Programmable Antenna Simulator

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Abstract—The main purpose of this work is the implementation of circuits with concentrated parameters that have the same input impedance as the VHF antenna of the radio P/PRC-525, in the frequency band from 33 MHz to 88 MHz, for the three positions most commonly used by the military in combat. These positions are: standing operator, lying operator and radio on the floor. In the first two positions, the radio is on the back of the operator.

Focusing on the measurement and simulation of the antenna in question, initially this document dedicates to the study of the antenna characteristics, and the methods that could theoretically describe its operation on the respective band of interest (33-88 MHz).

To satisfy this objective, it was used the MATLAB simulation program in order to facilitate the analysis of the method chosen.

As validation of the theoretical results obtained in MATLAB, it was used the simulator of antennas CST MICROWAVE STUDIO 2011, which is a very viable theoretical contribution in such matters.

After all the theoretical study performed, measurements were made with the antenna covering the band from 33 to 88 MHz, for each of the three positions of interest adopted by the military. For this purpose, it was used the measuring apparatus Network Analyzer.

About these measures, it was taken as reference the ones that closely match the theoretical results intended, and were designed the three circuits that simulate the input impedance of the antenna at the three positions of interest adopted by the military.

Finally, the three desired circuits were physically implemented. They were placed in a box which serves as support, protection, and connection to the radio equipment P/PRC-525. These three circuits represent the input impedance simulator of the radio VHF antenna. After its conclusion, it is possible to consider it an ideal representation of the antenna, meeting the objectives for which it was developed.

In general, all the objectives proposed have been completed.

Index Terms—antenna, input impedance, simulation, circuits.

1. INTRODUCTION

COMMUNICATIONS play a vital role in military organizations, either in performing daily activities or in the development of operations. The need for information has led to a supply of the means that allowed the decision making process and the operation of weapons systems. Given the characteristics of the current battlefield, the Command and Control Systems incorporate the latest technological innovations.

The radio P/PRC-525 represents a revolution in digital battlefield, allowing great flexibility in terms of frequency bands of operation, waveforms and functions [1].

This theme focuses on a topic of broad interest, not only on a personal level but also on a professional level, since it is based on a project of interest to the Portuguese Army.

It is important to note that this project started several years ago through the company EID, following a plan that would allow to test all the radios in a laboratory, saving, money, and possible diseases due to the constant contact with the radiation emitted by the antennas.

The study of the input impedance of an antenna is essential in the design and development of transmitters and the transmission line in which they are associated.

II. STUDY OF THE ANTENNA INPUT IMPEDANCE

A. Antenna of VHF

The antenna is an essential element in any communication system by electromagnetic waves, acting as an interface between the system elements that guide the wave and the environment in which it propagates. This is the electric component responsible for transmission and reception of electromagnetic waves [2].
In Fig. 1 is illustrated the antenna of VHF, which is used by the radio P/PRC-525 in version Manpack, in the frequency band of 33 MHz to 88 MHz. It is a laminar antenna with a length of 1.32 m [3]. The sides L1 and L2, which are illustrated in the figure above, measure 3 mm and 14 mm respectively.

This antenna is made of steel and coated with a layer of copper in order to have better conductivity. It is also covered by a soft plastic in order to protect it from the corrosive effects [4].

This antenna is optimized for the frequency of 56.8 MHz, which corresponds to a wavelength of 5.28 m (monopole of λ/4).

Generally, the input impedance of an antenna has the following form:

\[ Z_a = R_a + jX_a \]  

(1)

In which Ra represents the input resistance and Xa is the input reactance, which is associated to the electromagnetic energy stored near the antenna.

B. Theoretical value of the antenna input impedance

This theoretical impedance is the impedance that would be expected if the antenna were isolated and under ideal conditions. It should be understood by “ideal conditions” the existence of a radiating antenna in free space, in the absence of reflecting objects that may interfere with its operation.

The determination of the theoretical value of the antenna input impedance requires the use of formulations based on models that are generally difficult to implement, and which result in uncertain values of input impedance. However there are certain solutions which enable to reach more and more approximate results.

