Improving Medium Access in Through-The-Earth VLF-LF Communications

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***Abstract*---In order to improve the communication range of Through-The-Earth (TTE) radio using electrodes, the impedance load seen by power stage load must be minimized. This impedance depends on the wires, the electrode contact and the path between the electrodes (earth). Of the three elements, we cannot influence the earth impedance. The wire impedance can be minimized employing short cables and avoiding coiling them. This paper presents a method for characterizing the electrode contact impedance and provides suggestions to minimize it. Therefore some impedance measurements with several electrodes and a variety of contact conditions have been performed in order to improve our knowledge of medium access. To further prove the results measurements have been made with a voice radio application.**

***Index Terms* --- TTE, electrode impedance, medium access, earth impedance**

I. INTRODUCTION

TTE communications are usually deployed in hostile environments such as tunnels, mines, caves, etc. The electronic systems thus suffer from aggressive conditions caused by atmospheric dust and high humidity, mud, water and strokes in their transportation. In TTE communication the transmission channel carries out the propagation through a dissipative medium as can be the rock, the earth or the walls. There are two kinds of medium access solutions for wireless TTE communications: inductive coupling or current injection by means of ground electrodes. In order to be efficient, inductive loops work in resonance, offering a high quality factor. This reduces the transmission bandwidth, making this load not suitable for low frequency or high rate data communication systems. Thereafter, the best medium access solution for some applications is by means of ground electrodes [1].

Transmitters with ground electrodes include a modulator, a (switching) power stage, a load matching unit (transformer) and the electrodes (Fig. 1).

Manuscript received November 28, 2008; revised March 10, 2009; accepted April 15, 2009

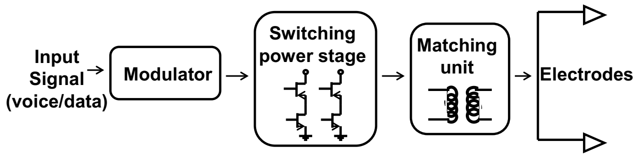


Figure 1. Block diagram of TTE transmitter system

In an efficient transmitter, the transformer turn ratio would be fixed in order to match the ideal load value. However, the range of variation of the load can even be of several orders magnitude, so the matching is almost never optimum. Electrode impedances in different locations must be known to be able to establish a range to properly design the matching stage of the transmitter.

To enable communications, the transmitter injects an AC current into the earth by means of a pair of ground electrodes. Lines of current link both electrodes and equipotential surfaces are created around them. The penetration of the current through the earth depends on the frequency of the signal and the conductivity of the soil. The earth behaves like a conductor, so skin effect is present in it, increasing signal attenuation with frequency. The penetration depth (distance in which signal is attenuated by the factor 1/e) depends also on the conductivity of the soil. Large values of conductivity are translated into low values of penetration depth. The receptor detects a voltage difference between the receiving electrodes (Fig. 2), that is a consequence of these current lines and thus dependent on the receiver electrode separation, the frequency of the signal, the quality of the contact and the soil conditions. The larger the separation between electrodes the larger the voltage difference detected in the receptor. Moreover, if the frequency of the signal increases, the magnitude of the impedance of the contact, as it will be seen in this article, decreases.

The impedance seen by the power stage of the transmitter varies greatly with the quality and surface of the contact, the humidity and salinity of the surrounding ground, and the separation and the number of pegs used [2].

The most commonly used electrodes are metallic rods for the surface unit and copper braid, immersed in water or buried in mud, for underground stations. Nevertheless, in a rocky medium the use of this kind of electrodes can be very complicated. On one hand electrode bars cannot be driven into the rock and moreover, it may occur that no water puddles are available.

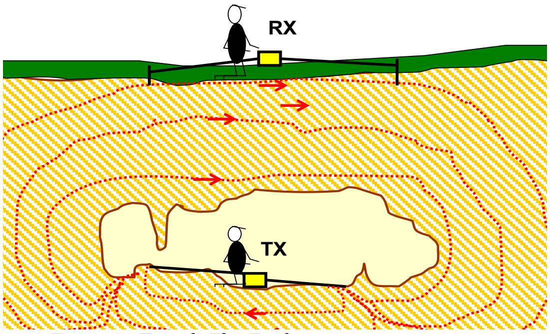


Figure 2. Trough-The-Earth communication system

The effect of the contact electrode in the communications performance has been presented in previous studies [2], [3]. As conclusion, a very high value of contact impedance results in a small current injected into the earth and a shorter communication range achieved. When dealing with a rocky surface, either at open air or inside a cave we should have to adapt our system to the soil conditions trying to obtain a good medium access in order to reduce the impedance seen by the communication system. Studies of the electrode impedance for different rock and soils appear in the literature [4-6] but, to the best knowledge of the authors, no references of the medium access in rocky materials for underground communication applications have been found.

In this paper, various configurations of electrodes adapted to rock access have been designed, tested, analyzed experimentally and compared. The modelling method will be presented. Furthermore, the results are used to propose an optimal method of electrode connection for minimizing the impedance and thus maximizing the penetration and communication range. An equivalent circuital model for the electrode impedance has also been included with parameter values for the different electrodes tested.

II. LOAD IMPEDANCE MODEL

In figure 3, the electronic equipment (both transmitter and receiver) is connected to ground using a pair of wires and two metallic electrodes. The total load impedance for the transmitter covers a wide range of impedance values depending of many factors, mainly the wire impedance Z_w, the earth impedance Z_e and contact electrodes impedance Z_c.

