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The 12th of October 2025 - Revision D

Experiments, Physics, and Sizing of HF Magnetic Loop Antennas

CONTENTS

1. Introduction

I wanted to conduct some traffic from my balcony, without using my shortened whip antenna, which isn't very efficient. So I considered a magnetic loop antenna, which also takes up little space. Moreover, making it myself made the project a little more interesting, even though I don't have the technical resources (welding station, large bender, etc.) to shape a copper tube loop.
So I opted for what was available to me: copper coils sold by DIY stores. These coils, intended for plumbing, therefore become solenoids in this case.

The aim is to build an antenna for the medium bands 40, 30 and 20 m and if possible, to extend it to the low bands (80, 60 m) and high bands (17 to 10 m).
I built a first antenna based on solenoids, resembling a tuned transformer like a Tesla coil, to refine the problem. Since it was inefficient and frequency-limited, I built a second antenna (a single-loop) from part of the first antenna.

After presenting the first antenna, I will physically justify its operation. Then I will move on to the second antenna (the final one) and provide some guidance on the sizing of this type of antenna.
Therefore, after other Hams, it is a matter of exploring the subject and, ultimately, giving some ideas to DIY enthusiasts.

Notations
In the rest of the text:

- The simple product is denoted "." or "x" or is not denoted if there is no ambiguity.
- In formulas and equations, the operators x and / take precedence over + and -
  Therefore, A x B + C must be understood as (A x B) + C.
  Similarly, the power takes precedence over all operators.
  Therefore, A x B^2 + C must be understood as (A x (B^2)) + C.
- The square root is denoted √(x)
- "§" for "paragraph"
- "≈" for "approximately"
- [x] means "reference number x," which is located in the "References" chapter at the very end of the article.
- " xEy " means " x 10^y ". For example, " 3E8 " and " 3 10^8 " have the same value.
- µ0: the magnetic permeability of the vacuum = 4.π.10^{-7} H/m
- The abbreviation “Cv” means “a Capacitor which is variable”.
- The abbreviation “Ca” means “a Capacitor which is adjustable”.

2. Description and experimentation on the first antenna

To avoid repeating the various experiments conducted to date on HF magnetic loop antennas, we will refer to a few articles in French in references [1], [2], and [3] and to the very comprehensive article (in English) in reference [4].
To make the connection with "magnetic" antennas in MW and LW, see reference [5].

2.1 Description of this antenna

The schematic diagram of this first antenna (i.e. a solenoid transformer + a load) is as follows, in transmission mode (Figure 1):

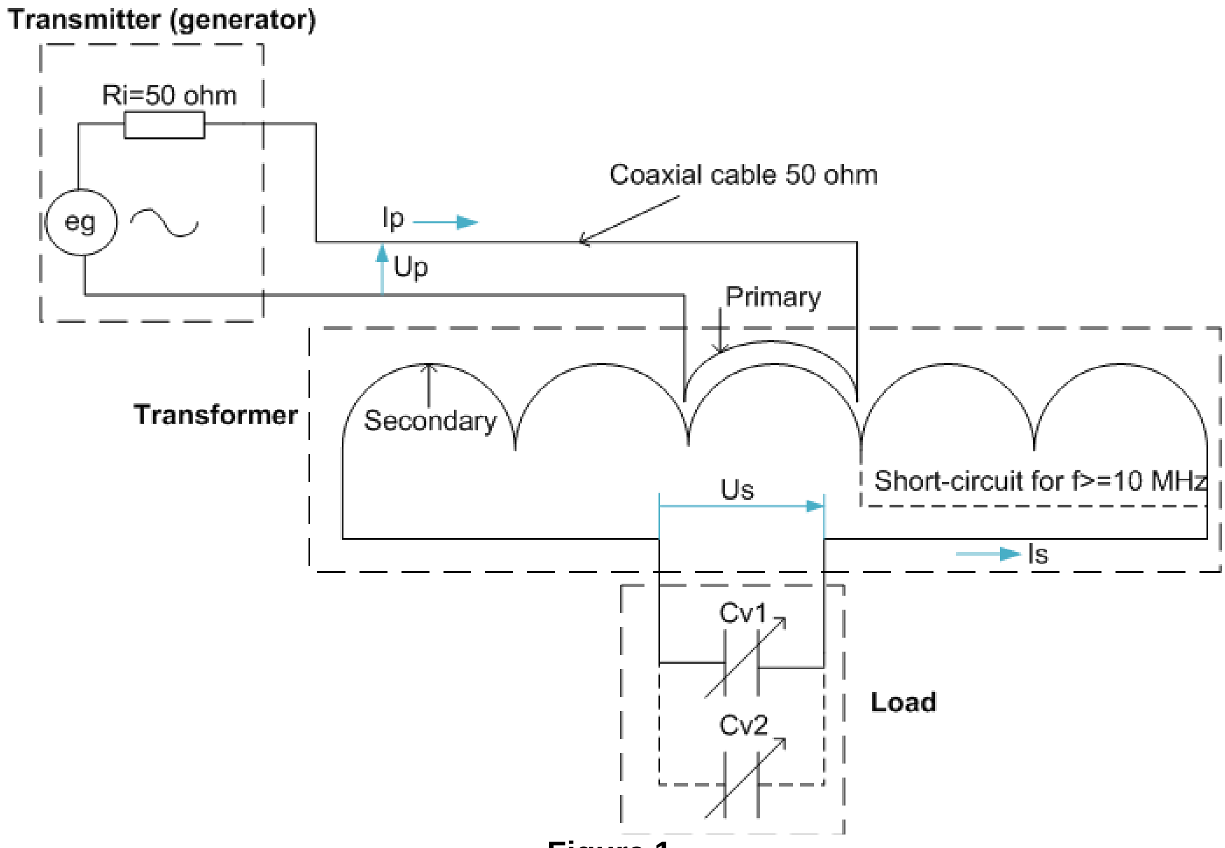


Figure 1

The author primarily intends to operate at 7 MHz (43 m) and, secondarily, at 3.5 MHz (86 m). Since the perimeter "P" of the main (secondary) solenoid must not exceed λ/4 (see [1]), so that the current is nearly uniform along this solenoid, a 10 m coil of 12/14 mm copper tubing is sufficient.
The directivity behavior of a magnetic loop antenna is shown in Figure 2 (the secondary part of the antenna is here called the "loop").
It should be noted that for P≥λ/3, the directivity is no longer the same and resembles less and less an "8" and more and more a "0".

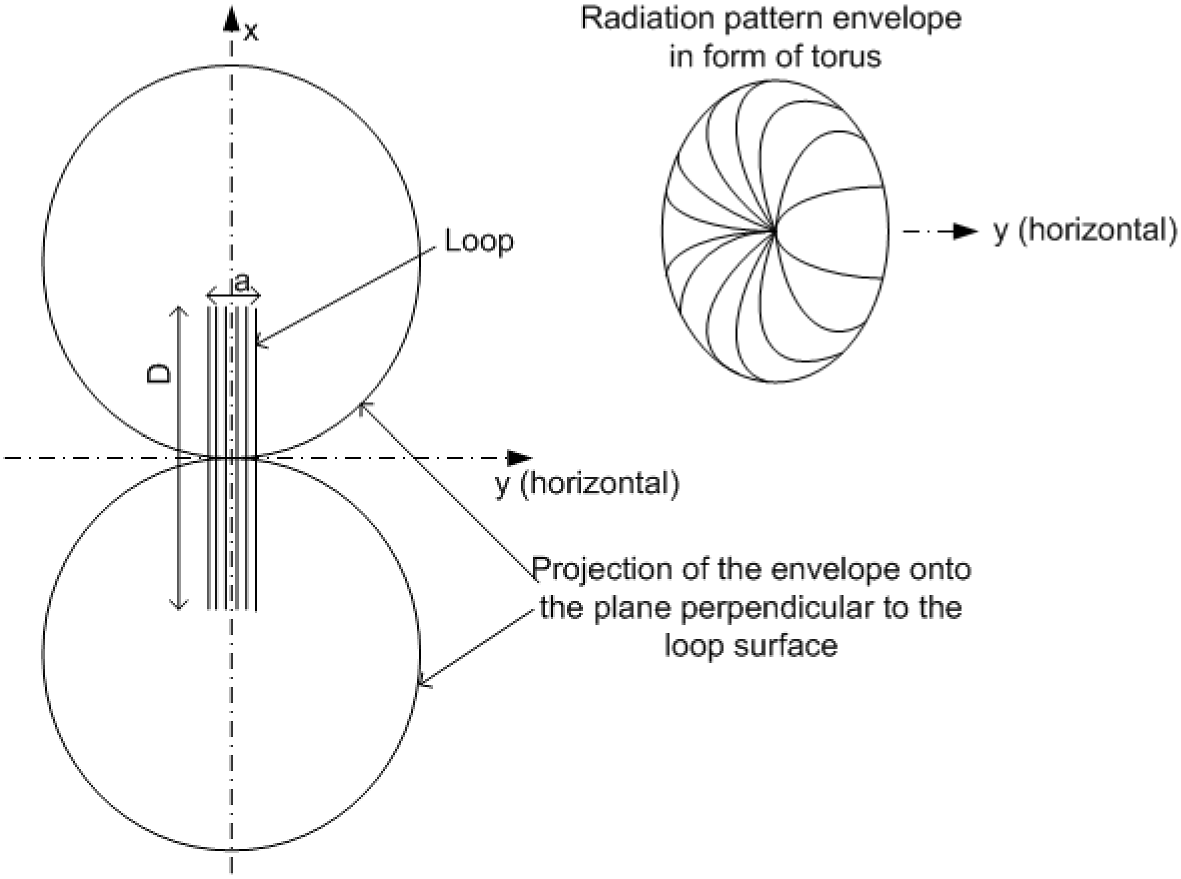


Figure 2

The best reception direction is horizontal, in the plane of the loop. Conversely, if the plane of the loop is perpendicular to the direction of propagation of a transmission, the loop will not receive it.