There is a need to make use of formulations based on simplified models or numerical models for the determination of these parameters.

Among the numerical methods, the method of moments is certainly the most used. In this case, the mathematical model of the antenna is performed using equations of electromagnetic potentials in the frequency domain. However, it has the disadvantage of being difficult to implement.

In terms of simplified methods, it is very difficult to get correct results on the value of the input impedance. However there are solutions to get the results with some approximation.

One of these methods is the method of cylindrical antenna, also called the integral equation method. This will solve an integral equation by a method of successive approximations, starting from the need to satisfy the condition of continuity of the tangential component of the electric field at the boundary between the external environment and cylindrical surface of the antenna. This was the method chosen to estimate the input impedance of the antenna.

To obtain a good approximation of mathematical solutions, this method assumes the following conditions:

- Cylindrical antenna made of a good conductor material and immersed in vacuum.
- Length L, with L=2 l
- Cylinder terminated by hemispheres with radius a
- \( l > a \)
- \( l < \lambda \)
- \( \beta a < \lambda \)
- \( Z_0 = 0 \) (considering perfect conductor)
- \( \delta \rightarrow 0 \)

**Formal solution of King & Middleton**

The formal solution of King-Middleton is one of the most reliable methods for solving the integral equation method, because it presents much more accurate results, being widely used for the theoretical calculation of the antenna’s impedance. This assumes the conditions considered in the method of cylindrical antenna.

The current’s intensity that runs through the antenna can be described by the following expression:

\[ I(z) = j \frac{V_T}{60 \Psi_{KM}} \left[ \frac{\sin(\beta(l-z))}{\cos(\beta)} + \frac{\Delta_{KM}^2(z)}{\Psi_{KM}^2} + \frac{\Delta_{KM}^2(z)}{\Psi_{KM}^2} + \ldots \right] \]  

(2)

In which \( V_T \) is the voltage applied to the terminals of the antenna, and \( \Psi_{KM} \) is the King-Middleton expansion parameter.

Known the current, it is possible to calculate the input impedance from the following ratio:

\[ Z_i = \frac{V_T}{I(0)} \]  

(3)
In a second-order development, the impedance of the antenna isolated can be calculated by the following equation:

\[
(Z_i)_2 = -j60\Psi_{KM} \left[ \cos(\beta) + \frac{(D_1)(\alpha_1^i + j\alpha_2^i)}{\Psi_{KM}} + \frac{\alpha_2^i + j\alpha_2^i}{\Psi_{KM}^2} \right] \\
\left( D_1 \right) = 2 - \frac{\Omega}{\Psi_{KM}} \\
\left( D_2 \right) = 2 - \frac{3 - \frac{\Omega}{\Psi_{KM}}}{\Psi_{KM}^2} \\
\left( D_3 \right) = 3 - 2\frac{\Omega}{\Psi_{KM}} \\
(4)
\]

In which, \( \alpha_i, \beta_1, \alpha_2 \) and \( \beta_2 \) are tabulated [5].

It should be noted that since the previous model treat the antenna as a cylinder terminated by a hemisphere of radius \( a \), the VHF antenna used in this work is approximated to a monopole with a radius of 8.5 mm (intermediate situation between the sides of the antenna L1 and L2).

Then, to confirm the use of the model, it is necessary to verify in advance whether there is concordance between the requirements for application of the method of King-Middleton and the antenna parameters concerned.

For an antenna with length \( l = 1.32 \) m and a radius \( a = 8.15 \) mm, it is obtained \( 3.41 < \lambda < 9.09 \) and \( 0.912 < |\beta| < 2.432 \) for the frequency band of interest (33 and 88 MHz). You can verify that \( l > a, l \lambda, \beta a << 1 \).

The study of all the methods analyzed, and in particular the formal solution of King-Middleton, was based on A. Fernandes [5] and J. Kraus [6].