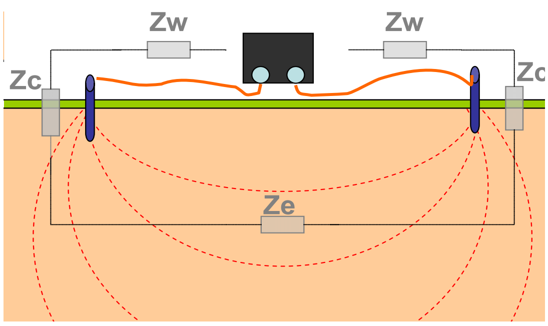
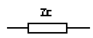
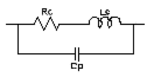
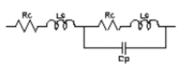


Figure 3. Ground Electrodes impedance model

A. Wire Impedance Z_w

In common operation, the connection between the system and the electrodes is made with multifillar copper wire, with a typical length between 20 and 50 meters. Its impedance (Z_w) could be modelled as an inductive-resistive series model for the VLF-LF frequency range. Generally, the wires used to connect the system with the electrodes are AWG 18-20 with a dc-resistance between 0.02 and 0.33 ohm/m. At high frequencies this resistance will rise due to skin effect on the conductor. The inductive component of the impedance increases depending on the layout, especially with the coiling of the wire. More complex models include the capacitive coupling between the winds of wire in the cable spool. Four possible wire impedance models are presented in Table I with the formulae for low and high frequency components. Two of them have been taken from the literature and the others have been developed for this work.

TABLE I.
WIRE IMPEDANCE MODELS

Model with equivalent circuit	Low frequency components	High frequency components
Extended 1 	$R_c = \frac{\rho l}{\pi a^2}$ $L_c(\mu H) = 0.002l\left[2.3\log\left(\frac{4l}{d}\right) - 0.75\right]$	$R_c = \frac{\rho l}{\pi a^2}\left(\frac{a}{\delta}\right)$
Extended 2 [7] 	$Z_c = -j\frac{\omega\mu_0}{2\pi}\frac{J_0(\gamma a)}{\gamma a J_1(\gamma a)}$	
Totally coiled [8] 	$R_c = \frac{\rho l}{\pi a^2}$ $L_e(\mu H) = \frac{0.8a^2N^2}{(6a + 9l_s + 10c)}$	$R_{ac} \cong R_{dc}\left(1 + \frac{\Psi}{3}\Delta^4\right)$ $C_p > (N-1)\frac{2r\varepsilon_r}{11.45\cosh^{-1}\left(\frac{d_e}{2a}\right)}$
Partially coiled 	$R_c = \frac{\rho l}{\pi a^2}$ $L_c(\mu H) = 0.002l\left[2.3\log\left(\frac{4l}{d}\right) - 0.75\right]$ $L_e(\mu H) = \frac{0.8a^2N^2}{(6a + 9l_s + 10c)}$	$R_{ac} \cong R_{dc}\left(1 + \frac{\Psi}{3}\Delta^4\right)$ $C_p = \frac{\varepsilon\pi pD}{d}$

For the sake of simplicity, among the models presented, we will consider for our applications only the model listed as "extended 1" model. In this expression a is the wire radio, l its length, ρ conductivity, d the wire diameter and δ the skin depth. The rest of the parameters of the wire impedance models expressions are described in detail in [7-8].

B. Earth Impedance Z_e

The current injected into the earth follows three transmission mechanisms [9-10]: ohmic (materials with free electrons), electrolytic (ionic conduction) and dielectric conduction (by variable electric field polarization). This causes the impedance to present associated reactive and resistive components. Thus, earth impedance (Z_e) depends on the soil humidity, soil water chemical composition (salinity), mineral conductivity, grain size, temperature and porosity.

Many models of earth impedance developed for geophysical studies can be found in the literature [11]. Electrical models include the effect described previously as a resistance and a capacitance in parallel as well as other components. Among the models, the Montaña one [12], shown in Fig. 4 has been considered. This model has proved to provide good results in our work.

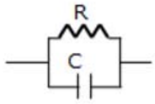


Figure 4. Montaña earth impedance model [12]

To optimize the communication process, we can neither change the earth impedance seen by the electrodes in a fixed situation nor modify the wire impedance (by practical limitations). Therefore the best way to reduce the impedance is to obtain the best medium access (i.e. making Z_c as small as possible).

C. Electrode Contact Impedance Z_c

Modelling the contact of the electrode with the earth presents high complexity. Three components can be identified in the total contact impedance [13]. The first one is the resistance of the conductor that forms the electrode. The second component is caused by the electro-chemical interface between the metal (electrode) and the soil ("solution"). The last one, the contact surface of the electrode with the earth, is known as the ground impedance. Only the third component is considered in most of the models. And only the earth surrounding the electrode to a short distance from it would be taken into account. It can be assumed that resistance is composed by several layers from the electrode surface up to a given distance beyond which the value does not vary (Fig. 5).

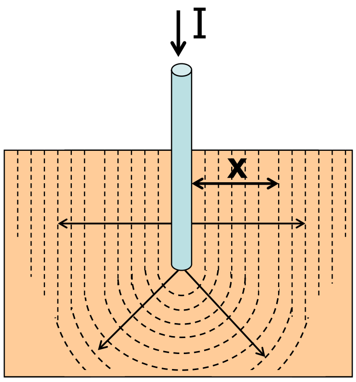


Figure 5. Resistivity layers around the electrode

The resistance in the electrode surface is represented in (1) [14] where l and d are the length and the diameter of the electrode respectively and ρ is the soil resistivity. Its value from a distance x to infinite would be calculated with equation (2). It can be seen that most of the contact is achieved with x equal to two times the electrode length. In [15] it is stated that the resistance between two electrodes depends mostly on the contact resistance with the earth, assuming that in most cases the earth resistance could be considered negligible.

$$R_0 = \frac{0.366\rho}{l}\log\left(\frac{3l}{d}\right) \tag{1}$$

$$R(x) = \frac{0.366\rho}{l}\log\left[\frac{l}{x}+\sqrt{1+\left(\frac{l}{x}\right)^2}\right] \tag{2}$$

Many applications can be found in the literature (grounding, lightning, geophysical prospecting and bioelectronics) that try to simulate the contact electrode behaviour with circuital models [13, 16-24]. Many of them are not suitable for the situation under study due to the size of the electrodes modelled or the frequency range considered. One example of a suitable one is the Gasulla model [21] shown in Fig. 6.