The received electric field (E) is assumed to be vertical, so the loops are necessarily in a vertical plane. For example, in Figure 3 below, the field directions are given for a square coil.
But the E field could be horizontal, and the antenna would then have to be in a horizontal position, but you have to choose carefully...

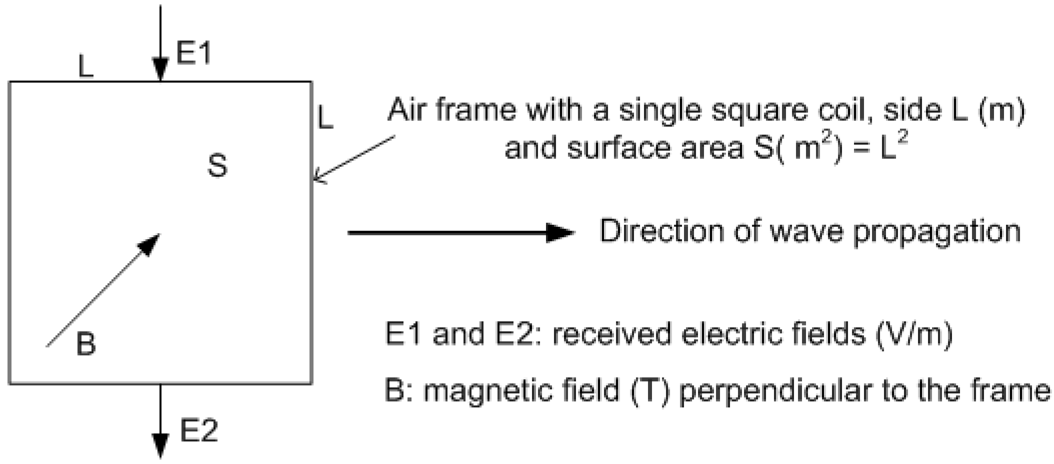


Figure 3

The copper coil acting as the secondary is 10 m long, 40 cm in diameter, and therefore consists of 7.96 turns.

The turns are spaced 3 cm apart (for no reason other than mechanical) and secured with two wooden planks, drilled, cut lengthwise, and then reassembled (see photo 1 below).

In existing single-turn constructions, the primary is a turn whose diameter is 5 times smaller than that of the secondary turn, so its surface area is 25 times smaller. Now we know that for a solenoid, the inductance is proportional to S (the surface area of the loop) and, roughly, to N^2 (N: number of turns). Therefore, with identical surfaces, if Ns is the number of turns of the secondary and Np that of the primary, it follows that Np/Ns must be equal to 1/√(25)=1/5, to maintain the same inductance ratio.
Therefore, ultimately, a crown of 2 m of 12/14 mm tube in the primary for 10 m of tube in the secondary will be perfect. The primary will be placed inside the secondary and fixed on the wooden boards (see photos 1 below), at the level of turns 3 and 4 of the secondary so as to take the magnetic flux of the secondary even at 14 MHz (with 4 turns short-circuited). Its diameter will be approximately 34 cm. The number of turns will be 1.87, or approximately 2 turns separated by 3 cm. We can already plan a loose coupling between primary and secondary.
We now need to tune the secondary section with one or two variable capacitors (Cv1 and Cv2 in Figure 1). Although it appears that the secondary is in parallel across the Cvs, this is not the case. In fact, we must imagine the generator between the inductor and the Cv(s). The secondary and the Cvs are in series (see [6]).
The value of the secondary inductance Ls can be estimated using the following practical formula from [7]: $Ls = \frac{S \times N^2}{\sqrt[3]{a} \times 12}$ with Ls in µH, S the loop cross-section in dm^2, and "a" the transverse length of the coil in cm (see Figure 2).
In our case, with D=4 dm, a=24 cm, and N=8, we find 23.2 µH.
But the simplest way is to measure it with an LC meter. Here we find 13.8 µH.

Note that for 30 and 20 m bands, the value of this inductance must be reduced. This is done by short-circuiting the last turn(s) of the secondary with a large-diameter conductor between two alligator clips connected to cable ties attached to the tube.

To tune the secondary to the desired frequency, Cv1 is used, which is between 1.0 and 23 pF, and Cv2 is used, which is between 22.5 and 521 pF (see Figure 1). Alligator clips are used for removable connections.

Note that the secondary has a certain parasitic capacitance.
According to a formula from [8], the parasitic capacitance Cp can be estimated as:

$$\mathrm{Cp} = 0.397 \times \sqrt[3]{\frac{2.63 \times 10^6 \times D^4}{a}}$$

With Cp in pF, D (diameter) in m, and a in m, as shown in Figure 2.
In our case, with D=0.4 m and a=0.24 m, we find Cp=26 pF.
However, it can be measured indirectly. Indeed, at resonance (minimum SWR), starting from the equation $Ls \times C \times (2 \times \pi \times f0)^2 \approx 1$ (from equation 6 in §3), we deduce C in pF, then Cp=C-Cv1 or Cp-(Cv1+Cv2). The author deduced that Cp is equal to approximately 18 pF.

> Note: the author has a SWR analyzer (also called a "Vector Network Analyzer," or "VNA"). Without this measuring instrument, it is difficult to develop an antenna.

For the 40, 30, and 20 m bands, only Cv1 is needed. For the 160, 80, and 60 m bands, Cv2 must be connected in parallel to Cv1, with Cv2 performing the coarse adjustment and Cv1 performing the fine adjustment.
Note that the author had to extend the Cv1 shaft with a shaft coupler and a plastic shaft (originally an insulated screwdriver) to avoid annoying hand effects.

Two photos (front and side) below show this (provisional) implementation.
You can see the small Cv1 in white with its long insulated shaft, and to its right, Cv2. Cv2 must be disconnected on both sides when not in use (for f≥7 MHz). You can see the secondary coil, and inside, the primary coil. In the profile picture, you can see the collars and crocodile clips for short-circuiting the coils. The setting here is for 7 MHz.

Photos 1

2.2 HF power, high voltage, and interference

It should be noted that in a series LC circuit, the voltage across the inductor and the Cv can be very high. It can be in the thousands of volts, depending on the power involved.

So be careful not to touch metal parts under voltage and prevent your pets from rubbing against this antenna...

The Cvs used here (Cv1 and Cv2) have a gap between the fixed and moving blades estimated at approximately 0.5 mm. For 0.5 mm, the maximum peak voltage before breakdown (electrical discharge producing a spark) should be approximately 2700 V. The maximum effective voltage should then undoubtedly be $1900\ V = \frac{2700\ V}{\sqrt{2}}$, but this is not certain in HF because breakdown is a complex ionization phenomenon that also has a thermal aspect. A conventional threshold will be set at 1900 V, but it could be between 1900 and 2700 V, or even less depending on the extent of the surface facing it and the roughness of the surfaces, this due to the peak effect (concentration of the electrostatic field) at the level of the micro-asperities.

The HF power must therefore be limited to avoid breakdown between a fixed and a moving blade of the Cv (see §3). Breakdown is not good for the Cv, disrupts transmission, and causes broadband interference.

> Note 1: in speech, if the gain is too high, breakdown occurs occasionally during modulation peaks.
>
> Note 2: one solution to achieve high voltages (5 kV or more) without breakdown and thus to support high HF power is vacuum Cv. See [2] and [4] on this subject.

Furthermore, in transmission, it seems that devices such as PCs or PC/XCVR interfaces tolerate electric fields better than magnetic fields, which could require lowering the transmission power. This is probably due to the fact that the electric field is rapidly absorbed by matter, unlike the magnetic field. This is also the reason why it is used, in VLF and LW, for underground near-field transmissions (<< 0.16 λ, see note below).

In all cases, to avoid failure of the PC or the PC/XCVR interface, ferrites must be installed on the various cables.

> Note: the electromagnetic field is formed at 0.16 λ, whether the starting point is a magnetic field (magnetic loop antenna) or an electric field (dipole antenna, for example), see [15] §2.

2.3 Adjustments

There are two adjustments to be made here:

- The resonance frequency with Cv1 and possibly with Cv1 and Cv2 in parallel. At resonance, the SWR displayed on the transmitter is normally minimal and close to 1. It should be noted that to reach resonance frequencies above 7 MHz (10 MHz for example), one or more turns are shunted to reduce the secondary inductance.
  Note that the optimum tuning (SWR close to 1) is only valid for the target

frequency. Below and above this frequency, the SWR increases. The measured bandwidth:

- varies between 7 kHz over 160 m and 47 kHz over 20 m, for a SWR ≤ 2 (i.e. 11% maximum reflected power),
- varies between 10.5 kHz over 160 m and 69 kHz over 20 m, for a SWR ≤ 3 (i.e. 25% maximum reflected power).

