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Electromagnetic sensors array for the determination of soil condition

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Abstract.

To detect soil condition we propose the use of a send/receive type of electromagnetic transducer, where the transmitter is a planar coil and the receiver is an array of coils with its plane perpendicularly to the transmitter plane. This way, the fields associated with the two coils are separated. The use of a layered soil model with parallel interface planes, for which the forward problem will be solved using the dyadic Green's functions, is proposed.

Keywords: soil condition, sensors array, dyadic Green's functions

1. Introduction

An important property of soil is salinity. A measure of salinity is the electrical conductivity of the soil. Thus, if the conductivity is greater than 4S/m, it indicates a severe accumulation of salts, which restricts the growth of most vegetables and plants. If the conductivity is between 2S/m and 4S/m, the soil has an average accumulation of salts and the growth of vegetation is not restricted but requires frequent irrigation [1].

Electromagnetic methods have been developed for the determination of soil condition: ground penetrating radar, which operates in 100MHz -2GHz frequency range [2]; tomography methods using more generators and receivers of electromagnetic field inserted in boreholes in soil, the time of flight being measured using the Q-transform [3]; broadband electromagnetic induction method using a transmitter coil excited by a low frequency alternate current and a small diameter receiver coil placed in the center of the transmitter (monostatic mode), or at a certain distance (bistatic mode). In both cases a complex system of two concentric transmitter coils, connected in series with diameters have been chosen in order that on a common axis the magnetic field would be null [4].

2. Selection of type, shape and dimensions of the emission coil of the transducer

The emission coil of the transducer must generate an electric field with a distribution as uniform as possible, when is supplied with an alternative current with amplitude I_0. In the same time, the geometrical dimensions cannot be exaggeratedly large from practical reasons, easy to understand. The electric field created by different types of emission coils, simulated using dyadic Green's function was analyzed: circular coil with 1m outer diameter, 0.992m inner diameter, 0.06m height, having 10 turns [5]; square coil with 1m outer side, 0.992m inner side, 0.06m height, having 10 turns [6]; plane rectangular spiral coil with 1m outer side, 0.004x0.006m^2 transversal section of conductor, 0.006m step and 10 turns. The calculation was made according to the method presented in sequel. The result of the simulation is presented in Figure 1, considering that the current density through the coils is the same 10^7A/m^2, and 10kHz frequency for plane rectangular spiral coil.

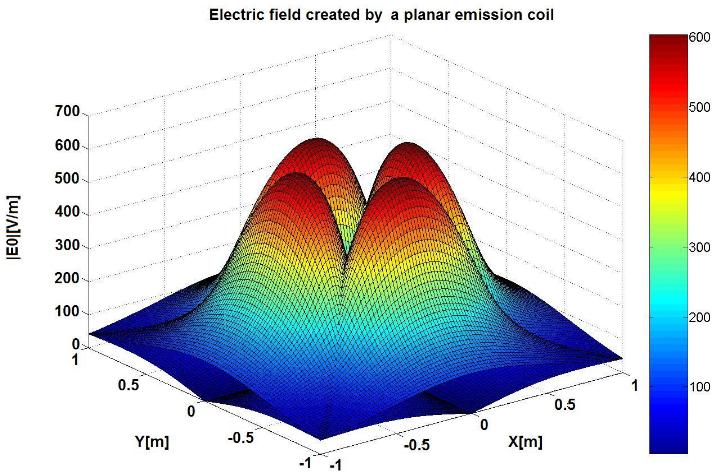


Figure 1. The electric field created by the transmission coil for planar rectangular spiral coil

3. Sensor array model

The electromagnetic sensors array designed for soil examination is presented in Figure 2.

