IMPEDANCE ADAPTERS FOR ELECTRIC FIELD SENSORS FOR VLF – LF. 15 kHz to 515 kHz

1.- INTRODUCTION.

1.1.- General comments on the topic under discussion.

Documents in References [1] and [2] describe the principle of operation, implementation and determination of the characteristic parameters of an electric field sensor intended for the reception of radio signals in the range of 15 kHz to 515 kHz. This particular receiving antenna system requires the use of an impedance adapter device that transforms the received energy available at a point in the system whose impedance level is variable and very high to another with a standard level of 50 Ω / 75 Ω such as that presented by modern reception systems. Reference [3].

This document describes two implementations of impedance adapters evolved from the practical experience gained with the initial implementation. They use discrete active devices, a JFET transistor as the input stage and BJT transistors as the output stages, in order to provide greater sensitivity and greater capacity for handling large-amplitude signals.

The basic design makes use of a dual power supply (+15V and -15V) and has an output power limit for linear operation of +14 dBm, while the second with a symmetrical output stage and higher bias currents of the active elements allows the maximum output power to be increased to +19.5 dBm.

As in the design described in Reference [1], both incorporate an input filter designed to reduce the high field levels of signals coming from AM broadcast stations in the medium wave band (530 kHz to 1710 kHz) and thus avoid overloading and generating intermodulation products.

The analysis and the different alternatives for the implementation of this filter are presented in Section 7. The current document incorporates general analyses that make it possible to optimize the sensor/adapter assembly regardless of its particular implementation.

Section 2 contains the theoretical analysis of the factors involved in the operation of the impedance adapter in conjunction with the electric field sensing electrode and how they define the efficiency of the transfer of the induced potential at the electrode relative to the input impedance of the adapter. The practical implementation of the basic version, its constructional, mechanical and electronic details, are incorporated in Section 3.

Section 4 contains the general characterization procedures that allow the determination of the frequency response, antenna factor (Fa), input capacity, sensitivity, and maximum signal level for linear operation. Calibration tables for all of these parameters for the basic impedance adapter implemented are included.

Section 5 shows photographs showing the construction details of the basic adapter. The circuit and operating description for the implementation with symmetrical output stage and increased dynamic range is included in Section 6. The analysis of the noise generated by the input circuit components and responsible for defining the sensitivity of the system is presented in Section 8.

Section 9 compares the expected external noise levels at the different operating frequencies with the sensitivity obtainable with the electric field sensing electrode assembly and adapters described. Section 10 contains the reference bibliography used as a basis for the different topics involved in the present development.

1.2.- Specifications.

Operating frequency range :	15 kHz to 515 kHz
Supply voltage :	+/-15 V
Supply current :	35 mA (version 1) 50 mA (version 2)
Output impedance :	50 Ω
Load impedance :	50 / 75 Ω
Typical antenna factor for L = 6.85 m :	0.265·1/m
Ideal sensitivity for S/N = 0 dB and B = 250 Hz :	0.065 µV/m (typical value)
Rejection of input frequencies outside operating range :	6 dB @ 840 kHz 12 dB @ 1080 kHz 20 dB minimum from 1300 kHz
Maximum output voltage for linear operation (15 kHz to 520 kHz):	+14.0 dBm in 50 Ω (version 1) +19.5 dBm in 50 Ω (version 2)
Maximum non-destructive input voltage :	30 Vpp

2.- THEORETICAL ANALYSIS.

Next, the relationship between the available potential between the electrode and the ground is analyzed as a function of the parameter that characterizes the electrode and the characteristics of the connected impedance between these points.

2.1.- Parameters of the electric field sensor.

For an electrode geometry such as that used in the implementation presented in the Reference document [1] and according to the electromagnetic simulation documented in Reference [2], the induced potential at the electrode (Ua) is related to its installation height and the magnitude of the incident electric field by the relationship:

$$Ua = 0{,}915 \cdot L \cdot E \quad [V] \qquad (1)$$

Where:

L : Height of the electrode with respect to the ground level [m]
E : Magnitude of the incident electric field [V/m]

On the other hand, the electrode can be represented by the serial electrical model shown In Figure 1:

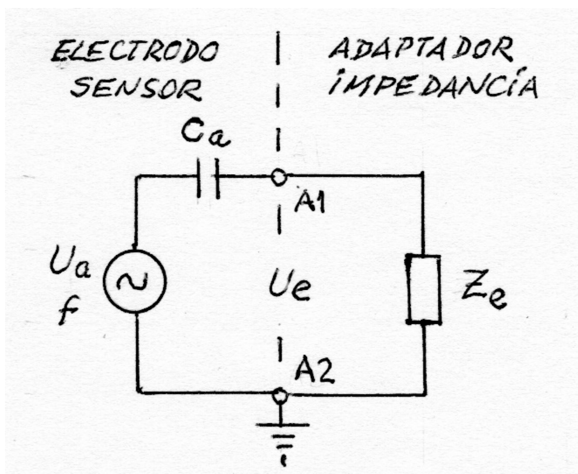


Figure 1.- *Electric Field Sensor Equivalent Circuit*

The amplitude generator (Ua) corresponds to the field-induced potential at frequency (f) and the capacitance (Ca) represents the capacitance seen between the electrode and the ground. The impedance (Ze) is the impedance corresponding to the device connected between the electrode and the grounding conductor.
Considering practical heights of the electrode position with respect to earth between 3 m and 10 m, Reference [2], the magnitude of the capacitance (Ca) within the frequency range of interest is:

$$Ca\ (15\ kHz\ a\ 515\ kHz) = 38{,}5\ pF \ \pm 1{,}5\ pF \qquad (2)$$

2.2.- Linking the electrode parameters and the load impedance.

The potential available between the electrode and ground when charged with an impedance (Ze) is:

$$Ue = Ua \cdot Ze / (Za + Ze) \qquad (3)$$

Where: $Za = - j / 2 \cdot \pi \cdot f \cdot Ca$

$Ze = Re + j\, Xe$: Impedance of the device connected to the electrode

If the impedance of the device connected to the electrode, impedance adapter, is fundamentally capacitive and defined by a magnitude capacitance (Ce), the ratio (3) becomes as follows:

$$Ue = Ua \cdot Ca / (Ca + Ce) \qquad (4)$$

With this condition, the link between the potential available in the electrode (Ue) and the potential (Ua) induced in it is related by a factor (k), independent of frequency, which we will define as efficiency:

$$k = Ca / (Ca + Ce) \qquad (5)$$

It follows from the above that if frequency-independent transfer is to be obtained, the input impedance of the adapter must be fundamentally capacitive over the entire range of operating frequencies.
On the other hand, the greater the magnitude of the electrode capacitance (Ca) with respect to the input capacitance (Ce) of the impedance adapter device, the greater the efficiency and therefore the greater the magnitude of the available potential (Ue).
The capacitance (Ca) of the electrode depends on its particular geometry and increases with its dimensions in the horizontal plane.

2.3.- Input capacitance of the adapter.

The input capacitance of the adapter, as seen by the field sensor electrode, is made up of the sum of three capacitances which are:

$$Ce = C_{JFET} + C_{EXT} + C_{PFIL} \qquad (6)$$

Where:

- **C_{JFET} :** Input stage capacitance of the JFET transistor.
- **C_{EXT} :** External capacitance linked to the gate terminal.
- **C_{PFIL} :** Parasitic capacitance of the input filter components.

The capacitance of the input stage itself is dependent on the type of JFET transistor used and the bias voltages between each of its electrodes.

The external capacitance linked to the terminal of the gate is that provided by the printed circuit board and by an additional capacitance (Cf) necessary to make the input filter for the attenuation of frequencies outside the operating range practically feasible. See the discussion in Section 7.
The capacitance of the printed circuit board is determined by the geometric dimensions of the conductive trace and the thickness and dielectric constant of the base material.
The parasitic capacitance of the input filter components is the result between the component elements and the surfaces attached to the ground terminal of the circuit.

3.- PRACTICAL IMPLEMENTATION OF THE BASIC VERSION.

3.1.- Diagram in blocks.

Figure 2 presents the block diagram of the active impedance adapter implemented in order to meet the requirements imposed on the design by the conditions determined by the analysis in Section 2.2.It consists mainly of two active stages (G1 and G2) consisting of a JFET input semiconductor device and a BJT output device.
It provides a fundamentally capacitive input impedance and a resistive output impedance (Ro = 50Ω) capable of exciting 50/75 Ω low impedance loads.
The RL lattice sandwiched in series between the electrode and the input stage (G1) forms a low-pass filter with the capacitance of the input stage ($C_{JFET} + C_{EXT}$) and is intended to reduce the levels of the induced signals in the sensor electrode to the frequencies corresponding to the broadcast band (530 kHz to 1710 kHz).Section 7 discusses the requirements for implementing this filter.
A transformer couples, in isolation, the 50/75 Ω load to the output power transistor (BJT) manifold.
Interspersed between the transformer output and the load is a low-pass filter with a cut-off frequency of 775 kHz in charge of limiting those frequencies above the range of interest.

