

Article

Electronic Device and Data Processing Method for Soil Resistivity Analysis

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Abstract: This paper presents a mathematical algorithm and an electronic device to study soil resistivity. The system was based on introducing a time-varying electrical signal into the soil by using two electrodes and then collecting the electrical response of the soil. Hence, the proposed electronic system relied on a single-phase DC-to-AC converter followed by a transformer for the soil-to-circuit coupling. By using the maximum likelihood statistical method, a mathematical algorithm was realized to discern soil resistivity. The novelty of the numerical approach consisted of modeling a set of random data from the voltmeters by using a parametric uniform probability distribution function, and then, a parametric estimation was carried out for dataset analysis. Furthermore, to validate our contribution, a two-electrode laboratory experiment with soil was also designed. Finally, and according to the experimental outcomes, our electronic circuit and mathematical data analysis approach were able to detect different soil resistivities.

Keywords: electronic circuit; soil resistivity; maximum likelihood



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1. Introduction

The development of electronic devices to read soil resistivity has been one of the most relevant topics in geophysics to investigate soil composition [1–10]. Hence, soil resistivity is a relevant indicator to indirectly determine soil properties such as salinity, moisture, and organic matter content, among others [5,7]. Therefore, the measurement of soil resistivity, as well as a well-tuned data analysis method are two significant issues [1–8,11–14]. From the instrumentation point of view, there are two approaches to obtain soil data: (1) contact and (2) non-contact methods. The contact method is based on the current-to-voltage soil response to an applied electric field. This contact method usually employs electrodes (or probes) [7]. For instance, the two-point method is schematically shown in Figure 1 [15]. Therefore, the soil resistivity can be inferred by reading the induced voltage V , recorded by a voltmeter, and the supplied current I , captured by an ammeter, as follows:

$$\rho = k \frac{V}{I}, \quad (1)$$

where ρ is the soil apparent resistivity in Ωm and k is a geometric parameter. This apparent soil resistivity ρ (1) is usually lumped and located at a depth $D/2$ between the electrodes, D being the electrodes' spacing (in meters).

The above soil resistivity principle is also applied to a different and improved electrode arrangement, the Wenner structure. See Figure 2.

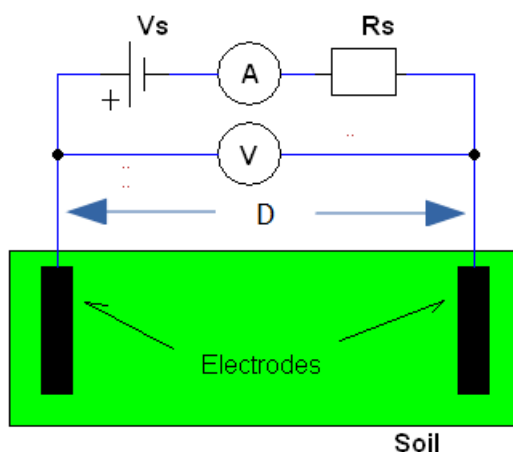


Figure 1. The electrical soil resistivity setup for the 2-electrode method. R_s is the internal resistance of the voltage source.

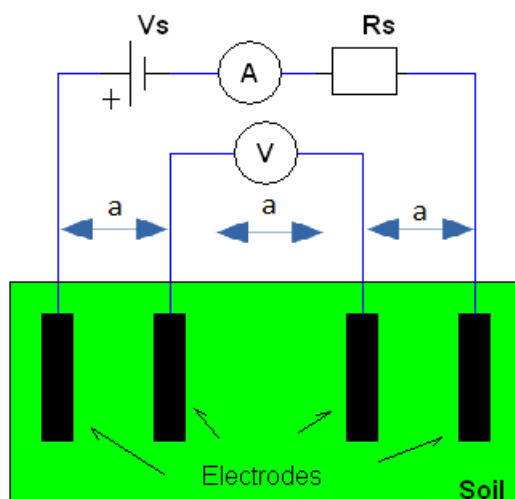


Figure 2. The 4-point electrode configuration of the Wenner approach.