- Impedance matching is done by finding the best position on the primary. We should aim for a SWR close to 1.
  For each band, we have a specific setting. The author used a cable tie on one end and a large black crocodile clip on the other for the setting (see photo 1, front).

  Note: autotransformer operation was tested. This does not work because the setting depends on the coaxial power cable (length and shape of the cable).

2.4 Antenna efficiency

The antenna efficiency is written as $\rho = \frac{Rr}{Rr+Rp}$. This is explained in §3.
Note that R=Rr+Rp is the total series resistance.

Rr is the radiation resistance $Rr = \frac{31171 \times (Ns \times S)^2}{\lambda^4}$, where Ns is the number of turns in the secondary and S is the area of a loop in the secondary (m^2).
Rr can also be written as a function of the frequency f and the diameter D of a loop (in m): $Rr = 2.3738E - 30 \times (D \times f)^4 \times Ns^2$

Rp is, as a first hypothesis, the ohmic loss resistance of the secondary coil, which can be expressed as $Rp = \frac{\rho c \times Lf}{Sf}$ for a tube of length Lf (m) and cross-section Sf (m^2) and ρc=$1.7.10^{-8}$ Ω.m for copper.
The skin thickness in m is δ=$\sqrt{\frac{\rho c}{\pi \times f \times \mu 0}}$ ([13] page 305)
With respect to the Joule effect, half the skin thickness must be considered (see [13] page 692), treating the tube like a thin plate.

$\mathrm{Sf}\ (m^2) \approx \frac{\pi \times \mathrm{De} \times \delta}{2}$ with De the outer diameter of the tube, i.e. 0.014 m here.
For example, at 7.03 MHz, we have Rr=9.4E-3 Ω and Rp=0.628 Ω. The efficiency ρ would therefore be 1.5%.

> Note: another method for estimating the skin effect, called "Dowell" (see [14] pages 73 and following), used for transformer windings, could be used. It gives a resistance value comparable to the previous value. The resistance variation is also in $\sqrt{f}$.

Unfortunately, the resistance presented by the antenna's secondary is much greater. Antenna efficiency is generally based on the ohmic resistance because it is easily calculated. But in fact, based on [11] page 13, it is also necessary to take into account the loss induced on the ground and the equivalent series resistance of the variable capacitor, to which must be added the proximity effect between turns and possible eddy currents due to the variable magnetic field generated by the solenoid itself.

> Note: for an air Cv, the parallel insulation resistance is enormous and the series loss resistance (due to the loss angle of the Cv) is very low. Consequently, the air Cv can be neglected. We can, a priori, neglect the loss induced on the ground, the estimation and loss mechanism of which are not clear. There remains the proximity effect between turns and the eddy currents, which could only be determined with a simulation. A simple estimate does not exist (to the author's knowledge), but its value is certainly not negligible.

To estimate the actual series resistance R, we must start from the measured bandwidth. For example, at 7 MHz, we measure a bandwidth of 41.3 kHz for a SWR≤3 (i.e. 25% maximum reactive power), called $B_{ROS=3}$.
Starting from a generator with internal resistance Ri=50 Ω powering a load with active and reactive components, after a few calculations, we can deduce that for an active power at -3 dB (i.e. 50% reactive power), the bandwidth, called B_{-3dB}, is equal to $B_{-3dB} = \sqrt{3} \times B_{ROS=3}$, or 71.5 kHz in the example.

After other calculations based on the results of §3 (incorporating the simplification on the term in Lp, cf. equation 6), it can be shown that the quality factor Qa of this antenna is approximately equal to half that of the secondary solenoid Qs.
Considering that the secondary sets the resonant frequency of the antenna as a first approximation (see §3), it follows that $Qs = \frac{Ls \times w0}{R}$, and therefore:
$Qa = \frac{Ls \times w0}{2 \times R} = \frac{f0}{B-3dB}$ and since $w0 = 2 \times \pi \times f0$, we have: $\frac{Ls \times 2 \times \pi \times f0}{2 \times R} = \frac{f0}{B-3dB}$
We deduce that the total series resistance R is:
$R = B_{-3dB} \times \pi \times Ls = \sqrt{3} \times B_{ROS=3} \times \pi \times Ls$, or 3.1 Ω in our example. We deduce that at f0=7.03 MHz:

- The equivalent resistance Rp is: Rp = R – Rr = 3.09 Ω (instead of 0.628 Ω as previously determined, excluding the proximity effect and possible eddy currents),
- The actual antenna efficiency $\rho = \frac{Rr}{Rr+Rp}$ is 0.3% (instead of 1.5%)
- The antenna quality factor Qa is $Qa = \frac{f0}{B-3dB}$ = 98
- The secondary quality factor Qs is $Qs \approx 2 \times Qa$ = 196

Note: since $Qa = \frac{f0}{B-3dB}$, if Qa is known, then we deduce that
$B-3dB = \frac{f0}{Qa}$ and $R = \frac{f0 \times \pi \times Ls}{Qa}$

Note that the efficiency ρ increases with frequency.
The actual HF power transmitted will be equal to the product of the transceiver's output (active) power and the efficiency. The remainder, i.e. the vast majority of the active power, will be dissipated as heat.

Note that the SWR slowly degrades as the transmitted HF power increases, without any possible correction. This is likely related to nonlinearities in the antenna elements. However, the exact cause is unknown.

3. Physical justification of the operation of this antenna

Figure 1 defines three blocks: the HF generator, the transformer, and the load (i.e. the Cv(s)).

The justification is based on Chapter V of the book in [9] ("Magnetic Coupling"). The model used corresponds to the ironless transformer on page 104 of [9]. You can also refer to book [10], pages 76 and 77. This model has the advantage of comparing the transformer to a quadrupole. It amounts to considering the magnetic effect of solenoid 1 on solenoid 2 (Lenz-Faraday law), then the effect of solenoid 2 on solenoid 1, via the mutual inductance M between the two solenoids. Note that "iron" losses (eddy currents here) are not taken into account. Similarly, the parasitic capacitance of the primary is neglected and is not shown.

In Figure 4 below, we model the complete set:

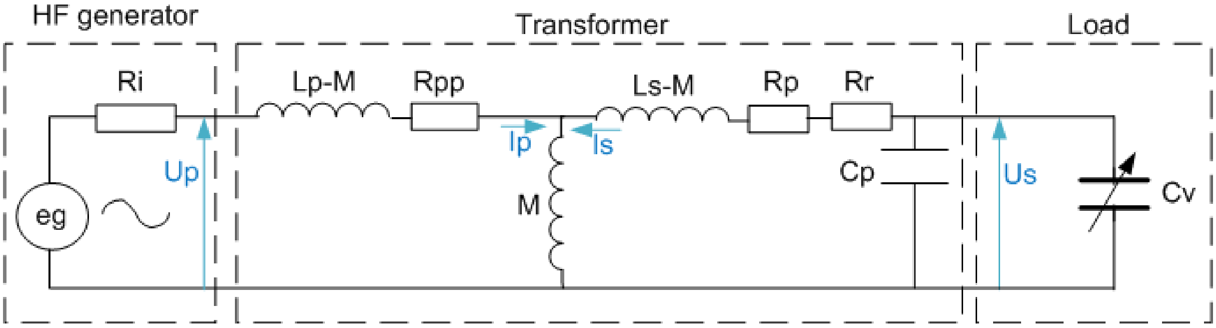


Figure 4

In the following, we neglect Rpp (the primary loss resistance) compared to the internal resistance of the generator (50 Ω).
Rp is the secondary loss resistance and Rr is the radiation resistance. They can be combined in the series resistor R (R=Rr+Rp). Cv can correspond either to Cv1 alone or to Cv1 and Cv2 in parallel. Cp is the secondary parasitic capacitance. Cv and Cp can be combined in a capacitor C.
We therefore obtain a simpler diagram in Figure 5.

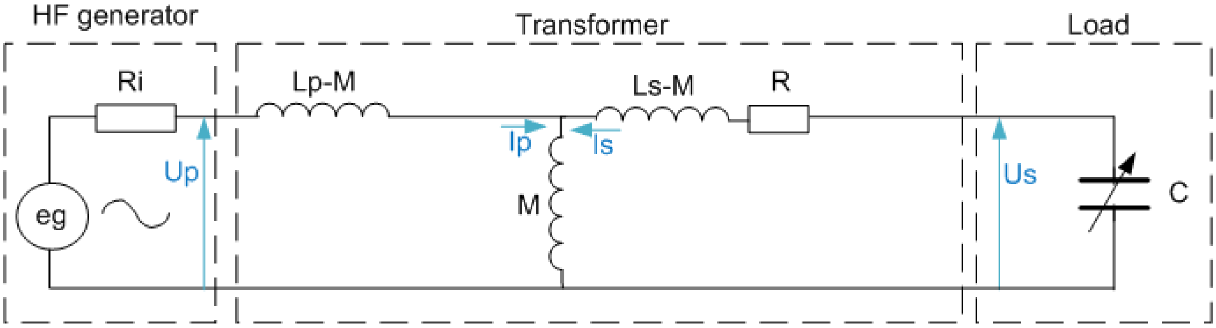


Figure 5

The transformer equations are:

$$Up = \frac{(Lp-M)\times d(Ip)}{dt} + \frac{M\times d(Ip+Is)}{dt}$$ (for the primary loop)

$$Us = R \times Is + \frac{(Ls-M)\times d(Is)}{dt} + \frac{M\times d(Ip+Is)}{dt}$$ (for the secondary loop)

Considering a harmonic analysis (i.e. based on sinusoids), we convert to complex numbers with:

$Ip = |Ip| \times \exp(j(w \times t + \varphi p))$ and $Is = |Is| \times \exp(j(w \times t + \varphi s))$
Therefore $\frac{d(Ip)}{dt} = j \times w \times |Ip| \times \exp(j(w \times t + \varphi p))$, with w being the angular frequency ($w = 2 \times \pi \times f$). We simplify the notation by writing: "$j \times w \times Ip$" for "$j \times w \times |Ip| \times \exp\left(j(w \times t + \varphi p)\right)$". The same applies to Is.

