THEORY OF OPERATION OF THE ELECTRIC FIELD SENSOR VLF – LF. 15 kHz to 515 kHz

1.- INTRODUCTION.

1.1.- General comments on the topic under discussion.

The reception of radio electric broadcasts in the frequency range from 15 kHz to 515 kHz presents additional challenges to traditional antenna design due to the large wavelengths involved, 20 km to 600 m.

In addition, as a result of the particular mechanisms of electromagnetic radiation propagation in this frequency range, the use of vertically polarized antennas is required.

It is not physically possible to make classical antennas such as quarter-wave monopoles on ground plane or directional Beverage antennas for use in receiving installations in urban, suburban and rural areas, except in the latter case, if the frequencies involved correspond to the upper end of the aforementioned range.

Thus, in almost all cases, the physical dimensions of the antennas must inevitably be much smaller than the operating wavelength.

The two basic alternatives to which the different practical implementations of small antennas can be assimilated are the Short monopole on ground plane and the Loop.

As a result of the above, the so called "antennas" actually become Electric field Sensors in the case of the Short monopole and Magnetic field sensors in the case of the Loop.

The Short monopole only responds to the Electrical component (E) of the electromagnetic radiation and the Loop only responds to the Magnetic component (H).

Section 2 of this document describes the theory, implementation and characterization of an Electric field Sensor whose geometry allows to increase the sensitivity obtainable by 6 dB compared to the traditional short monopole on ground plane. See the cover photo.

The practical implementation with its constructional, mechanical and electronic details are incorporated in Section 3.

Installation details and recommendations for optimal operation are presented in Section 4.

Section 5 contains the reference bibliography used as a basis for the different topics involved in this document.

2.- THEORETICAL ANALYSIS.

2.1.- Short monopole on ground plane.

For practical purposes, a short monopole on the ground plane may be defined as a conductor of length (L) less than one-tenth of one-quarter of the wavelength (λ) of operation arranged vertically on the surface of the earth and with its lower end isolated from it. References [1] and [3].

Although the definition implies a spatial geometry with revolution symmetry with axis on the conductor, for reasons of simplicity, Figure 1 shows a two-dimensional drawing of a cross-section, with a plane passing through the conductor axis.

In the case that it is used for reception, the potential generated by the electrical component (E) of the radiation is obtained between the lower end of the conductor and the ground.

A peculiarity resulting from the condition imposed on its length (L) against the wavelength (λ) is that the potential of any point of the conductor with respect to the ground is always the same and we will call it henceforth (Ua).

This makes it possible to analyze what happens when the conductor is immersed in a vertically polarized electromagnetic field, whose electrical component (E) is perpendicular to the earth's surface, as if it were an electrostatic problem.

All points on conductive surfaces are equipotential.

With this assumption and observing the basic rules of electrostatics, Reference [2], the electric field lines have been drawn with red strokes and the equipotential lines with black interrupted strokes.

In the areas away from the conductor, the electric field lines remain parallel to each other and terminate at the earth's surface (zero potential).

In the area near the conductor there are now field lines that curve and end above the conductor and also generate new lines that leave the conductor and end in the ground plane (zero potential).

The conductor is now at a non-zero potential. In order to relate what happens with the different magnitudes involved in a real case, a scale of heights expressed in meters has been incorporated in Figure 1 and it has been assumed that the magnitude of the uniform electric field in which the conductor is immersed is 1 V/m.

Thus, in areas far from the influence of the conductor, the equipotential lines are equally spaced and in correspondence with the respective heights with respect to the ground. As an example, at a height of 4 meters, the potential is:

$$U = H \times E = 4\text{m} \times 1\text{V/m} = 4\text{ V}.$$

In the vicinity of the vertical conductor, the distribution of the electric field and the equipotential lines are altered, with respect to the uniform condition, so that the rules of electrostatics are complied with.

This means that for this the conductor acquires a potential of 2V with respect to the ground and that this value corresponds to the average between the potential corresponding to the maximum height of 4m and the minimum height of 0m.

