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Numerical Analysis of Electromagnetic Coupling Effects in Measurements of Frequency Dependent Soil Electrical Properties

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Abstract—Recent studies show that the frequency dependent soil properties can significantly influence transient grounding resistance and, subsequently, lightning protection and reliability of the electrical grid. However, these properties require further research: for example, it is not clear what factors (apart from the low-frequency resistivity) should be taken into consideration to determine accurately the properties for a particular soil (without conducting laborious measurements). Additional experimental data are needed.

When measurements are conducted, the electromagnetic coupling between circuits can cause significant measurement error at frequencies about several MHz. In order to estimate this error, it is convenient to use a calculation method, as in this case, it is possible to set particular frequency dependent properties for the ground and compare those with the calculated ones (using an electrode array).

In the article, the electromagnetic coupling error is examined for several commonly used electrode arrays using the finite difference time domain method. This method allows simulating wires with infinite length, which is important for modeling pole-dipole and pole-pole arrays. Its drawback for this type of calculations, however, that it is relatively time-consuming. It was found that among the considered array configurations the error is smallest for the dipole-dipole arrays with the perpendicular allocation of the measurement wires and the pole-dipole array. By increasing the distance between particular parts of measurement wires, one can significantly reduce the error for some other arrays.

1. INTRODUCTION

Electrical soil parameters are important for choosing transmission line grounding configurations [1]. Recent works have demonstrated that the frequency dependent soil properties can strongly influence grounding potential rise and lightning performance of transmission lines [2–4]. It was also suggested that these properties can be evaluated based on the low-frequency conductivity [2, 5]. However, experimental curves of the properties can differ quite significantly for the same value of low-frequency resistivity [3]. This means that other factors should be taken into account if the same approach is used: determining the properties based on a small set of quantities (i.e., without conducting the measurements of the properties itself).

In order to find these factors (or, at least, extend existing experimental data), a large number of field measurements with different soils should be carried out. And for conducting these measurements, a simple and accurate measurement method is needed.

One of the possible measurement methods is based on using a hemispheric electrode [2]. However, this method has a drawback: measured potential difference between the hemispheric electrode and another point in ground includes the potential difference between the electrode and the soil (due to

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contact resistance). In other words, the poor contact between the electrode and the surrounding soil can lead to inaccurate measurement results (especially in the case of the high-resistivity soils for which the frequency dependence of the soil properties is most pronounced [2]). In order to avoid this error, special electrode arrays are used in geoelectrical resistivity and induced polarization (IP) surveys [6]. For these arrays, the potential difference is measured with electrodes which are electrically separated from the current electrodes.

At high frequencies, electromagnetic (EM) coupling between circuits can significantly influence measurement results and cause a substantial error. This problem is also known to geophysical induced polarization (IP) surveys [6]. However, IP surveys usually deal with lower frequencies and greater sizes of electrode arrays.

The purpose of this work is to estimate the error caused by the EM coupling between the measurement circuits and to determine appropriate arrays for measurements of the frequency dependent soil properties in the frequency range of lightning currents.

2. EVALUATION OF THE EM COUPLING ERROR FOR DIFFERENT ELECTRODE ARRAYS

There are several different electrode arrays used for conducting geoelectrical surveys [6]. In this work, Wenner, Schlumberger, dipole-dipole, pole-dipole and pole-pole arrays are examined.

Distance between electrodes is chosen based on the depth of investigation. There are two approaches to define the depth of investigation [7, 8]. The median value of the depth of investigation characteristic is used here [8].

The value of the depth of investigation was chosen to be about 0.7 m as it is close to depths at which grounding wires are usually located (due to the coarseness of the calculation grid, the depth values vary from 0.65 m to 0.72 m depending on the array).

2.1. FDTD Model

The finite difference time domain (FDTD) method has been selected for calculations [9]. As absorbing boundary conditions (ABC), the present study uses 10-cell convolutional perfectly matched layer (CPML) [9]. The CPML parameters [9]: $\sigma_{\max}/\sigma_{opt} = 1$, $\kappa_{\max}$ is 1, $\alpha_{\max}$ equals 10^{-5} with the scaling order 1. For the σ and κ the polynomial grading is used with the scaling order 3 (Therefore, σ_{opt} is approximately 0.034.) [9]. All conductors are modeled by means of thin wire modeling method [10–12]. The diameter of the measurement wires is 3 mm. To model wires with the infinite length, they penetrate CPML area. Duration of the calculated EM process is 400 μs.