So for the transformer we have:
$Up = (Lp - M) \times j \times w \times Ip + M \times j \times w \times (Ip + Is)$
$= Lp \times j \times w \times Ip + M \times j \times w \times Is$ (equation 1)
$Us = R \times Is + (Ls - M) \times j \times w \times Is + M \times j \times w \times (Ip + Is)$
$= R \times Is + Ls \times j \times w \times Is + M \times j \times w \times Ip$

For the load we have: $Us = \frac{-Is}{j \times C \times w} = \frac{j \times Is}{C \times w}$ (equation 2)
So, with respect to Us we have :
$Us = \frac{j \times Is}{C \times w} = R \times Is + Ls \times j \times w \times Is + M \times j \times w \times Ip$ therefore
$R \times Is + Ls \times j \times w \times Is - \frac{j \times Is}{C \times w} + M \times j \times w \times Ip = 0$ or

$$Is \times (R + Ls \times j \times w - \frac{j}{C \times w}) + M \times j \times w \times Ip = 0$$

Hence

$$Is = \frac{-(M \times j \times w \times Ip)}{\left(R + Ls \times j \times w - \frac{j}{C \times w}\right)} = \frac{-(M \times j \times w \times Ip)}{(\mathrm{R} + \mathrm{j} \times (\mathrm{Ls} \times \mathrm{w} - \frac{1}{\mathrm{C} \times \mathrm{w}}))}$$

$$Is = \frac{\left[-(\mathrm{Ls} \times \mathrm{w} - \frac{1}{\mathrm{C} \times \mathrm{w}}) \times (M \times w \times Ip)\right] - (j \times R \times M \times w \times Ip)}{\left(R^2 + (Ls \times w - \frac{1}{C \times w})^2\right)}$$

Therefore

$$\frac{Is}{Ip} = \frac{\left[-(\mathrm{Ls} \times \mathrm{w} - \frac{1}{\mathrm{C} \times \mathrm{w}}) \times (M \times w)\right] - (j \times R \times M \times w)}{\left(R^2 + (Ls \times w - \frac{1}{C \times w})^2\right)}$$ (equation 3)

The input impedance (Ze) seen by the HF generator is equal to $Ze = \frac{Up}{Ip}$. So starting from equations 1 and 2, we find after some developments:

$$Ze = \frac{\left[\langle \mathrm{R} \times (\mathrm{M} \times \mathrm{w})^2 \rangle + \mathrm{j} \times \langle (\mathrm{Lp} \times \mathrm{w}) \times \left(R^2 + (Ls \times w - \frac{1}{C \times w})^2\right) - (\mathrm{M} \times \mathrm{w})^2 \times (Ls \times w - \frac{1}{C \times w}) \rangle\right]}{\left(R^2 + (Ls \times w - \frac{1}{C \times w})^2\right)}$$ (equation 4)

At resonance (w=w0) we no longer have a reactive component but only an active component, therefore necessarily, from equation 4:

$$(\mathrm{Lp} \times \mathrm{w0}) \times \left(R^2 + \left(Ls \times w0 - \frac{1}{C \times w0}\right)^2\right) - (\mathrm{M} \times \mathrm{w0})^2 \times \left(Ls \times w0 - \frac{1}{C \times w0}\right) = 0$$

(equation 5)

There is no trivial solution to this equation due to the term:
$(\mathrm{Lp} \times \mathrm{w0}) \times \left(R^2 + (Ls \times w0 - \frac{1}{C \times w0})^2\right)$. We will neglect this term, which will be considered zero. The solution to the rest of equation 5:

$(\mathrm{M} \times \mathrm{w0})^2 \times \left(Ls \times w0 - \frac{1}{C \times w0}\right) \approx 0$ is given by $\left(Ls \times w0 - \frac{1}{C \times w0}\right) \approx 0$
This is obviously not the exact solution, but an approximate one.

> Note 1: it has been experimentally verified that a modification of Lp, by increasing the primary from 0.5 to 1.83 loops, does indeed vary the resonant frequency (as predicted by equation 5). But the frequency variation found is low (2% during the experiment), which justifies the hypothesis made.
>
> Note 2: this simplification will allow us to estimate the mutual inductance M and then the coupling coefficient K (see below), without needing a specific physical equation. It will also allow us to calculate Cp (see §2.1), then Qs and Qa (see §2.4).

From $\left(Ls \times w0 - \frac{1}{C \times w0}\right) \approx 0$, we deduce: $\mathrm{f0} \approx \frac{1}{2 \times \pi} \times \sqrt{\frac{1}{\mathrm{C} \times \mathrm{Ls}}}$ (equation 6).
Therefore, the antenna's resonant frequency is equated to the secondary's resonant frequency.

Starting from equation 4, we have at resonance (w=w0):

$$Ze = \frac{\mathrm{R} \times (\mathrm{M} \times \mathrm{w0})^2}{\left(R^2 + (Ls \times w0 - \frac{1}{C \times w0})^2\right)}$$ (real value)

To have a perfect adaptation to the emitter and therefore a SWR close to 1, it is necessary that: Ze=Ri=50 Ω, or: $\frac{\mathrm{R} \times (\mathrm{M} \times \mathrm{w0})^2}{\left(R^2 + \left(Ls \times w0 - \frac{1}{C \times w0}\right)^2\right)} = 50$ (equation 7)

Given the simplification made to equation 5, we have
$\left(Ls \times w0 - \frac{1}{C \times w0}\right)^2 = 0$ and therefore we have $Ze \approx \frac{(\mathrm{M} \times \mathrm{w0})^2}{R} \approx 50$ (equation 8)
We therefore deduce that $M \approx \frac{\sqrt{50 \times R}}{w0}$
As $M = K \times \sqrt{Lp \times Ls}$, and Lp, Ls and M are known, we can deduce the coupling coefficient $K = \frac{M}{\sqrt{Lp \times Ls}}$ (see [9] page 97).

> Note: if K, M, and Ls are known, we can deduce Lp: $Lp = \frac{M^2}{Ls \times K^2}$

Starting from equation 3 and still using the same simplification, we have at resonance: $\frac{Is}{Ip} \approx \frac{-j \times M \times w0}{R}$

Nevertheless, basic equations 5 and 7 depend on Ls, Lp, K, and R.
So if, for given parameters Lp, Ls, K, and R, we adjust C to satisfy equation 5, there is little chance of satisfying equation 7 on the first try. However, by successive approximation, we would eventually find an ideal Lp at f0.
The problem is that for a different frequency f0, to satisfy equations 5 and 7 simultaneously, the values of Lp and C will be different.

Note 1: Equations 5 and 7 form a system of two equations with two unknowns (C and Lp), with the other parameters (Ls, K, R, and w0) assumed to be known. Therefore, for a given w0, there is a particular pair of solutions (C and Lp).

Note 2: the Lp term was neglected in equation 5 because its influence was small. Therefore, it is likely that from one band to another, the ideal Lp values will differ little, and that the SWR remains acceptable (say, SWR ≤ 2), at a constant Lp. However, between the extreme bands (60 m and 10 m, for example), it is unlikely that an Lp adjustment can be avoided. Of course, if the antenna is intended for a single band, no adjustment will be necessary.

There are two solutions for adjusting Lp (modulo the note 2 above):

1. Either move the tap on the primary, if there are multiple loops, as in §2,
2. or modify the value of Lp with an adjustable capacitor ("Ca") in series with Lp (for a single-loop primary), as in §4. The Ca setting is valid for one band, but it changes from one band to another. Some tests show that the ideal Lp tends to decrease with frequency (i.e. the higher the frequency, the smaller the primary diameter should be). Therefore, Lp will be dimensioned for the lowest frequency ("Lp_{fmin}") and will be compensated with Ca for very high frequencies.

The general diagrams of the antenna ("transformer" + "load") in the two cases above are given in Figure 6 below. The indices used are: "s" for "secondary", "p" for “primary”, "v" for "variable," and "a" for "adjustable."

