wavehunter

An extraordinary shortwave receiver not only for hunting interference signals and foxes ...

There are more and more electromagnetically incompatible devices that interfere with shortwave reception. In order to locate such sources of interference and take appropriate measures to eliminate them, every active radio amateur should have a direction finding receiver that can also be used for fox hunting and occasional reception of broadcasts and amateur radio. That's why in 2015 I set myself the task of designing and building a receiver with the following characteristics:

- AM/SSB/CW reception on shortwave
- good directivity
- high sensitivity and selectivity
- band change via plug-in modules
- simple and easy-to-reproduce circuitry
- low power consumption
- small, lightweight and robust

The result is a *regenerative audion* with a *tuned small loop* that functions simultaneously as a directional antenna and as a selective receiving circuit and can be de-damped to a quality factor *Q* of over 20000 @ 10 MHz, resulting in very high sensitivity and selectivity. This concept is the practical implementation of valuable insights that were developed already at the beginning of the 20th century but have since been largely forgotten. The first part of this article describes its technical and historical background in detail, the second part starting on page 22 describes its construction. On the following video you can see and hear the "wavehunter" in operation:
http://cq-cq.eu/assets/dj5il_vi001e.mp4

the tuned small loop

For a portable handheld receiver only electrically small antennas with a max. dimension of << λ/10 are suitable. Ideally, small open (dipole) antennas only respond to the electric field component and their reception performance drops significantly inside buildings. In contrast, small closed (loop) antennas only respond to the magnetic field component, their reception performance hardly drops inside buildings and they allow for an ambiguous but sharp minimum-bearing.

The so-called *antenna effect* describes the undesirable property of real magnetic antennas to behave partially like an electric antenna, which leads to the coupling of electrical interference and impairs directionality. Loop antennas for direction finding therefore often have an electrical *Faraday-shield*: a metal tube or mesh that is interrupted at one point so that the magnetic field lines are not shortcircuited. However, the antenna effect can also be largely eliminated without this shielding by grounding the loop in the center and building and operationg it strictly symmetrical.

If the inductance of the loop is supplemented by a capacitance to form a resonant parallel circuit, a *tuned small loop* is created. It provides a *Q*-fold higher received signal strength and so its sensitivity and thus its ability to pick up weak signals increases with the transition from the untuned to the tuned loop and then with *Q*.

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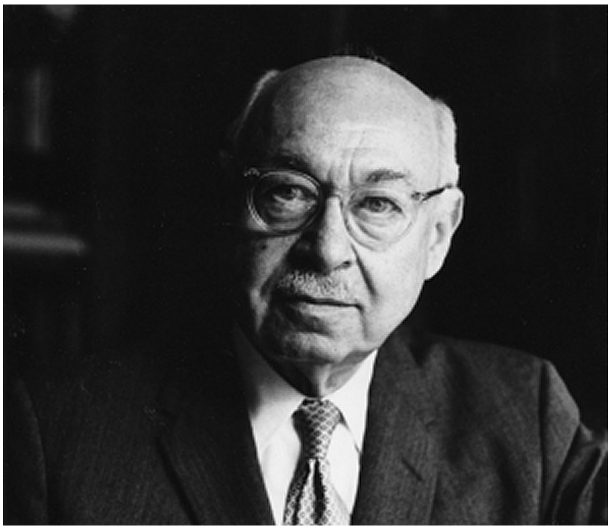
The concept of the *quality factor Q* was introduced in 1914 by **Kenneth S. Johnson** when he evaluated the purity or quality of inductors at the Western Electric Company with the ratio of inductive reactance to Ohmic loss resistance. Equivalent to this, but much more general, the quality factor Q of a resonator at steady state is defined as 2π times the ratio of stored energy to the energy lost during one oscillation period.

But why does the reception performance of the small loop increase with the quality factor *Q*, and how can *Q* be increased even further? If we focus on the sensitivity of a receiving system and thus on its ability to pick up weak signals, two names in particular have made history: *Rüdenberg* with his extremely interesting analysis of the receiving circuit, and *Armstrong* with his ingenious invention of the regenerative audion.



Reinhold Rüdenberg

Rüdenberg's receiving circuit

Reinhold Rüdenberg was born in Hanover in 1883. He obtained his doctorate in 1903 at the Technical University there, worked as an engineer for Siemens-Schuckert factory in Berlin from 1908, and qualified as a professor in 1913 at the Technical University of Charlottenburg. He then taught in Göttingen and Berlin, married Lily Minkowski (daughter of mathematician Hermann Minkowski) in 1919, and became head of the newly founded scientific department at Siemens in 1923. Rüdenberg held over 300 patents, including one for the electrostatic electron microscope. He emigrated to Great Britain in 1935, worked for General Electric Co. Ltd. until 1938, and lectured at the University of London. He then emigrated to the US, where he taught at Harvard University and MIT and died in Boston in 1961.

In his paper *"Der Empfang elektrischer Wellen in der drahtlosen Telegraphie"* (The Reception of Electric Waves in Wireless Telegraphy), published in 1908, Rüdenberg investigated the absorption of energy from the electromagnetic radiation field, discovered the radiation resistance and developed the concept of the effective length and effective area of an antenna. He coined the terms *"Strahlungswiderstand"* (radiation resistance) and *"Absorptionsfläche"* (effective area), which appear here for the first time in history. In 1926, Springer published a version of this paper in booklet form with the title *"Aussendung und Empfang elektrischer Wellen"* (Transmission and Reception of Electric Waves), which was practically identical in content but slightly rewritten and greatly extended. The following Rüdenberg quotes were translated from German by the author, his original formula symbols were retained.

Rüdenberg considers a *"receiving circuit"* consisting of a parallel resonant circuit with the loss resistance *R* and a coupled antenna, which draws energy from the electromagnetic field. He first notes that three aspects come into consideration for this *"resonator of wireless telegraphy"*, which must be taken into account simultaneously for the calculations:

- the receiving system has one or more distinct *natural frequencies* that make it capable of resonating with incident waves,

- it also has a certain *dissipative resistance*, which causes the electromagnetic energy oscillating in the resonator to be converted into heat or another recognizable form, and finally ...

- it exerts a *reaction* on the original radiation field because its circulating currents emit electromagnetic waves that disturb the initial field. As we shall see, this last point, which is still today little known, is of particular importance.

In order to obtain a *"good indication of the incoming waves"*, it was then customary to always tune the circuit to the frequency of the incoming waves by varying the inductance *L* or capacitance *C*. This causes resonance in the receiving system and gives *"the strongest effects possible under the given circumstances"*. Ultimately, it always comes down to extracting as much energy as possible from the radiation field through the receiving antenna and making it usable in the receiver. After these fundamental findings, Rüdenberg calculates ...

- the energy radiated into the resonator or *incident energy* W_E

- the *energy absorbed* by the useful and harmful resistances *R* of the resonator W_R

- the energy re-radiated by the antenna or *scattered energy* W_S

... and finally establishes the energy balance of this resonator: according to the law of conservation of energy, the absorbed and scattered energies must be in equilibrium with the incident energy, and thus $W_E = W_R + W_S$.

His calculations prove that both the absorbed energy W_R and the scattered energy W_S reach a strong maximum when the natural frequency of the receiving circuit coincides with the frequency of the radiation field. This fact was already known at the time, but only Rüdenberg provided the explanation. All three energy components, and thus also the usable energy, increase with the current circulating in the resonator, which is hindered by its capacitive and inductive reactances, the Ohmic loss resistances and the radiation resistance.

In order to obtain the highest possible current, the reactive resistances must first compensate each other, that is the receiving circuit must be in *resonance* with the primary radiation field. Unfortunately, this fundamental significance of resonance has been largely forgotten. In addition, the stronger the scattered field, the greater the incident energy, because at least the scattered energy must first be taken from the primary field by the receiving antenna. Rüdenberg isolates the summand $S\,\omega^2$ from the equations for the three energy components, which always appears in conjunction with the loss resistance *R*, and concludes quite correctly ...

"that, in addition to the Ohmic resistance of the wire conductors, a radiation resistance is also decisive for the strength of the current, which causes the current to remain finite even when the line resistance is negligible; it acts exactly like an ordinary resistor connected in series".

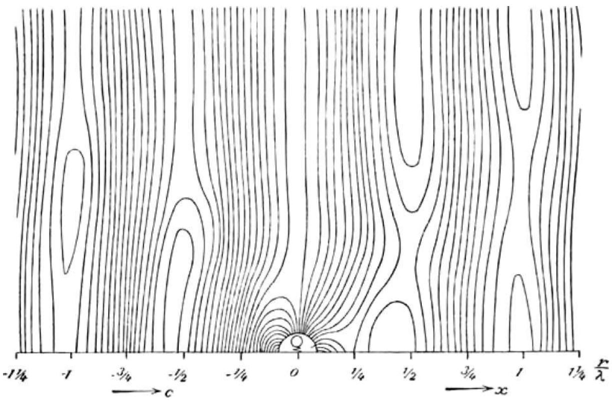
So when *R* approaches zero, the current does not always increase, but approaches a finite limit value which is caused by the *"attenuating effect of radiation"*. Finally, he develops an equation for this *radiation resistance* as a function of wavelength and effective antenna length, and calculates it for a quarterwave radiator correctly with 36.6 Ohms. He also proves the law originally discovered experimentally by Tissot, Duddel, and Taylor and now known as *resistance matching*, namely that the usable absorbed energy reaches a maximum when $R = S\,\omega^2$ and *"thus the detector resistance is exactly equal to the radiation resistance"*. This is the largest amount of energy that can be extracted from the radiation field by a single resonator. If the receiving circuit does not satisfy the two conditions of *resonance* and *resistance matching*, the absorbed energy is always considerably smaller. In the best case, the absorbed energy is equal to the scattered energy.

Rüdenberg recognizes from his equation for the maximum usable energy that the greater the wavelength of the incoming radiation, the greater the maximum energy absorption of the receiving circuit, and that the length of the equivalent dipole, which is a measure of the effective length of the receiving antenna, has no influence on the strength of the absorption. Later we will take a closer look at this extremely important finding and draw some interesting conclusions from it.

So according to Rüdenberg, energy absorption increases with wavelength and is independent of the actual dipole length. It is greatest when there is no harmful resistance in the receiving circuit and *R* therefore consists only of useful resistance, which is matched to the radiation resistance R_S, i.e. when $R = R_S$. Even in this most favorable case only half of the incident energy can be converted into usable energy in *R*, the other half is lost through radiation via the radiation resistance R_S and scattered back into space so that the antenna efficiency is at most 50%. This radiation is strongest for the limiting case $R = 0$, where the receiving antenna merely causes *scattering* of the incident energy.

Rüdenberg thus describes how a high-frequency current is generated in a receiving antenna by the incident *primary* radiation field, which flows through its radiation resistance and thus generates its own *secondary* radiation field. He also calculates the electric and magnetic *"lines of force"* in the vicinity of a receiving antenna, depicts them graphically, and describes his findings on the effect of the secondary radiation field:

"Within the interference range of a receiver, the incoming and transmitted waves interfere with each other [...] As a result of this interference, energy is transferred from the radiation field to the resonator and a certain amount of energy is scattered in all directions, especially towards the incident radiation, thus a diffuse reflection occurs. Behind the receiver, a kind of shadow formation occurs over short distances, as the primary and secondary fieldstrengths counteract each other while propagating in the same direction".



Electric lines of force in the vicinity of a monopole receiving antenna according to Rüdenberg.

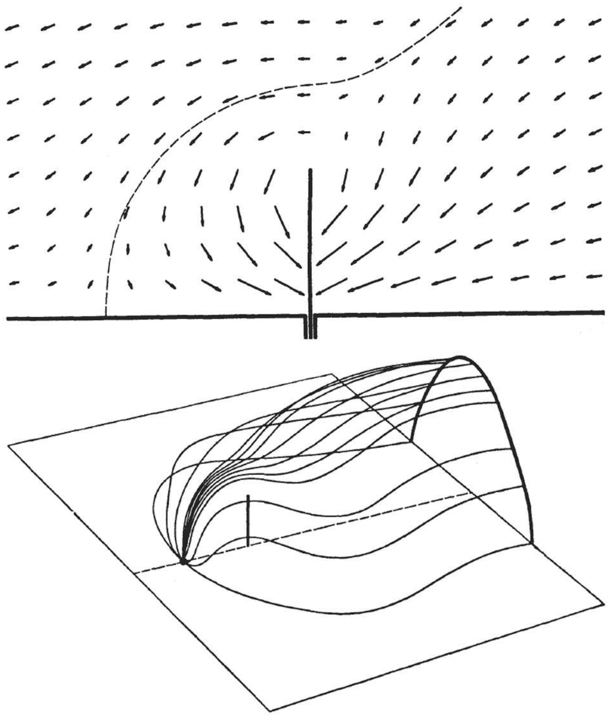
His graphical representation of the electric and magnetic field clearly shows how the secondary field in the vicinity of a receiving antenna retroreacts onto the primary field by curving the incoming field lines and concentrating them in front of the antenna, while a shadow effect occurs behind the antenna. The superposition of both fields thus leads to a complete change in the field strength distribution in the vicinity of the receiving antenna. Rüdenberg then states ...

"It is of interest to compare the energy absorbed by the resonator with the energy flow that travels through a specific area in the undisturbed radiation field, i.e. perhaps at greater distances from the receiver. We want to calculate the size of the area through which an equal amount of energy flows as is absorbed by the resonator from the field"

... and finally derives an equation for this *"absorption area"* of an antenna. According to the modern definition, the absorption area or effective area $A_e = \lambda^2 G / (4 \pi)$ is an area perpendicular to the direction of propagation through which, in the case of a plane electromagnetic wave with homogeneous power density *S*, the maximum reception power of the antenna with power matching $P_{max} = S \times A_e$ would pass through. Like the antenna gain *G* it is a measure of the reception power of an antenna, but in contrast to the antenna gain the absorption area also takes into account the wavelength. This allows the absolute reception power to be calculated directly for a given field strength which, as already proven by Rüdenberg, actually depends only on the wavelength λ and antenna gain *G*. For example, with a given power density a dipole for λ = 20m provides 100 times the reception power of a dipole for λ = 2m, for the same antenna gain the reception power therefore increases quadratically with the wavelength. However, if the antenna is resonant, loss-free, and matched, its geometric dimensions are completely irrelevant for the reception power.

The *Poynting vector* was named after the English physicist **John Henry Poynting**, who introduced it in 1884. It is the cross product of the electric and magnetic field vectors, is perpendicular to both, points in the direction of the energy flow, and its magnitude is the *energy flux density* or *power density* in W/m^2. Simulation (NEC) can be used to calculate the field vectors in the near field of a receiving antenna, resulting in the complex Poynting vector $S = E \times H$. Its time-averaged real part is the *effective power*, *irradiance* or *intensity* transported per unit of time through a unit of area.

In the 1970s, scientists **Friedrich Landstorfer** and **Hans Meinke** at the Institute for High Frequency Technology at the Technical University of Munich conducted intensive research into energy flow in electromagnetic wave fields and its graphical re-



Effective average energy flow into a short monopole receiving antenna. Top: time-averaged Poynting vector in the vertical plane through the radiator; all flow lines and thus energy entering the boundary envelope (the boundary flow line is drawn as a dashed line) through the absorption surface end at the feed point of the receiving antenna and are absorbed by it. Bottom: spatial representation of the semicircular absorption surface and the boundary envelope. (According to Friedrich Landstorfer et al., "Energieströmung in elektromagnetischen Wellenfeldern" [Energy flow in electromagnetic wave fields], Nachrichtentechnische Zeitschrift NTZ 1972, issue 5, p. 230)

presentation. The two figures above clearly show the average energy flow in the near field of a short monopole receiving antenna. All flow lines and thus energy entering the boundary envelope through the absorption area shown end at the feed point of the receiving antenna and are absorbed by it, and so it absorbs energy from the field through an absorption area that can be remarkably large in relation to its spatial extent.

With the quality factor *Q* of the small loop its reception power and thus inevitably also its absorption area increase, as if it were spanning a larger net in order to absorb correspondingly more energy from the field. And Landstorfer / Meinke have clearly demonstrated that this is not just a fictitious area, but a very real one.

resonance

Due to its central importance for the receiving circuit, let us take a closer look at this extremely interesting phenomenon. The term is derived from the Latin *"resonare"* (to echo) and in physics and engineering refers to the amplified covibration of a oscillatory system when it is subjected to a time-varying influence. In the case of periodic excitation, the excitation frequency or an integer multiple thereof must be close to a *natural frequency* of the system. The phenomenon can occur in all oscillatory physical and technical systems and is frequently encountered in everyday life.