And then, will be compared to an analysis conducted by CST simulation program, which is based on numerical methods to obtain their results.

The simulation program CST is based on a finite element method (FEM). A very general approach consists on the decomposition of Maxwell's equations in discrete elements, having as final result an array of algebraic equations. This can be described in the time domain and frequency.

In the case of using the program CST to obtain the results of isolated antenna under ideal conditions we can observe in the figure below, the antenna (yellow) connected to a 50 ohm port (red) that represents the connector of the radio, and a plane with a diameter of 3 m that simulates a perfect conductor plane.

Relatively to the perfect conductor plane, the diameter of 3m is related to the distant zone \( \lambda/2\pi = 1.5 \) m radius, in which this is the value where the wave is in a far field on situation and no longer depends on the primary source.

It’s necessary to take into account that the formal solution of King-Middleton is a method of development in series, which is used in a 2nd order approximation. This method considers that the impedance is what would be expected if the antenna were isolated and under ideal conditions.

Moreover, as the CST program simulates the antenna connected to a perfect conductor plane, instead of being isolated, eventually introduces certain changes comparing to the results obtained from the King – Middleton. So, in the end it’s closer to reality than the solution of King-Middleton.

C. Theoretical value of the antenna input impedance at desired positions

In their activity, the military use the radio P/PRC-525 attached to their back, and move as needed. Typically for performing communications they adopt certain positions, and it can be evidenced three of major interest, namely: standing operator, lying operator, and radio on the floor.

In cases where the antenna is near objects, such as other antennas, the input impedance shall be determined not only by the impedance itself, but also by mutual impedance between this and the other antennas and the currents flowing in them.

Calculation of mutual impedance using EletroMotive Force induced Method (EMF)

To calculate the mutual impedance, Schelkunoff developed a method which can extract the concept of mutual impedance considering two cylindrical antennas, with rays \( a_1 \) and \( a_2 \), with lengths \( l_1 \) and \( l_2 \), with a distance \( \rho \) between them,
excited symmetrically in the central point [5]. And in this case, the antenna 1 is the VHF antenna, and the antenna 2 is its image simulated by the ground plane.

Thus, \( I_1 = I_2 = I \), where \( I \) is the length of the monopole (\( l=1.32m \)).

Then, the mutual impedance between the two antennas can be described by the following expression:

\[
Z_{12} = \frac{Z_{om}^2}{I_{01}I_{02}} = \frac{R_{12} + jX_{12}}{I_{01}I_{02}} = R_{12} + jX_{12}
\]

And in this case,

\[
I_{01} = I_{02} = I = 1 + \frac{M(\beta h)}{Z_{om}} \cos(\beta h) = \frac{N(\beta h) - jZ_{om} \cos(\beta h)}{Z_{om}}
\]

In which \( Z_{om} \) is the average characteristic impedance of the cylindrical antenna.

Thus, the input impedance is given by:

\[
Z_1 = \frac{V_1}{I_{01}} = Z_{11} + Z_{12}
\]

In the situation of lying operator, it’s assumed the value of \( h=0.39m \), due to the height of the operator’s body with the radio on his back.

In this situation we have,

\[
I_{01} = -I_{02}
\]

And the input impedance of the antenna is given by:

\[
Z_1 = \frac{V_1}{I_{01}} = Z_{11} - Z_{12}
\]

**Calculation of mutual impedance using CST Microwave Studio**

The use of the program CST to obtain the antenna input impedance results, taking into account the mutual impedance, presupposes the use of two conducting planes. One simulates the ground plane and the other simulates the presence of the radio.

The conducting planes have a diameter of 3 m and 10 m. However, the second one is not very important whatever its size because the first conducting plane with a diameter of 3m occupies the entire near zone of the antenna.

We can see the example showed in the image presented below.

![Figure 4](image4.png) a) Position of lying operator; b) Position of standing operator; c) Radio on the floor.

What varies between the three positions in this study is the height \( h \) of the separation between the two conducting planes, and the antenna position.