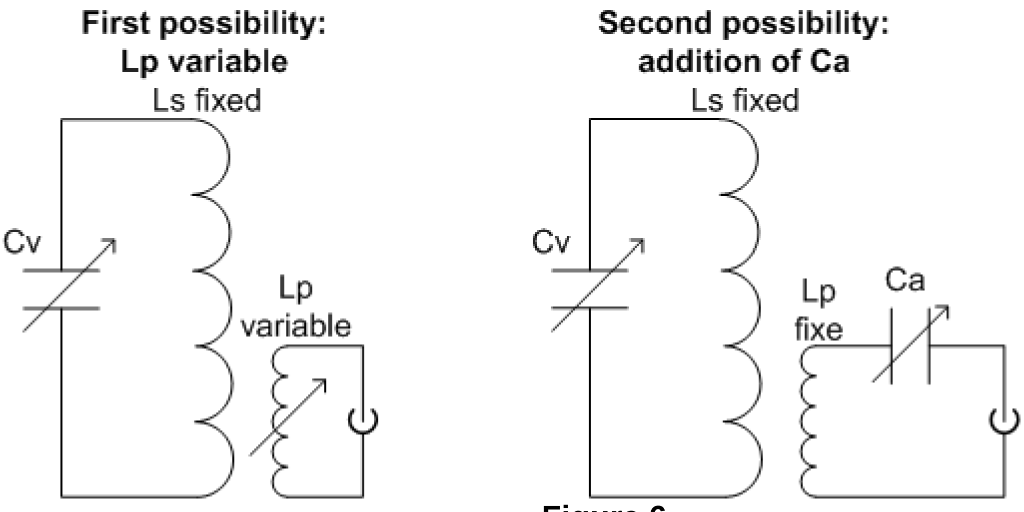


Figure 6

Moreover, the power (Ps) consumed by the antenna (at resonance) is equal to:

$Ps = \frac{Up^2}{Ze}$, hence $Ps \approx \frac{Up^2}{\frac{(M\times w0)^2}{R}} = R \times \left(\frac{Up}{M\times w0}\right)^2$

This justifies what was said previously about antenna efficiency:

$\rho = \frac{Rr}{Rr+Rp}$ with R=Rr+Rp

Example at f=7.03 MHz, at resonance

We know (see §2.4) that Rr=9.4E-3 Ω, Rp=3.09 Ω (§2.4) and R=Rr+Rp=3.1 Ω, the efficiency being 0.3%.

We assume that the transmitted power Ps is 10 W with a SWR of 1 (i.e. Ze=50 Ω) for f=7.03 MHz, or w0=4.417 E7 pulses/s.

From $Ps = \frac{Up^2}{Ze}$, we deduce that $Up = \sqrt{Ps \times Ze}$ = 22.36 V.

Note: the voltage and current values are effective values.

We know that $M \approx \frac{\sqrt{50 \times R}}{w0}$ = 2.82 E-7 H, or 0.282 µH.
Moreover, we measured Lp=1.28 µH for the portion of the primary used at 7 MHz.
With Ls=13.8 µH and Lp=1.28 µH, we deduce K=6.7% ($K = \frac{M}{\sqrt{Lp \times Ls}}$) which constitutes a loose magnetic coupling, normal for this type of transformer. Note that ferrite transformers, on the other hand, have a coefficient K close to 1.
Starting from $Ze = \frac{Up}{Ip}$, we deduce that at resonance, Ip=Up/50=0.447 A.
Furthermore, $\frac{Is}{Ip} \approx \frac{-j \times M \times w0}{R}$ so $Is \approx \frac{-j \times M \times w0 \times Ip}{R}$, or Is≈1.80 A.

At resonance, we have $Ls \times C \times w0^2 \approx 1$, so $C \approx \frac{1}{Ls \times w0^2}$ = 3.714 E-11 F, or 37.1 pF.
As $Us = \frac{j \times Is}{C \times w0}$ (equation 2), we deduce that at resonance, the effective voltage Us across the terminals of C and therefore of Cv is equal to 1095 V. In fact, at 10 W we do not break down, but at 50 W we break down, because at this power Us=2450 V, which is higher than the breakdown threshold of approximately 1900 V (see §2.2).

4. Description and experimentation on the second antenna

4.1 Limiting the number of loops and tube length

1) Let us show that, for a given tube length "Lt", it is advantageous to have a single loop. Indeed, in the previous case, with lt = 10 m, we have a number of loops Ns = 7.96. The radiation resistance RrNs is $RrNs = \frac{31171\times(Ns\times S)^2}{\lambda^4}$

At a constant Lt, if we switch to a single loop, the initial diameter is multiplied by Ns and the surface area S by Ns^2. In this case, the radiation resistance is equal to $Rr1 = \frac{31171\times(S\times Ns^2)^2}{\lambda^4}$. We see that $\frac{Rr1}{RrNs} = Ns^2$

Since the loss resistance Rp is probably proportional to Lt, it follows that at a constant length Lt, the radiation resistance and antenna efficiency are Ns^2 times greater with one loop than with Ns loops.

The problem is that for Lt=10 m, a loop with a diameter of 3.2 m would be required...

2) Let us show that we must limit the tube length Lt and therefore the value of Ls to increase the frequency.

Indeed, we naturally cannot make the antenna, with a Cv in series, resonate at a frequency higher than the loop's own resonant frequency f0p. Now, this one is approximately defined by (see §3, equation 6):

$f0p \approx \frac{1}{2\times\pi} \times \sqrt{\frac{1}{Cp\times Ls}}$ with Cp being the antenna's parasitic capacitance and Ls being the secondary inductance.

For the first antenna with a tube length of 10 m and approximately 8 turns, f0p is 10 MHz for an Ls value of 13.8 µH. A test was conducted with a tube length of 4.9 m and two turns: f0p rises to 14.3 MHz for an Ls value of 5.94 µH.

For a tube length of 2.45 m and a single turn, f0p rises to 31.7 MHz for an Ls value of 1.99 µH.

It is clear that if one wishes to work on high bands (for example, the 10 m band), the tube length must be limited.

4.2 Description of the second antenna

The proposed antenna has a single loop, on both the secondary and primary sides. The schematic diagram of the transmitting antenna (i.e. transformer + load) is as follows (Figure 7). Note that the impedance matching is performed with an adjustable capacitor Ca (see Figure 6, diagram on the right), which can be short-circuited for frequencies less than or equal to 10 MHz.

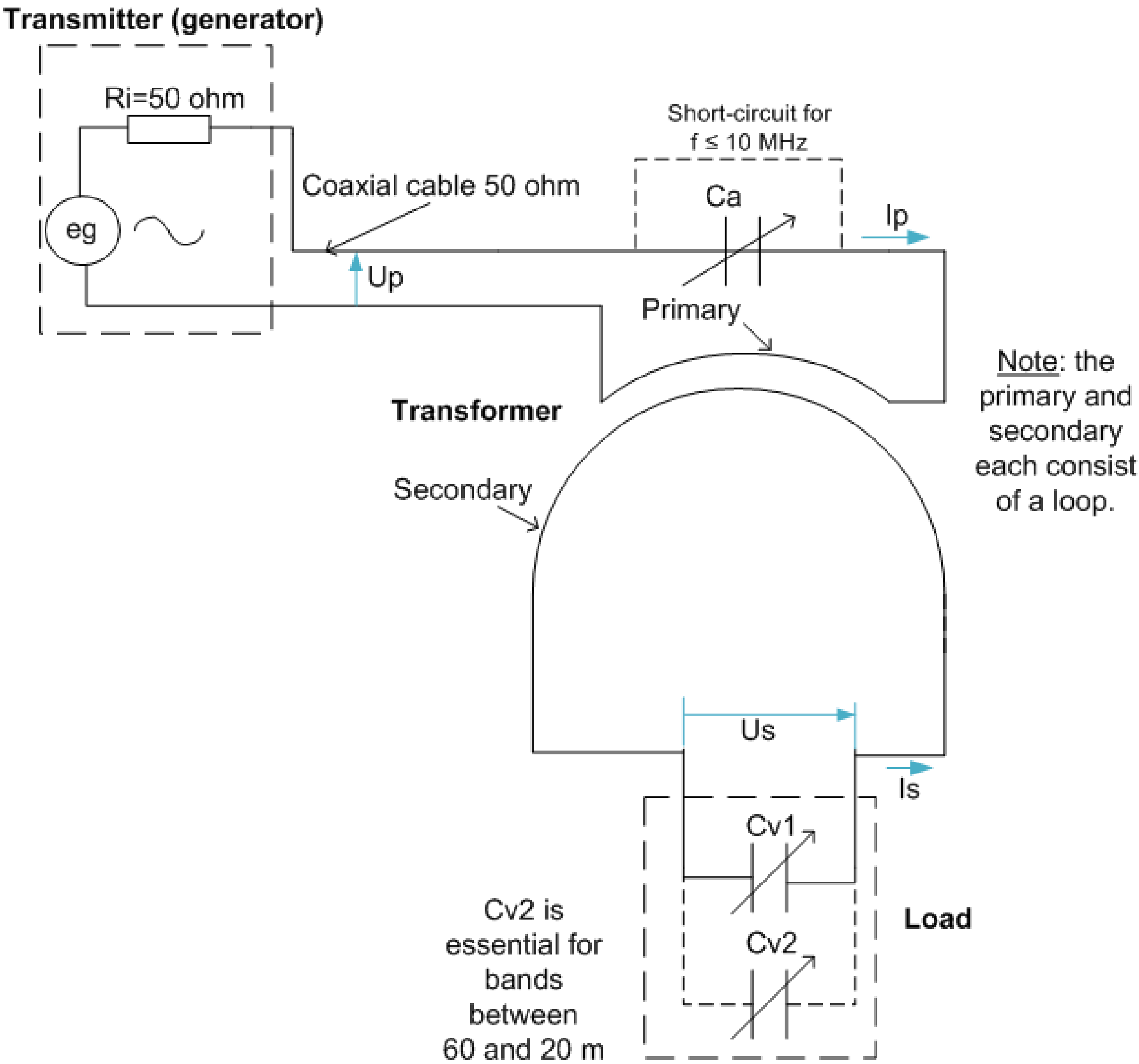


Figure 7

This antenna operates in bands between 60 and 10 m.
The primary loop has a diameter of 0.27 m. It is not a copper tube, but a large, bare coaxial cable flexible enough to allow its diameter to be modified during impedance matching tests. Its inductance Lp is 0.53 μH.
The secondary loop has a diameter (D) of 0.78 m . Its inductance Ls is 1.99 μH.