That is, the potential (Ua) induced at the monopole with respect to land is:

$$Ua = E \cdot L / 2 \qquad (1)$$

Where:

Ua : Field-Induced Potential [V]

E : Electric field [V/m]

L : Overall monopole length [m]

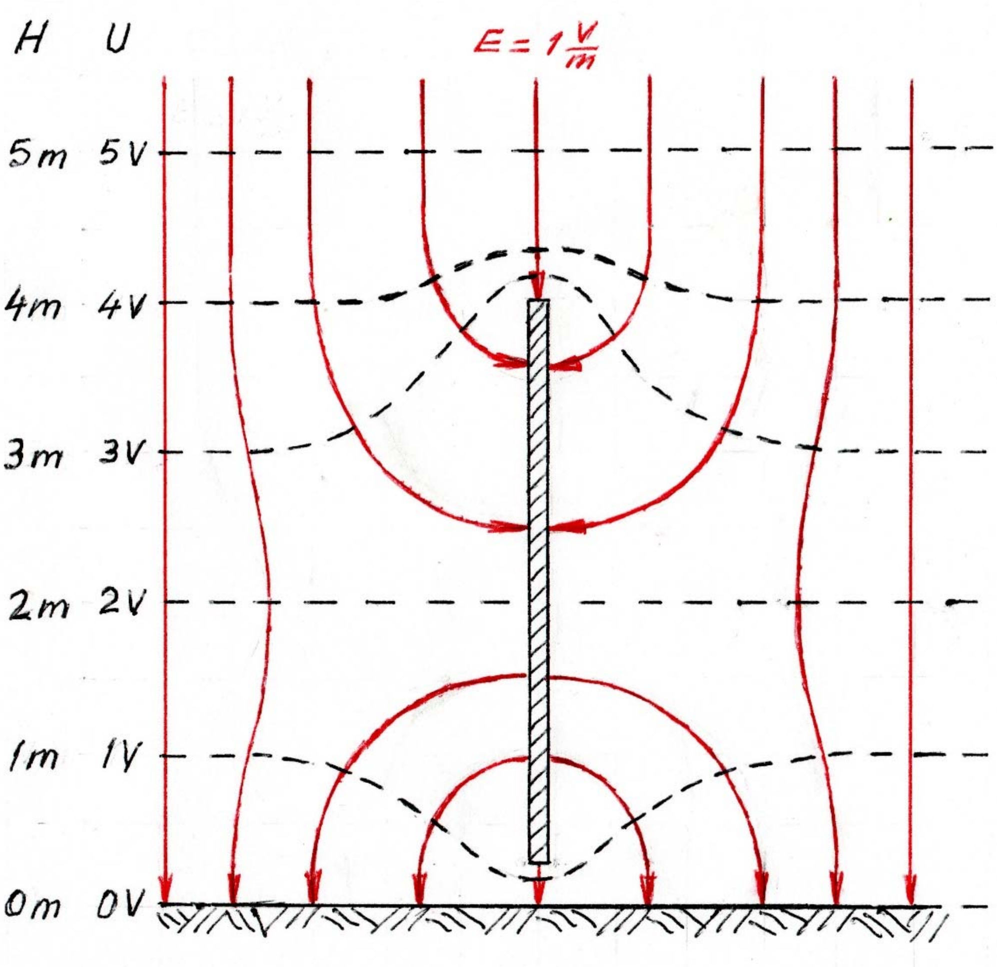

***Figure 1**.- Short monopole.*

2.2.- Electric field sensor.

The geometry of the proposed electric field sensor consists of a circular planar electrode, made of conductive material, arranged parallel to the ground plane at a height (L). Below the electrode is a vertical conductor in a position coinciding with the electrode center. The vertical conductor is in contact with the ground at the lower end and isolated from the electrode at the upper end.
Figure 2 shows a cross-section with a plane coincident with the vertical conductor axis.
The same electric field conditions of vertical polarization of magnitude 1 V/m and position in height (L) of the electrode equal to the length of the vertical conductor of the monopole have been assumed as described above.
Applying and observing the basic rules of electrostatics, Reference [2], the electric field lines have been drawn with red strokes and the equipotential lines for this new configuration have been drawn with interrupted black strokes. Figure 2.
In the area covered by the electrode, the field lines end above it and, being at a height of 4 m, it acquires a potential of 4V with respect to the ground.

