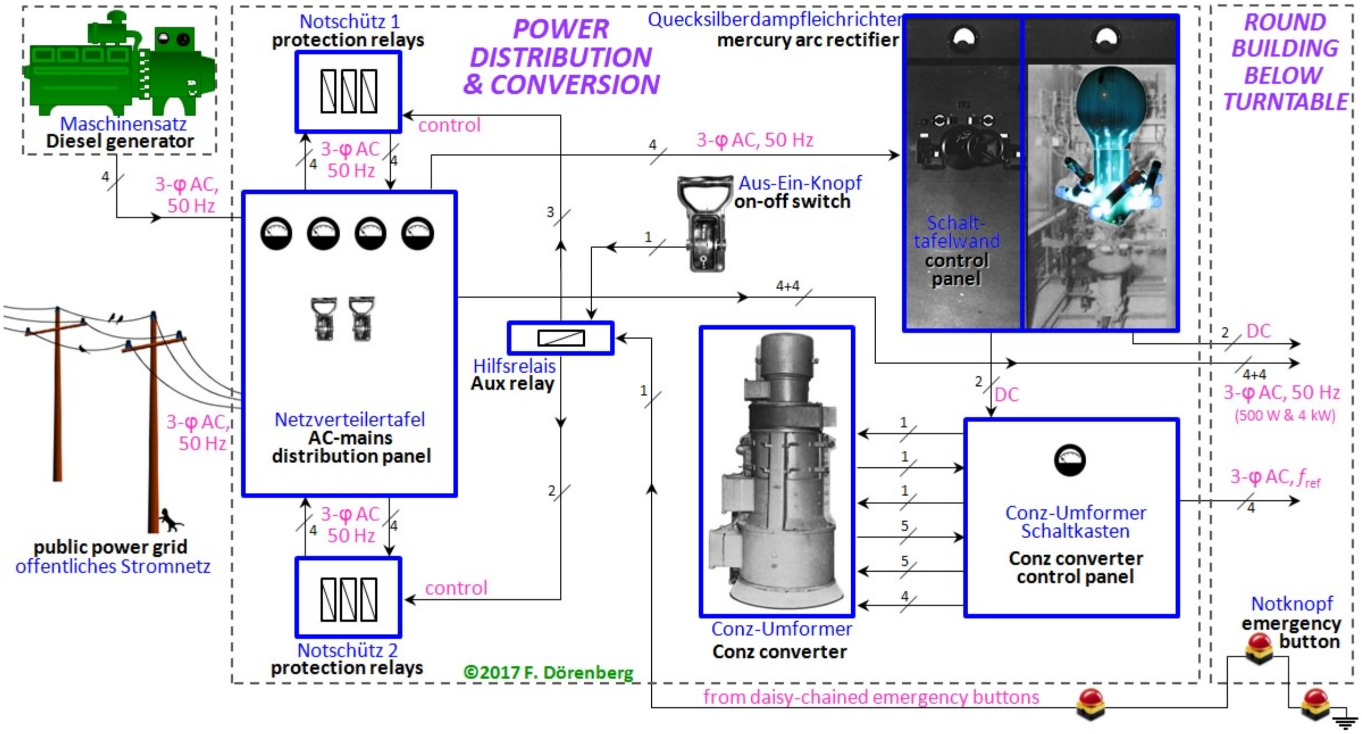


Fig. 174: Electrical power and signal interconnections of the round equipment room below the rotating superstructure

(source: derived from ref. 93, 189, and 190)

Several electrical power and signal cable types are used throughout the system (ref. 189):

NGA ("**N**ormen-**G**ummi-**A**der für feste verlegung in Schutzrohr"): rubber insulated wire for use in metal conduits.

NPA (metallumflochtener "**N**ormen-**P**anzer-**A**der"): metal-braided (armored) cable; ref. 197.

NMH ("**N**ormen-Gummischlauchleitung in **m**ittlerer Ausführung, **H**andgeräteleitung"): medium rubber-conduit cable for hand-held equipment,

"R.L.M. Erdkabel": military cable for in-ground use.

"GURO". This is one of the two primary brand names (the other being RAPID) of the *Paul Jordan Elektrotechnische Fabrik G.m.b.H. Co. KG* in Berlin-Steglitz (later Berlin-Lankwitz-Marienfelde). The GURO products covered weatherproof conduit cable & wire, insulation compounds, and cable installation material (ref. 224). The *Paul Jordan* company was founded in 1919 as a cable and wire manufacturer. In 2001, *Paul Jordan* (with its trade names and patents) was acquired by *Tyco Electronics Raychem G.m.b.H.* (TE). The Raychem company originally made special cables and wire for military and aerospace applications, and invented heat-shrink tubing in 1962. The activities of the Berlin company were transferred to lower-wage countries in Europe in 2018, and the company was closed.

Fig. 175: 1927 advertizing and cover of a 1939 product catalog of the Paul Jordan Elektrotechn. Fabrik company
(source catalog cover page: ref. 224)

The "Bernhard" cable and wire gauges vary from 1.1 to 12.6 mm diameter (= 1 to 125 mm^2 cross section). All gauges are specified for aluminium wire! The current rating of these cables varies roughly from 1 to 250 amps. This is about 20% less than for copper wiring of the same gauge.

SUPPLY OF ELECTRICAL POWER

The "Bernhard" installation had several consumers of electrical power:

Four electric locomotives. Reportedly one of the motor types was a low-rpm model, rated 10 kW (ref. 99). Let's assume all eight locomotive motors (two types of DC motor and one synchronous AC motor) had this rating. This would add up to 80 kW in total.

Two model *AS 4* transmitters, each with an output power of 500 watt, or 1 kW total. Each *AS 4* had a power supply model *NA 500*, with separate inputs for 220 and 380 volt 50 Hz 3-phase AC ("Drehstrom"), rated at 5 kVA. Ref 39C (p. 7) states that each *NA 500* was normally powered by a standard heavy motor-generator model "A" ("schwerer Maschinensatz A"), rated at 12 kVA (see Fig. 163 below), or the public power grid. Either way, the power source was loaded with 5 kW. I.e., ten times the transmitter output power, and 10 kW total for the two transmitters combined.

Miscellaneous items in the equipment room (three modulators, two printers, three projector lights in the optical disk assembly) - let's conservatively assume 1 kW.

Heating and lighting in the rotating cabin and equipment room below it, as well as in the ancillary building) - let's assume 4 kW.

Adding up the four types of electrical loads, we arrive at an estimated total load of 80 + 10 + 5 = 85 kW. To translate this to the required power from an AC source, we have to assume a worst-case phase angle φ between the generated voltage and current. For a reasonable cos(φ) = 0.8, the AC-power source would have to be dimensioned for at least 85 / 0.8 ≈ 106 kVA.

The table below shows the specified power supply for a number of *Wehrmacht* transmitters of the same era, including other beacon transmitters. The power supply outputs are all dimensioned for *at least* four times the transmitter output power.

Transmitter	Output power	Power supply
100 WS	100 W	900 W
AS 2	120 W	1.5 – 2 kVA
AS 4	500 W	5 kVA
As 33	1 kW	4 – 5 kVA
As 59	200 W	1.5 kW
As 60	1,4 kW	6 kW
S 345	200 W	1 kW
S 366 B	1,5 kW	8 kVA
S 524 A	600 W	2.8 kVA
S 521 Bs	1 kW	8 kW or 15 kVA

©2014 F. Dörenberg

Table-4: Specified power supply rating for a number of Wehrmacht transmitters
(based on various data sheets)

To be able to operate independently from the local public power grid, the "Bernhard" installation had its own local power generator, driven by a combustion engine (diesel or gasoline/petrol). Ref. 183 (pdf p. 18) states that "Bernhard" backup generator was powered by a diesel engine ("Notstrom-Diesel"). Ref. 180 implies that "Bernhard" station Be-0 near Trebbin had a 120 kVA backup diesel generator. Note that this station was also a test site, and probably had more ancillary buildings (labs, offices, kitchen, living quarters) with associated loads than a standard "Bernhard" station. Ref. 10 (§8) states that backup power was provided by a 160 kVA 3-phase 380 volt generator, driven by a 200 horse power (HP) diesel engine. I.e., 2.4 HP per kVA.

Based on the local situation (access to the local public power grid), the "Bernhard" installation typically included a high-voltage bunker ("Hochspannungsbunker"), e.g., ref. 99. It contained one or more transformers, to connect to the multi-phase regional *Hochspannungsnetz* (high voltage public power grid, 110-220 kV in Germany), or to the local *Mittelspannungsnetz* (6-60 kV, typically 10 or 20 kV). The local *Niederspannungsnetz* (several km) carried less than 1 kV. Incidentally, towards the end of the war, the minimum frequency of the 50 Hz power grid was reduced to 43.3 Hz in the Central German block, and 41 Hz in the Western German block. Ref.

14.

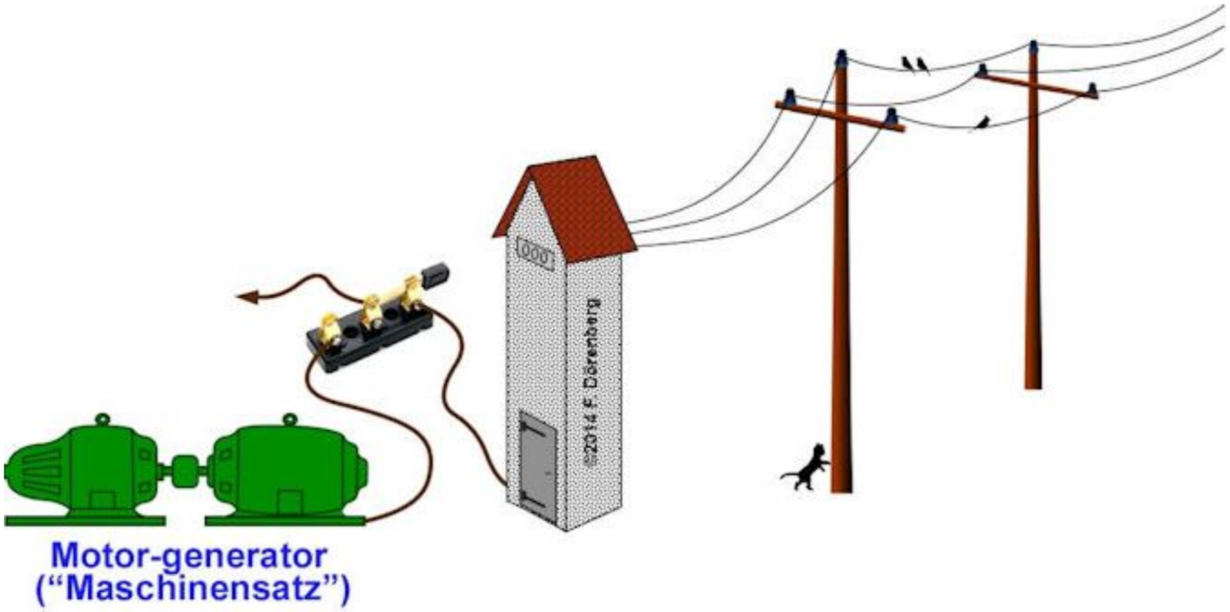
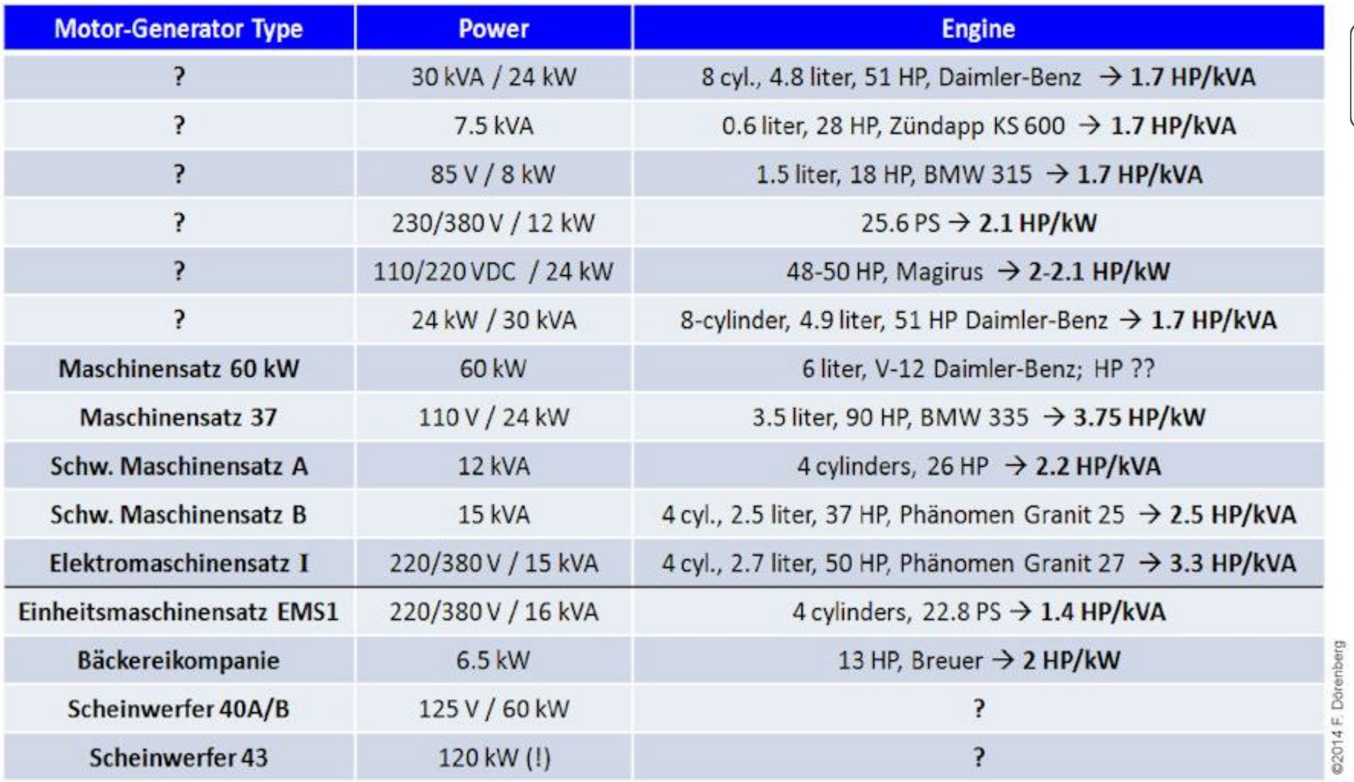


Fig. 176: The two sources of electrical power of the "Bernhard" installation

For comparison, the next table lists the horse power of the engine of a number of Wehrmacht electrical power generators ("Maschinensätze") for transmitters, various models of *Flak-Scheinwerfer* (search-lights for Anti Aircraft gun installations; ref. 152A, 152B) and even of a field bakery. This ranges roughly from 1.5 - 3 HP/kVA.



Motor-Generator Type	Power	Engine
?	30 kVA / 24 kW	8 cyl., 4.8 liter, 51 HP, Daimler-Benz → **1.7 HP/kVA**
?	7.5 kVA	0.6 liter, 28 HP, Zündapp KS 600 → **1.7 HP/kVA**
?	85 V / 8 kW	1.5 liter, 18 HP, BMW 315 → **1.7 HP/kVA**
?	230/380 V / 12 kW	25.6 PS → **2.1 HP/kW**
?	110/220 VDC / 24 kW	48-50 HP, Magirus → **2-2.1 HP/kW**
?	24 kW / 30 kVA	8-cylinder, 4.9 liter, 51 HP Daimler-Benz → **1.7 HP/kVA**
Maschinensatz 60 kW	60 kW	6 liter, V-12 Daimler-Benz; HP ??
Maschinensatz 37	110 V / 24 kW	3.5 liter, 90 HP, BMW 335 → **3.75 HP/kW**
Schw. Maschinensatz A	12 kVA	4 cylinders, 26 HP → **2.2 HP/kVA**
Schw. Maschinensatz B	15 kVA	4 cyl., 2.5 liter, 37 HP, Phänomen Granit 25 → **2.5 HP/kVA**
Elektromaschinensatz I	220/380 V / 15 kVA	4 cyl., 2.7 liter, 50 HP, Phänomen Granit 27 → **3.3 HP/kVA**
Einheitsmaschinensatz EMS1	220/380 V / 16 kVA	4 cylinders, 22.8 PS → **1.4 HP/kVA**
Bäckereikompanie	6.5 kW	13 HP, Breuer → **2 HP/kW**
Scheinwerfer 40A/B	125 V / 60 kW	?
Scheinwerfer 43	120 kW (!)	?

©2014 F. Dörenberg

Table-5: Engine power for a number of Wehrmacht generators

The photo below shows the 110 kVA emergency backup generator of the ["Goliath" *Kriegsmarine* transmitter station] for world-wide communication to submerged submarines (incl.

via Hellschreiber). It has a 150 HP diesel engine, ref. 218 (p. 188). That is, 1.4 HP/kVA. Note that the *main* generator, for the 1 megawatt (!) "Goliath" transmitter, had a power of 1800 kVA and was driven by a 2110 HP diesel engine! That is, about 1.2 kVA/HP.

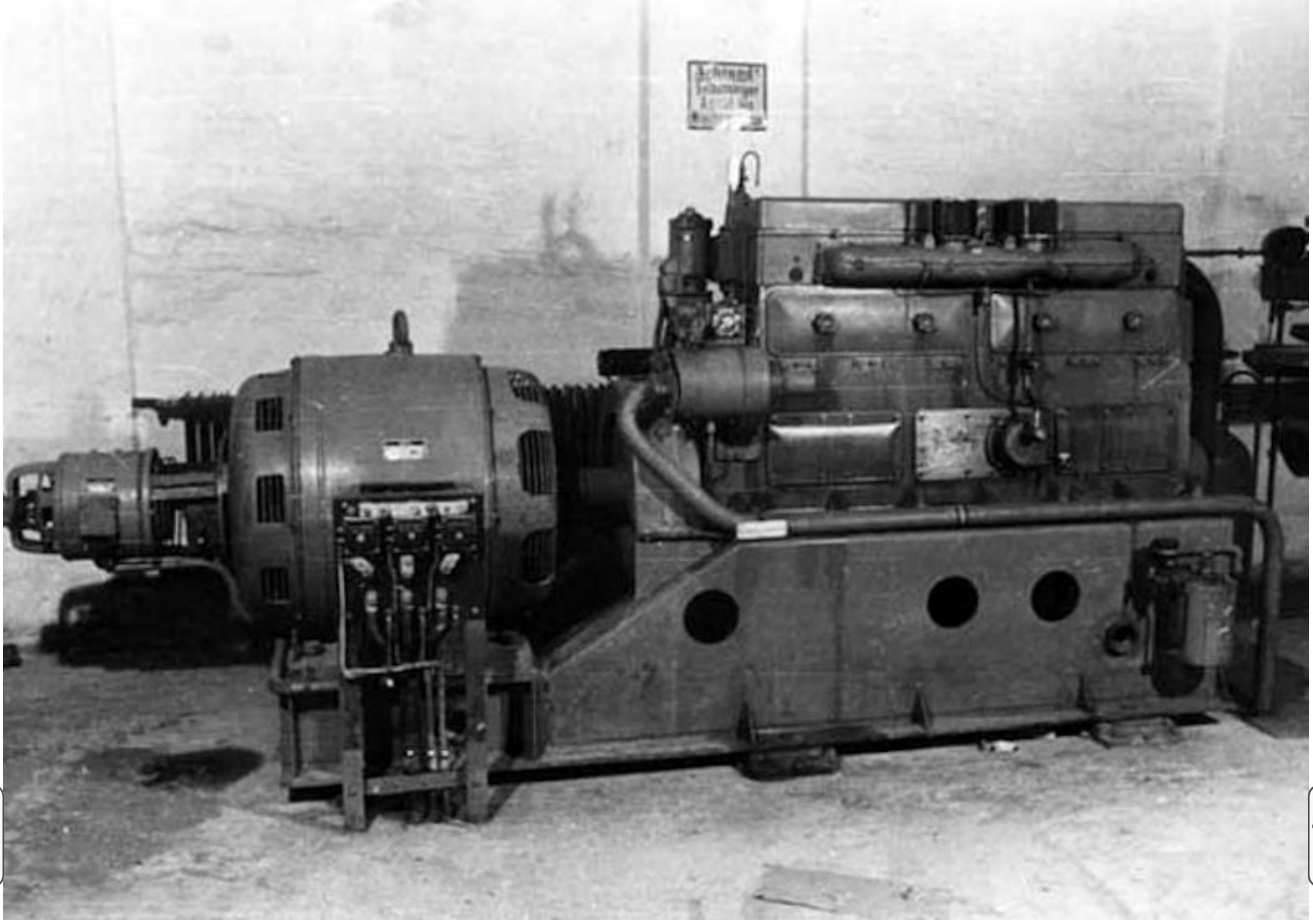


Fig. 177: Example of a 110 kVA, 3-phase 380 VAC diesel generator
(source: "Der Goliath in Bildern - Fotos vor 1946/47" web page)

Ref. 103 suggests that the generator(s) of the "Bernhard" station Be-14 at Aidlingen/Venusberg were powered by two engines that came from high-speed patrol boats of the French navy. However, the French navy's "vedette rapide" boats were standard British-built "Fairmile" models. The smallest model had two *Hall-Scott Defender* V12 gasoline (*UK*: petrol) engines of 650 BHP each. The larger "A" model had three 600 HP engines. Clearly a single engine would have been able to supply more power than needed for a Bernhard installation, even if power was also generated for the local FLAK unit and its search-light(s). On the other hand, this Be-14 station was built towards the end of the war, when materials other than rocks and stone were in increasingly short supply. A strong engine that costs nothing, is better than a correctly sized engine that is not available... There are two stone buildings near the ring of Be-14. In the middle of one of them, there is a rectangular concrete slab that measures 1.4 x 3.25 meters (4.6x10.7 ft). The slab has 6 pairs of shallow round dimples, 8 and 10 cm in diameter. The purpose of the slab in unknown. Possibly the dimples corresponded to mounting feet of a motor-generator, such as shown in the photo above.

