

Full Length Research Paper

Effect of the soil moisture variation on apparent resistivity profiles and a method of correction

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In order to get an apparent resistivity map of quite a large area which required a considerable amount of time (months) and because of the occasional availability of equipment and bad weather conditions causing postponing of certain campaigns, the area was divided into adjacent sub-areas which were mapped in a considerably separated measuring days. Because of the rainfall changes from one campaign to another, the final apparent resistivity map obtained by superposing all the different measuring day's maps is obviously misleading. In the first stage, this disturbing effect was highlighted by carrying out profiles in the beginning of each measuring day on a specific line of the grid (the first line) just before mapping the corresponding sub-area. This was achieved first for the shallowest part of the grid, and then for the deeper parts. In the second stage, a removal of this effect was performed by applying a method of correction which consisted of bringing a specific measuring day apparent resistivity values close to reference day values. Once a given measuring day apparent resistivity was corrected, the remaining random errors were estimated.

Key words: Moisture, temporal resistivity, rainfall, day reference, line reference.

INTRODUCTION

The dependence of the resistivity variations is due to soil moisture changes. Several parameters were investigated by many authors; one of these studies correlated between moisture content and both bulk dielectric and resistivity properties of porous media using borehole-borehole transmission radar and borehole resistivity profiles approaches, where long time monitoring of dielectric and resistivity profiles have been performed, allowing comparison of moisture changes with estimated rainfall inputs (Binley et al., 2002). Both temporal and spatial variability of the soil moisture content were also investigated by near surface measurements which revealed the importance of the size of the field tests (Broca et al., 2002).

Cosentino et al. (1979) found a correlation between the temporal variation of the schlumberger V.E.S and water

content of layered structures. In this work it has been shown in the first stage that for a given depth, high and low resistivity rocks are differently affected by the same amount of temporal soil moisture changes caused by precipitation (or evaporation), this was achieved by performing repeated profiles on a reference line of a grid suspected to contain important resistivity contrast. Later a method of correction for this effect was suggested. It consisted of multiplying all the specific measuring day apparent resistivity data by a factor taken as the ratio of the reference day mean apparent resistivity values to the considered day values, thus, the specific data profile became close to the day reference data profile, the latter is chosen as the day with the mean apparent resistivity value in the middle of all the other measuring day's mean values. The correction made using this criterion was efficient because of the results it gave: that is, the different day's profiles on the reference line became much closer to each other than they were. As an attempt to improve this correction, a synthetic day between all the measuring days with the apparent resistivity value in the

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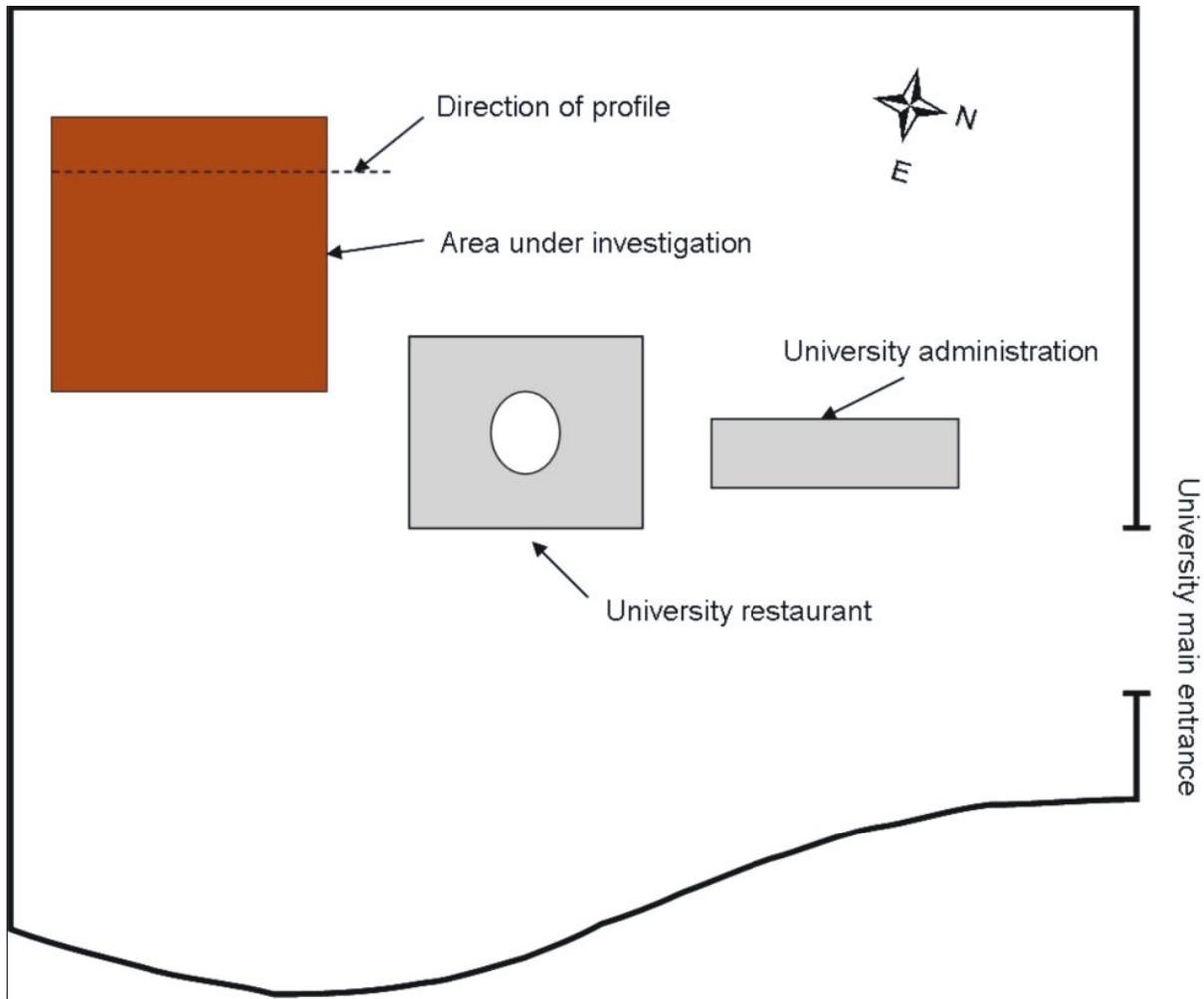


Figure 1. Location of the site.

middle of all the measuring day's apparent resistivity values was chosen and improvement of the method of correction was clearly seen.

After correction of this temporal effect, the relative shifts between profiles corresponding to different measuring days were viewed as observational errors estimated; they were found to be like the soil moisture effect, depending on the initial apparent resistivity values of the bedrock. For a given depth, temporal linearity of a resistivity was also verified, with the constant of linearity differing from one rock type to another.

AREA UNDER INVESTIGATION AND METHODOLOGY

A completion of the whole grid of measurements of quite a large area (a square of 30 m width) located at USTHB campus (Algiers suburb) for a given electrode spacing corresponding to a given depth, in one single day, or successive days was not possible because of some practical obstacles such as the limited availability of equipment, weather conditions and the large size of the area under investigation (Figure 1). The area was therefore split into

adjacent sub-areas, and measurements on each of these were taken in a corresponding measuring day (Takakura et al., 2007; Karous et al., 1993). The Wenner array was used and readings were taken at each one meter position of the center of the array.

For the fixed electrode spacing $a = 0.25$ m, for instance, six campaigns separated by several weeks were necessary to carry out measurements of the entire area. During the period of separating these campaigns, parameters like water content variation due to precipitation, evaporation or changing groundwater level would have occurred, and these changes will obviously have lead to resistivity measurement variations from one campaign to another (Rein et al., 2004). The mapping of the first sub-grid corresponding to the first campaign was carried out by taking apparent resistivity measurements on the first line of the grid; the array was then moved to the next line until all the first sub-grid was swept. In the beginning of the second day, (which could be separated from the first one by weeks), measurements on the first line of the first sub-grid already profiled were performed, the array was then moved to the first line of the new sub-grid (which is the second sub-grid) and then to the next line, until the second sub-grid was mapped, and so for the other remaining sub-grids (Figure 2). Each sub-grid was therefore mapped in a corresponding measuring day. Once the shallowest part of the area was mapped, the electrode spacing was increased and the same steps were followed.

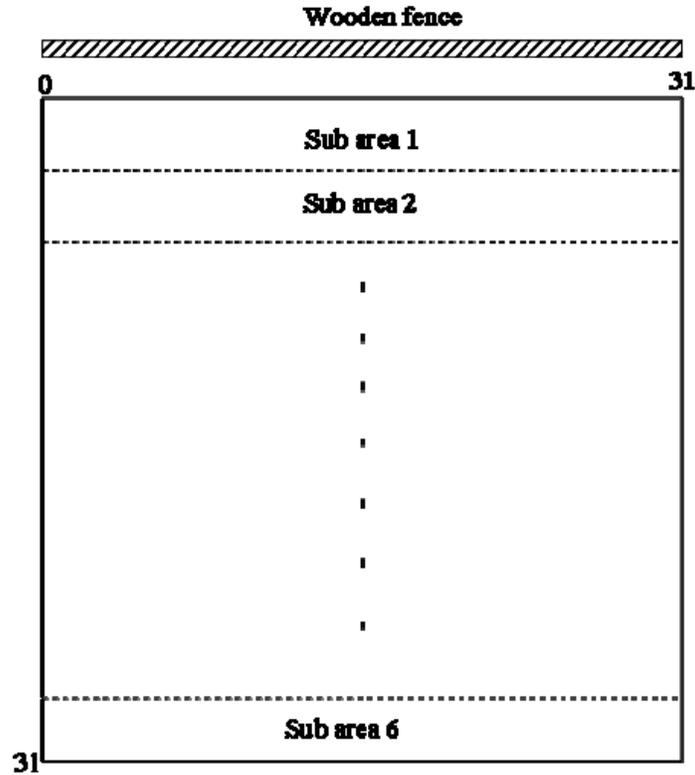


Figure 2. Area under investigation.