The increasing deflections at resonance are caused by the system absorbing and partially storing energy with each oscillation, and the increase in the deflections is limited by the fact that the energy supplied is increasingly consumed by the damping. As a result, a *steady state* is reached over time, in which the amplitudes remain constant and the oscillation frequency corresponds to the excitation frequency. The energy supplied with each oscillation is now completely consumed by the damping. After the excitation is switched off, the system releases the stored energy and gradually comes to rest in the form of a *damped oscillation* at its natural frequency.

The residents of Tacoma, Washington, experienced the power of resonance on November 7, 1940. Since its grand opening just four months ago, The 1800m long "Tacoma Narrows Bridge" had often swayed, earning it the nickname "Galloping Gertie". But on this day, the wind was blowing at 42 mph, and that was more than Galloping Gertie could handle. The wind speed itself would not have been a problem, but the torsion of the roadway changed the wind's angle of attack periodically with the structure's natural frequency, causing it to sway more and more until the suspension bridge finally collapsed and plunged 70 meters into Puget Sound. Its quality factor *Q* was obviously much higher than its mechanical design allowed. The film footage of this event is spectacular:
https://youtu.be/j-zczJXSxnw?si=N4DtDCbhcBEHtZuI

Tacoma Narrows Bridge, July 1940

A particularly demonstrative mechanical example of such an oscillatory system is a *pendulum* that, after being set in motion, is given a small, constant push in the direction of motion each time it passes its lowest point. It experiences a short impulse and absorbs energy, but it also constantly loses energy to air resistance and friction in the pendulum bearing, which dampens its movement. It stores the excess alternately as *potential energy* when it comes to rest briefly at one of its two apexes, and as *kinetic energy* when it reaches maximum velocits at its lowest point. During the transient state, the excess absorbed energy asymptotically approaches zero and thus the oscillation amplitude approaches its maximum value.

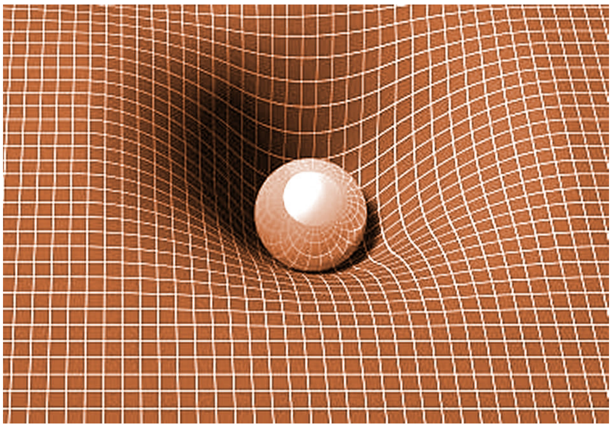
The inductive reactance of an untuned small loop as a receiving antenna does not allow any significant current to flow, so it can only extract very little energy from the primary radiation field and its absorption area is correspondingly small. By tuning to resonance with a parallel capacitor, its inductive reactance is compensated and the circuit current is increased enormously. Analogous to the mechanical pendulum this electrical *resonant circuit* is excited by the primary radiation field and absorbs a constant amount of energy from it during each period. But at the same time it loses $2\pi/Q$ times the growing total stored energy, which is exchanged as reactive power between the capacitance and inductance in time with the radiation field, to the resistances in the circuit. In an ideal lossless resonant circuit, the stored energy and thus also the amplitude of the voltage and current would grow to infinity under constant excitation. However, in a real lossy resonant circuit the energy consumed by damping increases with the stored energy, and thus the amplitudes grow asymptotically toward a limit value that is theoretically reached when the energy absorbed is equal to the energy consumed during one period.

As an analogy, we can imagine a balloon being filled from a gas cylinder. The volume of a leakproof balloon and the gas pressure inside would steadily increase. However, if it has a small hole, as the pressure inside increases more and more gas escapes, and so the volume and gas pressure grow more and more slowly until finally the gas loss corresponds approximately (but never completely) to the gas inflow per unit of time.

Ideally, the tuned small loop is only excited by the magnetic component of the primary radiation field, which induces a *source voltage* or *electromotive force EMF*, causing a current to flow in the circuit. When the primary magnetic field arrives, its first halfwave generates a current (the pendulum is triggered), which charges the capacitor and stores electrical energy in its concentrated field. After the current passes through zero it discharges, generating a reverse current which is now amplified by the second halfwave of the primary magnetic field, which is also opposite (a small push in the direction of the pendulum's movement), and generates a secondary field in the inductance of the loop that extends into space and stores magnetic energy. After the current passes through zero, this secondary field collapses, generating another reverse current, which is again amplified by the third halfwave of the primary magnetic field and therefore recharges the capacitor to a higher voltage. The current and voltage are therefore out of phase by 90°.

This cycle repeats itself over and over again, with the amplitudes of voltage and current and the secondary magnetic field building up asymptotically toward a limit value that characterizes the steady state and is approximately reached after Q periods.

The resistances in the resonant receiving circuit dampen it and limit voltage and current, and also analogous to the pendulum their reduction and thus a higher quality factor Q not only results in less energy loss, but also in higher energy absorption from the primary radiation field during each period. It is the predominantly *reactive near field*, in the case of the small loop the secondary magnetic field, which also grows in strength and extent with the quality factor Q and not only acts as an energy storage but also carries energy from the primary radiation field piggy-back into the receiving circuit, so to speak. Its ring-shaped magnetic field lines around the conductors of the loop concentrate in its center. In its steady state, it is Q times stronger than the primary magnetic field in the loop's immediate vicinity and, through superposition, pushes the time-averaged Poynting vector in the direction of its feed point. Like the drain of a bathtub, the secondary magnetic field sucks energy from the primary radiation field into the feed point - and the higher the quality factor Q and thus the demanded amount of energy, the larger the absorption area inevitably becomes.



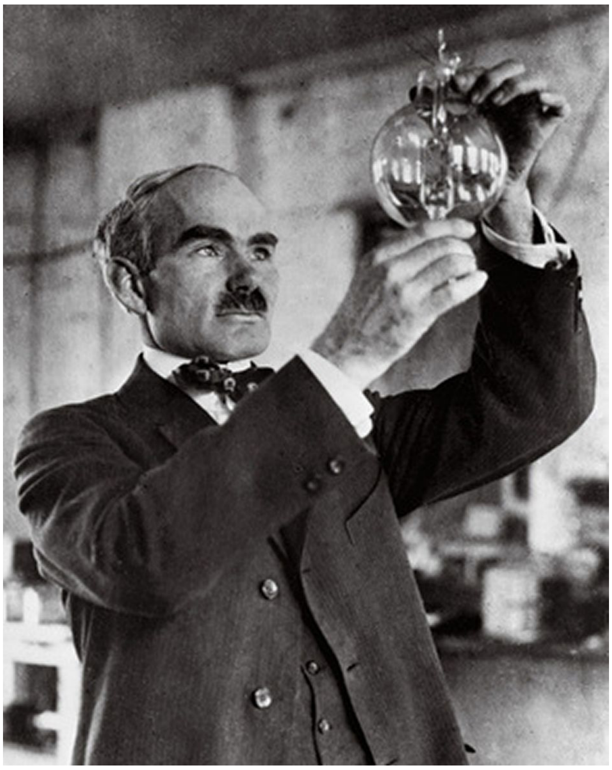
The effect of gravity is often visualized by a stretched rubber sheet with a ball lying on it. The heavier the ball, the greater the extent and depth of the depression it creates on the surface. If small marbles are rolled over the rubber sheet, their paths are deflected toward the ball by the deformed sheet, with the deflection increasing as the ball becomes heavier and the marbles come closer to it. Just like the effect of the depression in the rubber sheet, we can imagine the effect of the reactive near field of the antenna as an *energy sink* that directs the energy flow of the primary radiation field to its feed point.

If the amplitude of the exciting primary field changes abruptly, the energy-storing near field and thus the current and voltage in the receiving circuit cannot follow immediately but require approximately Q periods to adapt to the amplitude change and reach the steady state. For this reason, the bandwidth decreases and the selectivity of the resonant receiving circuit increases with increasing quality factor Q.

Armstrong's regenerative audion

While searching for a better detector for radio waves, the Englishman **John Ambrose Fleming** discovered that the *Edison effect* (thermionic emission) could be used for detection. He modified Edison's incandescent lamp and invented the *electron tube*. In 1904, he applied for a patent describing a two-electrode radio rectifier. He himself called his invention, which is widely regarded as the beginning of the electronic age, an *"oscillation valve"*. It enabled the oscillating radio signal from the spark-gap transmitters commonly used at the time to be rectified into a pulsating signal and thus made audible. As a much better detector for wireless telegraphy and the emerging telephony, this *"diode"* replaced the coherer and the crystal detector. However, the signal urgently needed to be amplified in order to receive distant transmitters and to enable the use of loudspeakers instead of headphones.

The American **Lee De Forest** developed his interest in wireless technology while studying at Yale University. After graduating, he worked at Western Electric and then set up his own business in 1902 with the De Forest Wireless Telegraph Company. He was particularly interested in receiving weak radio signals and, like Fleming, recognized the limitations of existing detectors. He initially pursued the idea of an electrolytic detector called *"responder"* and then investigated the suitability of electrodes in the flame of a Bunsen burner. Finally, in 1906 he added a *"grid"* as a third electrode to Fleming's diode, thereby slightly improving its rectifying properties and sensitivity. De Forest called this arrangement he invented the *"audion"*, today we call it three-electrode amplifier tube or *"triode"*. It expanded the capabilities of the electron tube from those of a pure rectifier or detector to those of an amplifier and even a generator for radio signals. However, more of a pragmatic experimenter than a scientist he had neither intended nor recognized these applications of his construction at first. This is the only explanation for why the grid was originally located outside the electron beam, in a position that was unfavorable for the control effect, rather than between the directly heated cathode and anode. In fact, De Forest candidly admitted that he did not know how or why his



Lee De Forest

audion worked - it just worked ...

In De Forest's 1907 patent, alongside the audion tube the audion circuit was presented, which later became known as the *grid audion*. The radio signals are inductively coupled from the antenna to a parallel resonant circuit feeding the grid, while the headphones are in the anode circuit called *"wing circuit"*. However, De Forest had achieved only minor improments, as the radio signals were hardly any stronger than with Fleming's diode.

Edwin Howard Armstrong was born in Manhattan in 1890 and spent his youth in Yonkers, New York. At the age of 13, he read about Marconi's radio experiments and was fascinated by the newly discovered wireless technology. While still at school, he built a 40 meters high antenna mast in his parents' garden for reception experiments, which he often climbed just for fun - Howard had no fear of heights and loved being up high. And as an enthusiastic ra dio amateur, he naturally experimented with every component he could get his hands on.

An uncle introduced him to Charles R. Underhill, an engineer and inventor at the "American Telegraph Company", who became his mentor and provided him with equipment to experiment with. Howard often visited him after school to learn the basics of wireless technology and discuss it with him. In 1909, he began studying electrical engineering under Prof. Michael Pupin at Columbia University in New York.

De Forest's audion tubes were sensitive and very expensive, but Pupin had some in his laboratory and made them available to Armstrong, who immediately began experimenting with them. He found that the signals became slightly louder when he bridged the headphones with a condensor, and its small capacitance was a strong indication of high frequency in the anode circuit. During the summer holidays of 1912, the fundamental axiom of radio technology at that time occurred to him: wherever high-frequency oscillations occur, tune the circuit! This gave him the brilliant idea of tuning the *"wing circuit"* to resonance with an inductor, and so he set to work in his attic laboratory at home.

Until the 1930s, it was assumed that frequencies above 1 MHz were useless for long-distance communication, and so coastal radio stations operated between 500 and 1000 kHz and radio stations for overseas traffic usually even below 60 kHz. On 22 September 1912, Armstrong tuned a normal grid audion to the longwave frequency of the Marconi press station in Wellfleet (Cape Cod) with the callsign WCC. At that time, all experimenters used this station as a 100% reliable test signal. He then inserted a coil variometer into the anode circuit, which had an astonishing effect: its tuning amplified the signal to an intensity that was incredible at the time !

The explanation for the cause of the unusual effect observed was difficult, but finally he had a brainwave: via the parasitic grid-anode capacitance of the tube, positive feedback of the signals from the *"wing circuit"* (anode circuit at the output) to the *"grid circuit"* (grid circuit at the input) took place, which obviously caused regeneration of the signals and their amplification by several tens of thousands of times.

To make the feedback more flexible and reliable, he eventually switched to inductive coupling. But Armstrong noticed something else on that memorable day: when he tuned the variometer, the signal initially became louder and louder, but then suddenly vanished and all that could be heard was a loud hissing sound. Armstrong quickly realized that his system was not only receiving signals, but also generating its own radio waves. Thus, in a single stroke of genius, not only was a highly sensitive receiver born, but also an effective electronic transmitter for undamped oscillations of almost any frequency. In fact, this circuit is functionally identical to the oscillator that **Alexander Meißner** patented just one year later.

Years later, Pupin said: *"Armstrong's system maintained its pitch with a degree of accuracy never before obtained by any apparatus constructed by man [...] It goes without saying that long-distance radio communication and radio broadcasting would be impossible without this invention"*. The high stability and consistency of these undamped oscillations were indeed fundamental prerequisites for their modulation and thus for the future transmission of sounds via radio waves. That's how the triode revolutionized radio technology and consigned spark, arc, and machine transmitters to history.

Edwin Howard Armstrong

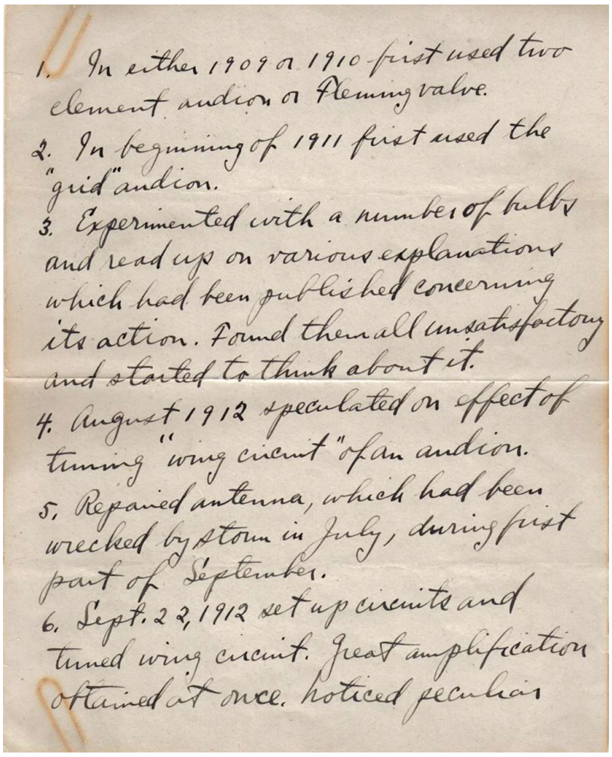
Armstrong's professors strongly advised him to apply for a patent. However, the student did not have the necessary $ 150, so on 31 January 1913 he had his circuit certified by a notary for only 25 cents. Now an assistant at his university, he did not apply for a patent for his regenerative audion until 29 October 1913, which was granted on 6 October 1914.

On 30/31 January 1914 Armstrong demonstrated his regenerative receiver to **David Sarnoff**, a young executive of the Marconi Telegraph Company, at the Marconi Belmar receiving station in New Jersey. They received very distant stations throughout that cold night, for 13 hours from 4 in the afternoon to 5 in the morning. The telegraph signals from San Francisco, Honolulu, South and Central America, Clifden / Ireland, Nauen / Germany and many others were incredibly strong and could be heard loud and clear throughout the room, even though the headphones were lying on the workbench. Three days later, the 22-year-old Sarnoff wrote a detailed report about this demonstration to his superiors, concluding with the following sentence: *"I am of the opinion that he has the most remarkable receiving system in existence"*.