Fig. 178: A concrete slab in the middle of an ancillary building of Be-13 at Aidlingen/ Venusberg

Below one of the windows of the round building of the "Bernhard" at Arcachon, there is an old 4-prong junction box with triangular shape. Near this box, several old cables enter the building through the wall, just above floor level. This appears to be where 3-phase AC-power entered from the generator in a nearby building.

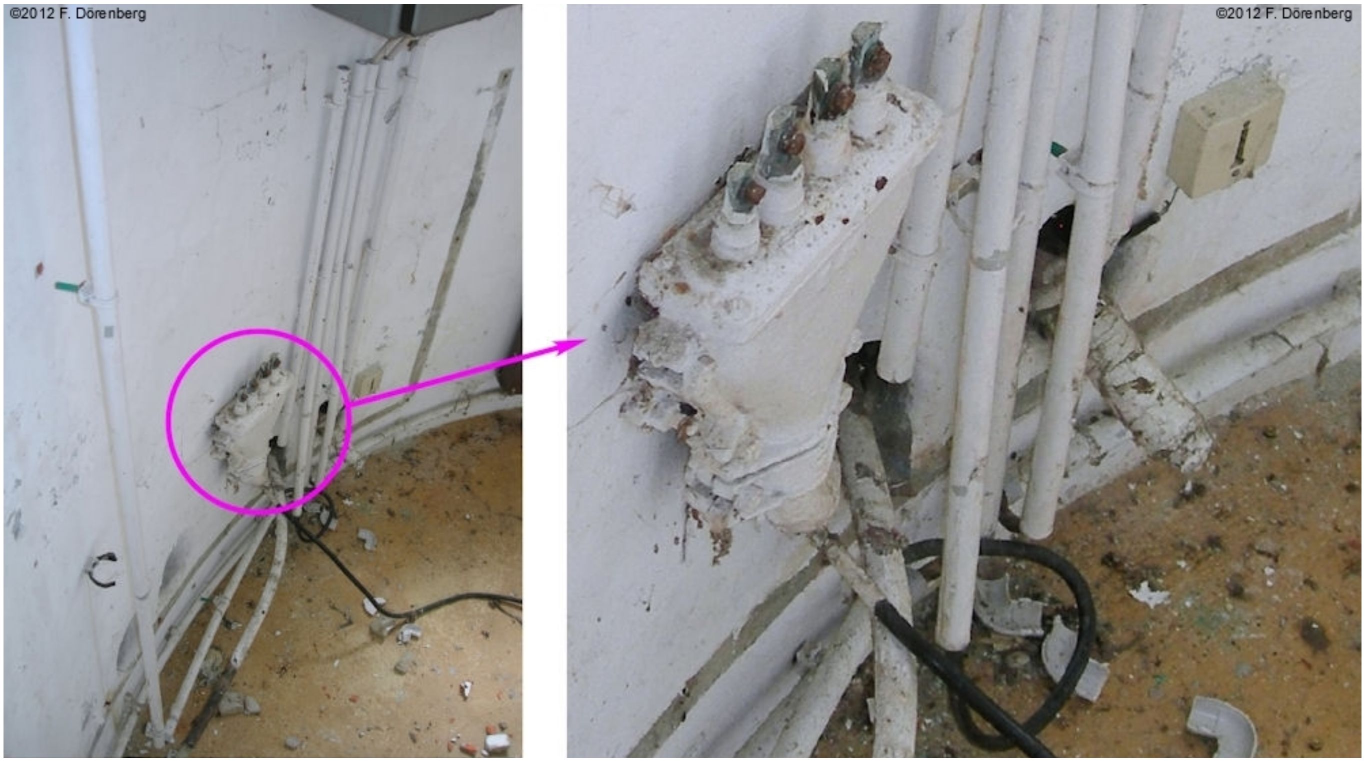


Fig. 179: Large 4-prong (3-phase) junction box on inside wall of the round building of Be-7 at Arcachon

REMOTE MONITORING-ANTENNA MAST & RECEIVER

The signals transmitted by the "Bernhard" beacon were monitored via a remote receiver and antenna. They were located at a nominal distance of 500 m (p. 21 in ref. 183 (German, 1943), but 400 m per ref. 13 (US, 1945) and 800 m per ref. 1 (UK, 1946) from the beacon. The postion relative to the beacon was accurately surveyed, so the relative bearing was accurately known.

So far, I have been able to determine the location of the monitoring antenna of the following Bernhard stations:

Trebbin (Be-0): ca. 220 m west of the concrete ring (note that this was initially a test/ development station).
Mt.-St.Michel-de-Brasparts (Be-2): ca. 920 m west-northwest. Ref. 174G.
Le Bois-Julien (Be-3): ca. 500 m northwest.
St.-Michel-Mt.-Mercure (Be-5): ca. 410 m southeast. Ref. 174H.
Bredstedt (Be-9): ca. 550 m southeast.
Hundborg (Be-10): ca. 1 km southwest.
Trzebnica/Trebnitz (Be-11): ca. 445 m south.
Nevid (Be-12): ca. 300 m southeast.
Buke (Be-13): ca. 550 m northwest.
Aidlingen/Venusberg (Be-14): ca. 900 m due west. Ref. 103.
Hornstein (Be-16): ca. 200 m.

The far-field of antennas starts about two wavelengths from the antennas, i.e., at about 20 m for the operating frequency of the "Bernhard". So, why locate the monitoring antenna and receiver so far away? Probably for three reasons. First of all, the input of a receiver close to the station would be overloaded, even during the passage of the "null" of the twin-beam radiation pattern, and the "null" would not be sharp enough close to the beacon. Secondly, it made obtaining good angular resolution during calibration adjustments easier. It is also possible that the Mercury Arc Rectifier of the locomotive drive system caused a lot of radio interference near the beacon. The latter was very important, in particular during calibration of the antenna radiation pattern. The 1935 Telefunken/Runge/Krügel/Grammelsdorff patent nr. 737102 proposes using a fixed-location remote receiver to check the direction of the beam-null, as measuring and balancing antenna feed-currents does not guarantee its correctness.

The vertical antenna was installed on top of a steel truss mast (lattice mast, cage mast; *D*: "Eisengittermast"). The antenna has a pointed tip, just like the feedpoint of the dipoles of the Bernhard's antenna arrays. A ladder was integrated into the mast. It consists simply of horizontal sections of L-bracket, mounted between one of the mast legs, and the braces to one of the adjacent mast legs. The box on which the antenna radiator is mounted, is about 50 cm wide. The monitoring receiver was located at the base of the antenna (p. 21 (pdf p. 18) in ref. 183, sheet 8 in ref. 189). The received signals were printed with a "Bernhardine" Hellschreiber-printer in the equipment room below the beacon's rotating superstructure (see Figure 169 above).

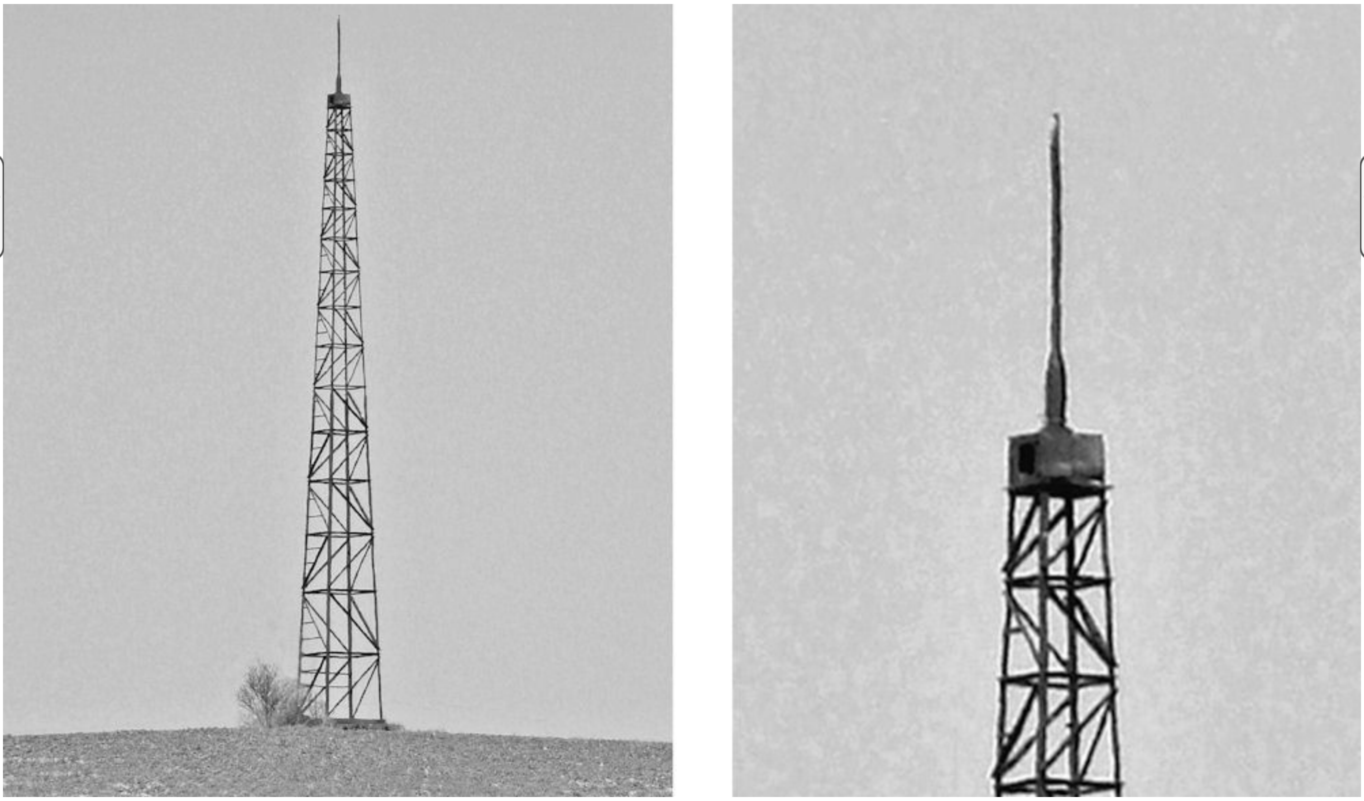


Fig. 180: The monitoring antenna mast of Be-11 at Trzebnica/Trebnitz
(photo (1980s): courtesy C. Piotrowski, used with permission)

This "Kontrollmast" (monitoring mast) had a height of 20 m (≈66 ft; p. 21 in ref. 183). According to US photographic intelligence (ref. 13), the mast was about 30 m (≈100 ft) tall, and the vertical antenna (hollow pipe) on top of it about 2.4 m (8 ft). Photometric analysis of the photo above shows that the antenna radiator (on top of the box at the top of the mast) is about 2.6 m tall, assuming a 20 m tall mast. I.e., it was a standard 1/4 wavelength vertical antenna. It has a pointed tip, just like the feedpoints of the vertical dipoles of the "Bernhard" antenna arrays, so possibly it was just half of such a dipole leg. The mast was installed on a concrete foundation.

The mast and antenna were built by *Hein, Lehmann & Co.*, the same company that built and installed the dipole antenna arrays of the Bernhard systems for Telefunken. The tall mast was delivered pre-assembled to the "Bernhard" site - at least at Aidlingen/Venusberg (ref. 103). Telefunken placed an order for six such masts in 1941, at a price of 2020 *Reichsmark* (RM) each (ref. 177C). This is equivalent to roughly US$12500 and €11500 end-2016, based on general inflation data (ref. 178A-178C). Note that Consumer Price Index (CPI) inflation data does not necessarily apply to specific products (such as antenna masts, electronics) or services. The billing does not state if the price included the actual antenna rod.

The photo below shows the mast of Be-11 at Trebnica/Trebnitz in Poland. It is the only "Bernhard" mast that has survived to date (2014). It is being used for antennas of a local FM radio station. The officially registered height of this "object" is 22 m (ref. 129).

Fig 181: Looking up inside the monitoring antenna mast, and the base of the mast at Be-11 Trzebnica/Trebnitz

(©2014 C. Piotrowski, used with permission)

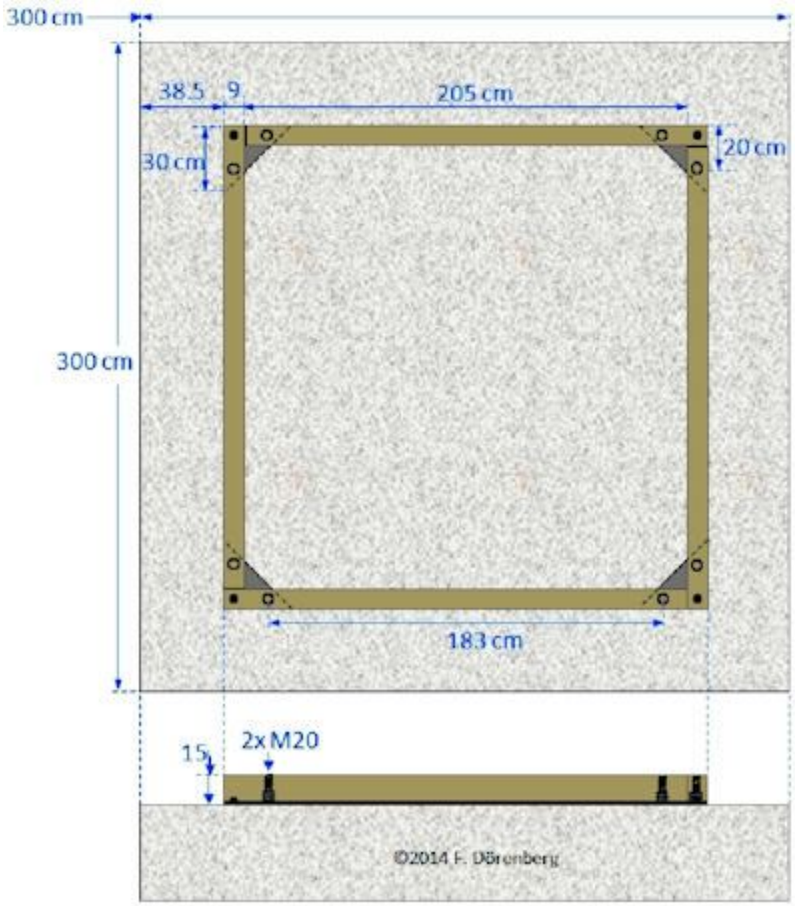


Fig. 182: The dimensions of the standard concrete foundation of the monitoring masts
(data source: Czarek Piotrowski, used with permission)

Each mast was placed on a 3x3 meter concrete slab foundation. The concrete slab is at least 75 cm thick (2½ ft). The one shown below on the left, has two oblong dimples (see arrows). They measure 19x17 cm and 21x21 cm, respectively. Their purpose is unknown. Possibly they are vertical holes in the concrete, for inserting steel posts for mounting equipment, such as shown in Fig. 184 below. Possibly, those posts were embedded in the concrete, and the photo shows the cutt off remnants.

Fig. 183: Concrete foundations of the monitoring mast of Be-9 at Bredstedt (left) and Be-10 at Hundborg
(sources: R. Grzywatz (Be-9); Hundborg Lokalhistoriske Arkiv (Be-10); both used with permission)

The monitoring receiver was located at the base of the mast (*D*: "*Empfänger am Fuß des Masts*"; p. 21 (pdf p. 18) in ref. 183, sheet 8 in ref. 189):

Fig. 184: Monitoring mast - remote-receiver and cable installed at the bottom of the mast
(source: ref. 13; probably Be-4 at La Pernelle,, based on the other photos in ref. 13)

The Figure above shows two equipment boxes installed near the bottom of the mast. Field line installations often had lightning protection at both ends: fuses (*D*: "Blitzschutzpatronen") in a junction box ("**A**nschluß**k**asten", AK). This may account for the second box.

The receiver was remote-tuned from the "Bernhard" station (*D*: "*fernbedienter Empfänger*"; p. 21 (pdf p. 18) in ref. 183, sheet 8 in ref. 189). Each "Bernhard" beacon used one of 32 operating channels in the 30-33.3 MHz frequency band. To be able to use the same monitoring receiver at all Be-stations, it had to be tunable from the control room beneath the rotating cabin. Another reason for remote-tuning is that the transmitting frequency could be changed for technical or tactical reasons. It took 1-2 minutes to change the receiver frequency to a new channel frequency (p. 27 (pdf p. 24) in ref. 183). The receiver audio was also fed to a monitoring loudspeaker in the guard office near the beacon (line item 29a on sheet 8 in ref. 189).

There was an underground cable between the receiver and the Hellschreiber printers & control equipment in the round room below the rotating superstructure of the beacon. There appear to be two different "remote receiver + cable" configurations:

> According to ref. 189, the cable was of type "Erdkabel RLM". This is a special in-ground cable with a very robust outer insulation ("Kabelmantel"). It had four conductors with a 1 mm^2 diameter (line item 28a on sheet 8 in ref. 189; ≈AWG #18). This would have supported two separate signal pairs, or three signal pairs with a common reference (e.g., ground/earth).
>
> Per ref. 10, it was a 5-pair telephone cable. According to that same reference, the remote receiver was a diode receiver with a single audio frequency amplifier stage. So, the cable would have supplied anode voltage and filament heater voltage to the remote

amplifier tube.

So, what kind of remotely tunable receiver was used? The aircraft that used the "Bernhard" beacons had an EBL-3 receiver on board. The "F" version of this receiver had remote-control. However, the control interface by itself already required 4 wires just for tuning (p. 87 and Fig. 17 in ref. 72). Note that the antenna mast is also referred to as a "Diodenmast" (e.g., ref. 99). This German term suggest that a "Diodenempfänger" was used (a.k.a. "Detektorempfänger", "Kristalldetektorempfänger"). This is known in English as a "crystal radio" or "crystal set". They were popular in the early days of radio, and got their name from a small piece of crystal that was used in the signal detector. In the 1930s, the inconvenient "crystal detector" was replaced with a diode. Such diode-receivers are not only simple, they are also *passive*. No separate source of electric power, such as a battery or DC voltage via a cable, is required: the simple circuit is powered by the received radio signals. Also, it is very easy to remote-tune a crystal radio: all that is needed is a small low-rpm DC motor that rotates the shaft of the tuning capacitor (esp. a capacitor without angular limitation). Two wire pairs would have sufficed for audio (2 wires) and DC power (2 wires, with reversible polarity to change tuning direction).

Would the audio output of a diode-receiver have been strong enough, without active amplification? This depends on three parameters:

The signal level required at the input of the Hellschreiber printer-amplifier in the cabin. A Wehrmacht *Hell Feldfernschreiber* had a specified nominal output signal amplitude of 2.5 volt (900 Hz tone pulses). To ensure proper printing at a receiving *Feld-Hell* machine, the maximum allowed cable damping was 5 Neper, which is about 43 dB, or a voltage attenuation factor of about 140x. That is, the printer amplifier required an audio input signal with a minimum amplitude of 2500 / 140 ≈ 18 mV.

The signal attenuation (damping) of the audio signals over field telephone cable with a length of 1 km (the maximum distance between the mast and the "Bernhard" ring). According to a 1945 manual of the *Hell Feldfernschreiber* (ref. 146), its range over standard field telephone cable of type DL500 was 36 km (22 km when wet), 60 km over regular pupin-cables (*D*: "bespultes Kabel", "Pupin-Kabel"; cable with a loading coil/ inductance at regular intervals, typ. 250 m for German field cable), and 160 km over special pupin-cable of type FL250. That is, worst-case 22 km for 43 dB damping, or no more than 2 dB for 1 km. The required minimum 18 mV plus 2 dB is about 23 mV. So that would have been the required minimum output signal of the diode-receiver.