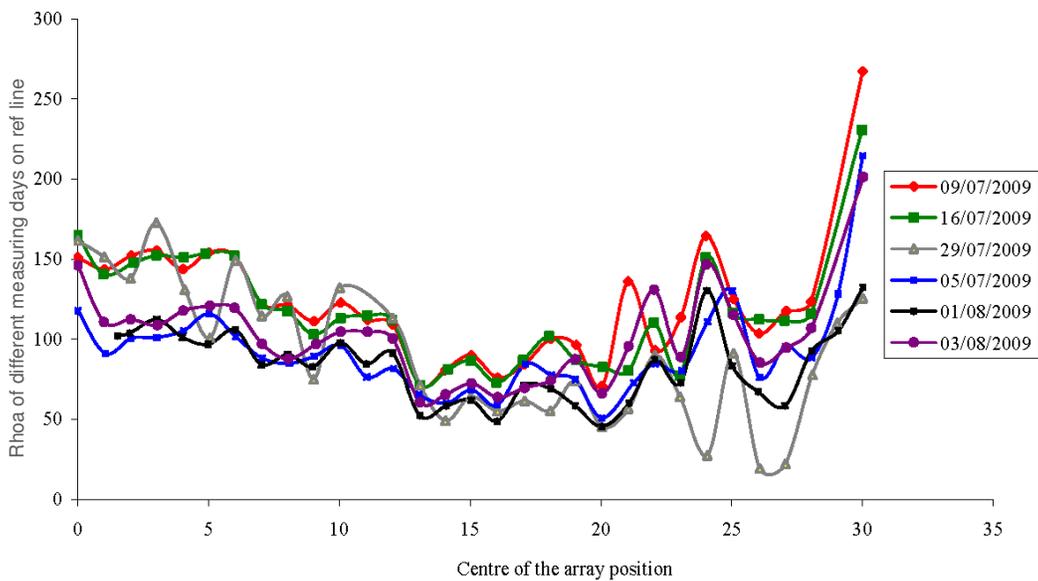


Figure 3a. Repeated profiles on the reference line, a = 0.25 m.

RESULTS

Effect of temporal moisture changes and random errors

The repeated control traverse profiles for each of the

measuring days for the different electrode spacing measurements $a = 0.25, 0.50, 1.00$ and 4.00 m are plotted respectively in Figures 3a, b, c and d. The general trends of all these profiles showed the resistivity variation in space, whereas, relative offsets suggested temporal

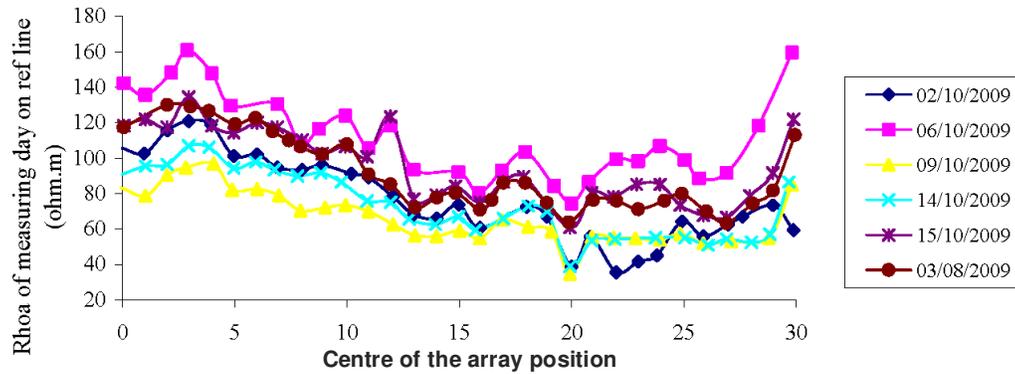


Figure 3b. Repeated profiles on the reference line, $a = 0.5$ m.

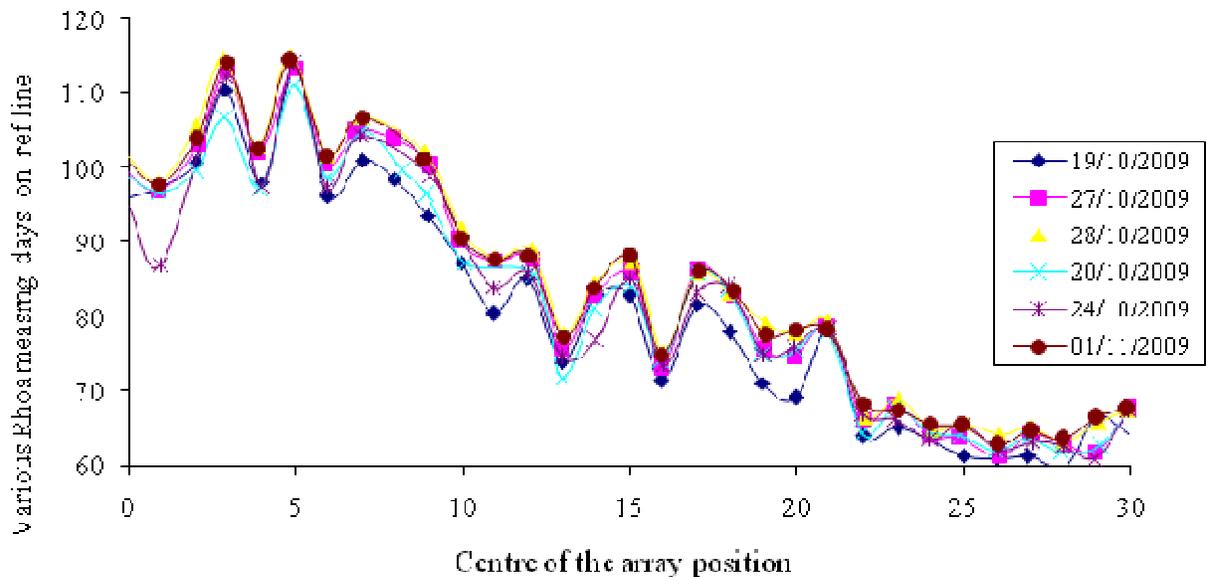


Figure 3c. Repeated profiles on the reference line, $a = 1.0$ m.

resistivity changes. These changes are due to:

- a) Temporal moisture changes.
- b) Random errors which include: Positioning errors, electrode spacing errors, instrumental and observational errors which could be of different sources such as grounding resistances too high for the transmitted current, resistivity range being too low, random variations in the accuracy of the instrument, electrical noise present in the ground, for example as a spontaneous D.C potential due to electrochemical polarization of the electrodes, industrial electrical currents caused by electrified railroads, power lines and other parts of noise of natural origin such as; telluric current, induction and effects of magnetic storms, etc (worldwide effect).

In comparing the reference profiles (all made on the same "reference line") for different days (Figures 3a to d), the most noticeable feature on these curves was that, for

the same amount of soil moisture change, resistive rocks showed large variations in their resistivity values while rocks with small resistivity values showed small variations (comparison between the offsets of the curves for low and high resistivity values). In order to check the variation of the effect of the soil moisture with depth, the regression lines of the standard deviations was plotted against the mean values for each of the 31 positions of the centre of the array along the test traverse, for the four electrode spacing measurements (Figures 4a and b), the curves on these figures showed the decrease of the slopes with the increase of depth, suggesting the decrease in contamination by the soil moisture changes effect as the resistivity is sought further down. Furthermore, this fact was emphasized when the most noisy profiles corresponding to the fourth measuring day for the spacing $a = 0.25$ m and also the fourth day for the spacing 0.5 m were excluded (Figure 4b).

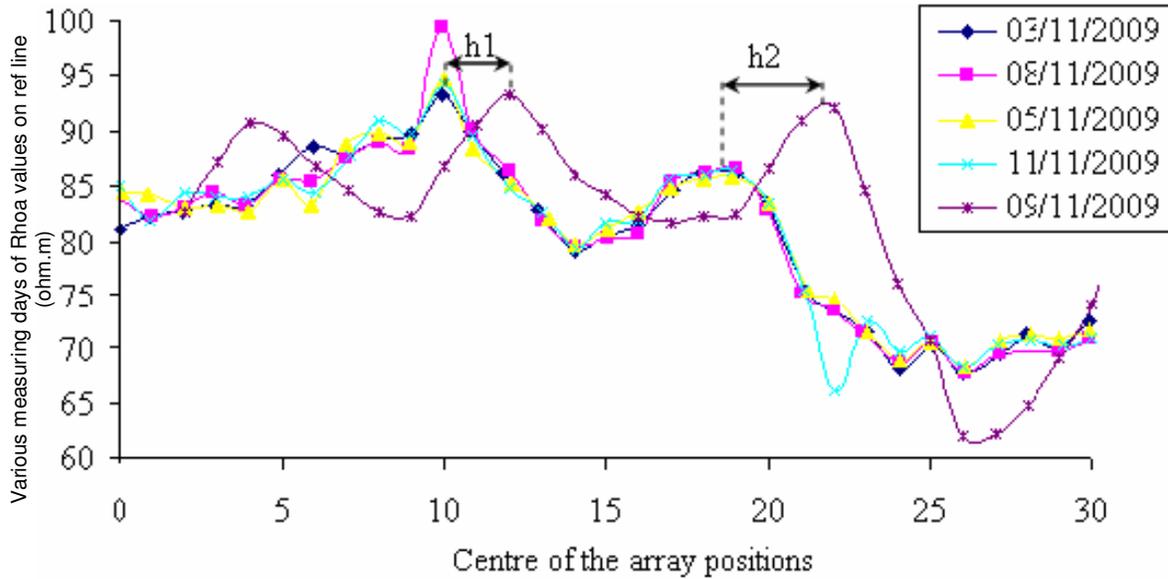


Figure 3d. Repeated profiles on the reference line, a = 4 m.