Between the EMF’s method analyzed using the MATLAB program, and analysis obtained by the program CST, the results taken as reference were the ones obtained by the CST program.

We can’t forget that the Schelkunoff’s method date from the 50s decade, and despite being the method that best portrays the desired situation in relation to the other methods studied, it is not very reliable.

The results from the theoretical calculation of the antenna’s input impedance at the positions of interest obtained from the simulation program CST are presented in
the appendix A, where the measured values are represented by a black line.

III. MEASUREMENT AND SIMULATION OF THE ANTENNA

The theoretical models obtained previously must be tested. In real situations the radio will operate without adequate grounding and with a distance to the ground that can vary considerably. In most applications, any measurements are usually of practical nature, and essential to the research of scientific events.

Measurements were made with the Network Analyser device to different conditions to obtain a number of measures which express as accurately as possible the behavior of the input impedance of the antenna in the frequency band of interest.

Measures to the VHF antenna were performed outdoors in conditions equivalent to those ideals.

The place chosen for this purpose was the football field of the Military Academy, since it minimally meets the conditions that are necessary to achieve the goal. Its dimensions are 100 m x 50 m (Length x Width).

Since the longest wavelength used was 9.09 m, to consider the football field an ideal place it should have in all directions over 90 m of free space, without any kind of obstacles, which is not the case.

The football field of the Military Academy is watered frequently, so the soil represents a good ground plane.

Were performed the following three sets of measures evidenced in the figure below.

![Image](image-url)

Figure 6 - Representation of measures: a) Antenna on top of the Network Analyser b) Antenna in front of the Network Analyser c) Network Analyser + Radio + Antenna.

In both situations, was placed the hand on the radio in order to simulate the contact with the human body, what actually happens when a military uses of radio.

It was possible to verify that whenever the hand was on the radio, or when there was greater human interference, the antenna impedance curve was closer to the ideal situation (corresponding to 50 Ohm). This fact can be explained taking into account that the human body is conductive, which will somehow enable a better ground plane.

These three measures were performed for the three positions of interest (standing operator, lying operator and radio on the floor).

From the three types of measures mentioned in the figure above, the results of the first measure where the antenna is connected to the radio P/PRC-525 were eliminated. This case was depreciated because despite the calibration done to the Network Analyser, it was noted the existence of losses above the other two cases. It is possible that this situation is due to the cable that connects the radio to the measuring device, because it was a bit long, and there is greater possibility of having losses.

In sum, despite the similarity between the measurements performed with the antenna placed on top and in front of the Network Analyser, it is noted that the impedance curves obtained with the antenna located in front of the measuring device, are closer to the theoretical values of the three positions.

Thus, these results were taken as reference.

The results from the measures done in the football field are presented in the appendix A, where the measured values are represented by a blue line.

It's possible to note in the results, the level of reliability of the Network Analyser, due to the proximity between measurements and theoretical results.

However, some of the existing errors may be related to the following facts: the ground is only an approximation to a perfect conductor, the dimensions of the football field are not ideal, at frequencies in question a conducting wire becomes resistive and inductive despite being as short as possible, and the fact that the antenna isn’t a cylinder with 8.5 mm radius as considered in the theoretical model.

In case of the lying operator position, despite there is no similarity between the theoretical results and the real measurements, it exists an analogy in the theoretical results between the CST and the EMF model, and in the real results between the measurements taken.

This disparity observed in the lying operator position between the measurements performed and theoretical results may be due to the fact that the antenna is not straight, making an arc that nearly touches in the ground. This case can be approximated to a short circuit at the tip of the antenna, which can justify such inequality.
IV. ANTENNA SIMULATION CIRCUITS

A. Introduction

This section has the objective of synthesizing and physically building three circuits using only passive components. Each circuit corresponds to one of the positions analyzed in the previous sections. These should simulate the curves of the antenna input impedance obtained on the football field of the Military Academy, with the antenna placed in front of the measuring device, which were the measures taken as reference. The antenna circuit simulation should be performed with concentrated parameters, because this is a requirement of this work. The calculation of a circuit with concentrated parameters presents some difficulties, mainly due to the wide range of frequencies, and the difference between the maximum and minimum values of the input impedance amplitude.