The RF field-strength induced at the remote antenna by the "Bernhard" transmitters and antenna system. Per the definition of the ITU (ITU-R BS.561-2), the field strength of a ½λ-dipole with an effective radiated power (ERP) of 1 kW is 222 mV per meter, at a distance of 1 km. Also see ref. 150. The "Bernhard" installation had an ERP of at least several kW (my estimate). I.e., at least several 100 mV per meter at the monitoring antenna. That would have been more than enough to generate 23 mV at the receiver output - at least during passage of the main lobes of the radiation patterns of the upper and lower antenna systems. The standard formula for field strenght at a given distance from a transmitting antenna is:

$$E = \frac{\sqrt{30 \cdot Power \cdot \left(10^{Antenna\ gain/10}\right)}}{distance}$$

where the field strength *E* is in volt-per-meter (V/m), the transmitter power is in watt, the distance in meters, and the antenna gain in dBi (= relative to a standard dipole). The

> "Bernhard" antenna system had a gain of about 12 dBi (see Fig. 41 & 46 in the "Bernhard" Antenna System section). At a range of 1 km and 500 W transmitter power, the formula yields a field strength of 488 mV/m. Note: the formula assumes transmission through "free space" (no ground losses). It also assumes a modulation depth of 100%. The antenna radiation pattern of the "Bernhard" sytem had a low elevation angle, and the transmitter was operated with less than 100% modulation. So, this calculated value is an upper limit.

The standard formula for field strenght at a given distance from a transmitting antenna is:
The remote receiver was not only used during normal operation of the beacon, but also during calibration and adjustment of the currents to the left- and right-hand antenna subsystems. The receiver audio could be connected to a strip chart recorder in the control room, for the purpose of recording the 360° antenna radiation patterns. It is possible that a diode receiver did not generate sufficient signal for accurate recordings, and an amplifier stage was required. It is always best (from a signal-to-noise ratio point of view)to place an amplifier right at the signal source, i.e., at the receiver, not at the other end of the cable.

The schematic below shows a crystal radio that can power a small loudspeaker (ref. 147). I.e., similar to a small 1-transistor radio, but completely without a tube or transistor amplifier! It has a double-tuned circuit, a full-wave diode rectifier, followed by a voltage-doubler. The output voltage across the capacitors can be connected directly to standard high-impedance headphones (4000 Ω). It can also be connected to a low-impedance load, such as a loudspeaker or a standard "600 Ω" phone line. To match that impedance, a simple output-transformer (about 1:6 to 1:10) must be used. Solid-state diodes were readily available at the time, such as "Sirutor" diodes that were used in various Hellschreiber models. These were quite suitable for crystal radios (ref. 148, 149), as they have a forward voltage (a.k.a. "knee" or "turn-on" voltage) of only 0.2-0.3 volt (Sirutor type 1b), unlike more modern silicon diodes.

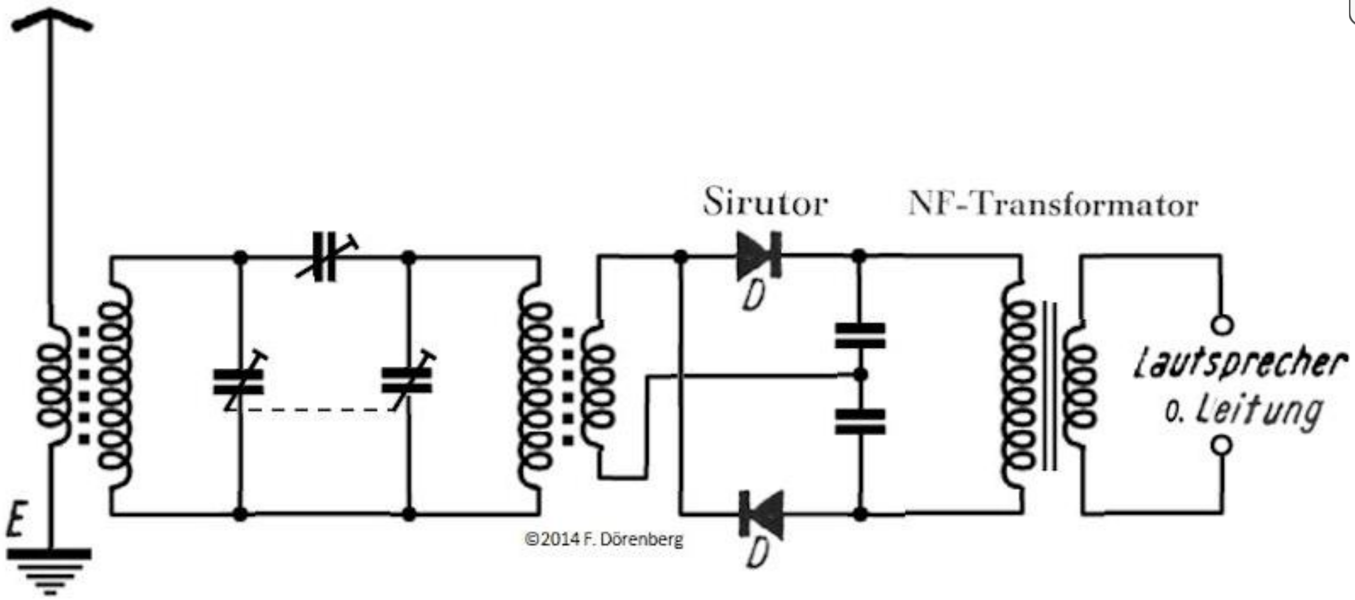


Fig.185: Schematic of a "crystal radio" receiver, capable of driving a small loudspeaker
(source: adapted from ref. 147)

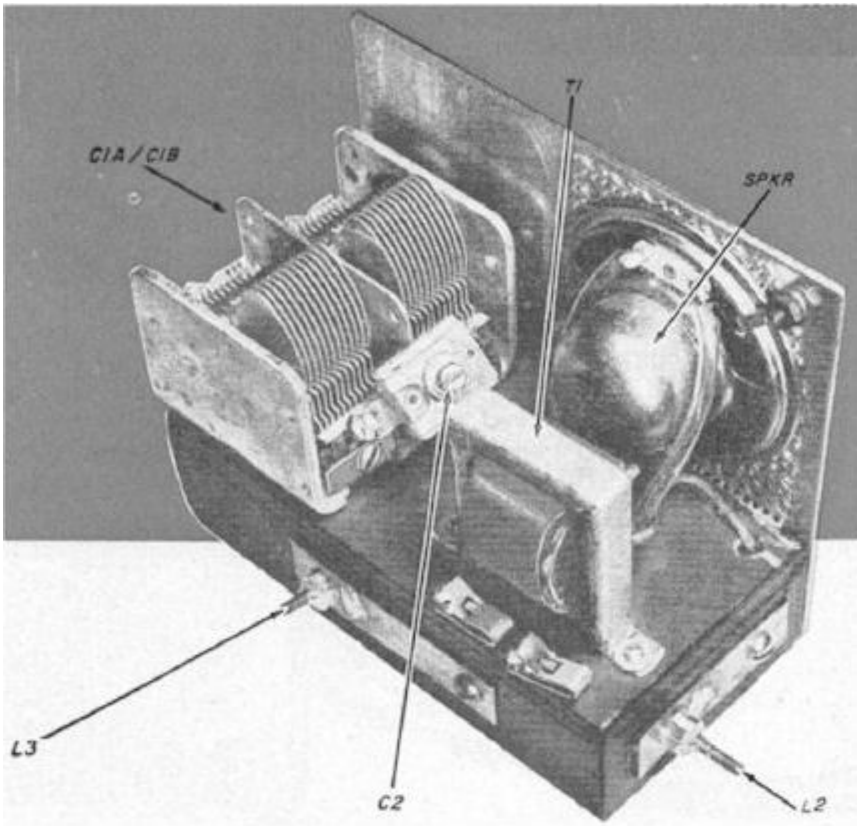


Fig. 186: A "crystal radio" receiver built per the schematic above
(source: ref. 147)

UNKNOWN / UNCONFIRMED / UNCLEAR ASPECTS

Open-wire feedline between the dipoles: characteristic impedance (spacing between the wires, wire diameter)?

Were the rails continuously welded rail or jointed?

Purpose/content of the four corner-sheds? Dead-weight?

Purpose of two different types of DC motors per locomotive?

Were both bogies of each locomotive motor-driven, and one or both axes of each driven bogie?

Which company was the manufacturer of the locomotives?

Purpose of dimples in the top of several of the concrete rings, between the rail ties/ shoes?

Purpose of a box with 5 kg of graphite (powder?) that was part of the standard equipment (sheet 20, ref. 189)?

Why was a special Telefunken crystal module needed in the AS 4 transmitters (improve the frequency accuracy/stability?).

Purpose of the remote tachometer in Locomotive nr. 4 (going to the rotating cabin), in addition to the tachometer track of the optical disk (in the round equipment building below the rotating cabin)?

Frequency of the accurately regulated 3-phase AC (50 Hz?), and the number of rotor poles of the synchronous AC motor of locomotive nr. 4?

PATENTS

Below is a listing of patents related to the "Bernhard" system.

Patent number	Patent office	Year	Inventor(s)	Patent owner(s)	Title (original)	Title (translated)
662457	RP	1935	W. Runge K. Röhrich	Telefunken GmbH	Antenneanordung zur Aussendung von zwei oder mehreren einseitig gerichteten Strahlen	Antenna arrangement for transmission of two or more uni-directional beams
692583	RP	1937	H. Gross	Conz Elektricitäts G.m.b.H.	Frequenzwandlergruppe zur Erzeugung konstanter Mittelfrequenz	Frequency converter for generation of constant mid-frequency
737102	RP	1935	W. Runge, L. Krügel, F. Grammelsdorff	Telefunken GmbH	Anordnung zur ständigen Kontrolle und zur Ein- bzw. Nachregulierung der geometrischen Lage eines Leitstrahls während des Leitvorganges	Arrangement for monitoring and adjustment of the geometric direction of a directional beam [A/N & E/T beacons, via monitoring receiver]
767354	RP	1936	-	Telefunken G. für drahtlose Telegraphie m.b.H.	Verfahren zur Richtungsbestimmung	Method for direction-finding [**this is the primary "Bernhard" patent**]
767512	RP	1938	A. Lohmann	Telefunken G. für drahtlose Telegraphie m.b.H.	Verfahren zur Richtungsbestimmung mittels rotierender Richtstrahlung	Method for direction-finding with a rotating directional beam
767523	RP	1938	A. Lohmann A. Bittighofer	Telefunken GmbH	Empfangseinrichtung zur Durchführung des Verfahrens zur Richtungsbestimmung	Receiver-side device for the implementation of the method for direction-finding
767524	RP	1938	A. Lohmann	Telefunken GmbH	Verfahren zur Richtungsbestimmung mittels rotierender Richtstrahlung	Method for direction-finding with a rotating directional beam
767525	RP	1939	A. Lohmann	Telefunken GmbH	Einrichtung zur Speisung eines rotierenden Richtantennensystems	Device for capacitive coupling of a transmitter to a rotating directional antenna system
767528	RP	1938	A. Lohmann	Telefunken GmbH	Verfahren zur Richtungsbestimmung	Method for direction-finding
767529	RP	1938	A. Lohmann A. Bittighofer	Telefunken GmbH	Einrichtung zur Erzeugung angenähert rechteckiger, zur Modulation des Kennzeichensenders dienender Abtastimpulse bei einem Verfahren zur Richtungsbestimmung mittels	Device for the generation of an approximately square pulse envelopes, for the direction finding method by means of

					Drehfunkfeuer	a rotating beacon
767531	RP	1939	A. Lohmann	Telefunken GmbH	Verfahren zur Richtungsbestimmung	Method for direction-finding [dipole antenna array arrangement with side-lobe suppression]
767532	RP	1939	A. Lohmann	Telefunken GmbH	Sendeanordnung zur Durchführung eines Verfahrens zur Richtungsbestimmung	Antenna arrangement for the implementation of a method for direction finding
767937	RP	1939	A. Lohmann	Telefunken GmbH	Einrichtung zur Durchführung eines Verfahrens zur Richtungsbestimmung	Device for implementation of a method for direction finding

Here are some ancillary patents:

Patent number	Patent office	Year	Inventor(s)	Patent owner(s)	Title (original)	Title (translated)
562307	RP	1929	J. Robinson	J. Robinson	Funkpeilverfahren	Method for direction finding [transmission of course pointer, or compass scale info via Nipkow-video]
620828	RP	1933	-	Marconi's Wireless Telegraph Co. Ltd.	Funkpeilverfahren	Method for direction finding [transmission of compass scale info via Nipkow-video]

Patent office abbreviation: RP = Reichspatentamt (Patent Office of the Reich), DP = deutsches Patentamt (German Patent Office).
Patent source: DEPATISnet

REFERENCES

Ref. 2: pages from the reknowned books and other documents by Fritz Trenkle

- **Ref. 2A:** "Die deutschen Funkführungsverfahren bis 1945" ["The German radio guidance systems through 1945"], Fritz Trenkle, Dr. Alfred Hüthig Verlag, 1987, ISBN 3778516477, 215 pp.
    - **Ref. 2A1:** p. 149 (X-Uhr / X-system clock).
    - **Ref. 2A2:** pp. 76-110, 224.
- **Ref. 2B:** "Die deutschen Funk-Navigations- und Funk-Führungsverfahren bis 1945" ["The German radio navigation & guidance procedures through 1945"], Fritz Trenkle, Motorbuch Verlag, 1995, 208 pp., ISBN-10: 3879436150.
    - pp. 62, 94-102.
- **Ref. 2C:** "Bordfunkgeräte - vom Funkensender zum Bordradar" ["On board radio equipment - from spark transmitter to radar"], Fritz Trenkle, Bernard und Graefe Verlag (publ.), 1986, 283 pp., ISBN 3-7637-5289-7. [table of contents]
    - **Ref. 2C1:** p. 61-63 - "Kommandoübertragungszusätze" ["Command uplink

accessories"].

Ref. 2C2: p. 83-95 - "Eigenpeil- und Zielflug-Verfahren - LW-MW-Peil und Zielfluggeräte" ["RDF and reverse-RDF systems - LW/MW RDF & approach equipment"]

Ref. 2C3: pp. 97-118 - "Leitstrahl-Verfahren" ["Guidance-beam systems"].

Ref. 2C4: p. 108 - photo "Große Knickebein Anlage bei Kleve", ["Large Knickebein installation near Cleves"; note: incorrectly identified by Trenkle as station K4 at Kleve, instead of K2 at Bredstedt].

Ref. 2C5: pp. 119-133 - "Drehfunkfeuer-Verfahren - LW, KW, UKW, DMW, bis 1945" ["Rotating-beam beacon systems, Longwave"].

Ref. 2C6: pp. 134-140 - "Hyperbel-Navigations-Verfahren" ["Hyperbolic navigation systems"]

Ref. 2C7: pp. 141-150 - "Entfernungsmeß-Verfahren" ["Distance measuring systems"]

Ref. 2C8: pp. 198-200 - "Kenngeräte (Bord-Transponder)" [FuG 25 "Zwilling", FuG25a "Erstling"]

Ref. 2D: "Versuch einer Zusammenstellung deutscher Funkgeräte 1939 ... 1945 LUFTWAFFE / HEER / MARINE (ca .1200 Geräte)" ["Attempt at a compilation of German radio equipment 1939 ... 1945 Air Force / Army / Navy (ca. 1200 equipment items)"], Wolfgang "Fritz" Trenkle, Issue VI.60 (1960), 100 pp. [file size: **38 MB**]. Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, Signatur/file nr. RL 2-V/211, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 5: "Instruments of Darkness: The History of Electronic Warfare, 1939-1945", new ed., Alfred Price, Greenhill Books, 2005, 272 pp., ISBN-10: 1853676160; original edition: William Kimber and Co., Ltd, 1967. **See note 1**

Ref. 5A: pp. 236-237; Same as pp. 274-275 in the excellent German translation: "Herrschaft über die Nacht: Spionen jagen Radar", Alfred Price, publ.: Bertelsmann Sachbuchverlag Reinhard Mohn, 1968, 304 pp., ASIN B0000BT35X.

Ref. 5B: p. 82 - second of sixteen photo pages.

Ref. 6: Transcribed reports from the British Air Ministry, Assistant Director of Intelligence (Prisoner Interrogation), A.D.I. (K) (a.k.a. "Felkin Reports", after their author). Source: The National Archives of the UK, ref. AIR40/2875 and 2876. Retrieved from www.cdvandt.org.

Ref. 6A: §19-23 in "Some further notes on G.A.F. Pathfinder procedure" ["EGON" procedure, new EGON procedure, Berhardiner Gerät, Erika Gerät, Y-Gerät, "X" Clock, Knickebein jamming], S.D. Felkin, A.D.I.(K) Report No. 187/1944, 25 April 1944, 5 pp.

Ref. 6B: §57-59 in "G.A.F. night fighters - R.A.F. Bomber Command countermeasures and their influence on German night fighter tactics" [transcript], S.D. Felkin, A.D.I.(K) Report No. 599/1944, 2 November 1944, 16 pp.

Ref. 6C: "G.A.F. Night Fighters - Recent Developments in German Night Fighting", S.D. Felkin, A.D.I. (K) Report No. 125/1945, January 1945, 18 pp.

Ref. 6D: "The GAF (German Air Force) Signals Organisation in the War" [incl. X-System, X-beam, Knickebein, Y-System (Benito), Zyklop/Cyclop, Erika, Sonne beacons in Spain, radar, FuG25/25A, IFF, Panorama, Centimetre Wave R&D, Egon, Gee, H2S, Berlin-Gerät, Kammhuber night fighting, Window, Wilde Sau, HS293], Samuel Denys Felkin, A.D.I.(K) Report No. 334/1945, 1 July 1945, 27 pp.

Ref. 6E: "Equipment of a Y-Site" [Berta I, Berta II, S16B, Sadir 80/100, Heinrich I (Peiler, D/F), Heinrich III, FuG 16ZE, FuG16ZY], S.D. Felkin, A.D.I.(K) Report No. 527B/1944, 25 Sept 1944, 13 pp.

Ref. 6F: "Radio and Radar Equipment in the Luftwaffe- I. Blind Landing and Airborne Communications Equipment" [report of interrogations of General Martini and other PoW's; topics: LFF, JLFF, Fu Bl 2, AWG 1, FuG 10 P, FuGe 16, FuGe 17, FuGe 18, FuGe 15, FuGe 24, FuGe 29], S.D. Felkin, A.D.I.(K) Report No. 343/1945, 1 July 1945, 6 pp.

Ref. 6G: "Radio and radar equipment in the Luftwaffe - II: Navigational aids" [D/F loop equipment, PeGe 6, FuG 141, FuG 142, FuG145; homing beacons: Schwanboje, Biene; beam systems: Zyklop, Sonne, Mond, Stern, Dora, Komet, Erika, Bernhardine, Hermine; Pulse systems: Ingolstadt, Truhe, Baldur, Baldur-Truhe, Baldur-Bernhardine; Ground control systems: Benito = "Y", Egon, Nachtlicht, Nachtfee, Barbara, Barbarossa, Rübezahl], S.D. Felkin, A.D.I. (K) Report No. 357/1945, 25 April 1944, 18 pp.

Ref. 6H: "Radio and radar equipment in the Luftwaffe - III: Electric altimeters" [FuG 101A, FuG 102, FuG 103, FuG 104], S.D. Felkin, A.D.I. (K) Report No. 362/1945, 27 July 1945, 3 pp.

Ref. 6J: "Fighter defence of Germany - Control of fighters by the "Y" Procedure" [Samuel Denys Felkin, A.D.I.(K) Report No. 525/1944, 14 pp.

Ref. 6K: "German knowledge of 'OBOE'", [transcript], S.D. Felkin, A.D.I. (K) Report No. 318/1944, 29 Juni 1944, 11 pp.

Ref. 6L: "Further Report on the Crew of the Ju.88 8-3 Z6 + FH of 1/K.G.66) shot down by A.A. 5 miles N.W. of Alost, on 23rd January 1945.(Previous A.D.I.(K) Report No.142/1945)" [incl. special navigation aids: EGON, "Y" procedure, "Y" clock, new "X" procedure = "Y" + EGON, FuG 28, Y-Clock (CRT), FuG 17, FuG 25A, FuG 217, Ju-88], S.D. Felkin, A.D.I. (K) Report No. 175/1945, 19 February 1945, 13 pp.

Ref. 7: "Beiträge der Firma Siemens zur Flugsicherungstechnik und Luftfahrt-Elektronik in den Jahren 1930 bis 1945 (Teil 1 & 2)", H.J. Zetzmann, in "Frequenz - Zeitschrift für Schwingungs- und Schwachstromtechnik"

Ref. 7A: Part 1: Vol. 9, Nr. 10, October 1955, pp. 351-360. [Wassermann radar FuMG 402, Wellenschieber, Jagdschloß / FuMH 404, PPI, Freya FuMG 41, Würzburg Riese]

Ref. 7B: Part 2 (pp. 387, 388, 392): Vol. 9, Nr. 11, November 1955, pp. 386-395. [RDF antennas for aircraft, Bernhard/Berhardine, transponder DME, D 2002, Kurskoppler, autopilot, FuG 135 Boden-Bord Kommando-Übertragungsgerät]

Ref. 10: "The German Bernhard Aircraft Navigational System", S/Ldr. G.W. Calvert, AIR 40/2162, Air Minsitry, Directorate of Intelligence (D. of I.), Air Intelligence, Technical, A.I.2(g), Report No. 1834, 20 February 1946, 30 pp. Item is in the collection of The National Archives; material with UK Crown Copyright, used in accordance with the Open Government License [pdf].

