FABRICATION AND EVALUATION OF AN ALTERNATING CURRENT SOURCE RESISTIVITY METER FOR GROUND WATER AND SOLID MINERALS EXPLORATION

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ABSTRACT

A compact, low-cost alternating current source resistivity meter with a stable current output was designed and fabricated for geo-electric sounding in an in – situ measurement to a depth of about 100 meters using locally sourced electronics and electrical components. Four contact principle of Van der Pauw conduction geometry was used for designing the circuit which consists of transmitter and receiver units. The transmitter unit consisted of a voltage generator integrated circuit (SG3524) which feed two π radian out of phase pulse trains, at the frequency of 225 Hz to a current generator unit, through two buffer transistors (BC558). A current limiter circuit was designed and incorporated in the transmitter circuit for selectable Signal Currents (SI) to be passed in-situ through the current electrodes. The receiver unit comprised a differential operational amplifier signal detector (AD8277A) connected through a low pass filter circuit to a microcontroller (PIC16F877A) and liquid crystal display. A microcontroller code was developed using a miKroBasic program which calculated the medium resistance using signal averaging technique. Pre-fabrication Simulation (PfS) tests of the whole circuit were carried out using proteus 7.2 professional. The fabricated meter and a Standard resistivity meter (Campus Omega) were used simultaneously for field measurements at two purposively selected test sites using vertical electrical sounding, while the degree of fitness (R^2) between measurements of both equipment were analysed and compared using inferential statistics. The statistical result shows that there was no significant difference between Standard resistivity meter and fabricated resistivity meter.

Keywords:MikroBasic program; Vertical Electrical Sounding; Signal Averaging Technique; Heterogeneous; In-Situ.

INTRODUCTION

Resistivity is an intrinsic property of a material that quantifies how strongly the material resists the flow of electrical current. It is defined as the electrical resistance of unit length and a unit cross-sectional area $(\rho = R\frac{A}{L})$. It is the inverse of electrical conductivity. Soil electrical resistivity is a key factor in determining soil type as each soil has its range of resistivity values based on its structure and fluid content. In-situ geoelectric sounding is a non-destructive method of estimating the electrical resistivity of soil layers within a shallow depth of the earth crust with the purpose of identifying the sub-surface materials present. The resistivity of a soil sample can be obtained using an earth resistivity meter. An earth resistivity meter is an instrument used to identify the composition of various earth strata and the depth at which each strata occurs and by detecting changes in earth composition, they can be used to point to the existence of buried objects. The first attempt to measure electrical resistivity of soils was made at the end of the nineteenth century with two-electrode technique, Whitney et al., (1897), Gardner (1898), and Briggs (1899) developed relationships between soil electrical resistivity and soil water content, temperature and salt content using the two electrode method. The method developed measures the sum of both soil resistivity and the contact resistivity between the electrode and soil. The latter is very erratic and unpredictable. Wenner (1915) based on the work of Schlumberger suggested that a linear array of four equally spaced electrodes would minimize soil-electrode contact problems if potential measuring and current-induced electrodes are separated in space. Since then all the electrical resistivity materials applied in geophysics and soil science have been based on the standard four electrode principle.

The method of four-electrode profiling has been used for resistivity measurement since 1931 for evaluating soil water content and salinity under field condition (McCorkle, 1931, Halvorson and Rhoades, 1976; Rhoades and Ingvalson, 1979, developed and introduced a four-electrode probe in the Wenner configuration to locate saline seeps on croplands in USA and Canada. Austin and Rhoades (1979) developed and introduce a compact low-cost four electrode salinity sensor into routine agricultural practices. A special soil salinity probe which utilized the same four-electrode principle was also designed for bore-hole measurements and for permanent installation in soils for infiltration and solidifies monitoring (Rhoades and Schilfgarde, 1976; Rhoades, 1979). An electrical cell used to measure electrical conductivity of soil samples, pastes and suspensions, was also developed based on four-electrode principle (Gupta and Hanks, 1972).

Relationships between electrical conductivity measured in-situ with four-electrode probe and conductivity of soil solution or saturated soil paste were developed (Nader, 1982; Rhoades *et al,* 1989). The method of four-electrode profiling was also used for evaluation of some other soil properties such as soil water content (Edlefsen and Anderson, 1941).

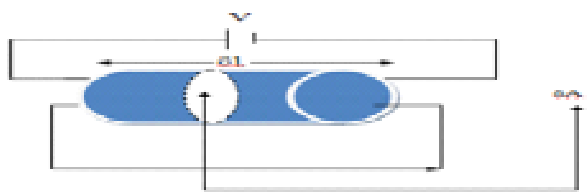


Figure 1: Basic resistivity across a homogeneous cylindrical material

MATERIAL AND METHOD

Theoretical framework of Electrical Resistivity Survey

The electrical resistivity of any material is defined as the resistance in ohms between the opposite faces of a unit cube of a material. In this study a case of a cylindrical material of length δl and cross sectional area δA as in Figure 1 was adopted. The resistance δR across the material is directly proportional to δl and inversely proportional to δA:

$$R \propto \frac{\partial l}{A} \;,\; R = \rho \frac{\partial l}{\partial A} \qquad (2)$$

where, ρ is a constant of proportionality known as the resistivity of the material.