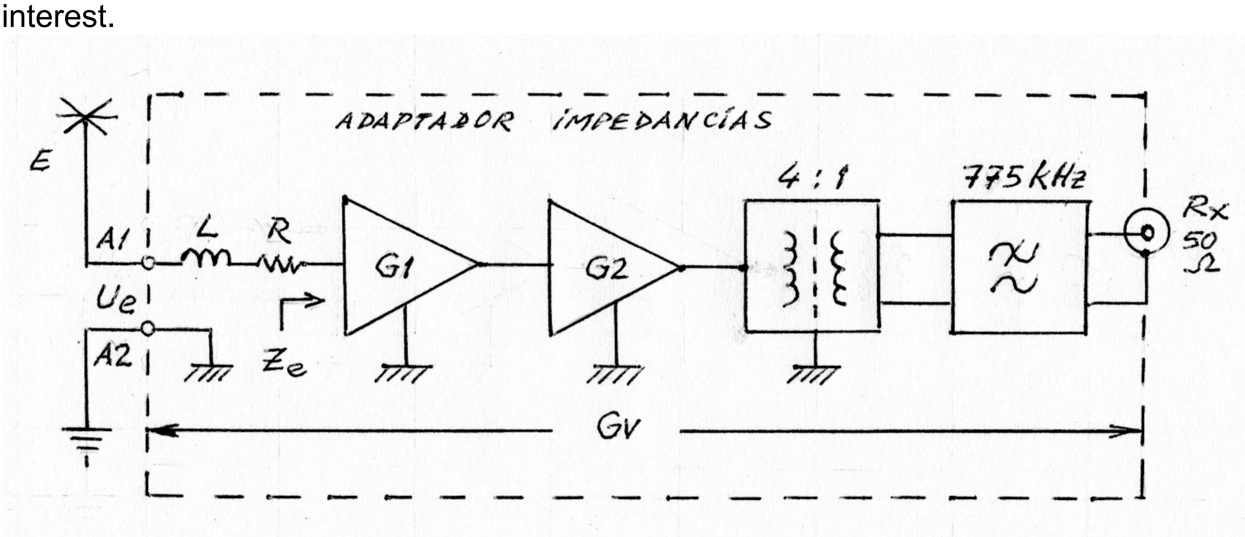


Figure 2.- *Block diagram of the basic impedance adapter.*

3.2.- Circuit of the impedance adapter and details of its implementation.

Figure 3 shows the detail circuit of the basic impedance adapter.
Between the electrode, terminal A1, and the JFET input are three 1.5 mH inductors and two 15 kΩ resistors that are part of the low-pass input filter mentioned in the previous sections. See discussion in Section 7.
The input stage consists of the JFET transistor (J308/J310) in the source follower configuration so as to present a high and fundamentally capacitive impedance (4 to 5 pF) in the frequency range of interest and a relatively low output impedance in the source (approx. 80 Ω).
Parallel to the gate terminal is a 4.7 pF capacitor (Cf) designed to generate a total stage input capacitance (Ce) such that the input filter is achievable at the cost of slightly degrading the factor (k).
A BJT transistor (BFR96) is used in the output stage in the common emitter configuration that has an input impedance that does not appreciably load the output of the input stage due to the negative feedback generated by the 100 Ω resistor in series with the emitter.
This resistor also stabilizes the gain of the stage so that it is stable and controlled, independent of the temperature and individual characteristics of the transistor used.
The output transformer (To) provides the necessary impedance matching between the BJT collector (800 Ω) and the 50/75 output Ω load.
The secondary is floating without any link to the ground potential to which the rest of the circuit is referred to avoid the possible generation of parasitic bonds between the ground of the sensor/adapter and the ground of the receiving system connected to it. The characteristics of the output transformer (To) are:

Impedance ratio :	800 Ω to 50 Ω
Core :	Ferrite cup material N30
	Al ≈ 7000 nH / turn ^{2} @ 1 MHz
Primary winding :	60 turn winding with Φa = 0.28 mm
	(one-half the width of the reel)
Secondary winding :	15 turn winding with Φa = 0.28 mm
	(on the second half of the reel)

The low-pass output filter is balanced and consists of two 4400 pF capacitors and two 8.2 µH inductors.
The BJT transistor (BC337) receives at its base a sample of the bias voltage developed on the source resistor of the JFET (510 Ω) and compares it with that of the 1N4148 diode, generating in the collector the bias correction voltage for the gate and thus keeping the source current stabilized at 10 mA.
During initial energization, the resistor (Rv) is not installed so that the current in the JFET will be less than 10 mA.
By measuring the voltage on the source resistor (510 Ω), values of (Rv) from 22 kΩ will be selected progressively and in a decreasing manner until the voltage increases and reaches the nominal 5.1 V.

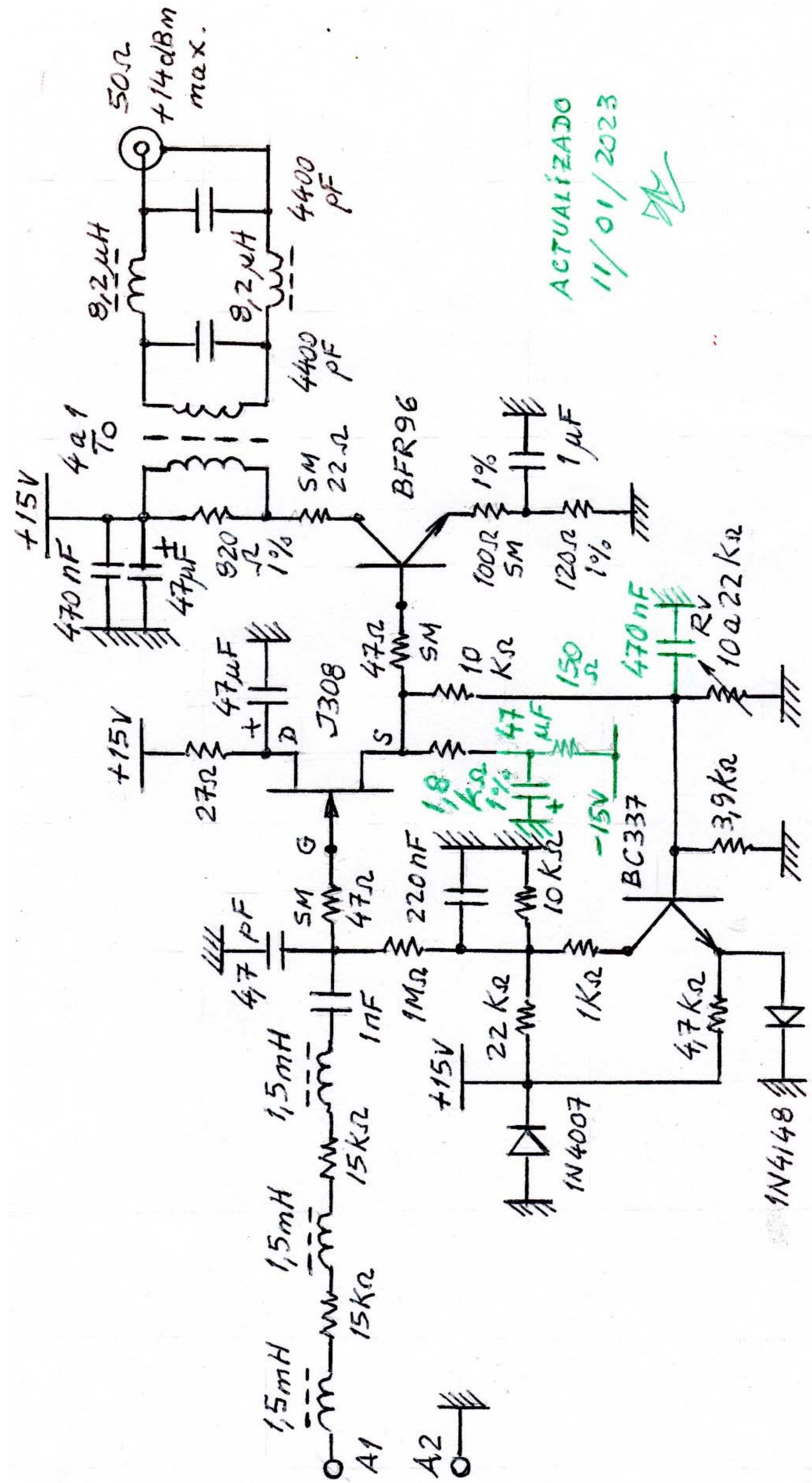


Figure 3.- *Basic Active Impedance Adapter Circuit.*

If the voltage on the source resistor is stabilized at +5.1V, the base voltage of the output transistor (BFR96) is also stabilized, which, thanks to the negative feedback generated by the emitter resistors (100Ω + 120Ω), will keep the emitter current stable at 20 mA.
The subsequent replacement of any of the signal transistors will not require any adjustment of the (Rv) value.
The supply voltages should be regulated at +15V and -15 V and no other values should be used, otherwise the optimal bias voltages of both signal transistors will be altered, resulting in loss of dynamic range and alterations in the general characteristics of the adapter.