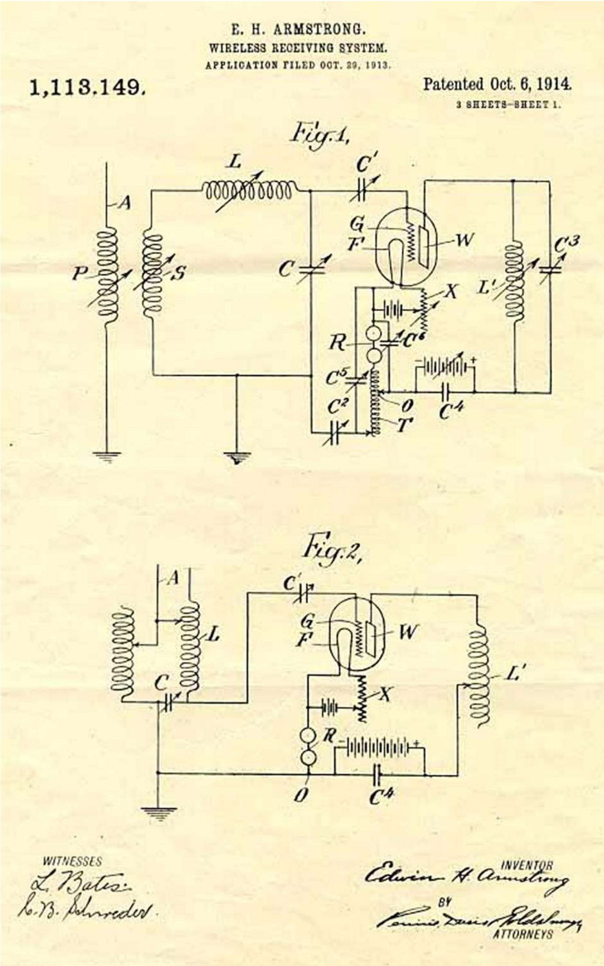
Armstrong scientifically investigated the audion amplifier for many years, carried out measurements, and was finally able to truly understand and explain its function - something De Forest had never managed to do. De Forest became increasingly indignant when he realized what the "greenhorn" Armstrong had achieved with the audion. His dictum was that there was no high frequency at the anode and that feedback was nonsense. On 12 March 1914 he and his assistant C. Logwood applied for protection for their oscillator circuit called *"ultra audion"*, which had no discernible feedback loop. With it, he was able to generate completely unattenuated oscillations and even sold some of these devices to the Navy. But it was Armstrong who proved that the ultra audion also had a feedback circuit when the internal tube capacitances were taken into account.

Subsequently a bizarre patent dispute developed that lasted 20 years and was ultimately won by De Forest. However, both then and now experts consider Armstrong to be the true inventor of positive feedback, with De Forest merely being the legal inventor. Columbia University described Armstrong as the greatest inventor of all time, including Marconi, in the field of radio technology. His regenerative receiver was followed in 1918 by the superheterodyne, whose circuit principle was henceforth used in virtually every radio and television set. In 1923, he married Marion McInnis, Sarnoff's secretary. They went to Palm Beach for their honeymoon, where he presented his bride with the world's first portable radio. During the 1930s, he invented frequency modulation and developed "high-fidelity" FM radio. He made countless groundbreaking inventions that made him a wealthy man, and he ultimately held 42 patents.

After a meteoric career, David Sarnoff became head of Radio Corporation of America (RCA), the world's largest manufacturer of AM radios and other electronics, as well as the National Broadcasting Company (NBC), RCA's most famous subsidiary and operator of the world's largest AM radio network.


1. In either 1909 or 1910 first used two element audion or Fleming valve.
2. In beginning of 1911 first used the "grid" audion.
3. Experimented with a number of bulbs and read up on various explanations which had been published concerning its action. Found them all unsatisfactory and started to think about it.
4. August 1912 speculated on effect of tuning "wing circuit" of an audion.
5. Repaired antenna, which had been wrecked by storm in July, during first part of September.
6. Sept. 22, 1912 set up circuits and tuned wing circuit. Great amplification obtained at once. Noticed peculiar

Armstrong's handwritten chronology of his invention of the feedback audion (1920, page 1 of 6)



Armstrong's regenerative receiver circuit in two variants, patented in 1914.

What Armstrong had not expected, however, was that RCA would use his patents without paying a cent, and that Sarnoff would betray their friendship and lead a secret cartel that worked by any means necessary to cripple the new FM radio and the fledgling television industry, which he saw as a threat to his AM networks.

Armstrong was eventually financially ruined and mentally broken by years of fighting RCA, and his end was tragic. On January 31, 1954, he had his luxury apartment on the west bank of the East River in New York all to himself for the night. His wife Marion was visiting her sister in Connecticut, and he had given the cook and two maids the night off. The worldfamous inventor, Ivy League professor, major, and Knight of the French Legion of Honor placed his handwritten suicide note on the bedroom dresser and went to the window. He pushed it open and felt a rush of icy winter air. For his fellow New Yorkers, the day that had just ended had been an ordinary Sunday, but for Major Armstrong it was an important anniversary. Exactly forty years earlier, he had experienced the full power of his first invention, a discovery that heralded his career as the most prolific inventor since Thomas Edison. On that distant 31 January 1914, a twentythree-year-old Edwin Armstrong had embarked on an unusual adventure. At that time, the ability to send information wirelessly through the air was little more than a parlor trick. At the beginning of the 20th century, the *"ether"* was only good for exchanging messages between two places using Morse telegraphy and gigantic technical effort - and that was spectacular enough. Armstrong believed he had invented a device that could change this - and he had a vision of radios for everyone, sensitive enough to receive broadcasts from all over the world.

He met David Sarnoff, who shared the inventor's youth and optimism and was one of the few who believed in Armstrong's idea. And because Sarnoff worked for a company that owned one of the largest antennas in the world, he offered to connect Armstrong's device to the antenna and put it to the test. The result shocked even the two young optimists when they suddenly picked up loud wireless signals sent from the other side of the planet, that could not or only faintly be heard with the best RCA receivers. From that day on, the two were united by their fascination for the untapped power of the invisible waves.

Major Armstrong took his coat and hat, removed the air conditioner from the window on the 13th floor, and took his last walk...

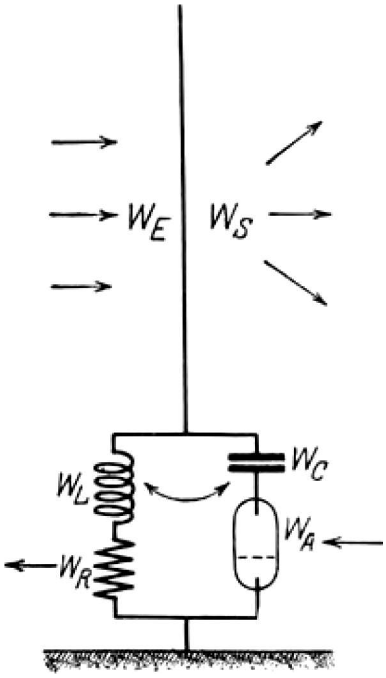
fanning

Armstrong's feedback does not actually cause any greater amplification of the Audion tube as such, and the intuitive idea that this causes the received signal to be amplified again and again is incorrect. In fact, it is a completely different and highly efficient type of amplification, which again is explained by Rüdenberg 1926 in *"Aussendung und Empfang elektrischer Wellen"* (Transmission and Reception of Electric Waves).

In Chapter 10 *"Entdämpfung des Empfängers"* (dedamping of the receiver) he first establishes that the Ohmic resistances as well as the radiation resistance prevent the development of a strong resonance in the receiving circuit. He presents a series of resonance curves for different qualitiy factors and shows that both the magnitude of the resonance effect and the sharpness of the resonance tuning - i.e. the selectivity - deteriorate with the resistances in the circuit. He then explains how the extremely high amplification of the feedback audion is achieved almost exclusively by artificially increasing the quality factor Q of the receiving circuit:

"With modern electron tube technology, it is now relatively easy to introduce negative resistance or fanning into the oscillating circuits by means of feedback, thereby neutralizing a considerable portion of the resistances. This results [...] not only in a

much narrower resonance, allowing for sharper tuning near other interfering waves, but also increases the current in the receiver many times over, so that reception is greatly enhanced".



Fanned receiving circuit according to Rüdenberg

Rüdenberg shows that the *negative differential resistance* R_A and thus the fanning energy W_A is supplied to the resonant receiving circuit from the electron tube, resulting in the energy balance $W_E + W_A = W_R + W_S$. The incident voltage generates a current, which can be made almost arbitrarily large by reducing the Ohmic resistances R in the circuit by means of the negative resistance R_A. He demonstrates that by this *fanning* not only the energy absorbed by the Resistances is increased, but that also more incident energy is extracted from the wave field and more energy is scattered. If the amount of fanning $|R_A|$ is increased from zero to R so that the Ohmic resistances are increasingly neutralized, all energies increase significantly but remain finite due to the effect of the radiation resistance R_S. For $|R_A| = R$ it is $W_E = W_S$ and $W_R = W_A$ and Rüdenberg recognizes:

"In this case of complete cancellation of the useful and harmful resistances, the total resistance power is therefore generated by the fanning energy itself, and the total incident energy is re-emitted as scattered energy. In this case, the energy flowing into the receiving antenna is no longer converted into useful energy, but is completely re-emitted. It now serves only to control the entire receiving system and to trigger the various amounts of energy acting within it."

The energy absorbed by the Ohmic resitances is then $W_R = W_E\ R / R_S$ and thus exceeds the incident energy W_E by the same amount by which the canceled resistance R is greater than the radiation resistance R_S. Rüdenberg notes:

"For such de-dampened receiving systems, it is therefore advisable to keep the radiation resistance R_S quite small and the useful resistance R quite large in order to achieve strong effects, and to neutralize the latter by means of a suitable fanning circuit. Compared to the optimum performance of the receiver without fanning [...], many times greater effects can then be achieved".

For this reason, the feedback audion enables an astonishing increase in reception performance, especially on electrically small antennas with their extremely low radiation resistance and comparatively high loss resistance. Finally, Rüdenberg describes what happens when the amount of fanning $|R_A|$ is increased beyond R, i.e. when $|R_A| > R$:

"The radiated power then exceeds the incident power considerably, so that the process can no longer be regarded as wave scattering. Rather, not only the absorbed power but also the radiated power is now largely supplied by the fanning. The incident power gradually decreases to the function of merely controlling the energy quantities of the receiver [...] Neighboring third receivers, which cannot hear the incoming waves on their own, are often stimulated to listen in by this amplification effect of strongly de-dampened resonant circuits. If the fanning is increased to such an extent that it completely neutralizes not only the Ohmic resistances but also the radiation resistance, or even further, all energies [...] become infinitely large. In reality, the feedback receiver becomes uncontrollable beforehand and excites itself at its natural frequency until a stable state is reached somehow through its non-linear characteristic cutve. The frequency of this receiver, which has been de-dampened to zero, is no longer necessarily dependent on the incident waves. Rather, the self-excited oscillations superimpose themselves on these, and the receiver acts entirely as a wild transmitter with its own frequency".

In 1927 Springer published a collection of lectures in book form under the title *"Die wissenschaftlichen Grundlagen des Rundfunkempfangs"* (The Scientific Fundamentals of Radio Reception). In the foreword, the editor Prof. Dr.-Ing. K. W. Wagner, writes:

"The lecture by Prof. Dr. Rüdenberg deals with the processes involved in the transmission and reception of electric waves, and in particular with the role played by antennas in this context. Every antenna also radiates a certain amount of energy back into

Typical early feedback audion with frame antenna

space when receiving electrical waves, a circumstance that must be taken into account if one wants to thoroughly understand the mode of operation and properties of a receiving antenna. The radiation from receiving antennas is also the cause of their mutual interference. Since radio broadcasting has become widespread across cities and rural areas, it has become more common to hear of fabulous reception performances being achieved with simple detector receivers. In all cases where this phenomenon has been investigated, it has been found that the detector device only received the distant transmitter when a neighboring, strongly de-damped and correspondingly strongly radiating tube device was tuned to the same distant transmitter. In reality, the detector receiver did not receive the radiation from the distant transmitter, but rather the secondary radiation from the tube apparatus, which thus unintentionally acted as a relay transmitter".

The early feedback audions were simple tube receivers that were usually operated with frame antennas on longwave. By fanning they achieved approximately the same sensitivity as large antennas and extremely good selectivity. However, in the 1920s frame antennas were increasingly replaced by long wires, and due to their comparatively high radiation resistance, the feedback audion could no longer fully demonstrate its strengths. Instead, as described by K. W. Wagner, it acted as a *"relay transmitter"* when operated improperly and caused interference in neighboring receivers, which is why, starting in 1924, an *"Audion Versuchserlaubneis"* (audion test permit) from the Reichspost was required for its operation in Germany. From the end of the 1930s insulating HF stages became popular, which prevented such interference but at the same time blocked the performance of this ingenious reception system. This is because the originally fanned receiving circuit acts as an extremely good amplifier with a very low noise figure at the ideal location, right at the front end of the signal path. It therefore has a decisive influence on the *noise figure* of the entire receiver, because the noise of the subsequent stages is negligible due to its extremely high amplification. In contrast, these isolating RF stages as conventional amplifiers have a significantly lower gain but a higher noise figure.

But why does feedback create negative resistance? The audion (the triode) has an extremely high but, like every amplifier, a finite differential (AC or small signal) input resistance. If we imagine the controlling receiving circuit as a voltage source with a serial internal resistance, then a voltage change ΔU at the input causes a current change ΔI with the same sign, so both are in phase. The differential input resistance $R_{AC} = \Delta U / \Delta I$ is positive and power is extracted from the receiving circuit, which dampens it. If part of the audion output voltage is now fed back to its input, the signal amplitude at the input increases with the degree of feedback. However, this reduces the voltage drop across the internal resistance and thus the signal current supplied by the voltage source, so that the control power is increasingly supplied from the output and the input resistance rises asymptotically towards infinity. As soon as the signal amplitude at the input is greater than that of the voltage source, the input resistance suddenly changes sign, i.e. it becomes negative and its magnitude now decreases asymptotically toward zero. The reason for this sign change is that the output now supplies more power to the input than the input absorbs. A positive voltage change ΔU at the input now causes a negative current change $-\Delta I$ so that both are in antiphase. The differential input resistance $R_{AC} = \Delta U / -\Delta I$ is therefore negative and the excess power supplied by the output is fed to the controlling receiving circuit, which fans or de-dampens it.

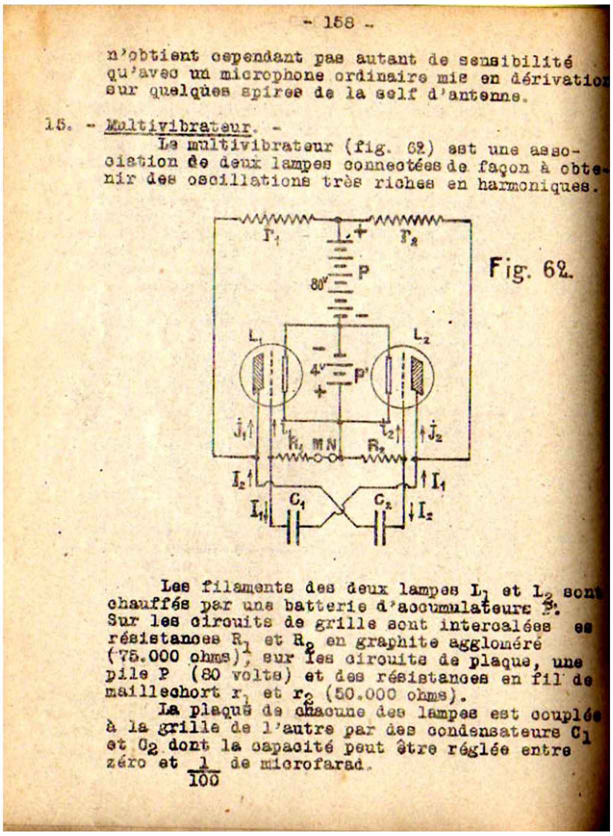
Summary: A feedback audion has a negative differential input resistance that de-dampens the receiving circuit by supplying it with energy according to exactly the same rules as those by which its loss resistance and radiation resistance convert it into heat and electromagnetic radiation. This artificial increase in the quality factor Q of the receiving circuit results in a preamplification that is thousands of times higher than the further multiplying nominal amplification of the audion together with enhanced selectivity.

the cross-coupled pair

The small symmetrical loop of my direction finder serves simultaneously as a receiving antenna and as the inductance of the receiving circuit. In order not to disturb its symmetry and thus its direction-finding effect, a symmetrical circuit must also be used to de-dampen the circuit. This task is performed by a pair of cross-coupled bipolar transistors, a simple but ingenious circuit whose ancestor was invented in tube technology more than 100 years ago and is now used as a *"cross-coupled pair"* or XCP for short in countless analog and digital circuit variants and applications. It can even be found in the incessantly paw-waving cat "Maneki-Neko," a Japanese mascot that is often seen in Chinese shops and restaurants.

The original form of the XCP was developed by two French engineers, **Henri Abraham** and **Eugene Bloch**. It first appeared in April 1918 in a secret document from the war ministry, and was finally published in June 1919. It consists of a pair of cross-coupled triodes, whereby the grids of the tubes are connected to the cathode (ground) via a resistor and to the anode of the other tube via a capacitor, and the anodes are connected to the operating voltage via a resistor. The modern systematic name for this arrangement is *"astable multivibrator"* because it periodically switches back and forth between its two possible states until it is switched off.