Using equations (1) and (2), equations (3) – (7) were deduced:

$$\partial R = \rho \frac{\partial l}{\partial A} = \frac{\partial v}{\partial i} \qquad (3)$$

Hence, $$\rho = \partial R \frac{\partial A}{\partial l} \qquad (4)$$

Also, $$\rho = \frac{\partial v}{\partial l} \cdot \frac{\partial A}{\partial I} \qquad (5)$$

$$\frac{\partial v}{\partial l} = \rho . \frac{\partial I}{\partial A} \qquad (6)$$

$$E = \rho . j \qquad (7)$$

where,
$E =$ electric field strength in Vm^{-1}
$\rho =$ resistivity in Ωm, and
$j =$ current density in Am^{-2}.

Most rock forming mineral are insulators, electrical current are carried through them mainly by the passage of ions in pore water. Thus most rocks conduct electricity by electrolytic rather than electronic process. It follows that porosity is the major factor of the resistivity of rocks, and the resistivity generally increases as the porosity decreases.

The effective resistivity of rock and its pore water can be expressed in terms of the resistivity and volume of the pore water present as given by Achie (1942) in equation (8)

$$\rho = \alpha \varphi^{-m} s^{-n} \rho^{\omega} \qquad (8)$$

where
ρandρw are the effective rock resistivity and the resistivity of the pore water respectively.

φ is the porosity, S is the volume fraction of pores with water; α, m and n are constants, where $0.5 \le \alpha \le 2.5$, $1.3 \le m \le 2.5$ and $n \approx 2$.

Design and fabrication procedures

For the design and fabrication of the resistivity meter, an alternating current source method rather than direct current apparatus was adopted. This was employed due to the fact that the direct current apparatus gives thermoelectric and drifts effects errors that are difficult to eliminate. Hence, A.C. methods are now more commonly used for precise electrical measurements. In our design we use a method similar to the method developed by Friend and Bett (1979) for measuring the specific resistivity and Hall effect in metallic specimens at low temperatures. The basic experimental arrangement is shown in the block diagram of Figure 2. An alternating sine- wave voltage is generated at a frequency, $f_0 = 225Hz$ and fed into a power amplifier unit which produces a commutative d.c signal with high current and of high voltage. The current I generated is passed through the sample via a pair of contacts P and Q, the resulting voltage V developed across another pair of contacts R and S is fed into a detector or demodulator which is made up of a differential amplifier and filter circuit . The resulting d.c component of the signal from the output of the detector is fed into a signal processing unit which is made up of a microcontroller and display units where the resistance of the sample is calculated and subsequently displayed. Based on the resistance value obtained, the resistivity of the specified location can be deduced. Vander Pauw (1958) reported that for an homogeneous sample in the form of a lamina of uniform thickness, the two sets of measurements plus the thickness of the lamina, suffice to determine the resistivity of the material- irrespective of the shape of the lamina and the location of the point PQRS.

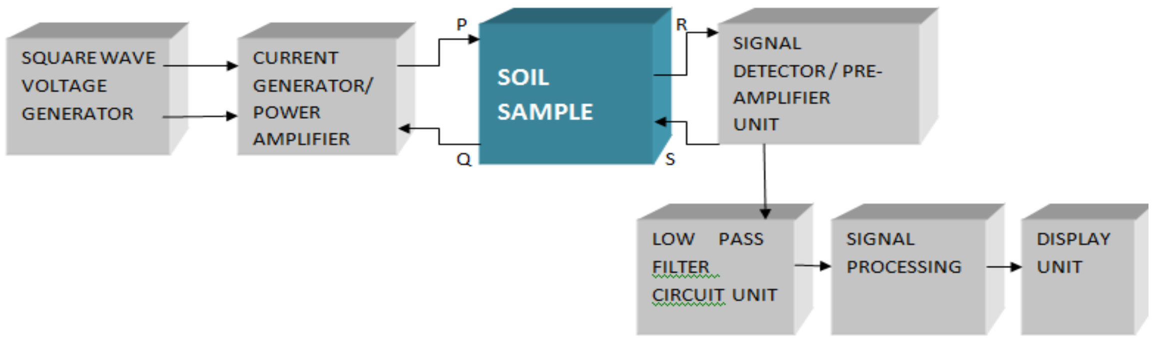


Figure 2: Block diagram of alternating current source resistivity meter

Sine Wave Voltage Generator

In generating sine wave voltage for the resistivity meter, a pulse width modulating IC SG3524 was used. SG3524 is an integrated switching regulator circuit that has all essential circuitry required for making a switching regulator in single ended or push-pull mode. The built in circuitries inside SG3524 include, pulse width modulator, oscillator, voltage reference, error amplifier, overloaded protection circuit, output drivers etc. Two pulse trains which are 180 degree out of phase were generated at pins 14 and 11 of the IC based on the resonant tank created as a result of capacitor connected between pin 7 and pin 8 and variable resistor (potentiometer) connected to pin 6 of the IC. The amplitude of the signal generated is varied using the variable resistor connected to pin 2 and via R_3 to pin 16 of the IC. To minimise, the effect of parasitic current, a low pass filter was used and the frequency of the signal is given in equation (9) as

$$f = \frac{1.30}{R_t C_t} \tag{9}$$

where,

R_t is the timing resistor, C_t is the timing capacitor and f is frequency of the signal which is equal to 225 Hz.