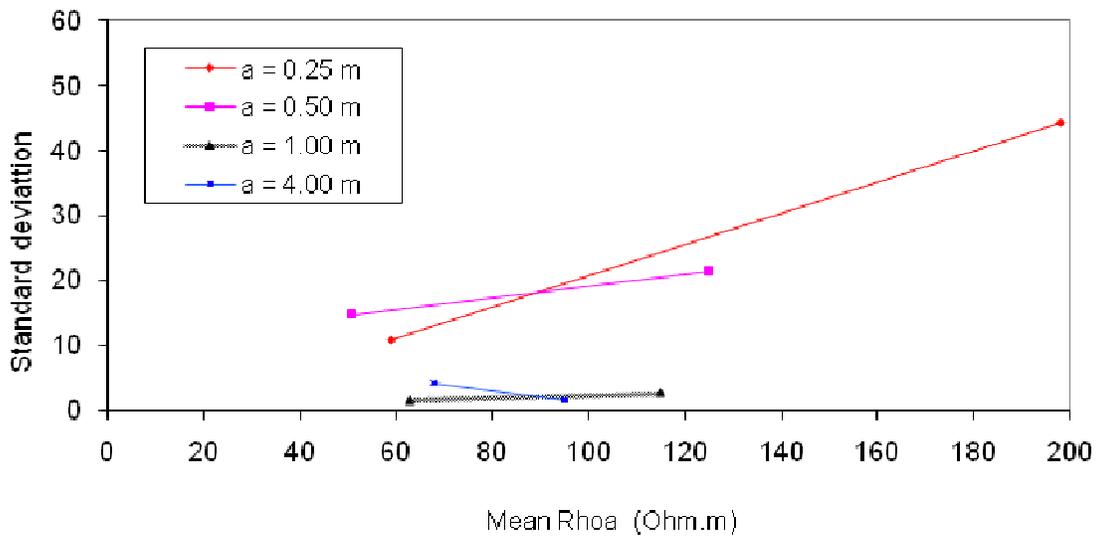


Figure 4a. Standard deviation versus mean Rhoa for each array posit and for the spacings: 0.25, 0.5, 1.0 and 4 m.

Correction of the temporal moisture changes effect and justification of the method used

Over a limited time frame, such as hours, the slow small variations in soil moisture content did not cause important changes in the resistivity of the ground beneath the electrodes, and therefore the variations were not regarded as a source of error. However, as the survey of the spacing for each of the electrodes earlier mentioned was carried out over quite a long period of time such as several weeks, the effect of the soil moisture content changed appreciably and altered the resistivity values

during the total survey. Therefore, to see the correct distribution of resistivity within the ground, a removal of this effect was necessary. In order to apply a correction for the soil moisture change, a set of readings on the control traverse corresponding to one specific day was chosen as a reference day to which other measuring days must be corrected. Figure 5 showed a scattered graph of the mean apparent resistivity values for the spacing 0.25 m for the soil moisture control traverses of each measuring day (Figure 4c and d). This graph showed that the mean resistivity value of the sixth measuring day (3rd August, 2009) was the closest to the

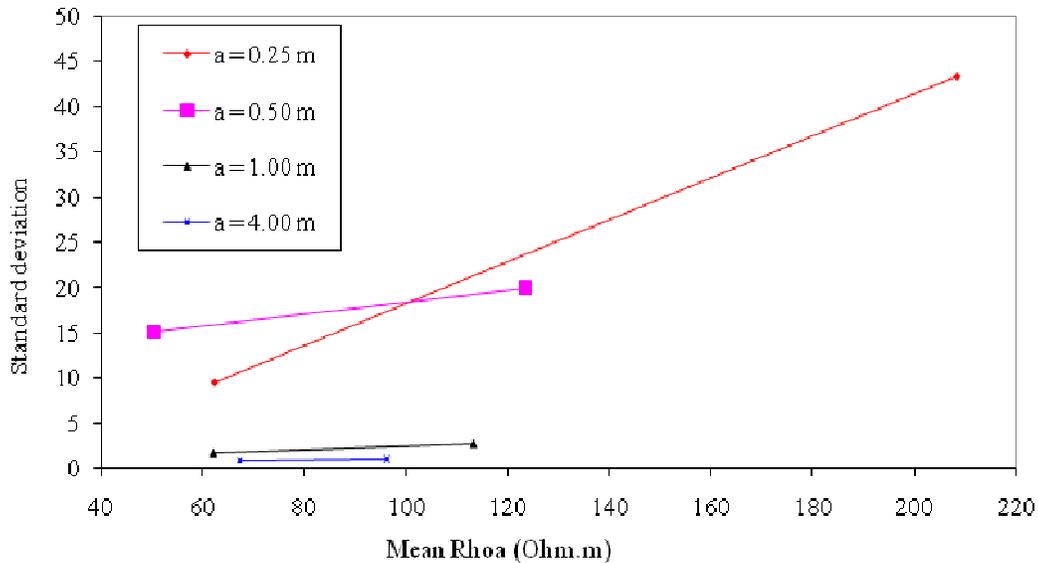


Figure 4b. Standard deviation versus mean Rhoa for the spacings: 0.25, 0.5, 1, and 4 m animals day excluded.

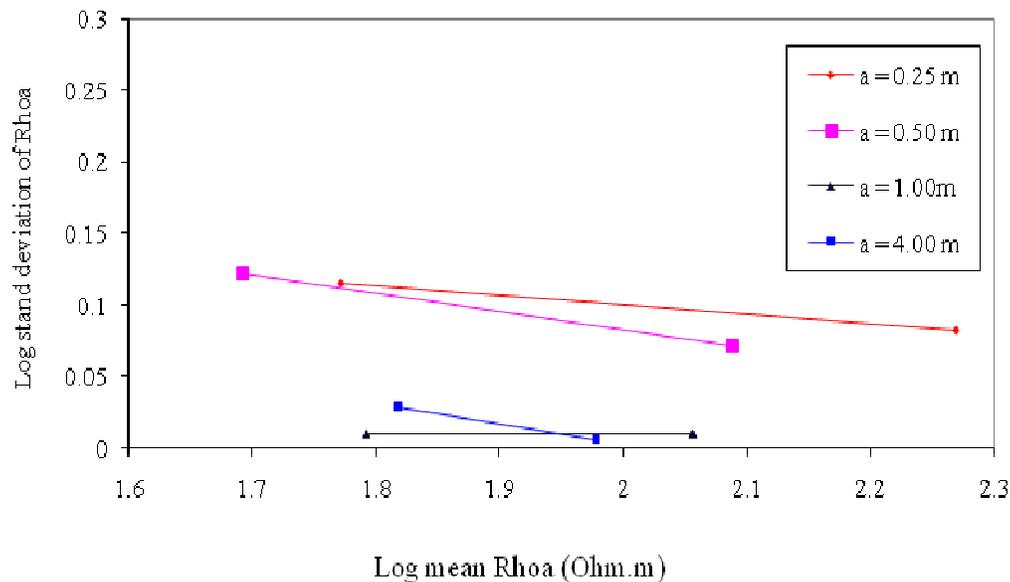


Figure 4c. Log standard deviation vers. Log mean Rhoa for every position of the centre of the array, spacings: 0.25, 0.5, 1 and 4 m.

average value of all the other days' mean values, so all the apparent resistivity of the other days must be corrected to this "reference day". Figures 6a and b showed the regression plot of the first and the fourth days' apparent resistivity profile data on the control traverse plotted against the reference day apparent resistivity data. Both Figures 3a and 6b showed that the fourth day was the noisiest measuring day as it contains a considerable amount of random errors, especially in the second half of the profile. Noise due to electrical current

is different from that supplied into the ground, or other measurement errors (bad connection of cables, low battery, etc.) may be responsible for this irregularity. Note that the scatter of the apparent resistivity values of the fourth day related to reference day indicated a non-linear relationship between the fourth measuring day and the reference day apparent resistivity values. This non-linearity was probably due to some of the random errors discussed earlier. Also note that the origins of the regression lines were fixed at (0, 0). This assumes that

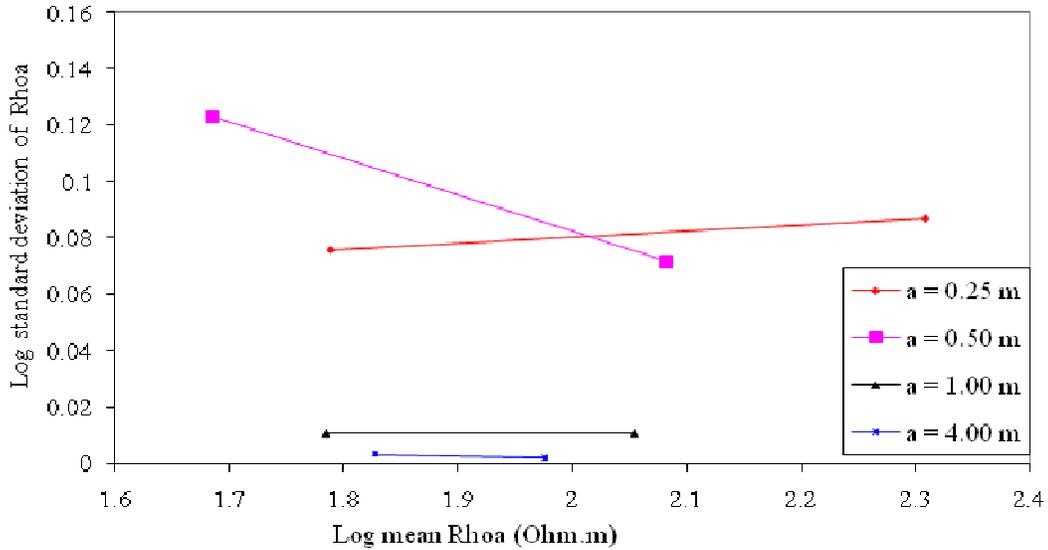


Figure 4d. Log stand dev. vs. Log mean Rhoa for every position of the centre of the array, spacings: 0.25, 0.5, 1 and 4 m; animals day excluded (4th day of 0.25 and 4 m).