Ref. 13: p. 4.05 and 4.09 in "Japanese Electronics", OPNAV-16-VP101, Photographic

Intelligence - Report 1", U.S. Naval Photographic Intelligence Center, January 1945, 166 pp. [33 MB]

Ref. 14: summary item 27 in "The German Wartime Electricity Supply - Conditions, Developments, Trends", British Intelligence Objectives Sub-committee (BIOS), Final Report 342, Item No. 33, 28 selected pages. Source: www.cdvandt.org

Ref. 15: "Beschreibung und Betriebsvorschrift für Funk-Navigationsanlage FuG 120" ["Description and Operating Instructions for Radio-Navigation System FuG 120" = "Bernhardine"], Telefunken Gesell. für drahtlose Telegraphie m.b.H., document FN-T-GB Nr. 1932, December 1944, 43 pp. [File size: 66 MB - a good-but-lower resoluton file is here 26 MB]. Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, Signatur/file nr. RL 3/7987, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

> **Ref. 15A:** higher quality version of pp. 16-20 (equipment photos); source: corporate archives of DTM Berlin, file nr. I.2.060C-00666.

Ref. 20: pp. 59-63 of "Richt- und Drehfunkfeuer" [Directional and rotating radio beacons], Chapter 3 of "Leitfaden der Funkortung: Eine systematische Zusammenstellung der Verfahren und Anlagen der Funkortung" [Guide to radio location: a systematic survey of radio locationmethods and installations], vol. 1 of "Lehrbücherei der Funkortung", Walter Stanner, 4th ed., Deutsche RADAR-Verlagsgesellschaft m.b.H., 1957, 160 pp.

Ref. 28: ITU conference 1938; "Propositions transmises au bureau de l'union, pour être soumises à la conference" [proposals to be submitted to the ITU conference], Vol. 1 of "Documents de la Conférence internationale des radiocommunications di Caire (1938)", International Telecommunications Union (ITU), Bern; no English version available; source: ITU

> **Ref. 28A:** pp. 218, 219: proposal nr 392 R by C.I.N.A - "Considérations générales sur la largeur de bande des émetteurs de t.s.f. modulés par signaux Siemens-Hell" [general considerations about the bandwidth of radio transmitters that are modulated with Siemens-Hell signals]; at 5 chars/sec (punch tape operation), the 12-line Hell-font with a shortest pulse of 2 msec and shortest pause of 3.12 msec has a shortest cycle of 5.12 msec, hence a max cycle rate of 195 Hz, and 97.5 Hz with manual/keyboard operation at 2.5 chars/sec. Tests by Siemens-Halske, Cable & Wireless (UK), and the German Central Postal Authority (R.P.Z) have concluded that a applying a low-pass filter with a corner frequency of 230 Hz at the transmitter is sufficient, and results in 390 Hz occupied bandwidth.

Ref. 29: "Bandbreitenfragen bei Anwendung der Siemens-Hell-Fernschreibtechnik" [signal bandwidth issues with A2 and A3 modulation], Rudolf Zimmermann, 7 pp., Technische Mitteilungen des Fernmeldewerks, Siemens & Halske A.G., Wernerwerk, Abteilung für Telegrafengerät, Berlin-Siemensstadt, May 1940, SH 7998, 1. 8. 40. T T1.

Ref. 34: "Most Secret War", R.V. Jones, Hamish Hamilton, 1978, 576 pp. [file size: 53 MB] **See note 1**

Ref. 39: Luftwaffe manuals for ground and on-board landing beam systems element. Source: www.cdvandt.org. Retrieved: January 2018, September 2020.

> **Ref. 39A:** "Funk-Landegerät Fu Bl I - Geräte-Handbuch, Beschreibung und Betriebsvorschrift", Luftwaffe Druckschrift D. (Luft) T.4065, April 1942, 50 pp.
>
> **Ref. 39B:** "UKW-Landefunkfeuer 120 Watt und 500 Watt, Aufbau-Anweisung", Luftwaffe Druckschrift D. (Luft) T.4458, June 1943, 8 pp.
>
> **Ref. 39C:** "AS 4 Anflugführungssender 4 - Geräte-Handbuch", Luftwaffe

Druckschrift D. (Luft) T.4456, June 1943, 36 pp.

Ref. 39D: "Ansteuerungs-Sender AS 2 - Geräte-Handbuch, Beschreibung und Wirkungsweise sowie Bedienung und Wartung", Luftwaffe Druckschrift D. (Luft) T.4452, May 1941, 38 pp.

Ref. 39E: "Antenne AFFA 2- Geräte-Handbuch, Beschreibung und Wirkungsweise sowie Bedienung", Luftwaffe Druckschrift D. (Luft) T.4454, September 1941, 17 pp.

Ref. 39F: "Beschreibung und Betriebsvorschrift für 5 Watt-Ultrakurzwellen-Einflugzeichensender EZS 2", Luftwaffe Druckschrift D. (Luft) T.4451, February 1941, 30 pp.

Ref. 39G: "Beschreibung und Betriebsvorschrift für Funkfeuer-Kontrolempfänger EBKS", Luftwaffe Druckschrift D. (Luft) T.4450, February 1941, 17 pp.

Ref. 39H: "120 Watt UKW Leitstrahlsender AS 3" ["UKW Landefunkfeuer, ortsfest"; non-mobile VHF landing beam beacon], Beschreibung Nr. 75/710, C. Lorenz AG, Berlin-Tempelhof, November 1942.

Ref. 72: "Funk-Landegerät Fu Bl 2 Geräte-handbuch" [EBL 2, EBl 3], D.(Luft)T.4058, February 1943, 120 pp. Source: www.cdvandt.org.

Ref. 77: "History of the German night fighter force, 1917-1945", Gebhard Aders, Jane's Publishing Company, 1st ed., 1979, 284 pp. [file size 62 MB]. **See note 1**

This is the translated and edited version (by A. Vanags-Baginskis and B. Gallagher) of the original German version "Geschichte der deutschen Nachtjagd: 1917-1945", Gebhard Aders, Motorbuch Verlag (publ.), 1977, 391 pp.

Ref. 77A: pp. 96, 182.

Ref. 77B: pp. 194, 195.

Ref. 77C: pp. 246, 237.

Ref. 91: pp. 60-69 in "Mémoires sans concessions", Yves Rocard, Grasset, 1988, 302 pp., ISBN-10: 2246411211.

Ref. 92: "Yves Rocard, père de la physique française d'après-guerre" ["Yves Rocard - father of post-war physics in France"], Emmanuel Grenier, in "Fusion", No. 86, May/June 2001, pp. 30-44.

Ref. 93: pp. 116-118 in "The High-Frequency War - A Survey of German Electronic Development" [file size: **225 MB**; a lower-resolution version is here, 56 MB], E.S. Henning, HQ Air Materiel Command (AFMC), Wright Field, Dayton/OH, Summary report No. F-SU-1109-ND, 4 June 1946.

Ref. 99 "Völlig in Vergessenheit geraten: Funkanlage bei Buke", Hans-Walter Wichert, in "Die Warte - Heimatzeitschrift für die Kreise Paderborn und Höxter", Nr. 24, December 1979, pp. 14-15, ISSN 0939-8686 (courtesy Mr. R. Gellhaus and H.-W. Wichert)

Ref. 103: "Aidlingen Venusberg", web-page of Forschungsgruppe Untertage e.V. [pdf]
Also part of "Pressebericht Tageswanderung zum Venusberg", Reiner Schopf, p. 28 in "Stadt Holzerlingen Nachrichtenblatt", 1 August 2014.

Ref. 115: Drawing of the cross-section of the Bernhard at Hundborg/Gåsbjerg hill, Jens Salmonson, 1982, source: Hundborg Lokalhistoriske Arkiv, used with permission.

Ref. 127: "Vliegveld Bergen NH 1938-1940", J.H. Schuurman, A.W. de Poel (ed.), Uitgeverij De Coogh, 2001, 336 pp., ISBN 9075440049

Ref. 128: personal correspondence with Y. Rose, December 2013 - April 2014

Ref. 129: "Trzebnica *Raszów*", source: RadioPolska website, accessed 2014.

Ref. 135: Section 4.2 and 4.3 in "Antennbuch", Karl Rothammel (DM2ABK), Deutscher Militär Verlag, 7th edition, 1969, 593 pp.

Ref. 136: "Die Antennen", Section I in "Fibel FuG 200 für den Funkwart und Bordfunkmechaniker" 2nd ed., April 1944, 53 pp.

Ref. 137: "Ausstrahlung, Ausbreitung und Aufnahme Elektromagnetischer Wellen", Ludwig Bergmann, Hans Lassen, Vol. 2 of "Lehrbuch der drahtlosen Nachrichtentechnik" ["Textbook of wireless communication"], Nicolai von Korshenewsky (ed.), Wilhelm T. Runge (ed.), Springer -Verlag (publ.), 1940, 286 pp. Source: libarch.nmu.org, retrieved 18 May 2020. [file size: 22 MB]

Ref. 137A: "Die Dipolreihe, Dipolgruppe, und Dipolebene" ["The dipole row, dipole array, dipole plane"], pp. 62-73.

Ref. 137B: "Richtantennen für Leitstrahlanordungen (Funkbaken)" ["Directional antennas for guide-beams (radio beacons)"], p. 97-98 in Chapter II.

Ref. 138: p. 15-20 in "Richtverbindungsgeräte", Vol. 2 of "Richtverbindungen", Riv-2, Luftnachrichtenschule Halle (Saale), 1st ed., September 1942

Ref. 139: array antennas

Ref. 139A: "High-frequency Antennas" in "Radio Antenna Engineering", Edmund A. Laport, McGraw-Hill Book Co., 1952, 560 pp., [pdf 30 MB] © Creative Commons License; also as free online e-Book here.

Ref. 139B: "The Linear Broadside Array", Chapter 4 in "Array and Phased Array Antenna Basics", Hubregt J. Visser, John Wiley & Sons, 2005, 378 pp.

Ref. 139B: "Reflective Array Antenna", Wikipedia [pdf]

Ref. 139C: "Phased Array Handbook", Robert J. Mailloux, 2nd ed., Artech House, 2005, 515 pp.

Ref. 139D: "Wire Array Antennas", Chapter 8 in "Antenna Toolkit", Joseph J. Carr (K4IPV), 2nd ed., Newnes, 2001, 263 pp.

Ref. 139E: "Multi-Element Arrays", Chapter 8 in "The ARRL Antenna Handbook", 21st ed., 2007, 976 pp.

Ref. 139F: "Antenna arrays", Mississippi State University ECE4990 course notes nr. 6, Patrick Donohoe, 2014 [pdf]

Ref. 139G: "Array Antennas", Chapter 20 in "Electromagnetic Waves and Antennas", Sophocles J. Orfanidis, 2014 [pdf]

Ref. 139H: "Arrays of Dipoles and of Apertures", Chapter 11 in "Antennas", John D. Kraus, 2nd ed., McGraw-Hill Book Co., 1988, 924 pp.

Ref. 139J: p. 170 in "Über die Richtcharakteristik von in einer Ebene angeordneten Strahlern" [About the directivity of planar arrays], H. Stenzel, in "Elektrische Nachrichten-Technik" (ENT), Vol. 6, Nr. 5, May 1929, pp. 165-181; source: cdvandt.org

Ref. 139K: "Ausgewählte Fragen über Theorie und technik von Antennen - Zusammengestellt aus Vorträgen anläßlich der Arbeitsbesprechung "Antennen" veranstalltet vom Generalbevollmächtigten für technische Nachrichtenmittel in Verbindung mit dem Vierjahresplan-Institut für Schwingungsforschung", 24-26 March 1943, Vol. 2, Zentrale für wissenschaftliches Berichtewesen der Luftfahrtforschung des Generalluftzeugmeisters (ZWB), Berlin-Adlershof; source: cdvandt.org

Ref. 139K1: pp. 134-144, "Grundsätzliches über Richtantennen" [basics of directional antennas], W. Moser

Ref. 139K2: pp. 45-63, "Der Einfluss der Reflektorwand auf die Ortskurve von Breitband - Rohrdipolen" [Effect of a reflector surface on the impedance of thick broadband dipoles], G. Dieckmann
Ref. 139K3: pp. 5-29, "Grundlagen der Breitbandantennenanlagen" [basics of broad-band antenna systems], O. Zinke
Ref. 139K4: pp. 223-231, "Neue Erfahrungen der Deutschen Reichspost in der Speisung von Antennen für lange und kurze Wellen" [new experiences of the with feeding long-wave & shortwave antennas], Ellrodt
Ref. 140: "Zum 75 jährigen Bestehen der Firma Hein, Lehmann & Co., A.-G., Düsseldorf 1888 - 1963", Heinz Steguweit, Düsseldorf (publ.), 1963, 123 pp.

Ref. 140A: "Zum 50 jährigen Bestehen der Firma Hein, Lehmann & Co. A.-G.", M. Foerster, in "Der Bauingenieur", Vol. 8, Nr. 11, 12 March 1927 , pp, 180-183. Source: Silesian University of Technology.

Ref. 141: "FuSAn, Peil- und Funkanlagen", Harry Lippmann, 2007. Source: Deutsches Atlantikwall-Archiv. [pdf]

Ref. 142: "Bandbreitenfragen bei Anwendung der Siemens-Hell-Fernschreibtechnik" [signal bandwidth issues with A2 and A3 modulation], Rudolf Zimmermann, 7 pp., Technische Mitteilungen des Fernmeldewerks, Siemens & Halske A.G., Wernerwerk, Abteilung für Telegrafengerät, Berlin-Siemensstadt, May 1940, SH 7998, 1. 8. 40. T T1.

Ref. 145: "Funk- und Bordsprechanlagen in Panzerfahrzeugen" ["Radio and intercom systems in armored vehicles"], Vol. 3 of "Die deutschen Funknachrichtenanlagen bis 1945", H.-J. Ellissen, Marketing & Technik Verlag, 1991, 240 pp., ISBN 3-928388-01-0. [pdf **See note 1**, file size: **68 MB**; a lower-resolution version is here,10 MB]:

Ref. 145A: pp. 88-92, "Funkleitstrahlverfahren" [Lorenz guide beams for infantry and armoured vehicles]

Ref. 145B: pp. 166-169 , "Schleifringübertrager allgemein" ["Slip ring assemblies - general"]

Ref. 146: p. 3 in "Instruktion för Hellskriv-apparat" [in Swedish], Kungl. Arméförvaltningens Tygavdelning, SiB/040:3045, 13 July 1945, 40 pp. (courtesy Willi Reppel, SM6OMH)

Ref. 147: "High-Power Crystal Set", Walter B. Ford, in "Popular Electronics", August 1960, pp. 63-65

Ref. 148: "Empfangsversuche mit dem Sirutor", F. Nitturra, in "Funkschau", Vol. 13, Nr. 2, February 1940, p. 29

Ref. 149: "Anregungen zum Detektorempfang", H.-A. Dennig, in "Funkschau", Vol. 16, Heft 8/9, August/September 1943, p. 80

Ref. 150: "Crystal Set Analysis", Berthold Bosch (DK6YY), March 2002, 15 pp. [pdf]

Ref. 152: Luftwaffe search-lights

Ref. 152A: "Scheinwerfer der deutschen Luftwaffe", C. Mattner, in "Zeitschrift des Vereines deutscher Ingenieure", Bd. 18, Nr. 33, 14 August 1937, pp. 953-955

Ref. 152B: "pp. 136-139 in "Der Flakscheinwerferkanonier", Ernst Schlachtmann, "Handbücher der Luftwaffe - Der Dienstunterricht in der Flakartillerie - Ausgabe für den Flakscheinwerferkanonier", 3rd ed., Verlag E.S. Mittler & Sohn, 1939, 155 pp.

Ref. 154: "Das Mädchen, die Katze und der Amboss - Auszüge aus '100 Jahre Ziehl-Abegg'", source: industrieanzeiger.de

Ref. 155: p. 16 in "PLAKAT - Gedanke und Kunst: Einiges aus der Plakat-Praxis", Propaganda Stuttgart, 1912, 63 pp.

Ref. 156: "The Science of Locomotion - Why Rail Has 20X Energy Saving Advantage Over Rubber Tire Road Vehicles". Source: Brooklyn Historic Railway Association.

Ref. 157: "Railway Engineering", Karim H. Al Helo, Department of Building Construction Engineering, University of Technology, Iraq, 64 pp.

Ref. 158: "Adhesion in the wheel-rail contact under contaminated conditions", Yi Zhu, Licentiate thesis at the Royal Institute of Technology, Stockholm/Sweden, 2011, 100 pp. [pdf]

Ref. 159: slide 24 in "Railroad Transportation Energy Efficiency", C. Barkan, University of Illinois at Urbana-Champaign, 2007, 61 slides [pdf]

Ref. 160: "Some graphical solutions to electric railway problems", A.M. Buck, in "University of Illinois Bulletin", Vol. XIII, No. 47, 1916, 40 pp.

Ref. 161: "The characteristics and control of rectifier-motor variable speed drives" [mercury-arc rectifiers], P. Bingley, in "Proc. of the IEE Part II: Power Engineering", Vol. 99, Issue 69, June 1052, pp. 189-202 (Author's reply to discussion: pp. 205-206)

Ref. 162: Ward-Leonard drive systems

- **Ref. 162A:** "Ward Leonard drives 75 years of development", K.A. Yeomans, IEEE Electronics and Power, Vol. 14, Nr. 4, pp. 144-148
- **Ref. 162B:** "Electrical Transmission of Power", H. Ward Leonard, United States Patent Office, Patent No. 463,802 [pdf]
- **Ref. 162C:** "A new system of electric propulsion", Harry Ward Leonard, in "Transactions of the American Institute of Electrical Engineers (AIEE)", Vol. IX, Issue 1, January 1892, pp. 566-577
- **Ref. 162D:** "Volts vs. Ohms; Speed Regulation of Electric Motors", Harry Ward Leonard, in "Transactions of the American Institute of Electrical Engineers (AIEE)", Vol. XIII, January 1986, pp. 373-386
- **Ref. 162E:** "Ward Leonard System", pp. 445-446 in "Synchros and Servomechanisms", Chapter 21 in "Basic Electricity", United States. Dept. of the Army, Naval Education and Training Program Development Center, FM 55-506-1, 22 April 1977, 490 pp.
- **Ref. 162F:** "Leonard Doppel-Umformer U65a (neuere Form)", F 054a, Ln 20 347-1, 2 pp. (3 kW generator, 9 kW motor). Source: www.cdvandt.org
- **Ref. 162G:** "Beiträge der Firma Siemens zur Flugsicherungstechnik und Luftfahrt-Elektronik in den Jahren 1930 bis 1945 (Teil 1 & 2)", H.J. Zetzmann, in "Frequenz - Zeitschrift für Schwingungs- und Schwachstromtechnik", Part 1: Vol. 9, Nr. 10, 1955, pp. 351-360, Part 2 (pp. 387, 388, 392): Vol. 9, Nr. 11, 1955, pp. 386-395
- **Ref. 162H:** "Type 7", RAF Ventnor Radar website [pdf]

Ref. 163: Mercury Arc / Vapor Rectifiers

- **Ref. 163A:** "Mercury cathode tubes: Ignitron, Excitron, Sendytron", Chapter 6, pp. 210-255, of "Gas-discharge tubes", H.L. van der Horst, Philips Technical Library series, 1964, 318 pp.
- **Ref. 163B:** "Mercury Arc Rectifier Practice", F.C. Orchard, Pittsburg Instruments Publ. Co., 1936, 255 pp. [pdf 19 MB]
- **Ref. 163C:** "Mercury Arc Power Rectifiers - Theory and Practice", O.K. Marti, H. Winograd, 1st ed., McGraw-Hill Book Co. Inc., 1930, 478 pp. [pdf 38 MB]
- **Ref. 163D:** "Der Quecksilberdampf-Gleichrichter (Stromrichter) der

Starkstromtechnik", Weissbach, in "Funk-Technik - Zeitschrift für das gesamte Elektro- Radio- und Musikwarenfach", pp. 15, 18, 19 in Nr. 1, 1948, and pp. 63, 66, 67 in Nr. 3, February 1948

Ref. 163E: pp. 681-688 in "Electrical machines" R.K. Rajput, 4th ed., Laxmi Publications, 2006, 881 pp.

Ref. 163E: "Converters, the mercury arc rectifier and supply to electric railways", Chapter 10 in "Electric Railways 1880-1990", Michael C. Duffy, IET, 2003, 452 pp.   [pdf]

Ref. 163F: "Some notes on ignitrons and thyratrons", F. Dörenberg, 2014, 3 pp.

Ref. 163G: "Controlling the DC output voltage of a Mercury Arc Rectifier", F. Dörenberg, 2014, 2 pp.