The circuit was developed during the war years of 1916/17 as part of secret military research in the field of radio espionage and was intended for precise frequency measurement in wireless telegraphy. Until then, calibrated oscillating circuits had been used for this purpose, but it was extremely difficult to achieve a measurement error of less than 1% in this way. Abraham and Bloch called their arrangement *"multivibrateur"* because it can generate a square wave of almost any frequency which is very rich in harmonics and depends only on *R* and *C*. In fact, harmonics up to the 150th were detectable, and so it was now possible to calibrate a wave meter with high accuracy using the multivibrator. To do this, by comparison with a high-precision tuning fork and adjustment of *R* and *C* to zero-beat a square wave signal with e.g. exactly 1000 Hz was generated, then the wave meter was tuned to resonance with the harmonics and its scale calibrated to the frequency.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n'obtient cependant pas autant de sensibilité qu'avec un microphone ordinaire mis en dérivation sur quelques spires de la self d'antenne.

15. - Multivibrateur. -

Le multivibrateur (fig. 62) est une association de deux lampes connectées de façon à obtenir des oscillations très riches en harmoniques.

Fig. 62.

Les filaments des deux lampes L_1 et L_2 sont chauffés par une batterie d'accumulateurs P'. Sur les circuits de grille sont intercalées es résistances R_1 et R_2 en graphite aggloméré (75.000 ohms), sur les circuits de plaque, une pile P (80 volts) et des résistances en fil de maillechort r_1 et r_2 (50.000 ohms).

La plaque de chacune des lampes est couplée à la grille de l'autre par des condensateurs C_1 et C_2 dont la capacité peut être réglée entre zéro et $\frac{1}{100}$ de microfarad.

The "Multivibrateur" by Abraham and Bloch, described in a secret document from 1918

Shortly after the end of World War I, in October 1918, the two British engineers and physicists **William Eccles** and **Frank Jordan** presented their *"trigger relay"* in a lecture and essay. Its circuit was nothing more than a simple modification of Abraham and Bloch's multivibrator. The grids were no longer connected via a capacitor but directly to the anode of the other tube. In addition, the circuit was not used as a generator but to *process* a signal that was coupled to the grid of one tube via a transformer. An external pulse switches one tube on and the other off, and the system then remains in this state until it is reset. The result is an extremely sensitive and fast switch which, after being triggered by a signal edge, does not return to its initial state when a second signal edge of the same type is applied. And although this reset could be triggered automatically by an opposite signal edge, according to the description it should be done manually by the operator. That is why the authors called their circuit a *"one-stroke relay"*, i.e. a trigger switch. Eccles and Jordan did not exploit the full potential of their circuit, but their paper is still considered groundbreaking in the history of science because this bistable circuit, originally called *"trigger"*, later became known as *"flip-flop"* and, with its ability to store, clock, and count in binary, became the basic building block of modern digital technology.

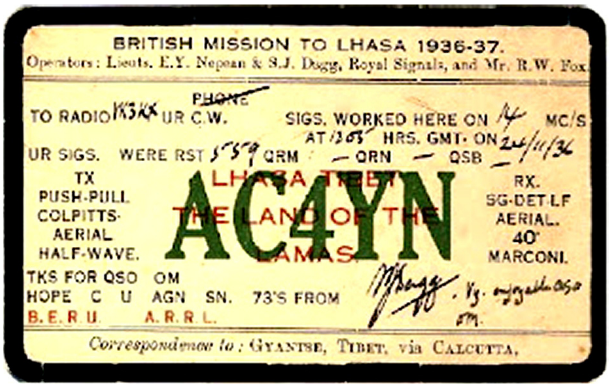
In September 1919, Eccles and Jordan published the *"oscillation generator"*, another variant in which an LC resonant circuit with a centrally grounded inductor is de-damped by two cross-coupled triodes. In this form, it is no longer a flip-flop circuit, but rather the two triodes generate a negative differential resistance between their anodes (i.e. across the resonant circuit). It is easy to see that this is nothing more than the symmetrical push-pull variant of the Meißner oscillator. Apparently, the resonant circuit can be excited more freely and easily than with a single tube because energy is supplied alternately by both tubes during each half-wave. Eccles commented: *"It is found that these cross-coupled circuits oscillate more freely than single circuits"*.

In April 1920, Captain **Laurence Turner** presented a variant of the "trigger relay" in which the grids are not directly coupled to the anodes but via resistors, as the *"Kallirotron, an aperiodic negative-resistance triode combination"*. In this variant, the capacitors of the original multivibrator by Bloch and Abraham were simply replaced by resistors. The name *"Kallirotron"* is derived from the Greek for a device that runs or turns well or beautifully. Turner saw it as a general standard circuit for processing any radio signals and designed it for what Eccles and Jordan did not have in mind, namely automatic switching at every sign change of the signal edge. In this way, not only could individual pulses be amplified but also constantly changing signal edges, such as those found in Morse telegraphy or human speech.

Turner points out that the "trigger relay" is merely an unstable variant of his Kallirotron, because only the two resistors he added enable stable switching. And so the Kallirotron gave rise to the general bistable circuit - the real flip-flop - which is capable of switching between two states at every second change of sign of the signal voltage, which means frequency halving, binary counting and storage of one bit. Turner summarized its mode of operation as an *amplifier for short and fast voltage changes*. In the same publication, he also presented its application as an amplitude-modulated LC oscillator and explained: *"Any negative-resistance device can obviously be used to produce sustained oscillation"*. Only when the circuit is redrawn it becomes apparent that this is the cross-coupled oscillator.

In 1937, **H. J. Reich** presented a *"low distortion audio-frequency oscillator"* based on Turner's Kallirotron. He demonstrated that, in order to achieve low harmonic content, the amount of negative resistance around the operating point should increase with the oscillation amplitude, and that Turner's Kallirotron exhibits this property. In 1944, he pointed out once again that it could be used as the basis for a *"push-pull negative resistance oscillator"* and presented mathematical proof that a negative resistance exists between the two anodes. In fact, cross-coupled triodes can be used to build oscillators with extremely low harmonic content and high frequency stability due to the inherent gentle amplitude limitation. The Kallirotron oscillates almost unerringly with high amplitude, which is why it bears its name and why it was particularly popular as a power oscillator up to the VHF range in the 1930s. For example, *Sir Evan Neapan, G5YN*, was the first amateur radio station in Tibet operating a self-excited, keyed power oscillator in a Kallirotron circuit as a transmitter on 14 MHz with an input power of approximately 100 watts under the callsign *AC4YN*.

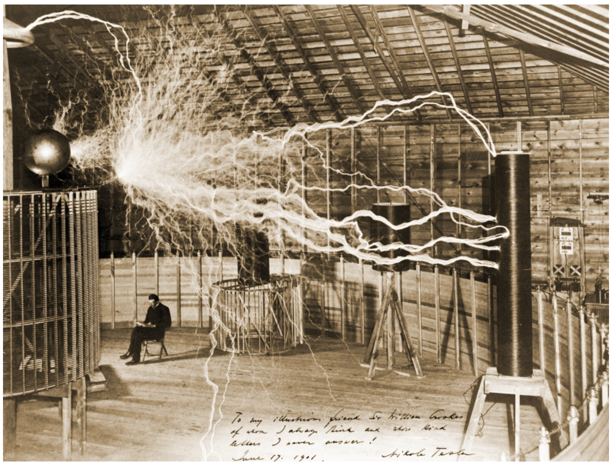
In my feedback audion, two cross-coupled PNP transistors are used to de-dampen the receiving circuit. The circuit (see p. 23) corresponds to the "oscillation generator" by Eccles and Jordan, but with an additional detector function. A signal in the symmetrical receiving circuit controls the two transistors in antiphase, whereby the negative half-wave on one side of the circuit triggers the transistor on the other side, thereby supplying energy to the positive half-wave present there. The common 68 KΩ emitter resistor sets the positive emitter voltage (i.e. the negative base bias voltage) in the range of the non-linear kink in the characteristic curve with very low quiescent current, resulting in a rectifier effect. The feedback potentiometer can be used to vary the operating point and thus the gain in this range. From the perspective of the emitter resistor, the cross-coupled pair functions as a full-wave rectifier. Together with the 27 pF capacitor it forms an RC low-pass filter with a cutoff-frequency of 87 kHz. This prevents the emitter voltage from following the rapid amplitude changes of the amplified high-frequency signal, but it can follow the slow changes of its low-frequency envelope, i.e. the modulation. Its AC voltage component feeds the subsequent two-stage AF amplifier which, despite its high gain of approx. 70 dB, can be very easily and efficiently decoupled from the operating voltage.



epilogue

Feedback was patented almost simultaneously in different places: Alexander Meißner's oscillator in April 1913, high-frequency amplification with feedback and subsequent demodulation in July 1913 by Telefunken, and unfortunately not until October 1914 the "regenerative circuit" with simultaneous high-frequency amplification and demodulation by Edwin Howard Armstrong, the true inventor of this ingenious concept. Thus, positive or regenerative feedback dominated electronic circuits from 1912 onwards for several decades, while negative feedback was not invented until around 1930. Variable feedback then came back to life in the 1950s as the so-called *"Q-multiplier"* for electronic de-damping of resonant circuits.

Today, an audion is understood to be a *tuned radio frequency (TRF) receiver* in which, in contrast to the superheterodyne receiver or *"superhet"* which was also also developed by Armstrong, the actions



Nikola Tesla, Colorado Springs 1901

of frequency selection, high-frequency amplification and demodulation take place on the same frequency.

The audion with variable feedback, or *regenerative audion* for short, is an ingenious concept that can be used in many different ways. In general, it acts as a variable *Q-multiplier* for the receiving circuit, with a corresponding increase in sensitivity and selectivity. In addition, it operates below the oscillation onset as an *envelope detector* for AM signals, but above that as an *autodyne*, i.e. as a self-oscillating direct-conversion detector for CW and SSB signals, and even as a *homodyne* or *synchrodyne* for synchronous detection of strong radio stations. A single control not only determines the operating mode, but also provides continuous control over selectivity and RF gain. With skillful handling, even the weakest signals can be "pulled in" with increased sensitivity and selectivity. It is the ingenious concept of the feedback audion that has made long-distance reception of radio signals possible with minimal circuitry and simple antennas.

How does **Nikola Tesla** fit into this picture? The work of this outstanding genius was always closely linked to the concepts of *resonance* and *feedback*, starting with experiments on mechanical resonance (in 1898, he almost brought down the entire building that housed his laboratory with a small electromechanical oscillator) to global wireless energy supply by exciting resonances in the waveguide between the Earth's surface and the ionosphere. In an article from September 1911, one year before Armstrong's invention of the regenerative circuit, he remarked about his receiver: *"[it] concentrates the energy transmitted over a wide area into the device".*

In fact, Tesla had been using feedback since 1899 to excite his receiving circuits thus increasing the quality and absorption area of his antennas. On 3 August of that year, he described in his notes several receiver circuits in which he fed high-frequency currents from the secondary side of a resonant transformer back to a coherer on the primary side. In this receiver variant, which according to Tesla's description used a *"self-exciting process"*, the coherer became much more sensitive to received signals and he noted: *"This method has been found excellent and will have, besides telegraphy, many valuable uses since by its means effects too feeble to be recorded in other ways may be rendered sufficiently strong to cause the operation of any suitable device"*.

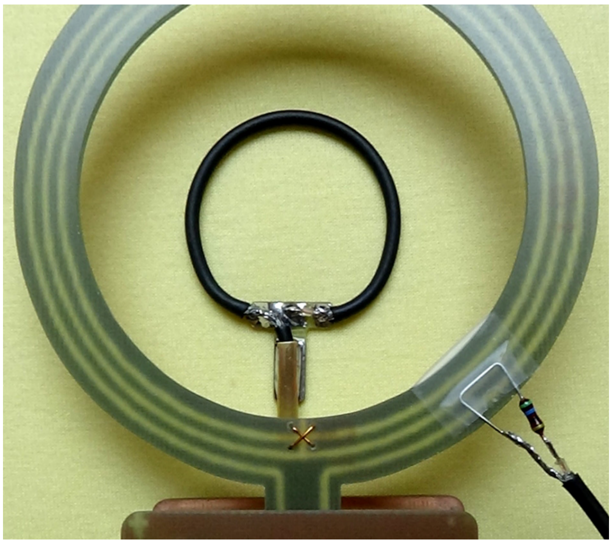
measurements

The following formula symbols are used in the measurements and calculations:

A	geometric loop area [m²]
$b_{HF,\,NF}$	-3dB HF-, AF-bandwidth
b_N	effective noise bandwidth [Hz]
E	electric field strength
f	frequency [MHz]
h_e	effective height [m]
l_e	effective length [m]
λ	wavelength [m]
Q, Q_0	quality factor, natural quality factor
R	series resistance in the circuit
R'	resonance resistance of the circuit
R_S, P_S	radiation resistance, power
R_V, P_V	loss resistance, power
R_A, P_A	fanning resistance, power
U_E, P_E	incident voltage, power
U_N, P_N	noise voltage, power
U_{ND}, P_{ND}	noise voltage density, power density
U_S	signal voltage
W	number of turns
X_L	inductive reactance
SNR	signal-to-noise ratio (S+N)/N [dB]
MDS	minimum detectable signal

The subsequent relative measurements in the energy-storing magnetic field of the receiving circuit were performed using a *Siglent SDG 2082X Function Arbitrary Waveform Generator* and *SVA 1032X Spectrum & Vector Network Analyzer*. In addition, a *signal injector* and a *magnetic field probe* were constructed. The measurement setup is shown on the following picture.

The *signal injector* at the bottom right is fed from the generator via RG-174 coaxial cable and consists of a small triangular wire loop with a 56 Ω resistor inserted. It is fixed with adhesive tape on the copper-free side of the epoxy loop so that its approx. 10 mm long short side runs centrally and parallel to the 4 copper tracks on the other side. The *magnetic field probe* behind the epoxy loop feeds the spectrum analyzer and consists of a small circular loop with a diameter of approx. 4 cm, also made of RG-174 coaxial cable. The cable is fed through a short brass tube, which is fixed to the rear wall of the receiver approx. 2 cm behind the epoxy loop using adhesive tape. A small T-piece made of printed circuit board material is soldered to the end of the tube



and serves to fix and connect the probe: the end of the inner conductor is soldered to the cable shield just above the exit point, leaving the end of the shield unconnected. In this way, the cable shield acts as a Faraday shield for electric fields.

thermal noise

Thermal or *Johnson-Nyquist noise* plays a central role in the following measurements and calculations because it determines the threshold sensitivity of a receiver. It is white noise caused by the thermal motion of charge carriers in conductive media whose temperature is above absolute zero. Every Ohmic resistance R is a source of noise, it supplies the open-circuit voltage ...

$$U_N = \sqrt{(4\,k\,T\,R\,b_N)} \;\; [V]$$

... with the Boltzmann constant $k = 1.387 \times 10^{-23}$ J/K, temperature $T\,[K]$, resistance $R\,[\Omega]$ and effective noise bandwidth $b_N\,[Hz]$. In short-circuit operation, the noise power ...

$$P_N = U_N^2 / R = 4\,k\,T\,b_N \;\; [W]$$

... is converted into heat in this resistance. A load resistance matched to this noise source has the same value R for maximum power transfer, due to voltage division only half the voltage drops across it and thus the extracted noise power is one quarter or ...

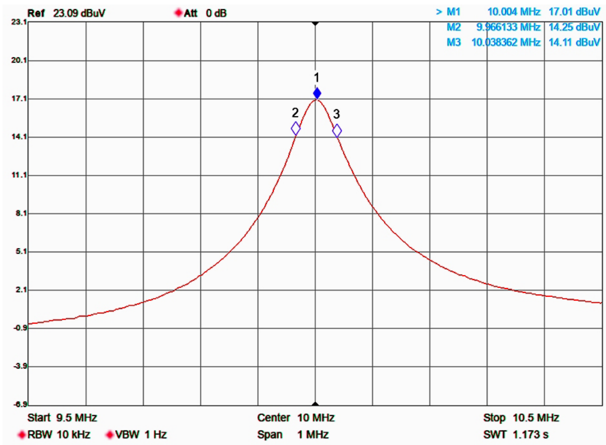
$$P_N = U_N^2 / (4\,R) = k\,T\,b_N \;\; [W]$$

In contrast to noise voltage, noise power is completely independent of R, regardless of whether it is a carbon film resistor with several megaOhms or a short piece of wire with a few milliOhms. The values for a bandwidth of 1 Hz are referred to as *spectral noise voltage density* $U_{ND}\,[V/\sqrt{Hz}]$ or noise power density $P_{ND}\,[W/Hz]$. The noise voltage increases with $\sqrt{b_N}$ and the noise power b_N, where b_N stands for the *effective noise bandwidth* of an ideal bandpass filter with a rectangular "brick wall" response curve that allows the same noise power to pass as the real filter under consideration. For a tuned resonant circuit $b_N = \pi\, f / (2\,Q)$ and because the natural -3dB HF bandwidth $b_{HF} = f / Q$ we get b_N by multiplying b_{HF} with the factor $\pi / 2 = 1.57$.