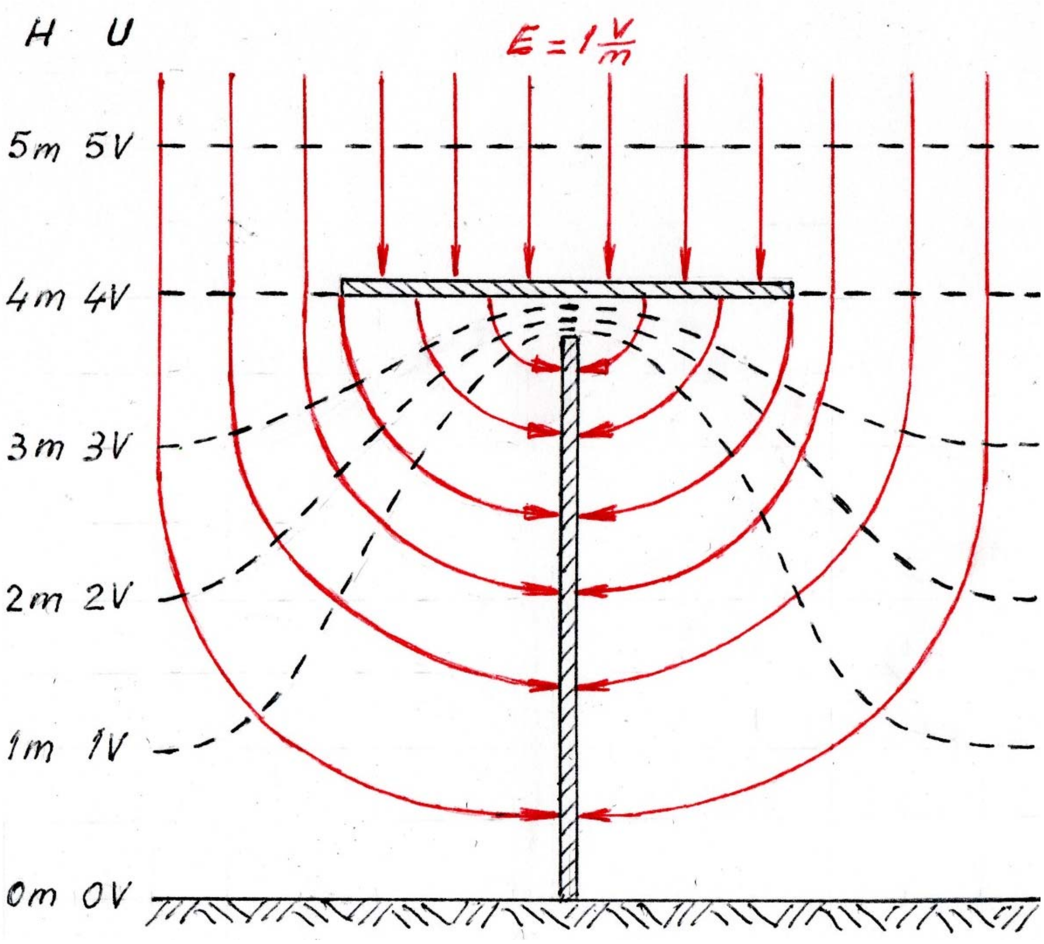

Figure 2.- *Electric Field Sensor.*

Below the electrode, field lines are generated that curve and end above the vertical conductor that is at zero potential (ground).

Outside the electrode area, but in close proximity to it, some field lines also curve over the vertical conductor.

In areas farther away from the structure, the field remains undisturbed, terminating the field lines directly on the surface of the earth.

The result of the redistribution of the field and the equipotential lines is that the electrode now acquires a potential of 4 V with respect to the vertical conductor which is at zero potential.

In conclusion, the potential (Ua) acquired by the electrode with respect to the vertical conductor is:

$$U_a = E \cdot L \qquad (2)$$

Where:
U_a : Field-induced potential [V]
E : Electric field [V/m]
L : Electrode ground height [m]

Comparing the results obtained from the induced potential (Ua) for the case of the monopole, Equation (1), and for the field sensor, Equation (2), it is concluded that for the same length of the monopole and the height at which the electrode is located, the induced potential at the electrode is always twice (6 dB) higher.

