Patrick Lindecker (F6CTE)
Maisons-Alfort (France)
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Study of an active antenna for LW and MW

CONTENTS

1. Introduction

Wanting to monitor OM traffic on 137 kHz (long wave) and 475 kHz (short wave), and not being an antenna or electronics engineer, I looked at (or even studied) a number of documents to understand reception on these bands (transmission will perhaps come later). The goal here is to build a simple active antenna (antenna + amplification and RX matching electronics) that can power my TS440S transceiver, which has the advantage to go down to 30 kHz in reception.
Beyond the Ham bands, we will examine which transmissions can be decoded by Multipsk/Clock software in LW/MW, between 60 and 518 kHz.

This article is therefore also a summary of what I have read on the subject, hence the large number of references.

After presenting the LW/MW transmissions, we will describe the air loop and ferrite loop antennas, then the vertical whip antenna. We will choose among these three antennas. Then, we will discuss the electronic aspect.

Notations

In the rest of the text:

- The simple product is denoted "." or "x" or is not denoted if there is no ambiguity.
- The square root is denoted √(x).
- "§" for "paragraph".
- [x] means "reference number x," which is located in the "References" chapter at the very end of the article.

Constants and variables used

- c: the speed (celerity) of light = 3.10^{8} m/s
- µ0: the magnetic permeability of a vacuum = $4.\pi.10^{-7}$ H/m
- µr: the relative magnetic permeability (=1 for air)
- f: the transmission frequency, here f=137000 Hz
- λ: the wavelength λ=c/f, here λ=2190 m
- ρ: the resistivity of the wire, here $1.7.10^{-8}$ Ω.m for copper
- π: Pi=3.1416
- t: for time (s)
- rf: radius of the copper wire used
- D: diameter of the circular loop
- L: length of one side of a square loop
- N: number of loops in the magnetic antenna

2. The Ham bands and utility frequencies in LW/MW

2.1 The “137 kHz” Ham band

This band is also called the "2-kilometer band." It has been allocated to the worldwide amateur service since 2000. It extends from 135.7 kHz to 137.8 kHz (see [1] for the band plan). The effective radiated power (ERP) is limited to 1 W, with a maximum transmitter power of 500 W in France (the power difference will be dissipated as heat by the antenna).

Since the maximum transmit power is 1 W and not 800 kW as for the Allouis transmitter (time signals on 162 kHz), it follows that reception levels are extremely low. Consequently, only narrowband digital modes (say ≤ 10 Hz) are used, decodable at very low signal-to-noise ratios, such as QRSS (slow CW).

Apparently, there doesn't seem to be much traffic on this band (even at night). You have to be very patient... For all practical purposes, it should be noted that, according to those who use this band, we hear more modern modes like WSPR (receiver tuned to 136 kHz) than QRSS.

2.2 Longwave propagation

Like all longwave transmissions (and below), transmission occurs solely through the ground, following the Earth's curvature (see [2]). This is known as "surface wave" propagation (between the ground and the ionized D layer of the atmosphere). This transmission is enhanced at night. During transmission, the polarization (direction of the electric field) must be vertical, as a horizontally polarized wave would be quickly absorbed by the ground. Therefore, a vertical transmitting antenna positioned as high as possible would be ideal. During reception, to receive a maximum electromagnetic field, the antenna must also be vertically polarized. Therefore, a whip antenna or a loop antenna in the vertical plane are possible choices.

Note that due to the ability of longwaves to penetrate the ground, this band is used in a ground transmission system called "Nicola" and used in caving (see [1] and [4]).

The range, which increases with surface conductivity, is 1000 km, or even more if propagation occurs over salt water.
However, if we call "d" the distance between transmitter and receiver, it should be noted that the received electric field decreases as a function of:

- 1/d at short distances (normal decay in the "far field"),
- but as a function of $1/d^2$ at long distances, due to ground absorption.

See [3] §4.c and figure 2 in [2], where the curve changes from a linear to a quadratic evolution.

2.3 The "630 m" (or "475 kHz") Ham band

There is another Ham band, in MW, located between 472 and 479 kHz and called the "630-meter band." It is open to Hams on a secondary basis in France. Some countries benefit from an extension of this band. The digital modes used are the same as those used in 137 kHz.
However, there is more traffic than in 137 kHz, for example in WSPR (receiver set to 474.2 kHz).

2.4 Utility Frequencies in MW/LW

While the goal here is, of course, to receive the 137 and 475 kHz Ham bands, it is also, more broadly, to be able to decode, either with Clock software for time signals or with Multipsk for other signals, the following transmissions:

- 60 kHz: MSF, JJY, and WWWB time signals
- 75 kHz: HBG time signal
- 77.5 kHz: DCF77 time signal
- 128.1, 134.6, and 138.0 kHz: IEC 870-5
- 147.3 kHz: DDH 47 50 baud RTTY
- 162 kHz: former France-Inter time signal
- 198 kHz: BBC time signal
- between 191 and 285 kHz: NDB beacons (see [24])
- between 283.5 and 325 kHz: DGPS stations
- between 490 and 518 kHz: NAVTEX.

3. Air loop and ferrite loop antennas

3.1 Introduction

In the following, we will assume that the receiving frequency is 137 kHz. This is located in the Ham LW band.
For reception (and transmission as well), given the wavelength λ (λ=2190 m), the only choice is between shortened antennas, either capacitive (whip or vertical dipole) or inductive (air loop or ferrite loop antenna). In all cases, the efficiency is very low. See [5] to [8] on this subject.

3.2 Directivity

Both capacitive and inductive antennas are subject to the magnetic and electric components of the electromagnetic field, components which, as a reminder, are in phase, perpendicular to each other and located in a plane perpendicular to the direction of propagation (see [9]).

The magnetic loop is more sensitive to the magnetic component the more perpendicularly it passes through the loop.

Below is the radiation envelope of a circular frame (air or ferrite). For a square-section frame, the envelope is not as ideal (see [16]).