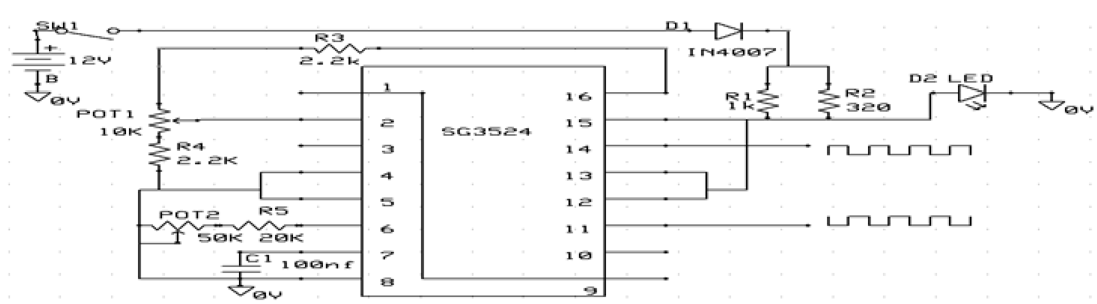


Figure 3: Square wave voltage generator schematic circuit diagram

The Current Generator/Power Amplifier

The current generator constructed was designed to provide maximum current of about 300mA. This high current generated is supper-imposed on the signal derived from the voltage generator, this thus create alternating current drive in the primary source of a 250 W step up transformer thus serving as power amplifier. The current generator is made up of two driver transistor BC558 and four (4) Mosfet transistor mounted on an adequately sized heat sink for dissipation of heat. In the circuit two driver transistors BC 558 which are voltage controlled transistor amplifier of high input impedance, low output noise, better linearity and low inter- electrode capacitance were used as current boost to turn ON and OFF four Mosfet transistors in a push–pull arrangements. The Mosfet transistor arrangement represent a class B push-pull voltage amplifier in a Darlington pair connection using high current Mosfet transistor IRF250 with maximum current drains rating of 15A. The signals from pins14 and 11of the PWM SG3524 are fed to the base of the two buffer transistors BC 558, the output signals obtained from the collector-emitter junction are amplified to high current value capable of switching ON and OFF the gates of the Mosfet transistors, thus serving as a preamplifier unit for the current generator. The operation principle of the current generator is shown in Figure 4.

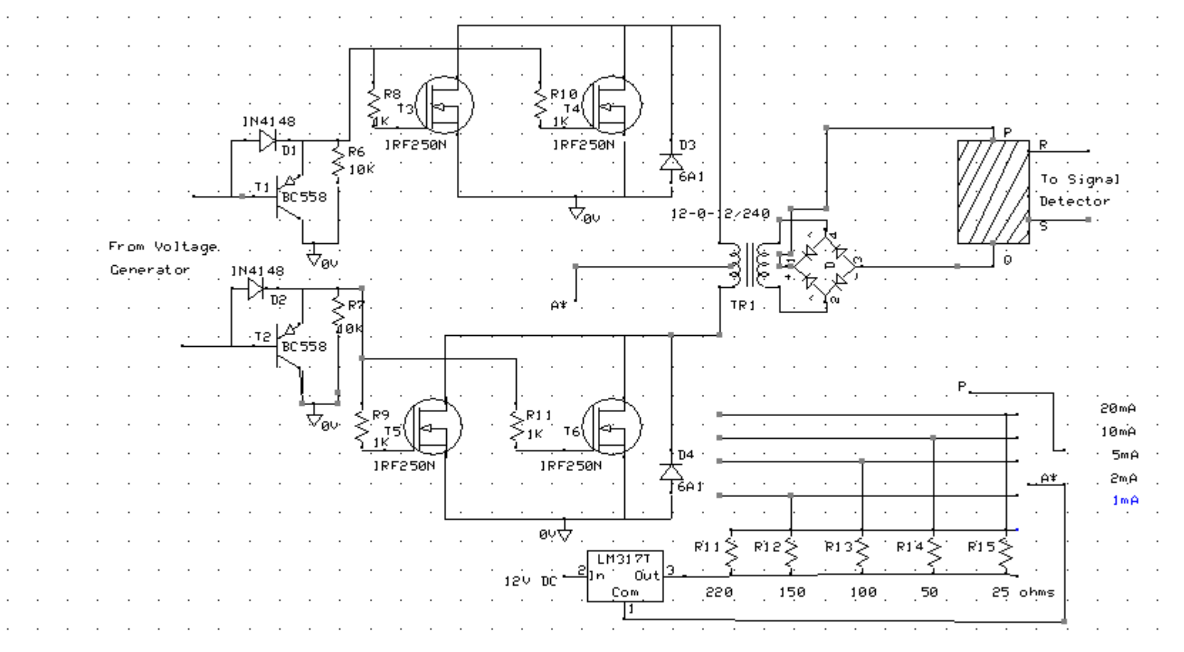


Figure 4: Current generator/ power amplifier schematic circuit diagram.