2.2.1.- Electrical model of the Electric Field Sensor.

In the theoretical analysis of the electric field sensor, for simplicity's sake, the rules of electrostatics were applied, which implied that the electrode had no electrical link with the vertical conductor that is in contact with the earth.

In the actual application, it is necessary to make contact with the electrode and the earth to obtain the desired potential (Ua).

Every real device has its own impedance (Ze) that will inevitably link the electrode to the ground.

As the sensor will operate with alternating signals in a range of 15 kHz to 515 kHz, it is necessary to determine the electrode's own impedance (Za) in order to then calculate the influence of the charge (Ze) on the actual potential obtainable.

By using an electromagnetic simulation program based on the NEC2 core, the magnitude of the impedance seen between the electrode and the ground conductor was determined. The problem definition for the simulation is as follows:

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CM Sensor Campo Electrico para VLF-LF
CM Adaptador de impedancias en extremo superior
CM Analisis capacidad equivalente
CM Altura electrodo: L = variable
CM Electrodo: D=1,80 m d=4 mm
CM Frecuencia: 20 a 500 kHz
CM Electrodo
GW 1 36 0 0 0 0 0.90 0.20 0.002
GM 0 7 0 0 45 0 0 0
CM Altura electrodo (L)
GM 00 0 0 0 0 0 0 6
CM Soporte
GW 2 240 0 0 0 0 0 6.00 0.002
CM Escala
GS 0 0 1.000000
CM Caracteristicas del plano de tierra
GE 1 0 0
GN 1
CM Excitacion
EX 0 2 240 0 1.00000  0.00000
CM Frecuencia
FR 0 21 0 0 0.020 .02
RP 0 181 1 1000 -90.00 90.00 1.00000 1.00000
FR 0 21 0 0 0.020 .02
RP 0 1 361 1000 90.00 90.00 1.00000 1.00000
EN
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For the simulation it has been considered that the electrode is not a solid disk, as assumed in the theoretical analysis, but is made up of eight conductors of circular section arranged at 45 degrees between each other as it has been implemented in reality.

Practical heights of the electrode position relative to ground between 3 m and 7 m have been considered.

The result of the reactive component of electrode impedance (Za) as a function of frequency is presented in Figure 3. The real component is less than 1 ohm even at the highest frequency, so compared to the magnitude of the reactive component, it is negligible and will not be considered in the future.