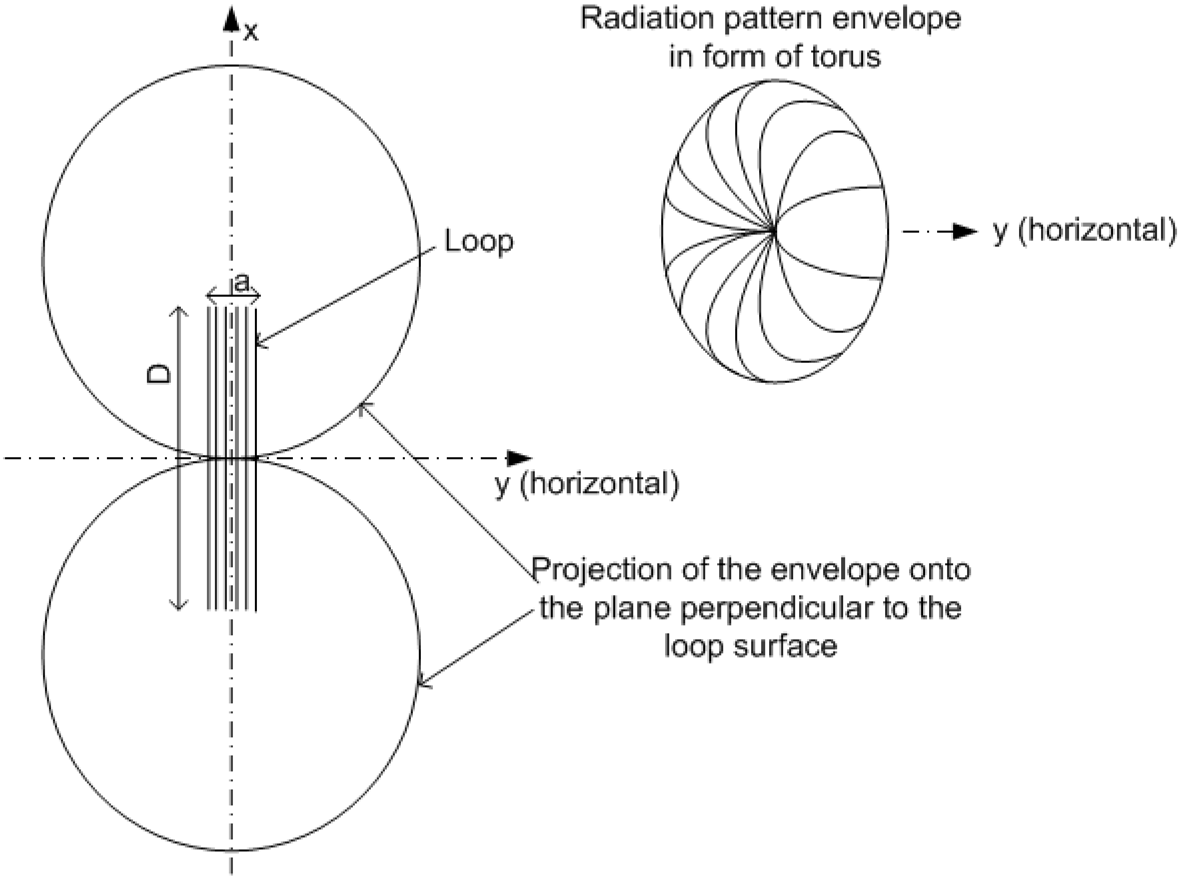

Figure 1

It follows that the best reception direction is horizontal, in the plane of the loop, and conversely, if the plane of the loop is perpendicular to the propagation direction of a transmission, the loop will not receive it.

Given that the received electric field (E) is vertical, the loop is necessarily vertical. Placed horizontally, the signal being listened to becomes very weak. For more information, see [16].

3.3 Estimating the voltage induced on the antenna

For example, if we take an air loop antenna composed of a square coil:

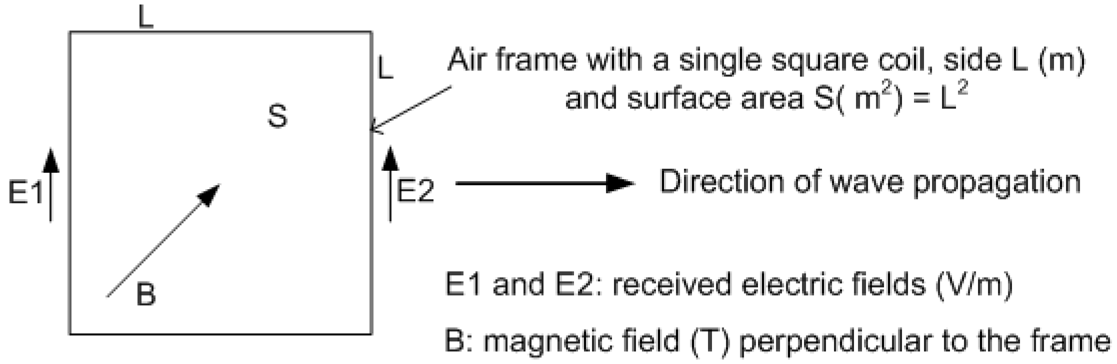

Figure 2

We assume here that the magnetic and electric fields are coupled, so that the receiving antenna is located outside the reactive field zone, i.e. at a distance greater than or equal to $\lambda/(2.\pi)$, i.e. more than 350 m from the transmitting antenna. Under this condition, we have E/B=c (in a vacuum or air).

Since the signal is sinusoidal, we have $B=B0.\cos(2.\pi.f.t)$ and $E=E0.\cos(2.\pi.f.t)$ with f being the frequency and t being the time.

Calculating the emf (electromotive force) "e" induced by the magnetic field
We know that according to Faraday's law: $e = - d(\Phi)/dt$ with Φ the magnetic flux (passing through the coil) equal to $B.S.\cos(\theta)$
Since in our case, B is perpendicular to the frame, it follows that $\cos(\theta) = 1$.
Therefore $e = -d(\Phi)/dt = -d(B.S)/dt = -S.d(B0.\cos(2.\pi.f.t))/dt = 2.\pi.f.\ B0.\sin(2.\pi.f.t).L^2$ $= E0.\ 2.\pi.f.\sin(2.\pi.f.t).L^2/c$ (because B0=E0/c)
Since $f=c/\lambda$ it follows that $e= E0.2.\pi.\sin(2.\pi.f.t).L^2/\lambda$
In terms of rms voltage, we have $e_{rms}= E_{rms}.2.\pi.L^2/\lambda$ with $E_{rms}=E0/\sqrt{2}$
For N turns, we have $e_{rms}= E_{rms}.2.\pi.N.S/\lambda$ (with $S= L^2$).