All subsequent calculations assume a reference temperature of $T_0 = 290\,K$ (17° C). A 50 Ω resistor at the input of a receiver therefore generates a noise power density of $P_{ND} = k\,T = 4.02 \times 10^{-21}\,W/Hz = -204\,dBW/Hz = -174\,dBm/Hz$, this value represents the theoretically achievable minimum noise floor of an ideal receiver at a temperature of 17° C.

natural quality factor

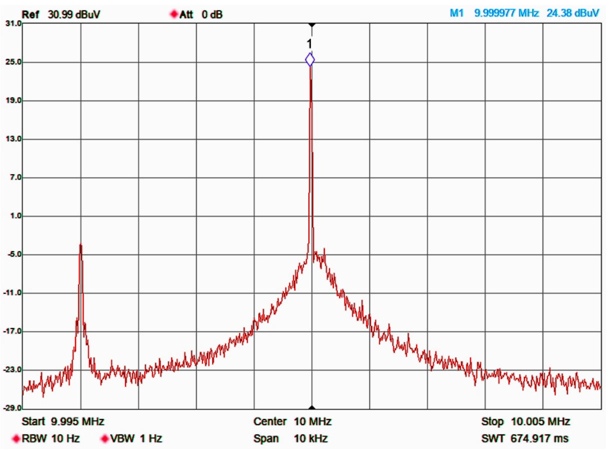
A noise signal (stdev = 500 mV, mean = 0 mV) is fed in from the generator and the spectrum analyzer is set to a center frequency of 10 MHz corresponding to a wavelength of $\lambda = 30\,m$. The receiver is switched on and tuned to 10 MHz with the regeneration completely turned down. The following resonance curve is obtained with a resolution of 3 dB vertically / 100 KHz horizontally per unit. The strong smoothing of the curve is achieved by the high resolution bandwidth RBW = 10 KHz. The markers M2 and M3 are set to the -3dB points, so the HF bandwidth of the receiving circuit is $b_{HF} = 10038\,KHz - 9966\,KHz = 72\,KHz$ and thus the *natural quality factor* $Q_0 = f / b_{HF} = 10000\,KHz / 72\,KHz = 139$.



For comparison, the bandwidth was also measured at a much greater distance of 40 cm between the small loop and the magnetic field probe, resulting in a correspondingly lower amplitude but no significantly different value. The probe therefore couples only very weakly to the receiving circuit as desired and has no significant influence on its quality factor and resonance frequency, even at a distance of only 2 cm from the loop plane.

fanned signal-to-noise ratio

Next, the signal injector is removed and the regeneration is turned up to just below the oscillation onset. With the very low resolution bandwidth RBW = 10 Hz and a resolution of 6 dB vertical / 1 KHz horizontal per unit, the following spectrum is now obtained:



The marked test signal at 10 MHz has an amplitude of U_S = *24.4 dBµV* and originates from an unknown transmitter. 4 kHz lower, at 9.996 MHz, the signal from the Russian time signal transmitter RWM in Moscow can also be seen. The resonance curve shows the noise in the reactive near field of the fanned receiving circuit. It merges into the noise floor of the analyzer on the left and right, therefore it appears much flatter at its base than it actually is. Its maximum amplitude @ 10 MHz is *-5.0 dBµV*, the HF bandwidth at this regeneration setting is approx. b_{HF} = *500 Hz* corresponding to a fanned quality factor of $Q = f / b_{HF} = 20000$ and the effective noise bandwidth is $b_N = 1.57 \times b_{HF} = 785$ *Hz*. Thus, the noise voltage U_N converted from *RBW = 10 Hz* to b_N = *785 Hz* and the signal-to-noise ratio *SNR* are:

$$U_N = -5.0\ dB\mu V + 10 \log (785 / 10) = 13.9\ dB\mu V$$
$$SNR = U_S - U_N = 24.4\ dB\mu V - 13.9\ dB\mu V = 10.5\ dB$$

When the spectrum was recorded, the test signal on the high-precision S-meter of my Elecraft K4D shortwave transceiver on a matched vertical dipole had a slightly fluctuating signal strength of about *S 7* and the noise in 400 Hz bandwidth was around *S 3.5* (S 9 = 50 µV @ 50 Ω with 6 dB / S-unit). The digital filter slopes are extremely steep, so this bandwidth can be considered the equivalent noise bandwidth without conversion. Antenna simulation with EzNEC yielded approx. 3 dB ground losses, so on a lossless antenna the values would be half an S-unit higher, resulting in a corrected value for the signal of *S 7.5 = 17.7 µV* i.e. U_S = *25.0 dBµV* and for the noise floor *S 4 = 1.58 µV* i.e. U_N = *4.0 dBµV*. Thus, the noise voltage U_N converted from b_N = *400 Hz* to the effective noise bandwidth b_N = *785 Hz* of the fanned small loop and the signal-to-noise ratio *SNR* are:

$$U_N = 4.0\ dB\mu V + 10 \log (785 / 400) = 6.9\ dB\mu V$$
$$SNR = U_S - U_N = 25.0\ dB\mu V - 6.9\ dB\mu V = 18.1\ dB$$

The external noise received with the K4D is therefore *18.1 dB -10.5 dB = 7.6 dB* below the noise of the small loop, which is obviously dominated by its thermal noise.

mathematical analysis

The *effective height* of an untuned small loop is:

$$h_e = 2 \pi W A / \lambda = 2 \pi W A f / 300$$

In an electromagnetic field, the open-circuit *incident voltage* is:

$$U_E = E\, h_e$$

It is induced by the magnetic field *H* and is proportional to the magnetic flux density $B = \mu_0 H$ perpendicular to the plane of the. In this equation, U_E is calculated from the electric field strength *E* as a substitute, so it only applies in the undisturbed radiation field where electric and magnetic field components are linked via the field's wave impedance $Z_0 = E / H = 120\, \pi\, \Omega = 377\, \Omega$.

If the inductance of the loop is supplemented by a capacitance to form a resonant parallel circuit, a small tuned loop is created. The voltage incident from the primary field U_E remains unchanged, but the loop fortifies the field strength in its energy-storing reactive near field (magnetic field) by the quality factor *Q* and therefore supplies a correspondingly higher voltage across the circuit:

$$U_E' = Q\, U_E = Q\, E\, h_e$$

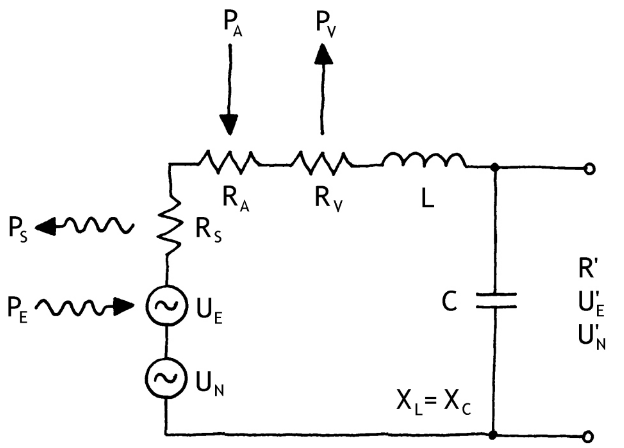
At the same time, reception on the resonance frequency *f* becomes selective with a -3dB bandwidth of:

$$b_{HF} = f / Q$$

With the extremely high maximum quality factor of approx. 20000 @ 10 MHz it is only 500 Hz, so that the high frequencies (i.e. the fast amplitude changes) of an AM broadcast signal sound suppressed.

equivalent circuit diagram and relationships

The following equivalent circuit diagram of the *fanned resonant receiving circuit* consists of the two voltage sources U_N (thermal noise voltage) and U_E (incident voltage) in series with the radiation resistance R_S, negative fanning resistance R_A, Ohmic loss resistance R_V (this also includes useful resistances transformed into the circuit, because from the perspective of the receiving circuit they cause energy loss) as well as an inductance *L* and, parallel to this series combination, a capacitance *C*. The series resistance $R = R_S + R_V + R_A$, which dampens the circuit



current, appears as an equivalent parallel or resonance resistance $R' = R\,Q^2$ across the circuit. As long as $R << X_L = 2\,\pi\,f\,L$ the following relationships apply as a good approximation [Hz, Ω, H, F]:

$$R' = X_L^{\,2} / R = X_L\,Q = R\,Q^2 = L / (R\,C)$$
$$R = X_L^{\,2} / R' = X_L / Q = R' / Q^2 = L / (R'\,C)$$
$$Q = X_L / R = R' / X_L = \sqrt{(L / C)} / R = R' / \sqrt{(L / C)}$$
$$U_E' = Q\,U_E \quad U_N' = Q\,U_N$$

Because $R'\,R = X_L^{\,2}$, $X_L = \sqrt{(R'\,R)}$ is the geometric mean of R' and R. The smaller the series resistance R and the larger the inductive reactance X_L (i.e. the greater the L/C ratio), the lower the attenuation of the circuit and the higher its quality factor Q , the current circulating in the circuit, the resonance resistance, the voltage across the circuit, and ultimately the sensitivity and selectivity. Incidentally, an impedance transforming LC- or π-circuit is nothing more than a resonant parallel circuit which, as described in the section "Resonance", acts as a *resonance transformer*.

fanned power balance

If the circuit is loaded by a parallel resistance R_P, it reduces the resonance resistance R' in accordance with Ohm's law and is transformed into the circuit so that the effective series resistance increases by $X_L^{\,2} / R_P$. The circuit is therefore additionally damped, which reduces its quality factor Q.

However, if this is a *negative differential resistance* (i.e. *fanning*), then the series resistance in the circuit is reduced, not physically but effectively. The circuit is thus artificially de-damped and its quality factor Q increases ("Q-multiplier"). This negative fanning resistance R_A transformed into the circuit now reduces the series resistance to an effective value of $R = R_S + R_V + R_A$ and thereby increases the current $I = U_E / R$ in the receiving circuit and its quality factor Q. In accordance with Rüdenberg, this results in the following powers:

$$P_E = I^2\,R = U_E^{\,2} / (R_S + R_V + R_A)$$
$$P_V = I^2\,R_V = U_E^{\,2}\,R_V / (R_S + R_V + R_A)^2$$
$$P_S = I^2\,R_S = U_E^{\,2}\,R_S / (R_S + R_V + R_A)^2$$
$$P_A = I^2\,R_A = U_E^{\,2}\,R_A / (R_S + R_V + R_A)^2$$

The voltage U_E incident from the field therefore meets less resistance due to the fanning, and so the circuit current and the power P_E incident from the field as well as the effective area A_e increase linearly with Q. However, the loss resistance R_V remains physically unchanged and, together with the radiation resistance R_S, absorbs more power at this increased current than is absorbed from the field. The loss power P_V and radiation power P_S therefore increase quadratically with Q^2 , and exactly this additional power P_A is supplied by the fanning. If $R_A = -R_V$ then $P_V = P_A$ and $P_S = P_E$ so that the total power loss is supplied by the fanning and the whole incident Power is re-scattered as radiated power. It is then $P_V = P_A = P_E\,R_V / R_S$.

radiation- and loss-resistance

The radiation resistance of a small loop is approximately:

$$R_S = 320\,\pi^4\,(W\,A)^2 / \lambda^4$$

The circular loop of my direction finder has 4 turns with a mean diameter of *8.75 cm* which gives an area of $A = \pi\,r^2 = 0.006\ m^2$. For $\lambda = 30\ m$ this results in a radiation resistance of $R_S = 0.00002\ \Omega$ which is negligible for the following calculations, the Ohmic loss resistances in the receiving circuit are orders of magnitude higher. The previously measured natural quality factor of my loop with $L = 2.6\ \mu H$ is $Q_0 = 139$ @ *10 MHz* and thus its loss resistance is $R = X_L / Q_0 = 2\,\pi\,f\,L / Q_0 = 1.18\ \Omega$.

untuned small loop

In the previous measurements, a test signal @ 10 MHz was received on the Elecraft K4D corrected for the ground losses with $S\ 7.5 = 17.7\ \mu V$ i.e. $U_S = 25.0\ dB\mu V$ on a matched vertical dipole. To determine the corresponding field strength, this voltage at the matched input resistance $R_I = 50\ \Omega$ of the receiver must be converted with the radiation resistance of the halfwave dipole $R_S = 73\,\Omega$ to the incident voltage U_E and then with the effective length l_e to the electric signal field strength E_S:

$$U_E = 2\,U_S\,\sqrt{(R_S / R_I)} =$$
$$2 \times 17.7\ \mu V\,\sqrt{(73 / 50)} =$$
$$42.8\ \mu V$$
$$l_e = \lambda / \pi = 9.55\ m$$
$$E_S = U_E / l_e = 42.8\ \mu V / 9.55\ m =$$
$$4.5\ \mu V/m$$

If we now replace the dipole with our initially *untuned* small loop with $D = 8.75\ cm$ and $L = 2.6\ \mu H$, we obtain incident signal voltage U_S as follows:

$$A = \pi r^2 = 0.006\ m$$
$$h_e = 2\ \pi\ W A / \lambda = 0.005\ m$$
$$U_S = U_E = E_S\ h_e = 0.0224\ \mu V$$

The Ohmic loss resistance *R* of the small loop generates *thermal noise*. With its measured natural quality factor $Q_0 = 139$ and an assumed AF-bandwidth of the receiver of $b_{NF} = 10\ KHz$ the thermal noise voltage density U_{ND} and noise voltage U_N as well as the signal-to-noise ratio *SNR* are given by:

$$R = X_L / Q_0 = 2\ \pi f L / Q_0 = 1.18\ \Omega$$
$$U_{ND} = \sqrt{(4\ k\ T_0\ R)} = 0.000138\ \mu V/\sqrt{Hz}$$
$$U_N = U_{ND} \sqrt{(1.57 \times b_{NF})} = 0.0173\ \mu V$$
$$SNR = 20 \log (U_S / U_N) = 2.2\ dB$$

tuned small loop

Now the small loop is tuned to resonance using parallel capacitance. Because the bandwidth of the receiving circuit $b_{HF} = f / Q_0$ remains significantly greater than the AF-bandwidth $b_{HF} >> b_{NF}$ we get across the circuit:

$$U_S = U_E' = Q_0 E_S\ h_e = 3.1\ \mu V$$
$$b_{HF} = f / Q_0 = 72\ KHz >> b_{NF}$$
$$U_{ND} = Q_0 \sqrt{(4\ k\ T_0\ R)} = 0.0192\ \mu V/\sqrt{Hz}$$
$$U_N = U_{ND} \sqrt{(1.57 \times b_{NF})} = 2.41\ \mu V$$
$$SNR = 20 \log (U_S / U_N) = 2.2\ dB$$

The signal and noise voltages across the circuit are now both higher by a factor of Q_0 so that the *SNR* remains unchanged. If the *natural quality factor* Q_0 of the receiving circuit is increased the signal voltage rises linearly with Q_0, but due to the decrease in *R* the noise voltage density and the noise voltage only rise with $Q_0 \sqrt{(1 / Q_0)} = Q_0 / \sqrt{Q_0} = \sqrt{Q_0}$. Consequently, the *SNR* in the AF-bandwidth of the receiver increases with $U_S / U_N = Q_0 / \sqrt{Q_0} = \sqrt{Q_0} = 10 \log Q_0$ *[dB]*, i.e. by 3 dB when the quality factor is doubled. For the highest possible sensitivity it is therefore essential to aim for a high *natural quality factor* of the small loop.

tuned and fanned small loop

If the receiving circuit is now de-damped or fanned to an *artificial quality factor* of $Q = 20000$, the noisy loss resistance *R* exists still exists unchanged in the receiving circuit and so we get across the circuit:

$$U_S = U_E' = Q\ E_S\ h_e = 448\ \mu V$$
$$b_{HF} = f / Q = 500\ Hz << b_{NF}$$
$$U_{ND} = Q \sqrt{(4\ k\ T_0\ R)} = 2.76\ \mu V/\sqrt{Hz}$$
$$U_N = U_{ND} \sqrt{(1.57 \times b_{HF})} = 77.3\ \mu V$$
$$SNR = 20 \log (U_S / U_N) = 15.3\ dB$$

So the signal voltage and, due to the unchanged R, the noise voltage density continue to rise with *Q*. Therefore as long as $b_{HF} >> b_{NF}$ the noise voltage also rises linearly with *Q* and the *SNR* remains constant. As the quality factor continues to increase b_{HF} decreases, but as it approaches b_{NF} the noise voltage increases more slowly and so the *SNR* begins to rise. When finally $b_{HF} << b_{NF}$ the noise voltage rises as with the natural quality factor only with $\sqrt{Q}$ and thus the *SNR* rises with $Q / \sqrt{Q} = \sqrt{Q} = 10 \log Q$ *[dB]*, i.e. by 3 dB when the quality factor is doubled.