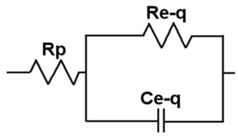


Figure 6. Electrical Gasulla model of contact electrode impedance [21]

In the previous model R_p is the contact resistance dependent on the shape and size of the electrode, C_{e-q} is the electrode surface capacity and R_{e-q} that is a resistive value that is electrolyte dependent. Different models will be compared with measurements in the following section to understand which one represents better the electrode contact impedance and its parameter values for each electrode tested.

The impedance of the contact ground electrode varies greatly depending on the type of soil surrounding it (material, humidity, salinity, temperature…), the depth of penetration in the earth and the characteristics of the electrodes (shape, size and material). In [25] we can see that the contact electrode impedance diminishes with humidity and salinity and that some materials like bentonite are very appropriate to improve the contact in earth installations. Regarding the shape and size, the larger the contact surface of the electrode with the earth, the smaller the impedance. Therefore, the deeper the electrode penetration, the lower its impedance value.

III. CONTACT ELECTRODE IMPEDANCE MEASUREMENT METHOD

One set of experimental measurements was carried out Estrecho Quinto (Huesca) in Spain in October 2007. In order to generalize the results, a homogeneous bare rock area was selected to minimize the earth impedance variation. We consider it as a constant value for all the situations under study. The test rock is a sun dried thick horizontal stratum of Miocene sandstone. The electrical resistivity measured was 571 Ω/m. A reference electrode formed by a parabolt was fixed in a hole in the rock covered with wet bentonite. Figure 7 shows this reference electrode in measurement set number 1.

Figure 7. Parabolt as reference electrode in measurement

Radially, surrounding the reference electrode, several configurations of electrodes have been tested as shown Fig. 8.

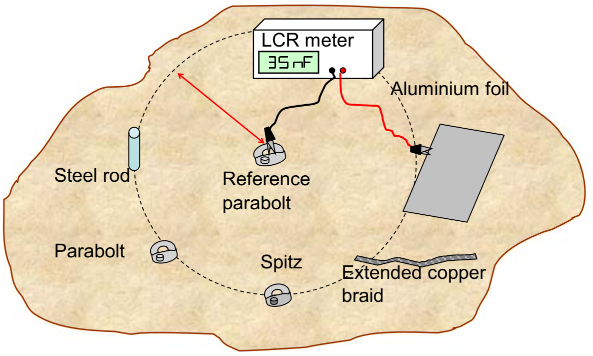


Figure 8. Experiment configuration

To measure the impedance, a LCR meter Fluke 6306 was used for nine different values of frequency in the range of 50 Hz and 1 MHz. After a first set of measurements, the validity of them was confirmed by a second set with deviations of the values lower than 5 %.

The total impedance value measured corresponds to a model in series of the impedance Z_w+Z_e+Z_c as could be seen previously in Fig. 3, Z_c is the value of the contact impedance of the reference parabolt plus the contact impedance of the electrode under test. The reference parabolt impedance and the earth impedances involve a constant factor, common in all cases. That is not relevant for the experiment because the aim of the study is to find the best medium access configuration. Z_w has been measured and considered negligible due to the short length of the wires (1 meter) and operating frequency.

The following electrode configurations were tested:

1. Parabolt
2. Copper braid extended
3. Spitz
4. Aluminium foil isolated with a plastic sheet and non isolated.
5. Steel rod electrode

The copper braid was one meter in length and the aluminium foil was 30x45 cm. The steel rod electrode was a cylindrical bar of 20 cm in length and 1 cm in diameter. Spitz and parabolt are devices widely used for climbing and caving. Some pictures of the electrodes under study appear are depicted in Fig 9.

The impedance of the listed electrodes was measured in three different conditions: dry, wet with a salty solution (sodium chloride solution) and wet with bentonite.

IV. Results

A. Impedance Measurements

Figures 10-14 below show the values of impedance measurements. The LCR meter offers for each frequency the magnitude and phase components for the equivalent series model. Once converted into real (R) and imaginary part (X), they are represented in Ohms as a function of frequency. For copper braid and aluminium foil, magnitude and phase have instead been represented for clarity purpose. Fig. 10, Fig. 11, Fig. 12, Fig.13 and Fig.14 show the data obtained for the parabolt, copper braid, spitz, aluminium foil and steel rod electrode measurements respectively. All measurements, except that of the aluminium foil, present the results in the three possible contact conditions: dry, wet with salty water and wet with bentonite. The aluminium foil electrode measurements plotted in the figures are taken in different conditions: isolated from the rock with a plastic sheet and in direct contact, without the isolation layer, with salty water and wet bentonite in the interface between the foil and the rock.

a)

b)

c)

Figure 9. Detail of a) copper braid in with bentonite, b) spitz with bentonite and c) aluminium foil electrodes in Estrecho Quinto