In the synthesis of circuits are known the frequency response requirements of a given excitation also known, and it is necessary to find a circuit that meets these demands. From this study sometimes we can obtain different solutions like several circuits that meet the same conditions, or we can get no solution [8].

According to Khilari, the synthesis of circuits can be performed using passive circuits, active circuits or digital techniques. The use of digital techniques is considered neither realistic nor economic. Between using circuits with passive or active components, the preference is given to passive circuits since these do not require excitation sources incorporated [9].

The elements allowed in passive circuits are: resistances, capacitors and coils.

In this type of circuits all the inductive effect is concentrated on the coils, all the capacitive effect is concentrated on the capacitors and all the resistive effect comes from resistances.

Currently there are some applications used for circuit’s synthesis, however all these applications only synthesize standard transfer functions. It is difficult to find something that can be used in the synthesis of an arbitrary transfer function.

B. Synthesis of the Antenna Simulation Circuits

The objective of the circuit’s synthesis is to obtain a circuit from a given transfer function.

When is given an excitation $B(s)$ to a system, and this has a response $A(s)$, the transfer function $H(s)$ of the system is:

$$H(s) = \frac{B(s)}{A(s)} \quad (14)$$

Before synthesize $H(s)$, it’s necessary to verify if the transfer function is realizable or not, using passive elements. To do this there are two important conditions for performing the network, which are causality and stability.

To consider a network causal, there can’t exist a response (output) without excitation (input) and it can’t exist current without any tension. There is a cause and effect relationship between the input and output of a network [8].

On the other hand, the network is considered stable if there are no power sources, and therefore there are no oscillations. This restriction means that the poles and zeros of the transfer function must be located on the left side of the complex plane.

A network with a finite number of elements (R, L, C) has an input impedance of the form:

$$Z(s) = \frac{B(s)}{A(s)} = a_n s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0$$

$$\quad = b_n s^n + b_{n-1} s^{n-1} + \ldots + b_1 s + b_0$$

Where all the coefficients $a_i, b_i$ are real [10].

Thus, the first approach to the problem of synthesizing the antenna circuit’s simulation in each of the three desired positions was to transform the input impedance curves obtained from the measures of the previous section in functions $Z(s)$. To accomplish this task, it was used the MATLAB function *invfreqs*, which finds a transfer function $Z(s)$ that corresponds to a given complex frequency response. This complex response corresponds to the impedance curve that is intended to transform in a transfer function [11].

After obtaining the desired transfer functions, it was necessary to choose a model among the numerous existent, that allowed transforming the function $Z(s)$ in a passive circuit elements.

The only model in which it was possible to obtain a more approximate response was the Foster’s model, which is one of the most known and used.

This model is based on the partial fraction expansion, that in the case of a transfer function such as $Z(s)$, the result is the connection in series of the existing elements [10].

To obtain these elements, namely the partial fractions of the function $Z(s)$, it was used another tool of MATLAB: the function residue [11].

The equation $Z(s)$ is then as follows:

$$\frac{b(s)}{a(s)} = \frac{r_1}{s-p_1} + \frac{r_2}{s-p_2} + \ldots + \frac{r_n}{s-p_n} + k(s) \quad (16)$$

What is equivalent to:

$$\frac{b(s)}{a(s)} = Z_1(s) + Z_2(s) + \ldots + Z_n(s) \quad (17)$$
However, after obtaining the partial fractions of the transfer function of each desired position, a problem appeared, which was the existence of pairs of complex poles. The presence of these poles always made this equation impossible.

After an extensive research on the Internet, it was found that it is possible to implement a pair of fractions with conjugated poles

\[
\frac{\frac{a+jb}{s-(\sigma+j\omega)}}{\frac{a-jb}{s-(\sigma-j\omega)}}
\]

as illustrated in Fig.7 [12].