> Note: the measured inductance values (Ls and Lp) are consistent with the formula given in [12]: $L = \mu 0 \times \left(\frac{D}{2}\right) \times \left(\ln\left(4 \times \frac{D}{a}\right) - 2\right)$, where a is the radius of the tube (0.007 m) for Ls or the coaxial cable (0.004 m) for Lp.

To tune the secondary to the desired frequency, we have Cv1 which is between 1.0 and 23 pF and Cv2 which is between 22.5 and 521 pF. Cv2 is essential for bands between 60 and 20 m. On 20 m we need the minimum capacitance of Cv2 (22.5 pF) but 320 pF on 60 m (with Cv1 at maximum).
To match the impedances, Ca is available, which ranges from 22 to 666 pF. On Ca, there is no high-voltage problem as on Cv1 and Cv2. Ca is not necessary for bands between 60 and 30 m and is optional for the 20 m band (the minimum SWR is 1 with

Ca and 1.7 without). For information, at 14.05 MHz, Ca is set to 549 pF, while at 29.7 MHz, it is set to 31 pF (Ca decreases as the frequency increases).

Note: crocodile clips are used for removable connections.

The $B_{ROS=3}$ band ranges from 14.5 kHz at 5.368 MHz to 269 kHz at 29.7 MHz, including 76 kHz at 18.1 MHz.

Experimentally, assuming that the parasitic capacitance Cp1 of a loop is proportional to the diameter (not verified), we can approximate Cp1 (in pF) by:
$Cp1 = \frac{D}{0.78} \times \left[\left(\left(\frac{31.7}{fM} \right)^{2.02} \times 2.6 \right) + 10 \right]$ where D is the diameter in m and fM is the frequency in MHz. Cp1 decreases as the frequency increases.

The antenna quality factor Qa (dimensionless) decreases with frequency. It can be roughly approximated, with fM being the frequency in MHz, by:

$$Qa = \left(\frac{29.7}{fM} \right)^{0.5 + (\frac{fM}{29.7})} \times 63.8$$

The total series resistance R (equal to R = √3 x $B_{ROS=3}$ x π x Ls = f0/Qa x π x Ls, see §2.4) increases with frequency (to the power of about 1.5), but the radiation resistance increases even faster with frequency (to the power of 4), resulting in efficiencies that vary between 0.9% at 40 m and 23.5% at 29.7 MHz, passing through 2.35% at 30 m and 15% at 15 m.
The base losses compared to an unshortened antenna are therefore quite high (for example, -16.3 dB at 30 m and -8.2 dB at 15 m).

Note: the change to the power of 1.5 of the total series resistance is probably due to eddy currents in the thickness of the skin, induced by the variable magnetic field generated by the loop itself.

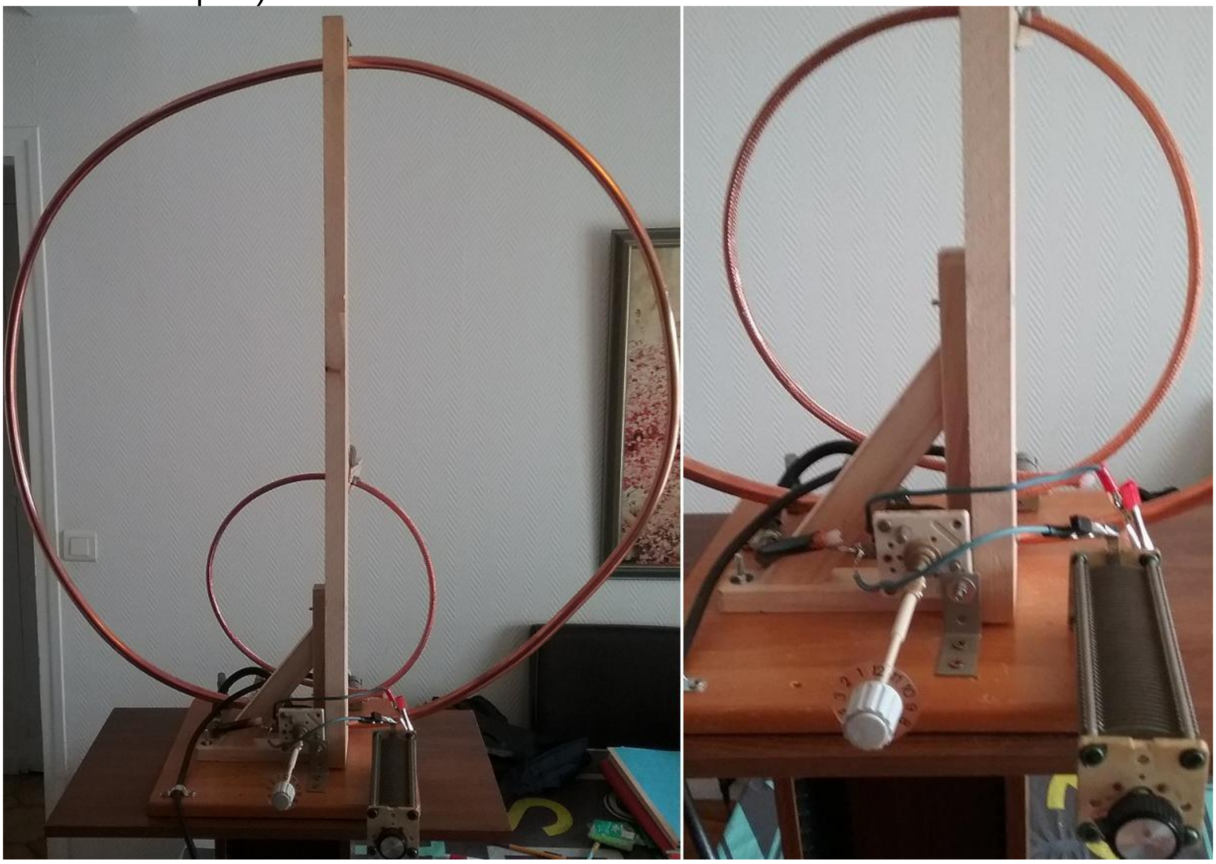
Note that the calculated voltage across the variable capacitors is less than or equal to 776 V for 10 W at 21 MHz. We could therefore work at 60 W for a breakdown threshold of 1900 V (see §2.2). In fact, up to 100 Watts (corresponding to Us = 2450 V), the author did not observe any breakdown on Cv1 at 21 MHz.

Note: the advantage of Cv1 is that it has only two moving plates and two fixed plates, so the facing surface is small (especially at 21 MHz and even more so at 28 MHz), which reduces the probability of breakdown compared to Cv2, which has many facing plates.

It should be noted that the calculated average coupling coefficient K is 6.4%, with a 20% variation depending on the frequency. Based on the results, we approximate K with the formula $K(\%) = 5.5 \times \left(Sup\left(\frac{f(MHz)}{18.1},\ 1, \frac{18.1}{f(MHz)} \right) \right)^{0.31}$

Note: this slight variation in K with frequency may not be physical but due to accumulated errors.

Photo 2 below shows what this antenna looks like. It shows the primary (copper tube) and secondary (bare coaxial cable) loops, Cv1 with its extended axis, and Cv2 connected to Cv1 by crocodile clips. In the background, the right-hand photo shows the "adjustable" capacitor Ca (which is actually a small standard variable capacitor with a demultiplier).



Photos 2

4.3 Sizing the single-loop antenna

<u>4.3.1 Practical Method</u>

<u>Determining the diameter D of the secondary loop</u>

A rough calculation based on the estimates of the parasitic capacitance Cp1 and the inductance Ls (see §4.2) shows that, knowing the maximum frequency fMax in MHz that we wish to achieve, the maximum diameter Dsec (in m) of the secondary loop must be of the order of $Dsec = \frac{24.7}{fMax}$. This dimension corresponds to the resonance frequency of the single loop at fMax. This maximum diameter value gives a loop perimeter approximately equal to λ/4, which means that the behavior will be as expected for this type of antenna in terms of directivity (see Figure 2). However, the effective diameter must be smaller than $Dsec = \frac{24.7}{fMax}$, taking into account the minimum Cv (from “Cv1” in Figure 7) added to Cp1.

> <u>Note 1</u>: Cv1 should be a low-capacitance variable capacitor (for example, minimum Cv = 1 pF and maximum Cv = 23 pF), but with the blades as widely spaced as possible, due to the high voltages generated (several thousand V depending on the HF power). 0.5 mm between the fixed and moving blades is

the minimum. Cv1 is used for high-frequency tuning and for fine-tuning at low frequencies.

Note 2: the Cv1 + Cv2 assembly could be replaced by a vacuum capacitor with a demultiplier, but it's quite expensive... If it were also remotely controlled, that would be ideal. Note that some DIY Ham enthusiasts make their own high-voltage capacitors.

First, the primary loop diameter (Dpri) will be set at 20% of the secondary loop diameter (Dsec). For both the primary and secondary loops, a large, stripped coaxial cable can be used (at least initially) for testing. At the end of the tests, the secondary loop coaxial cable will be replaced with copper tubing (e.g., 12/14 mm).
At this point, the setup in Figure 7 is complete except for Cv2 (necessary only at low frequencies) and Ca, which will be sized at the end.