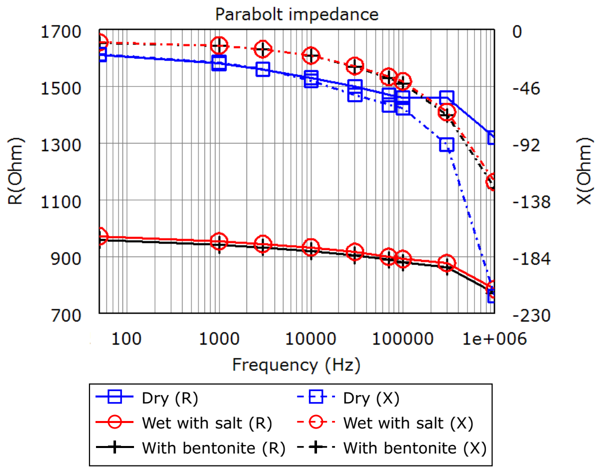


Figure 10. Real and imaginary components of parabolt impedance

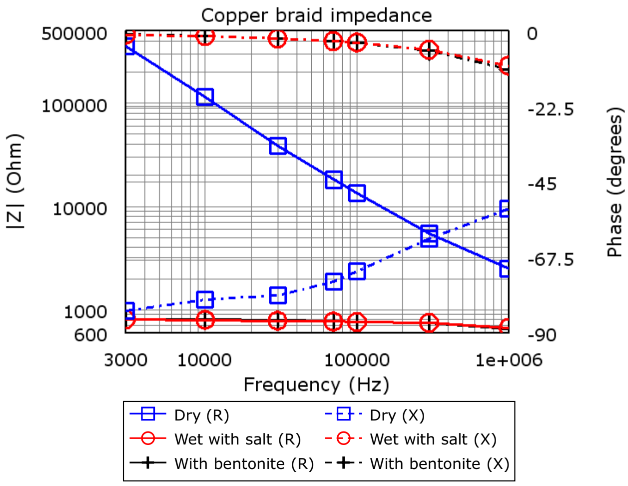


Figure 11. Magnitude and phase components of copper braid impedance

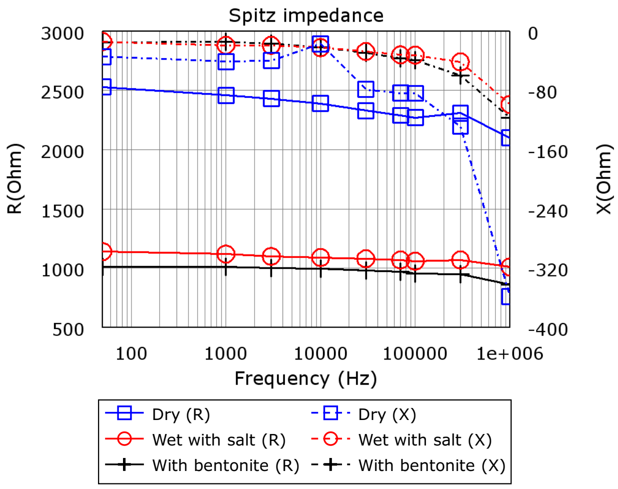


Figure 12. Real and imaginary components of spitz impedance

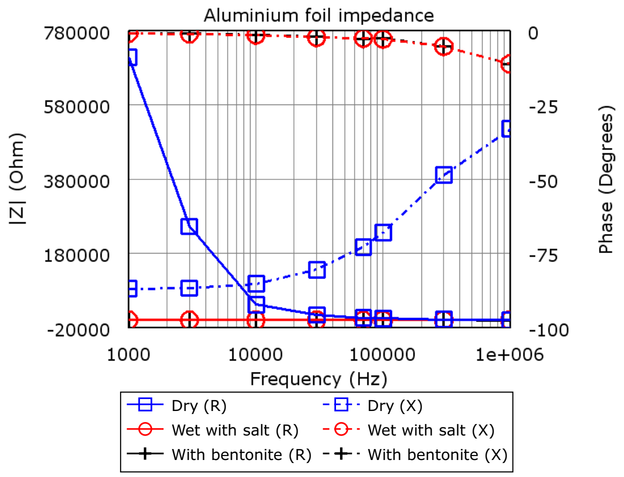


Figure 13. Magnitude and phase components of aluminium foil impedance

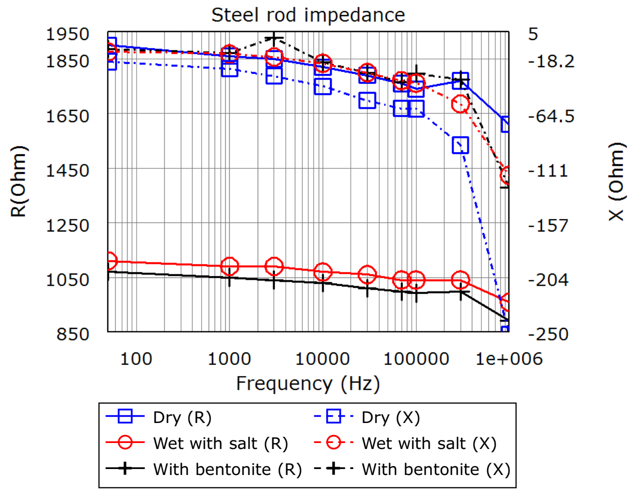


Figure 14. Real and imaginary components of steel rod impedance

The previous figures show that the real value of the impedance decreases with frequency in all the electrodes under study. Moreover, the reactive component of the impedances measured presents a capacitive behaviour. This capacitance decreases if the surrounding rock was wet. A simple explanation is that the air filled hollows in the electrode-ground contact that generate capacitive impedance (Fig. 15). The holes are now filled with salty water or bentonite. The air disappears as dielectric and a material with a higher electrical permittivity replaces it, thus increasing the capacity and reducing the imaginary value of the impedance. If we introduce a more conductive substance in the interface between the electrode and the rock as salty water, the resistive component of the impedance also decreases.

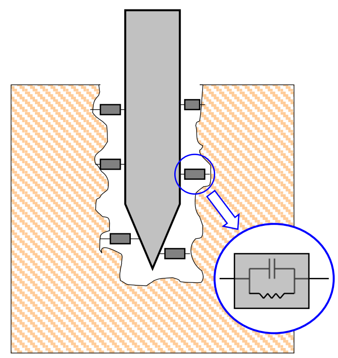


Figure 15. Capacitive and resistive effect of electrode contact

Fig. 16 represents a comparison of the module of the different electrodes' impedance under bentonite wetted conditions. It can be seen that steel rod electrode presents the largest magnitude and the copper braid the lowest one. Aluminium foil and parabolt offer similar responses under condition.

