ELECTROMAGNETIC ANALYSIS OF SHORT MONOPOLE AND ELECTRIC FIELD SENSOR AS RECEIVING ANTENNAS FOR VLF – LF

1.- INTRODUCTION.

The procedure used to determine the magnitude of the potential induced by a distant emitter in two different types of antennas for VLF - LF using electromagnetic simulation based on the NEC2 core is presented.
The antennas analyzed are the traditional Short monopole and the Electric field Sensor developed by the author and whose theory and implementation are described in Reference [1]. In both cases, an active impedance adapter with the same input impedance is considered to be used.
The final objective of the analyses is to determine the magnitude of the error that is made when analyzing the operation of them by means of a simplified procedure, based on the electrostatic theory as presented in the Reference document [1], with respect to a more rigorous evaluation by means of an electromagnetic simulation.
With the results obtained from the simulations, the values of the Sensitivity corresponding to the Electric field Sensor are corrected as presented in the aforementioned document. See Sections 4 and 5 of this document.
To generate excitation, the antennas are subjected to radiation produced by a distant emitter using a vertical quarter-wave radiator on the ground plane. For each of the frequencies to be analysed, the distance between the receiving antenna and the transmitter antenna is adjusted so that the transmitter is four times greater than the boundary distance between the near and far field areas. Reference [2].
In addition, the analyses are performed at three different frequencies (125kHz, 250kHz and 500kHz) as a numerical verification that the operation of both antennas, with the load conditions imposed by the active impedance adapter, is independent of the working frequency.

2.- PHYSICAL AND ELECTRICAL MODELS OF THE ANTENNAS.

Both the Short monopole and the Electric field Sensor are considered to have a total height of 6 meters from the ground plane.

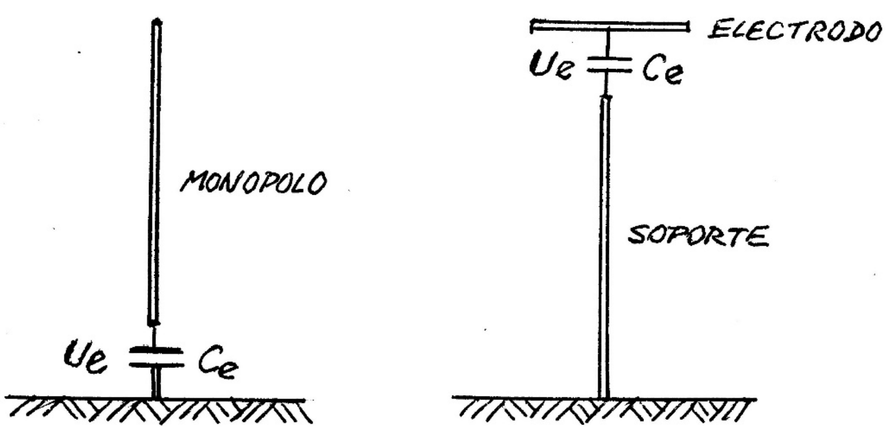

Figure 1.- *Physical diagrams of the antennas analysed.*

In the case of the short monopole, the potential generated is taken, by means of an active impedance adapter, between the lower end of the vertical conductor and the ground.
For the electric field sensor, the same impedance adapter is considered active, but the potential is obtained between the electrode and the conductive support that is linked to the ground.
Figure 1 shows the physical schematics of both antennas. Although both antennas are physically different and so are the points to which the active impedance adapter is linked, the impedance presented by them is fundamentally capacitive and therefore can be represented by the same electrical model, such as the one illustrated in Figure 2:

Where:

Ua = Induced potential in the antenna. [V]
Ca = Equivalent antenna Capacitance. [pF]
Ue = Potential at impedance adapter input. [V]
Ce = Impedance adapter input capacitance. [pF].

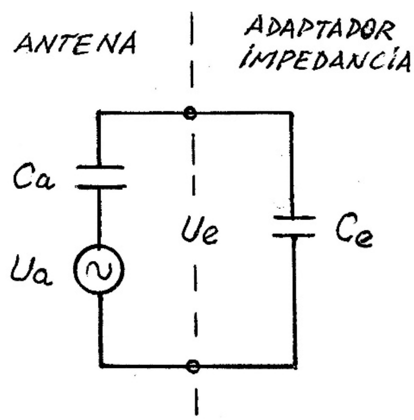

Figure 2.- *Generic electrical diagram of the antennas.*

In both cases, the input impedance of the impedance adapter is considered to be purely capacitive and to be Ce = 15 pF.
However, the equivalent capacity of both antennas is different and their magnitudes are:

Short monopole: Ca = 48,0 pF ± 1,5 pF

Field Sensor: Ca = 38,5 pF ± 1,5 pF

From the analysis of the wiring diagram in Figure 2 it can be deduced that the potential (Ue) available at the input of the impedance adapter is:

Short monopole: Ue = Ua 48,0 / (48,0 + 15) = Ua 0,762 (1)

Field Sensor: Ue = Ua 38,5 / (38,5 + 15) = Ua 0,720 (2)

From the electromagnetic simulations, the result will be the magnitude of the current (Ic) in the place where the capacitance (Ce) is connected, with it and the reactance of (Ce) at the operating frequency, the value of the potential in its terminals (Ue) is determined.
Equations (1) or (2), depending on the antenna in question, deduce the magnitude of the induced potential (Ua) for each antenna.