The Signal Detector

In developing signal detector or demodulator for the resistivity meter, a differential operational amplifier circuit (Fig. 5) was used. The operational amplifier was connected in a differential mode to the potential electrode R and S. It has a 1kΩ carbon resistor, each connected to the inputs of the inverting and non-inverting terminals and a 1kΩ Cermets potentiometer connected in the feedback path to the inverting terminal, while another 1kΩ potentiometer was connected to the ground at the input of the non-inverting terminal. The differential signal and its noise components amplified by the high gain differential amplifier, are fed to the input of a low pass filter shown in Fig.6, to reduce noise associated with the signals which comes partly from sources such as induced signal from ionosphere , pick up noise from the mains at a frequency of 50Hz, Johnson noise due to some electronics components such as resistors in the circuit and also noise due to mechanical vibrations of the equipment in the presence of magnetic field. In the receiver circuit, the effect of some of these noise on the signal have been avoided, for example the noise from the main has little effect on the signal due to the fact that the received frequency of the constructed resistivity meter is a d.c commutative signal, at corner frequency, $f_c \pm 455Hz$, which is far away from the frequency of domestic power supply at 50Hz, while the effect of other remaining noise are minimized using a low pass-filter.

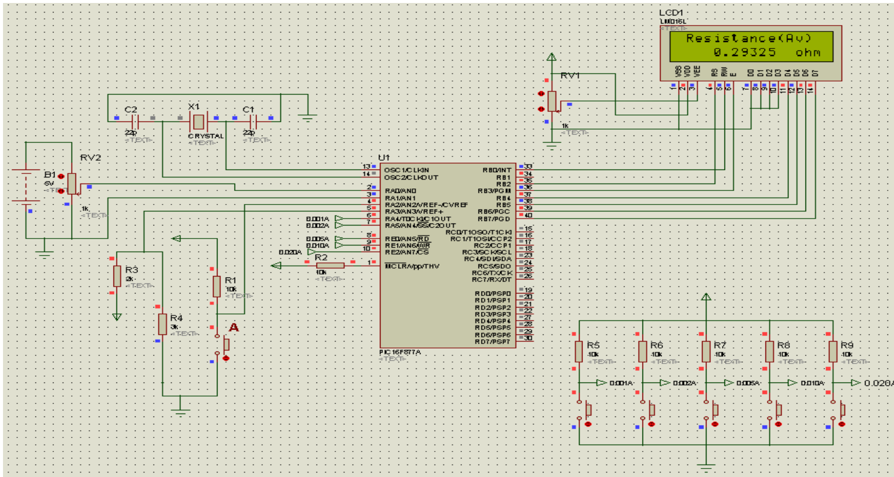


Figure 5: Resistivity signal detector with differential operational amplifier circuit

Field Testing

After the design and construction of the fabricated resistivity meter (FRM) has been made, there is need for field testing. This was done by comparing the FRM with standard resistivity meter (SRM) Campus Omega model using a Schlumberger array method (Fig. 6).

In the resistivity method, specifically Schlumberger array, accurately known artificially generated electric currents are transmitted into the ground via two electrodes P and Q (Figure 2), the resulting potential difference δv between the electrodes R and S are measured at the surface. Electrodes P and Q are regarded as the potential electrodes or current source or sink respectively, while R and S are regarded as potential electrodes with equal and opposite strength. Deviation from the pattern of potential differences expected from homogeneous ground provide information on the form and electrical properties of the subsurface in-homogeneities.

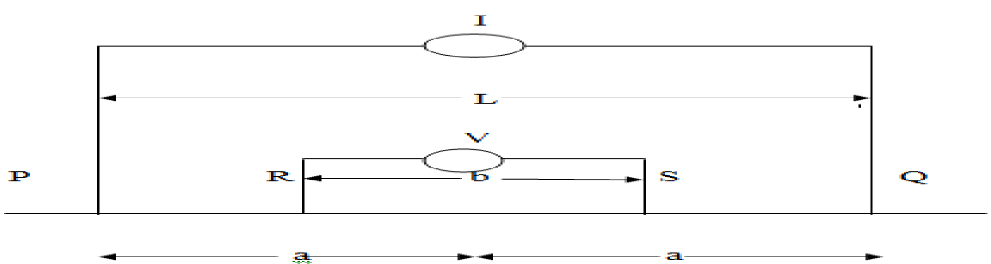


Figure 6: Schlumberger arrangement

Plate 1: Field Testing using Standard and Fabricated Resistivity Meter

The FRM and SRM were used simultaneously for field measurements at two purposively selected test sites T_1 and T_2 using vertical electrical sounding (VES), while the degree of fitness (R^2) between measurements of both equipment were analysed and inference was deduced using t-test at 0.05 significant level.