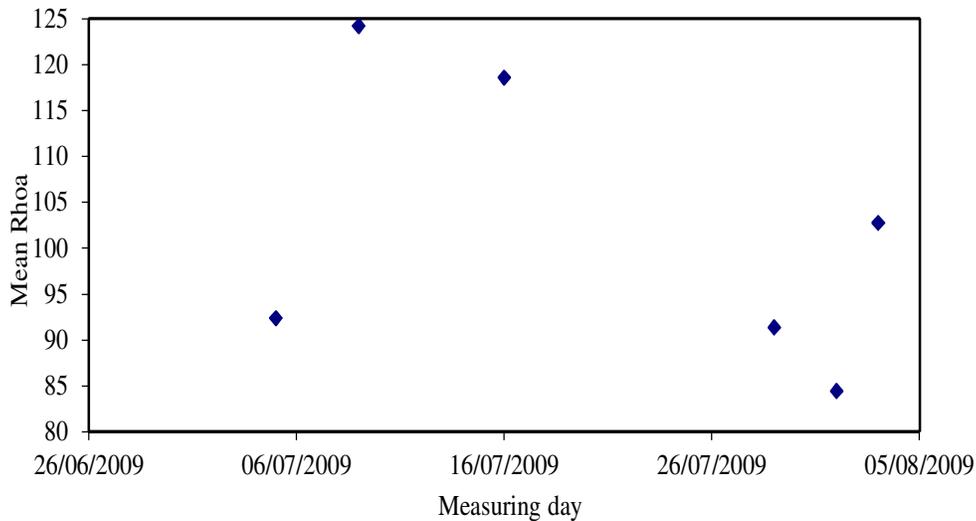


Figure 5. Scatter graph of mean Rhoa vs. measuring days.

the same resistivity model was applicable for each measuring day. That is, the relationship between the *i*th particular day's apparent resistivity mean value and the reference day's apparent resistivity mean value is given by:

$$\rho_i = k_i \rho_r \tag{1}$$

Where, k_i is a simple multiplication factor showing variation in the degree of saturation of the soil. If otherwise:

$$\bar{\rho}_i = k_i \bar{\rho}_r + b \tag{2}$$

The additional factor b will be due to random errors, and it was found to be negligible as compared to the *i*th day mean apparent resistivity value. We will illustrate a method of correction and give the justification of using it. It consists of correcting the different profiling days to the reference day, thus, making the offsets between different profiles as small as possible. In Figures 6a and b if the scale is the same on the x and y axes, the slope of the reference day line would be 45° as the gradient is 1. The correction is made simply by the multiplication of the considered day's apparent resistivity values by a correction factor close to 1.0. This factor is taken as the gradient of the particular day's line. This was most easily

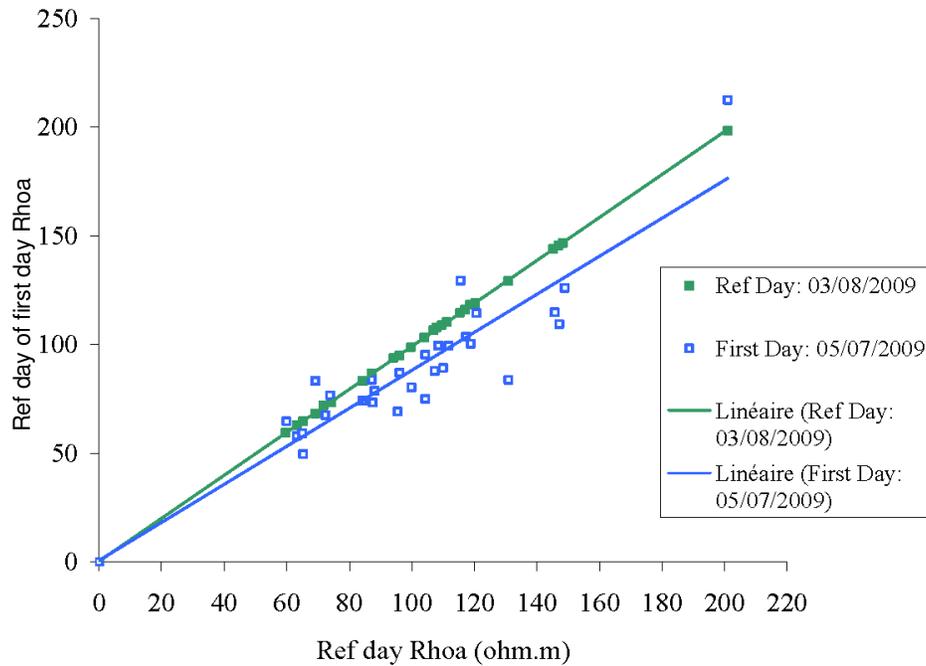


Figure 6a. Regression line of ref day and first day Rhoa vs. ref day Rhoa.

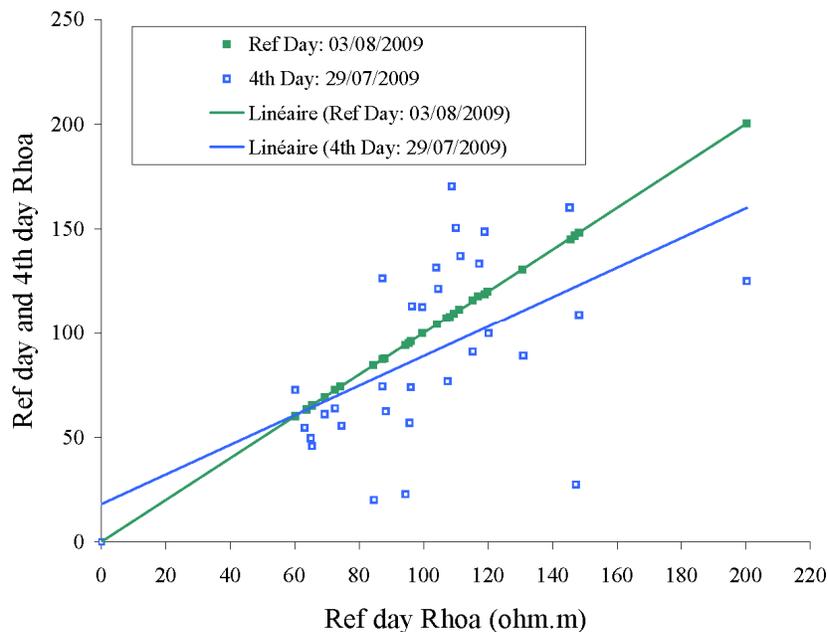


Figure 6b. Regression line of ref day and 4th day vs. ref day Rhoa.

calculated from the mean apparent resistivity value of the reference day and the mean apparent resistivity value of the particular day. The correction factors are given in Table 1a. It is important to note that the correction factors for the spacing of 1.00 and 4.00 m are the closest to the value 1.0, thus, the correction was not needed for these two spacing measurements. This may be explained by

the fact that the region near the surface was the most affected by the rapid variations in the soil moisture content. This region was regarded as a damping medium for rain. The effect of the rain was similar to a high frequency wave attenuated progressively with depth, and as such the correction of this effect becomes less needed at depth. Figure 7 showed various measuring day's

Table 1a. Day Ref Rhoa closest to all measuring days Rhoa.

Electrode spacing	Date	Correction coefficient
a = 0.25 m	05/07/09	$K_1 = 1.121$
	09/07/09	$K_2 = 0.831$
	16/07/09	$K_3 = 0.871$
	29/07/09	$K_4 = 1.131$
	01/08/09	$K_5 = 1.223$
	03/08/09	$K_6 = 1.000$
a = 0.5 m	02/10/09	$K_1 = 1.198$
	06/10/09	$K_2 = 0.825$
	09/10/09	$K_3 = 1.415$
	14/10/09	$K_4 = 1.254$
	15/10/09	$K_5 = 0.969$
	17/10/09	$K_6 = 1.000$
a = 1.00 m	19/10/09	$K_1 = 1.017$
	20/10/09	$K_2 = 1.000$
	24/10/09	$K_3 = 1.000$
	27/10/09	$K_4 = 0.984$
	28/10/09	$K_5 = 0.967$
	01/11/09	$K_6 = 0.971$
a = 4.00 m	03/11/09	$K_1 = 1.001$
	05/11/09	$K_2 = 1.000$
	08/11/09	$K_3 = 1.000$
	09/11/09	$K_4 = 0.970$
	11/11/09	$K_5 = 1.001$

profiles after applying this method of correction. In order to improve this method of correction, a day reference was taken as a day in the middle of all the measuring days as the drift effect of the soil moisture change. This may have its average value between all the measuring days, this day corresponds to the third measuring day (16/07/09) for the spacing 0.25 m and the factors of correction in this case are those presented in Table 1b. Compared to the results of Table 1a, we did not get the expected improvement. However, if we correspond to this considered day, a synthetic mean apparent resistivity value situated in the middle of all the mean apparent resistivity values of all measuring days, which is approximately 100 $\Omega \cdot m$; a noticeable improvement is got, and the improved coefficients are in Table 1c. Figure 8 shows the offsets between the first day profile, the day reference profile, and the first day corrected profile closer to the latter. Figure 9 also showed the different days profiling of the control traverse lying on top of each other after the correction was carried out, and may be compared with Figure 6a before correction.

For a pragmatic justification of the method of correction, a regression line is drawn for the various profiling days with the standard deviations against the mean of apparent resistivity values for the electrode

spacing $a = 0.25$ m (Figure 10a). This curve showed a linear relationship. That is, a day with a higher mean apparent resistivity value has higher fluctuations, and a day with the small mean apparent resistivity value has less fluctuations. The variation in the amount of the fluctuations follows the variation in the saturation with time, that is, the fluctuations in the dry day high mean apparent resistivity value, which corresponds to the increase in the apparent resistivity of all the rocks underneath the reference line is due to the removal of the moisture (by evaporation) and reflects the variation in the nature of the rocks is under this line, whereas, the small amounts of fluctuations about the wet day low mean apparent resistivity value indicated that these variations are mainly dependent on the amount of water present which tends to lower all the apparent resistivity values of the rocks under the considered line. Therefore, to bring the mean apparent resistivity value of the i th day close to the mean apparent resistivity, the value of the reference day and the mean apparent resistivity of that particular day must be multiplied by a constant k , which is taken as the ratio of the reference day mean apparent resistivity value to the particular day mean apparent resistivity value.