3.- ELECTROMAGNETICS SIMULATIONS.

From the physical schematics of the antennas, Figure 1, the files describing them are generated to be interpreted by the electromagnetic simulation program.
To maintain far-field conditions, the distances separating the transmitting antenna (Tx) from the receiving antenna (Rx) are different for each analysis frequency.
At the same time, for each distance, the power delivered to the transmitting antenna is modified accordingly so that the field strength at the receiving antenna is the same at all frequencies.
The simulation program only provides as a result the magnitude of the circulating currents for each of the segments into which the conductors describing an antenna are decomposed.
To achieve a good degree of accuracy in the magnitude of the currents, all conductors representing both antennas have been sectioned into segments of only 25 mm in length.
To determine the potential magnitude (Ue) it is necessary to calculate the product of the magnitude of the current flowing through the segment where the capacitance (Ce), which represents the impedance adapter, is connected, with the corresponding reactance.
Like this:

$$Ue = Ic / 2 \cdot \pi \cdot f \cdot Ce \quad [V] \qquad (3)$$

Then the induced potential in the antenna (Ua) is calculated using the ratios (1) or (2) depending on whether it is the Short monopole or the Electric field Sensor:

Short monopole: $$Ua = Ic / 0{,}762 \cdot 2 \cdot \pi \cdot f \cdot Ce \quad [V] \qquad (4)$$

Field Sensor: $$Ua = Ic / 0{,}720 \cdot 2 \cdot \pi \cdot f \cdot Ce \quad [V] \qquad (5)$$

The relationship of induced potentials (Ua) between each of the two antennas operating at the same frequency will determine the degree of validity of the simplified comparative analysis used in the document describing them. Reference [1].
In addition, with the magnitudes of the induced potentials (Ua) for the same antenna operating at different frequencies, it will be shown that both generate a potential that is independent of the frequency.

3.1.- Files and results of the simulations of the Electric Field Sensor.

3.1.1.- Frequency 125 kHz.

CM Electric Field Sensor for VLF - LF
CM Determination of Induced Potential
CM Impedance adapter between electrode and holder
CM Altura electrodo: H = 6 m
CM Electrodo: N = 8   D = 1,80 m   d = 4 mm
CM Soporte vertical: d = 4 mm
CM Frecuencia: 0,125 MHz
CM Excitación: Monopolo de 1/4 lambda
CM Distancia entre TX y RX: 4800 m
*CM **
CM Electrodo
GW 3 36 0 0 0 0 0.90 0 0.002
GM 0 7 0 0 45 0 0 0
CM Altura electrodo (H)
GM 100 0 0 0 0 0 0 6
CM Soporte
GW 2 240 0 0 0 0 0 6.00 0.002
CM Monopolo TX
GW 10 578 0 4800 0 0 4800 578 0.250
CM Escala
GS 0 0 1.000000
CM Características del plano de tierra
GE 1 0 0
GN 1
CM Impedancia de entrada Adaptador Impedancias (15 pF)
LD 0 2 240 240 1 1e-9 15e-12
CM Excitación (256 kW en 36 ohms)
EX 0 10 1 0 3036 0.00000
CM Frecuencia
FR 0 5 0 0 0.115 0.005
RP 0 181 1 1000 -90.00 90.00 1.00000 1.00000
EN

The current in segment 240 (upper end) of conductor 2 (support) where the capacitance (Ce) is connected is:

$$Ic = 4{,}6818 \cdot 10^{-5} \quad [A]$$

With Xc = 84883 Ω you get:

$$Ue = 3{,}974 \quad [V]$$

Using the ratio (5) results:

$$\boldsymbol{Ua = 5{,}519 \quad [V]}$$

3.1.2.- Frequency 250 kHz.