The comparism made in Figures (7a and 7b) between the FRM and SRM for VES 01 and VES 02 shows a very good correlation coefficient of 0.92 and 0.95 which implies that the two meters gives similar trend in their result and the their results are strongly correlated. For the error correction, regression analysis was carried out and a linear equation was developed for the two resistivity meter survey result.

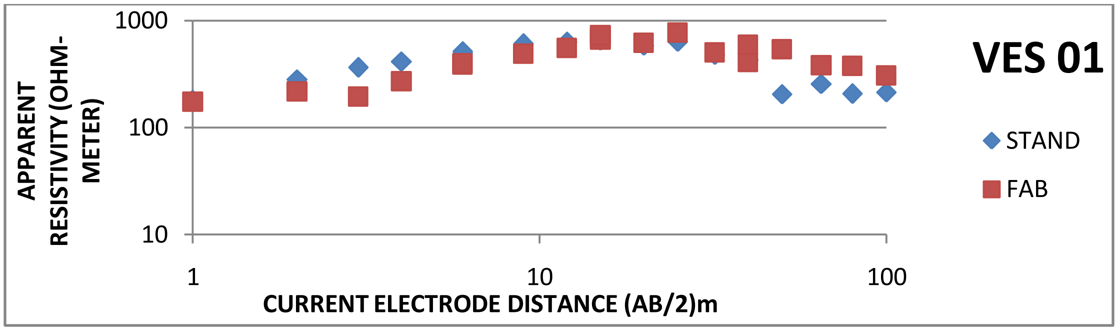
RESULT AND DISCUSSION

Result of Field Testing

Plate 1 depict the pictorial representation of the cased FRM place at the right hand side and the SRM at the left hand side for resistivity survey. The result obtained for the resistivity survey were then compared as presented in Figure 7(a-b) for VES 01 and VES 02.

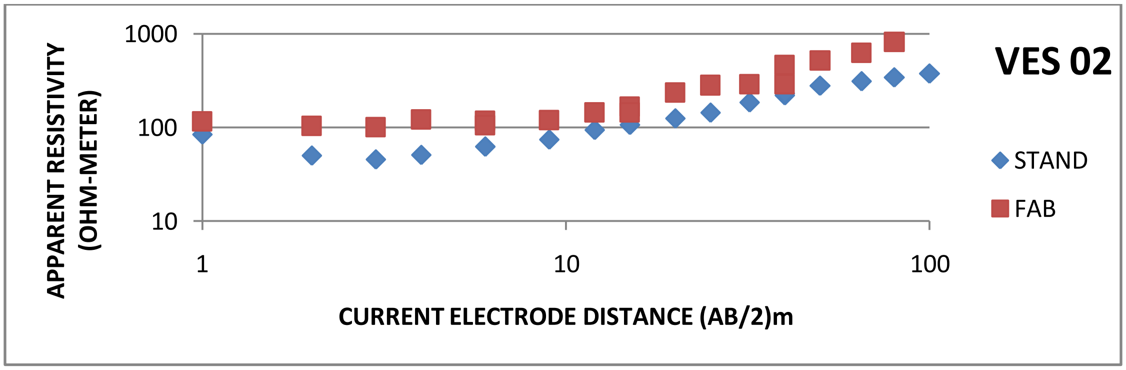
The graph of resistance measured by FRM (X) against those of SRM (Y) for the two sites (figures 8a and 8b) gives a linear equations 4 and 5 with their degree of fitness (R^2)

$$Y = 1.068X + 0.298 \quad R^2 = 0.984 \quad (4)$$
$$Y = 1.136X - 0.172 \quad R^2 = 0.989 \quad (5)$$



	STAND	*FAB*
STAND	1	
FAB	0.92	1

Figure 7a: Log-log graph of apparent resistivity (Ωm) against current electrode spacing (AB/2) m



	Std	*Fab*
Std	1	
Fab	0.95	1

Figure 7b: Log-log graph of apparent resistivity (Ωm) against current electrode spacing (AB/2) m

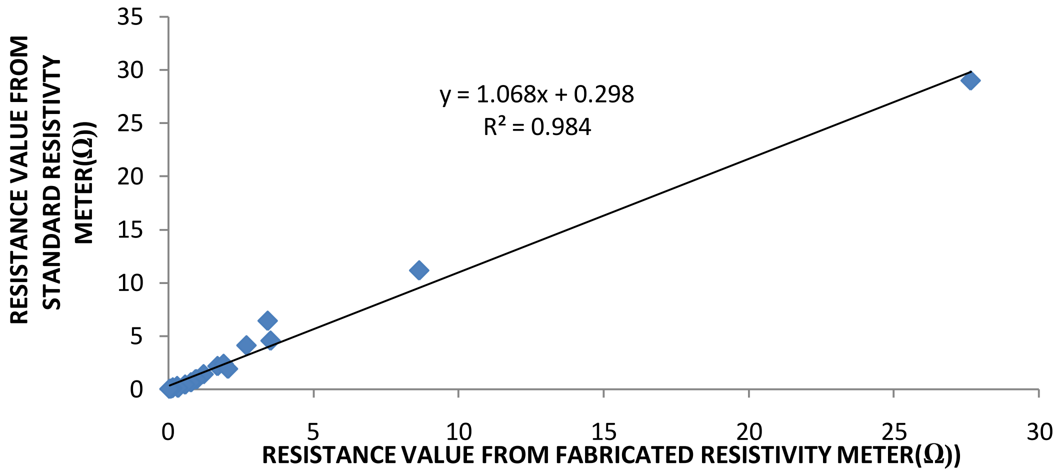


Figure 8a: Calibration graph of standard resistance values (Ω) against fabricated resistance values (Ω)