The regression line of the standard deviation of

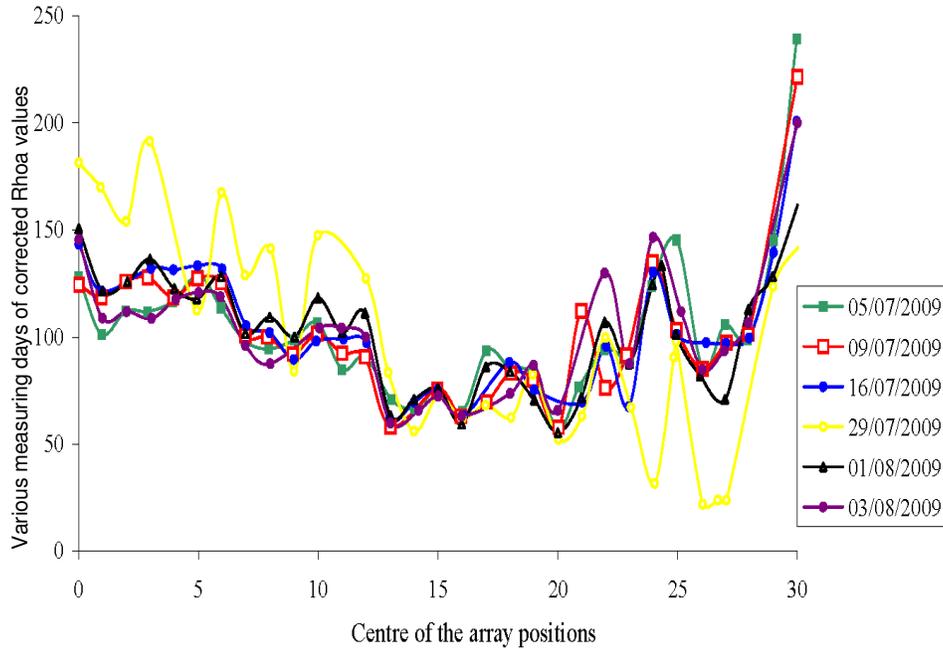


Figure 7. Corrected Rho (Ohm. m) profiles.

Table 1b. Day ref in the middle time of all measuring days.

Electrode spacing	Correction coefficient
a = 0.25 m	$K_1 = 1.287$
	$K_2 = 0.954$
	$K_3 = 1.000$
	$K_4 = 1.299$
	$K_5 = 1.404$
	$K_6 = 0.871$

Table 1c. Day ref in the middle time and synthetic mean Rho closest to all measuring days Rho.

Electrode spacing	Correction coefficient
a = 0.25 m	$K_1 = 1.085$
	$K_2 = 0.804$
	$K_3 = 0.843$
	$K_4 = 1.094$
	$K_5 = 1.183$
	$K_6 = 0.968$

apparent resistivity values for each data point on the control traverse is also plotted against the mean values. This graph is also linear (Figure 10b). This suggested that for a particular day i , and a position j :

$$(\rho_{i, cor})_j = k_i \cdot (\rho_{i, ncor})_j$$

For instance a day 1 resistivity values are corrected as follows:

$$(\rho_{1, cor})_0 = k_1 \cdot (\rho_{1, ncor})_0$$

$$(\rho_{1, cor})_1 = k_1 \cdot (\rho_{1, ncor})_1$$

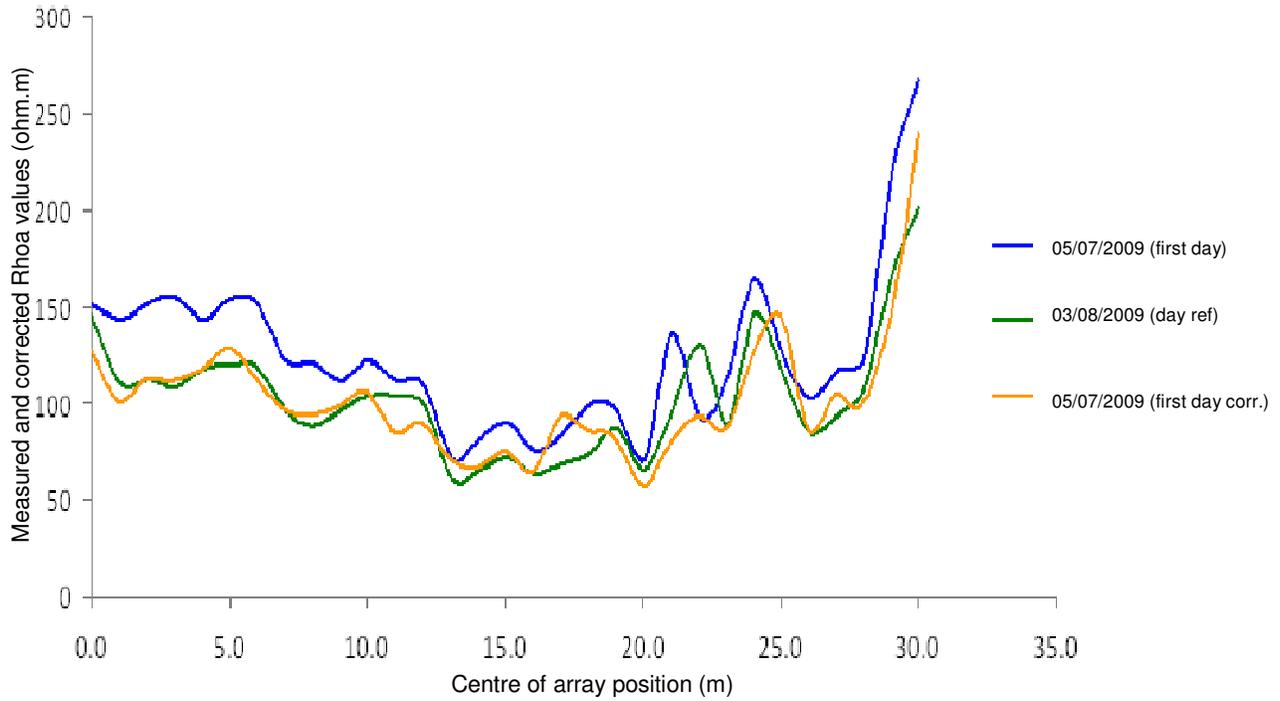


Figure 8. Rhoa values on ref line.

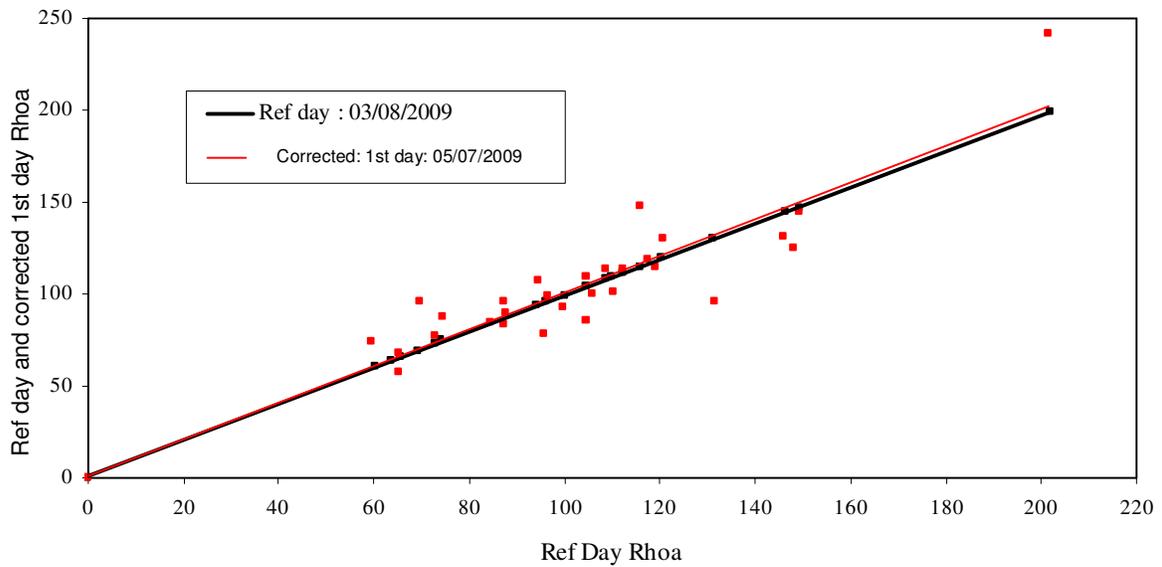


Figure 9. Regression line of Ref. day and corrected 1st day vs. ref. day Rhoa.

$$(\rho_{1,cor})_{30} = k_1 \cdot (\rho_{1,ncor})_{30}$$

$$(\rho_{2,corr})_1 = k_2 (\rho_{2,ncor})_1$$

And for the second day:

$$(\rho_{2,corr})_{30} = k_2 (\rho_{2,ncor})_{30}$$

$$(\rho_{2,corr})_0 = k_2 (\rho_{2,ncor})_0$$

And so forth for the other days.