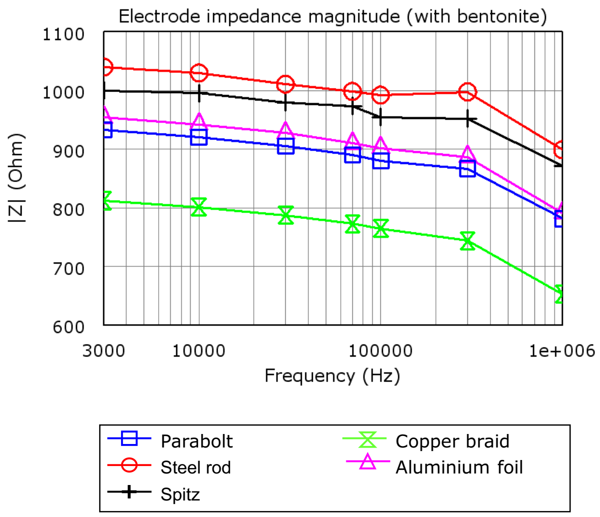


Figure 16. Comparative of electrode impedance magnitude for "with bentonite" conditions

B. *Optimization of Load Impedance*

A comparison has been made between some circuital models found in the literature that represent contact electrode impedances and measurements for wetted "with bentonite" conditions. The aim of this comparison is to extract the model that better matches the measurements for each type of electrode in order to apply it in other underground studies. The optimization has been made with the state of the art CAD tunning and optimizing tools [26] and a further finer optimization and comparison of models with Matlab software [27]. To achieve this, it is necessary to model all the elements involved in the measurement: the wire, earth and the reference electrode impedances. As it has been seen before, for the wire a resistive-inductive series model is considered. For the earth, a resistive-capacitive parallel model is found to be suitable. A complete circuital model for the measurement can be seen in Fig. 17. In all the experiments only the $Z_{electrode}$ component varies (grey in Fig.17).

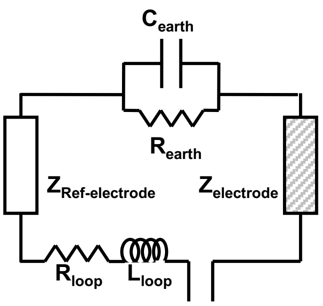
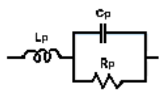
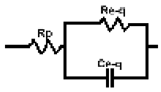
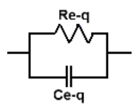


Figure 17. Circuital model representing ground electrodes impedance

The first optimization is realized with the parabolt electrode, considering the same contact impedance in both electrodes and estimating in that way the $Z_{Ref-electrode}$ and the earth and wire impedances. These values would be assumed as constant for the rest of the electrodes studied and are presented in Table III. The Nelder-Mead Simplex method [29], an unconstrained nonlinear optimization method, is employed in the optimization function. Several contact impedance models fitted to the measured data have been compared by means of the mean quadratic error between optimized model and data, in real and imaginary part.

The different contact electrode impedance models used in this study are shown in Table II. Other models can be found in the literature [31, 32] but these only have been selected due to their simplicity. As well as the circuital model, the theoretical expressions have been included in Table II for the case of a vertical rod shape electrode. In these expressions, a represents the rod radius, l its length and ρ the earth resistivity. For Wang model the meaning of the different parameters can be consulted in reference [18].

TABLE II.
CONTACT ELECTRODE IMPEDANCE MODELS

Model	Equivalent circuit	Parameters
De la Vega [14]		$R_p = \frac{\rho}{\pi 2l} ln \frac{4}{\pi}\frac{2l}{a}\ (\Omega)$
Rüdemberg [10]		$R_p = \frac{\rho}{4\pi l}\log\left(\frac{2l}{a}\right)(\Omega)$ $C_p = 2\pi\varepsilon l\left(\log\frac{2l}{a}\right)^{-1}(F)$ $L_p = \frac{\mu_0 l}{2\pi}\log\left(\frac{2l}{a}\right)(H)$
Gasulla [15]		$R_p = \frac{\rho}{2\pi l}\ln\frac{2l}{a}(\Omega)$
Wang [18]		$R_{e-q} = \frac{E_T}{j_0}$ $C_{e-q} = \frac{\varepsilon_0\varepsilon_r}{\delta^H}$

Other electrode topologies as horizontal bars, rings or grids have been studied by many authors but for this application it is only necessary to know which electrical model to apply. For the present experiment the parameter expressions are not of interest. As can be seen in previous expressions, all the components are soil conditions and electrode size dependant. And, of course, they vary with the shape of the electrode.

For the parabolt optimization the values obtained for the earth, wire and electrode impedance appear in Table III.

TABLE III.
GROUND ELECTRODE MODEL PARAMETERS VALUES

Parameter	Value
R_{earth}	20 Ω
C_{earth}	4.97 pF
R_{loop}	19.9 Ω
L_{loop}	2.43 nH
R_p	439.8 Ω
L_p	14.7 μH
C_p	154 pF

Figs.18-22 represents the impedance magnitude and phase measured and simulated, with the circuital equivalent model that results, substituting the electrode impedance with the optimal model obtained after optimization process. The parameters for optimal model are also presented.

The parabolt presents an impedance response that can be described as with an inductance in series with a resistance and capacitance in parallel, model described for the contact electrode impedance by Rüdemberg. This can be seen in Fig. 18, where the parameter values are also represented.

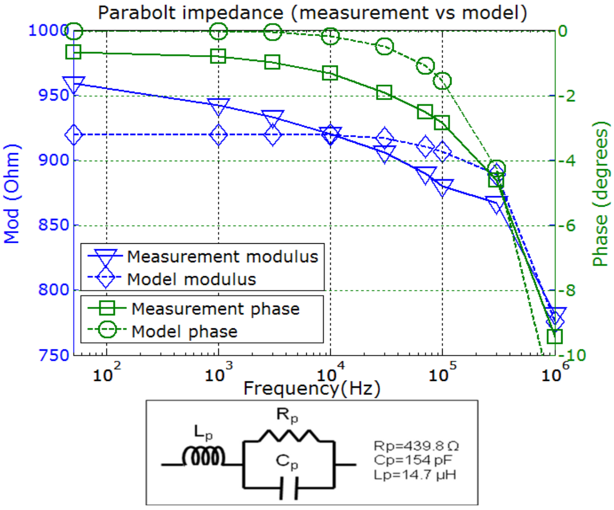


Figure 18. Comparison between contact impedance model and measurements for parabolt electrode with optimum model parameters

In the case of spitz electrode, the optimum model corresponds to a Gasulla model (Fig. 19).