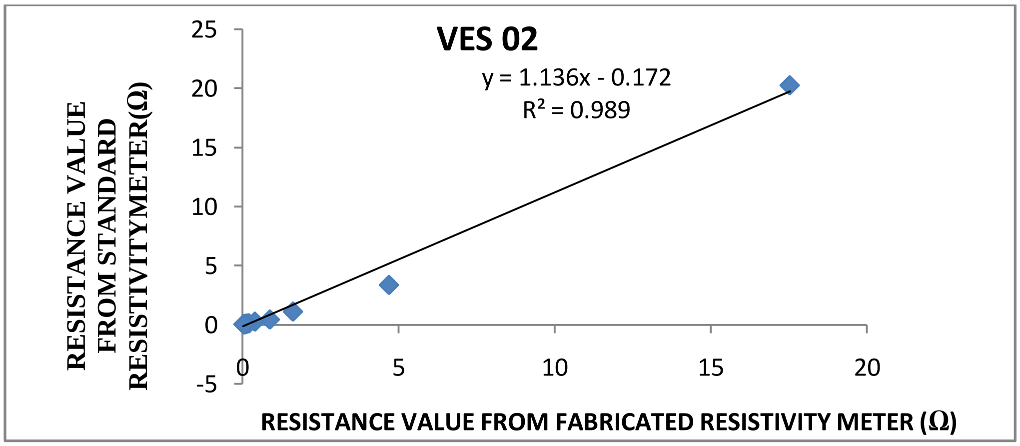


Figure 8b: Calibration graph of standard resistance values (Ω) against fabricated resistance values (Ω)

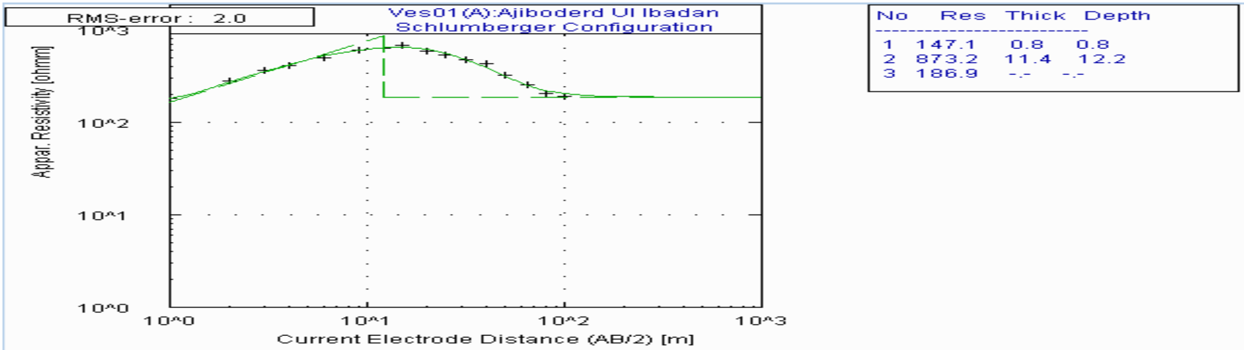
Depth and layer estimation results

The VES results were presented in form of computer iteration curves drawn based on computer programs written as "Resist" software based on Orellana and Mooney (1966), Koefoed (1979) and O'Neils (1984) majorly for the purpose of depth and layer classifications.

The VES 01 accounted for three layered model of AH and KQ types of curve with configuration of apparent resistivity $\rho_1 < \rho_2 > \rho_3$. The layers resistivity are:147.1, 873.2, 186.9 and 163.6, 957.3, 279.2 (Ωm) for the SRM and FRM respectively (Figs. 10). The thicknesses are in the order of: 0.8, 11.4, ∞ (m) and 1.3, 10.0, and ∞ (m) for the standard and fabricated meter respectively (Figures 9). The lithographic geo-sectional of the VES 01 both for SRM and FRM which display the soil types in each layer based on the resistivity, thickness and the depths of penetration obtained were presented in Figures 11. The first layer accounted for a top soil, while the second layer suggests a lateritic clay soil. The third layer indicated a weathered basement formation.

Three layered model of AH and KQ types of curve with configuration of apparent resistivity $\rho_1 > \rho_2 < \rho_3$ were as well obtained for VES 02. The layers resistivity are: 121.8, 43.0 , 572.0 (Ωm) and for SRM while the values 136.5, 68.0 and 1095.0 (Ωm) were obtained for the FRM (Figures 10). The thicknesses: 0.5, 4.9 and ∞ (m) were deduced for the SRM while that of FRM are in the order of 0.5, 5.0, ∞ (m). The lithographic geo-sectional revealed the first layer as a top soil, the second layer as weathered basement formation, while the third layer accounted for fresh basement formation (Figure 12) The second layer with lower resistivity suggest an aquifer layer due seepages of water from nearby stream.