4.- MEASURED CHARACTERISTICS.

4.1.- Frequency-dependent transfer.

The frequency-dependent transfer between the induced voltage at the electrode (Ua) and the output voltage of the impedance adapter (Uo) is determined by an RF generator and an intermediate network, between it and the impedance adapter, which emulates the impedance of the sensor electrode.
Figure 4 shows the link between the different elements for carrying out the transfer determination.
The values obtained from the test allow the determination of the Antenna Factor (Fa) without the need to generate an electric field (E) of known magnitude to subject the field sensor to it and perform its characterization. Reference [7].

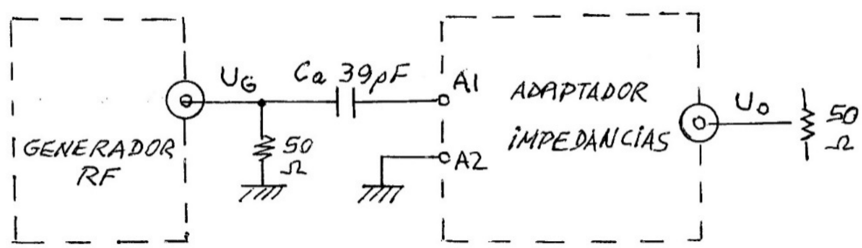


Figure 4.- *Circuit for the characterization of the impedance adapter*

From the analysis of the circuit it can easily be deduced that:

U_G = Ua = Induced voltage at the electrode [V]
Ca = Equivalent Electrode Capacitance [pF]
Uo = Impedance Adapter Output Voltage [V]

The value of (Ca) used for the determination of the transfer was 39 pF and corresponds to the capacitance of the sensor electrode constructed as described in the Reference document [1] and whose value was determined by the electromagnetic simulation presented in Reference [2].
For a different geometry and size than the one indicated, the corresponding value for that capacitor must be used in the determinations.

Figure 5.- *Recording of the transfer of the adapter with the emulation of the electrode.*

Figure 5 shows the transfer of the assembly consisting of the active impedance adapter with the electrode emulation circuit indicated in Figure 4, while Table 1 below contains the numerical results obtained.
The Uo/U_G ratio has been called Gvk because it is the product of two cascading transfers, the transfer (Gv) of the set of two stages (G1 and G2) that constitute the impedance adapter and the transfer defined as efficiency (k) in Section 2.2.

Frequency [kHz]	***U_G [mV]***	***Uo [mV]***	***Gvk = Uo / U_G***
15	*209*	*121*	*0,5789*
20	*209*	*124*	*0,5933*
40	*209*	*126*	*0,6029*
60	*209*	*127*	*0,6077*
80	*209*	*127*	*0,6077*
100	*209*	*127*	*0,6077*
150	*209*	*125*	*0,5981*
200	*209*	*125*	*0,5981*
250	*209*	*124*	*0,5933*
300	*209*	*124*	*0,5933*
350	*209*	*122*	*0,5837*
400	*209*	*120*	*0,5742*
490	*209*	*117*	*0,5598*
520	*209*	*116*	*0,5550*
550	*209*	*114*	*0,5455*
775	*209*	*89*	*0,4258*
1000	*209*	*51*	*0,2440*

(Table 1)

4.2.- Input capacitance.

The input capacitance is determined again using the test circuit in Figure 4 where the capacitor (Ca) is removed by a direct connection between the generator and the impedance adapter input.
In this way, the value of the adapter's own Gv transfer is obtained, i.e.:

$$Gv = Uo / Ue \qquad (7)$$

This measurement is sufficient to be performed on a single frequency at the lower end of the working frequency range and with a generator signal level not exceeding 300 mV peak-to-peak.
In the determination made on the adapter implemented and described in this document, a frequency f = 40 kHz and an amplitude of 210 mV peak-to-peak were used.
The value obtained under these conditions was:

$$Gv = 0{,}7847 \qquad (8)$$

On the other hand, from the determination of Gvk as indicated in Section 4.1 (Table 1), for the 40 kHz frequency it was obtained:

$$Gvk = Gv \cdot k = 0{,}6029 \qquad (9)$$

Combining results (8) and (9) results:

$$k = Gvk / Gv = 0{,}6029 / 0{,}7847 = 0{,}7684 \qquad (10)$$

With this result, it can be deduced that of the induced potential (Ua) available at the electrode, 76.8 % (- 2.3 dB) is obtained as potential (Ue) at the input of the implemented impedance adapter, considering Ca = 39 pF as the value corresponding to the dimensions of the electrode indicated in the Reference document [1].
If higher efficiency is to be achieved, a larger electrode should be used so that it has a higher capacitance (Ca).
Another way to increase efficiency is to reduce the input capacitance of the adapter. But this has practical limits, such as the capacitance of JFETs and subsequently the practical impossibility of performing input filtering as a result of the reduction in the self-resonance frequency of the high-value inductors required for their implementation.
Applying the definition of efficiency (k) as given in equation (5) and with the value of Ca = 39 pF used in the determination of Gvk, as indicated above, it follows that the input capacitance of the impedance adapter is:

$$Ce = (Ca / k) - Ca = (39 / 0{,}7684) - 39 = 11{,}75 \text{ pF} \qquad (11)$$

4.3.- Antenna Factor.

The Antenna Factor (Fa) is defined as:

$$Fa = E / Uo \quad [1/m] \tag{12}$$

Where: E = Electric field of the wave incident on the electrode. [V/m]
Uo = Output potential of the impedance adapter. [V]

Using the ratio (1), indicated in Section 2.1, which links the electric field (E), the potential (Ua) induced in the electrode and the height (L) at which the electrode is located and entering it in definition (12) we get:

$$Fa = Ua / 0{,}915 \cdot L \cdot Uo = U_G / 0{,}915 \cdot L \cdot Uo \quad [1/m] \tag{13}$$

Where:

U_G = Generator emulating the potencial (Ua) at the electrode by the incident field (E). [V]
L = Height at which the electrode is located with respect to ground. [m]
Uo = Impedance adapter output potential. [V]

Applying equation (13) with the values of (Uo/UG) obtained from Table 1 and considering an electrode installation height L = 6.85 m, Table 2 corresponding to the calibration of the antenna factor (Fa) is obtained:

Frequency [kHz]	***Fa [1/m]***
15	*0,276*
20	*0,269*
40	*0,265*
60	*0,263*
80	*0,263*
100	*0,263*
150	*0,267*
200	*0,267*
250	*0,269*
300	*0,269*
350	*0,273*
400	*0,278*
490	*0,285*
520	*0,288*

(Table 2)

If neither the geometry nor the dimensions of the electrode have been altered, it is possible to obtain the Antenna Factor for a different installation height (Lx) by applying the following correction equation:

$$Fa(Lx) = Fa(6{,}85)\ 6{,}85 / Lx \quad [1/m] \tag{14}$$

4.4.- Sensitivity.

The sensitivity of the electric field sensor and impedance adapter assembly is defined as the magnitude of the signal field (Es) that would produce at the output of an ideal noiseless system a potential (Uo) of magnitude equal to that obtained as a consequence of the impedance adapter's own noise (Uno) when the external field is zero.
In the form of an equation:

$$\text{Sensitivity} = Es\ [uV/m] \quad \text{Con} \quad Es / Eno = 1 \quad (S/N = 0\ dB) \qquad (15)$$

The noise power added by the active impedance adapter is determined with the same arrangement of elements corresponding to Figure 4 where the voltage provided by the generator is zero ($U_G = Ua = 0$) and which corresponds to the external field condition E=0.
Under these conditions, the noise power (Pno) values, expressed in [dBm], measured at the output of the system with a bandwidth of 250 Hz and loaded with 50 Ω are listed in Table 3.
In addition, the corresponding values converted to potentials (Uno) expressed in [uV] are included.

Frequency [kHz]	***Pno [dBm]***	***Uno [µV]***
15	*- 117,4*	*0,302*
20	*- 118,0*	*0,282*
40	*- 119,8*	*0,229*
60	*- 120,3*	*0,216*
80	*- 120,5*	*0,211*
100	*- 120,6*	*0,209*
150	*- 120,8*	*0,204*
200	*- 121,0*	*0,199*
250	*- 121,1*	*0,197*
300	*- 121,1*	*0,197*
400	*- 121,5*	*0,188*
500	*- 121,9*	*0,180*

(Table 3)

With the definition of Antenna Factor, equation (12), presented in Section 4.3 and applying it to the values (Uno) it is possible to calculate the magnitude of the external field (Eno) of equivalent noise:

$$Eno = Fa \cdot Uno \qquad (16)$$

Applying equation (16) with the magnitudes of the noise potentials (One) in Table 3 and the corresponding Antenna Factors from Table 2 using the definition indicated in (15) yields the ***Sensitivity*** values listed in Table 4.
These values correspond to an electrode height of 6.85 meters above ground level and a receiving system bandwidth of 250 Hz.