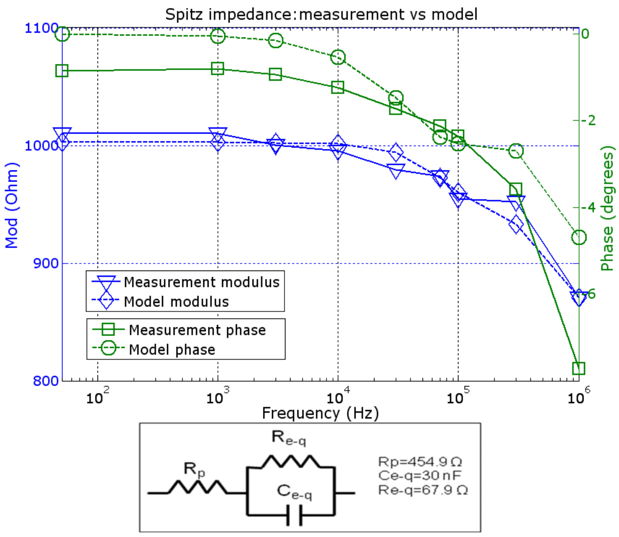


Figure 19. Comparison between contact impedance model and measurements for spitz electrode with optimum model parameters

Steel rod electrode is best modelled also with Rüdemberg model according to the optimization results shown in Fig. 20.

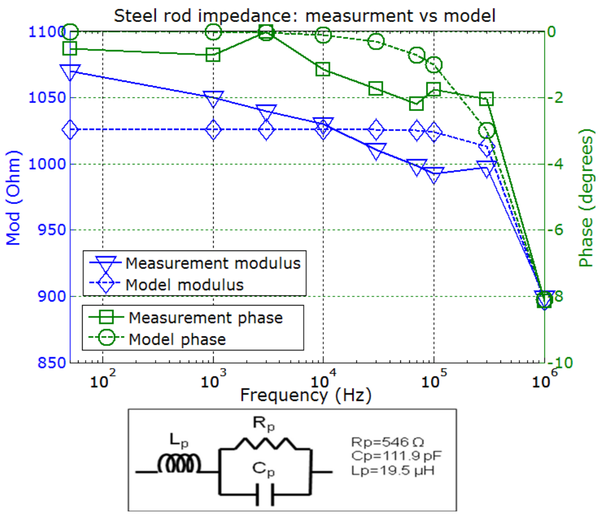


Figure 20. Comparison between contact impedance model and measurements for steel rod electrode with optimum model parameters

The behaviour of the copper braid electrode adjusts also to Gasulla model. Fig. 21 shows the comparison between the measured data and the model impedance for copper braid with bentonite with the model parameters described.

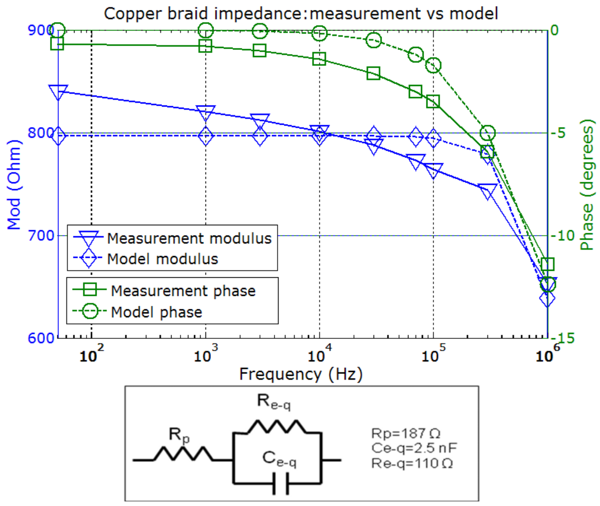


Figure 21. Comparison between contact impedance model and measurements for copper braid electrode with optimum model parameters

The last electrode tested, the aluminium foil, different in shape from the other electrodes, can be matched to a Gasulla model with the parameters shown in Fig. 22.

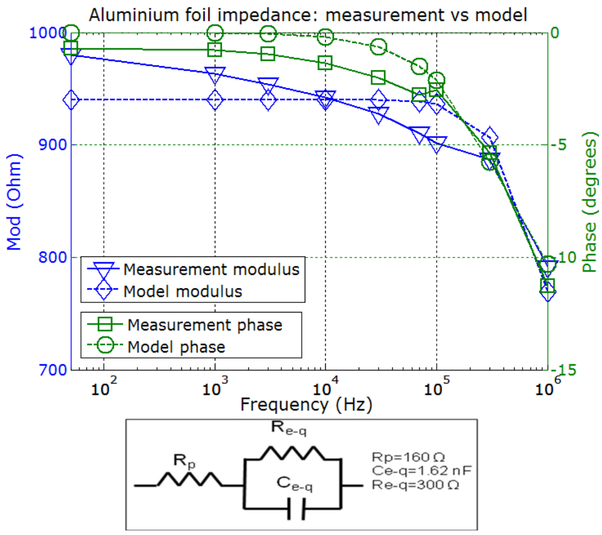


Figure 22. Comparison between contact impedance model and measurement for aluminium foil with optimum model parameters

As seen in Fig. 18-22, two models can be used to fit the measured data: Gasulla and Rüdemberg. Analyzing the sum of the real and imaginary part root mean square errors among different models it can be seen that both models present similar error values, much smaller than the errors obtained when modelling with De la Vega and Wang alternatives. As an example, for parabolt electrode, the error in De la Vega model was 6.20 compared to 4.6 for the Rüdemberg one.

For the parabolt electrode, the optimizations have been carried out for dry and wet conditions as well as with bentonite in order to know which parameters are modified by a conductor material in the contact surface. The results of the optimization are presented in Table IV.

TABLE IV.
PARABOLT MODEL PARAMETERS VALUES

Parameter	Contact conditions		
	Dry	Wet (salty water)	With bentonite
R_p	1046 Ω	447.8 Ω	438.8 Ω
C_p	62.3 pF	171.7 pF	154 pF
L_p	33.2 μH	17.6 μH	14.7 μH

In the previous table, it can be seen that the resistive value of the contact impedance decreases by half if the electrode is surrounded by a conductive material as salty water or bentonite. The inductive component also decreases in the same way and the capacitive one rises in wet conditions referred to the dry situation.