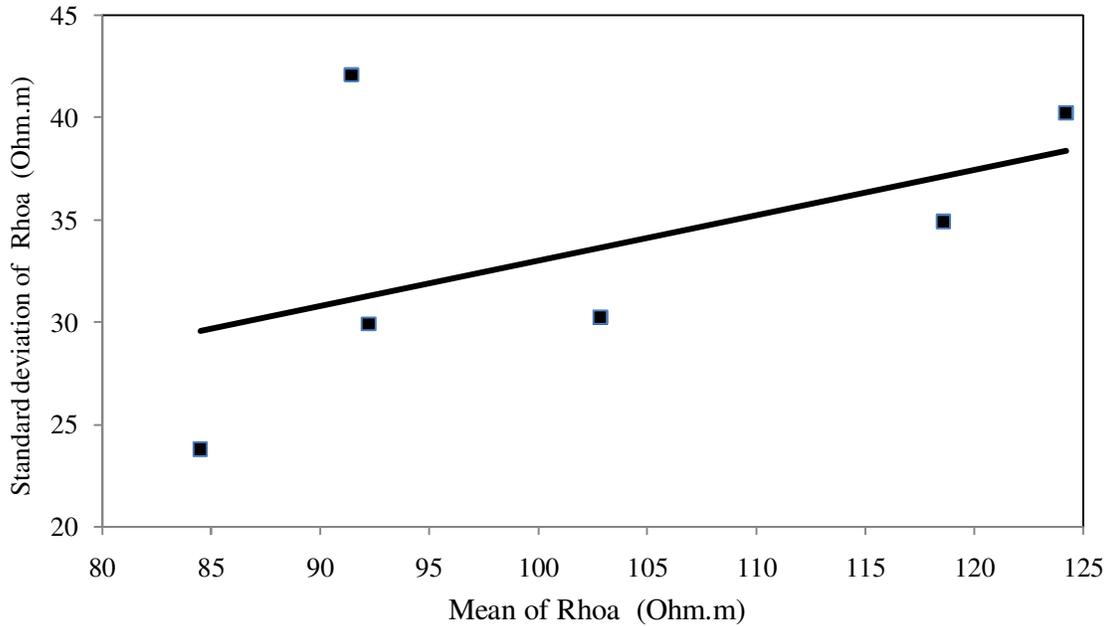


Figure 10a. Stand dev. of Rho (avg. of 31 Rho values on one traverse line) vs. mean for each day, $a = 0.25$ m.

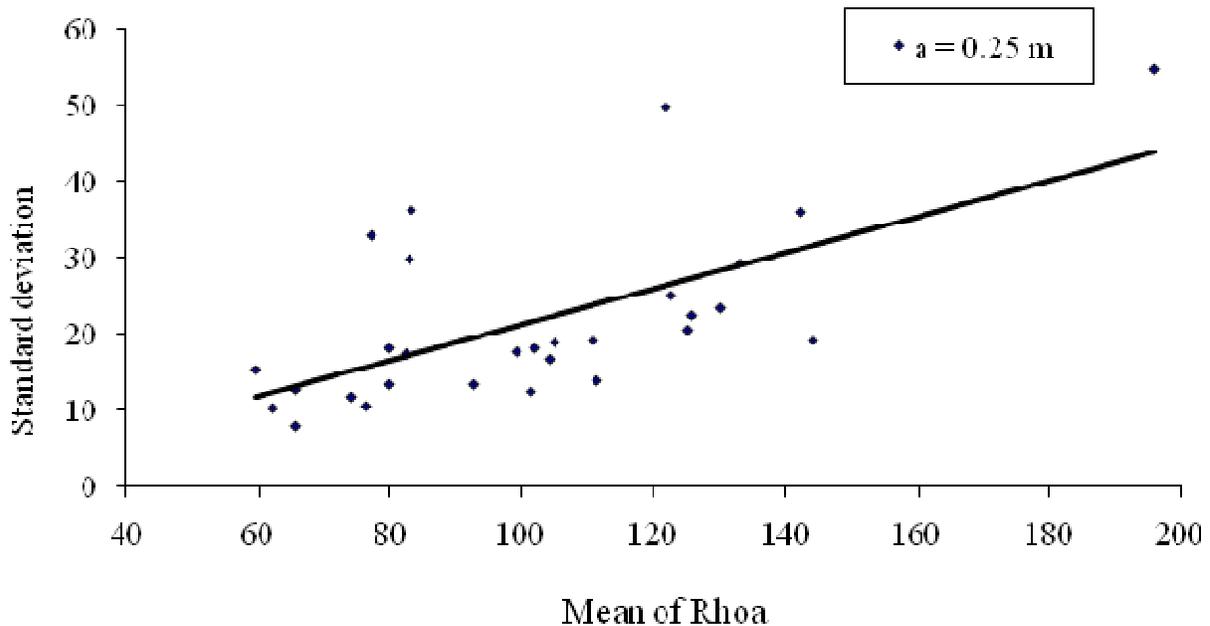


Figure 10b. Stand dev vs. mean of Rho for each position on ref line profile.

In order to test the scaling correction factor, logarithms of the apparent resistivity values of the control traverse may be taken. As shown in Figure 10c, the profile curve of the logarithm of the apparent resistivity values on the control traverse are offset by a constant amount at every position corresponding to $\log k$. This was confirmed by

plotting logarithm values of the standard deviations against logarithm values of the mean apparent resistivity values for each profiling day. Figure (10d) showed that when the anomalous day (the fourth measuring day for $a = 0.25$ m) which contains large amount of random errors (as seen in the earlier discussion), is excluded, the

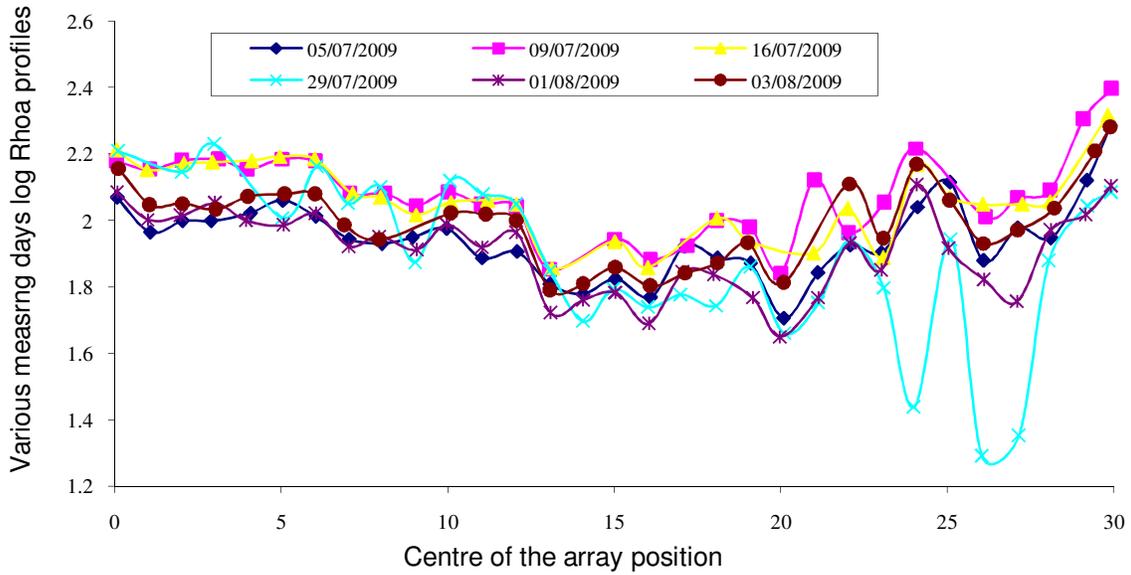


Figure 10c. Repeated Log Rho profiles, a = 0.25.

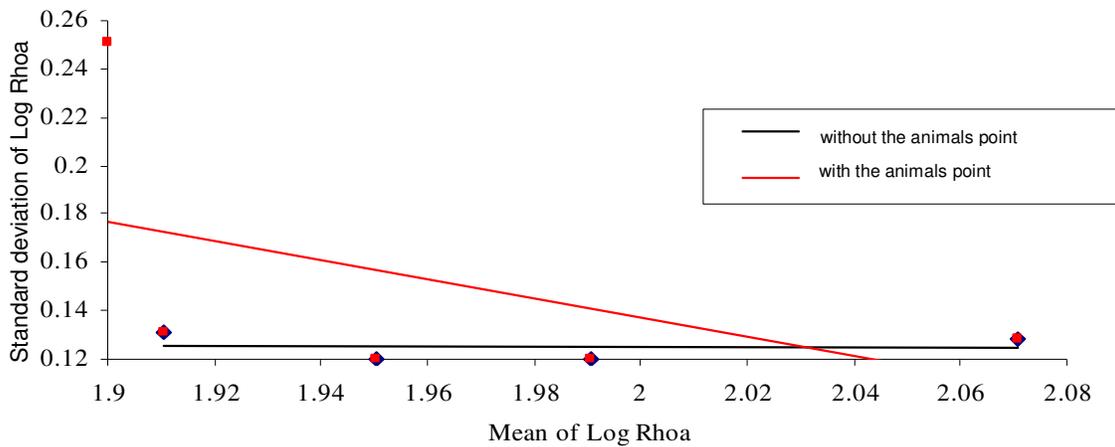


Figure 10d. Stand vs. mean of Log Rho (average of 31 log Rho on the ref line) for each of the 6 measuring days.

standard deviations now varies independently of the mean and are almost constant. This suggested that all the profiling days have the same amount of fluctuations due to the nature of the ground modified by the varying soil moisture content. The particular day mean log apparent resistivity value was brought close to reference day mean log apparent resistivity value by a simple arithmetic addition. That is:

$$(\log \bar{\rho}_i)_{cor} = (\log k_i) + (\log \bar{\rho}_i)_{ncor} \tag{3}$$

Where; $\bar{\rho}_i$ is the i^{th} day mean value.