Calculating the induced emf (electromotive force) "e" from the electric field
In fact, calculating the voltage induced by the electric field is very complex for a magnetic loop (see [10] §3.3.1.4). The calculation given below is simplistic but helps to understand what is happening. It is therefore given for information purposes (hence the italics). It is based on Figure 2.

> *If the electric field E1 is $E1=E0.\sin(2.\pi.f.t)$ then $E2=E0.\sin(2.\pi.f.t+\Delta\varphi)$, with $\Delta\varphi$ representing the slight phase delay of E2 relative to E1, due to the travel time of L at the speed of light. Therefore $\Delta\varphi=2.\pi.f.L/c=2.\pi.L/\lambda$.*
> *The voltage induced by E1 is $e1=E1.L$ and that induced by E2 is $e2=E2.L$.*
> *Let e be the induced voltage difference: $e=e2-e1$*
> *After some trigonometric calculations, we find:*
> *$e \approx E0.\Delta\varphi.\cos(2.\pi.f).L = E0.2.\pi.\cos(2.\pi.f.t).L^2/\lambda$*
> *In terms of rms voltage, we have $e_{rms} \approx E_{rms}.2.\pi.L^2/\lambda$*

Special case of the ferrite frame

Ferrite concentrates the magnetic field lines (see [21] and [22]).

Schematically, we have (ignoring discontinuities):

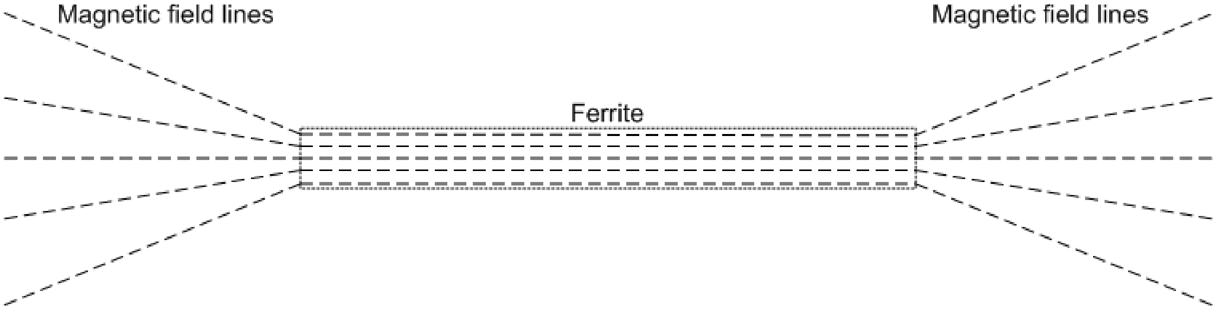

Figure 3

This concentration of field lines is reflected by the relative magnetic permeability "μr" (=1 for air and from 10 to several thousand for ferrites). The magnetic field B in the ferrite is therefore multiplied by μr.

For N turns wound around the ferrite, we ultimately have $e_{rms} = E_{rms}.2.\pi.N.S.\ \mu r / \lambda$

3.4 Effective height (Heff)

In reception, this height corresponds to the length by which the received electric field E_{rms} must be multiplied to obtain the induced voltage e_{rms} (see [14]).

From the above, we see that Heff = 2.π.S/λ, for one turn. For example, for S = 1 m2, we obtain Heff = $2.87.10^{-3}$ m, which is very low. This height can be compared to that of a vertical λ/4 antenna (i.e. 547 m): Heff = λ/(2.π) = 349 m.

This means that with a 1 m² loop, we receive an induced voltage 121,000 times lower than that obtained with a λ/4 antenna.

More generally, for a coil of N turns, wrapped around a material with relative permeability μr, we have: Heff = 2.π.N.μr.S/λ (see also [15]).

For example, for a coil of 25 loops of 1 m² of an air frame, Heff = $7.17.10^{-2}$ m.

3.5 Radiation resistance (Rr)

For a loop, a precise calculation (see [10] §3.3.1.4), taking into account the electrical and magnetic radiation impedances, shows that for loops with a diameter much smaller than λ, the electrical signal is negligible at low frequencies, because the reactive part of the electrical radiation impedance is enormous and blocks the electrically generated emf. It can be suspected that the opposite must be true for a short whip.

The magnetic radiation resistance given by [10] can, after some calculations, be translated into the better-known form: $Rr=31171.S^2/\lambda^4$, with S being the loop area (m^2).

Recall that the radiation resistance is proportional to the power radiated by the antenna, with the remaining power supplied to the antenna being consumed (in the form of heat) in the loss resistor ("Rp"). For example, for a 1 m^2 loop, Rr=$1.35.10^{-9}$ ohm, which is very low.

More generally, for a winding of N turns, wrapped around a material with relative permeability μr (=1 for air), we have according to [15]: $Rr = 31171.(N.\ \mu r.S)^2/\lambda^4$

For example, for a winding of 25 loops of 1 m^2 of an air frame, we have

Rr = $8.47.10^{-7}$ ohms.

3.6 Loss resistance (Rl)

Here, we will consider the main loss to be the ohmic losses of the antenna, taking into account the skin effect. We neglect the proximity effect between wires and losses due to the antenna's immediate environment.

We know that the resistance Rl of a conductor of length Lw (m) and cross-section Sw (m^2) is equal to: Rl=ρ.Lw/Sw with ρ=$1.7.10^{-8}$ Ω.m for copper.

For a square loop (see Figure 2), Lw=4.L.N and for a circular loop of diameter D: Lw=π.D.N

According to [12] and [13], we have the skin thickness δ= $\sqrt{\frac{\rho}{\pi\times f\times\mu 0}}$

Note that δ is equal to$1.77.10^{-4}$ m (or 0.177 mm) at 137 kHz.

With regard to the Joule effect, half the skin thickness must be considered (see [25] page 692), treating the tube as a thin plate.