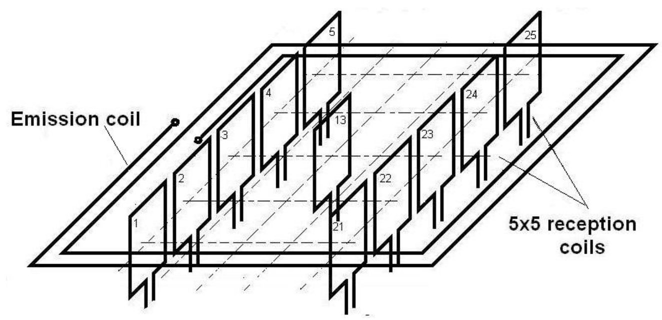


Figure 2. Electromagnetic sensor array for determining soil condition

Using the dyadic Green's function [7] and the volume integral method, the field produced by a rectangular transmission coil of dimension 2ax2b, cross section $\varepsilon_1 x \varepsilon_2$ supplied with a current with frequency ω and amplitude I_0, is given by

$$\bar{E}_0(\bar{r}) = j\omega\mu_2 \int_{Vsource} \overset{\leftrightarrow}{G}_{12}(\bar{r},\bar{r}')\bar{J}(\bar{r}')d\bar{r}' \quad (1)$$

where $\bar{J}$ is given in [6], and for the plane rectangular spiral coil, the expression for $\bar{J}$ components is written for the length of coil's sides modified due to the step.

When the emission coil is parallel to the soil surface, the field produced will be transverse electric (TE). When a stratified plane soil model is used, to simplify, we present only a model with two layers. The expression of the dyadic Green's function $\overset{\leftrightarrow}{G}_{12}$ (source in air and the observation point in the soil), in Fourier space is

$$\tilde{G}_{12} = \frac{j}{8\pi^2}\begin{pmatrix} k_y^2 & -k_xk_y & 0 \\ -k_xk_y & k_x^2 & 0 \\ 0 & 0 & 0 \end{pmatrix} F_-(z,z')\frac{1}{k_{1z}k_s^2}\exp\left(jk_x(x-x')+jk_y(y-y')\right) \tag{2}$$

where
$$F_-(z,z') = \left[e^{-jk_{2z}z} + e^{jk_{2z}(z+2d_2)}\tilde{R}_{23}\right] e^{jk_{2z}d_1}\tilde{T}_{12}e^{-jk_{2z}d_1}e^{jk_{1z}z'}\tilde{M}_2 \tag{3}$$

$$\tilde{M}_2 = \left[1-\tilde{R}_{23}\tilde{R}_{21}e^{2jk_{2z}(d_2-d_1)}\right]^{-1} \tag{4}$$

$k_{1z} = \left(k_1^2-k_s^2\right)^{1/2}$; $k_{2z} = \left(k_2^2-k_s^2\right)^{1/2}$; $k_1^2 = \omega\mu_1\left(\varepsilon_1 + j\frac{\sigma_1}{\omega}\right)$; $k_2^2 = \omega\mu_2\left(\varepsilon_2 + j\frac{\sigma_2}{\omega}\right)$, $\tilde{T}_{12}$ and $\tilde{R}_{23}$ are the generalized transmission and reflection coefficients respectively [6], d_1 and d_2 are the distances from the XOY at the upper face of first and second soil layers. The region of interest in soil is discretized into $N_x x N_y x N_z$ identical cells with $\Delta x\times\Delta y\times\Delta z$, small enough, thus the field in the cell is approximated by the field in the center of the cell. The equations are discretized using the point-matching variant of the moment method [8]. The presence of material discontinuities is equivalent to an auxiliary current source that creates the field described by dyadic Green's function $\overleftrightarrow{G}_{22}(\overline{r},\overline{r}')$. Due to the TE character of the field, the function will not present singularities, so that the integrals over the volume of the body will be well defined, being written in Fourier space as

$$\tilde{G}_{22} = \frac{j}{8\pi^2}\begin{pmatrix} k_y^2 & -k_xk_y & 0 \\ -k_xk_y & k_x^2 & 0 \\ 0 & 0 & 0 \end{pmatrix} F_\pm(z,z')\frac{1}{k_{2z}k_s^2}\exp\left(jk_x(x-x')+jk_y(y-y')\right) \tag{5}$$

where $F_+(z,z') = \left[e^{-jk_{2z}z'} + e^{jk_{2z}(z'+2d_2)}\tilde{R}_{23}\right]\left[e^{jk_{2z}z} + e^{-jk_{2z}(z+d_2)}\tilde{R}_{12}\right]\tilde{M}_2$ for z>z';