Frequency [kHz]	*Es [µV/m]*	
15	*0,083*	
20	*0,076*	
40	*0,061*	
60	*0,059*	
80	*0,056*	
100	*0,055*	
150	*0,055*	
200	*0,053*	
250	*0,053*	
300	*0,053*	
400	*0,052*	
500	*0,052*	***(Table 4)***

4.5.- Maximum permissible field level for linear operation.

The maximum signal level for linear operation is the conventional measurement condition that corresponds to the level for which the transfer deviates by 1dB (89%) from the line defined by a perfectly linear transfer.
The test circuit is the one in Figure 4 where now the measurement procedure consists of increasing step by step the signal level provided by the generator while recording the corresponding magnitude (Uo) of the signal at the output of the impedance adapter and calculating the constant (Gv) that links both magnitudes.

$$Gv = Uo / U_G \tag{17}$$

When the value of (Gv) at high signal levels is reduced to 89% of that at low levels, the maximum level for linear operation has been reached by definition.
The procedure is repeated at different frequencies within the operating range of the adapter because the linearity limit is generally dependent on the operating frequency.
The maximum signal level at the output of the implemented adapter when it is loaded with 50 Ω was independent of the operating frequency and value:

$$Uo(1dB) = 3{,}20 \text{ V peak to peak} \quad (15 \text{ kHz a } 520 \text{ kHz})$$
$$Uo(1dB) = +\ 14 \text{ dBm} \tag{18}$$

This maximum voltage level at the output is converted to maximum electric field levels over the electrode (Es max) using the values of the Antenna Factor (Fa), for the corresponding frequencies according to Table 4, applying the following equation:

$$Es\ máx = Fa \cdot Uo(1dB) \tag{19}$$

As the Antenna Factor (Fa) is dependent on the installation height (L) of the electrode, the results shown below correspond to a height of 6.85 meters above ground level:

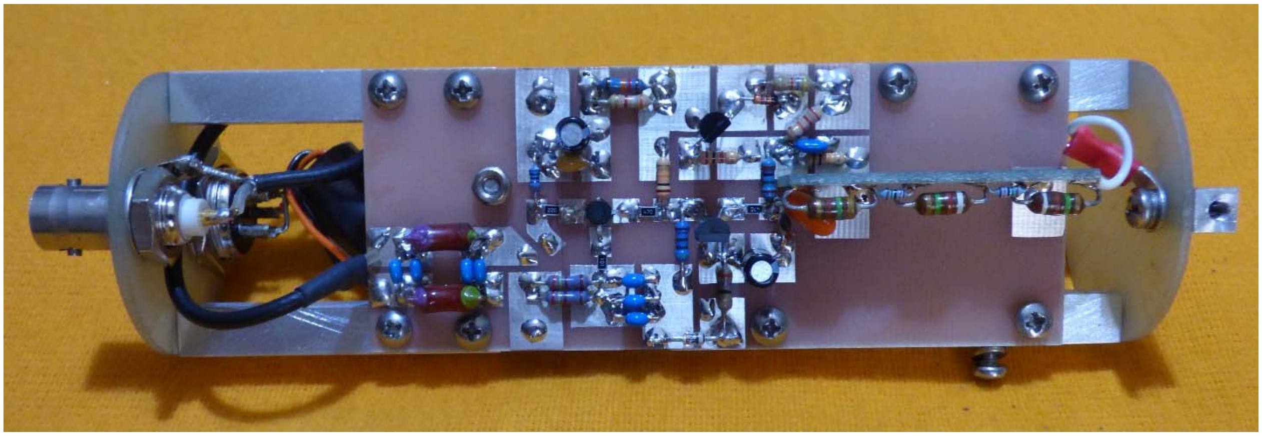
Frequency [kHz]	***Es peak to peak máx. [V/m]***	
15	*0,88*	
20	*0,86*	
40	*0,85*	
60	*0,84*	
80	*0,84*	
100	*0,84*	
150	*0,85*	
200	*0,85*	
250	*0,86*	
300	*0,86*	
400	*0,89*	
500	*0,92*	***(Table 5)***

The result obtained is equivalent to saying that the maximum level of the field of the incident electromagnetic radiation (E), expressed in effective values, for the system to operate linearly must be less than or equal to:

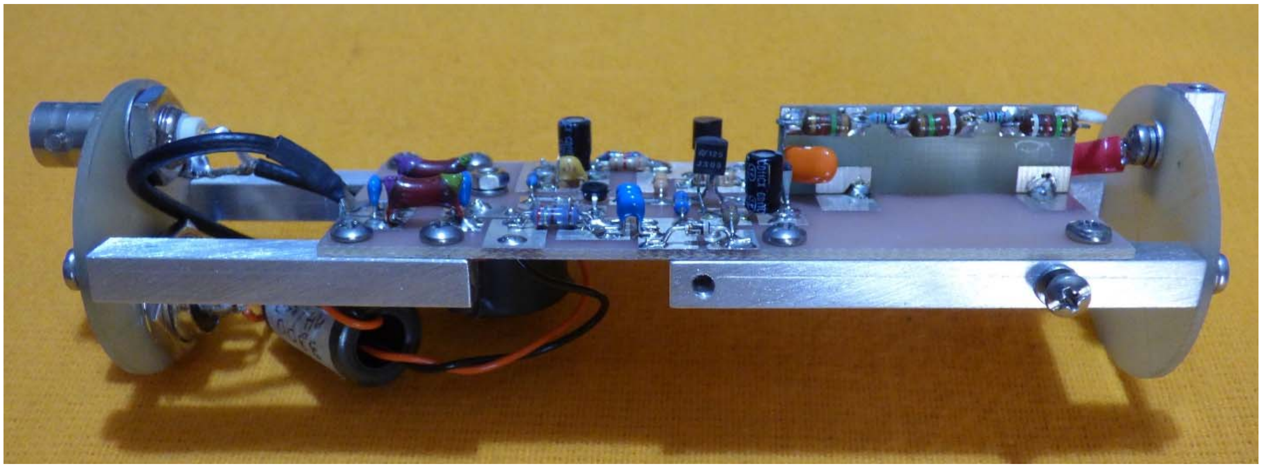
$$Es \leq 300 \text{ mV/m}$$

For another electrode installation height, the values of (Fa) corresponding to the new height (L) calculated with equation (14) in Section 4.3 shall be used when equation (19) is applied.

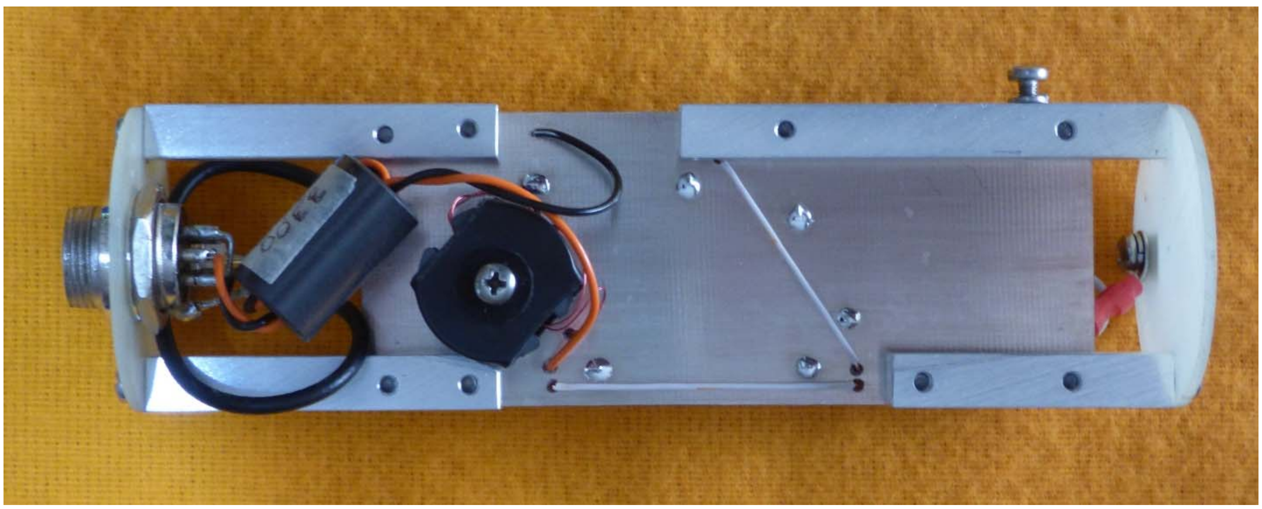
5.- PHOTOGRAPHS.