If rw is the radius of the wire cross-section, the effective cross-sectional area of the wire Sw is equal to: $Sw = (\pi \times rw^2) - \left(\pi \times (rw - \frac{\delta}{2})^2\right)$ if rw>δ/2

or $Sw = \pi \times rw^2$ if rw≤δ/2 (no skin effect)

At this point, knowing ρ.Lw and rw, we can determine Rl.

For example, for a 1x1 m square frame composed of 25 wire loops with a radius rw=0.25 mm, we have Rl=14.86 ohms.

For a coil wound around a ferrite core, we must also take into account the resistance Re, which corresponds mainly to eddy current losses. This resistance, integrated with the resistance Rl, lowers the quality factor of the inductor.

3.7 Antenna efficiency

The antenna efficiency is written as ρ=Rr/(Rr+Rl). It is very low for a short antenna (see [6] and [11]).

For example, for a 25-loop winding of a 1 m^2 airframe, we have ρ=$8.95.10^{-8}$, which is extremely low.

3.8 Inductance and parasitic capacitance of a winding

For the tuned series voltage step-up circuit (see Figure 5), we need to estimate (roughly) the inductance of the coil as well as its distributed parasitic capacitance.

<u>Inductance</u>

For an air coil, we can use the following practical formula from [17] (this document also proposes a manufacturing process for an elegant air coil):

$Lloop = \frac{S\times N^2}{\sqrt[3]{a}\times 12}$ with Lloop in μH, S the loop cross-section in dm^2, and "a" the transverse length of the coil in cm (see Figure 1).

Other, more complex and perhaps more precise formulas can be found in [10] §3.3.1.2 and [15].

For a ferrite antenna, we could use $Lloop = \frac{\mu0 \times \mu r \times S \times N^2}{a}$ but this formula is imprecise because the "apparent" μr is not known. The formula $Lloop = \frac{Al \times N^2}{10^9}$ from [23] seems more precise. Here, Lloop is in H. Al is the specific inductance, given in [23], as a function of the ferrite rod.

Parasitic capacitance

According to a formula from [15], the parasitic capacitance can be estimated as:

$$\mathrm{Cloop} = 0{,}397 \times \sqrt[3]{\frac{2{,}63 \times 10^6 \times w^4}{a}}$$

With Cloop in pF, w=L or D (in m) and a (in m) according to Figure 1.

For example, for a 1x1 m square coil composed of 25 loops wound over a=2 cm, we have Lloop= 4100 μH and Cloop=202 pF.

Note that for these values, the resonant frequency "fr" of the coil is equal to fr = 1/(2.π.√(Lloop.Cloop))=174200 Hz. This frequency (fr) must be greater than the highest target frequency.

3.9 Resistance to interference

As shown in [18], the level of natural noise or noise related to human activity increases as the frequency decreases. At 137 kHz, the external noise level is therefore high, particularly in urban areas. Note that noise related to human activity is mainly electrical, not magnetic, noise whose electrostatic induction is received in the near field. Since the loop antenna is not very sensitive to the electric field in the near field, it follows that this antenna is relatively protected against this type of noise. See [19] on this subject. From now on, we will consider this antenna to be insensitive to noise of human origin in urban areas. Note that in the far field, there is no protection against noise (regardless of its origin), as it then belongs to the electromagnetic field.

4. Whip antenna

This vertical antenna is the subject of an article in [5], whose main results are reproduced.

The directivity is naturally omnidirectional in the horizontal plane, and zero vertically.

The effective height of this antenna is equal to Heff=L/2, if L is the height of the whip. Therefore, the induced voltage is equal to $e_{rms}=E_{rms}.L/2$

The radiation resistance is equal to $Rr=40.\pi^2.(L/\lambda)^2$

The parasitic capacitance is: $\mathrm{Cwhip} = \frac{20 \times \pi \times L}{\mathrm{Ln}\left(\frac{2 \times L}{Rw}\right) - 1}$ with Rw being the radius of the whip. The loss resistance (Rl) can be calculated as for the loop antenna by replacing Lw with L. It is negligible (like Rr).

The inductance of a straight conductor, and therefore the one of the whip (Lwhip), is equal to 1 μH/m. It is also negligible.

For example, for a 1.5 m whip with an average radius of 2 mm, we find Heff = 0.75 m, Rr = 0.18 mohm, Cwhip = 15 pF, Lwhip = 1.5 µH, and Rl = 23.4 mohm.
This antenna therefore boils down to an e_{rms} generator on the Cwhip capacitor.

The whip is primarily sensitive to the electric field and therefore to industrial and domestic noise in urban areas. This is its main drawback in reception.

5. Input stage principle

5.1 For the whip antenna

The antenna is considered as a generator of induced voltage e_{rms} followed by the antenna's own impedance. As proposed in [5], the capacitive reactance of the whip antenna is not compensated by an inductor. The bandwidth is therefore very wide, which has the advantage of not requiring frequency adjustment.

We will use an impedance matching preamplifier. For simplicity, we will assume that the signal input is a MOS FET transistor whose input impedance consists of a capacitor Ci of approximately 4 pF and a resistor of 1 TΩ, in parallel. We will ignore the 1 TΩ resistor. We will assume that the output impedance of the preamplifier is much lower than that of the antenna, i.e. 50 ohms. The input stage upstream of the receiver is therefore as follows.

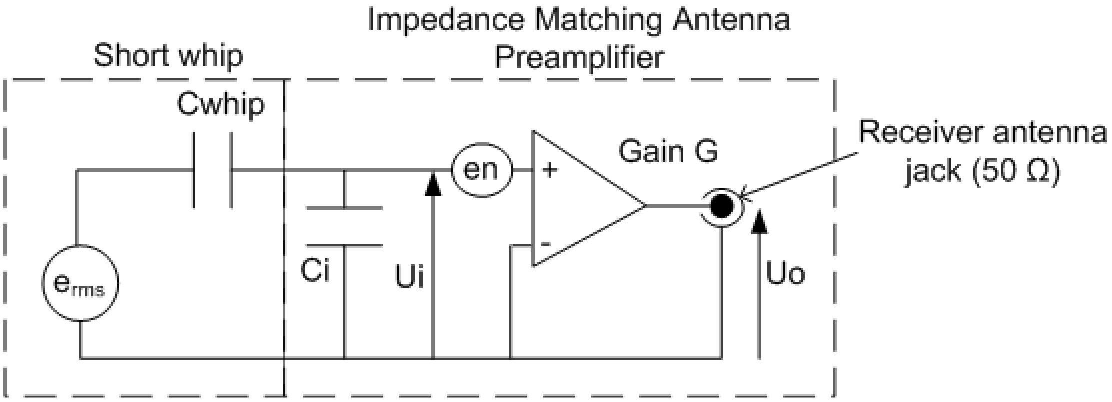

Figure 4

At the output of the capacitive divider, the signal voltage (QRSS in our case) Ui is equal to Ui = e_{rms} . Cwhip / (Cwhip + Ci), or Ui = e_{rms} . 0.79 in our example.
Note that the noise voltage induced by the antenna is not reduced by the Cwhip/Ci attenuator.