CM Electric Field Sensor for VLF - LF
CM Determination of Induced Potential
CM Impedance adapter between electrode and holder
CM Altura electrodo: H = 6 m
CM Electrodo: N = 8   D = 1,80 m   d = 4 mm
CM Soporte vertical: d = 4 mm
CM Frecuencia: 0,250 MHz
CM Excitación: Monopolo de 1/4 lambda
CM Distancia entre TX y RX: 2400 m
CM **
CM Electrodo
GW 3 36 0 0 0 0 0.90 0 0.002
GM 0 7 0 0 45 0 0 0
CM Altura electrodo (H)
GM 100 0 0 0 0 0 0 6
CM Soporte
GW 2 240 0 0 0 0 0 6.00 0.002
CM Monopolo TX
GW 10 288 0 2400 0 0 2400 288 0.250
CM Escala
GS 0 0 1.000000
CM Características del plano de tierra
GE 1 0 0
GN 1
CM Impedancia de entrada Adaptador Impedancias (15 pF)
LD 0 2 240 240 1 1e-9 15e-12
CM Excitación (64 kW en 36 ohms)
EX 0 10 1 0 1518 0.00000
CM Frecuencia
FR 0 5 0 0 0.240 0.005
RP 0 181 1 1000 -90.00 90.00 1.00000 1.00000
EN

The current in segment 240 (upper end) of conductor 2 (support) where the capacitance (Ce) is connected is:

$$Ic = 9{,}3624 \cdot 10^{-5} \quad [A]$$

With Xc = 42441 Ω you get:

$$Ue = 3{,}973 \quad [V]$$

Using the ratio (5) results:

$$\boldsymbol{Ua = 5{,}519 \quad [V]}$$

3.1.3.- Frequency 500 kHz.

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CM Electric Field Sensor for VLF - LF
CM Determination of Induced Potential
CM Impedance adapter between electrode and holder
CM Altura electrodo: H = 6 m
CM Electrodo: N = 8   D = 1,80 m   d = 4 mm
CM Soporte vertical: d = 4 mm
CM Frecuencia: 0,500 MHz
CM Excitación: Monopolo de 1/4 lambda
CM Distancia entre TX y RX: 1200 m
CM ********************************************************
CM Electrodo
GW 3 36 0 0 0 0 0.90 0 0.002
GM 0 7 0 0 45 0 0 0
CM Altura electrodo (H)
GM 100 0 0 0 0 0 0 6
CM Soporte
GW 2 120 0 0 0 0 0 6.00 0.002
CM Monopolo TX
GW 10 143 0 1200 0 0 1200 143.5 0.250
CM Escala
GS 0 0 1.000000
CM Características del plano de tierra
GE 1 0 0
GN 1
CM Impedancia de entrada Adaptador Impedancias (15 pF)
LD 0 2 240 240 1 1e-9 15e-12
CM Excitación (16 kW en 36 ohms)
EX 0 10 1 0 759 0.00000
CM Frecuencia
FR 0 5 0 0 0.490 0.005
RP 0 181 1 1000 -90.00 90.00 1.00000 1.00000
EN
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The current in segment 240 (upper end) of conductor 2 (support) where the capacitance (Ce) is connected is:

$$Ic = 1{,}8705 \cdot 10^{-4} \quad [A]$$

With Xc = 21221 Ω you get:

$$Ue = 3{,}970 \quad [V]$$

Using the ratio (5) results:

$$\boldsymbol{Ua = 5{,}513 \quad [V]}$$

3.2.- Files and results of the simulations of the Short monopole.

3.2.1.- Frequency 125 kHz.

CM Short monopole for VLF - LF
CM Determination of Induced Potential
CM Monopole to ground impedance adapter
CM Longitud: L = 6 m
CM Frecuencia: 0,125 MHz
CM Excitación: Monopolo de 1/4 lambda
CM Distancia entre TX y RX: 4800 m
CM **
CM Monopolo corto RX (L)
GW 2 240 0 0 0 0 0 6.00 0.002
CM Monopolo TX
GW 10 578 0 4800 0 0 4800 578 0.250
CM Escala
GS 0 0 1.000000
CM Características del plano de tierra
GE 1 0 0
GN 1
CM Impedancia de entrada Adaptador Impedancias (15 pF)
LD 0 2 1 1 1 1e-9 15e-12
CM Excitación (256 kW en 36 ohms)
EX 0 10 1 0 3036 0.00000
CM Frecuencia
FR 0 5 0 0 0.115 0.005
RP 0 181 1 1000 -90.00 90.00 1.00000 1.00000
EN

The current in segment 1 (lower end) of conductor 2 (monopole) where the capacitance (Ce) is connected is:

$$Ic = 2{,}7102 \cdot 10^{-5} \quad [A]$$

With Xc = 84883 Ω you get:

$$Ue = 2{,}300 \quad [V]$$

Using the ratio (4) results:

$$\boldsymbol{Ua = 3{,}019 \quad [V]}$$

3.2.2.- Frequency 250 kHz.