(a)



(b)

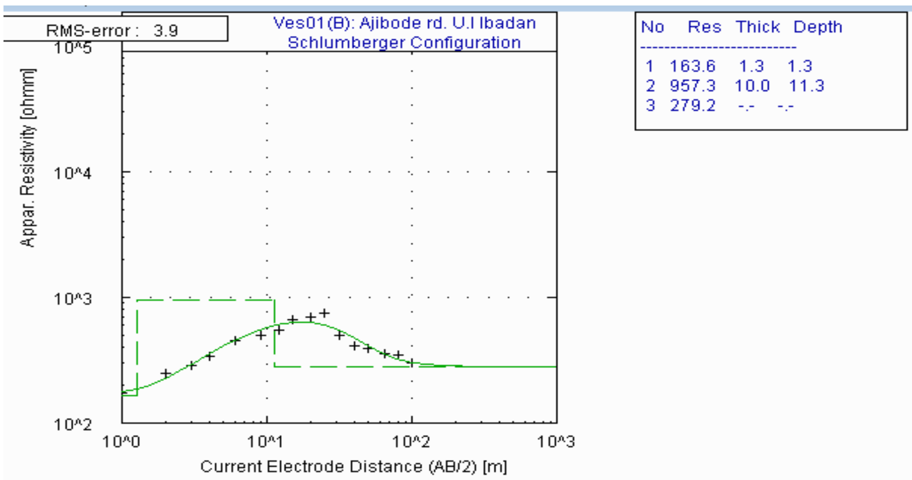
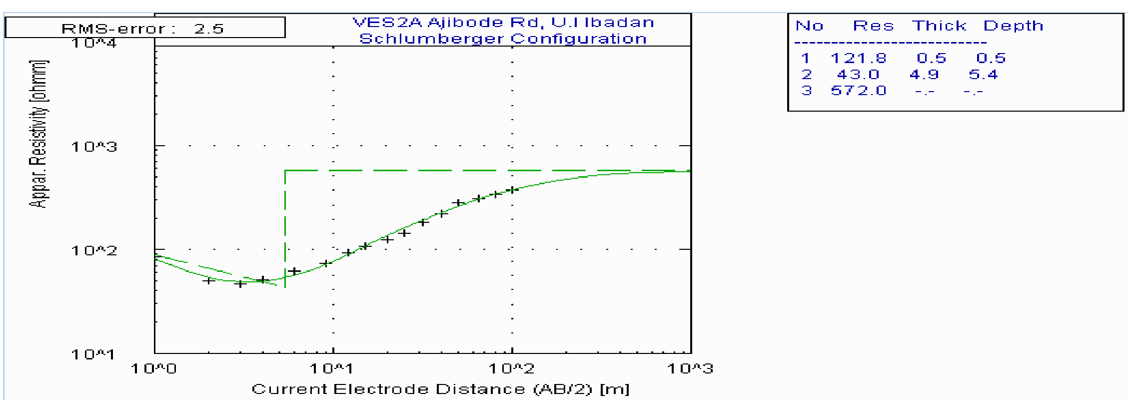


Figure 9: The computer iteration curves/apparent resistivity versus current electrode separation for (a) SRM (b) FRM for depth estimation in VES 01

(a)



(b)

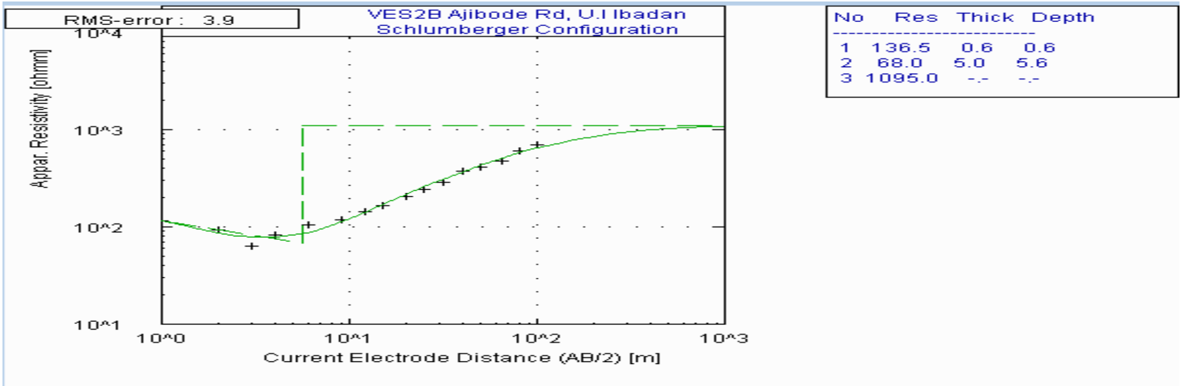


Figure 10: The computer iteration curves/apparent resistivity versus current electrode separation for (a) SRM (b) FRM for depth estimation in VES 02