"en" represents the MOS FET noise, which depends on f. At 137 kHz, we have approximately 4 nV/√Hz, or 12 nV for a bandwidth of 10 Hz. This noise will be integrated into the electronic noise of the receiver.
Note that for a MOS FET, the noise current is negligible.

The preamplifier will be assumed to be able to amplify the signal with a gain "G" between 1 (voltage follower) and 10 (20 dB).

5.2 For air loop and ferrite loop antennas

The antenna is considered as an induced voltage generator e_{rms} followed by the antenna's own impedance, consisting of the loss resistance Rl and the loop inductance Lloop, this assembly being connected in parallel with the distributed parasitic capacitance Cloop (see [15]). The inductive reactance is compensated by the capacitance Cv, as proposed in [7] and [15], such that the circuit Lloop / (Cloop + Cv + Ci) is tuned, thanks to Cv, to the frequency f of 137 kHz. The inductor's quality factor Q is equal to Q=Lloop.2.π.f / Rl. The received bandwidth B_{-3dB} is therefore narrow and equal to B_{-3dB}=f / Q.
This circuit also increases the voltage (signal and noise) since at resonance we have Ui/e_{rms}=Q.
In our example in §3, we obtain Q=376, therefore B_{-3dB}=364 Hz.

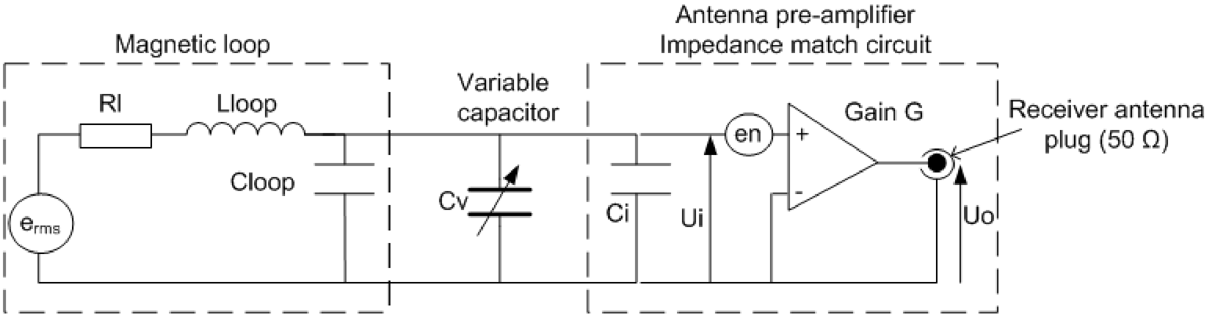

Figure 5

6. Comparison between antennas and antenna selection

6.1 Noise source levels

<u>Bandwidth noise</u>
In [20], we find a formula giving the noise level, in terms of electric field, for a short vertical antenna: Nbn_per_m(dBµV/m)=Fa+10.log(B)+20.log(f)-95.5
We will assume that this formula also applies to a loop antenna.
Fa is equal to 75 dB in quiet areas but 100 dB in urban areas. B is the bandwidth in Hz. f is equal to 0.137 MHz.
For B, we choose 10 Hz, because this bandwidth corresponds to the bandwidth required for QRSS mode 1 (slow CW).

The "band noise" level in µV/m is therefore:
- Nbn_per_m = -27.8 dBµV/m or 0.041 µV/m in a quiet area
- Nbn_per_m = -2.88 dBµV/m or 0.718 µV/m in an urban setting.

This certainly applies to a whip. For a frame, we can consider the band noise level to be equal to 0.041 µV/m (41 nV/m), i.e. the level in a quiet area, regardless of location, assuming that the frame is indeed completely insensitive to industrial and domestic noise in an urban setting.

In the following, we will assume that the antenna is installed in a quiet area (Nbn_per_m = 41 nV/m).

Electronic Noise
The TS-440S documentation states that the receiver's sensitivity in USB, between 100 and 150 kHz, is 2.5 µV for a 10 dB internal signal-to-noise ratio, probably over a 2.2 kHz band. Based on this, we can estimate that the noise generated by the receiver over a 10 Hz band is 53 nV.
Since the noise generated by the preamplifier is 12 nV, the total "electronic" noise is Nen = 54 nV (= $\sqrt{(53^2 + 12^2)}$).

Overall Noise
Once the band noise level Nbn in µV has been determined, the overall noise level Nn (band noise + electronic noise) in µV will be determined: $Nn = \sqrt{Nbn^2 + Nen^2}$

6.2 Minimum signal level for QRSS 1 decoding at the receiver

To decode QRSS 1 mode, the minimum signal-to-noise ratio ("S/N min") is -20 dB relative to a 3 kHz band. Relative to the 10 Hz band, the S/N min must be equal to 3. Therefore, the minimum signal level (Ns_{min}) (in terms of power) must be 3 times greater than the overall noise level (Nn) over the 10 Hz band considered. It follows that Ns_{min}=3 x Nn.