For the Wenner approach, where the geometric parameter k (1) is expressed in terms of the distance of the probes, the apparent soil resistivity is now given by [2]:

$$\rho = 2\pi a \frac{V}{I}, \quad (2)$$

where a is the spacing of the probes (in meters). In this method, the lumped location of this apparent resistivity is at a depth of approximately $a/2$. In field experimentation, the parameter a can be varied between a few centimeters and almost 30 m [2,4]. Indeed, there are other electrode distributions, such as the fall-of-potential, clamp-on, and Schlumberger methods. See [2] for more details. On the other hand, the non-contact method uses electromagnetic (EM) wave radiation propagation into the soil to study the reflected signals induced by the soil itself [16]. In contrast, capacitive resistivity is one of the techniques that extends the use of the resistivity method to an environment where the galvanic coupling of the electrodes is difficult (frozen ground, hard rocks, etc.). This technique allows rapid fieldwork without the galvanic coupling of electrodes. The main problem is the complicated calculation of the forward resistivity for a simple model [17]. The electrode–soil contact-based system has the advantages of not requiring user configuration and measuring at different soil depths [18].

Therefore, the non-contact EM system is lighter in weight, smaller in size, and, thus, easier to handle [19].

The paper's main contributions can be split into two stages. First, a low-cost electronic system device able to detect variation in soil resistivity was designed. Second, a novel statistical data analysis method was introduced to study the soil resistivity. Our electronic circuit used a single-phase DC-to-AC converter followed by a transformer-to-soil-impedance coupling. This converter was operated at 45.5 Hz. This value was set due to the transformer being rated at 50 Hz and due to the availability of electronic components for circuit realization. On the other hand, the proposed soil data method was based on the maximum likelihood statistical theory. This was employed to extract important soil data features to discriminate different soils' resistivities. Additionally, a two-point soil experimental laboratory platform was also developed to support our findings. According to the experimental outcomes, our approach was effective at detecting dissimilar soil resistivities.

The rest of the paper is structured as follows. Section 2 describes our electronic circuit for soil resistivity testing, whereas the proposed data processing approach is given in Section 3. Section 4 shows our experimental laboratory platform along with the obtained results to validate our principal contribution. Finally, Section 5 gives some conclusions.

2. Electronic Instrumentation

Our electronic instrumentation design was based on a DC-to-AC converter commonly employed in the field of power electronics [20], where we integrated a transformer to couple the soil resistivity to the device via the electrodes (see Figure 3). In this electronic circuit, the supplied complementary switching signals at the pins *a* and *b* came from an oscillating circuit, as shown in Figure 4. In other soil resistivity devices, the data measurement is performed at the probe level [2]. In our approach, we collected the data in the circuit excitation stage using the voltmeters V_A and V_B , respectively. Therefore, any change in the soil resistivity would be reflected in the primary stage of the transformer in the circuit. To complete the circuit description, in Figure 3, the transformer was connected following the format 15:230 V, the primary being 15 V and the secondary 230 V. Moreover, the oscillating circuit in Figure 4 used the basic free-running multi-vibrator scheme [21], and it was implemented using the operational amplifier Op₁ (see Figure 4). We set $R = 10$ k Ω and $C = 1$ μ F. The resulting frequency oscillation was about 45.5 Hz [21]. The rest of the circuit produced complementary commuting signals. Note that the voltmeter V_B may also be used to evidence that the system is working properly.

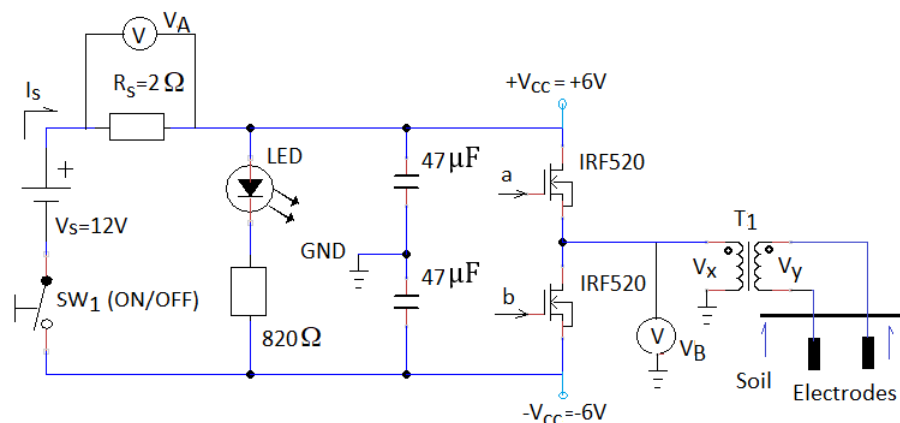


Figure 3. The single-phase DC-to-AC converter followed by a transformer. This circuit receives complementary switching signals at the pins *a* and *b*, which are generated by the circuit shown in Figure 4.