This independence was also noticed on the plot of the

regression line of the standard deviation against the mean for each of the 31 apparent resistivity data pointing on the control traverse (Figure 10e). Therefore for any observation point i , for day 1 for instance:

$$(\log \rho_{1,cor})_0 = \log k_1 + (\log \rho_{1,ncor})_0$$

$$(\log \rho_{1,cor})_1 = \log k_1 + (\log \rho_{1,ncor})_1$$

$$(\log \rho_{1,cor})_{30} = \log k_1 + (\log \rho_{1,ncor})_{30}$$

The correction to the log data may be done by a simple arithmetic shift of the whole curve for the particular day,

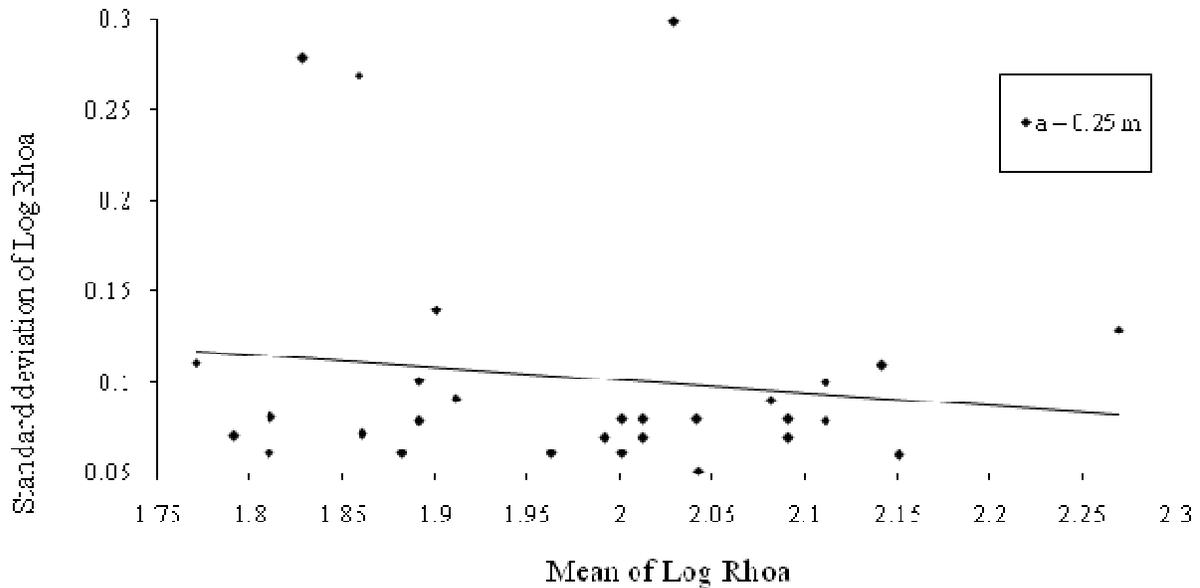


Figure 10e. Stand dev of Log Rhoa vs. mean of 6 measuring days for each posit on ref line profile.

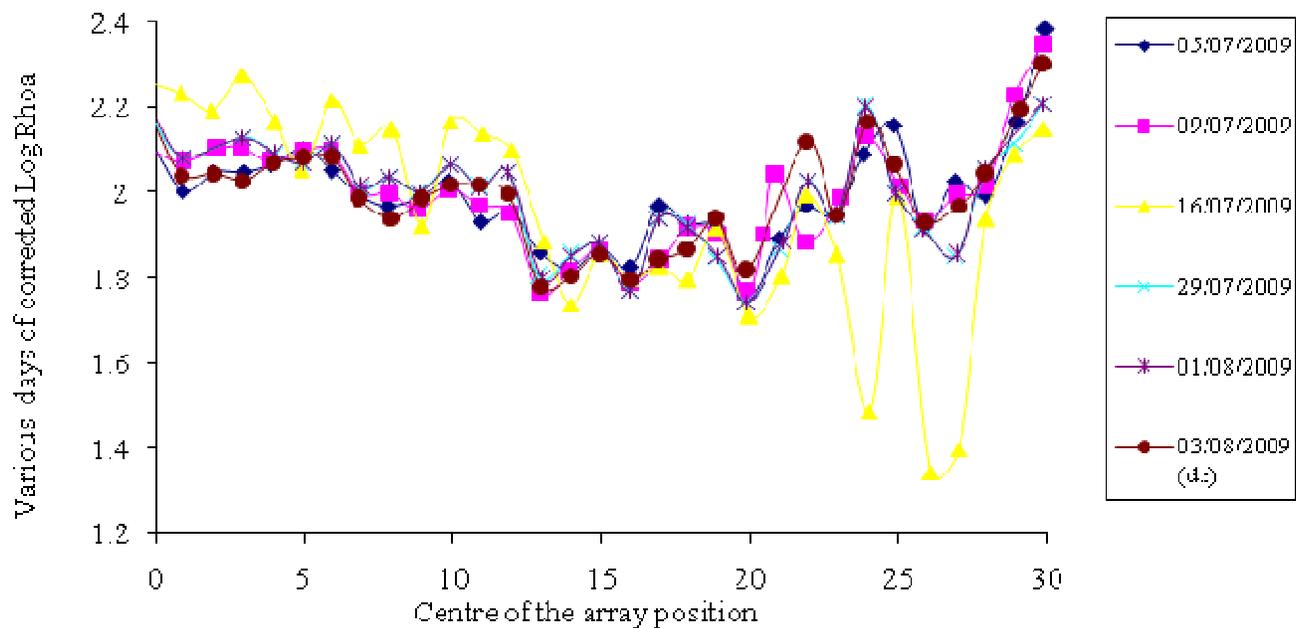


Figure 11. Corrected repeated Log Rhoa, $a = 0.25$ m.

so that it will lie on top of the reference day curve (Figure 11).

Temporal linearity of apparent resistivity for a given rock

In order to check for a temporal resistivity variation of a given rock type beneath the control traverse, relative

ratios of apparent resistivity values corresponding to different measuring days for the control traverse position corresponding to the highest, the medium and the lowest mean apparent resistivity values on the control traverse are calculated and the results are summarized in Table 2. These ratios for the extreme mean values $\rho_a = 195.65 \Omega \cdot m$ and $\rho_a = 65.2 \Omega \cdot m$ are found to be almost constant; this suggested a linear relationship between different measuring day's apparent resistivity values in time for a

Table 2. Temporal Rhoa ratio.

Mean temporal resistivity ($\Omega.m$)	Temporal coefficient
$(\rho_a)_{mean} = 65.2$	$C_1 = \rho_1 / \rho_2 = 0.86$ $C_2 = \rho_2 / \rho_3 = 0.84$
$(\rho_a)_{mean} = 145.6$	$C'_1 = \rho'_1 / \rho'_2 = 0.89$ $C'_2 = \rho'_2 / \rho'_3 = 0.96$ $C'_3 = \rho'_3 / \rho'_4 = 0.91$
$(\rho_a)_{mean} = 195.65$	$C''_1 = \rho''_1 / \rho''_2 = 0.93$ $C''_2 = \rho''_2 / \rho''_3 = 0.65$ $C''_3 = \rho''_3 / \rho''_4 = 0.93$ $C''_4 = \rho''_4 / \rho''_5 = 0.93$ $C''_5 = \rho''_5 / \rho''_6 = 0.86$

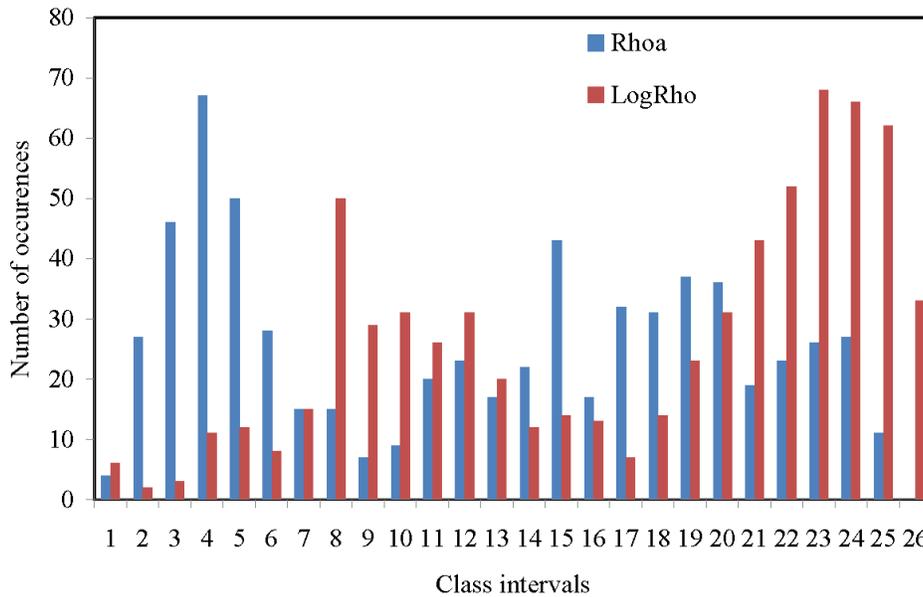


Figure 12. Frequency distribution of Rhoa and Log Rhoa, a = 0.25 m.

given rock type. It is important to note that $\rho_1, \rho_2, \rho_3 \dots$ are in an increasing order. Only the constants of linearity 0.8 and 0.9 could be considered, this is justified by the fact that the horizontal distribution of apparent resistivity shows two distinct dry and wet sub areas, as seen in Figure 12.

Estimation of errors

As a result of applying the method of correction mentioned, various measuring day's profiles became significantly close to each other as seen in Figures 7 and 11. In order to give an estimation of total errors which included soil moisture changes and random effects for

the shallowest part of the control traverse (a = 0.25 m) the difference between the maximum and the minimum value of the apparent resistivity corresponding to each of the different measuring days has been calculated for consecutively high and low resistivity rocks, before correction. After correction, these differences represent random errors, and the difference between the total and random errors are nothing more than the soil moisture effect errors. The results of these estimations are summarized in Table 3. The means and the standard deviations of the grids were computed for the spacing of each of the electrodes used to map the test area. These are given in Table 4. The standard deviations, regarded as errors decreased with depth, as the shallowest parts were expected to the most affected by random errors.

Table 3. Moisture and Random errors before and after corrections.

Rock with highest mean apparent resistivity value (ρ_a)_{max} = 198.2 Ω.m	
Before correction	Total errors: ($\Delta \rho_a$) _T = 67% (ρ_a) _{max}
After correction	Random errors: ($\Delta \rho_a$) _{rand} = 37.84% (ρ_a) _{max} Moisture errors: ($\Delta \rho_a$) _{Ms} = 29.16% (ρ_a) _{max}
Rock with lowest mean apparent resistivity value (ρ_a)_{min} = 62 Ω.m	
Before correction	Total errors: ($\Delta \rho_a$) _T = 30.36% (ρ_a) _{min}
After correction	Random errors: ($\Delta \rho_a$) _{rand} = 11.94% (ρ_a) _{min} Moisture errors: ($\Delta \rho_a$) _{Ms} = 21.42% (ρ_a) _{min}

Table 4. Distribution of random errors with depth.