CM Short monopole for VLF - LF
CM Determination of Induced Potential
CM Monopole to ground impedance adapter
CM Longitud: L = 6 m
CM Frecuencia: 0,250 MHz
CM Excitación: Monopolo de 1/4 lambda
CM Distancia entre TX y RX: 2400 m
CM ***
CM Monopolo corto RX (L)
GW 2 240 0 0 0 0 0 6.00 0.002
CM Monopolo TX
GW 10 288 0 2400 0 0 2400 288 0.250
CM Escala
GS 0 0 1.000000
CM Características del plano de tierra
GE 1 0 0
GN 1
CM Impedancia de entrada Adaptador Impedancias (15 pF)
LD 0 2 1 1 1 1e-9 15e-12
CM Excitación (64 kW en 36 ohms)
EX 0 10 1 0 1518 0.00000
CM Frecuencia
FR 0 5 0 0 0.240 0.005
RP 0 181 1 1000 -90.00 90.00 1.00000 1.00000
EN

The current in segment 1 (lower end) of conductor 2 (monopole) where the capacitance (Ce) is connected is:

$$Ic = 5{,}4181 \cdot 10^{-5} \quad [A]$$

With Xc = 42441 Ω you get:

$$Ue = 2{,}299 \quad [V]$$

Using the ratio (4) results:

$$\boldsymbol{Ua = 3{,}018 \quad [V]}$$

3.2.3.- Frequency 500 kHz.

CM Short monopole for VLF - LF
CM Determination of Induced Potential
CM Monopole to ground impedance adapter
CM Longitud: L = 6 m
CM Frecuencia: 0,500 MHz
CM Excitación: Monopolo de 1/4 lambda
CM Distancia entre TX y RX: 1200 m
*CM ***
CM Monopolo corto RX (L)
GW 2 240 0 0 0 0 0 6.00 0.002
CM Monopolo TX
GW 10 143 0 1200 0 0 1200 143.5 0.250
CM Escala
GS 0 0 1.000000
CM Características del plano de tierra
GE 1 0 0
GN 1
CM Impedancia de entrada Adaptador Impedancias (15 pF)
LD 0 2 1 1 1 1e-9 15e-12
CM Excitación (16 kW en 36 ohms)
EX 0 10 1 0 759 0.00000
CM Frecuencia
FR 0 5 0 0 0.490 0.005
RP 0 181 1 1000 -90.00 90.00 1.00000 1.00000
EN

The current in segment 1 (lower end) of conductor 2 (monopole) where the capacitance (Ce) is connected is:

$$Ic = 1{,}0813 \cdot 10^{-4} \quad [A]$$

With Xc = 21221 Ω you get:

$$Ue = 2{,}295 \quad [V]$$

Using the ratio (4) results:

$$\boldsymbol{Ua = 3{,}011 \quad [V]}$$

4.- SUMMARY OF RESULTS.

The results obtained from the simulations and calculations presented in Sections 3.1 and 3.2 are summarized below:

Antenna	***Freq. [kHz]***	***Ua [V]***
Short	*125*	*3,019*
Monopole	*250*	*3,018*
	500	*3,011*
Electric field	*125*	*5,519*
Sensor	*250*	*5,519*
	500	*5,513*

The ratio of induced potentials (Ua) between the two antennas for the same operating frequency are:

Frequency [kHz]	***Relation = Ua_{EFS} / Ua_{SM}***	***Relation [dB]***
125	*1,828*	*5,24*
250	*1,829*	*5,24*
500	*1,831*	*5,25*

Ua_{EFS} : *Induced Potential in the Electric field Sensor*
Ua_{SM} : *Induced Potential in the Short Monopole*

From the above summaries it can be concluded that:

- ***The ratio of induced potentials between the two antennas for all frequencies is 1.829 (5.24 dB) instead of the factor 2 (6 dB) inferred in the simplified analysis presented in the Reference document [1].***

- ***The induced potentials in both antennas are independent of the operating frequency.***

5.- CORRECTION OF THE SENSITIVITY VALUES OF THE ELECTRIC FIELD SENSOR.

Below are the values of the corrected Sensitivity determined from the electromagnetic analysis presented after affecting the original values, Reference [1], by the following correction expression:

$$\text{Corrected Sensitivity} = (\text{ Original Sensitivity})\cdot 2 / 1{,}829 \qquad (6)$$

Es = 0,190 [uV/m] @ ***f = 15 kHz***
Es = 0,175 [uV/m] @ ***f = 20 kHz***
Es = 0,149 [uV/m] @ ***f = 30 kHz***
Es = 0,143 [uV/m] @ ***f = 40 kHz***
Es = 0,141 [uV/m] @ ***f = 60 kHz***
Es = 0,142 [uV/m] @ ***f = 490 kHz***
Es = 0,147 [uV/m] @ ***f = 520 kHz***

6.- REFERENCE DOCUMENTS.

[1].- Theory of operation of the Electric field Sensor. VLF - LF. 15 kHz to 520 kHz. Rev. I01. Eng. Daniel A. Esteban. January 2024.

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