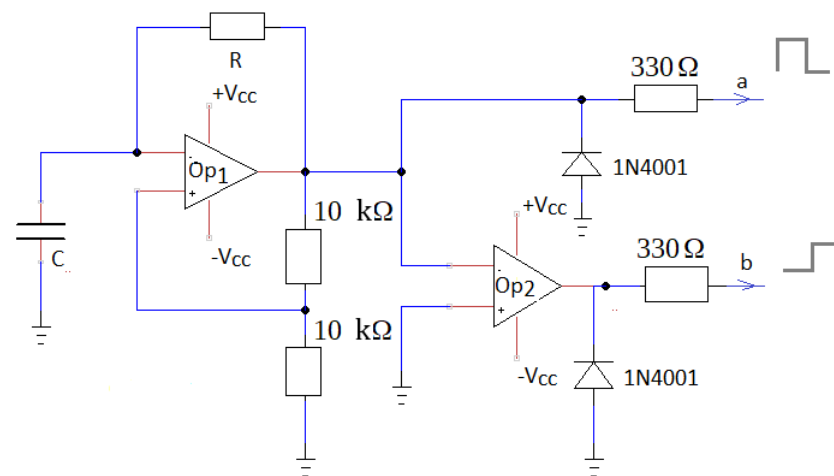


Figure 4. The circuit to produce the complementary switching signals at points *a* and *b* and then supplied to the DC-to-AC converter, as shown in Figure 3. The values *R* and *C* are programmed to tune the frequency of these commuting signals. The operational amplifiers Op₁ and Op₂ are realized by using the LM741C integrated circuit.

3. Design of the Experimental Soil Resistivity Platform

The measurement of soil resistivity samples can be performed in a laboratory [22–27]. To design our experimental soil resistivity platform by using the configuration of the two-point probes, we integrated a soil sample with the circuit, as shown in Figure 5. In this figure, in the aluminum container, we had some soil (the specimen or sample) with a different resistivity from the reference soil surrounding it. Hence, our soil resistivity meter should be able to distinguish among different soil specimens in this container. Figures 6 and 7 present the overall experiment realization, including the electronic instrumentation part.

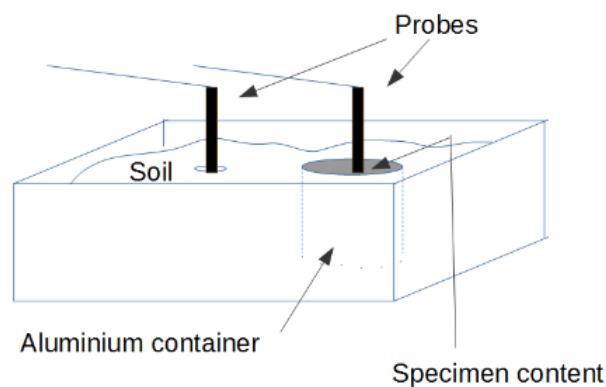


Figure 5. Schematic description of our experimental soil platform. Important realization note: the electrode must not be in contact with the aluminum container.

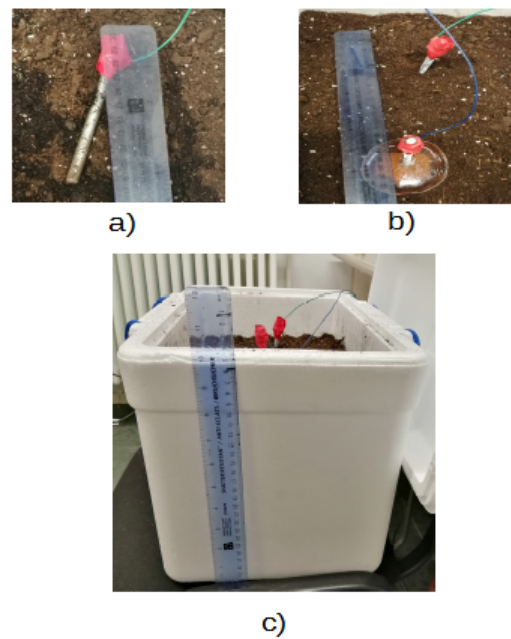


Figure 6. Experimental soil platform: (a) a photo of an electrode; (b) a photo of both electrodes and the aluminum container; and (c) a front view of the realization.