Fig. 23 shows a Smith chart representation of the three situations for contact parabolt impedance. The contact impedance is close to the resistive line of the Smith chart for dry conditions and presenting a reactive response with frequency in wet and bentonite situations, although this reactive part is small compared to the resistive one. So contact impedance can be considered almost resistive.

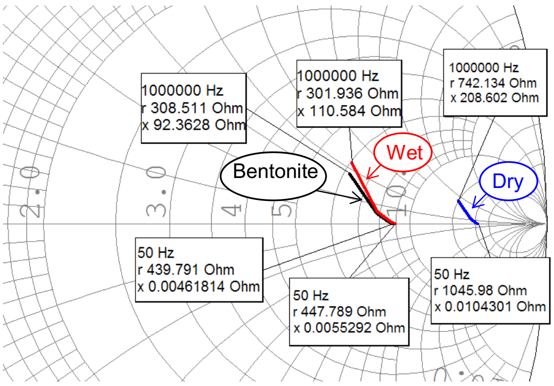


Figure 23. Smith chart of parabolt contact impedance for dry, wet with saline solution and wet with bentonite conditions.

An additional set of measurements was made in Salto del Roldán (Huesca) in Spain in March 2008, in order to analyze whether the electrode contact optimal model depends on the soil properties. The rock selected to obtain these experimental data was a conglomerate with a measured electrical resistivity of 2.17 kΩ/m.

In this location the same electrodes were studied, but only the parabolt and the copper braid results are presented. Bentonite was used to improve the contact with both electrodes and the reference electrodes was also a parabolt. The same optimization method described for the previous measurement set was used for these impedance data. Fig. 24 and 25 shows the comparison between the optimal model and the data measured, in magnitude and phase for parabolt and copper braid electrodes in Salto del Roldán.

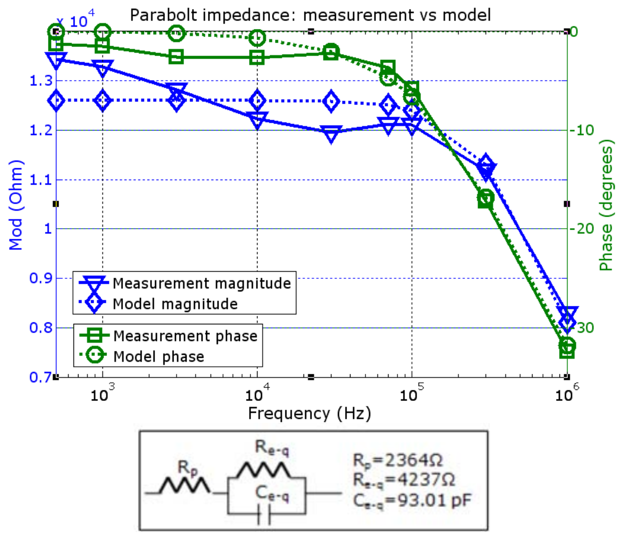


Figure 24. Comparison between contact impedance model and measurement for parabolt in Salto del Roldán with optimum model parameters

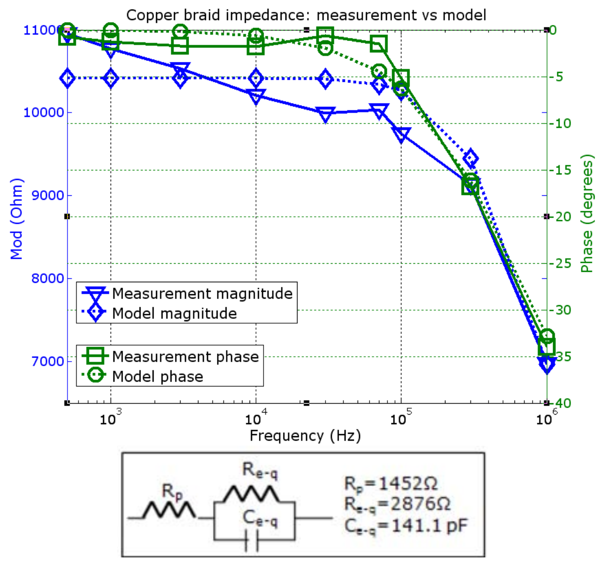


Figure 25. Comparison between contact impedance model and measurement for cooper braid in Salto del Roldán with optimum model parameters

As shown in previous figures optimal model for the same electrode varies depending on the rock conditions. The model that better fits the measured data for parabolt and copper braid electrode is the Gasulla model. The optimal model for parabolt in conglomerate has changed from the previous measurement captured in sandstone. This shows that the optimal electrode model depends on the type of rock.

V. ELECTRODE IMPEDANCE FOR TTE COMMUNICATION

As it was previously stated, the contact electrode impedance is one of the most relevant elements in TTE communication.

Lower electrode impedance allows more current being injected into the earth, thus reaching a larger communication range. This can be seen in following TTE communication example which model is illustrated in Fig.26

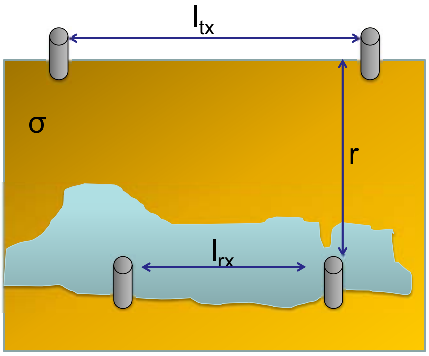


Figure 26. TTE communication model with electrodes.