$F_-(z,z') = \left[e^{jk_{2z}z'} + e^{-jk_{2z}(z+2d_1)}\tilde{R}_{21}\right]\left[e^{-jk_{2z}z} + e^{jk_{2z}(z+d_2)}\tilde{R}_{23}\right]\tilde{M}_2$ for z<z'

The dyad $\overleftrightarrow{G}_{22}$ is analytically integrated on the cell volume. For the case z = z', the value is given by

$$\int_{z_p+\frac{\Delta z}{2}}^{z'} G^+_{22lm}dz' + \int_{z'}^{z_p+\frac{\Delta z}{2}} G^-_{22lm}dz' \tag{6}$$

where z_p is z coordinate of the p^th cell center, $l, m \in \{x,y,z\}$, G^+_{22lm} is the expression for z>z' and G^-_{22lm} for z<z'.

If in the ground is a buried object, having the electric conductivity σ_f, the total electric field is given by

$$\overline{E}_2(\overline{r}) + j\omega\mu_2\sigma_2\int_{Vbody}\overleftrightarrow{G}_{22}(\overline{r},\overline{r}')\overline{E}_2(\overline{r}')\left[\frac{\sigma_f(\overline{r}')}{\sigma_2}-1\right]d\overline{r}' = \overline{E}_0(\overline{r}) \tag{7}$$

In order to obtain $\overline{E}_2(\overline{r})$, the discretized variant of the Fredholm equation was solved using the Moore-Penrose inversion [9]. The perturbation field in air due the presence of conductive object is

$$\bar{E}_1(\bar{r}) = j\omega\mu_2\sigma_2 \int_{Vbody} \overleftrightarrow{G}_{21}(\bar{r},\bar{r}')\bar{E}_2(\bar{r}')\left[\frac{\sigma_f(\bar{r}')}{\sigma_2} - 1\right] d\bar{r}' \tag{8}$$

If the cells, in which the conductive object is discretized, are partially in one medium and partial in the other, for the stratified soil model, σ_2 will have the value corresponding to the location of the cell. The induced electromotive force in one receiver coil, C being the contour of the receiver coil, will be

$$e(\bar{r}) = \oint_C \bar{E}_1(\bar{r}) d\bar{r} \tag{9}$$

The expressions of $\overleftrightarrow{G}_{21}$ components are obtained using similar procedures.

Placing the sensor array above the soil with two layers: the superior layer has 0.3m thickness and 0.1S/m conductivity and the second has $5\text{x}10^{-2}$ S/m conductivity; the e.m.f induced in the reception coil from the center of the array, for a current density of 10^8A/m through emission coil and 10kHz frequency is calculated. The distance between the plane of emission coil and the superior layer of soil is modified between 0 and 1m. Each of the reception coils has $0.05\text{x}0.05\text{m}^2$ dimension and 100 turns. The results of simulation are presented in Figure 3.

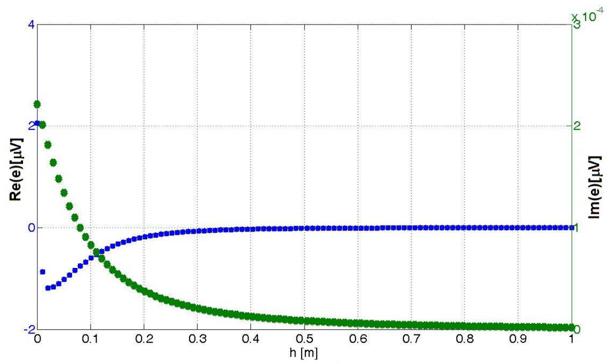


Figure 3. Dependence of e.m.f. induced in central coil of array, function of lift-off for a soil with two layers