Figure 1 shows electrode arrays that were used in the article. FDTD cell size for the cases (i) and (j) is 0.2 m; the cell size for the other cases is 0.25 m. The cell size values were chosen based on calculations with different cell sizes. The cell size bigger than 0.25 m can lead to inaccurate results, and cell size smaller than 0.2 m does not increase appreciably calculation accuracy (but increases calculation time). All the measurement wires are located one cell above the ground. Side view of the dipole-dipole array is shown in Fig. 2. Other arrays are modeled in a similar way. In the models, when the current source or voltage calculation gap is located between two rods, they are placed exactly in the middle (or slightly shifted if the amount of cells between rods is even, like in the Fig. 2). When there is only one rod (pole-pole, pole-dipole arrays), current source and voltage calculation gap are located two cells from the rod. However, as long as the shortest wavelength of interest is significantly bigger than array sizes, shifting the current source or voltage calculation gap one or two cells along the axis of their direction causes only negligible difference in calculation results.

The frequency-dependent soil properties are modeled with the Debye relaxation model using auxiliary differential equation method [9, 13, 14]. The n-term Debye function expansion:

$$\hat{\epsilon}_r(\omega) = \epsilon_\infty + \sum_{p=1}^{n} \frac{\Delta\epsilon_p}{1 + j\omega\tau_p}, \tag{1}$$

where n is the number of Debye poles. The parameters ϵ_∞, $\Delta\epsilon$, and τ of the expansion are calculated with hybrid particle swarm-least squares optimization approach [15]. The parameters are calculated to

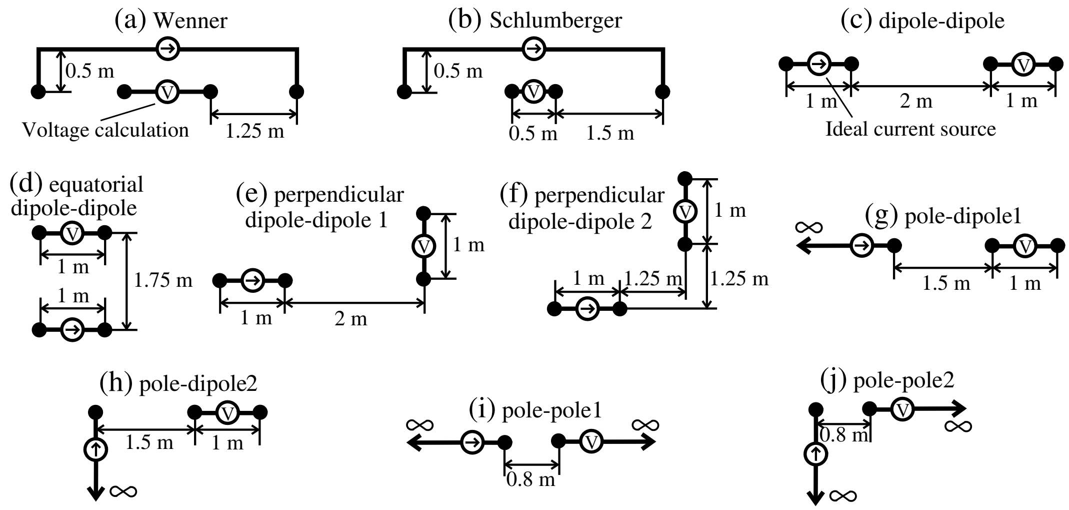

Figure 1. Examined arrays. Top view.

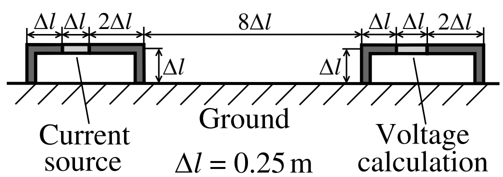

Figure 2. Side view of the dipole-dipole array (c).

fit experimental expressions for the real and imaginary parts of the relative permittivity [5]:

$$\epsilon_r'(f) = \epsilon_\infty + \frac{\tan(\pi\gamma/2)\cdot 10^{-3}}{2\pi\epsilon_0(1\,\mathrm{MHz})^\gamma}\sigma_0 h(\sigma_0) f^{\gamma-1}, \tag{2}$$

$$\epsilon_r''(f) = \frac{\sigma_0 h(\sigma_0)\cdot 10^{-3}}{2\pi f\epsilon_0}\left(\frac{f}{1\,\mathrm{MHz}}\right)^\gamma, \tag{3}$$

where $h(\sigma_0) = 1.26\cdot\sigma_0{}^{-0.73}$, $\epsilon_\infty = 12$, $\gamma = 0.54$, σ_0 — low frequency conductivity in mS/m, f is the frequency in Hz.