Ref. 163H: "Sur le courant de reaction de l'arc electrique", Jules-Célestin Jamin, Georges Maneuvrier, p. 1615-1619 in "Comptes Rendus des Séances de l'Académie des Sciences", Vol. 94, January-June 1882, 1795 pp.

Ref. 163J: "Method of Transforming Electrical Energy", Peter Cooper Hewitt, US Patent No. 780,999; filed April 25, 1902 (patented January 31, 1905), 7 pp.

Ref. 163K: "Electric-Discharge-Controlling Device and Method of Operating the Same", Irving Langmuir (General Electric), U.S. Patent No. 1,289,823; filed November 6, 1914, published December 31, 1918, 5 pp.

Ref. 163L: "DC Power Transmission - Mercury-Arc to Thyristor HVdc Valves", Deepak Tiku, in "IEEE Power & Energy Magazine", Volume 12, Nr. 2, March-April 2014, pp. 76-96   [pdf]

Ref. 163M: "Physik und Technologie der Quecksilberdampfventile für die Hochspannungs-Gleichstrom-Übertragung", Johannes Mitterauer, presented at VDE-Tagung "75 Jahre Hochspannungs-Gleichstrom-Übertragung (HGU), Entwicklung - Technologie - Anwendung", Berlin, 26-27 September 2011   [pdf]

Ref. 163N: "Principles of Mercury Arc Rectifiers and Their Circuits", David Chandler Prince, Francis Brooke Vogdes, McGraw-Hill Book Co., 1st ed., 1927, 233 pp.   [pdf]

Ref. 163P: "Current and Voltage Wave Shape of Mercury Arc Rectifiers", H. D. Brown, J. J. Smith, pp. 973-984 in "Trans. of the American Institute of Electrical Engineers", Vol. 52, Issue 4, December 1933.

Ref. 163Q: "The development of power electronics in Europe", Frank Dittmann, 2004 IEEE Conf. on the History of Electronics, Bletchley Park/UK, June 2004, 14 pp.   [pdf]

Ref. 163R: "Vom Quecksilberdampfgleichrichter zur Leistungselektronik", A. Schmidt, J. Schräder, in "Elektrotechnische Zeitung (ETZ)", Vol. 101, 1880, Nr. 16/17, pp. 955-960.

Ref. 163S: "Thyratrons and their applications to radio engineering", A.J. Maddock, in "Electrical Communication - A Journal of Progress in the Telephone, Telegraph and Radio Art", published by International Standard Electric Corp., pp. 339-378. Source: worldradiohistory.com, accessed 16 September 2020.

Ref. 163T: "Brunswick West Mercury-Arc Tramway Substation", Nomination for the Engineering Heritage Australia Heritage Recognition Program, Version 11, November 2019, 29 pp. Source: engineersaustralia.org.au, retrieved 26 May 2022.

Ref. 164: documents of the Combined Intelligence Objectives Sub-Committee (CIOS). Source: cdvandt.org.

Ref. 164A: "Institutes of the Bevollmaechtigter fuer Hochfrequenz-Forschung", CIOS, Item No. 1 & 7, File No. XXXI-37, May 1945, 215 pp.; source: cdvandt.org.

- **Ref. 164A1:** p. 30 (Bernhardine).
- **Ref. 164A2:** pp. 44-46, 49-51 (Erika 1, 2, 3, 4; Erika "fine method").
- **Ref. 164A3:** pp. 52-56 ("Investigation of Komet Experimental Site at Ismaning").
- **Ref. 164A4:** pp. 192-199 (German Radio Counter Measures, RCM).

Ref. 164B: "The I.T.T., Siemens and Robert Bosch Organizations" [incl. Lorenz: Elektra, Sonne, Mond, Knickebein, Erika, Goldwever, Hermine, 6-mast Lorenz Adcock D/F based on British patent, Lorenz Blind Approach/Landing, IFF, radar], CIOS, Item No. 1, 7 & 9 (Radar, Signal Communications, Physical & Optial Instruments and Devices), File No. XXXI-38. Source: cdvandt.org. Retrieved 22 September 2019.

Ref. 164C: "Report on C. Lorenz A.G." [history, factories, relationship with Philips & Telefunken, Stuttgart UHF radio link (FuG0s, FuG03a), Feuerzauber & Feuermolch Oboe-jammer, FuG200, FuG226/Neuling], CIOS, Item No. 1, File No. XXV-12, 13 pp. Source: cdvandt.org. Retrieved 7-Feb-2020.

Ref. 164D: "Beacon Transmitters", in "Inspection of Philips Works at Eindhoven", Robert Watson Watt, CIOS Target Number 1/42, transcript of CIOS file No. III-1, 23-26 September 1944, 56 pp. Source: cdvandt.org. Retrieved 27 March 2022.

Ref. 172: copy of item in file AIR 29/284 "Central Interpretation Unit (CIU) Medmenham; Interpretation reports and aerial photos (1943)". Item is in the collection of The National Archives; material with UK Crown Copyright, used in accordance with the Open Government License [pdf].

Summary of the contents of ref. 172A.

Ref. 172A: "German “Windjammer” R.D.F. Stations", part of "Monthly interpretation review for July 1943", 7 pp.

Ref. 173: copy of items in file AIR 14/3577 "Signals investigation on 27 to 35 Mc/s "Windjammer" (1943/1944)". Items are in the collection of The National Archives; material with UK Crown Copyright, used in accordance with the Open Government License [pdf].

Summary of the contents of ref. 173A-173E.

Ref. 173A: ""Windjammer" observation", by R.A. Fareday (Noise Investigation Bureau [Electronic Intelligence], N.I.B., London), dated 20th June 1944, 1 page.

Ref. 173B: "Possible "Windjammer" transmissions", report by Flight Lieutenant Douglas of 192 Sq., dated 16th December 1943, 1 page.

Ref. 173C: "192 Squadron Flight report No. 215/43" by F/Lt Robinson to Squadron Leader Burtler, dated 15th November 1943 (actual report by P/O G.F. Evans of 13th November 1943), 6 pages.

Ref. 173D: "Windjammer – Arcachon", letter from Air Ministry A.I.4. [intelligence branch section supervising RAF Y Service] to Commanding Officer of 192 Squadron, dated 16th July 1943, 1 page + 1 aerial photo.

Ref. 173E: "The Windjammer and Dreh-Elektra", by 192 Squadron Leader J. Whitehead, dated 18th June 1943, 1 page.

Ref. 174: copy of items in file AIR 14/3594 "Windjammer" station: photographs and interpretation reports. Includes vertical and low oblique aerial photographs of 'Windjammer' radar sites in Germany and France (1943/1944)". Items are in the collection of The National Archives; material with UK Crown Copyright, used in accordance with the Open Government License [pdf].

Summary of the contents of ref. 174A-174J.

Ref. 174G: "Interpretation report No. G.590" dated 6th October 1942, of aerial photo taken over locality Morlaix, W/T station Mt. St. Michel, at altitude of 12k ft during Sortie Q/21 on 24th September 1942, 2 pages + 1 photo.

Ref. 174H: Letter entitled "W/T: Pouzauges/St.Michel-Mont-Mercure" on behalf of Group Captain commanding R.A.F. Station Medmenham to Squadron Leader Whitehead (A.I.4), dated 29th March 1943, 1 page + 3 photos.

Ref. 175: articles about the "Y" service and RAF 192 Squadron

Ref. 175A: pp. 512-516, 524 in "Activities at Knockholt", J.A. Reeds, Appendix B in "Breaking Teleprinter Ciphers at Bletchley Park - General Report on Tunny with Emphasis on Statistical Methods (1945)", 1st ed., I.J. Good, D. Michie, G. Timms (J.A. Reeds, W. Diffie, J.V. Fields, eds.), John Wiley & Sons, IEEE Press, 2015, 735 pp.

Ref. 175B: "Account of 192 Squadron radio countermeasures operations" [part of the 'Y' service; "Bernhardine"], Frances Grundy, 1945, 8 pp. Source: IBCC Digital Archive, accessed June 16, 2021. Content is available under a CC BY-NC 4.0 International license (Creative Commons Attribution-NonCommercial 4.0).

Ref. 176: post-war correspondence [in German] between Mr. Kurt Pfaender (frmr. Telefunken employee) and Telefunken, as well as Telefunken-internal, regarding past wages (back pay) and reimbursement of expenses incurred by Mr. Pfaender for transportation of Telefunken equipment from Trebbin to a site near Hannover, during February & March of 1945; source: corporate archives of DTM Berlin, part of file nr. I.2.060C-00499:

Ref. 176A: Letter from Mr. Kurt Pfaender to the HR office of Telefunken in Berlin, with claims; dated 15 November 1950, 1 p.

Ref. 176B: Letter from Mr. Albrecht Leyn (Telefunken/Hannover) to Mr. Gothe (Telefunken/Berlin), recollecting payments of bills & sale of items to Mr. Pfaender; dated 18 September 1951, 2 pp.

Ref. 176C: Telefunken memo about conversation with Mr. Pfaender on 20 December 1951, regarding claims of the latter; dated 27 December 1951, 1 p.

Ref. 176D: Letter from Kurt Pfaender to Telefunken in Berlin, describing the course of events; dated 12 January 1952, 2 pp.

Ref. 177: post-war letters [in German] from the company "Hein, Lehmann & Co. Eisenkonstruktionen, Brücken- und Signalbau K.-G." in Berlin-Tempelhof to Telefunken in Berlin, with claims ("Altforderungen") regarding delivery and installation of various types of antenna systems (arrays, tube & lattice masts, wooden masts, metal-clad wooden huts, verticals, dishes, turntables, for "Bernhard", "Marius", "Marius II", "Uran II", "Forsthaus-KF", etc.), installations in Germany, Hungary, Monte Carlo, Croatia, etc., during the period of July 1942 through the end of the war (8 May 1945); source: corporate archives of DTM Berlin, file nr. I.2.060C-00541:

Ref. 177A: Letter from Hein, Lehmann & Co. to Telefunken with payment status of 17 Telefunken purchase orders and the resulting outstanding significant claim; dated 19 June 1949, 2 pp.

Ref. 177B: Letter from Hein, Lehmann & Co. to Telefunken with adjusted claims, based on assessment of Telefunken counter-claims; dated 19 June 1950, 8 pp.

Ref. 177C: Letter from Hein, Lehmann & Co. to Telefunken, with further justification for claims regarding delivery & installation of 12 "Bernhard" antenna systems (against purchase order of July 1941) for Be-2 - Be-8 and Be-12, of 6 associated "Dioden-Masten" antenna masts (based on price quote of September 1941), and delivery (without installation) of the antenna systems of Be-1 and Be-9 - Be-11; dated 5 February 1951, 3 pp.

Ref. 178: Reichsmark vs. US Dollar and Euro exchange and equivalency data:

Ref. 178A: "Deutsche Bundesbank - Average Currency Exchange Rates 1908-1951 Mark / Reichsmark / Deutsche Mark (M/RM/DM) vs. France FRF / Austria K,S / USA $ / UK £ / Netherlands HFL", Vs 801, 12 pp. Retrieved 2017. [pdf]

Ref. 178B: source of US dollar inflation (CPI, buying power) calculator: www.usinflationcalculator.com.

Ref. 178C: Tabulated exchange rate of Reichsmark to US$, with conversion to 2016 US$ and Euro, Frank Dörenberg, 21 May 2017; based on ref. 178A/B.

Ref. 179: "Votragsnotiz", draft presenter notes addressed to the *General-Nachrichtenführer* (Gen-Nafü), 3 September 1944, 3 pp.

Covers original plans for geographic coverage (France, German Reich) with Bernhard stations, state of completion of the various Be-stations, status of introduction of the Bernhard/Bernhardine method for night-fighters (Nachtjagd).

Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/Germany (Signatur) file nr. RL 2-V/6, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016"

Ref. 180: Layout of the Bernhard installation in Trebbin, based on a sketch from an eyewitness (name and date unknown); source: corporate archives of DTM Berlin, file nr. I.2.060C-07823.

Ref. 181: "Drehfunkfeuer System Telefunken - Teil 1: Verfahrensbeschreibung EC1-4262", Adalbert Lohmann, Berlin, October 1942, 129 pp., copy nr. 29, personal copy of Albrecht Leyn; source: corporate archives of DTM Berlin, file nr. I.2.060C-06172. [file size: **62 MB**; a lower-resolution version is here, 28 MB]

Ref. 183: "Das Drehfunkfeuer-Verfahren Bernhard und Bernhardine, System Telefunken" ("Verfahrensbeschreibung Bernhard, Bernhardine", description of the Bernhard-Bernhardine method), Adalbert Lohmann, Telefunken Gesellschaft für drahtlose Telegraphie m.b.H., Berlin-Zehlendorf, Telefunken document EC 1 4310, July 1943, 28 pp., copy nr. 11; source: corporate archives of DTM Berlin, file nr. I.2.060C-04403.

Ref. 188: List of 1929-1940 patents of the Conz company (and its employees) regarding frequency conversion and motor speed control; source: DEPATISnet (search-engine of the German patent & trademark office, DPMA).

Ref. 189: "Stückliste zum Kabelplan "Bernhard"" [parts list of "Bernhard" wiring diagram], Telefunken document EC1-4237, 6 July 1942, 23 pp.; source: corporate archives of DTM Berlin, part of file nr. I.2.060C-07753.

Ref. 190: "Kabelplan "Bernhard"" [system block diagram], Telefunken Gesellschaft für drahtlose Telegrafie m.b.H., document EC1-4237, 27 June 1942, 1 sheet; source: corporate archives of DTM Berlin, part of file nr. I.2.060C-7753.

Ref. 191: Chapter 4.4 (pp. 93-118) in "Die Geschichte des Quecksilberdampf-Gleichrichters bei BBC Deutschland 1913 - 1963", Peter Rudolf Wetzel, dissertation University of Stuttgart, 2001, 359 pp., OCLC nr. 51713376.

Ref. 192: "Electronic Rectifiers and Valves", A. Güntherschulze [pdf], translation of

"Elektrische Gleichrichter und Ventile" by Norman A. de Bruyne (translator), John Wiley & Sons 1928, 227 pp.

Ref. 193: "Justier- und Prüfvorschriften für Schienenkranz" [Adjustment and verification instructions for circular rail track], Telefunken Gesellschaft für drahtlose Telegrafie m.b.H., Berlin-Zehlendorf, document nr. EC1-4160, 12 June 1942, 11 pp., p. 7 & 9 missing; source: corporate archives of DTM Berlin, part of file nr. I.2.060C-07753.

Ref. 195: first page of "Aenderung des Modulators für Zeigersender "BERNHARD"" [modification of the "Bernhard" compass scale transmitter modulator], Telefunken GmbH, document nr. EC1-4157B, February 1943; source: corporate archives of DTM Berlin, part of file nr. I.2.060C-07755.

Ref. 196: "Quarzvorsatzstufe für die 500 Watt-Sender der Anlage "BERNHARD"" [crystal front-end for the "Bernhard" 500 watt transmitters], E-Stelle Rechlin, dept. EB8-SE0525B, date unknown, 1 p.; source: corporate archives of DTM Berlin, part of file nr. I.2.060C-07755.

Ref. 197: pp. 11-13, 24 in "Kabel-Herstellung: Kabelaufbau, Werkstoffe, Verfahrenstechnik" [cable manufacturing], Walther Ehlers, Hermann Lau, Springer-Verlag (publ.), 1956, 434 pp.

Ref. 198: FuG 120a and Psch 120a

Ref. 198A: "Ergänzung zur Beschreibung FuG 120 - Nachtrag: FuG 120a, Peilschreiber Psch 120a" ["Supplement to description of FuG 120, Appendix FuG 120a, Psch120a printer"], Telefunken Abt. FN/TL, August 1944, 11 pp. Source: corporate archives of DTM Berlin, file nr. I.2.060C-07754.

Ref. 198B: "Funknavigationsanlage FuG 120 a - Einzeladerverlegung" [wiring list & diagram], Telefunken Gesell. für drahtlose Telegraphie m.b.H., document nr. V/F 2297, December 1944, 2 pp. Source: corporate archives of DTM Berlin, file nr. I.2.060C-07754.

Ref. 198C: "Reglerkasten Rgk 120a" [control box], Telefunken Gesell. für drahtlose Telegraphie m.b.H., document nr. V/F 2298, December 1944, 2 pp. Source: corporate archives of DTM Berlin, file nr. I.2.060C-07754.

Ref. 198D: "Peilschreiber Psch 120a Stromlaufplan, Schaltplan-Stückliste" [schematic & parts list], Telefunken Gesell. für drahtlose Telegraphie m.b.H., document nr. V/F 2334, 1 & 12 December 1944, 3 pp. Source: corporate archives of DTM Berlin, file nr. I.2.060C-07754.

Ref. 198E: "Peilschreiber P.Sch.120a - Ln 28 997 - Gerät-Nr. 124-270 A - Beschreibung und Betriebsvorschrift" ["PSch120a Description and Operating Instructions"], Siemens Fernmelde Technik, Siemens & Halske AG, Wernerwerk für Telegrafiegeräte, Berlin-Siemensstadt, 23 pp. No date on document, but schematic is dated 24 August 1944.

Ref. 198F: "F-Geräte Peilschreiber Psch 120a", RLM, outline drawing of the Peilschreiber Psch 120a (= Gerät Nr. Ln 28997) with attached mounting frame (= RP, Gerät Nr. Ln 28998), no date marked on document, 1 p. Source: corporate archives of DTM Berlin, part of file nr. I.2.060C-07759.

Ref. 198G: "Unterlagenmappe für FuG. 120a" ["Document folder for FuG. 120a"; file size: **98 MB**; a lower-resolution version is here,18 MB]; source: Air Documents Division, T-2, AMC, Wright Field, Microfilm No. R 2262 F 314; comprising:

"Einbauvorschrift für Anlage FuG 120 a (Einzeladerverlegung)" ["Installation instructions"], Telefunken FR/TL, VF 2299; "Leitungskontrollplan für Anlage FuG 120 a" , VF 2853; "Einbau-

Prüfvorschrift für Anlage FuG 120 a" [Test instructions], VF 2332; "Anlagen-Prüfvorschrift für Anlage FuG120 a (In Verbdg. m. Fu Bl 2 u, FuG X)", VF 2333.

F-Geräte (Ln-Blätter): Umformerfußplatte (UF 120), Ln28980 (Telefunken, October 1947); Rahmen (RSV 120), LN28981, (Telefunken, October 1947); Siebgerät-Fußplatte (SGF 120), Ln28928 (Telefunken); Umschaltgerät (UG 120), Ln28983 (Telefunken); Verteilerdose (VD 120), Ln28984 (Telefunken); Schreibverstärker (SV 120), Ln28985 (Telefunken); Sprechknopf, feststellbar (Spk f 1a), L28986 (Frieseke & Höpfner, Potsdam-Babelsberg); Zwischenleitungkopplung (ZLK VIII S 3), Ln28987 (Frieseke & Höpfner, Potsdam-Babelsberg); Umformer (U 120), Ln28988 (Telefunken); Siebgerät (SG 120), Ln28989 (Luftfahrtgerätewerk, Berlin-Hakenfelde); Peilschreiber (Psch 120 a), Ln28997 (Siemens & Halske A.-G, WWT); Rahmen für Drehfunkfschreiber (RDFS 120), Ln28998, Siemens & Halske A.-G, Berlin-Siemensstadt); Reglerkasten (Rg K 120a), Ln29311 (Telefunken, Berlin-Zehlendorf).

"Stromlaufplan Peilschreiber Psch 120a", V/F 2334 (1 December 1944).

"Schaltplan-Stückliste Peilschreiber Psch 120a", V/F 2334 (Telefunken, 12 December 1944, 2 pp.).

"Stromlaufplan Reglerkasten Rgk 120a", V/F 2298 (Telefunken, 9 December 1944); "Schaltplan-Stückliste Reglerkasten RgK 120a", V/F 2298 (Telefunken, 1 December 1944, 1 p.); "Stromlaufplan Umschaltgerät UG 120", EB8 Schaltbild Nr. 95b (Telefunken); "Stromlaufplan Sieb", T.Str. 4211/4, T.bk.103a (Siemens & Halske A.-G, WW, 22 July 1943); "Aufstellung der Ersatzteile SG.120, "Aufbau des Gerätes, Beschreibung der Schaltung", T.Beschr. 4211/4 (Siemens & Halske A.-G, Wernerwerk); "Grundschaltplan Stromversorgung" [schematic, power supply; single-page version is here]; "Grundschaltplan Schreibverstärker" [schematic, printer amplifier; single-page version is here].

"Prüfung des Schreibverstärkers SV 120 auf dem Endplatz" ["Testing the installed SV 120"], Telefunken - EB5, EB8-Pv105 (13 December 1943);

"Schaltbild der Anlage Fu G 120a" [interconnect scheme, system; single-page version is here], V/F 2297, 4 December 1944; "Zusatzschaltplan zur F-Anlage FuG 120 a, V/F 2336" [schematic] (Telefunken, 4 December 1944); "Leitungsplan" [wiring diagram], V/F 2335 (Telefunken, 12 December 1944)."VL-Stückliste Nr. 3809, Leitungs- und Montagematerial Bord-Anlage FuG 120 a" [parts list], Telefunken Fliegerabteilung, 22 September 1944.