6.3 Minimum electric field for QRSS 1 decoding with a short whip

From the above, we can write, at the receiver input:

- the band noise level received by the whip is equal to:
  Nbn(nV) = Nbn_per_m x Heff x G (with Nbn_per_m = 41 nV, Heff = L/2, and G being the preamplifier voltage gain). We can therefore determine Nn then Ns_{min},

- the signal (assumed QRSS 1) received by the whip is equal to, with Ew_QRSS the electric field in nV/m received at the antenna:
  Ns(nV) = Ew_QRSS x Heff x Cwhip / (Cwhip+Ci) x G

From Ns_{min}, we deduce the minimum electric field at the antenna, to decode QRSS 1:
Ew_QRSS min = 2 x Ns_{min} x (Cwhip+Ci) / (L x Cwhip x G)

Using the example in §4, we find:

- if G=1: Nbn(nV)=30.7 nV, Nn=62 nV, Ns_{min}=186 nV, Ew_QRSS min= 315 nV/m,
- if G=10: Nbn(nV)=307 nV, Nn=312 nV, Ns_{min}=937 nV, Ew_QRSS min= 158 nV/m. The gain G allows to lower the decoding threshold (Ew_QRSS min), down to 156 nV/m for an infinite gain.

Limit Value
If the whip is very large, Cwhip becomes much larger than Ci. Then we tend towards:
Nn = 41 x L/2 x G, Ns_{min} = 61.5 x L x G then Ew_QRSS min = 123 nV/m

Conclusion: with a large whip and/or high gain, the QRSS 1 decoding threshold can be quite close to 123 nV/m. However, since this antenna lacks selectivity, the input level at the receiver can be high, with the potential risk of saturation distortion.

However, if the gain and whip height are reduced, the decoding threshold increases, hence a compromise must be made.

6.4 Minimum electric field for QRSS 1 decoding with an air frame

From the above, we can write, at the receiver input:

- the band noise level received by the frame is equal to:
  Nbn(nV) = Nbn_per_m x Heff x Q x G (with Heff=2.π.N.μr.S/λ and μr=1). We can therefore determine Nn then Ns_{min},

- the signal (assumed QRS1) received by the frame is equal to, with Ew_QRSS the electric field in nV/m received at the antenna:
  Ns(nV) = Ew_QRSS x Heff x Q x G

From Ns_{min}, we deduce the minimum electric field at the antenna, to decode QRSS 1:
Ew_QRSS min = Ns_{min} / (Heff x Q x G)

Using the example in §3, we find:

- if G=1: Nbn(nV)=1107 nV, Nn=1108 nV, Ns_{min}=3323 nV, Ew_QRSS min= 123.1 nV/m.
- if G=10: Nbn(nV)=11065 nV, Nn=11065 nV, Ns_{min}=33196 nV, Ew_QRSS min= 123.0 nV/m (the limit is 123 nV/m for an infinite gain).

Here, the limit value is also 123 nV, and the gain of 10 is irrelevant.
Furthermore, there is no risk of distortion because the antenna is selective.

<u>Conclusion</u>: with a loop of reasonable size, without the need for amplification and without the risk of distortion, we are close to the minimum threshold of 123 nV for decoding QRSS 1.

6.5 Minimum electric field for QRSS 1 decoding with a ferrite loop

The formulas for calculating Nbn(nV) and Ns(nV) are the same as for the air loop, except that μr is greater than 1.
To compare the ferrite loop with the air loop, we will assume that the inductance is equal to that of the air loop, i.e. 4.1 mH. The ferrite will be assumed to be the reference “R33-0.37-400” from [23] with an Al=62, a section S of 0.694 cm^2 and a length a of 10.2 cm. Starting from
$Lloop = \frac{\mathrm{Al} \times N^2}{10^9}$ (see §3.8), the number of turns is
$N = \sqrt{10^9 \text{ x Lloop(H)/Al}}$ =257.

Starting from $Lloop = \frac{\mu0 \times \mu r \times S \times N^2}{a}$ (see §3.8), we can deduce that the "apparent" μr is:
$\mu r = \frac{Lloop \times \mathrm{a}}{\mu0 \times S \times N^2}$= 72.6 (for a theoretical μr of 600).
Cloop is negligible (<1 pF).

The resistance Re due to "eddy currents" is assumed to be equal to 20 Ω, in series with the inductance. In this regard, ferrites with a "cloverleaf" cross-section are

preferred over solid rods (see [8] on this subject). The wire, assumed to be 0.25 mm in diameter, introduces a resistance of 2.6 Ω (very optimistic compared to measurements made on older windings).
Ultimately, Rl is 22.6 Ω (20 + 2.6).
The quality factor Q is 156 at 137 kHz, so B_{-3dB} = 879 Hz.

With this example, we find:

- if G = 1: Nbn(nV) = 24 nV, Nn = 59 nV, Ns_{min} = 177 nV, Ew_QRSS min = 306 nV/m.
- if G = 10: Nbn(nV) = 237 nV, Nn = 243 nV, Ns_{min} = 730 nV, Ew_QRSS min = 126.1 nV/m (the limit is 123 nV/m for infinite gain).

There is no risk of distortion due to saturation because the antenna is selective.

Conclusion: the same results are obtained as with an airframe antenna, if the signal is amplified.

6.6 Antenna Selection

With sufficient gain and a good height, the whip antenna can operate at the minimum decoding threshold. Its advantages are:

- no need to tune a frequency,
- its lack of horizontal directivity.

It is therefore simple to use.

Its disadvantages are:

- the risk of distortion because there is no selectivity,
- its sensitivity to industrial and domestic noise in urban areas.

For a magnetic loop antenna, the advantages and disadvantages are reversed compared to the whip antenna.
Its disadvantages are:

- the need to set a frequency (that of the tuned circuit). However, this selectivity limits the noise level,
- its horizontal directivity, which requires the user to orient this antenna.

Its main advantage is its lack of sensitivity to industrial and domestic noise in urban areas (in the near-field).

The ferrite loop antenna is as good as the air loop antenna, provided the signal be amplified. Furthermore, it is compact and therefore easy to orient.

Ultimately, the author, who lives in the city, chooses a ferrite loop antenna.
Note that in the countryside, a whip antenna might be the preferred choice.

7. Amplification and matching electronics

7.1 General schematic

Various active antenna schematics can be found online, for example, in [21] and [24].

The author provides the general schematic of his active antenna below.