Photograph 1*.- Top view*



***Photograph 2**.- Side view.*



***Photograph 3**.- Bottom view.*

6.- IMPLEMENTATION OF THE VERSION WITH INCREASED DYNAMIC RANGE.

<u>6.1.- Modifications with respect to the basic design.</u>

The basic concept of impedance adapter operation described in the previous sections is retained, but in order to increase the dynamic range to allow operation in areas with high density of broadcast emitters (530kHz to 1710kHz), the following three modifications are made to the original design:

- Increased current and bias voltage of the input JFET transistor. The bias current is raised from 10 mA to 20 mA and the voltage from 10 V to 13.6 V. Reference [4]. This requires the use of U308/U310 transistors to replace the J308/J310 used in the original version.

- Change of single-output stage configuration to symmetrical dual-polarity power (+15 V and –15 V) and 50% increase in bias current of BJT transistors.

- Capacitive coupling of the output transformer to prevent core pre-magnetization and reduce the linearity of magnetization inductance.

6.2.- Block diagram.

Figure 6 presents the block diagram of the impedance adapter implemented with the modifications described in the previous section.
The input stage (G1) consists of a JFET semiconductor device type U308/U310 that has greater dissipation than the J308/J310 used in the basic version. The output stage (G2) is composed of two complementary BJT transistors (Q1 and Q2) in a symmetrical configuration with 200 Ω of output impedance.
The RL network sandwiched in series between the electrode and the input stage (G1) forms a low-pass filter with the capacity of the input stage (C_{JFET} + C_{EXT}) and is intended to reduce the levels of the induced signals in the sensor electrode to the frequencies corresponding to the broadcast band (530 kHz to 1710 kHz) and has identical characteristics to that used in the basic design. Section 7 discusses the requirements for the implementation of this filter.
The 2 to 1 output transformer is capacitively linked to the output stage and coupled in isolation from the ground potential to the 50/75 Ω load presented by the receiving system. Interleaved between the transformer output and the load can be interleaved with the same low-pass filter used in the basic version already described, allowing to limit those frequencies above the range of interest that may have entered the system given the limited attenuation capacity of the input filter. This will reduce potential intermodulation problems at the receiver to which the adapter is attached.

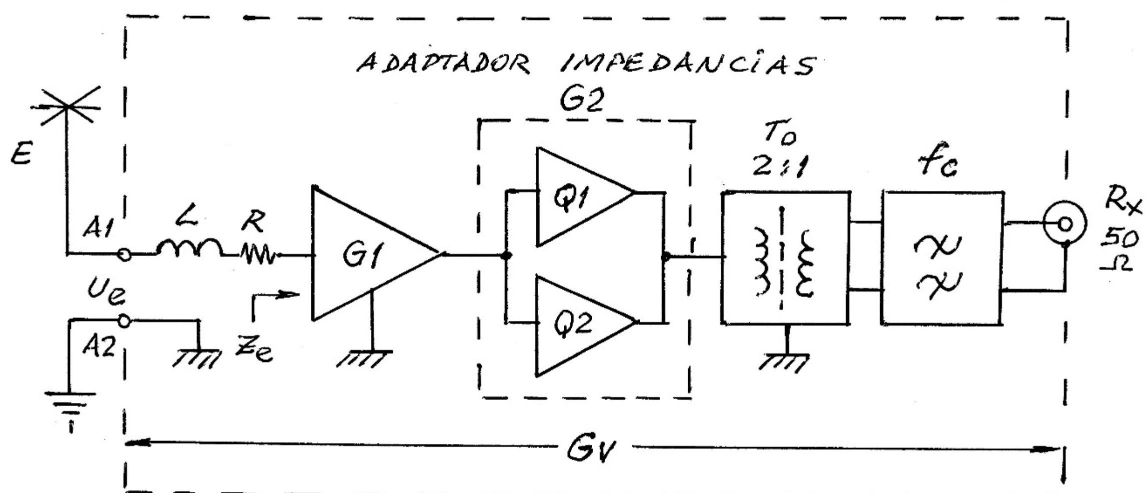


***Figure 6**.- Block diagram of the impedance adapter (version 2).*

6.3.- Circuit of the impedance adapter and details of its implementation.

Figure 7 shows the detail circuit of the active impedance adapter.
Sandwiched between the electrode, terminal A1, and the JFET input are three 1.5 mH inductors and two 15 kΩ resistors that are part of the low-pass input filter mentioned in the previous sections. See discussion in Section 7.
The input stage is composed of the JFET transistor (U308/U310) in the source follower configuration in order to present a high impedance in the gate and fundamentally capacitive (4 to 5 pF) in the range of the frequencies of interest.
Parallel to the gate terminal is a 4.7 pF capacitor (Cf) designed to generate a total stage input capaciance (Ce) such that the input filter is practically achievable..
Operating with a bias current of 20 mA, it produces a relatively low output impedance at the source of approximately 40 Ω.
The output stage is composed of the complementary BJT transistors (BC327 and BC337) in an unconventional push-pull configuration, operating in class A, where both transistors operate in series for bias voltages and currents but do so in parallel and phase opposition for signal currents.
The 200 Ω resistor connected to the collectors defines the output impedance of the stage. Emitter resistors (100 Ω) define the stage gain regardless of the individual characteristics of the transistors used and the operating temperature.
The input impedance is in the order of 2700 Ω so it represents a reduced load effect compared to the output impedance of the input stage, ensuring a more linear operation of the input stage.
If the adapter is to operate for extended periods in areas with ambient temperatures above 25°C, small individual heatsinks should be installed on all transistors (FET and BJT) to reduce their joint temperature.
The output transformer (To) provides the necessary impedance matching between the collectors of the complementary BJT transistors (200 Ω) and the 50 / 75 Ω output load.
The secondary is floating without any link to the ground potential to which the rest of the circuit is referred to avoid the possible generation of parasitic bonds between the ground of the sensor/adapter and the ground of the receiving system connected to it. The characteristics of the output transformer (To) are:

Impedance ratio :	200 Ω to 50 Ω
Core :	Ferrite cup material N30 Al ≈ 7000 nH / turn ^{2} @ 1 MHz
Primary winding :	30 turn winding with Φa = 0.28 mm (about one-half the width of the reel)
Secondary winding :	15 turn winding with Φa = 0.28 mm (On the second half of the reel)

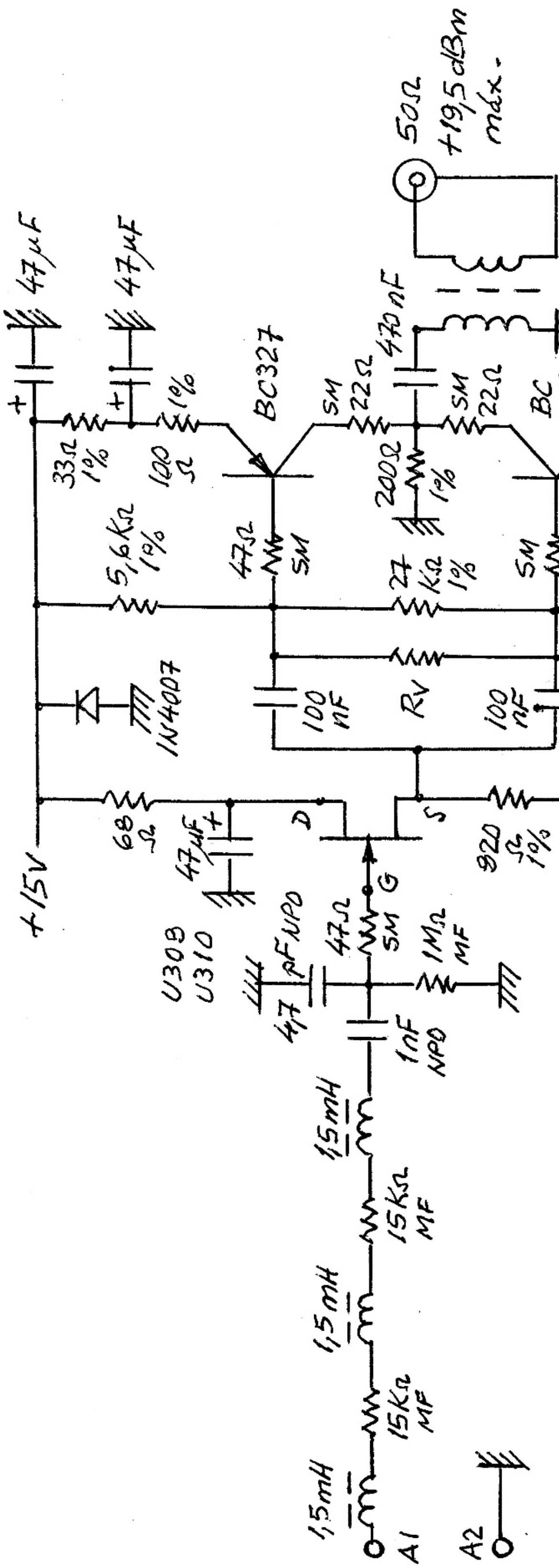


***Figure 7.-** Impedance adapter circuit (version 2).*

During initial energization, the resistor (Rv), connected in parallel with the 27 kΩ resistor, arranged between the output transistor bases (BJT), is not installed in such a way that the bias current in the transistors will be less than the nominal 30 mA of operation.
By measuring the voltage on any of the emitter resistors (100 Ω), values of (Rv) from 470 kΩ will be selected progressively and in decreasing order until the voltage increases and reaches 3.0 V, which will correspond to the 30 mA bias current.
The supply voltages should be regulated at +15V and -15 V and no other values should be used, otherwise the optimal bias voltages and currents of the transistors will be altered, resulting in loss of dynamic range and alterations in the general characteristics of the adapter.