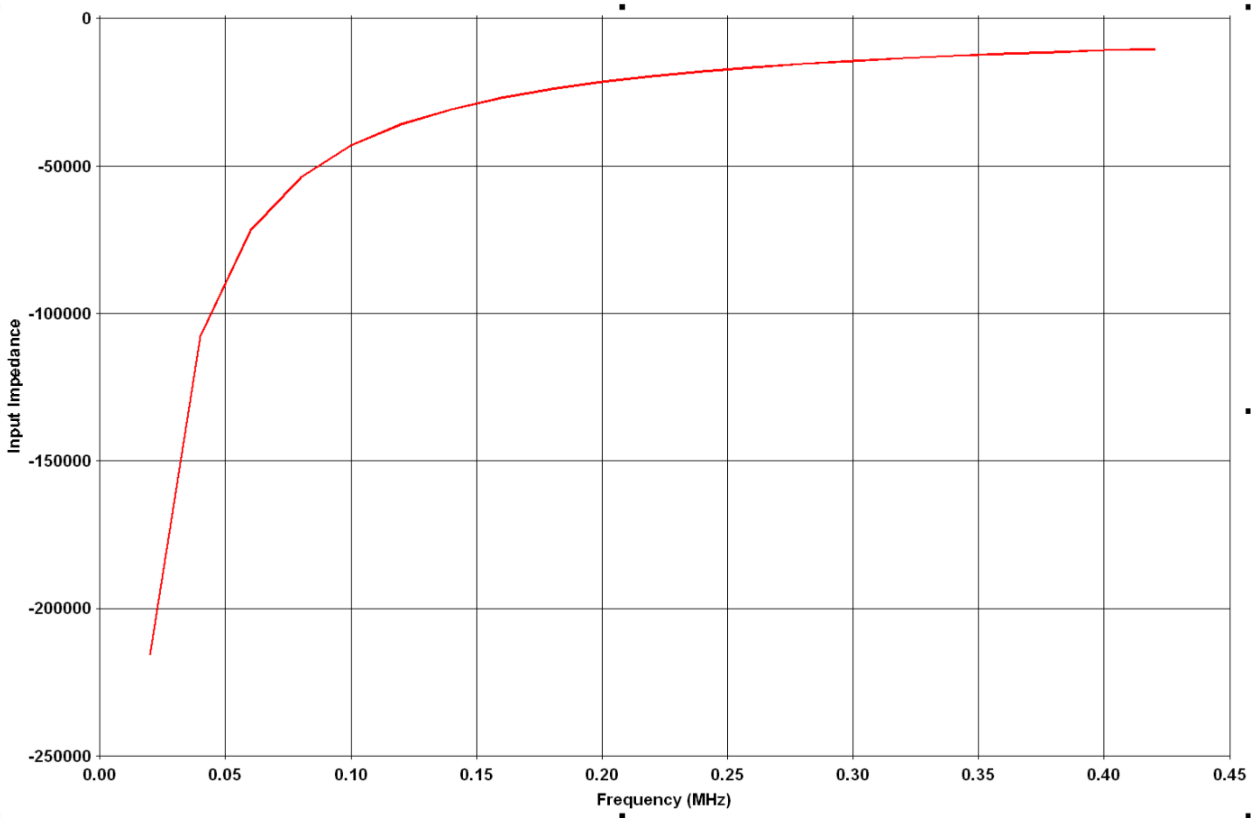

Figure 3.- *Variation of electrode reactance with frequency.*

From the graph it can be seen that the magnitude of the impedance varies between 220000 ohms at 20 kHz and 10700 ohms at 500 kHz.

With the values of the reactances at the different frequencies and heights of the electrode, it follows that the impedance seen between the electrode and the ground conductor is fundamentally a capacitive of magnitude:

$$Ca\ (15\ \text{kHz a } 515\ \text{kHz}) = 37{,}5\ \text{pF} \pm 1{,}5\ \text{pF} \qquad (3)$$

On the basis of the result obtained, the electrical model of the field sensor can be drawn as shown in Figure 4.

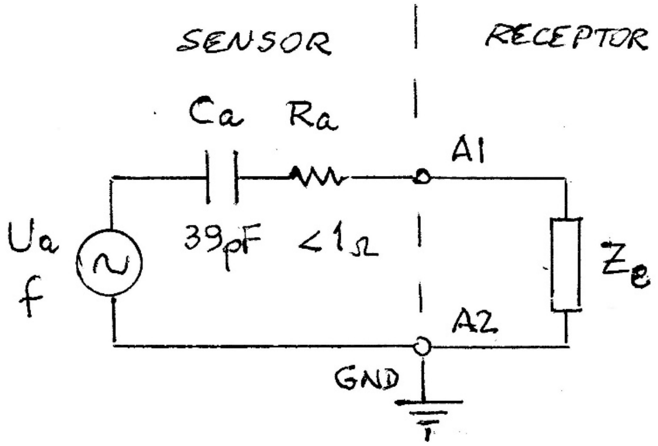

Figure 4.- Equivalent circuit of the passive electric field sensor.

The amplitude generator (Ua) corresponds to the field-induced potential at frequency (f) and the capacitor (Ca) represents the capacitance seen between the electrode and the ground
The impedance (Ze) corresponds to the receiving device connected between the sensor and the grounded conductor.

3.- PRACTICAL IMPLEMENTATION.

3.1.- Electrode and vertical conductor for grounding.