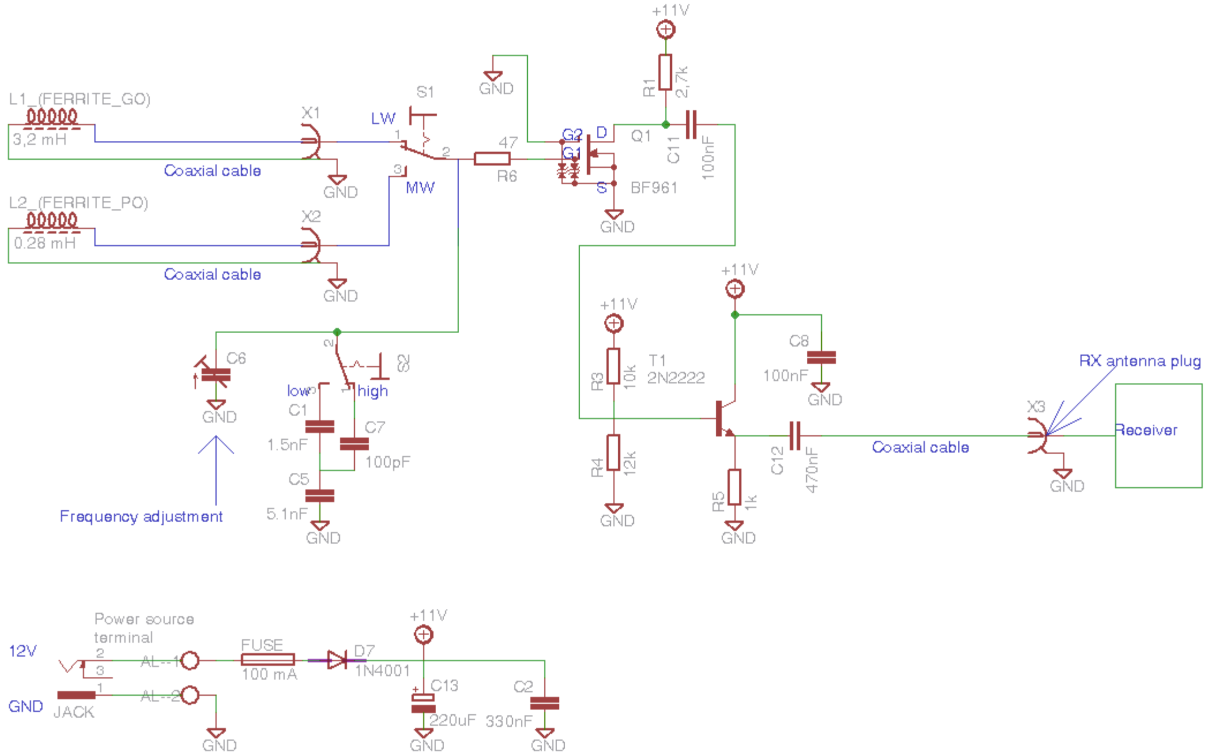

Figure 6

The goal is to cover the radio band between 60 and 518 kHz. This can only be achieved with two bands (LW/MW), each divided into two frequency blocks ("low" / "high").

The inductance values (LW: 3.2 mH and MW: 0.28 mH) are those taken from the ferrite core used by the author.

This diagram is based on the last diagram in [21], using what the author had on hand. The 12 V power supply is assumed to be stabilized. Apparently, this preamplifier operates from 5 V up to at least 13.8 V stabilized.
The first MOSFET transistor (BF961) operates as a common source (amplifier) with gate G2 at 0 V. In this configuration, there is no signal distortion (or saturation). The second transistor, a bipolar transistor (2N2222), operates as a common collector (voltage follower).
The overall voltage gain of the preamplifier (G) is approximately 3.

The two coaxial cables (50 or 75 Ω) between the ferrite and the LW/MW switch form a shield up to the metal box containing the electronics. These cables should not be too long (≤ 0.5 m), as they introduce a certain capacitance (approximately 40 pF per m of coaxial cable), which is placed in parallel with the CV (C6). However, the length of the coaxial cable at the preamplifier output is not critical.

For the low frequency block (switch set to "low"), we have the CV capacitance (21 to 522 pF) connected in parallel with C1 and C5 in series (which forms a capacitance of 1.16 nF).

For the high frequency block (switch set to "high"), we have the CV capacitance of 100 pF connected in parallel with C7 (actually, with C7 and C5 in series).

With these inductance and capacitance values, we experimentally obtained:

- LW / low block: 60 to 82 kHz,
- LW / high block: 81 to 202 kHz,
- MW / low block: 199 to 272 kHz,
- MW / high block: 268 to 551 kHz.

The amplifier is very selective because the quality factor is approximately 115 in the "low" position and around 55 in the "high" position.

Given the simplicity of the electronics, the author soldered the components onto two pieces of copper stripboard (one for the power supply, the other for the preamplifier).

This active antenna was compared with a 1.5 m vertical whip (connected directly to the receiver), receiving DCF77, for signal-to-noise ratio (measured by Multipsk). The difference is 20 dB in favor of the active antenna. The DCF77 time signal is therefore decodable by Clock with the active antenna but not with the whip.

Tip: the input level should be reduced by the Windows mixer to avoid saturating the signal and ensure proper decoding.

The following photo shows what this active antenna looks like from the outside, with the PC and receiver, and the Clock program decoding the France-Inter time frames.
The active antenna is installed on a rotating support. The CV, being too large, could not be placed inside the metal box. It is connected to the LW/MW switch by a short coaxial cable.
The audio signal (at a constant level) from the receiver is transmitted to the PC's "Microphone" input, the level being adjusted by the Windows mixer.
Of course, the active antenna must be installed outdoors or, at the very least, indoors but pressed against the window (except for France Inter, which seems to be received in any condition, even facing a wall...).

Note regarding the failure of using Operational Amplifiers (OAs)
The author tried replacing the BF961 with an OA (TL081) as a non-inverting amplifier, then replacing the 2N2222 with an OA as a voltage follower. In all cases, the OA generates self-oscillation.

7.2 Other Schematics

You can also use a ready-made preamplifier, such as the one available at this address: https://www.radioelec.com/preamplificateurantennerecepteurpogo-xml-354_384-1303.html
Below is the schematic of the active antenna incorporating this preamplifier.