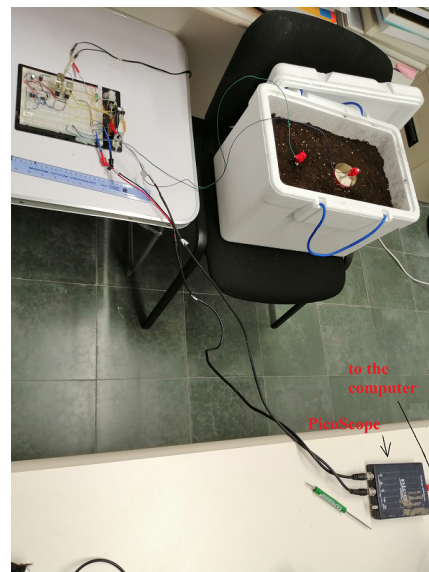


Figure 7. An overview of the soil resistivity experimental platform. The PicoScope device is a data-acquisition card, here employed to read the voltage values V_A and V_B via a computer.

4. The Soil Resistivity Data Analysis Approach

The proposed electronic device generated soil resistivity information given by the cited voltmeters V_A and V_B . These signals had some uncertainties due to several factors of the soil's properties. Therefore, for the soil resistivity data analysis, we could assume that these signals had a uniform probability distribution, which can be represented by:

$$f(x) = \begin{cases} \frac{1}{\beta - \alpha} & \alpha \leq x \leq \beta \\ 0 & \text{otherwise.} \end{cases} \quad (3)$$

The main motivation for using the above expression was because, from the experimental point of view, the data were time varying, but bounded around a mean value.

Therefore, the parameters α and β can be considered as indicators to distinguish different soil resistivities. For the distribution function (3), the method of moments was not useful to determine the parameters α and β . It can produce an estimated value of the parameter β less than the maximum observed value and an estimation of the parameter α greater than the observed minimum value [28]. Thus, the estimation of these parameters was carried out by using the maximum likelihood estimation method (MLE). The likelihood function for a sample of size n is [28]:

$$L(\alpha, \beta) = \begin{cases} \frac{1}{(\beta - \alpha)^n} & \alpha \leq x \leq \beta, n \in \mathbb{N} \\ 0 & \text{otherwise.} \end{cases} \quad (4)$$

To estimate the parameters α and β from the sample data, we needed the maximum of the function (4). We may obtain this by solving the gradient vector equation: $\vec{\nabla} L = \left(\frac{\partial L}{\partial \alpha}, \frac{\partial L}{\partial \beta} \right) = \vec{0}$. Since the partial derivatives of the function (4) with respect to the parameters α and β were:

$$\begin{aligned} \frac{\partial L}{\partial \alpha} &= \frac{n}{(\beta - \alpha)^{n+1}} \\ \frac{\partial L}{\partial \beta} &= \frac{-n}{(\beta - \alpha)^{n+1}} \end{aligned} \quad (5)$$

we had to determine when both equations were zero. However, since $n \neq 0$, the gradient never vanishes, so we could not use this method. Moreover, in Equation (5), the partial derivatives are both zero if and only if their denominators tend to infinity, that is when one of these two parameters tends to infinity with respect to the other. Therefore, to estimate these parameter values, we followed the MLE reasoning presented in [29]. From Equation (4), it is easy to see that the likelihood function tends to its maximum value when the difference $\beta - \alpha$ is as small as possible. Given a sample of n observations and supposing that x_{min} is the smallest and x_{max} the largest one in the sample, in this case, α cannot be greater than x_{min} , and β is less than x_{max} . Therefore, the lowest positive value of $\beta - \alpha$ is $x_{max} - x_{min}$, and the maximum likelihood estimators for an n -sized sample are:

$$\begin{aligned} \hat{\alpha} &= x_{min} \\ \hat{\beta} &= x_{max}. \end{aligned} \quad (6)$$

These estimations were important because the intermediate observations of a given sample were not considered, resulting in an effective analysis tool for soil resistivity diagnosis.