The transition from the untuned to the tuned loop thus resulted in a 139 times or $20 \log Q = 43\ dB$ higher signal voltage and selective reception with an HF-bandwidth of $b_{HF} = 10\ MHz / 139 = 72\ KHz$. The artificial increase of the quality factor to $Q = 20000$ by a factor of $20000 / 139 = 144$ resulted in a further $20 \log 144 = 43dB$, i.e. a total increase in signal voltage of $20 \log 20000 = 86\ dB$.

effective area

From the electric field strength *E* and effective height of the small loop $h_e = 2\ \pi\ W\ A\ f / 300$ we get the incident voltage $U_E = E\ h_e$ and with the loss resistance of the receiving circuit $R = X_L / Q = 2\ \pi\ f\ L / Q$ the incident power $P_E = U_E^2 / R$. The irradiance is the amount of the time-averaged Poynting vector $|S| = E^2 / Z_0 = E^2 / 377\ \Omega$. Dividing the incident power by the irradiance yields the effective area $A_e = P_E / |S|$. By substituting and simplifying, the electric field strength *E* disappears and we finally get [m², MHz, uH]:

$$A_e = 0.0263\ W^2 A^2 f\ Q / L$$

For $W = 4$, $A = 0.006\ m^2$, $f = 10\ MHz$, $L = 2.6\ \mu H$ and its natural quality factor $Q_0 = 139$ the effective area is $Ae = 0.008 m^2$ corresponding to a circle with a diameter of 10 cm, and finally for the fanned loop with $Q = 20000$ we get $Ae = 1.16\ m^2$ corresponding to a circle with a diameter of 1.2 m. The incident power is then only *20 dB* or approx. *3 S-units* below that of a half-wave dipole for 10 MHz with an effective area of $A_e = 0.13\ \lambda^2 = 117\ m^2$.

noise figure

The *noise figure* $F = 10 \log (SNR_{IN} / SNR_{OUT})$ *[dB]* of a stage is the quotient of the input SNR and the output SNR, i.e. a measure of how much the stage deteriorates the signal-to-noise ratio. If stages are connected in series, the higher the gain of the first stage and the smaller the combined noise figure of the subsequent stages the more it dominates the noise figure of the entire cascade.

The fanning circuit with its negative resistance R_A is a linear active single-port (two-pole) with negative conductance. It acts as an amplifier with a single port, so the input port and output port are identical, and its behavior is easier to understand if it is considered on the basis of conduction theory as a *reflection amplifier*. So, on the one hand we have the receiving circuit with its natural quality factor as a signal and noise source (the thermal noise of its loss resistances), but on the other hand we also have the fanning circuit, which acts as an amplifier and generates additional thermal noise. We obtain the noise figure F_A of the fanning circuit by subtracting the measured *SNR* from the previously calculated *SNR* of the tuned and fanned small loop (which assumed ideal noise-free fanning):

$$F_A = 15.3\ dB - 10.5\ dB = 4.8\ dB$$

The low-noise fanning of the receiving circuit with the highest possible natural quality factor Q_0 results in an amplifier with low noise figure at the ideal position, namely at the very front of the signal path. It significantly determines the noise figure of the entire receiver, because due to its extremely high amplification, the noise of the subsequent AF stages has only a minor effect.

threshold sensitivity

The threshold sensitivity or the *"minimum detectable signal" MDS* of the tuned small loop is the field strength level at which a signal to be received just barely emerges from its thermal noise floor and can be measured. First, we calculate the *incident voltage* U_E in the receiving circuit and its *thermal noise voltage* U_N with the *natural quality factor* Q_0 of the circuit, b_N in Hz and f in MHz:

$$U_E = E\ 2\ \pi\ W\ A\ f\ /\ 300$$
$$U_N = \sqrt{(4\ k\ T_0\ b_N\ R)} = \sqrt{(4\ k\ T_0\ b_N\ 2\ \pi\ f\ L\ /\ Q_0)}$$

If we set $U_E = U_N$ and solve for the field strength, we obtain the electrical noise field strength E_N equivalent to the thermal noise of the receiving circuit:

$$E_N\ 2\ \pi\ W\ A\ f\ /\ 300 = \sqrt{(4\ k\ T_0\ b_N\ 2\ \pi\ f\ L\ /\ Q_0)}$$
$$E_N = 300\ \sqrt{(4\ k\ T_0\ b_N\ 2\ \pi\ f\ L\ /\ Q_0)}\ /\ (2\ \pi\ W\ A\ f)$$
$$= 1.52 \times 10^{-8}\ \sqrt{(b_N\ f\ L\ /\ Q_0)}\ /\ (W\ A\ f)$$
$$= 1.52 \times 10^{-8}\ \sqrt{(b_N\ L)}\ /\ (W\ A\ \sqrt{(f\ Q_0)})\ \ [V/m]$$
$$= 0.0152\ \sqrt{(b_N\ L)}\ /\ (W\ A\ \sqrt{(f\ Q_0)})\ \ [\mu V/m]$$
$$= 10\ log\ b_N L - 20\ log\ WA - 10\ log\ fQ_0 - 36.4\ \ [dB(\mu V/m)]$$

By adding the noise figure F_A of the fanning circuit, we finally obtain the threshold sensitivity of the fanned receiving circuit:

$$MDS = 10\ log\ b_N L - 20\ log\ WA - 10\ log\ fQ_0 - 36.4 + F_A\ \ [dB(\mu V/m)]$$

This equation applies to a tuned small loop, regardless of the artificial quality factor Q to which it is fanned, for the equivalent noise bandwidth $b_N = 1.57\ b_{HF} = 1.57\ f\ /\ Q$. For the loop tuned to $f = 10\ MHz$ and fanned to a quality factor of $Q = 20000$ corresponding to a bandwidth of $b_{HF} = 500\ Hz$ with $F_A = 4.8\ dB$, $L = 2.6\ \mu H$, $W = 4$, $A = 0.006\ m^2$ and $Q_0 = 139$ is therefore $MDS = 2.5\ dB(\mu V/m)$.

If the frequency f is changed only by varying the capacitance C and the bandwidth is kept constant by readjusting the fanning, then the field strength of the MDS decreases with $\sqrt{(f\ Q_0)}$. However, as determined by measurement, Q_0 and thus also the series resistance R rise with f, and thus the *MDS* effectively decreases with $\sqrt{f\ \sqrt{f}} = \sqrt{\sqrt{f^3}} = f^{3/4} = f^{0.75}$ i.e. with approx. 4.5 dB per octave (frequency doubling). So if the *MDS* is known at frequency f_1 it can be converted to frequency f_2 as follows:

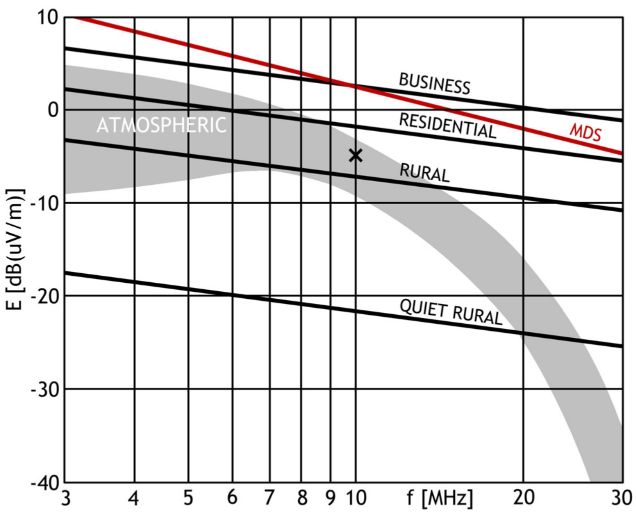
$$MDSf_2 = MDSf_1 - 20\ log\ (f_2\ /\ f_1)^{0.75}$$

MDS and external noise

External electromagnetic noise on shortwave consists mainly of atmospheric and artificial noise. *Natural atmospheric noise* is caused by electrical discharges in the atmosphere as a result of thunderstorms, rain and snowfall, sandstorms, etc. It can propagate over long distances on shortwave via the ionosphere and depends on location, frequency, time and season. Between 1957 and 1968, as part of an international program of the URSI, the atmospheric noise between 13 KHz and 20 MHz was measured by a network of stations distributed worldwide and equipped with standardized ARN-2 radio noise recorders, and a spherical harmonic coefficient model was created from the measured data.

Artificial "man-made" noise is caused by electrical devices, systems, and networks. The model still used today for this noise component is based mainly on measurements taken in the US in the 1970s in the following area categories: *"Business"* (mainly shops, offices, shopping centers, and industrial companies with main roads and highways), *"Residential"* (mainly residential buildings and isolated shops without busy main roads), *"Rural"* (mainly agricultural with few residential buildings), *"Quiet Rural"* (extremely quiet and remote rural areas with no roads or residential buildings). A *"Radio Noise Calculator"* with detailed description of all noise components and their models is available here (click to open): http://cq-cq.eu/rnoise.htm

The following diagram shows for the shortwave range from 3 to 30 MHz and an effective noise bandwidth of $b_N = 785Hz$ the field strength of the *MDS* of the tuned small loop fanned to a -3dB bandwidth of $b_{HF} = 500\ Hz$ (red line) compared to the external noise components. The black lines show the median value of the expected *artificial noise* for the four area categories, and the gray band shows the variation of the *natural noise* for my location in southwestern Germany at 48° N / 8° W between the annual median value (lower boundary) and maximum value (upper boundary). The natural noise should therefore be within the gray band in 50% of all measurements



and below it in the remaining 50%. For reception on a matched lossless half-wave dipole, electric field strength values E [dB(µV/m)] and S values (S 9 = 50 µV @ 50 Ω with 6 dB / S-unit) can be converted into each other using the following equations:

$$S = (E - 20 \log f + 51.9) / 6$$
$$E = 6 S + 20 \log f - 51.9$$

The noise floor was received with the Elecraft K4D @ 10 MHz in 400 Hz bandwidth corrected for ground losses with S 4, converted to an bandwidth of 785 Hz this corresponds to S 4.5 or to an electric field strength of *-4.9 dB(µV/m)*, marked with a cross **x** in the diagram. It is about 3 dB below the value expected for my location in a typical residential area. The MDS of the wavehunter @ 10 MHz is *2.5 dB(µV/m) + 4.9 dB(µV/m) = 7.4 dB* or slightly more than one S-unit above the external noise at my location, i.e. approx. S 5.5. This sensitivity is insofar remarkable as it is achieved with an antenna whose geometric dimensions (8.75 cm loop diameter) correspond to only 0.3% of the wavelength $\lambda = 30$ m.

operating the wavehunter

The small loop is utilized directly as the resonan circuit's coil of the feedback audion. This has the advantage that no additional tuning of the antenna circuit to resonance and no preamplifier is required, but at the same time has the disadvantage of low frequency stability because the loop is thermally and mechanically unstable and is also influenced by nearby objects. In practice, however, the advantages of this design for the intended purpose have been shown to outweigh the disadvantages.

The loop only responds to magnetic field lines that can reach through it, so to speak. Therefore, maximum signal voltage (maximum bearing) is obtained when the field lines are perpendicular to the plane of the loop. If the received TEM wave is vertically polarized (the magnetic field lines then run horizontally), the loop must therefore be vertical and its plane positioned in the direction of incidence.

For a much sharper minimum bearing, the direction finder must be rotated vertically by 90°, so that you are looking through the loop toward the source of radiation. If, on the other hand, the TEM wave is horizontally polarized (the magnetic field lines then run vertically), the loop must be horizontal. In theory, it is not possible to determine the direction like this, but in practice there is always a certain amount of vertical polarization.

To take advantage of the versatility and performance of this small receiver, you need to understand how to operate it properly. Here are some important tips:

- For *AM radio* reception, for maximum sensitivity and selectivity regeneration is turned up to just *BELOW* the onset of oscillation, allowing the audion to operate as an *envelope detector*. Onset of oscillation is indicated on the frequency of an AM station by heterodyne howling and on clear frequencies by an abrupt increase in high-pitched noise.

- If very strong radio stations are too loud even with the volume control completely turned down, turning down the regeneration makes the reception quieter. As long as reception is not disturbed by a nearby station and therefore high selectivity is not required, the volume of radio stations can generally be adjusted with the regeneration control.

- A high frequency stability is required for the reception of *amateur radio in SSB or CW*. Because the loop is part of the resonant circuit and determines the frequency, the direction finder should not be held in the hand and moved, but placed on a stable surface. For maximum sensitivity and selectivity regeneration is turned up to just *ABOVE* the onset of oscillation, so that the audion operates as an *autodyne*, i.e. a self-oscillating or direct-mixing detector. If normal frequency tuning is not sensitive enough, the regeneration control is turned up slightly above the oscillation point and then used for fine-tuning of the frequency. For larger frequency excursions, the regeneration must be readjusted in all operating modes for optimal reception.

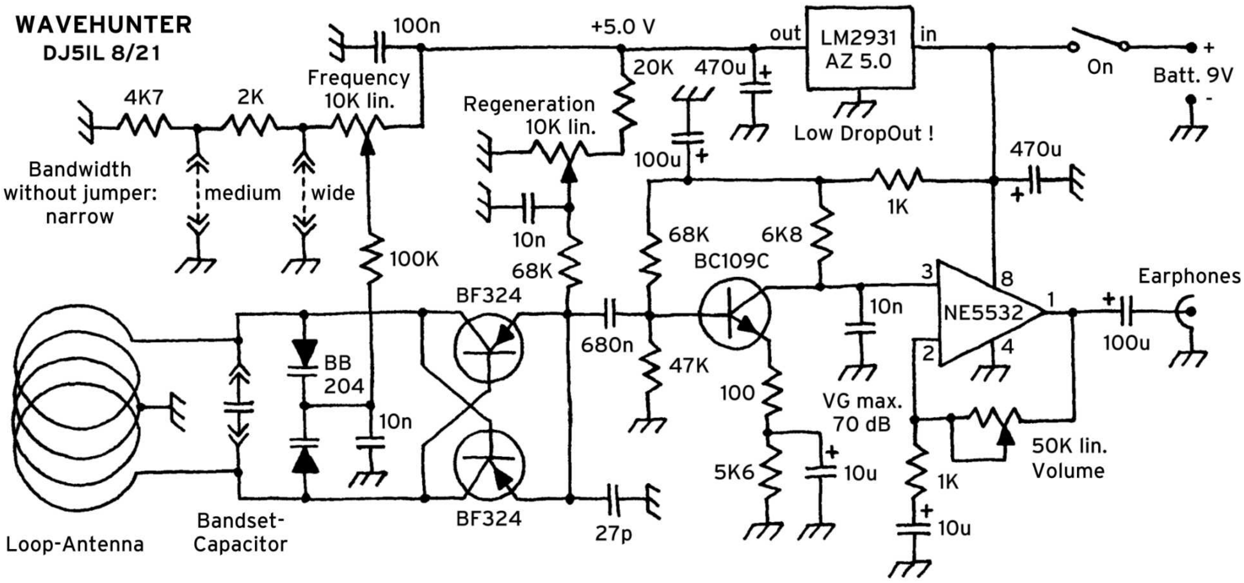
- Under certain conditions, the oscillation frequency of the audion synchronizes with strong carrier signals. The *autodyne* then becomes a *homodyne* or *synchrodyne* and the stronger the carrier signal, the weaker the oscillator signal, and the smaller their frequency offset, the easier this happens. This property allows synchronous reception of strong radio stations, which is characterized by less selective fading and generally better reception quality. To achieve this, the regeneration is turned up to just

ABOVE the onset of oscillation and the frequency is slowly varied so that the pitch of the heterodyne howling becomes lower. At a very low pitch the howling disappears abruptly, the oscillator has then locked in and the receiver works as a synchrodyne. This amazing synchronization of coupled oscillators was discovered already in 1665 by the Dutchman Christiaan Huygens. While observing two pendulum clocks suspended from a beam, he noticed something strange: no matter what position the pendulums started in, after half an hour at the latest they swung completely in sync - either exactly in phase or in antiphase.

• Due to the characteristic curve of the varicap, when the bandwidth jumper is set to *"wide"* the frequency changes much faster at the lower frequency limit than at the upper frequency limit when turning the control. In the *"medium"* and *"narrow"* positions this effect is much less pronounced. Because the frequency setting must be much more sensitive when receiving amateur radio than when receiving broadcasts, amateur radio bands should extend as far as possible to the upper frequency limit of a band module.

• When the position of the bandwidth jumper is changed only the lower frequency limit of the inserted band module changes, the upper frequency limit remains unchanged.

construction



IMPORTANT NOTES:

Potentiometers: high-quality types must be used, linear rotary potentiometers from the RK11K series by ALPS were used in the sample device.

MM2931 AZ5.0: can be replaced by other +5.0 V fixed voltage regulators, but a low dropout (LDO) type should be selected for longest possible battery life. The current consumption of the receiver is typically approx. 5 mA.

NE5532: is extra low-noise and can drive low-impedance loads, but prone to oscillations when inputs are not connected (indicated by high current consumption). Pins 5 / 6 / 7 should therefore be cut off as close as possible to the IC housing using side cutters.