7.- ANALYSIS AND IMPLEMENTATION OF THE INPUT FILTER.

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The low-pass input filter is practically essential in the vast majority of reception system installation sites as a result of the great proliferation of AM transmitters in the 530 kHz to 1710 kHz band.
Its presence greatly alleviates the requirements for handling large amplitude signals by the active stages of the adapter.
As will be seen in the following sections, the implementation of the filter presents practical problems that make it impossible to design a filter that attenuates the entire range of unwanted frequencies by the same magnitude.
Therefore, it may be necessary to implement the filter with a particular frequency response and adapted to each specific installation site.

7.1.- Requirements for the design of the filter.

The requirements imposed by both the characteristics of the field sensing electrode and the input stage of the adapter mean that the conditions imposed on the filter design are not the traditional ones. They are:

- a).- The output impedance of the generator, field sensing electrode, is primarily capacitive (Ca).

- b).- The load impedance, the input impedance of the impedance adapter, is fundamentally capacitive (Ce).

- c).- The filter topology cannot include branches in shunt because this would reduce the efficiency in the use of the potential available in the electrode. Factor (k) defined in Section 2.2 equation (5).

- d).- The relationship between the input potential of the impedance adapter (Ue) and the induced potential at the electrode (Ua) must remain unchanged and independent of the frequency as if the filter did not exist.

Condition (c) imposes the limitation that the filter can only incorporate components sandwiched in series between the generator and the load.
As what is required is a low-pass filter, the components that can be interleaved are inductors and/or resistors which, in combination with the input capacity determined by the first stage configuration of the adapter, will produce attenuation at frequencies above the operating frequency range.
Figure 8 shows the basic filter circuit that meets requirements a), b) and c) above.

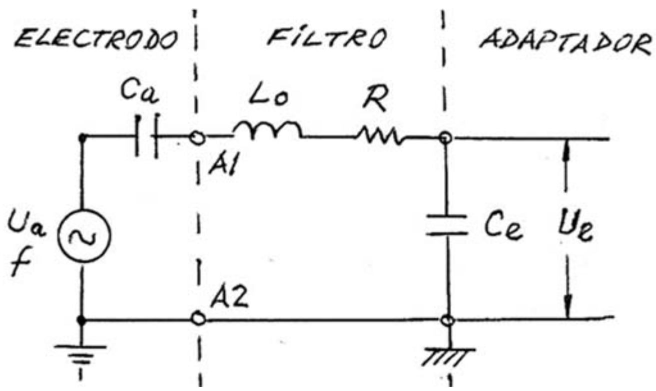


Figure 8.- *Input filter circuit.*

As can be deduced from the circuit analysis, the presence of the inductor (Lo) generates a series resonant frequency with the capacitance of the electrode (Ca) and the input of the adapter (Ce). This resonance produces an inevitable increase in the input potential (Ue) at that frequency.
The insertion of the appropriate value resistor (R) allows the Q of the resonance to be controlled and the frequency response to be kept flat as required by condition d).
As a result of the low values of the capacitances (Ca) and (Ce) and the low frequencies involved, the respective XCa and XCe reactances are also very high.
This means that in order to achieve useful attenuation values with the insertion of the inductor (Lo), it must have high inductance values so that the corresponding reactance (XLo) is higher than the capacitive reactances (XCa and XCe) at the frequencies at which attenuation is to be introduced.

7.2.- Practical implementation of the basic filter.

In order to obtain attenuation values that help reduce the overload of active adapter devices, inductance values in the order of 5 mH for (Lo) are required in practice.
The practical realization of inductors of this magnitude means that inevitably their parasitic capacitance (Cpo) can produce self-resonant frequencies so low that they can fall very close to or within the range of the useful operating frequencies of the impedance adapter, introducing unwanted alterations in the frequency response.
Figure 9 is a derivation of Figure 8 where the parasitic capacitance of the inductor (Cpo) and an external capacitance (Cp1) have been included, which can be used in some cases to obtain predetermined parallel resonant frequencies as will be explained later.

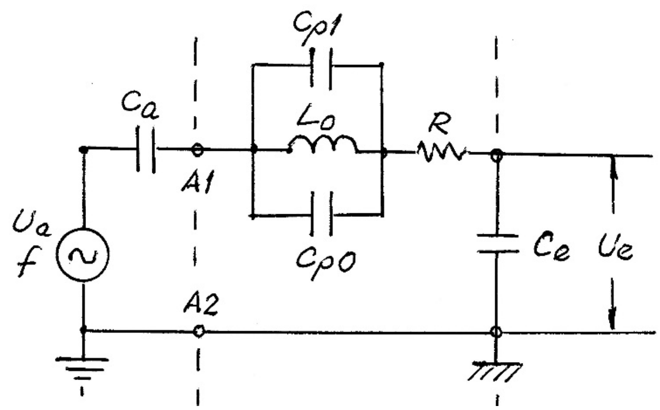
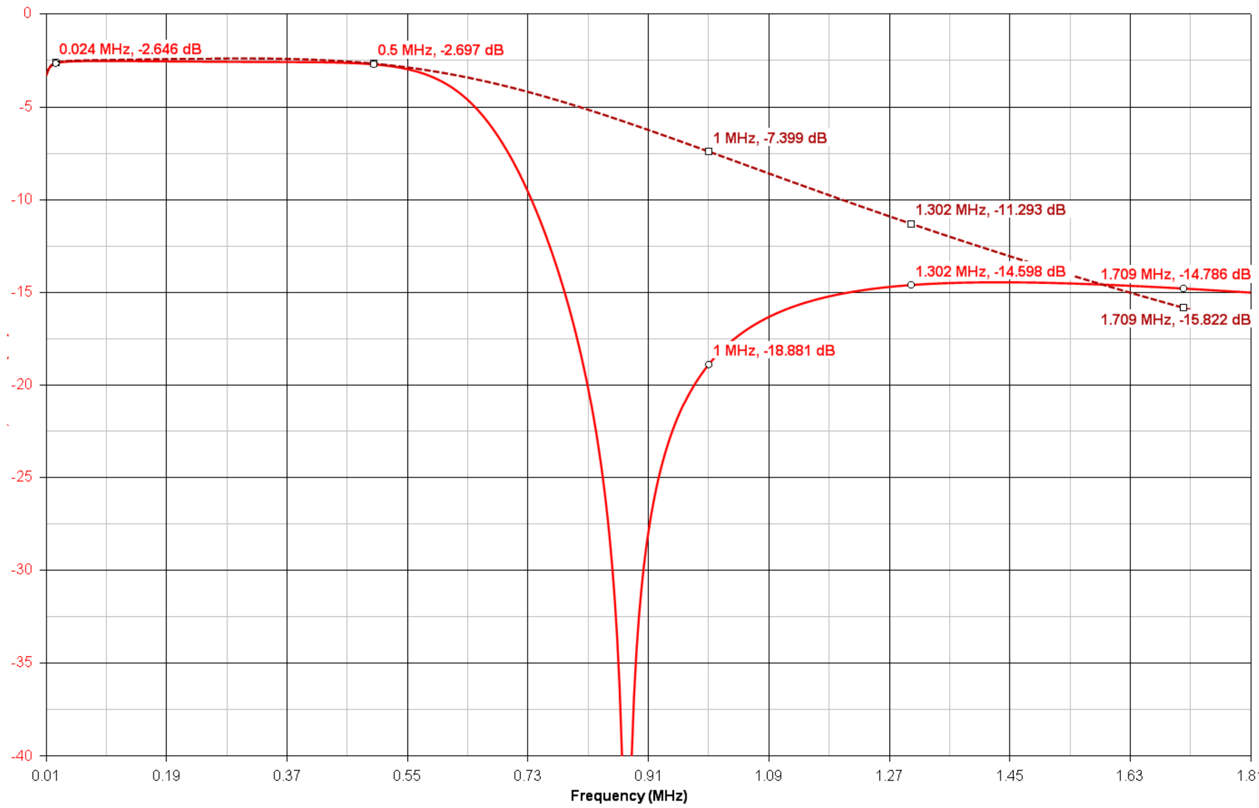