With the aim of reducing weight and fundamentally wind resistance, the electrode, instead of being solid, consists of eight aluminum rods of 900 mm (minimum length) and 4 mm in diameter arranged at 45 degrees between them.
The rods are inserted into a central piece of aluminum that has eight radial perforations on its periphery with the corresponding fastening screws as shown in Photograph 1.
At the same time, the piece has a reduction in its diameter at the lower end that allows it to be inserted into the upper end of a polystyrene insulating tube of 150 mm in length and 25 mm in diameter (yellow in Photograph 1) that keeps the electrode of the support tube insulated, which is in turn the vertical conductor that is linked to earth.
The connection between the vertical support tube and the lower end of the insulation is made by means of an aluminium insert that is inserted into the ends of both tubes.
The screws used to hold the insulating tube in position, both at the lower and upper ends, in turn allow the electrical connection with the impedance adapter described in the Reference document [4].
Neither the diameter of the electrode rods nor that of the support tube are critical in their dimensions. They can be increased if environmental conditions require it to give greater mechanical strength to the structure.
The length and diameter of the insulating tube is also not critical, but it should not be made too short if the sensor is anticipated to operate in rainy or snowy weather conditions.

Photograph 1.- *Detail of the support piece of the rods that make up the electrode.*

3.2.- Impedance adapter requirements.

With the values of the electrode's own impedance obtained from the electromagnetic simulation and whose values are between 220000 ohms and 10700 ohms of capacitive ballast, it follows that it is not possible to make a direct link between the sensor and the communication receivers that nominally have resistive input impedances (Ze) of 50 / 75 ohms.

It is necessary to sandwich between the two a device that performs the appropriate impedance transformation. Reference [4].

As the magnitude of the impedance of the sensor is variable with frequency, the use of a passive adaptation network would require it to be implemented with adjustable components to adapt it to each operating frequency.

In its replacement, it is advisable to implement an active impedance adapter that is capable of supporting low load impedances, such as those of communication receivers, but which at the same time has a sufficiently high input impedance (Ze) compared to (Za) so that the resulting potential (Ue) at the output of the voltage divider formed by Za and Ze is as close as possible to (Ua).

The voltage actually available when the sensor is charged with a capacitance (Ce) is:

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

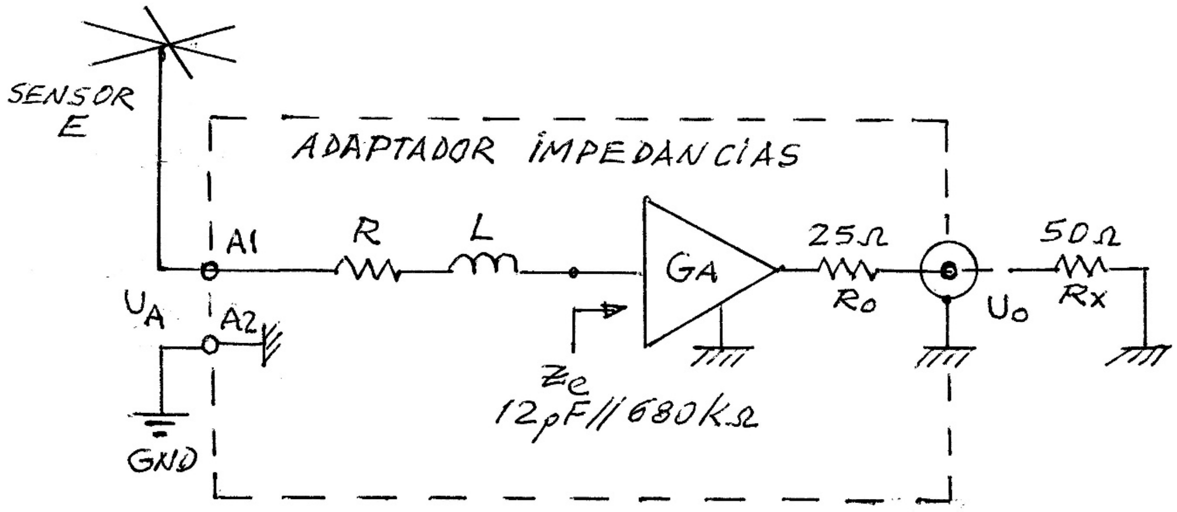

Figure 5.- *Block diagram of an active impedance adapter.*

Figure 5 shows the block diagram of an active impedance adapter implemented to meet the design requirements of the electric field sensor.
It consists mainly of an active stage (Ga) consisting of semiconductor devices such as JFET and BJT.
Provides a low output impedance (Ro=25/50 ohms) capable of exciting low impedance loads 50/75 ohms.
The RL network sandwiched in series between the electrode and the input of the active stage forms a low-pass filter with the capacitance of the active stage (12 pF) designed to reduce the levels of the signals induced in the sensor to the frequencies corresponding to the broadcast band (530 kHz to 1700 kHz).