Resistivity (in $\Omega\cdot\mathrm{m}$) can also be derived from [5]:

$$\rho(f) = \frac{10^3}{\sigma_0 + \sigma_0 h(\sigma_0)\left(\frac{f}{1\,\mathrm{MHz}}\right)^\gamma}. \tag{4}$$

The calculated expansion parameters for the frequency range 10 kHz–4 MHz are shown in Table 1.

Table 1. The ϵ_∞, $\Delta\epsilon$, and τ parameters of the four-term Debye function expansion.

ρ_0, $\Omega\cdot\mathrm{m}$	ϵ_∞	$\Delta\epsilon_1$	τ_1, s	$\Delta\epsilon_2$	τ_2, s	$\Delta\epsilon_3$	τ_3, s	$\Delta\epsilon_4$	τ_4, s
100	24.456	744.767	$2.912\cdot10^{-5}$	147.352	$3.874\cdot10^{-6}$	72.661	$6.756\cdot10^{-7}$	36.849	$8.513\cdot10^{-8}$
1000	18.643	399.754	$2.906\cdot10^{-5}$	79.139	$3.857\cdot10^{-6}$	38.965	$6.698\cdot10^{-7}$	19.679	$8.414\cdot10^{-8}$
9000	15.670	220.659	$2.898\cdot10^{-5}$	43.651	$3.843\cdot10^{-6}$	21.472	$6.682\cdot10^{-7}$	10.868	$8.422\cdot10^{-8}$

2.2. Depth of Investigation

Depth of investigation values for cases (a)–(h) are calculated based on expressions (2), (3), (5), (6) given in [16], and for the cases (i), (j) expression (12) from [16] is used (as mentioned above, median values of the curves are calculated [8]). Calculated depths of investigation for the considered arrays (Fig. 1): (a) 0.65 m; (b) 0.66 m; (c) 0.70 m; (d) 0.72 m; (e) 0.69 m; (f) 0.67 m; (g) 0.72 m; (h) 0.72 m; (i) 0.69 m; (j) 0.69 m.

2.3. Calculation of the Soil Properties

The methodology of calculation of the soil characteristics is similar to that used in [2] for the measurements. From the current entered into the ground and voltage between two ground points, it is possible to derive resistivity $\rho(\omega)$ and permittivity $\epsilon'(\omega)$ of soil. The current and voltage are related to the resistivity and permittivity via the equation:

$$\hat{Y}(\omega) = \frac{\hat{I}(\omega)}{\hat{V}(\omega)} = k\left(\frac{1}{\rho} + j\omega\epsilon'\right), \tag{5}$$

where k is the geometric factor that depends on a particular electrode array [6].

Geometric factors for electrode arrays can be easily calculated using the electrostatic analogy for direct current fields. A common formula for the geometric factor is [17]:

$$k = \frac{2\pi}{\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{R_1} + \frac{1}{R_2}}, \tag{6}$$

where r_1 and r_2 are the distances from the first potential electrode to the first and the second current electrodes, and R_1 and R_2 are the distances from the second potential electrode to the two current electrodes. Some formulae for geometric factors can also be found in the geophysical literature [6].

Geometric factors for arrays in Fig. 1: (a) 2.5π; (b) 6π; (c) 24π; (d) 13.282π; (e) 56.052π; (f) 19.431π; (g) 7.5π; (h) 7.5π; (i) 1.6π; (j) 1.6π.

Due to the nature of the calculation method, the calculations are performed in the time domain (after that, fast Fourier transform is applied to the known current and voltage).

For the current pulse a single Heidler function is used [18]:

$$I(t) = \frac{i_m}{\eta} \frac{\left(\frac{t}{T}\right)^n}{1 + \left(\frac{t}{T}\right)^n} \exp\left(-\frac{t}{\tau}\right) + 0.5\tau, \tag{7}$$

where $\tau = 3.7 \cdot 10^{-7}$, $T = 1.4 \cdot 10^{-5}$, $\eta = 1$, $n = 10$, $i_m = 1\,\mathrm{A}$.