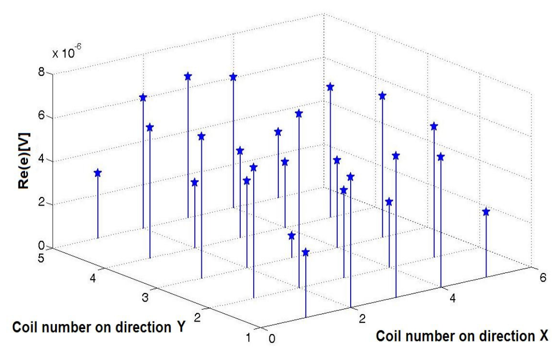


Figure 4. The real component of e.m.f. induced in the array's coils

If we calculate the e.m.f. induced in all the coils of the array, for the same soil model, and a lift-off of 1m, for the real component of the induced signal, the values presented in Figure 4 are obtained. It can be observed that, due to the distribution of the field created by the emission coil, the coils which form the reception array do not deliver signals with equal amplitudes. This fact must be corrected introducing a weight matrix.

4. The super-resolution procedure

The super-resolution procedures are currently used in application as sonar and radar. First is defined a weight matrix for the real components, respectively for the imaginary component of signal induced in the array's coils so that the signals delivered by the sensor array should be approximately equal. The role of the matrix is: assures signals delivered by the reception coils of the array, equally, when this it is placed over a soil zone having homogeneous conductivities in layers, either when the same small dimension conductive object is successively placed exactly below the center of the coils from array. It eliminates the apparition of the 1st rank ambiguities, when a small dimension conductive object is placed between the array's coils, supplying information to the other reception coils.

Noting with w_{ij} the weight value corresponding to the coils of whose center is indexed by the pair (i,j), we define the beamformer's output signal for the reception coil indexed (i,j) to be

$$z_{ij} = w_{ij} \bullet y_{ij} \tag{10}$$

where z can be amplitude or phase output, y can be the amplitude or phase of e.m.f induced in the reception coil.The weight matrix can be written

$$w = \begin{pmatrix} w_{11} & w_{12} & .. & w_{N} \\ w_{21} & w_{22} & .. & w_{2N} \\ : & : & :: & : \\ w_{M1} & w_{M2} & .. & w_{MN} \end{pmatrix} \tag{11}$$

where M and N represent the number of rows, respectively, columns of the uniform arrangement of the reception coils that form the sensor array. We define the array's sensibility matrix as

$$\overline{A} = \overline{w} * \overline{w}^{H} \tag{12}$$

where the superscript H denote the hermitic matrix (the transpose conjugate matrix).

We can define a new matrix S, as being

$$\overline{S} = \overline{A}\left(\overline{A}^{H}\overline{A}\right)^{-1}\overline{A}^{H} \tag{13}$$

where superscript "-1" represent the inverse of the matrix.

The autocorrelation matrix of the response signal of the array can be defined as

$$\overline{R}_{xx} = \overline{z} * \overline{z}^{H} \tag{14}$$

The super-resolution method uses the maximum likelihood estimation procedure [9] for the case of coherent sources. The source locations are estimated to lie at the points in space where the function $(\overline{S} * \overline{R}_{xx})$ is maximal. The use of the super-resolution procedures simultaneous leads to the improvement of the signal to noise ratio (SNR), too. SNR is defined to be the ratio of mean square value of the signal and noise components, which conceptually expresses the ratio of signal and noise powers.

If a single sensor was located at the spatial origin, its response to a noise corrupted signal would be

$$y(t) = s(t) + n(t) \tag{15}$$

where n represents the noise field. This noise may be attributed to the sensor (thermal noise, for example) or to background radiation.

$$SNR_{sensor} = \frac{\varepsilon\left[s^{2}(t)\right]}{\varepsilon\left[n\ \ (t)\right]} = \frac{R_{s}}{R_{n}} \tag{16}$$

where R_s and R_n denote the signal's correlation function and the noise correlation function. The array gain G is defined as the ratio of the array's SNR and the sensor's SNR.