4.- INSTALLATION RECOMMENDATIONS.

The recommendations involve the selection of the most suitable place within a property to install the sensor, how to select the height at which to place it depending on the environment and the intended sensitivity, and finally what are the requirements of the electrical grounding of the support mast.

4.1.- Installation site.

The uniformity of an electric field (E) is maintained if the ground surface is flat and there are no objects such as trees, fences, vehicles, people, animals, buildings and any other object that, although dielectric, introduces an alteration between the magnitude of the field and the corresponding associated electric potentials (U).
Objects made of materials of low conductivity (brick) in contact with the earth automatically force the surface generated by them to take on a potential very close to zero, significantly altering the position of the equipotential surfaces.

From the above, it follows that if the aim is to obtain from an electric field sensor the maximum sensitivity corresponding to its geometry (electrode size and installation height), it is mandatory that the installation site be as close as possible to the ideal conditions (flat terrain free of surrounding objects).

As the ideal installation site will be available in very few practical cases, a greater or lesser degree of degradation in the actual sensitivity obtainable with respect to the theoretical maximum should always be expected.

This is the disadvantage of electric field sensors where their Antenna Factor (Fa) is easily influenced by the particularities of the environment around them. Another factor to take into account is the possible capacitive coupling with elements that have disturbing electrical potentials such as transmitter antenna conductors, low, medium or high voltage power lines and telecomunications lines.

As the evaluation of all the above-mentioned factors is very complex, in practice it may be advisable to carry out several preliminary temporary installations in order to assess the best site before carrying out the final installation according to the intended sensitivity and the maximum acceptable noise level at the frequencies of interest.

4.2.- Selection of the electrode height.

From the theoretical point of view, according to Equation (2) presented in Section 2.2, it is only necessary to choose the value of the height (L) at which the electrode is installed to obtain the induced potential (Ua) necessary in a field of known magnitude (E). In the same proportion as the height increases, the induced potential increases.

Changing the height of the electrode produces only very small changes in the capacitance of the electrode (Ca) so that the ratio between (Ua) and (Ue), Equation 4 of Section 3.2, remains virtually unchanged.

In other words, the sensitivity is controlled by simply adjusting the installation height (L) of the electrode.

When it is not possible to have a large enough area at the required installation site to reduce the disturbing effects of surrounding objects on the electric field (E) in the electrode area, the electrode height (L) may be increased so that the objects are at levels below the electrode level.

This will make it possible to recover the lost sensitivity at the cost of a higher electrode installation height.

4.3.- Grounding.

As explained in the theoretical analysis of electric field sensor operation, Section 2.2, the potential that is induced at the electrode is referred to the ground potential. To do this, the impedance adapter must make contact with the ground potential via the electrode support tube.

The grounding of the ground has no special requirements in terms of the magnitude of the grounding javelin's resistance. As the input impedance of the impedance adapter is very high, even a grounding resistance of the order of 1 kΩ will be perfectly adequate.

This is true if the power supply that provides power to the impedance adapter has a floating (non-grounded) output. If this is not the case, in order to avoid the introduction of disturbing signals, the grounding resistance of the support tube should be of a much smaller magnitude than that corresponding to the grounding of the power source.
Ideally, there should be a low-impedance equipotential earth network to which all the elements of the installation that need to be grounded are connected.
This solution is used in the installation of the field sensor and the author's reception system.

5.- REFERENCE DOCUMENTS.

[1].- ANTENNAS, Second Edition. 1988. John D. Kraus. Mc Graw - Hill Inc.

[2].- ELECTROMAGNETICS, Secon Edition.- 1973. John D. Kraus. Keith R. Carver. Mc Graw - Hill Kogakusha Ltd.

[3].- Active Antennas for Radiomonitoring. Application Note, 8GE02. Rohde & Schwarz.

[4].- Impedance adapters for Electric Field Sensors for VLF - LF. 15kHz to 515kHz. Rev.I01. Eng. Daniel A. Esteban. January 2024.

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