Figure 9.- *Input Filter Circuit with Real Components.*

A commercially produced molded type 4.7 mH inductor as originally intended for use for the basic adapter filter described in Sections 2, 3, 4, and 5 has a parallel parasitic capacity (Cpo) on the order of 7 pF.
This produces a self-resonating frequency of 877 kHz, which was too low, since above this frequency the attenuation is progressively reduced as a result of the capacitive coupling generated by the parasitic capacitance of the inductor.
Figure 10 shows the results of the simulations of the frequency response of the filter considering an ideal inductor of 4.7 mH, without parasitic capacity, and the real case with the same inductance value but with 7 pF of parasitic capacity.
In both cases, the resistor for the Q reduction of the serial resonance has been optimized to keep the frequency response flat in the through-band. The value of this resistor results from the order of 30 kΩ to 33 kΩ depending on the case.
In particular, the application of the receiver system at the author's installation site required maximum attenuation in the area between 1300 kHz and 1600 kHz, where the nearest and most powerful AM stations are located.
In this frequency range, the attenuation is approximately constant at 14.5dB.
For this reason, the filter thus initially implemented was not fully useful for the purposes proposed.

7.3.- Practical implementation of the input filter.

As parasitic capacity is largely defined by the geometry in the construction of the inductors, rather than by the value of their inductance, three commercially produced molded inductors of 1.5 mH each were used, which also have a parasitic capacitance of approximately 7 pF, producing a self-resonant frequency of 1550 kHz.
This implementation generates a maximum attenuation in the area of the frequencies of interest (1300 to 1600 kHz) and the equivalent series capacity of 2.3 pF produces a minimum final attenuation of 20.3 dB from 2800 kHz.
The 30 kΩ resistor required to reduce Q and optimize frequency response within the passband was subdivided into two resistors of 15 kΩ each as indicated in the adapter circuits in Figure 3 and Figure 7.



Stroke Line: Ideal Inductor
Continuous Line: Real Inductor

Figure 10.- *Frequency responses of the filter made with a 4.7 mH inductor and a 30 kΩ resistor.*

Figure 11 shows the frequency response corresponding to the filter implemented with the three inductors in series as described above.
If the available or purpose-built inductors have self-resonance frequencies higher than those necessary to produce the desired frequency response, an external capaciance (Cp1) of such a value as to bring the resonance to the required value must be added.
Whenever a subdivision of the total required inductance is made, all component parts must be equal, inductances and parasitic capacities and consequently equal resonant frequencies.
If this condition is not respected, the frequency response will exhibit multiple attenuation maxima, with intermediate zones of minimum attenuation depending on the degree of discrepancy between the respective resonant frequencies of each part into which the inductance has been subdivided.

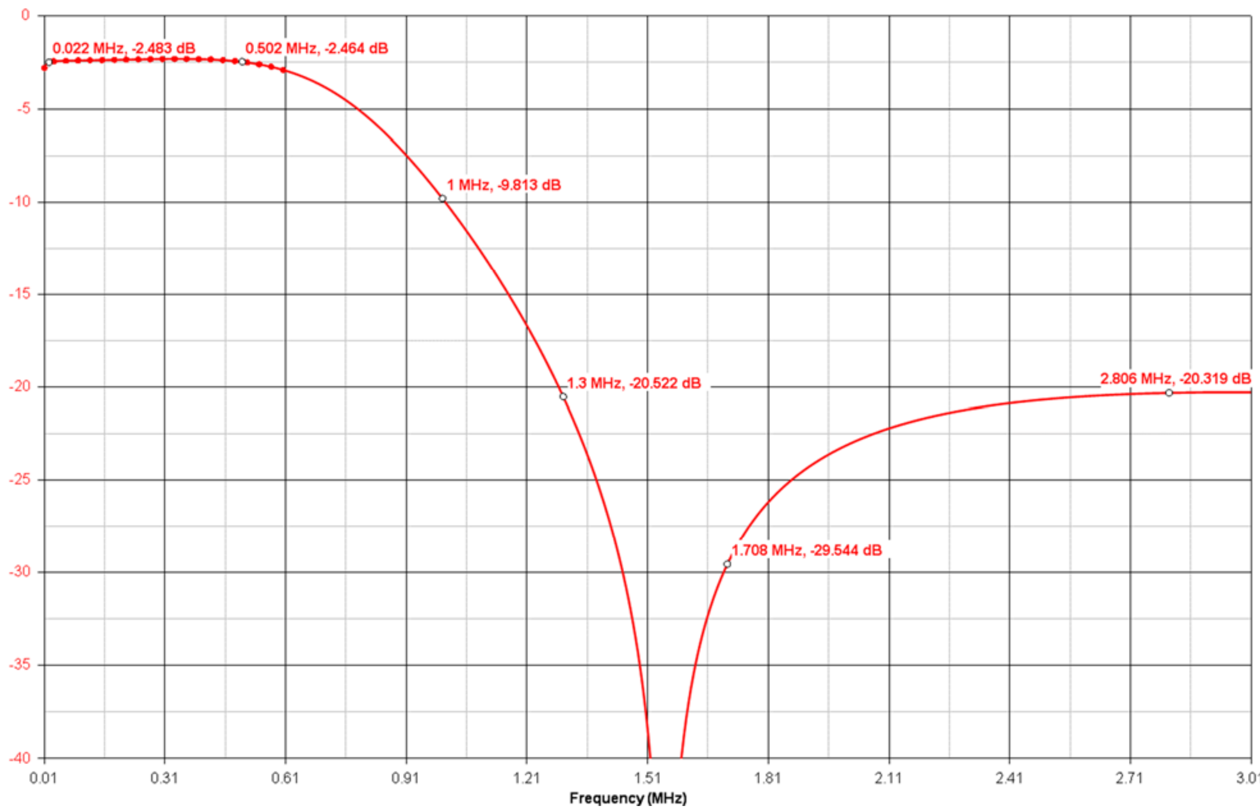


Figure 11*.- Frequency response of the actual filter implemented with three 1.5 mH inductors and two 15 kΩ resistors. Circuits in Figure 3 and Figure 7*.

8.- ANALYSIS OF THE NOISE LEVEL GENERATED IN THE INPUT STAGE.

For the noise analysis of the input stage, within the frequency range of interest (15 kHz to 515 kHz), the input circuit is reduced to the model in Figure 12 where:

Ua = Induced signal potential at the Electrode.
Ca = Electrode's own capacitance.
Ce = Stage input capacitance with JFET.
Rf = Input Filter Q reducing Resistor.
Unrf = Noise potential generated by Rf.
Rc = JFET gate polarization Resistor.
Unrc = Noise potential generated by Rc.
Unfet= Input equivalent noise potential generated by the JFET.
Une = Total Noise potential at JFET input.
Uno = Noise potential at adapter output.

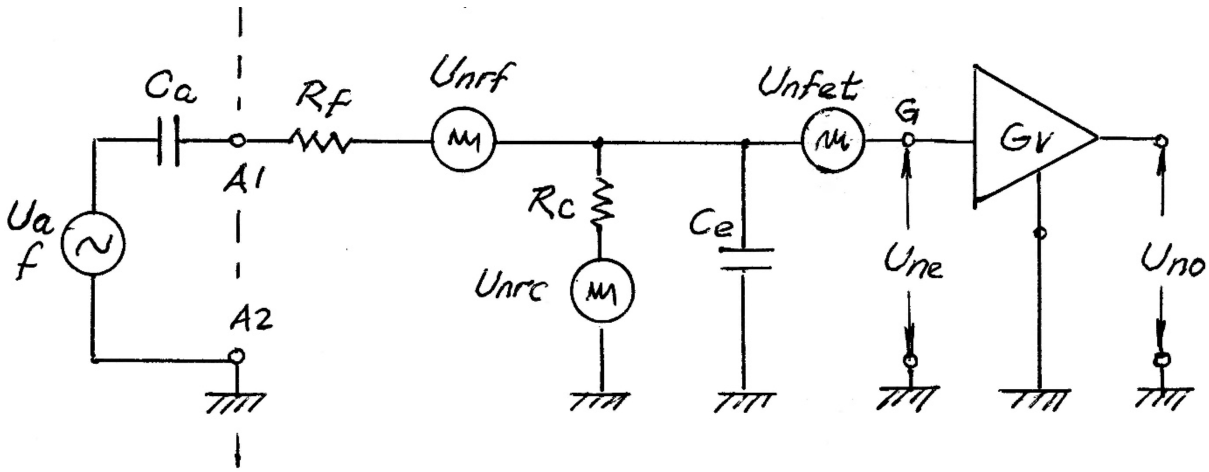


Figure 12.- *Model for the evaluation of the different noise sources of the input circuit.*

8.1.- Potencial (Un1) generado sobre la compuerta del JFET por el resistor (Rf).