BC109C: can be replaced by other low-noise NPN transistors.

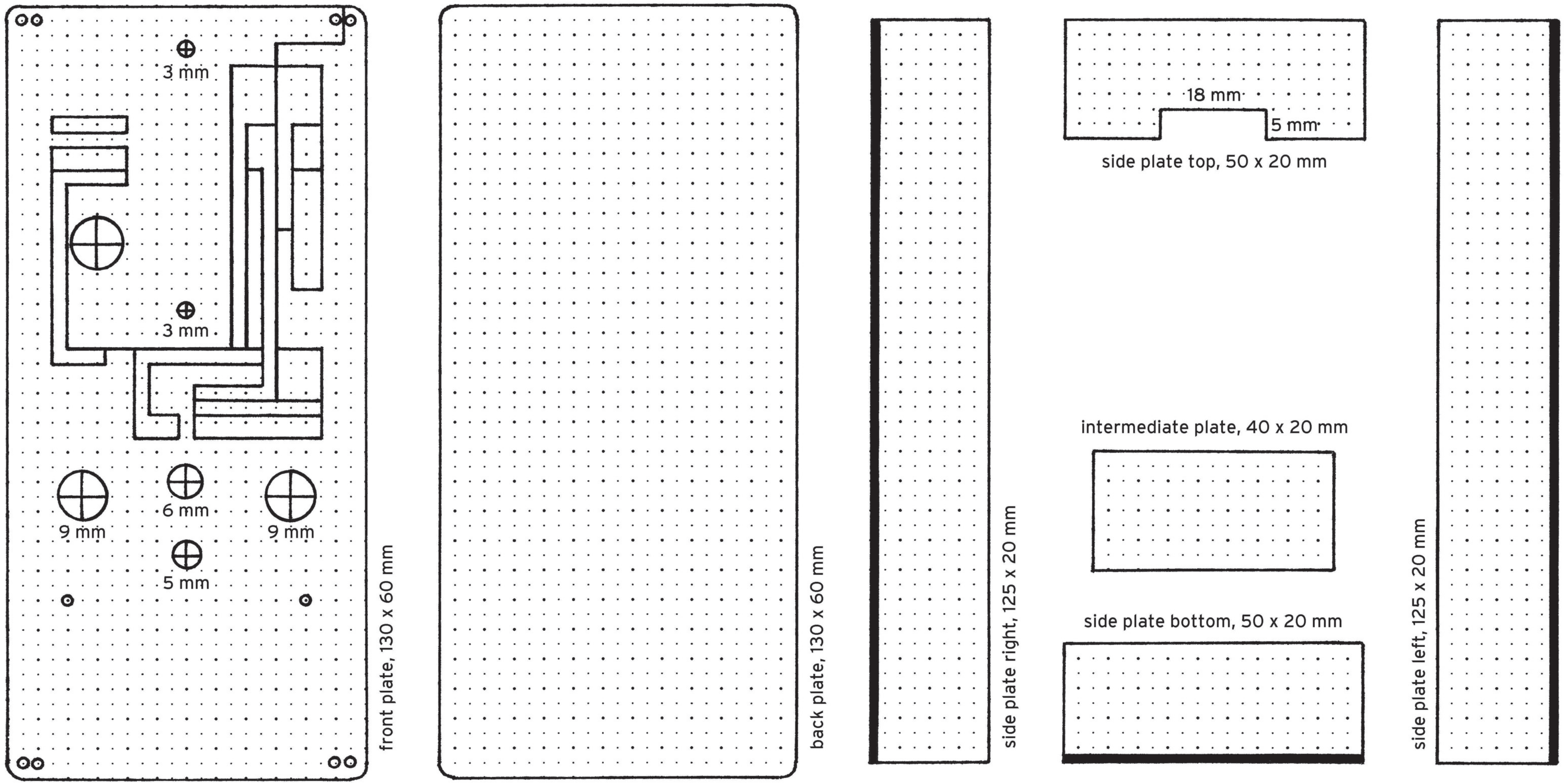
BF324: can be replaced by BF506 or other PNP HF transistors, but a type with very low parasitic capacitance should be selected. This is the case with HF transistors with a high transit frequency and low maximum permissible collector current (< 30 mA). Reason: the parasitic transistor capacities are part of the resonant circuit capacity, and if they are large the regeneration has a strong influence on the frequency tuning. If oscillation occurs already when the regeneration is less than half turned up, the resistance from the potentiometer to the emitters (typically 68 KΩ) should be increased.

BB204: according to the data sheet, type "B" has a capacity per diode of approx. 37 pF @ 0 V / 15 pF @ 5 V and can be replaced by other varicaps (including single diodes connected in series) with a similar capacity range.

Loop-Antenna: consists of 4 concentric traces which are interconnected by wire bridges in a cross pattern for the best possible symmetry. It has an inductance of approx. 2.6 µH and, without a band set capacitor with the BB204B it can cover the following frequency ranges depending on the bandwidth jumper: wide 12.9 - 17.3 MHz / medium 14.6 - 17.3 MHz / narrow 15.8 -17.3 MHz.

Bandset-Capacitor: preferably Styroflex, Silver Mica or high-quality ceramic, pluggable on a small circuit board with pin-header (band module). *Do never use trimmers, as they can cause frequency jumps and drift.* For example, with 56 pF + 5.6 pF in parallel depending on the bandwidth jumper the following frequency ranges can be covered: wide 9.1 -10.3 MHz / medium 9.6 -10.3 MHz / narrow 9.9 10.3 MHz. If an inductor is used instead of a capacitor, the natural frequency range of the loop can be extended upwards beyond 17.3 MHz. For example, with 1.6 µH (29 turns 0.3 mm CuL on Amidon T50-6 toroidal core) an upper frequency limit of 21.6 MHz is achieved.

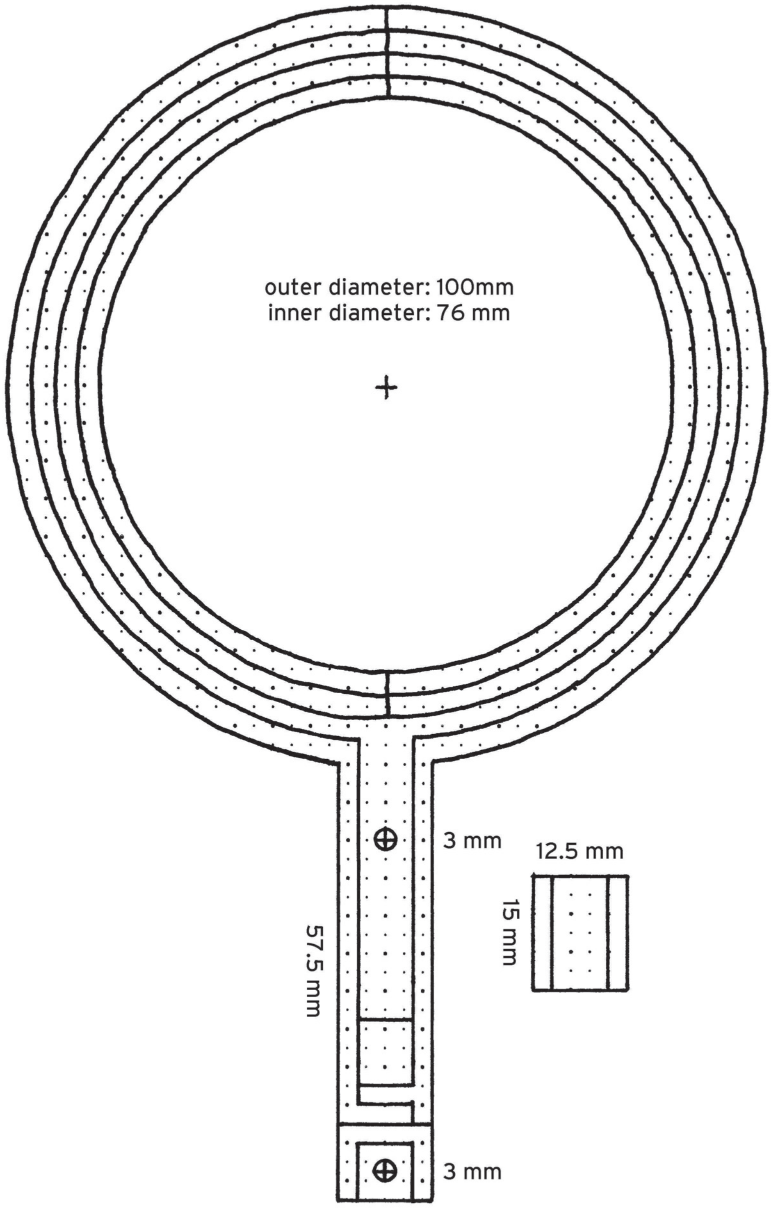
Earphones: All commercially available types can be used. The solder tabs of the 3.5 mm stereo jack for the left and right earphones are connected with a wire bridge so that both are running in parallel.



SAWING / MILLING / DRILLING PLAN CABINET WITH AF-BOARD
scale 1:1, copper side, PCB material epoxy 1.5 mm single-sided

KEY:

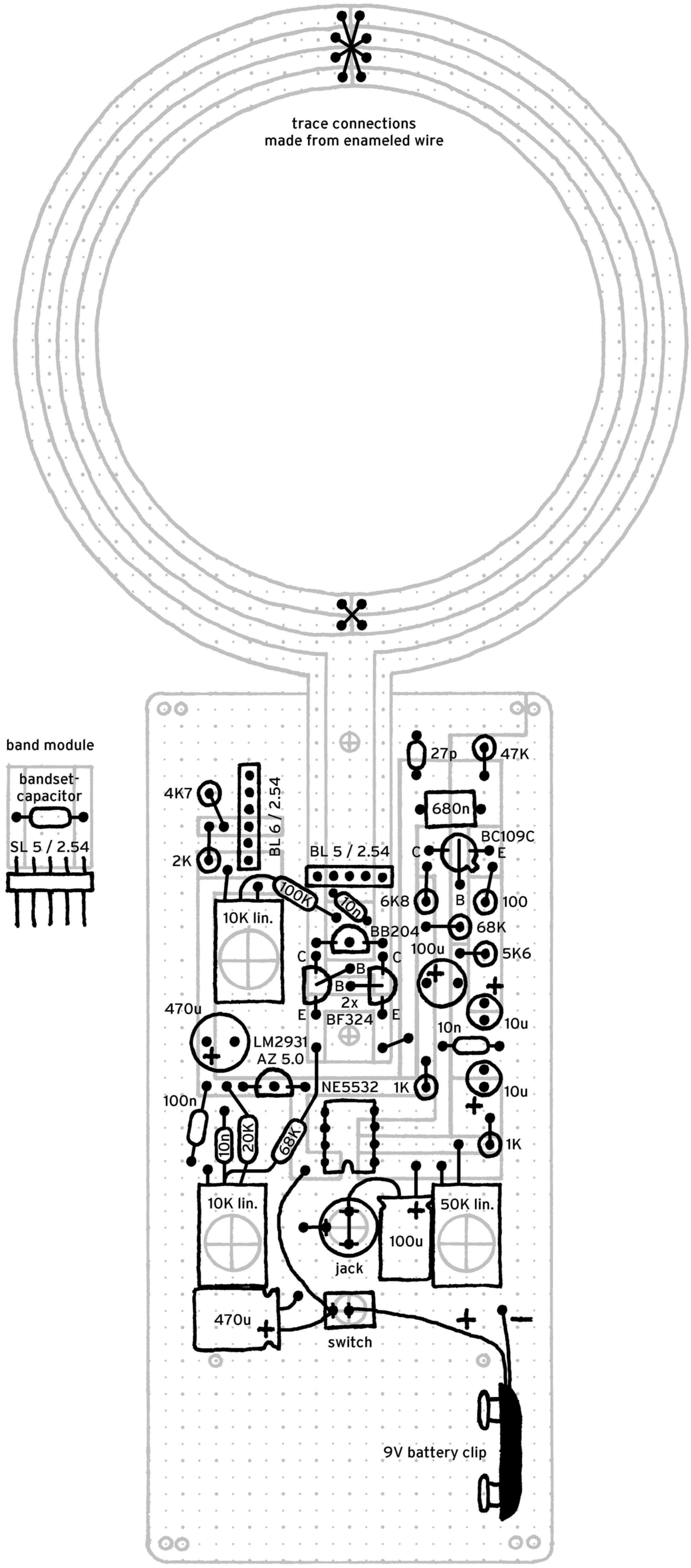
— = sawing line (outline) / milling line
▬ = chamfer the edge to prevent contact with overlying copper surface
⊕ = drill hole with appropriate diameter
⊙ = drill lightly, only as a mark for side / intermediate plates



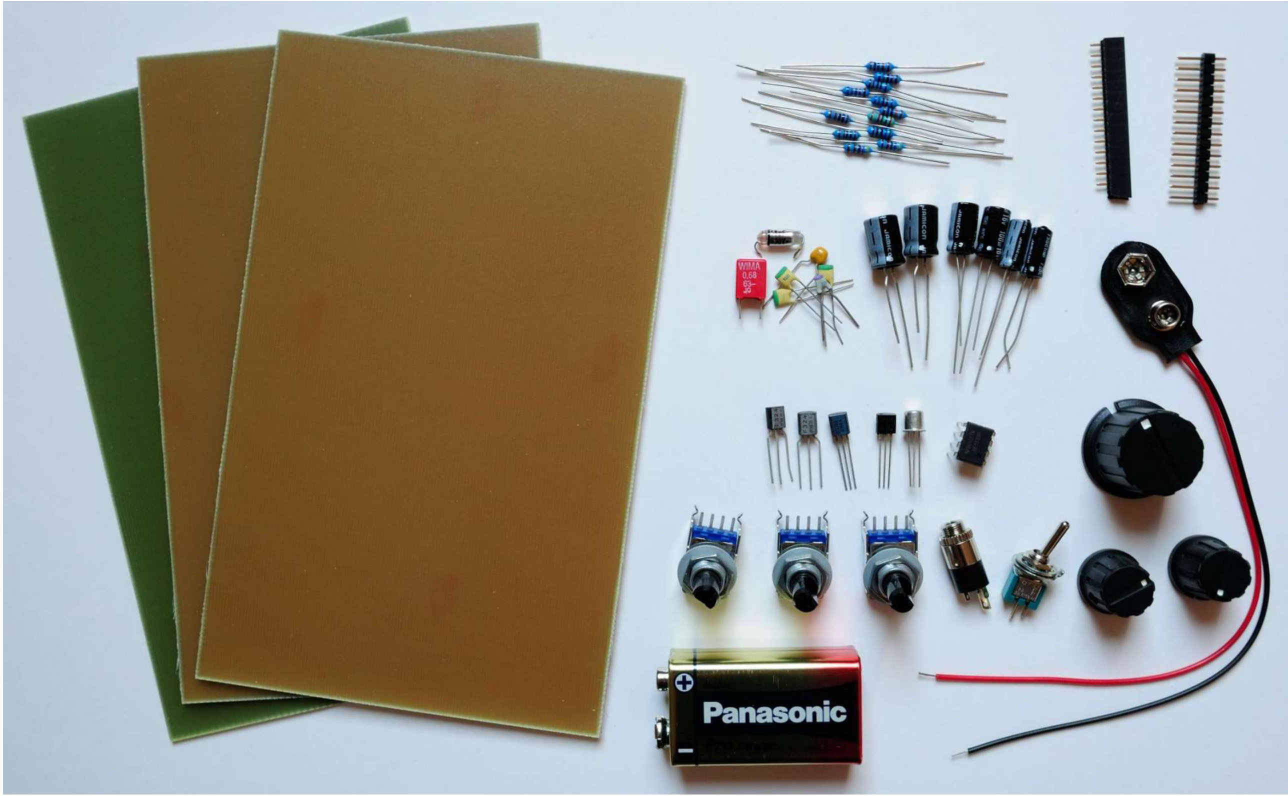
KEY:

- (thin line) = sawing line (outline) / milling line
- (thick line) = chamfer the edge to prevent contact with overlying copper surface
- ⊕ = drill hole with appropriate diameter
- ⊙ = drill lightly, only as a mark for side / intermediate plates