![Figure 7 – Realization of a pair of complex poles.](image)

Where,

\[
C = \frac{1}{2a} (F) \quad (18)
\]

\[
R_i = \frac{-2a^2}{a\sigma - b\omega} (\Omega) \quad (19)
\]

\[
C = \frac{2aR_i}{R_i (\omega^2 + \sigma^2) + 2(a\sigma + b\omega)} (H) \quad (20)
\]

\[
R_2 = -L \left( \frac{b\omega}{a} \right) (\Omega) \quad (21)
\]

Then will be focused the three desired positions (standing operator, lying operator and radio on the floor), where will be analyzed the necessary steps since the achievement of the transfer function of each position, until the design and conception of the antenna simulation circuit.

C. Design’s Stage of the Antenna Simulation Circuits

In the schematics of the simulation circuits that will be presented below, are shown the values of the components used, which correspond to the ones obtained by the model discussed previously.

Standing operator

\[
Z(s) = \frac{9.796 \times 10^{10} s^2 + 8.366 \times 10^{18} s + 1.349 \times 10^{28}}{s^3 + 1.184 \times 10^8 s^2 + 2.988 \times 10^7 s + 5.747 \times 10^3} \quad (22)
\]

Lying operator

\[
Z(s) = \frac{8.114 \times 10^{10} s^2 + 5.598 \times 10^{18} s + 7.26 \times 10^{27}}{s^3 + 9.747 \times 10^7 s^2 + 2.065 \times 10^7 s + 2.496 \times 10^3} \quad (24)
\]

D. Conception’s Stage of the Antenna Simulation Circuits

Radio on the floor

\[
Z(s) = \frac{1.165 \times 10^{11} s^2 + 9.318 \times 10^{18} s + 1.321 \times 10^{28}}{s^3 + 1.849 \times 10^9 s^2 + 2.849 \times 10^7 s + 1.536 \times 10^3} \quad (23)
\]
This section aims to present the entire process of construction and development of the three antenna circuit simulation.

As is known, there is always a small difference between theory and reality. In order to correct this difference, rather than seeking correct values, we tried to find tunable capacitors and coils with correct values, we tried to find tunable capacitors (trimmers), taking into account the frequency range of interest, and built the coils with conducting wire. Therefore, after circuit’s construction, it is possible to adjust the characteristic curves of the input impedance, by tightening and loosening the capacitor screw, and the space between the turns of the coil.

Table 1 - List of the component’s nominal values of the three positions of interest (in each resistance is presented its nominal value, power which can dissipate and precision) – conception’s stage.

<table>
<thead>
<tr>
<th>Designation</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>C1 (pF)</th>
<th>C2 (pF)</th>
<th>L1 (nH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standing operator</td>
<td>7.87Ω, 0.6W, 0.1%</td>
<td>976Ω, 0.25W, 0.1%</td>
<td>2.32Ω, 0.25W, 0.1%</td>
<td>4.2/20</td>
<td>5.2/30</td>
<td>178, 98</td>
</tr>
<tr>
<td>Radio on the floor</td>
<td>2 Ω, 0.6W, 1%</td>
<td>412Ω, 0.25W, 0.1%</td>
<td>8.66kΩ, 0.25W, 0.1%</td>
<td>4.2/20</td>
<td>6.8/45</td>
<td>247, 86</td>
</tr>
<tr>
<td>Lying operator</td>
<td>9.1Ω, 0.6W, 1%</td>
<td>1.05kΩ, 0.25W, 0.1%</td>
<td>2.87kΩ, 0.25W, 0.1%</td>
<td>5.2/30</td>
<td>5.2/30</td>
<td>225</td>
</tr>
</tbody>
</table>

In the figure below, it can be seen the final result of the antenna simulation circuits of the three desired positions.

Figure 11 - a) Support box; b) Antenna simulation circuit.

The advantage of the construction of the circuits in the air, it’s because it allows to realize a circuit with dimensions that would hardly be obtained if it was carried out in a board.