Electrode spacing (m)	Mean apparent Resistivity values (Ω .m)	Standard deviation (Ω .m)
a = 0.25	70.79	33.68
a = 0.50	70.78	22.18
a = 1.00	73.02	12.92
a = 4.00	80.43	7.53

Suppose that a synthetic “true” apparent resistivity for the position “i” of the control traverse is ρ_{ti} , to which the random errors are added on both the reference day and the observation day. Assuming also that the particular observation day’s ‘r’ and the reference day ‘r’ contained the same amount of errors. The random errors for each of these two days are estimated by:

$$(\sigma_r)^2 = (1/(n-1)) \sum_{i=1}^n (\rho_{ri} - \rho_{ti})^2 \quad (4)$$

$$(\sigma_s)^2 = (1/(n-1)) \sum_{i=1}^n (\rho_{si} - \rho_{ti})^2 \quad (5)$$

Where n is the number of data points on the control traverse and here n = 31. Since:

$$(\rho_{si} - \rho_{ri})^2 = [(\rho_{si} - \rho_{ti}) - (\rho_{ri} - \rho_{ti})]^2 = (\rho_{si} - \rho_{ti})^2 + (\rho_{ri} - \rho_{ti})^2 - 2(\rho_{si} - \rho_{ti})(\rho_{ri} - \rho_{ti}) \quad (6)$$

And the sum:

$\sum_{i=1}^n 2(\rho_{si} - \rho_{ti}) \cdot (\rho_{ri} - \rho_{ti})$ tend to zero, because of the assumption that the errors are random, so the number of positive products should be equal to the number of negative products, summing these products gives zero as a result. Therefore:

$$\sum_{i=1}^n (\rho_{si} - \rho_{ri})^2 = \sum_{i=1}^n (\rho_{si} - \rho_{ti})^2 + \sum_{i=1}^n (\rho_{ri} - \rho_{ti})^2 \quad (7)$$

Dividing all the terms of this equation by (n-1) gives:

$$(\sigma^2)_{tot} = (1/(n-1)) \sum_{i=1}^n (\rho_{si} - \rho_{ri})^2 = (1/(n-1)) \sum_{i=1}^n (\rho_{si} - \rho_{ti})^2 + (1/(n-1)) \sum_{i=1}^n (\rho_{ri} - \rho_{ti})^2 \quad (8)$$

Where σ^2_{tot} is the variance.

Assuming that the random measurement errors are of the same magnitude in each survey line, we get:

$$\sigma^2_s = \sigma^2_r$$

So,

$$\sigma^2_{tot} = 2 \sigma^2_s \text{ and } \sigma_s = \sigma_{tot} / \sqrt{2}$$

These random errors for each measuring day for the spacing 0.25 m are computed and given in Table 5. Note that the fourth measuring day has the highest value of random errors, thus, the irregularity of this day is likely due to this type of errors. In order to see the variation of these errors with respect to the variation of the electrode spacing, the first measuring days for the spacing 0.5 and 1.0 m are also given in this table.

DISCUSSION

A piece of the reference line corresponding to high

Table 5. Temporal distribution of random errors.

Electrode spacing (m)	Measuring day	Random error (stand. Deviation) σ ($\Omega.m$)	Average ($\Omega.m$)
a = 0.25	05./07/09	$\sigma_1 = 10.73$	$\sigma_{av} = 14.29$
	09/07/09	$\sigma_2 = 10.20$	
	16/07/09	$\sigma_3 = 9.51$	
	29/07/09	$\sigma_4 = 30.28$	
	01/08/09	$\sigma_5 = 10.73$	
a = 0.50	02/10/09	$\sigma_1 = 9.9$	
a = 1.00	19/10/09	$\sigma_2 = 2.155$	

apparent resistivity changes on the right side of Figure 3a may contain partially saturated rocks, as for type of rocks the bulk resistivity is given by:

$$\rho_t = I F \rho_w \quad (9)$$

Where: ρ_w , is the resistivity of water content and I is the resistivity index is given by:

$$I = S^{-n}, \text{ (where usually } n = 2)$$

S is the degree of saturation, and is given by the ratio of the volume of the fluid to the volume of the pores:

$$S = V_f / V_p$$

F is the formation factor and is given by:

$$F = a_p / \Phi^m$$

Φ , is the porosity of the rock; a_p , m , are empirical constants which depend on the structure of the pores and the degree of cementation. For this type of rocks the resistivity index is the most dominant factor controlling the resistivity variation, so the variation in this factor by a few percent will cause changes in the bulk resistivity by several orders of magnitude.

A small variations of resistivity corresponding to a low resistivity rocks in the middle of the reference line may contain saturated rocks, as for this type of rocks the resistivity index $I = 1$, and Equation 1 becomes:

$$\rho_t = F \rho_w$$

Taking $a_p = 1$ and $m = 2$ in Equation 1, the last equation becomes:

$$\rho_t = \Phi^{-2} \rho_w$$

This means that the bulk resistivity as in Equation 1, varies also linearly with the resistivity of the water content and the constant of proportionality is equal to Φ^{-2} , therefore, for this type of rocks, the most dominant factor determining the bulk resistivity is the porosity. These notes are in agreement with the conclusions made by Parkhamenko (1967) and Jakosky and Hopper (1937). Figure 3d shows a horizontal shift of the fourth measuring day's profile (09/11/2009) compared to the other profiles (h_1 and h_2), this is possibly due to the operator taking the right reading on the wrong position of the center of the array, as the extremity of the tape was taken on the wrong position. Instead of this profile, another one should be carried out on the same day after repositioning the tape in the right place; unfortunately this irregularity was noticed later during the data analysis stage.

The results of Table 3 confirmed the earlier mentioned proportionality of both soil moisture effect errors and random errors with the initial apparent resistivity. In Table 5, one may notice the decrease in magnitude of the errors for the first measuring day with the increase in the electrode spacing, because random errors are a smaller proportion of electrode spacing, and the averaging of the apparent resistivity is made over larger volume.

The two regression lines of the standard deviation against the means for each position of the centre of the array for the spacing 0.25 and 0.5 m in Figures 4.a and b cross each other, this is possibly due to the important amount of time separating the profiling on the reference line for these two spacing measurements as most of the profiles for the spacing 0.25 m were performed in the month of July, whereas, the profiles for the spacing 0.5 m were performed in the month of October. When logarithmic values are taken, these curves are nearly horizontal and below each other as the electrode spacing increases (Figures 4c and d). The remaining offsets of Figures 7 and 11 will represent random errors which are proportional to the absolute values of apparent resistivity that is, large apparent resistivity values are highly affected

by random errors, while small values are less affected.

Conclusion

While estimating the correction factor for the moisture changes effect, we assumed that this factor is the same for all the measuring points on the control traverse. For the electrode spacing of 0.25 m, the area under investigation is formed by two distinct sub areas from the point of view of the horizontal distribution of apparent resistivity, and because of the two distinct temporal constants of linearity corresponding to each of the two patches, instead of using only one single correction factor, we can calculate by the same way a correction factor for each sub area, and this is more necessary when mapping large areas containing sub areas with large horizontal apparent resistivity contrasts.

The reference line profile corresponding to a specific measuring day does not represent all the corresponding sub-grid measuring points, as the temporal variability differs from one point of the sub-grid to another. For a full and more accurate investigation for temporal resistivity changes, measurements should be carried out in the beginning of each campaign for all the measuring points of the sub-grids previously mapped. In spite of the enormous time which taken for this operation, it will constitute an experimental check for the spatio-temporal variability of the sub-soil. In order to seek accurately the effect of the soil moisture variation on the apparent resistivity, the interval of small and large values of this parameter should be defined more accurately. As part of a further work, it will be of value linking between the temporal variation of water content with the temporal variation of resistivity by measuring simultaneously these two factors for different soil types under a specific physical conditions (pressure, temperature, evaporation) (Besson et al., 2007). Due to the fact that the entire campaign was carried out between the months of July

and October, the relationship between the apparent resistivity of temporal variations and the variations of the temperatures is worth investigating. Rapid fluctuations of the apparent resistivity values for a given measuring day on the control traverse could be viewed as “geological” noise and this should be removed. In spite of these missing details, this piece of work would enable separation of errors, and better interpretation of resistivity maps carried out over long period of time. A comparison of various measuring days from the point of view of their contamination by random errors is also possible.

REFERENCES

- Besson A, Cousin I, Nicoullaud B, Bourennane H, Pasquier C, Dorigny A, Dabas M, King D (2007). Caractérisation de la structuration spatio-temporelle des teneurs en eau des sols à l'échelle parcellaire par résistivité électrique. 6ième colloque GEOFCAN – 25-26/09/2007 – Bondy, France, pp. 79-81.
- Binley A, Winship P, Jared WL, Pokar M, Middleton R (2002). Seasonal variation of moisture content in unsaturated sandstone inferred from borehole radar on resistivity profiles. *J. Hydrol.*, 267: 160-172
- Cosentino P, Cimino A, Riggio AM (1979). Time variation of the resistivity in a layered structure with unconfined aquifer. *Geoexploration*, 17:11-17.
- Jakosky JJ, Hopper RH (1937), the effect of moisture on the direct current resistivities of oil sands and rocks. *Geophysics*, 2: 33-55.
- Karous M, Kelly WE, Anton J, Havelka J, Stojc V (1993), Resistivity methods for monitoring spatial and temporal variations in groundwater contamination. *Groundwater Quality Management* (Proceedings of the QGM 93 Conference held at Tallinn, September 1993) IAHS Publ. n°. 220, 1994, pp. 21-28.
- Parkhomenko EI (1967). *Electrical Properties of rocks*, Plenum Press, New York.
- Rein A, Hoffmann R, Dietrich P (2004). Influence of natural time-dependent variations of electrical conductivity on D.C. resistivity measurements. *J. Hydrol.*, 285:215-232.
- Takakura S, Nishi Y, Sugihara M, Ishido T (2007). Repeated resistivity and GPR surveys for the monitoring of water content and temperature in the unsaturated zone. *American Geophysical Union, Fall meeting, Abstract # H 23A-1009.*