5. Experimental Results

In this section, we present three experimental settings for three different soil samples to study them from the resistivity point of view:

- Case 1: The aim of this first experiment was to detect a change from high to low resistivity by adding salty water to the aluminum container;
- Case 2: This experiment had the objective of measuring the change from high to medium resistivity by filling the aluminum container with sawdust;
- Case 3: The main objective of this scenario was to detect a resistivity change when the aluminum container was filled with cat litter.

In all cases, the experimental data were raw data, that is they were not obtained by any filtering process, so they had a certain randomness.

5.1. Case 1: Experiment with Salty Water

The experimental results related to measuring the change of the soil resistivity when the aluminum container was filled with salty water are shown in Figure 8. This case corresponded to a change in the soil specimen from high resistivity, the empty aluminum container, to a low one. This was because salty water is a conductive liquid. The experiment began when the electronic instrument was in the off position and then powered on at about

4 s. Later, the aluminum container was filled with salty water for 8 s. Therefore, this process ended around 12 s, as shown in the Voltmeter A and B diagrams. See Figure 8. To test our data analysis method, we performed the statistical parameter estimation presented in (6) on the data collected from the experiment. This was done by setting $n = 100$, corresponding to approximately 0.66 s of data acquisition from our experiment; a moving window of size n was applied, and then, Equation (6) was used for each window up to the end of the data file. The first 100 data were used, then the second set of 100 data, and so on. Figure 9 proves that our instrument and data analysis approach were sensitive to soil resistivity variation.

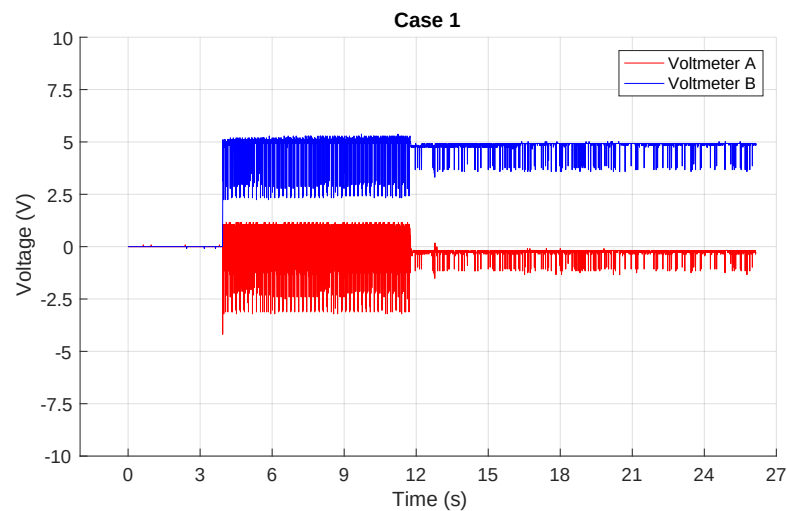


Figure 8. Case 1: Experimental results. During approximately 8 s (from approximately 4 s to 12 s), we filled the container with salty water, then stopped. The voltmeter detected this change of salinity with a small delay.

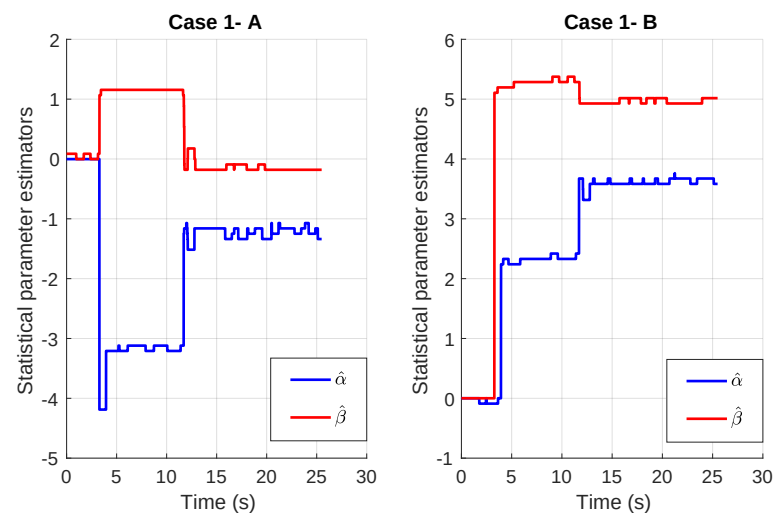


Figure 9. Case 1: Data analysis evolution of the likelihood estimation of the decision parameters $\hat{\alpha}$ and $\hat{\beta}$ (6). At approximately 12 s, both parameters detected different soil resistivities.