Since antenna efficiency increases with the diameter Dsec, the largest possible diameter Dsec for the specified maximum frequency fMax and the minimum Cv (from "Cv1") will need to be determined experimentally. To do this, we start with $Dsec = \frac{24.7}{fMax}$. With the transmitter, we generate an FM carrier at the frequency fMax and at low HF power (say less than 5 W), and we gradually reduce the diameter Dsec, until a minimum ROS is obtained at the frequency fMax. Be careful of the high voltage on the secondary loop and on Cv1.

Note 1: this SWR will be minimal but probably far from SWR=1, which is normal at this level of sizing because the impedance matching has not yet been done. This will be done when the final primary loop and the adjustable capacitor Ca have been installed. This simply involves adjusting the resonant frequency of the secondary loop to fMax.

Note 2: of course, a VNA or an HF generator can also be used in place of the transceiver in FM, the aim being to generate a low-power carrier. The advantage of the transceiver is that it (usually) has its own SWR meter. Now, a VNA with low latency and displaying the SWR to two decimal places would be ideal.

Note 3: an analog SWR meter is preferable to a digital SWR meter due to the latency of the latter type of device. Furthermore, it is generally easier to discern a small variation in SWR on an analog device.

Determining the maximum Cv

At this point, Cv1 and Cv2 have been mounted (see Figure 7), but Ca is still not mounted (or it is short-circuited).

Note: Cv2 should be a large-capacity variable capacitor (e.g., 20 to 500 pF), with the blades as widely spaced as possible (0.5 mm between fixed and moving blades being the minimum). Cv2 is used for coarse adjustment at low frequencies, while Cv1 is used for fine adjustment at these low frequencies.

With Cv1 set to its maximum capacity, we will verify that Cv2 allows the resonant frequency to be adjusted to the lowest expected frequency (fmin). To do this, with our transmitter, we generate an FM carrier at frequency fmin and at low power, and we ensure that we can achieve a minimum SWR with Cv2. If Cv1 and Cv2 are at their maximum capacity but no minimum SWR has occurred, we will need to increase the capacity of Cv2.

Determining the primary loop diameter

At this point, Ca is still not mounted (or it is short-circuited). We continue to generate a carrier at fmin.

We use a large, stripped coaxial cable for testing the primary loop, which we can keep at the end of the tests or, if necessary, replace with a copper tube.

The diameter of the primary loop Dprim must be sized for the lowest frequency (fmin). We must obtain a ROS equal to or very close to 1. We will start with a diameter equal to or greater than 20% of the diameter of the secondary loop and we will increase it little by little until we obtain a ROS=1. Be careful to turn off the generator before touching the primary loop.

Sizing the "adjustable" capacitor Ca

Ca must be a large-capacity variable capacitor (e.g., 20 to 500 pF). Since there are no high-voltage issues with this capacitor, a standard variable capacitor will do. Ca is used for impedance matching between the transmitter's 50 ohm output and the antenna's resistance. Capacitor Ca artificially reduces the size of the primary loop (see Figure 6).

For this test, with the transmitter in FM, we will generate a carrier at a variable frequency starting at frequency fmin and ending at the highest frequency (fMax).

At the lowest frequency (fmin), Ca is short-circuited. We check that the SWR is equal to or very close to 1.
Then we increase the frequency by changing the amateur band (e.g., going from 7 to 10 MHz). We adjust Cv1+Cv2 for the minimum SWR. If this ROS is equal to or close to 1, Ca remains short-circuited.

We continue in this way, increasing the frequency. At some point, we will no longer be able to achieve a SWR of 1. We will then have to commission Ca and adjust it for a SWR of 1, probably with a relatively large capacitance.
Then, as the frequency increases, the capacitance of Ca will have to be reduced. At the highest frequency (fMax), we will ensure that Ca has a sufficiently low capacitance to achieve a SWR of 1. If the minimum SWR is not very good (say, >1.5), we will either have to replace Ca with a variable capacitor with a lower minimum capacitance, or slightly reduce the diameter of the primary loop, but in this case, we will have to repeat the entire Ca test.

Miscellaneous notes

- Once the assembly and sizing are complete, note the approximate settings for each amateur band. This will save time later.

- At low frequencies (for those where Ca is not used), if you are not too particular about the SWR and given the low bandwidth of this type of antenna, you can adjust the Cvs (Cv1+Cv2) "by ear" based on the "maximum receive noise level" criterion, with the receiver tuned to the desired frequency, in SSB mode. The level will increase sharply when the correct setting for Cv1+Cv2 is reached.

- As soon as the HF power is increased, you must ensure that there are no sparks at Cv1 and Cv2. Note that even if you can't see the sparks, you can hear them. If necessary, limit the HF power to avoid these breakdowns.

- It should be noted that the SWR degrades beyond a certain HF power threshold (approximately 50 W HF). It is possible to increase the SWR to 1.5 or even 2 by increasing the power from this threshold. The author is not clear on the explanation (non-linearity or the onset of ionization without breakdown in the Cv). In this case, the HF power will be limited to the SWR degradation threshold (50 W a priori).

4.3.2 Computer calculation method

The appendix proposes a procedure in Delphi 6 (Pascal) for theoretically sizing a single-loop antenna, with the secondary loop being made of 12/14 mm copper tubing. Note that a different tube diameter would modify the estimates of Qa, R, K, Cp1, Ls, M, etc.
The proposed calculations are derived directly from the previous chapters of this document, except for the calculation of Ca (Ca min and Ca max), which is described below.

The results provided by this procedure are guidelines for a starting configuration, which will then need to be refined. Note that no public program is associated with this procedure. This is simply information.

Calculation of Ca
This calculation is very imprecise, probably because it is based on results that are already insufficiently precise, or perhaps because the model is too simple, particularly the parasitic capacitances of the primary and the coaxial cable between the transceiver and the antenna primary, which have not been taken into account.

At resonance (w=w0), for simplicity, let's write $A = Ls \times w0 - \frac{1}{C \times w0}$
and $B = (M \times w0)^2$
Equation 5 becomes $(Lp \times w0) \times (R^2 + A^2) - (B \times A) = 0$
Equation 7 becomes $\frac{R \times B}{R^2 + A^2} = 50$

We find $A = (+or\ -)\sqrt{\frac{R \times B - 50 \times R^2}{50}}$

If the term under the root is less than 0 (unphysical), this means that Ze is less than 50 ohms (to have at least A=0) and therefore we do not need a capacitor Ca.

Otherwise, $Lp = \frac{B \times A}{w0 \times (R^2 + A^2)}$ (formula 1). The term "A" must be positive to remain physical (Lp>0).

Before calculating Ca, we will have dimensioned Lp at the lowest frequency ("Lp_{fmin}"): starting from $K = \frac{M}{\sqrt{Lpfmin \times Ls}}$, we deduce $Lpfmin = \frac{M^2}{Ls \times K^2}$.

We will calculate "Lp_f" using formula 1, for a given HF frequency ("f"). "Ca" will compensate for the difference Lp_{fmin} - Lp_f. "Ca" at f will therefore be sized so that:

$(Lpfmin \times 2 \times \pi \times f) - (Lpf \times 2 \times \pi \times f) = \frac{1}{Ca \times 2 \times \pi \times f}$ or:

$Ca\ at\ f = \frac{1}{(2 \times \pi \times f)^2} \times \frac{1}{(Lpfmin - Lpf)}$.

We will test the desired frequency spectrum in 100 KHz steps and extract the values of Ca min and Ca max with their corresponding frequency.

Procedure results

We provide the desired minimum and maximum frequencies in MHz, then the minimum capacitance in pF of the variable capacitor available, as well as the outer radius of the tube or primary coaxial cable in mm.

For example, for an antenna covering a frequency range from 10.1 MHz to 52 MHz, with a minimum Cv of 1 pF and a radius of the primary loop coaxial cable of 4 mm (i.e. the parameters: (10.1,52,1,4)), we obtain the following results:

- Secondary loop diameter: 0.476 m
- Secondary loop inductance: 1.080 µH
- Maximum Cv value: 208 pF
- Primary loop diameter: 0.258 m
- Primary loop inductance: 0.575 µH
- Ca max: 95 pF at 22.3 MHz
- Ca min: 25 pF at 42.3 MHz

Other results, such as efficiency or bandwidth at a given frequency, are not calculated, but could easily be added.

Note: the antenna given in this example has not been tested.

5. Conclusion

A few tests conducted with a nearby Ham, with the aim of comparing this antenna with a short vertical whip-type antenna, seem to indicate that it is superior, at equal transmission power and if properly oriented. Moreover, a quick calculation indicates that the efficiency of the whip antenna is lower than that of the magnetic antenna, regardless of frequency. However, a true comparison would require a protocol, precise measurements, and a clear space, beyond the scope of the author.
A definite advantage is that tuning a whip antenna is time-consuming because the length of the sliding strand must be adjusted until the correct SWR is obtained, whereas tuning variable capacitors is simpler and faster (if you can see the SWR meter).

Like the whip antenna, it doesn't take up much space, which is useful on a balcony. Furthermore, it covers all frequencies between its minimum and maximum frequency, which is advantageous for SWLs.
However, this type of antenna necessarily has much lower performance than a non-shortened antenna (dipole or vertical, for example). Moreover, a simple FT8 test associated with PSKReporter shows that the average difference in signal-to-noise ratios is of the order of magnitude of the losses expressed in dB (see §4.2).