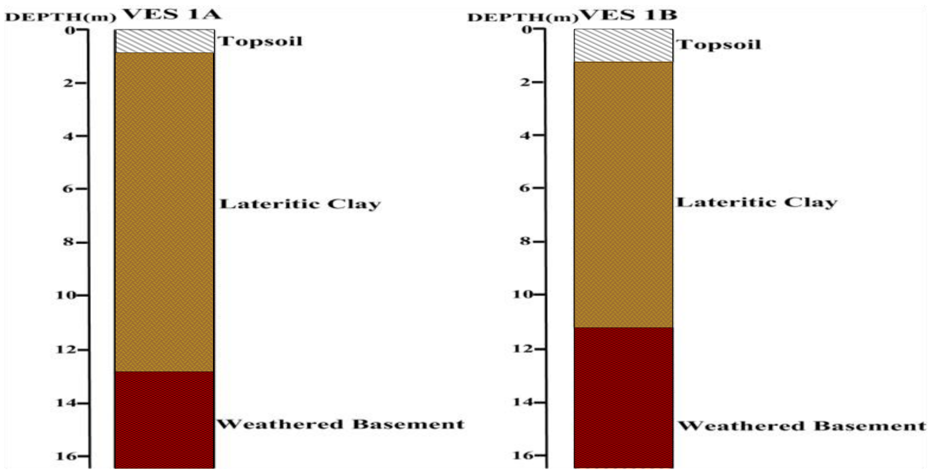


Figure 11: Lithographic cross sectional graphs of (a) SRM (b) FRM for VES 01

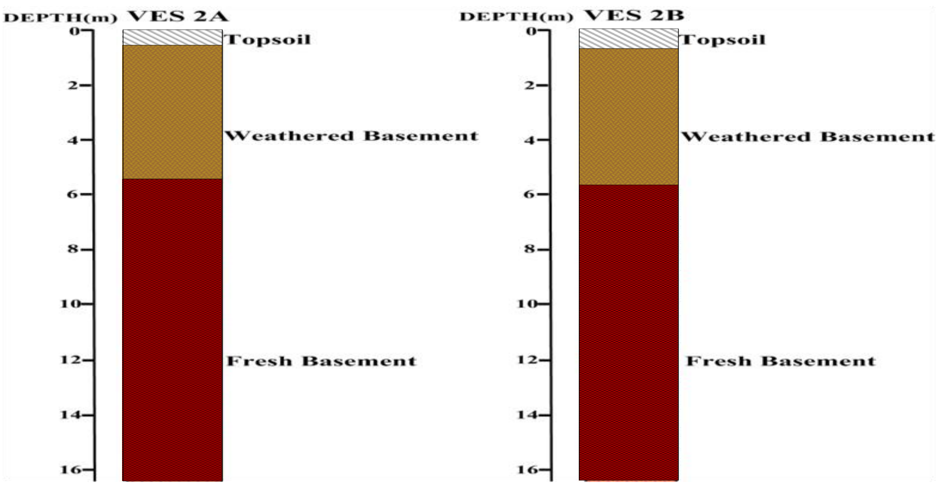


Figure 12: Lithographic cross sectional graphs of (a) (a) SRM (b) FRM for VES 02

T-test Inference result

Table 1 accounted for the statistical T-test result made for the accuracy validation between SRM and FRM for VES 01 and VES 02. The VES 01 accounted for t-value of -0.012 with the p-value of 0.991 at two tailed while VES 02 revealed t-value of -0.072 with the p-value of 0.943. When p-value > 0.05, no significant difference is said to exist. Hence, the p-value result obtained therefore indicates that there exist no significant difference between SRM and FRM used in this study.

Table 1: T-test result for VES 01 and VES 02

		t-test for Equality of Means								
		F	Sig.	T	Df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Variation in resistance reading of SRM and FRM	Equal variances assumed for VES 01	0.010	0.919	-0.012	36	0.991	-.016	1.412	-2.881	2.849
	Equal variances assumed for VES 02	0.019	0.890	-0.072	36	0.943	-.308	4.306	-9.042	8.426

CONCLUSION

From the measurements carried out using the standard and locally fabricated resistivity meters and from the analysis of the results, it can be concluded that the local resistivity meter, was found to be reliable for in-situ resistivity measurement in which it clearly confirmed the heterogeneous nature of the earth subsurface. Also, the embedded code made the local resistivity meter easily repairable. At a lower production cost of ₦150,000 compared to ₦1.7 million which is 8.82% the cost of the imported resistivity meter of similar technical specification, the locally fabricated resistivity meter can serve as a cost effective substitute for geo-electric sounding for (i) location of fracture zone (ii) ground water exploration (ii) archaeological investigation (iv) mineral exploration and environmental site studies and (v) soil salinity detection. The minimum resolution reading of the meter can be improved upon by using 12 bit ADC PIC microcontroller. Also with a correlation coefficient results obtained, the locally fabricated resistivity meter will give an approximate resistance reading as imported standard resistivity meter.

Conflict of interest

The authors declares no conflict of interest

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