The noise potential generated by the resistor (Rf) is:

$$Unrf = (4 \cdot k \cdot T \cdot B \cdot Rf)^{1/2} \quad [V]$$

Where:

$k = 1{,}38^{-23}$ J/K
$T = 300$ K
$B = 250$ Hz
$Rf = 30000\ \Omega$

Finally you get the result:

$$Unrf = 0{,}352\ \mu V \qquad (20)$$

As can be deduced from the model in Figure 12, the thermal noise potential (Unrf) generated by the damping resistor (Rf) turns out to be in series with the potential induced at the electrode (Ua).
The consequence of this is that the noise potential generated by this resistor has the same relative weight as the induced potential in the electrode and will therefore also be affected by the frequency-independent k-factor determined in Section 4.2 equation (10):

$$k = Ca / (Ca + Ce) = 0{,}7684$$

The resulting noise potential (A1) at the JFET input is:

$$Un1 = k \cdot Unrf = 0{,}7684 \cdot 0{,}352 = 0{,}270\ \mu V \qquad (21)$$

8.2.- Potential (Un2) generated on the JFET gate by the resistor (Rc).

The noise potential generated by the resistor (Rc) is:

$$Unrc = (4 \cdot k \cdot T \cdot B \cdot Rc)^{1/2} \quad [V]$$

Where:

$k = 1{,}38^{-23}$ J/K
T = 300 K
B = 250 Hz
Rc = 1 MΩ

Finally you get the result:

$$Unrc = 2{,}035\ \mu V \qquad (22)$$

As can be deduced from the model in Figure 12, the thermal noise potential (Unrc) generated by the gate bias resistor (Rc) turns out to be affected by a frequency-dependent attenuation determined by the low-pass filter constituted by the 1MΩ resistor in series with the noise generator (Unrc) and the parallel of the Ca and Ce capacitances as load.
From the analysis of this filter, it can be deduced that the attenuations depending on the frequencies of interest are:

f	***Atenuation***	
[kHz]	***[dB]***	***[V/V]***
15	*-14,5*	*0,188*
20	*-16,7*	*0,146*
30	*-19,9*	*0,101*
60	*-25,4*	*0,054*
120	*-29,9*	*0,032*
240	*-32,5*	*0,024*
480	*-32,8*	*0,023*

Applying to the magnitude of (Unrc) obtained in (22) the correction due to the attenuation indicated in the table above, the corresponding values of (Un2) are obtained:

f [kHz]	***Un2 [µV]***
15	*0,383*
20	*0,297*
30	*0,206*
60	*0,109*
120	*0,065*
240	*0,048*
480	*0,047*

(Table 6)

8.3.- Potential (Unfet) generated by the active device.

From the specifications corresponding to JFET transistors (J308/J310, U308/U310) the noise potential (Unfet) equivalent to the input, considering the worst condition corresponding to the minimum frequency of 15 kHz and referring to a bandwidth of 250 Hz is:

$$\text{Unfet} = 0{,}032\ \mu\text{V} \qquad (23)$$

8.4.- Total noise potential (Une) generated by the input stage.

Having referred the noise potential generators of the resistors to the input of the JFET gate, considering the attenuations introduced by the circuit according to the location of each of them, the total noise level (Une) referred to the JFET input is calculated by means of the equation:

$$\text{Une} = (\text{Un1}^2 + \text{Un2}^2 + \text{Unfet}^2)^{1/2} \qquad (24)$$

Table 7 below summarizes the results of applying equation (24) and the corresponding values of the noise potential at the output of the impedance adapter (Uno) calculated by multiplying the above by the gain (Gv) of the adapter:

f [kHz]	***Une [µV]***	***Uno = Gv Une [µV]***
15	*0,470*	*0,369*
20	*0,403*	*0,316*
30	*0,341*	*0,276*
60	*0,293*	*0,230*
120	*0,280*	*0,220*
240	*0,276*	*0,217*
480	*0,276*	*0,217*

(Table 7)

Comparing these calculated results with the corresponding measured values presented in Section 4.4, Table 3, the correspondence between the two is verified with errors in the order of 1.5 dB derived from the process of practical measurement of noise levels of very low magnitudes.

Table 7 shows that for all frequencies above 30 kHz, the noise generated by the filter's Q-reduction resistor (Rf) is dominant.
At frequencies below 20 kHz, the noise generated by the gate bias resistor (Rc) begins to dominate.
Over the entire frequency range of interest (15 kHz to 515 kHz) the noise generated by the JFET does not contribute significantly to the total noise level.

In order to obtain the noise levels and consequently the expected sensitivity, it is important that metal film resistors are used for both resistors (Rf and Rc) in the implementation of the adapters.

9.- EXTERNAL NOISE LEVELS IN VLF - LF.

In order to assess whether the sensitivity obtained from the combination of electric field sensor and impedance adapter, determined in Section 4.4, is suitable for the reception of weak signals in the proposed frequency range (15 kHz to 515 kHz), it is necessary to know the level of external noise, of natural and artificial origin, in the installation area of the receiving system.
For frequencies above 300 kHz, information on the expected noise levels depending on the frequency and installation area is documented in the Reference publication [5].
For frequencies below 300 kHz, the only documentation that contains some of the necessary information is the Reference [6] which provides measured values only particularly at frequencies below 30 kHz.

9.1.- Noise levels in the range of 300 kHz to 500 kHz.

From Reference [5] we obtain the equation that relates the level of the electric field (Ene) of noise to the noise factor (Fam) corresponding to the frequency (f) and the type of installation area of the receiving system:

$$20 \log(Ene) = Fam + 20 \log(f) + 10 \log(B) - 95{,}8 \quad [dB_{(\mu V/m)}] \qquad (25)$$

Where: Fam = External Noise Factor [dB]
f = Frequency [MHz]
B = Bandwidth [Hz]

From the graph of the document, the factors (Fam) corresponding to an area with a minimum noise level such as the so-called Rural Quiet are obtained:

Fam = 67,5 dB @ 300 kHz
Fam = 62,0 dB @ 500 kHz

Replacing these values in equation (25) and considering a bandwidth (B) of 250 Hz yields:

$$Ene = 0{,}183\ \mu V/m \ @\ 300\ kHz$$
$$Ene = 0{,}162\ \mu V/m \ @\ 500\ kHz \qquad (26)$$

The sensitivity value calculated in Section 4.4, Table 4, from the noise measurements of the impedance adapter in combination with the electric field sensor electrode installed at a height L = 6.85m resulted:

$$Es = 0{,}053\ \mu V/m \ @\ 300\ kHz\ y\ 500\ kHz \qquad (27)$$

Comparing the noise levels obtained in (26) with the sensitivities determined (27) it can be deduced that, even with the degradation of the sensitivity introduced by the input filter resistor, the external noise level for a Quiet Rural area is between 10.8 dB and 9.7 dB higher than the noise level of the implemented system in the range of 300 kHz to 500 kHz.

9.2.- Noise levels in the range of 15 kHz to 60 kHz.

In this frequency range, the sources of noise generation are atmospheric discharges, the disturbances of which reach great distances as a result of the particular mechanisms of propagation of electromagnetic energy in the waveguide formed by the ionosphere and the Earth's surface.
The minimum measured values documented in Reference [6], originally determined with a bandwidth of 400 Hz, have been referred to a bandwidth (B) of 250 Hz for comparisons:

$$\begin{aligned} Ene &= 20\ \mu V/m\ @\ 15\ kHz \\ Ene &= 10\ \mu V/m\ @\ 30\ kHz \end{aligned} \qquad (28)$$

The value of the worst-case sensitivity calculated in Section 4.4, Table 4, from the noise measurements of the impedance adapter in combination with the electric field sensor electrode installed at a height L = 6.85m resulted:

$$Es = 0{,}083\ \mu V/m\ @\ 15\ kHz \qquad (29)$$

Comparing the minimum noise levels reported (28) with the worst sensitivity determined between 15 kHz and 30 kHz (29) it can be deduced that, even with the degradation of the sensitivity introduced by the input filter resistor and the JFET gate polarization resistor, the minimum reported external noise level is between 47.6 dB and 41.6 dB higher than the noise level of the implemented system in the range of 15 kHz to 30 kHz.

9.3.- Conclusion.

The sensitivities obtained with the impedance adapters described allow the detection of signals whose minimum magnitudes are only limited by the natural and artificial noises expected in the installation areas with the lowest documented levels.

10.- REFERENCE DOCUMENTS.

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Revision I01: 07/01/2024