Refer to [11] for a more complete comparison between magnetic loop antennas and other antennas.

As for sizing, a single secondary loop of the largest possible diameter D within the limit of $D = \frac{24.7}{fM}$, with fM the maximum frequency to be transmitted in MHz, is the best solution for this antenna. See §4.3 for details.

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APPENDIX (called by §4.3.2 - Comments are in French)

```
PROCEDURE
DIMENSIONNEMENT_D_UNE_ANTENNE_MAGNETIQUE_HF_MONO_BOUCLE_EN_TUBE_DE_CUIVRE_1
2_14_mm(F_minimum_MHz,F_maximum_MHz,Cv_minimum_pF,ap_mm:DOUBLE);
{On donne les fréquences minimum (F_minimum_MHz) et maximum (F_maximum_MHz)
souhaitées ainsi que la capacité minimum du condensateur
variable en pF (Cv_minimum_pF) dont on dispose et le rayon extérieur du
tube ou du coaxial primaire (ap_mm) en mm. Par exemple: (5.368,29.7,1,4)}
{Nota: il faut ajouter l'unité Math de DELPHI dans le USES de l'unité}
VAR as_mm,F_MHz,Ds_m,C_pF,Cp1_pF,Ls_H,Mu0,Cv_max_pF:DOUBLE;
VAR D_mm,Ds_mm,Dsmax_mm,Dp_mm,Dpmin_mm:WORD;
VAR R_ohm,R_ohm_fcourant,Qa,Qa_fcourant,M_H,K_moyen,M_H_moyen,Lp_H:DOUBLE;
VAR Lp_courant_H,Dp_m,Ca_pF,K,K_fmax,A,B:DOUBLE;
VAR F_Courant_KHz,Ca_min_pF,Ca_max_pF,F_Ca_min_KHz,F_Ca_max_KHz,Ze:DOUBLE;
VAR Fr_HKHz:LONGINT;
BEGIN
 {Hypothèses}
 Mu0:=4E-7*Pi;{perméabilité magnétique du vide  en H/m}
 as_mm:=7;{rayon extérieur du tube secondaire en mm, fixe}

 {***Détermination de Ds en m (diamètre de la boucle secondaire)***}
 Dsmax_mm:=ROUND(24.7*1000/F_maximum_MHz)+1;
 FOR D_mm:=Dsmax_mm DOWNTO 1 DO{test mm par mm, par décroissance}
 BEGIN
  Ds_m:=D_mm/1000;
  Cp1_pF:=(Ds_m/0.78)*(Power(31.7/F_maximum_MHz,2.02)*2.6+10);
  C_pF:=Cp1_pF+Cv_minimum_pF;
  Ls_H:=Mu0*Ds_m/2*(ln(4*Ds_m/(as_mm/1000))-2);
  F_MHz:=1E-6/(2*Pi*SQRT(Ls_H*(C_pF*1E-12)));
  {On a trouvé. Ds entre D_mm et D_mm+1. On prend Ds intermédiaire}
  IF F_MHz>F_maximum_MHz THEN
  BEGIN
   Ds_m:=(D_mm+0.5)/1000;
   Cp1_pF:=(Ds_m/0.78)*(Power(31.7/F_maximum_MHz,2.02)*2.6+10);
   Ls_H:=Mu0*Ds_m/2*(ln(4*Ds_m/(as_mm/1000))-2);
   BREAK;
  END;
 END;

 {***Détermination de Cv_max en pF***}
 C_pF:=1E12/(Ls_H*SQR(2*Pi*F_minimum_MHz*1E6));
 Cp1_pF:=(Ds_m/0.78)*(Power(31.7/F_minimum_MHz,2.02)*2.6+10);
 Cv_max_pF:=C_pF-Cp1_pF;

 {*** Calcul de Lp (maximum) à F_minimum_MHz + le diamètre du primaire Dp.
 Nota: Lp "idéal" baisse avec la fréquence***}
 {Détermination de Qa, puis R à F_minimum_MHz, puis M}
 Qa:=Power(29.7/F_minimum_MHz,0.5+F_minimum_MHz/29.7)*63.8;{facteur de
 qualité de l'antenne}
 R_ohm:=(F_minimum_MHz*1E6/Qa)*Pi*Ls_H;{résistance série}
 M_H:=SQRT(50*R_ohm)/(2*Pi*F_minimum_MHz*1E6);{inductance mutuelle}
 {Détermination de K, Lp et du diamètre de la boucle primaire Dp}
 {Calcul du coefficient de couplage K à F_minimum_MHz}
 IF F_minimum_MHz>18.1 THEN K:=0.055*Power(F_minimum_MHz/18.1,0.31) ELSE
 K:=0.055*Power(18.1/F_minimum_MHz,0.31);
 Lp_H:=SQR(M_H)/(SQR(K)*Ls_H);
 Dpmin_mm:=ROUND(1000*Lp_H*0.2E6)-1;{valeur de Dpmin_mm sûrement en-dessous
 de la valeur réelle}
 FOR D_mm:=Dpmin_mm TO 10*Dpmin_mm DO{test mm par mm, par croissance}
 BEGIN
  Dp_m:=D_mm/1000;
```

```
  Lp_courant_H:=Mu0*Dp_m/2*(ln(4*Dp_m/(ap_mm/1000))-2);
  {On a trouvé. Dp est entre D_mm-1 et D_mm. On prend donc la valeur Dp
  intermédiaire}
  IF Lp_courant_H>Lp_H THEN
  BEGIN
   Dp_m:=(D_mm-0.5)/1000;
   Lp_H:=Mu0*Dp_m/2*(ln(4*Dp_m/(ap_mm/1000))-2);{on calcule le Lp exacte
   correspondant à ce Dp}
   BREAK;
  END;
 END;

{***Détermination de Ca_min et Ca_max en pF à F_maximum_MHz, calcul très
peu précis car basé sur des résultats de calcul eux-mêmes imprécis***}
 Ca_min_pF:=1E10; Ca_max_pF:=0;//initialisation
 {Tous les 100 KHz, calcul de K, Qa, R, A, B puis Lp_courant_H et Ca_pH}
 FOR Fr_HKHZ:=ROUND(INT(F_minimum_MHz*10)) TO ROUND(F_maximum_MHz*10) DO
 BEGIN
  F_Courant_KHz:=Fr_HKHz*100;
  IF F_Courant_KHz>18100 THEN
K_courant:=0.055*Power(F_Courant_KHz/18100,0.31) ELSE
K_courant:=0.055*Power(18100/F_Courant_KHz,0.31);
  M_H_courant:=K_courant*SQRT(Lp_H*Ls_H);;
Qa_fcourant:=Power(29700/F_Courant_KHz,0.5+F_Courant_KHz/29700)*63.8;{facte
ur de qualité de l'antenne}
  R_ohm_fcourant:=(F_Courant_KHz*1E3/Qa_fcourant)*Pi*Ls_H;
  B:=SQR(M_H_courant*(2*Pi*F_courant_KHz*1E3));//(M.w0)2
  A:=(R_ohm_fcourant*B-50*SQR(R_ohm_fcourant))/50;
  IF A<0 THEN
  BEGIN{Le Ca est inutile car Ze<50 ohms}
   //Ze:=B/R_ohm_fcourant; WRITELN(F_Courant_KHz:5:0,' inutile
Ze=',Ze:5:2);
  END ELSE
  BEGIN
   A:=SQRT(A);
Lp_courant_H:=A*B/((2*Pi*F_courant_KHz*1E3)*(SQR(R_ohm_fcourant)+SQR(A)));
   Ze:=B/R_ohm_fcourant;
   IF Ze>50.5 THEN {Entre Ze de 50 à 50,5 ohm, un Ca n'a pas d'intérêt}
   BEGIN
    {Ca_pa: compensation pour arriver à Ze=50 ohm}
    Ca_pF:=1E12/(SQR(2*Pi*F_Courant_KHz*1E3)*(Lp_H-Lp_courant_H));
    {WRITELN(F_Courant_KHz:5:0,' Ca=',Ca_pF:5:2,' Ze=',Ze:5:2);}
    {Détermination des Ca min et max et de leurs fréquences associées}
    IF Ca_pF>Ca_max_pF THEN
    BEGIN
     Ca_max_pF:=Ca_pF; F_Ca_max_KHz:=F_Courant_KHz;
    END ELSE
    IF Ca_pF<Ca_min_pF THEN
    BEGIN
     Ca_min_pF:=Ca_pF; F_Ca_min_KHz:=F_Courant_KHz;
    END;
   END;
  END;
 END;
 {Affichage des résultats pricipaux}
WRITELN('Ds_m=',Ds_m:5:3,' Ls_microH=',Ls_H*1E6:5:3,'
Cv_max_pF=',Cv_max_pF:6:2,' Dp_m=',Dp_m:5:3,' Lp_microH=',Lp_H*1E6:5:3);
IF (Ca_max_pF>0) AND (Ca_min_pF<1E10) THEN
 WRITELN('Ca_max(pF)=',Ca_max_pF:5:2,' à F(kHz)=',F_Ca_max_KHz:5:0,'
Cv_min(pF)=',Ca_min_pF:5:2,' à F(kHz)=',F_Ca_min_KHz:5:0);
END;
```