According to [28], the receiver voltage in TTE propagation with electrodes in parallel direction follows expression (3).

$$V_{rx} = \frac{V}{2Z_c} \frac{l_{tx} l_{rx}}{4\pi\sigma r^3} \left(1 + \gamma r + \gamma^2 r^2\right) e^{-\gamma r} \qquad (3)$$

with V voltage in transmitter, Z_c electrode contact impedance, l_{tx} and l_{rx} the transmitter and receiver electrode spam respectively, r is the receiver depth, σ the earth conductivity and γ , the propagation constant that can be approximated by expression (4).

$$\gamma \cong j\omega\mu\sigma \qquad (4)$$

In this example it has been supposed an electrode spam of 10 meters in transmitter and receiver, a receiver depth of 50 metres and a transmitter output voltage of 50 V_{pp}. The earth is supposed homogeneous with a conductivity of 10^{-2}mS/m. The wire and earth impedance values are considered negligible with regard to contact electrode impedance. The highest and lowest impedance contact values measured in this paper (corresponding to dry steel rod and copper braid with bentonite electrodes respectively) have been considered for comparing the system performance. At an operating frequency of 70 kHz, the electrodes impedance values are those shown in Table V.

TABLE V.
IMPEDANCE OF WORST AND BEST ELECTRODE MEASURED

	Electrode	
Parameter	Steel rod dry	Copper braid with bentonite
R	1760	772
X	-60.3	-40.9

The magnitude of the receiver voltage calculated is 180mV and 412mV for a dry steel rod and copper braid with bentonite respectively, showing and improvement of 56% in receiver voltage from a bad to a good medium access in transmitter. This result shows the great importance of the research in electrode impedance for TTE communication applications.

To further prove the results in this paper, the different electrodes have been tested in a TTE communication application. The experiment was developed in surface, in Estrecho Quinto (Huesca) in Spain. A pair of electrodes was used to inject a sinusoidal current of 70.8 kHz into the earth. This frequency was chosen because the cave radio [30] developed by GTE works close to this range. One of the emitter electrodes was a parabolt used as reference and the other electrode was changed in order to establish a comparison between the different electrodes. In the receptor, located at 30 metres from emitter, a voltage signal was picked up by a pair of rods electrodes with a one meter span. A high rate A/D converter, a low noise amplifier and a computer were used to measure the rms (root mean squared) value of the voltage captured by the electrodes. This value was calculated applying the FFT to the digital signal captured and measuring the rms voltage for the emitted signal frequency. The measurement set up is shown in Fig. 27.

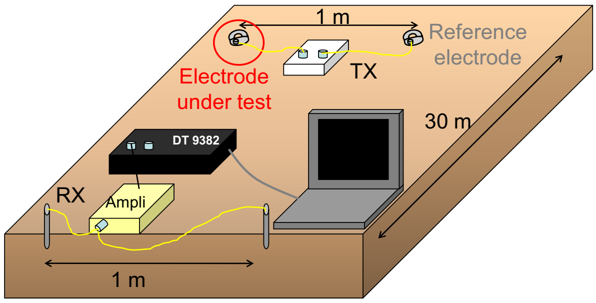


Figure 27. TTE surface communication experiment setup.

The improvement in receptor voltage in dBV respect to the worst electrode tested, the steel electrode, are presented in Table VI where also the injected emitter peak-to peak current data are presented.

TABLE VI.
RECEPTOR VOLTAGE AND EMITTER INJECTED CURRENT VALUES

Electrode	V_{RMS} (dBV) improvement	I_{pp} (mA)
Parabolt	0.7	20.4
Copper braid	1.38	22
Steel rod	0	18.4
Aluminium foil	1.16	21.1

In previous Table it is shown a more than one dBV improvement in receiver voltage from using copper braid electrode opposite steel rod. This improvement would be greater if both electrodes were copper braid.

Besides the experiment of communication at a fixed frequency, the improvement of voice quality signal employing TEDRA [30] radios was also tested. Communications at 30 meters with two electrodes, copper braid and steel rod, were compared. Due to the span among electrodes being fixed only to one meter, the communication range was short. In the case of steel rod the voice communications was intelligible while with copper braid maintaining a voice conversation with clarity was possible. This proves that a good contact is of paramount to communicate and that the best medium access must be reached. Two pictures of this experiment are presented in next figure.

Figure 28. TEDRA communication experiment with different electrodes

VI. Conclusions

In this article several electrode configuration impedances have been measured in different contact conditions trying to understand the best medium access solution. The analysis performed in this paper and the results obtained in the experiments conclude that there are many options that can be used as electrodes on rocky surface inside a cave or at open air. According to the results presented in the previous section, the best medium access could be supplied by a copper braid with bentonite that offers the lowest impedance value. Another conclusion is that for the same electrode, comparing all the possibilities, the best situation occurs surrounding the electrodes with bentonite or immersing it in a salty water puddle. This improvement is more relevant at low frequencies. The contact obtained only with dry electrodes is too bad to obtain a good medium access.

This paper also shows that contact electrode impedance can be modelled by Rüdemberg or Gasulla model, depending on the electrode type. The paper also proves by field measurements in different terrains that model also depends on the rock type.

The model parameter values for parabolt electrode have been analyzed in the three different contact conditions studied in this paper, concluding that, the addition of a more conductive material as salty water implies a decrease in the resistive value by half and an increase in capacitive one, resulting in a small overall impedance value for low and high frequencies.

This paper shows that the reactive component of the impedance is much smaller than the resistive values in all cases. Therefore, the suggested strategy for achieving a good medium access is considering the electrode configuration that offers the smaller resistive value of contact impedance ignoring the reactive component.

Finally the improvement in receiver voltage depending on the emitter electrode has been proved, in real TTE communication conditions. Copper braid shows a better behaviour versus other electrodes. Comparing this electrode with steel rod in radio communication with TEDRA shows that even with a very short electrode span it is possible to have a voice communication with copper braid but not with steel rod.

The results of the work developed in this article could be applied in several fields as geophysics, grounding installations and, of course, TTE communications.

Acknowledgments

This work has been funded by the projects DPI2006-07928 (MCYT, Spanish Government) and PM053/2006 (Gobierno de Aragon), and by the agreement between the Gobierno de Aragon and the Universidad de Zaragoza regarding the WALQA research laboratory.

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