Ref. 198H: "Neu zu bearbeitende Geräte" ["New equipment, still to be processed"], p. 59 of 417 in "Fertigungsführung Nr 117328 /45 Geheim" ["Production management - Secret"], 2 January 1945, in "Anlagen zum Kriegstagebuch - Technische Luftrüstung" ["Appendices to the War Diary - Technical Air Armement"], Vol. 3, 417 pp. Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) in Freiburg/Germany, file nr. (Signatur) RL 3/2570; used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 198J: "Peilschreiber P.Sch.120a - Ln 28 997 - Gerät-Nr. 124-270 A - Beschreibung und Betriebsvorschrift" ["Peilschreiber PSch120a - Description and Operating Instructions"; file size: 26 MB; a lower-resolution version is here,5 MB], Siemens Fernmelde Technik, Siemens & Halske AG., Wenerwerk für Telegrafiegeräte, Berlin-Siemensstadt, 23 pp.

Ref. 201: 3 photo pages from "Unterlagenmappe und Bedienungsvorschrift zu den Bordnavigationsgeräten "FuG 120" und FuG 120a"" ["Documentation file and operating instructions to on-board navigation equipment FuG 10 and 120a"], Telefunken Gesell. für drahtlose Telegraphie m.b.H., TFK FN/TL Bord, August 1944; source: corporate archives of DTM Berlin, file nr. I.2.060C-07760.

Ref. 207: p. 65 in "Hamburgs alte Fabriken - einst und jetzt", E. Freiwald, G. Freiwald, Sutton Verlag, 2013, 159 pp.

Ref. 208: carbon pile regulators:

Ref. 208A: "Carbon Pile Regulator" pp. 11-13 in "Aircraft Electrical Systems", E.H.J. Pallett, Pitmann Publ., 1976, 166 pp.

Ref. 208B: "Carbon pile regulators", June 1945 [pdf]

Ref. 208C: Pintsch advertising, p. II in "Elektrotechnische Zeitung", Nr. 12 (21 March), 1935.

Ref. 211: "Amplitude Modulation and Demodulation", Frank Dörenberg, V1.1, August 2017, 8 pp.

Ref. 214: "Vindmotor med automatiska regleringsanordningar" [wind turbine with automatic control devices]; Finnish patent nr. 3606 [Finnish title "Tuulimoottori itsetoimivilla ohjejärjestelyillä"]; inventors: Eduard Abegg, Carl Gustaf Oscar Grevillius; owner: Fridolf Leonard Schaumann; awarded 25-Feb-1909, 44 pp.

Ref. 215: p. 246 in "Disturbance signals in a feedback control system", section 4.4 in "Modern Control Systems", Richard C. Dorf, Robert H. Bishop, Prentice Hall publ., 12th ed., 2011, 1083 pp.

Ref. 218: "Der Längstwellensender Goliath bei Kalbe (Milde)", Klaus Herold, pp. 169-190 in "100 Jahre Funktechnik in Deutschland: Funksendestellen rund um Berlin", Wolfgang Behnke, Vol. 1 of "100 Jahre Funktechnik in Deutschland", Wissenschaft-und-Technik Verlag, 3rd ed. 2004, 342 pp., ISBN: 3-936124-65-5 ***See note 1***

Ref. 221: "Dr. phil. Siegmund Loewe (1885-1962)", Herbert Börner, in "Funkgeschichte", Vol. 12 (1989), Nr. 67, pp. 9-13 [pdf]

Ref. 223: "PSU and generator for Bernhardine Hundberg Denmark", US National Archives and Records Administration (NARA), Scan Nr. 9821 111SC 269041; courtesy Mike Dean.

Ref. 224: several pages from the 20 page April 1939 product catalog and price list for GURO and RAPID products of the Paul Jordan Elektrotechnische Fabrik G.m.b.H. Co, KG. in Berlin-Steglitz.

Ref. 228G: pp. 200-204 in "Rotating beacons", Section 4.12 of "Radio Aids to Civil Navigation", Reginald Frederick Hansford (ed.), Heywood & Co. Ltd. (publ.), 1960, 623 pp.

Ref. 229: *civil* equi-signal beam systems (Scheller, Fixed-course & Four-Course ranges, E/T & A/N beacons, Visual Ranges, Visual Aural Ranges)

Ref. 229A: articles in German and Dutch language

Ref. 229A1: "Über die Wirkung von Schellers drahtlosen Kursweiser auf das Flugzeug" ["About the impact of Scheller's wireless direction pointer on aircraft", Eberhard Buchwald, in "Zeitschrift für drahtlose Telegraphie und Telephonie sowie des Gesamtbereichs der elektromagnetischen Schwingungen", Vol. 15, Nr. 2, February 1920, pp. 114-122. Source: hathitrust.org, retrieved April 2021.

Ref. 229A2: "Neue Versuche über funkentelegraphische Richtsender" ["New trials with directional spark transmitter stations"; A/N system], Franz

Kiebitz, in "Zeitschrift für drahtlose Telegraphie und Telephonie sowie des Gesamtbereichs der elektromagnetischen Schwingungen", Vol. 15, Nr. 4, April 1920, pp. 299-310.

Ref. 229A3: "Zur Geschichte der Richtwirkungs- und Peilversuche auf den Flugplätzen Döberitz und Lärz" ["History of radio directivity- and direction-finding tests at Döberitz and Lärze airfields"], Richard Baldus, Eberhard Buchwald, Rudolf Hase, in "Jahrbuch - Zeitschrift für drahtlose Telegraphie und Telephonie", Vol. 15, Nr. 2, February 1920, pp. 99-100. Source: hathitrust.org, retrieved April 2021.

Ref. 229A4: "Über Richtempfangsversuche im Flugzeug" ["About directional reception in airplanes"], Eberhard Buchwald, in "Jahrbuch - Zeitschrift für drahtlose Telegraphie und Telephonie", Vol. 15, Nr. 2, February 1920, pp. 101-113. Source: hathitrust.org, retrieved April 2021

Ref. 229A5: "Das Kaiserliche Telegraphen-Versuchsamt" ["The Imperial Telegraphy Test Institute"], in "Telefunken Zeitung", Vol. 3, No. 1, January 1914, pp. 7-9. Source: radiomuseum.org, retrieved 11 April 2021.

Ref. 229A6: "Neuere Arbeiten auf dem Funkbaken-Gebiete" ["Recent work in the field of radio beacons"; Lorenz, E/T keying, magnetic-bias keying, VHF beacon], Ernst Kramar, "Hochfrequenztechnik und Elektroakustik", Vol./Nr. 40, September 1932, pp. 88-92. [Abstract].

Ref. 229A7: "Lorenz-ultra-korte golf-landingsbaken voor vliegtuigen" ["Lorenz VHF landing beacon for aircraft"], H. Veenstra (Lorenz; based on E. Kramar), in "Radio-Nieuws", Vol. 18, Nr. 3, 15 May 1935, pp. 49-61. Source: nvhrbiblio.nl, retrieved 24 May 2022.

Ref. 229A8: "De Nederlandsche radiobakens" ["The Dutch radio beacons"; incl. B.R.A. 101], pp. 59-66 in "Radio en Luchtvaart" ["Radio and aviation"], S. van der Molen, No. 5 of "Meulenhoff's Luchtvaartserie", J.M. Meulenhoff (publ.), 1936, 107 pp. Source: us.archive.org, retrieved 22 May 2022.

Ref. 230: German & British WW2 RDF, radio-navigation systems, and associated jamming systems / countermeasures

Ref. 230A: p. 46 in "The Secret War", Brian Johnson, Pen and Sword (publ.), 2004, 352 pp.

Ref. 230B: Table 1 in "Verfahren und Anlagen der Funkortung" ["Radio-navigation methods and installations"], W. Stanner, in "Elektrotechnische Zeitung (ETZ)", Ausgabe A, Vol. 75, Nr. 13, 1 July 1954, pp. 438-442. [circular LoP, hyperbolic LoP, Consol, Consolor, Decca, Loran, range of various systems incl. "Erika", "Erich", "Hermine", and "Mond"]

Ref. 230C: articles and books about the Battle of the Beams

Ref. 230C1: "Pulling the crooked-leg", R.V. Jones, in "New Scientist", 23 February 1978, pp. 493-496.

Ref. 230C2: "Milestones - Battle of the Beams", Carlo Kopp, in "Defence Today", January/February 2007, pp. 76, 77. [pdf]

Ref. 230C3: "The Battle of the Beams - Part 1-3", D.V. Pritchard (G4GVO), in "Practical Wireless", Vol. 64, No. 1, Issue 970, January 1989, pp. 43-47; No. 2, Issue 971, February 1988, pp. 46-49; No. 3, Issue 972, March 1988, pp. 30-34. Source: worldradiohistory.com, accessed 1 September 2020. Also published as "The Battle of the Beams - Part 1-3", D.V. Pritchard (G4GVO), in "Ham Radio Magazine", June 1989, pp. 29-38; August 1989, pp. 20-29; October 1989, pp. 53-61. Source:

worldradiohistory.com, accessed January 2014.

Ref. 230C4: "Battling the Radio beams", "Part 1: Headache and Aspirin" and "Part 2: Bromide, Domino and Benjamin", Bruce Taylor (HB9ANY), in "RadCom Magazine", Radio Society of Great Britain (RSGB), Vol. 96, No. 5, May 2020, pp. 80-82, and Vol. 96, No. 5, June 2020, pp. 82-84. Source: researchgate.net, retrieved September 2022.

Ref. 230D: "Most Secret War: Britisch Scientific Intelligence 1939-1945", R.V. Jones, Hamish Hamilton (publ.), 1978, 576 pp. **See note 1**

Ref. 230E: "The Secrete War", 7-part BBC/Imperial War Museum (IWM) TV broadcast series from 1977 [available on DVD and some episodes also on YouTube)]

Ref. 230E1: episode 1: "The Battle of the beams" (radio navigation beams used by the Germans for more accurate bombing, and the British countermeasures).

Ref. 230E2: episode 2: "To see a Hundred Miles" (radar).

Ref. 230E3: episode 3: "Terror Weapens" (the V1 and V2).

Ref. 230E4: episode 4: "If..." (inventions that never became operational, or were delayed, imagining what could have happened if they had been).

Ref. 230E5: episode 5: "The Deadly Waves"(magnetic mines and degaussing measures).

Ref. 230E6: episode 6: "Still Secret" (Bletchley Park and the Enigma Code, including the Colossus computer).

Ref. 230E7: episode 7: "The Battle of the Atlantic" (1978).

Ref. 230F: articles about the **X-Verfahren** ("X-Procedure), **X-Gerät** ("X-Equipment"), **Y-Verfahren** ("Y-Procedure"), **Y-Gerät** ("Y-Equipment"); this Y-navigation method is not to be confused with the "Y" fighter-guidance method (incl. Y-Peiler ("Y-D/F system") which is also referred to as "Y-verfahren", nor with the British radio monitoring/intercept Y-Service.

Ref. 230F1: pp. 48-49 (X-Gerät, Y-Gerät) in "German Radio Communication Equipment", US War Department Technical Manual, TME 11-227, June 1944, 61 pp.

Ref. 230F2: "Fliegerhorst Köthen" ["Köthen airfield"], source: Militärhistorisches Museum Anhalt, accessed 11 August 2020. [pdf]

Ref. 230F3: pp. 14-27 in "The First Pathfinders - The Operational History of Kampfgruppe 100, 1939-1941", Kenneth Wakefield, William Kimber (publ.), 1981, 265 pp.

Ref. 230F4: pp. lxx-lxxiv in "The Bombing War: Europe, 1939-1945", Richard Overy, Penguin Books Ltd. (publ.), 2014, 852 pp. (published 2013 by Allan Lane, published 2015 as "The Bombers and the Bombed: Allied Air War Over Europe, 1940–1945")

Ref. 230F5: "Der gezielte Blind-Bomben-Wurf - Die deutsche Lösungen: Das X-verfahren, Das Y-verfahren (Kampf)" ["The targeted blind bomb drop - The German solutions: the X-Procedure, the Y-procedure"], Heinrich Pusch (Oberst a.D. (Colonel, retired); Gruppenkommandeur Kampfgruppe 100 in 1939, Kommandeur Luftnachrichten-Regiment 31 in 1941 and Ln-Regiment 56 in 1943], date unknown (but after 1949/50, based on references to volumes of Winston Chruchill's memoires published in 1949 & 1950, see ref. 230F6 & 230F7 below), 71 pp. [file size: 57 MB; a good-but-lower resoluton file is here 16 MB]. Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/Germany,

Signatur/file nr. ZA 3/402a, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230F6: "The Wizard War", Chapter XIX (pp. 337-352) in "Alone", Book II in "Their Finest Hour" [file size: 29 MB], Vol. II (of 6) of "The Second World War", Winston S. Churchill, Houghton Mifflin Co. (publ.), 1949, 836 pp. Source: readerssection.com, accessed 30 December 2021.

Ref. 230F7: "The offensive in the Aether", Chapter XVI (pp. 248-259) in "The Onslaught of Japan", Book I in "The Hinge of Fate" [file size: 23 MB], Vol. IV (of 6) of "The Second World War", Winston S. Churchill, Houghton Mifflin Co. (publ.),1950, 476 pp. Source: readerssection.com, accessed 30 December 2021

Ref. 230F8: "Das Y-verfahren. Eine Weiterentwicklung des X-Verfahrens. Erdacht von Dr. Ing. Hans Plendl, 1940 Flieger-Oberstabingenieur bei der Erprobungsstelle der Luftwaffe Rechlin/Mecklb." ["The Y-Procedure. An evolution of the X-Procedure. Conceived by Hans Plendl, 1940, Pilot – Senior Staff Engineer at the Luftwaffe test center at Rechlin/ Mecklenburg"], 32 pp. Source: Bundesarchiv (BArch) Freiburg/Germany (Signatur) file nr. ZA 3/402a, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230F9: "I./K.G.66 - Kurzer Abriss der technischen und taktischen Einsatzgrundlagen der I./K.G.66 (Zielfindergruppe West) in verschiedenen Kriegsphasen" ["Short overview of technical and tactical operationprinciples of No. 1 Group of Kampfgeschwader 66 (Pathfinder Group West)"], [keywords: target finding & marking; Ju-88 S, Ju-188 E; Vannes, Poix, Le Bourget; I./K.G.100; X-Verfahren, Y-Verfahren, Egon, 1324/Truhe-Verfahren; detailed list of I./K.G.66 aircraft/crew losses 30-May-1943 - 11-Apr-1945], Hans Herbestreit, ca. 1970, 14 pp. Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/Germany, Signatur/file nr. RL 10/638, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230G: "Chapter II and III in "R. V. Jones and the Birth of Scientific Intelligence", James Martinson Goodchild, PhD thesis, University of Exeter, March 2013, 640 pp. [pdf] Accessed 12 May 2019.

Ref. 230H: "Electronic Warfare and the Night Bomber Offensive", Rob O'Dell, pp. 97 - 117 in "Air Power Review", Royal Air Force, Volume 10, Number 1, Spring 2007.

Ref. 230J: "Radio Navigation Systems for Aviation and Maritime Use — A Comparative Study" [RDF, Consol/Consolan, Navaglobe, VOR, VORTAC, VOR/ DMET, Navarho/Navarho-H/-HH/-Rho, Decca, Standard Loran (Loran-A), Loran-C, Radio Mesh Systen], W. Bauss (tech ed.), Advisory Group for Aeronautical Research and Development (AGARD), North Atlantic Treaty Organization (NATO), AGARDOgraph 63, Pergamon Press, 1963, 232 pp. Translation of the German publication "Funkortungssysteme für Luft- und Seefahrt - Eine vergleichende Gegenüberstellung", Verkehrs- und Wirtschaftsverl. Dr. Borgmann (publ.). [pdf, file size **58 MB**]. The following are articles taken from this book.

Ref. 230J1: "Radio Direction-Finding on Board Aircraft and Ships", W.T. Runge, pp. 19-28.

Ref. 230J2: "Consol and Consolan", Ernst Kramar, pp. 29-39.

Ref. 230J3: "VOR-System", K. Bärner, pp. 43-57.

Ref. 230J4: "Decca". H. Lueg, pp. 81-101.

Ref. 230J5: "Standard-Loran", Ernst Kramar, pp. 113-118.

Ref. 230K: "The Navigational Beam System "Elektra-Sonne" [Elektra, Sonne, Elektra-Sonne, Mond; complete German description, short translated summary in English], Otto von Heil, FIAT Final Report No. 1105, Field Information Agency Technical (FIAT), US Office of Military Government for Germany, 17 June 1947, 177 pp. Source: www.cdvandt.org. Accessed: March 2019.

Ref. 230L: "Funknavigation, Elektra, Sonne, Mond, Stern, Erika", J. Goldmann (Lorenz), Vorträge vor Fernmelde-Ingenieuren der Luftwaffe - Luftnachrichtenschule Halle (Saale) [Luftwaffe Signals School], February 1944, 22 pp. [file size: **25 MB**]

Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, file nr. (Signatur) RL 2-V/48, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230M: "Sonne Planungen" [planning of Sonne sites], Luftnachrichten telegram, dated 29 July 1944, signed by Capt. Franz, 1 p.

Document mentions Sonne station Liebau, Sonne stations 12 (Warsaw) & 23, Großsonne station 32 (Danzig), and new Sonne site near Oppeln.
Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, file nr. (Signatur) RL 2-V/6, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230N: "Bumerangstörung im Ruhrgebiet" [Jamming of "Bumerang" (German codename for **Oboe**-guided British Mosquitoes) in the Ruhr area), Nr. 82 514/44 g.Kdos. (3.Abt.III)

Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, file nr. (Signatur) RL 2-V/6, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230P: original correspondence of the Director General of Luftwaffe Signals Corps (General Nachrichtenführer). Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/Germany, file nr. (Signatur) RL 2-V/5., used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230P1: "Anruf Gen.Martini wegen Erstellung Boden-Truhe West" [telephone call with General Martini regarding construction of Boden-Truhe West]. Letter/telegram from Gen. Nachrichtenführer (1.Abt.II), addressed to Chef. der Ln.Inspektion. Letter ref. OKL Gen.Nafü. Nr. 10 955/44 g.Kdos. (1. Abt.II). Letter is dated 18 June 1944. Letter states that due to current situation, the forward-looking Boden-Truhe West station will not be constructed and construction of the rearward-looking Boden-Truhe West station will be accelerated, using transmitters of the prior. The planned transmitters will be transported from France, but with trucks/ lorries (wood gas) instead of by rail.

Ref. 230P2: "Fernmündliche Rücksprache Major Kluge - Hptm. Gottschalk am 30.6.44" [telephone conversation Major Kluge - Captain Gottschalk]. Letter from Gen.Nafü (1.Abt.), addressed to Lfl.Kdo. 3 - Höh.Nafü, General der Navigation, and General der Kampfflieger. Letter ref. OKL Gen.Nafü. Nr. 11 092/44 g.Kdos. (1. Abt.II). Letter dated 8 July 1944. Letter states that, due to operational and test reasons, construction of radio navigation stations "Komet 2 (Laharie)", "Komet 3 (Labouheyre), and "Dora 2 (Morlaix) cannot be finished. Due to failure of "Erika 2 (Cherbourg)", the "Erika" system can no longer be used in the West. Therefore, "Erika 1 (Boulogne)" can be dismantled and parts (transmitter etc.) be secured.

Ref. 230P3: "Sender for Bodentruhe" [transmitters for Truhe ground station]. Letter from Gen.Nafü (1.Abt.), addressed to Gen.Nafü/Ln.Insp (5.Abt/6.Abt). Letter is dated 8 July 1944. Letter describes allocation of 3 "Feuerstein" transmitters instead of "Feuerzange" transmitters to "Bodentruhe West", also mentions 3 "Merkur" transmitters are to be modified for "Bodentruhe West", schedule for delivery of additional "Merkur" and "Feuerstein" transmitters to be provided.

Ref. 230P4: "Abschalten von Rundfunksendern." [Shutdown of (public) radio broadcast transmitters]. Letter from OKL.Gen.Nachrichtenführer. Letter ref. 11 987/44 geh. (1.Abt.II). Letter is dated 2 July 1944. Letter states that, as agreed with OKW and RPromin [Reichs Propaganda Ministerium], the request for shutting down radio broadcast transmitters during jamming/interference of radio beacons for day & night fighters, is denied. Reasons given by RPromin: 1) the current regulations already imply large scale shutdowns, further reduction is unacceptable for the propaganda, 2) the population interprets shutdowns as sign of imminent air raids. Shutdown for other reasons would cause unrest, and 3) Broadcast transmitter frequencies are fixed. If broadcast transmitters interfere with radio beacons or other services, Lfl.Kdo. must make sure that those services use other frequencies. As in other Luftflotten regions, restriction of radio beacons improves spread of utilized frequencies.