In relation to the study of the power that can be transmitted to each circuit without damaging the respective components, there is a need to leave a note.

It should be taken in mind that the power supplied from the radio to the antenna varies between 0.1 – 10 W.

The capacitors are made of ceramic, and have a threshold voltage of 100 V.

The coils were constructed with conducting wire as mentioned above, so there is no problem with respect to the power that is placed on the simulation circuits for its proper operation.

Thus, if it is supplied to the simulation circuit a power value higher than expected, the only components that may cause problems are the resistances, which may not be able to dissipate a maximum power supplied.

Taking into account the resources available and possible to acquire, it is possible that some components do not support a certain level of tension, and there is the need to establish a limit to the power transmitted by the radio.

In reality a resistance has always an inductive or capacitive part which is larger or smaller, depending on the level of accuracy.

At this point, it was used the simulation program PSpice in order to determine the maximum power that passes in the different components, for determining the maximum power that may be supplied to the circuits, in accordance with their capabilities. This task was performed for the worst case, considering for each situation a minimum impedance of 50 Ohm.

Thus, the power values for the position of standing operator, radio on the floor, and lying operator are respectively, 0.74 W, 0.3 W and 0.37 W.

The results from the antenna’s simulation circuits are presented in the appendix A, where the measured values are represented by a red line.

V. CONCLUSIONS

Given the growing communications importance, either commercial as military, ever more there is a need to study the equipment designed for the purpose, in order to obtain better performance overall.

Therefore, this study had as purpose the creation and development of a simulator of the VHF antenna that equips the radio P/PRC-525, to simulate its input impedance in the frequency range of interest (33-88 MHz), for the three positions most used by the military in their functions, which are: standing operator, lying operator and radio on the floor.

From the realization of this simulator, it’s possible to conclude that despite the high work frequency range of the radio, which allows large impedance variations, and the difficulty to find real components with values exactly equal to the theoretical values, it ends up as an ideal representation of the intended measures.

It just has a limitation that is the power which is supplied to the circuit by radio.

This work can be the basis for further work in this promising area. It would be interesting and productive to develop the simulator in order to complete its only limitation.

It is necessary to choose resistances with higher power and with the same high precision, because in the case of decreasing this feature it will become impossible to obtain results similar to those obtained.

Nowadays, it is essential the existence of this type of simulators, once that these accelerate progress in this scientific area in education, research and development.
APPENDIX A

In this appendix are presented the results taken as reference from the theoretical study, the measures performed in the football field, and the analysis of the simulation circuits of the antenna for the three situations of interest.

**Standing operator**

![Figure 12](image1.png) - Amplitude of the input impedance for standing operator position – with antenna in front of Network Analyser (experimental values) (blue); antenna simulation circuit (red); CST theoretical values (black).

![Figure 13](image2.png) - Phase of the input impedance for standing operator position – with antenna in front of Network Analyser (experimental values) (blue); antenna simulation circuit (red); CST theoretical values (black).

![Figure 14](image3.png) - Resistance of the input impedance for standing operator position – with antenna in front of Network Analyser (experimental values) (blue); antenna simulation circuit (red); CST theoretical values (black).

**Radio on the floor**

![Figure 15](image4.png) - Reactance of the input impedance for standing operator position – with antenna in front of Network Analyser (experimental values) (blue); antenna simulation circuit (red); CST theoretical values (black).

![Figure 16](image5.png) - Amplitude of the input impedance for the radio on the floor position – with antenna in front of Network Analyser (experimental values) (blue); antenna simulation circuit (red); CST theoretical values (black).

![Figure 17](image6.png) - Phase of the input impedance for the radio on the floor position – with antenna in front of Network Analyser (experimental values) (blue); antenna simulation circuit (red); CST theoretical values (black).

![Figure 18](image7.png) - Resistance of the input impedance for the radio on the floor position – with antenna in front of Network Analyser (experimental values) (blue); antenna simulation circuit (red); CST theoretical values (black).
Lying operator

REFERENCES