$$G \equiv \frac{SNR_{array}}{SNR_{sensor}} \tag{17}$$

If we assume that the noise is uncorrelated spatially from sensor to sensor, we find that the expression of the unnormalized mean square value of the signal term equals $R_s\left|\sum_{i=1}^{N}\sum_{j=1}^{M} w_{ij}\right|^2$ and the expression for unnormalized mean square noise power in the array output becomes $R_n\sum_{i=1}^{N}\sum_{j=1}^{M}\left|w_{ij}\right|^2$. Thus the SNR becomes

$$SNR_{array} = \frac{R_s\left|\sum_{i=1}^{N}\sum_{j=1}^{M} w_{ij}\right|^2}{R_n\sum_{i=1}^{N}\sum_{j=1}^{M}\left|w_{ij}\right|^2} \quad , \quad G = \frac{\left|\sum_{i=1}^{N}\sum_{j=1}^{M} w_{ij}\right|^2}{\sum_{i=1}^{N}\sum_{j=1}^{M}\left|w_{ij}\right|^2} \tag{18}$$

Introducing in the equation (18) the values used for the weight matrix of our sensor array, we will obtain an array gain G=0.7*N*M, that will lead to a substantial improvement of the signal to noise ratio, in comparison with the one of an individual sensor array.

The super-resolution procedure developed above was tested with synthetic data obtained from the solving of forward problem for the case of a buried conductive sphere, having 1m diameter, 10^6 S/m conductivity and the center is at 10 m under the surface of a soil with a single layer with $5*10^{-2}$ S/m conductivity. The sphere was discretized in 5^3 cells. The current density through emission coil was considered 10^8 A/m^2 and frequency 10kHz

The results obtained are presented in Figure 5, using the phase information. If the synthetic data are corrupted by an additive noise with normal distribution and having amplitude greater than 15% of signal's amplitude, the precision of localization is worse.

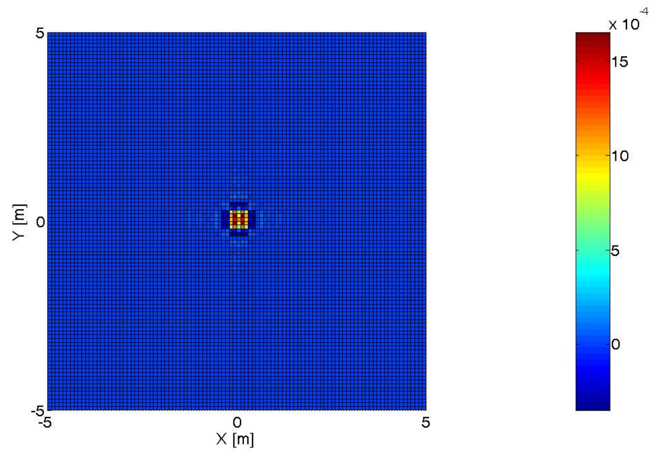


Figure 5. The image of a conductive sphere

5. Experimental set-up and preliminary results

The experimental set-up is presented in Figure 6. The emission coil is coupled with AG1012 power amplifier - T&C Power Conversion Inc., USA. The density of current through emission coil was 10^7 A/m^2, the frequency 22kHz, the duration of one measurement being limited at approximate 1second, to avoid superheating. The reception of the signals is made with a Lock-in Amplifier, SRS 850 - Stanford Research Systems, USA.

From a 3x3m^2 surface of ground, the vegetation has been removed, the soil was compressed and over it, a concrete plate without metallic reinforcement, with dimension 1x1x0.3m^3 was placed. Before compressing, from the soil were taken samples in order to determine the electric conductivity and the water content.