Ref. 230Q: articles about **Knickebein**

Ref. 230Q1: "Knickebein - ein «Leitfaden» der Luftwafe (Wehrmacht)" ["Knickebein - a "guide line" of the Luftwaffe"; general description and site visits of all Kn locations except Kn-1, Kn-5, Kn-11, Kn-13], web pages by christianCH, update of 5 April 2021. [pdf, file size: 19 MB] **See note 1**. [*In Sept/Oct-2022 email exchanges, christianCH also provided me with dimensions he measured at Kn-8: concrete block (1.4x1.4 m), base plate (84x60 cm; 8 through-holes Ø 2 cm), the square plate on top of it (33x33 cm), and of the 2-step cylindrical pivot (Ø 14 cm with 4mm wall thickness and Ø 11 cm, respectively), and also the width of the outer concrete ring at (large) Kn-12 (same as small Kn ring, and with radial grooves in top = depressions for cross-ties, no signs of rail attachments)*].

Ref. 230Q2: pp. 245-247 in "Gleichgeschaltet: Maulburg im Nationalsozialismus und die Rolle von Hermann Burte im Dritten Reich" ["Alignment: Maulburg under the national socialism and the role of Hermann Burte in the Third Reich"], Hansjörg Noe, Verlag Waldemar Lutz (publ.), 448 pp., ISBN 978-3-922107-09-5. [Extract]

Ref. 230Q3: p. 16 of "Knickebein" thread in the forum of geschichtsspuren.de, post by ChristianCH on 30-Mar-2014. [Extract]

Ref. 230Q4: p. 2, 3 in "Krigsminner 1940-45 i Klepp kommune" ["War memories 1940-45 in the Klepp municipality"], F. Ravndal, T. Ødemotland, A. Jakobsen, T. Erga, O. Håland, B. Bore, A. Hatteland, J. Sørbø, T. Reve, Laget (publ.), 1990, 8 pp. Source: Norwegian National Library, accessed 31 July 2020.

Ref. 230Q5: "Kontrollpunkten der Knickebein-Anlage 4 (Karten), dabei

Gesamtübersicht der Kontrollpunkte, Bereich zwischen Kranenburg und Donsbrüggen" [file size: 34 MB] ["Radiation-pattern check points for Knickebein Nr. 4 (= Kleve-Materborn) in the area between Kranenburg and Donsbrüggen"], 8 maps with check points marked by small red dots and red lines, some measured field strength values are written in green (dated January 1942), Kranenburg = ca. 13 km west of K4; Donsbrüggen = ca. 12 km northwest of K-4; 2 maps with check points in The Netherlands (just north & south of Groesbeek = ca. 18 km west of K-4)]. Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, Signatur/file nr. RL 19/6/64 - 19/6/84 (frmr. RL 19/537), used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230Q6: "Knickebein" [incl. difference between KG 100 and other LW Kampfverbände], Luftwaffenführungsstab Ia (KM), adressed to "I L", 6 October 1940, g.Kdos, 1 page + 1 map. Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/Germany, Signatur/file nr. RM 7/2372, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230Q7: "Navigatorische Ausnutzung von Fernfunkfeuern Ukw. (Knickebein)" ["Utilization for navigation of long-range VHF radio beacons (Knickebein)"], memo Az. 47 p 14, B.Nr. 545/40 g.Kdos., signed by Major Schubert for the Chief of Staff of Luftflottenkommando 2, 5 May 1940, 3 pp. [Keywords: Knickebein, coordinates / radio frequency / center beam pointing direction for Stolberg & Kleve, width of the dots & dashes zones, vertical extent of the radiation pattern, 2 pp. utilization guidelines "Merkblatt" - not to be taken into the aircraft; if taken prisoner, no information shall be divulged]. Source: Bundesarchiv (BArch) Freiburg/ Germany, Signatur/file nr. RL 19-6/40 (frmr. RL 19/537), low quality microfiche, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230Q8: "Planung und Erstellung von UKW-Fernfunkfeuern (FFuFd) für die Funknavigation der Luftwaffe" ["Planning for, and construction of, long-range VHF radio navigation beacons of the Luftwaffe"], memo Az. 47 f 68, Nr. 2714/39 g.Kdos., addressed to Reichsminister of Aviation, Supreme Commander of the Luftwaffe, and Chief of the Signal Corps; draft signed by Flight Staff Engineer Gosewisch, 10 September 1939, 12 pp. [Keywords: high priority construction of beacons for Luftwaffe operations over the North Sea; requirements for the first 5 rotable beacons (3x Telefunken G.m.b.H. (high power (3 kW); up to 1200 km range (depending on radio set and aircraft altitude); to be located at Stolberg, Cleve, Borkum; code name *Knickebein*; antenna system weight ca. 200 metric tons), 2x C. Lorenz A.G. (lower power (500 W); up to 300-600 km range; to be located at Bad St. Peter and on the isle of Sylt; code name *Karussel*) in terms of equisignal beam width ±0.2° initially (later ±0.1°), dots & dashes zones width ±12°, rotability range ±45° from center beam-direction, radio frequencies compatible with FuBl 1 radio set (29.8-33.6 MHz, 5 fixed frequencies`+ 2 field-modifiable); degree to which the terrain around the beacons must be flat and unobstructed; remote monitoring radio receiver at each site; diagram with dimensions of the Knickebein antenna system and the rotation tracks; table for standard landing beam + Knickebein + Karussel with (humidity dependent) ranges

for 3 receiver types (each with 2 different antennas); graph with 0.3° equisignal beam-width and useable altitude vs. range based on beacon signals audibility = vertical usability boundaries of the equisignal beam lobe]. [file size: 25 MB]. Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/Germany, Signatur/file nr. RL 19-6/40 (frmr. RL 19/537), low quality microfiche, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230Q9: "Geodätische und elektrische Einmessung der Knickebein-Anlage - Richtlinien über die geodätische und elektrische Einmessung der Knickebein-Anlagen - Anforderungen für die Auswahl und Vermessung des Kontrollbogens bei Knickebein-Anlagen" ["Geodetic and electrical calibration of the Knickebein stations - Guidelines for the calibration - Requirements for the selection and measurement of the verification-arc of Knickebein installations"], As. 47 f 57 Nr. 72/41 g.Kdos., draft signed by Flight Staff Engineer Gosewich, 17 January 1941, 9 pp. [Keywords: all measurement points to be marked with concrete marker (graphic), 0.5° spacing between adjacent markers, 1:5000 maps for Knickebein K-2, sample data sheet for measurements of both dots & dashes beams)]. Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, Signatur/file nr. RL 19-6/40 (frmr. RL 19/537), low quality microfiche, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230Q10: "Erläuterungsbericht zu dem Vermessungsarbeiten für den U.K.W.B Kleve - Ergänzung zum Eläuterungsberiche" ["Explanatory report regarding the measurement activities for the Kleve VHF beacon + supplement"; measurement points must have visual contact with the beacon, distance from beacon: measurement with a truck, so measurement points must lie on accessible roads; min & max distance from beacon: 0.8 and 2 km (exceptions possible); no check points allowed near power lines; check point spacing 0.5°; check points marked with marker stone, sign, or nothing; check points also to be marked on the outer concrete ring of the beacon; mentions map in ref. 230Q5], signed by Dip.-Ing Schmitt, 7 pp. Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/Germany, Signatur/file nr. RL 19-6/40 (frmr. RL 19/537), low quality microfiche, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230Q11: "Krigsminne" ["War memory"], p. 21 in "Kommunedelplan - Kulturarv i Klepp 2005-2016" ["Municipal sub-plan - Cultural heritage in Klepp 2005-2016]", 32 pp. Retrieved October 2020. English translation of p. 21 is here.

Ref. 230Q12: "Battle of Britain 50 år - Tyske navigasjons- systemer og britiske mottiltak" ["Battle of Britain 50 years - German navigation systems and UK countermeasures"], Halfdan Krohn, pp. 6-13 in "Norsk Militært Tidsskrift", Vol. 160, Nr. 12, December 1990. Source: www.nb.no.

Ref. 230Q13: "Knickebein på Haugabakka, Klepp", Jan-Martin Nøding (LA8AK, SK 2005), on his webpage "Radarstasjoner og spesielt radionavigasjonsutstyr i Rogaland 1940-45" ["Radar stations and especially radio navigation equipment in Rogaland (Stavanger area)"], update of 29 September 2004. Retrieved 15 June 2022. [pdf]

Ref. 230Q14: "Die Festung Sylt: Geschichte und Entwicklung der Insel Sylt unter militärischem Einfluss 1894 - 1945", Harald Voigt, Nordfriisk

Instituut (publ.), 1992, 254 pp.

Ref. 230Q15: "Leitstrahlanlage - von Maulburg aus lenkten die Nazis Jagdbomber ins Feindesland" ["Guide beam station - From Maulburg, the Nazis guided fighter-bombers to enemy country"], Gerald Nill, in "Badische Zeitung", 18 August 2020. [pdf]

Ref. 230Q16: photo number MMD 465-5-3 on contact photo sheet 20 "Canadians in Germany - Date: 10 to 14 Feb. '45, Place: In and Around Cleve & Nijmegen, Photographer: Lieut. M.M. Dean" in "North West Europe - Album 87 of 110, 9 Feb. 45 - 1 March 1945", Canadian Army Numerical 46289-47274 (photo number range), Government of Canada, Library and Archives Canada. Retrieved 11-Oct-2021.

Ref. 230Q17: "Les stations radars de la Gouinerie et du Petit Parc" and "La guerre 39 - 45" , web pages of the Mairie de Digulleville (townhall), accessed September 2022. [pdf]

Ref. 230Q18: "A new look at "The Wizard War", Alfred Price, pp. 15-23 in "Royal Aircraft Historical Society Journal", Issue 28 [Proceedings of the Society's "Electronic Warfare" seminar held at RAF Museum Hendon, 10 April 2002], 2003, 158 pp.

Ref. 230Q19: "La guerre des radars; 1 - Knickebein - Bernhard" [incl. photos Kn-10, Kn-11], Y. Delefosse, C. Delefosse, in "Archéologie Bunker Magazine", No. 6, 1986, pp. 4-9. Source: 16 August 2017 post on loup-mouton.blogspot.com, retrieved 31 July 2020. [*In an October-2022 email exchange, Mr. Y. Delefosse, one of the two authors, confirmed to me that the 1940 photo (ECPA collection) of a Small Kn may have been taken at Kn-11, the photo of the concrete support block was taken at Kn-6, the block has a concrete base below ground level that is wider than the block (thickness & width of that base unknown), the steel I-beam track is 18 cm wide.*]

Ref. 230Q20: Second World War Canadian Army Air Photo Collection, Laurier Military History Archive (LMHA), Laurier Centre for the study of Canada, Wilfried Laurier University, Box 0261 - 2 of 2 "Germany/The Netherlands; North Rhine-Westphalia/Gelderland: Reichswald, Nijmegen, Kleve", Squadron 4, sortie nr. 1614, sortie date: 14 Jan 1945, page 2, negative nr. 4032.

Ref. 230Q21: Letter from the Stadtarchiv Kleve [City Archive of Kleve], 12 December 2003, content posted in geschichtsspuren.de forum entries on 21 November and 12 December 2003 by EricZ [pdf]

Ref. 230Q22: Project'44 - Canadian Overseas Survey and Mapping 1939-1945, W.E. Storey Collection, Sheet 4202-2; the full-size map is here.

Ref. 230Q23: "Station de radio-guidage codée "K11" (Emetteur Knickebein puis See-Elefant en 1944), Saint-Fiacre (Lanmeur)", source: patrimoine.region-bretagne.fr, retrieved September 2022. [pdf]

Ref. 230Q24: "Knickebein Transmitter, Noto", Technical Report, Advanced Headquarters Northwest African Air Forces (NAAF), Capture Intelligence Section, A-2, August 1943. The Report cover page is here.

Ref. 230Q25: "Parcours découverte - Le Mont Pinçon pendant la Seconde Guerre Mondiale" ["A walking discovery tour - Mont Pinçon during WW2"], brochure of the Tourist office of the Pays de Vire / Collines de Normandie, August 2020, 8 pp. [pdf]

Ref. 230Q26: "Knickebein - France, Boulogne sur Mer, inland, Haut

Pichot". Source: bunkersite.com, accessed 20 October 2022. [pdf]

Ref. 230Q27: ""Knickebein" Homing-Antenna Device", Wilhelm Runge, United States Army Air Forces (AAF), Air Materiel Command (AMC), Air Documents Division (T-2), Report F-TS-2603-RE (Translation 2603), March 1947, 27 pp. [Knickebein is a directional antenna used for navigational purrposes, operating in a frequency range of 30 to 33.3 megacycles. The antenna array has a large number of dipoles in a row in order to obtain horizontal beaming and a sharply defined beacon. In addition, vertical beaming is provided to increase the range. Each of the two antenna parts is fed alternately in the rhythm of the signals E-T (dot-dash). A deviation of two and one-half degrees from the beacon axis results only in an amplitude change from seven to seven and one-half scale deviation. Under normal aircraft noise conditions 6.5% is the lowest threshold for safe reception of signals. Further experimentation proved that faster switching from one signal to the other facilitated the identification. The device consists of two stators and one rotor which has no slip contacts. The difference in capacitance, necessary for switching, is produced by the change of the positions of the rotor. Both connection points are stationary, one to the small and the other to the large stator.]

Ref. 230Q28: "Der Deutsche Rundfunk bis zum Inkrafttreten des Kopenhagener Wellenplans" [sorry: pp. 355-363 only!; "German broadcast radio, up to the entry into force of the Copenhagen Frequency Plan" (a.k.a. The "Copenhagen Plan", annex to the 1948 "European Broadcasting Convention"], Gerhart Goebel, in "Archiv für das Post- und Fernmeldewesen", Vol. 2, Nr. 6, August 1950, pp. 355-454. [pdf; sorry: pp. 355-363 only!]

Ref. 230Q29: "Das Fernsehen in Deutschland bis zum Jahre 1945" ["Television in Germany up to 1945], Gerhart Goebel, in "Archiv für das Post- und Fernmeldewesen", Vol. 5, Nr. 5, May 1953, pp. 259-393. [pdf]. [file size: 26 MB].

Ref. 230Q30: "Rundfunksender auf Rädern: die fahrbaren Rundfunksendeanlagen der Deutschen Reichspost in den Jahren 1932 bis 1945" ["Broadcast transmitters on wheels: the mobile broadcast stations of the German Reichspost in the years 1932 - 1945"], Bernd-Andreas Möller, Vol. 13 of "Schriftenreihe zur Funkgeschichte", Gesellschaft der Freunde der Geschichte des Funkwesens (GFGF; contributor), Verlag Dr. Rüdiger Walz (publ.), 2003, 197 pp., ISBN-13: 978-3936012026.

Ref. 230Q31: Imperial War Museum Combat Film No 8913 - "Wing Commander Bird-Wilson of 126 Squadron on 5 August 1944 at 12:00, flying Supermarine Spitfire. Target: radar." The extracted clip starts at 17:35. The page of RAF No. 126 Squadron Operations Record Book for 1-5 August 1944 is here (adapted from AIR 27/927-927-12).

Ref. 230Q32: p. 43 in "Bodenfunkmessgeräte der deutschen Luftwaffe bis 1945" ["Ground-based radar systems of the German Luftwaffe through 1945"], Werner Müller, Vol. 132 of "Waffen-Arsenal, Waffen und Fahrzeuge der Heere und Luftstreitkräfte", Podzun-Pallas Verlag (publ.), 1992, 49 pp., ISBN 3-7909-0422-8.

Ref. 230R: articles about the **X-Verfahren** ("X-Procedure), **X-Gerät** ("X-Equipment"), **Y-Verfahren** ("Y-Procedure"), **Y-Gerät** ("Y-Equipment"); this Y-navigation method is not to be confused with the "Y" fighter-guidance method

(incl. Y-Peiler ("Y-D/F system") which is also referred to as "Y-verfahren", nor with the British radio monitoring/intercept Y-Service.

Ref. 230R1: pp. 48-49 (X-Gerät, Y-Gerät) in "German Radio Communication Equipment", US War Department Technical Manual, TME 11-227, June 1944, 61 pp.

Ref. 230R2: "Fliegerhorst Köthen" ["Köthen airfield"], source: Militärhistorisches Museum Anhalt, accessed 11 August 2020. [pdf]

Ref. 230R3: pp. 14-27 in "The First Pathfinders - The Operational History of Kampfgruppe 100, 1939-1941", Kenneth Wakefield, William Kimber (publ.), 1981, 265 pp.

Ref. 230R4: pp. lxx-lxxiv in "The Bombing War: Europe, 1939-1945", Richard Overy, Penguin Books Ltd. (publ.), 2014, 852 pp. (published 2013 by Allan Lane, published 2015 as "The Bombers and the Bombed: Allied Air War Over Europe, 1940–1945")

Ref. 230R5: "Der gezielte Blind-Bomben-Wurf - Die deutsche Lösungen: Das X-verfahren, Das Y-verfahren (Kampf)" ["The targeted blind bomb drop - The German solutions: the X-Procedure, the Y-procedure"], Heinrich Pusch (Oberst a.D. (Colonel, retired); Gruppenkommandeur Kampfgruppe 100 in 1939, Kommandeur Luftnachrichten-Regiment 31 in 1941 and Ln-Regiment 56 in 1943], date unknown (but after 1949/50, based on references to volumes of Winston Chruchill's memoires published in 1949 & 1950, see ref. 230R14 & 230R15 below), 71 pp, p. 14 & 16 missing. [file size: 49 MB]. Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/Germany, Signatur/file nr.ZA 3/402a, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230R6: "The Wizard War", Chapter XIX (pp. 337-352) in "Alone", Book II in "Their Finest Hour" [file size: 29 MB], Vol. II (of 6) of "The Second World War", Winston S. Churchill, Houghton Mifflin Co. (publ.), 1949, 836 pp. Source: readerssection.com, accessed 30 December 2021.

Ref. 230R7: "The offensive in the Aether", Chapter XVI (pp. 248-259) in "The Onslaught of Japan", Book I in "The Hinge of Fate" [file size: 23 MB], Vol. IV (of 6) of "The Second World War", Winston S. Churchill, Houghton Mifflin Co. (publ.),1950, 476 pp. Source: readerssection.com, accessed 30 December 2021

Ref. 230R8: "Das Y-verfahren. Eine Weiterentwicklung des X-Verfahrens. Erdacht von Dr. Ing. Hans Plendl, 1940 Flieger-Oberstabingenieur bei der Erprobungsstelle der Luftwaffe Rechlin/Mecklb." ["The Y-Procedure. An evolution of the X-Procedure. Conceived by Hans Plendl, 1940, Pilot – Senior Staff Engineer at the Luftwaffe test center at Rechlin/ Mecklenburg"], 32 pp. Source: Bundesarchiv (BArch) Freiburg/Germany (Signatur) file nr. ZA 3/402a, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230R9: "I./K.G.66 - Kurzer Abriss der technischen und taktischen Einsatzgrundlagen der I./K.G.66 (Zielfindergruppe West) in verschiedenen Kriegsphasen" ["Short overview of technical and tactical operationprinciples of No. 1 Group of Kampfgeschwader 66 (Pathfinder Group West)"], [keywords: target finding & marking; Ju-88 S, Ju-188 E; Vannes, Poix, Le Bourget; I./K.G.100; X-Verfahren, Y-Verfahren, Egon, 1324/Truhe-Verfahren; detailed list of I./K.G.66 aircraft/crew losses 30-May-1943 - 11-Apr-1945], Hans Herbestreit, ca. 1970, 14 pp. Source:

Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/Germany, Signatur/file nr. RL 10/638, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 230S: articles about "**Komet**" ("Comet")

Ref. 230S1: "Tysk Retningsantenneanlæge i Kølby Vest for Nibe" ["German Directional Antenna Installation in Kølby, west of Nibe"; rotating-beam system "Komet" ????], Commission for the Inspection of German Radio Stations Constructed in Denmark, report by Capt. Bahnsen and Prof. Jørgen Rybner of site visit on 12 Dec 1945, 3 pp. Courtesy M. Svejgaard, used with permission. English translation by me is here.

Ref. 230T: "Scientific Intelligence", R.V. Jones, 12 February 1947 lecture, "CIA Studies in Intelligence" Vol. 6, No. 3 (Summer 1962), pp. 55-76. Source: cia.org, accessed 12 August 2020. [pdf]. This is a slighly edited version of the original 12 February 1947 lecture, as first published in "Journal of the Royal United Services Institution", nr. 42, August 1947, pp. 352-360.

Ref. 230U: "Radio navigation equipment", Section three of "Graphic survey of radio and radar equipment used by the Army Air Force", U.S. Army Air Forces, Air Technical Service Command, 1 May 1945, 68 pp. [file size: 21 MB].

Ref. 230V: "Navigational Aids" [MF & HF D/F, SBA, Radio Ranges, Gee, SCR 277, B/T, BABS, GCA], pp. 24-28 in "The signals war: A brief history of no. 26 Group", AIR 14/3562, UK Air Ministry, Bomber Command, December 1945.