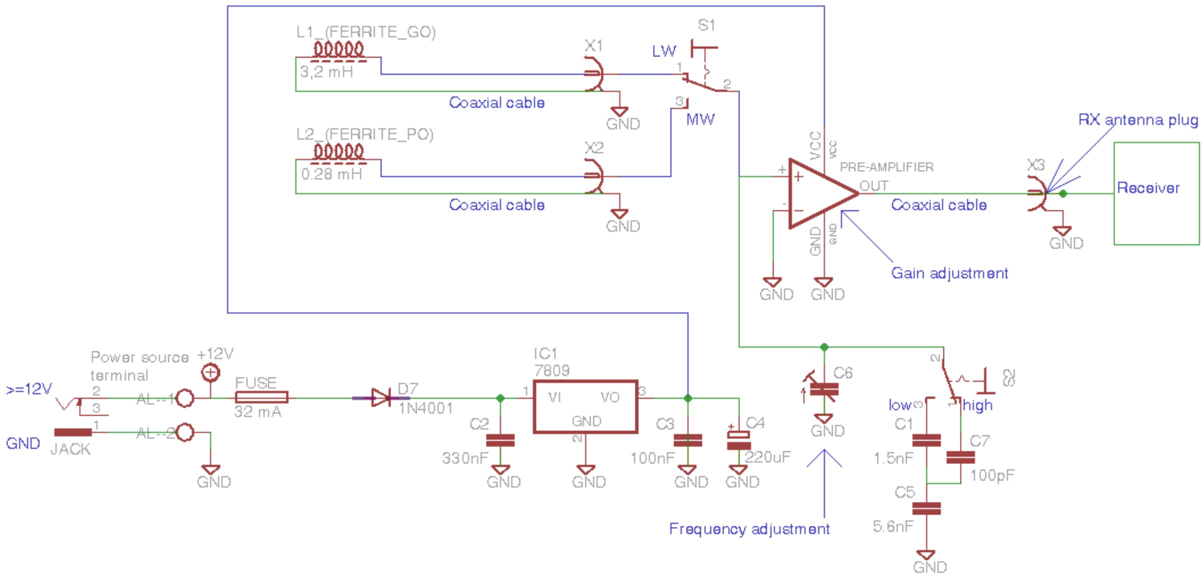

Figure 7

The input impedance of this preamplifier does not seem very high, which limits the quality factor (Q) of the tuned circuit to 27, at 137 kHz for the diagram above, the bandwidth at -3 dB being 5 kHz, a value that remains reasonable. However, the amplifier's voltage gain is significant: up to 200 times (!).

The stabilized 9 V power supply from a minimum voltage of 12 V is standard.
Note that if an external stabilized voltage between 5 and 12 V is available, components C2 and IC1 can be omitted.

Note that the following diagram was previously tested. It used varicap diodes instead of a CV and capacitors in parallel.

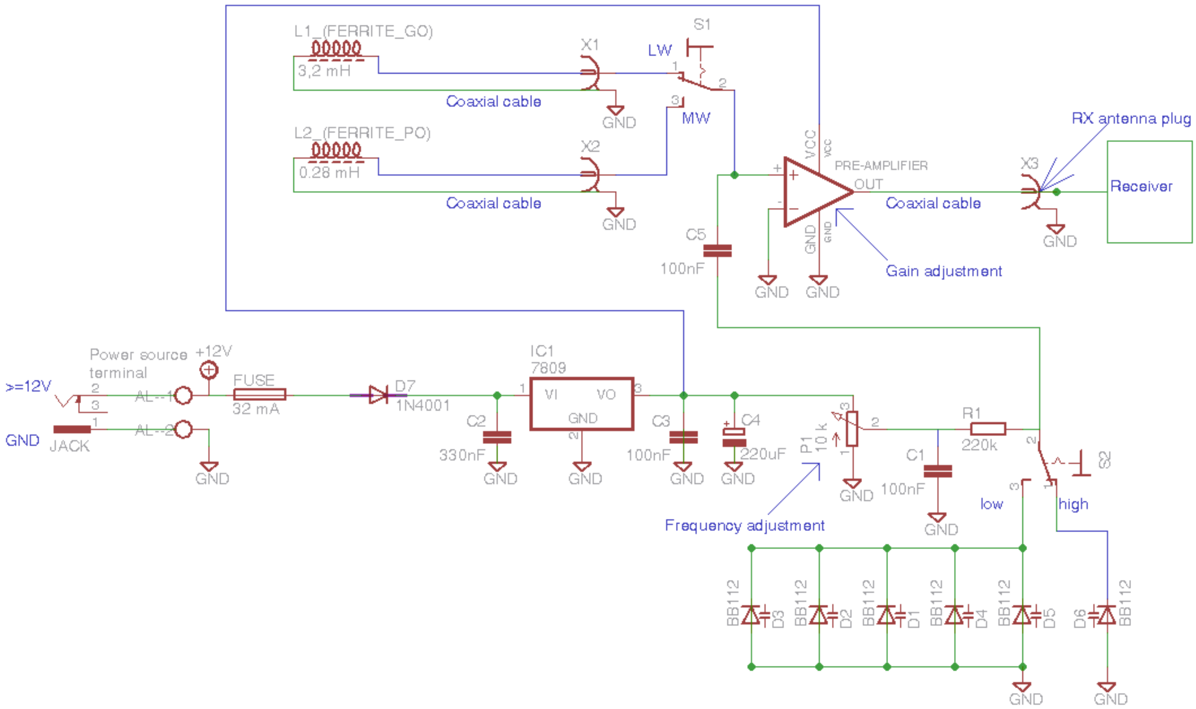

Figure 8

These diodes allow:

- remote frequency control,
- any frequency tuning range, by setting the number of Varicap diodes in parallel.

The disadvantage of Varicap diodes is that the tuned circuit is more damped compared to a CV: Q=14 at 137 kHz for Varicap diodes versus 27 for the CV.

8. Conclusion

In urban areas, an active antenna based on a ferrite core is well suited for receiving and decoding LW/MW transmissions. An air loop should perform as well (or even better) than a ferrite core, but the author has not tested this possibility.
In the countryside (absence of noise from human activity), a simple vertical whip may be sufficient, but this has not been verified either.

This antenna, based on a ferrite core, must be connected to electronics that allow:

- signal amplification,

- matching the high impedance of the tuned circuit to the receiver's 50 Ω input.

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