5.2. Case 2: Experiment with Sawdust

In this case, the previous experiment was repeated, but now, the container was filled with sawdust. Figure 10 presents the experimental outcomes related to measuring the soil resistivity variation when the aluminum container was being filled. This example corresponded to a change in the soil specimen from a high-resistivity scenario to a medium-resistivity event. This experimental testing again started with the instrument in the off position, then powered on at about 4.8 s. Later, the aluminum container was filled with

the sawdust. This process ended at around 14 s. Figure 11 shows the corresponding data processing result as in the previous experiment. From Figure 11, we proved that our instrument and data analysis approach were sensitive to soil resistivity variation. However, it should be noted that, in this case, the parameter $\hat{\alpha}$ was more sensitive than the other. In this case, the change of soil resistivity was hard to detect from the voltmeter diagrams (see Figure 10), but it can be appreciated from the data analysis, as shown in Figure 11. Finally, Figure 12 shows the aluminum container filled with the sawdust.

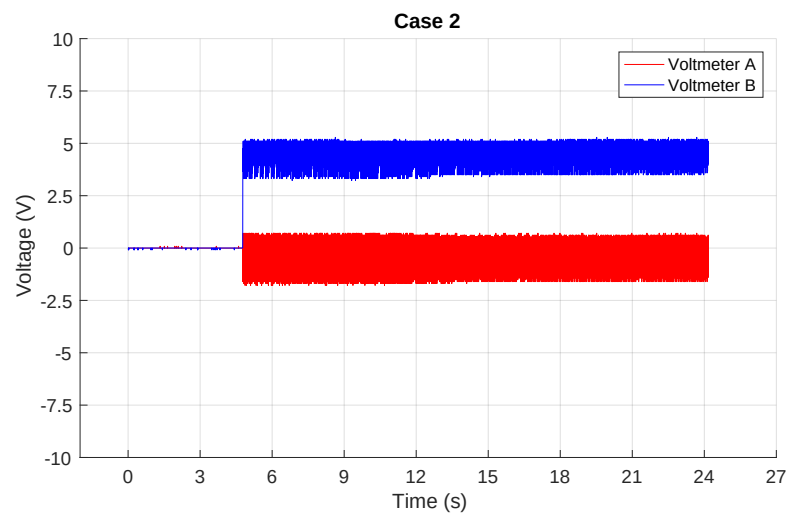


Figure 10. Case 2: Experimental results, where a change in soil resistivity is hard to read.

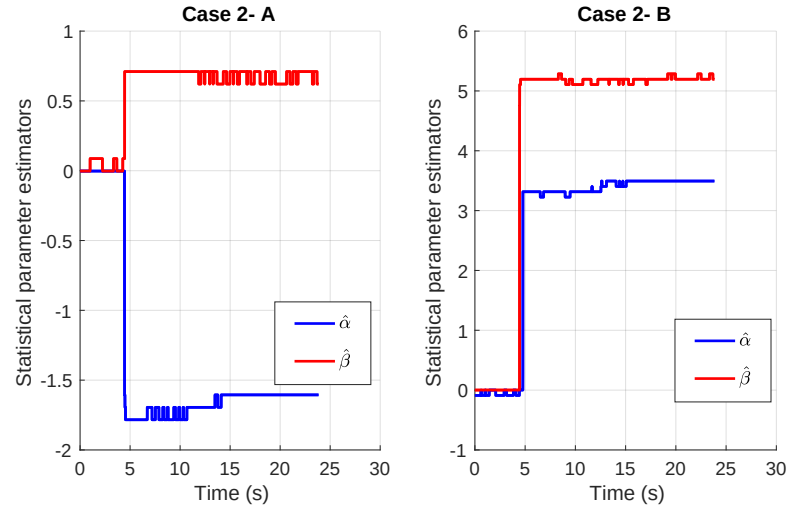


Figure 11. Case 2: Time evolution of the likelihood estimation of the parameters $\hat{\alpha}$ and $\hat{\beta}$. Case 2-A shows, at approximately 14 s, that parameter $\hat{\alpha}$ detected a change in soil resistivity.