Ref. 230W: "Aerial Navigation and Traffic Control with Navaglobe, Navar, Navaglide, and Navascreen", H. Busignies, Paul R. Adams, Robert I. Colin, in "Electrical Communication - A Journal of Progress in the Telephone, Telegraph and Radio Art", published by "International Standard Electric Corp.", Vol. 23, No. 2, June 1946, pp. 113-143. Source: worldradiohistory.com, retrieved 17 August 2020.

Ref. 230Y: "Radionavigation in the UK in World War II", F.C. Richardson, in "The Journal of Navigation", Vol. 45, Issue 1, January 1992, pp. 60-69. Source: en.booksc.org, accessed April 2021. [pdf, **See note 1**]

Ref. 230Z: "Zielfluggeräte nach "Dieckmann-Hell"" [Dieckmann-Hell airplane radio direction finding systems; Luftwaffe ZVG 15 / 16 / 17 Z, FuG 141], Werner Thote, in "Radiobote", Vol. 13, Nr. 76, September-October 2018, pp. 14-19. Source: radiobote.at

Ref. 235: "The invention of synchronous rotations by means of Paul la Cour's Phonic Wheel as used in Telegraphy", P. Chr. Dresing, in "The Telegraphic Journal and Electrical Review", Vol. XX, No. 476, 7 January 1887, pp. 31, 32.

Ref. 243: "Belsize Park Deep Shelter", Nick Catford, 27 January 2000, Retrieved 30 August 2019. [pdf]

Ref. 244: Luftwaffe & Royal Air Force fighter intercept & control methods ("Jagdverfahren"), maps, and related topics

Ref. 244A: "Nachtjagd" [intro, descriptions, and evaluations], Luftwaffe document, date unknown, 18 pp. Source: German Russian Project for digitization of archives in the Russian Federation. Retrieved 29 August 2019.

Ref. 244B: "Bestimmungen über Nachtjagd" [descriptions of methods, and instructions to Flak organisation regarding night fighting], 1st Flakdivision, Berlin, 19 November 1943, 12 pp. Source: German Russian Project for digitization of archives in the Russian Federation. Retrieved 29 August 2019.

Ref. 244C: "Mosquito Nachtjagd", [specific fighter and flak tactics against

incoming British "Mosquito" fighter-bombers] 1st Flakdivision, Berlin, 7 March 1944, 5 pp. Source: German Russian Project for digitization of archives in the Russian Federation. Retrieved 29 August 2019.

Ref. 244D: "Das Y-verfahren für Tag- und Nachtjagd" [file size: **115 MB**; good-but-lower-reslution file is here **36 MB**], document without reference number, without date, without place, 113 pp.

Complete description of the "Y" procedure for day & night fighter control from ground plotting stations with short wave equipment.
Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, file nr. (Signatur) RL 2-V/38, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 244E: "Anlage 1 zu Luftflottenführungsabteilung Ia op2 Nr. 500/41 geh." [file size: **28 MB**; good-but-lower-resolution file is here, **4 MB**]. Map is not dated.

Map covers area of Belgium, The Netherlands, Denmark, northern Germany incl. Berlin. Map is marked with locations of militärische Sperrgebiete, Nachtsperrgebiete, Nachtjagdgebiete, Dunkle Nachtjagdsräume.
Map size: 4x2 (WxH) A4-sheets. Map is low-quality blueprint copy.
Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, file nr. (Signatur) RL 20/186/K.

Ref. 244F: "Einsatzbeispiel für einen Feindeinflug" (example of response to intruding enemy aircraft). Map is not dated. [file size: **84 MB**; good-but-lower-resolution file is here, **10 MB**].

Map shows ground track of enemy bomber stream arriving from Britain with target Frankfurt, intercepting fighters, timing, etc. Map includes large & detailed table of the entire nightfighter intercept process, from long-range radar detection to "kill", with step-by-step status/activity/ communication at the level of Flugmeldekompanie, Nachtjagdraum, Fühlungshalter, Jagdgruppe, Flugmeldungszentrale, Fluko, and Flak; the entire sequence covers 1 hr 40 min.
Map size: 4x5 (WxH) A4-sheets.
Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, file nr. (Signatur) RL 36/443.

Ref. 244G: "Luft-Navigationskarte in Merkatorprojektion - Erweitertest Blatt Deutschland mit Jägernetz", Bodenorganisation Großraum-Nachtjagd Luftflotte Reich, July 1944. Source: Bestand/File 500, Findbuch/Index 12452, Akte/record 286 of the German-Russian Project for the Digitization of German Documents in Archives of the Russian Federation. Retrieved 28 August 2019.

Ref. 244H: "Nederland en de Duitse Nachtjacht - Van jager tot prooi" (The Netherlands and German night fighting - from hunter to prey), W.H. Lutgert, R. de Winter, pp. 536- 545 in "Militaire Spectator", vol. 183, nr. 12, December 1994. Accessed September 2019. [pdf]

Ref. 244J: "Nederland en de Duitse Nachtjacht - Van jager tot prooi (Deel 2)" (The Netherlands and German night fighting - from hunter to prey - part 2), W.H. Lutgert, R. de Winter, pp. 5-17 in "Militaire Spectator", vol. 184, nr. 1, January 1995. Accessed September 2019. [pdf]

Ref. 244K: "De Luftwaffe en Nederland - Balans van een oorlogserfenis" (The Luftwaffe and The Netherlands - legacy of a war), W.H. Lutgert, R. de Winter, pp. 450- 459 in "Militaire Spectator", vol. 184, nr. 10, October 1995. Accessed

September 2019. [pdf]

Ref. 244L: "Nachtjagd-Navigationskarte - Groborientierung der Nachtjäger" ["Night-fighting navigation charts - Coarse orientation of the nigh- fighters"] and "Nachtjagd - Taktiken und Technik der Nachtjäger" ["Night-fighting - tactics and techniques of the night fighters"], Heiko Müller, in "Klassiker der Lutffahrt", No. 5, 2013, pp. 41-43 and 44-48, respectively. Source: archive.org, open source, accessed April 2024.

> Includes "Nachtjagdnavigationskarte - herausgegeben von NJG.3.-NO" [night-fighter navigation chart issued by the Nachrichten-Offizier of the No. 3 night fighter-wing, Nachtjagdgeschwader 3]. Map is not dated. Bernhard-stations Be-0, Be-6, Be-8 through Be-12 are also marked on this map.

Ref. 244M: "Tag- und Nachtjagd, 3. Jagddivision (als beispiel)". Map is dated 29 July 1944. [file size: **24 MB**; good-but-lower-resolution file is here, **9 MB**].

> Map covers area of The Netherlands to Heilbronn/Germany. Map is marked with location of Tagjagdstellungen and Fu.M.G. sites (1., 2., and 3. Ordnung; dunajafähig vs. nicht dunajafähig).
> Map size ca 3x2 (WxH) sheets of size A4. Map scale 1:1.000.000
> Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, file nr. (Signatur) RL-3-1527.

Ref. 244N: "Jagd-Einsatz im November 1943", Anlage 3 (appendix 3) to "Lfl.Kdo3, Führ.Abt(1)/1c No. 15684/43 Kdos". [file size: **19 MB**]

> Large bar graph for each day of November 1943, with total number of fighter sorties for each day, split into "day" and "night" fighter. Also: table with statistics for each day: number (with type(s) of aircraft) for each type of sortie/mission: "Alarmstart" / "Überwachung und Sperre" / "Geleitschutz" / "Begleitschutz u. Augnahme"; / "Nachtjagd" (night fighter) / "Fernjagd" (long range intercept); also: total number of sorties/missions, number of enemy kills (incl. type of enemy aircraft), own losses.
> Size: size: ca. 3x3½ (WxH) A4-sheets.
> Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, file nr. (Signatur) RL-3-1527.

Ref. 244P: "Abschüsse der Nachtjagd im Bereich Luftwaffenbefehlshaber Mitte", Anlage 2 (appendix 2).

> Graph with three lines: "hell" (helle Nachtjagd), "dunkel" (dunkle Nachtjagd), "kombiniert" (kombinierte Nachtjagd). Graph covers monthly statistics regarding enemy kills for the period April 1941 - March 1942.
> Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, file nr. (Signatur) RL-3-1527.

Ref. 244Q: "Anzahl der voll u. bedingt (ab Juli 1941) bzw. eingeschränkt (ab Mai 1943) einsatzfähigern Besatzungen" and "Anzahl der einsatzbereiten Kampf-Flugzeuge" . [file size: **17 MB**]

> Graph with monthly statistics for the period mid-1939 - mid-1939: number of available flight crews and number of operational fighter planes), separate curves for "Tagjäger" (day fighters) and "Nachtjäger" (night fighters; from late 1940 onward).
> Also: interesting large table with 53 key dates of the WW2, from 1 September 1939 (German invasion of Poland) through 15 August 1944 (anglo-american landing in southern France).
> Size: ca. 1½ x3 (WxH) A4-sheets.

Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, file nr. (Signatur) RL-3-1527.

Ref. 244R: "Fighter defence of Germany - Control of fighters by the "Y" Procedure", Samuel Denys Felkin (Chief Interrogator at Bletchley), transcribed report from the British Air Ministry, **A**ssistant **D**irector of **I**ntelligence (Prisoner Interrogation), A.D.I. (K) Report No. 525/1944, 14 pp. Source: The National Archives of the UK, ref. AIR40/2875 and 2876. Retrieved from www.cdvandt.org.

Ref. 244S: "Das "Y-Verfahren" für Tag- und Nacht-Jagd (Navigations-Verfahren)" ["The Y-Procedure for day and night fighter control (navigation method)"], author unknown, date & place unknown, 114 pp. The 1960s file coversheet of the Militärgeschichtliches Forschungsamt (Research Office for Military History) suggests that it dates to 1940/41, 114 pp. [file size: : **82 MB !!!!** - with reduced resolution]

Keywords: Y-Verfahren, Y-Führung, Y-Stelle, Y-Stellung, Y-Anlage, Y-Station, Y-Einrichtung, E 16, FuG 16, Graetz-E-Mess-Gestell, Siemens-E-Mess-Gestell, Heinrich Peiler, ZVG 16, ZE ZY Zeiger, Schildkröte, PQK, S 16.

Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, file nr. (Signatur) RL 2-V/38, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 244T: "Die Deutschen Nachtjagdverfahren" ["The German nigh fighter procedures"], Walter Grabmann, Generalmajor a.D., date unknown, 22 pp.
[Helle Objektjagd, helle Gebietsjagd, Himmelbett, Verfolgungsnachtjagd [pursuit night], Objektjagd "Leichentuch" / "Milchglas", 1-mot Objektjagd "Wilde Sau", Fernnachtjagd [long-range night], Zusammenarbeit mit Jäger-Flak, 13 maps].

Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, file nr. (Signatur) ZA 3/402a, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 244U: "Funkübermittlung der feindliche Luftlage" ["Transmission of enemy aircraft situation via radio" (reportage, running commentary)], excerpt of a report dated 22 March 1945 by Morgenstern, chef to the Generalnachrichtenführer Chief Signal Officer), 14 June 1956, 9 pp. Source: Bundesarchiv (BArch) Freiburg/Germany, Signatur/file nr. ZA 3/402b, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 244V: "Feindreportagen" ["Running commentary on enemy aircraft"] and "Bernhard-Führung" ["Bernhard guidance"], §II and §VII, respectively, in "Nachrichtenbefehl April 1945 (Nachtjagd)", 1. Jagddivision, Nafü 3 - Nr. 2600/45, 18 March 1945, 5 pp. Source: Bestand/File 500, Findbuch/Index 12476, Akte/record 90, pages 31-36 of the German-Russian Project for the Digitization of German Documents in Archives of the Russian Federation. Retrieved November 2021.

Keywords: Verfolgungsnachtjagd, Führungswellen, Gruppenbefehlswellen, Geschwaderbefehlswellen UKW (Tast) Bord-Bord, Divisionsführungswellen Lgw, Kzw, UKW der 1.J.Div., Divisionsklärungswellen (Tast), Y-Linienverteilung für Aufklärer, Y-Linien für 1-mot. Nachtjagd, Mosquito-Jagd (Silber), Feindreportagen, Kennung für Fu. G 25, Rufzeichen und Rufnamen, Optische Gruppenkennung und Wellen für flg. Funkfeuer, Verschlüsselung eigener Standort- und

Flughöhenangaben, Gebietsnachtjagd, Flugsicherung.

Ref. 253: antenna directivity

Ref. 253A: "Berechnung der Charakteristik von Richtantennen" [calculation of radiation pattern of directional antennas, free-space and with ground influence], A. Engel, Berlin, 15 pp., in "Ringbuch der Luftfahrttechnik", Vol. 15: V. Ausrüstung, C. Funkpeilung, 4. Berlin-Adlershof, Zentrale f. wiss. Berichtswesen b. d. Deutschen Versuchsanst. f. Luftfahrt, 1938. [file size: **25 MB**]

Ref. 253B: "50 Jahre Antennentechnik" [Telefunken, incl. dipole arrays with reflectors, patents], W. Berndt, pp. 197-204 in "50 Jahre Telefunken - Festschrift zum 50 jährigen Jubileum der Telefunken Gesellschaft für drahtlose Telegraphy m.b.h. - Gleichzeitig als 100. Ausgabe der Telefunken Zeitung", Vol. 26, Nr. 100, May 1953, 164 pp. Source: nvhrbiblio.nl, retrieved 19 February 2020.

Ref. 265: "The composition and friction-reducing properties of leaf layers", Michael Watson, Benjamin White, Joseph Lanigan,Tom Slatter, Roger Lewis, in "Proceedings of the Royal Society A", Vol. 476, Issue 2239, 29 July 2020, pp. 34 pp. [pdf]

Ref. 282: papers about Luftwaffe transmission via radio of enemy aircraft positions.

Ref. 282A: "Feindreportagen" ["Running commentary on enemy aircraft"] and "Bernhard-Führung" ["Bernhard guidance"], §II and §VII, respectively, in "Nachrichtenbefehl April 1945 (Nachtjagd)", 1. Jaddivision, Nafü 3 - Nr. 2600/45, 18 March 1945, 5 pp.

Keywords: Verfolgungsnachtjagd, Führungswellen, Gruppenbefehlswellen, Geschwaderbefehlswellen UKW (Tast) Bord-Bord, Divisionsführungswellen Lgw, Kzw, UKW der 1.J.Div., Divisionsklärungswellen (Tast), Y-Linienverteilung für Aufklärer, Y-Linien für 1-mot. Nachtjagd, Mosquito-Jagd (Silber), Feindreportagen, Kennung für Fu. G 25, Rufzeichen und Rufnamen, Optische Gruppenkennung und Wellen für flg. Funkfeuer, Verschlüsselung eigener Standort- und Flughöhenangaben, Gebietsnachtjagd, Flugsicherung.
Source: Bestand/File 500, Findbuch/Index 12476, Akte/record 90, pages 31-36 of the German-Russian Project for the Digitization of German Documents in Archives of the Russian Federation. Retrieved November 2021.

Ref. 282B: "Funkübermittlung der feindlichen Luftlage – Auszug aus einem Bericht des Obst. Morgenstern, Chef beim Generalnachrichtenführer vom 22.3.1945" ["Radio transmission of the enemy air situation (aircraft positions) – Excerpt from a report dated 22 March 1945 of Col. Morgenstern, Chief adjoint to the lead Signal Corps General"], Gen.Nafür (1. Abt.) Nr.11 319/45 geh., 9 pp.

Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, (Signatur) file nr. ZA 3/402, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 282C: "Die Bildung der Luftlage. 1935 – 1944 (Flugmeldedienst, Funkmeßdienst, Funkaufklärung)" ["The creation of (enemy) air situation (aircraft position status). 1935 – 1944 (enemy aircraft warning service, radar service, radio intelligence service)"], Obst. A.D. Greffrath, 1946, 7 pp.

Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, (Signatur) file nr. ZA 3/402, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 282D: "Die Bildung der Luftlage" ["The creation of (enemy) air situation (aircraft position status)"], Gen.Maj. a.D. Walter Grabmann, no date - possibly 1946, 10 pp.

Source: Bundesarchiv-Militärarchiv (BArch-MA, BAMA) Freiburg/ Germany, (Signatur) file nr. ZA 3/402, used in accordance with "Erstinformation für Ihren Besuch im Bundesarchiv in Freiburg, Stand Juni 2016".

Ref. 283: Philips transmitter vacuum tubes, NSF/Philips (beacon) transmitters, NSF/ Philips companies:

Ref. 283A: pp. 320, 321 in "Zendbuizen" ["Transmitter tubes"], J.P. Heyboer, Vol VII of "Electronenbuizen" ["Vacuum tubes"], Philips Technische Bibliotheek, N.V. Philips' Gloeilampenfabrieken, Meulenhoff & Co. N.V. (publ.), 1946, 321 pp. Source: frank.pocnet.net, retrieved 11 May 2022.

Ref. 283B: "Philips zendlamp PA 12/15", Philips transmitter tube datasheet, 2 pp. Source: frank.pocnet.net, retrieved 11 May 2022.

Ref. 283C: pp. 209-211 in "Spanne en Spanningen - De veertigjarige geschiedenis van de n.v. Philips' Telecommunicatie Industrie voorheen n.v. Nederlandsche Seintoestellen Fabriek" ["The 40 years history of Philips Telecom Industries, formerly NSF"], Willem Vogt, 1958, 354 pp. Source: nvhrbiblio.nl, retrieved 24 May 2022.

pp. 209-211 -- NSF beacon and broadcast transmitter systems, 1934-1941.

Ref. 283D: "Radio landing beacons for aerodromes", P. Zijlstra, in "Philips Technical Review", Vol. 2, No. 12, December 1937, pp. 370-376. Source: nvhrbiblio.nl. Dutch version is in "Philips Technisch Tijdschrift", Vol. 2, Nr. 12, December 1937.

Ref. 283E: "Position finding and course plotting on board an aeroplane by means of radio" [incl. V.P.K. 35, B.R.A. 101], G.P. Ittmann, in "Philips Technical Review", Vol. 2, No. 6, June 1937, pp. 182-190. Source: nvhrbiblio.nl.

Ref. 283F: "The Philips ultra short wave radio beacon type B.R.A. 075/4", P. Zijlstra, in "Philips Transmitting News", Vol. 4, No. 6, December 1937, pp. ???.

Ref. 283G: "Philips ultra shortwave beacon type B.R.A. 200/8" [NSF], R.F. Volz, A.G. de Jager, in "Philips Transmitting News", Vol. 5, No. 4, December 1938, pp. ???

Ref. 283H: "Some theoretical considerations on the Philips short wave radio beacon" [NSF], P. Zijlstra, in "Philips Transmitting News", Vol. 6, No. 3/4, December 1939, pp. ???

Ref. 292: "Führungs- und Navigationsverfahren, Bordfunksprech- und Bordfunknavigationsgeräte, Bordfunkmeßgeräte, Eigener und feindlicher Hochfrequenzeinsatz, Störsender, feindliche Bordfunkmeßgeräte, Feindliche Navigationsverfahren, Stand 1.1.1945", 6 pp. Source: TBD.

Tables: **Guidance & navigation methods** (UKW-Peiler; Y-Anlage; Egon; Bernhard-Anlage; Jagdhütte; Bodentruhe-Anlage; Sonne-Anlage); **Radio telephony & navigation equipment** (FuG 16ZY; FuG 15, FuG 125; FuG 24 SE; FuG 120, FuG 130, FuG 29, FuG 123); **On-board radar** (FuG 220 / Li SN2; FuG 228 / Li SN3; FuG 218 VR / Neptun VR; FuG 218 QR / Neptun QR; FuG 240 / Berlin N 1a; FuG 244 / Bremen O; FuG 200 / Hohentwiel; FuG 224 / Berlin A; FuG 217 / Neptun RII; FuG 25a / Erstling; FuG 227 I-III / Flensburg; FuG 350 Z/ ZX, Naxos Z/ZX, Naxos ZR; FuG 280 / Kiel; Falter), Luftlageaufklärung (Wassermann MI-MY, Elefant, Klein Heidelberg, Freya, Würzburg Riese,

Jagdschloß, Forsthaus F, Jagdschloß Michael B, Jagdschloß Z / Forsthaus Z, Jagdwagen, Korfu/Naxos/Naxburg); **Jammers** (Heinrich I & II, Karl I & II, Feuerstein I & II, Feuerzange, Feuerhilfe, Feuerland I, Abfrage-Ballstörgerät, Roland I & II, Klystron Röhre); **Enemy on-board radar** (Rotterdam/Rotterdam-X/ Belfort/Meddo, ASV/ASD/Rotterdam, Luchs/Grille/Frankfurt, Monica/Luchs/Fish Pond, Village-Inn); **Enemy radio navigation systems** (Hyperbel, Long Range, Bumerang, Diskus, Mikro-M). Status of 1 January 1945.

Note 1: due to copyright reasons, this file is in a password-protected directory. Contact me if you need access for research or personal study purposes.

External links last checked: January 2024 unless noted otherwise.

Back to Top