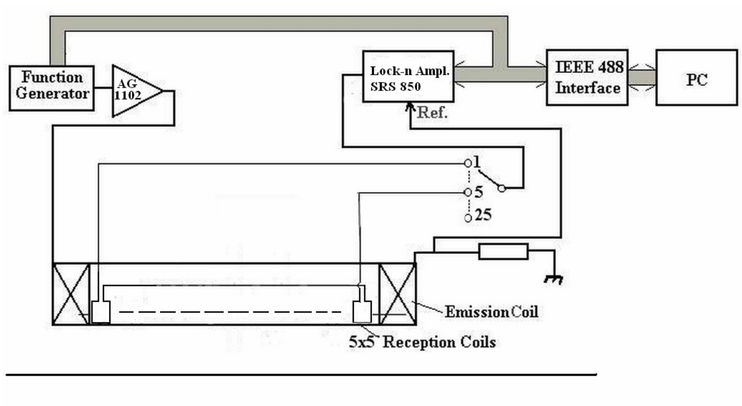


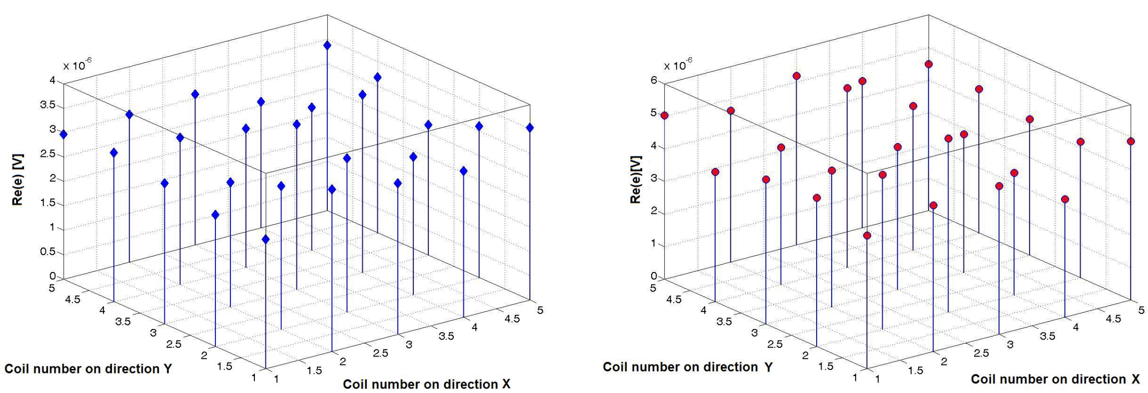
Figure 6.Experimental set-up

The conductivity of the soil on which the measurements were made has been varied through water addition and supplementary compressing. The results are presented in Table 1.

Table 1.

No. of sample	Weight % water	Bulk density [g/cm^3]	Conductivity [S/m]	Low frequency relative dielectric permittivity
#1	0.29	1.49	0.217	3
#2	1.31	1.36	15.4	9.1

The results obtained in laboratory were extrapolated in the field, but, with a certain degree of imprecision. The results delivered by the array placed at 1m height over the first layer of soil, using the super-resolution procedure, are presented in Figure 7a and b, for the two conductivities of the soil, obtained by moisturizing.



a b

Figure 7. Signals delivered by the sensors from array, using the super-resolution procedure for the concrete plate with 0.3m thickness and soil conductivity 0.217S/m (a), respective 15.4S/m (b)

For the first type of soil (#1) the signal from the array (averaging the values delivered by each sensor after the application of super-resolution procedure) has the value (3.073±0.29)μV and for the second (#2) was (4.36±0.36)μV. Similary situations happen in the case of using phase information, too. Simulating the same configuration we obtain average value of e.m.f. induced in the coils from array is 2.880μV for the sample #1 and respective 3.953μV for #2.

The differences between the calculated and measured values are due, especially to the difficulty to realize a constant conductivity in the deepness of the soil.

6. Conclusions

To evaluate the soil condition we propose the electromagnetic method using a rectangular plane spiral coil and a series of rectangular reception coils of which plane is orthogonally on the plane of the emission coil. In this way, the direct induction between the emission coil and the reception one is avoided. The method for solving the forward problem using dyadic Green's function and integral volume methods and an algorithm of super-resolution which allow the improving of the signal to noise ratio as well as the localization of the conductive buried objects were developed. If the amplitude of noise exceeds 15% of the amplitude of the signal, the localization is made, but with lower correctitude.

Acknowledgements

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