Figure 12. Case 2: The aluminum container filled with wood sawdust.

5.3. Case 3: Experiment with Cat Litter

In this last experiment, we repeated the same experimental process, but using cat litter. Now, the aim was to obtain a dynamic detection system for resistivity, and the cat litter met our goal due to its granular texture. The corresponding experimental outcomes are shown in Figures 13–15. Once again, our instrument and data analysis approach were also sensitive to this soil resistivity variation.

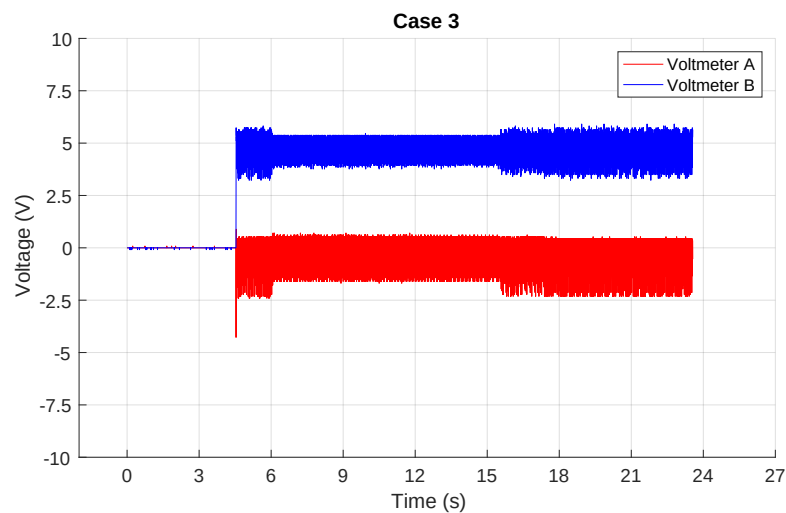


Figure 13. Case 3: Experimental results. During approximately 9 s, the aluminum container was filled with cat litter, as the voltmeter diagrams evidence.

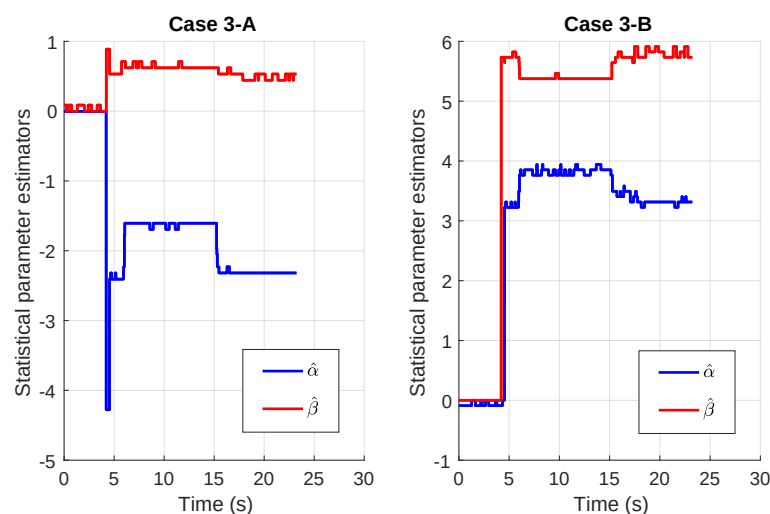


Figure 14. Case 3: Time evolution of the likelihood estimation of the parameters $\hat{\alpha}$ and $\hat{\beta}$. As for the previous scenarios, the parameters confirmed the detection of soil resistivity changes.



Figure 15. Case 3: The aluminum container filled with cat litter.

6. Conclusions

In this paper, an electronic device for soil resistivity analysis was developed. Our design was conceived as a soil instrument to measure the variability of soil resistivity. This included a pilot experimental platform to validate our contribution, followed by a data processing method based on the MLE technique. According to our experimental outcomes, our approach was able to detect soil resistivity variations. Therefore, when both voltmeter readings were unable to discern a change in the soil resistivity, the proposed MLE approach was able to. Therefore, from the numerical point of view, a model of a random dataset was developed and used for data diagnosis. Hence, the α and β parameters can be used as features for dataset comparison. Finally, this approach was low in cost.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating current
DC	Direct current
EM	Electromagnetic
MLE	Maximum likelihood estimation method

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