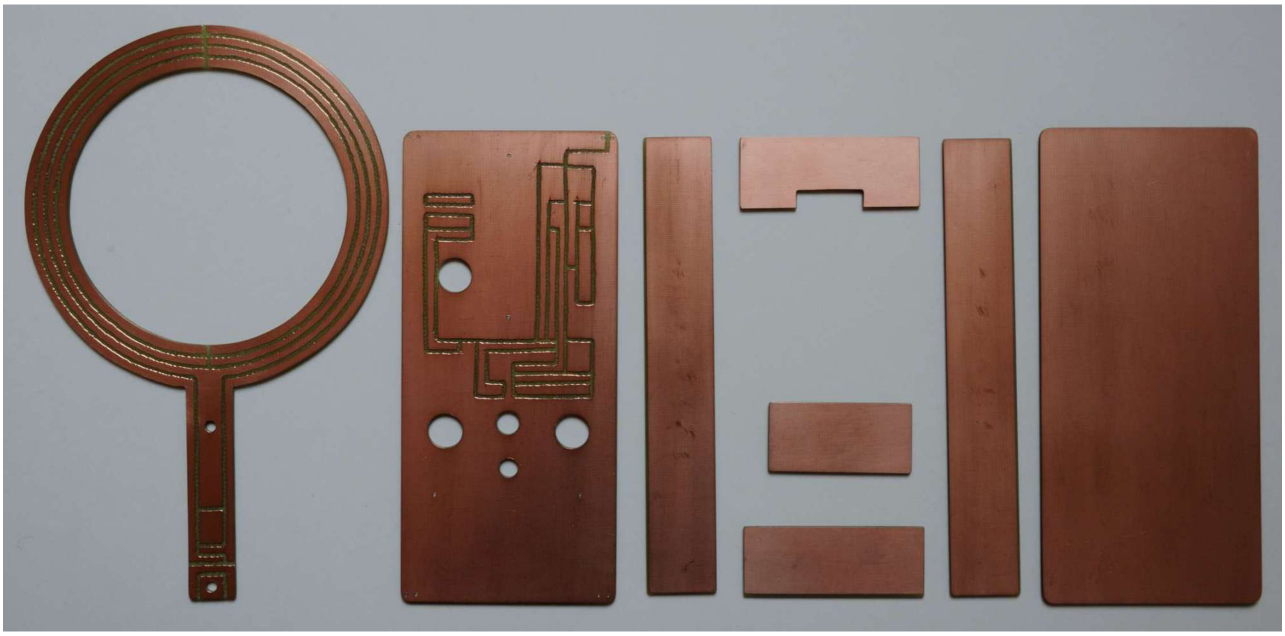
SAWING / MILLING / DRILLING PLAN
LOOP-ANTENNA WITH HF-BOARD AND BAND MODULE
scale 1:1, copper side, PCB material epoxy 1.5 mm single-sided



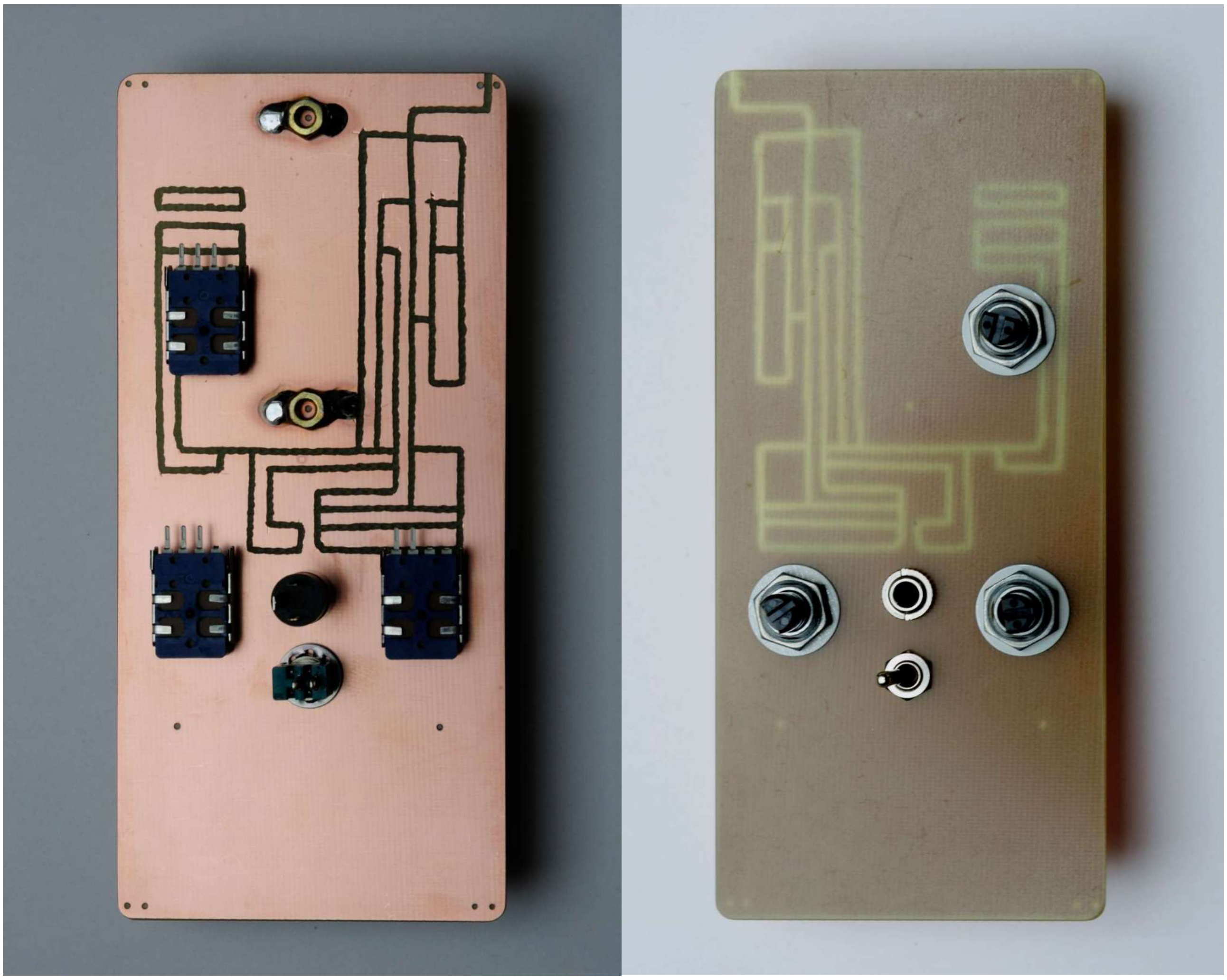
PARTS PLACEMENT DIAGRAM
scale 1:1, copper side = component side



These few components are required for the *wavehunter*: 3 single-sided epoxy boards 160 x 100 mm, 12 resistors, 7 capacitors, 6 electrolytic capacitors, varicap, 3 transistors, voltage regulator, op-amp, 3 potentiometers, 3.5 mm stereo jack, toggle switch, socket strip, pin strip, battery clip, 9V battery, 3 rotary knobs. Only 4 brass nuts and M3 screws are missing on the picture.

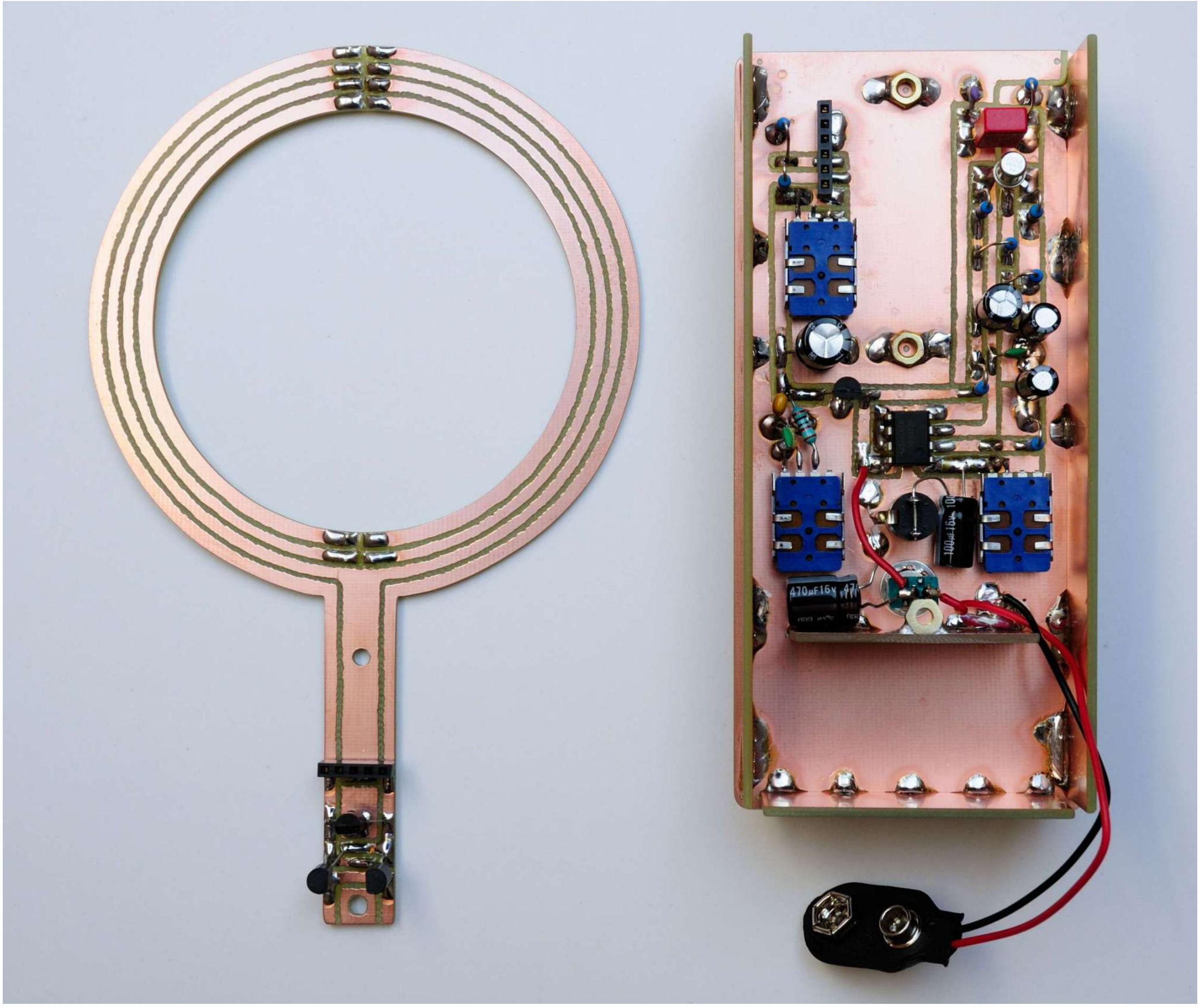


The loop-antenna and all 7 cabinet parts made of epoxy circuit boards have been cut, drilled, and milled. The conductor tracks were not etched, but cut out with a hand milling machine.



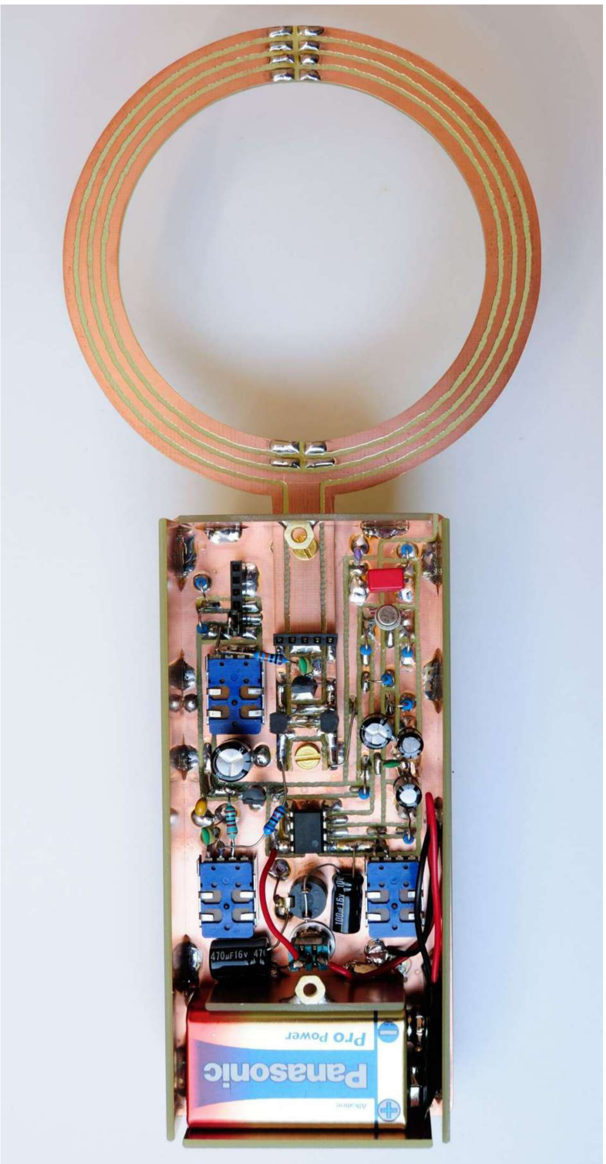
The copper-clad back (left) and front (right) of the front panel. Two brass nuts were soldered to the back, which will later hold the loop-antenna, and potentiometers, earphone jack, and toggle switch were mounted. The remaining components will later be soldered directly onto the copper-clad side of the front panel and the loop-antenna without drilling any holes.

The track bridges from enameled wire were inserted through the drilled holes on the front of the loop-antenna and soldered to the copper tracks on the back.



Loop-antenna (left) and cabinet (right) of the *wavehunter* fully assembled. The HF part of the circuit consists only of the varicap, a 10 nF capacitor and the cross-coupled pair of PNP transistors and is located together with a 5-pin socket strip (into which the band module will be plugged later) on the mounting strip of the loop antenna. The AF part with all the controls and the power supply is located on the front panel. The left, right, and bottom side plates, as well as the intermediate plate for separating the battery compartment, have been soldered vertically to the front panel. The top side plate is still missing, as it can only be soldered in place after the loop antenna has been installed.

Pay attention to the milling line in the upper right corner of the front panel, which extends to its upper edge: the side panel must be positioned just to the right of this milling line and the milling line must not be bridged by solder. In addition, the upper edges of the left, right, and bottom side plates on the copper side m u s t be chamfered so that they cannot make contact with the copper surface of the back plate. These measures prevent ground loops and the inevitable AF-feedback that occurs as a result.

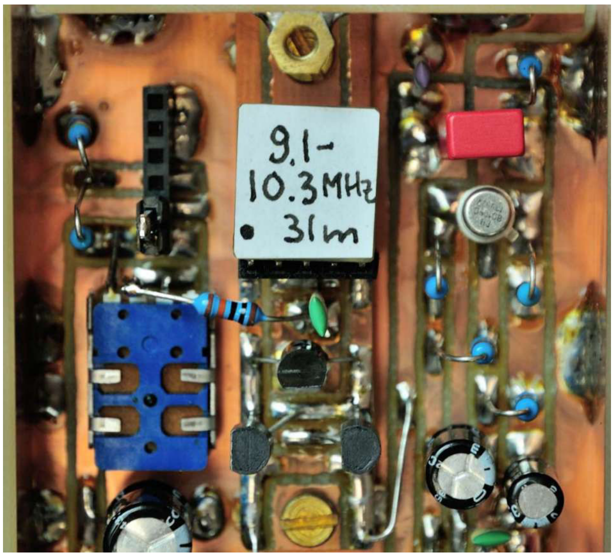


On the left is a view from behind into the open cabinet of the almost finished *wavehunter*. After mounting the loop-antenna with two shortened screws, the components connecting the HF part on the loop-antenna to the AF part on the front panel were soldered in place: 100 KΩ from the frequency potentiometer slider to the varicap, 68 KΩ from the regeneration potentiometer slider to the emitters of the two cross-coupled PNP transistors, and a wire bridge from their emitters to the 680 nF capacitor.

The top side plate was soldered in place, and two brass nuts were soldered to the center of the upper edge of the top side plate and the intermediate plate to secure the back plate, then filed down to a flat surface. The battery was inserted, and the two holes for securing the back panel were measured and drilled so that the back panel could be mounted later with two screws.

Finally, the rotary knobs were mounted and labeled with Dymo embossing tape. In addition, two narrow strips of epoxy were cut to size and attached with double-sided adhesive tape of half the width above and below the frequency tuning knob so that a frequency scale made of thin cardboard can be inserted under their edges pointing towards the knob, which is calibrated for the corresponding band module. The picture on page 1 shows the front view of the finished *wavehunter* with the frequency scale inserted for the 9.1 -10.3 MHz band module.

On the right is the view on the inserted band module for the frequency range 9.1 -10.3 MHz. The bandset-capacitor (here 56 pF + 5.6 pF in parallel) is located on its copper-clad rear side. Before soldering the 5-pin header to the small board, bend its solder ends at right angles with flat-nose pliers so that the band module fits horizontally under the back plate. The dot marks the position of the bandwidth jumper on the vertical 6-pin socket strip (in the top position it has no function). This band module would cover the range 9.6 -10.3 MHz on the middle (medium bandwidth) and 9.9 -10.3 MHz on the upper (narrow bandwidth) plug position of the bandwidth jumper.



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