2.4. Calculation Process

The calculations are performed in the following manner: first, frequency dependent soil properties are set in the FDTD model (together with the particular electrode array), then, calculation with the model is performed. In the absence of EM coupling between measurement circuits, the calculated soil characteristics should coincide ideally with those that were set initially for the soil in the model. Due to the EM coupling, however, the calculated characteristics differ from those that were set in the model and the difference depends on a particular array.

The whole calculation sequence is outlined in Fig. 3. Steps according to the figure:

1. Choosing an electrode array and location of measurement wires.
2. Calculation of the depth of investigation for the chosen array according to [7, 8]. If the value of the depth of investigation is too small or too big, the distance between the electrodes is changed and the depth of investigation is recalculated.
3. Choosing the soil properties.

4. Approximation of the soil properties according to Debye function expansion (1) if the properties are frequency dependent (which is the case for the current article). For the calculations in the work, data from Table 1 are used.
5. Setting the array and soil properties in the calculation model.
6. Calculation of the voltage between the potential electrodes. During the calculations, the current for the ideal current source is set by function (7).
7. Applying fast Fourier transform to the known current and the calculated voltage. Calculation of the resistivity and permittivity based on the Equation (5) and known geometric factor for the electrode array.
8. Comparison of the calculated resistivity and permittivity with those that were set initially for the soil in the model.

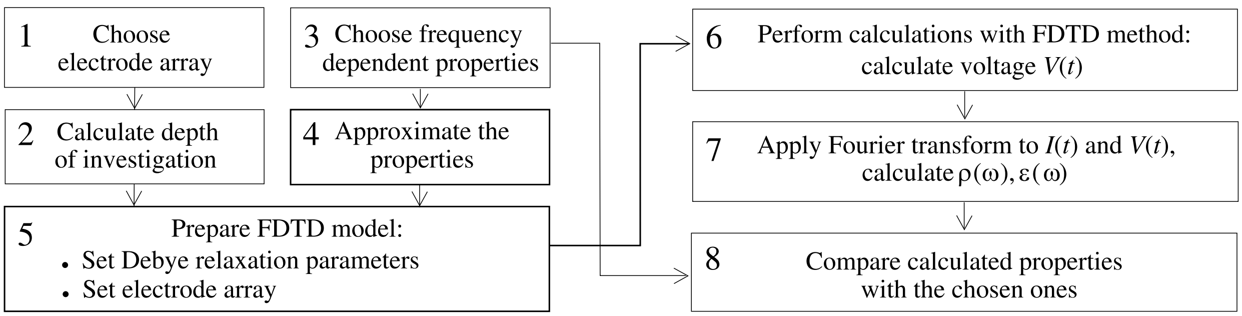

Figure 3. Calculation sequence.

2.5. Calculation Results

Calculated frequency dependent resistivity and permittivity (for the low-frequency resistivity values $100\,\Omega\cdot\mathrm{m}$, $1000\,\Omega\cdot\mathrm{m}$, $9000\,\Omega\cdot\mathrm{m}$) are shown in Figs. 4–6 ("initial" values are those that were set in the model, step 5 in Fig. 3). It is seen from the calculation results that they strongly depend on the array.

The insignificant error in the low-frequency range (about 10–20 kHz) for all the arrays is most probably caused by CPML absorbing boundary conditions (even though CPML is relatively accurate for low frequencies comparing to other ABCs, due to many thousands of calculation iterations, the small error is still possible). Error due to EM coupling is much more significant.

The error for the arrays with parallel wires is significant. Interestingly, the error may be noticeable for the case with perpendicular wires too, see case (j). Seemingly, not only the angle between wires is important but also their length.

From the results it can be seen that the resistivity error strongly depends on both the array configuration and low-frequency resistivity, and the error mostly exists in the high-frequency range (which is important as this range corresponds to the first microseconds of lightning pulse and this error can lead to erroneously calculated overvoltages across transmission line insulators). While the permittivity error strongly depends on the array only for the low resistivity soil and it is relatively small for the high resistivity soils.

The smallest error corresponds to the pole-dipole array (h) and perpendicular dipole-dipole arrays (e) and (f). If the soil resistivity is higher than $1000\,\Omega\cdot\mathrm{m}$, most arrays can be used for the frequencies up to about 1 MHz.

From the calculations in [2], one can conclude that frequency dependent resistivity has a greater impact on calculated GPR (ground potential rise) than permittivity: the calculated GPR is accurate even if the averaged frequency dependent permittivity is used [2], while the frequency dependent resistivity (for different ρ_0) influences calculation results significantly [2]. Thus, it is important to measure the resistivity accurately.

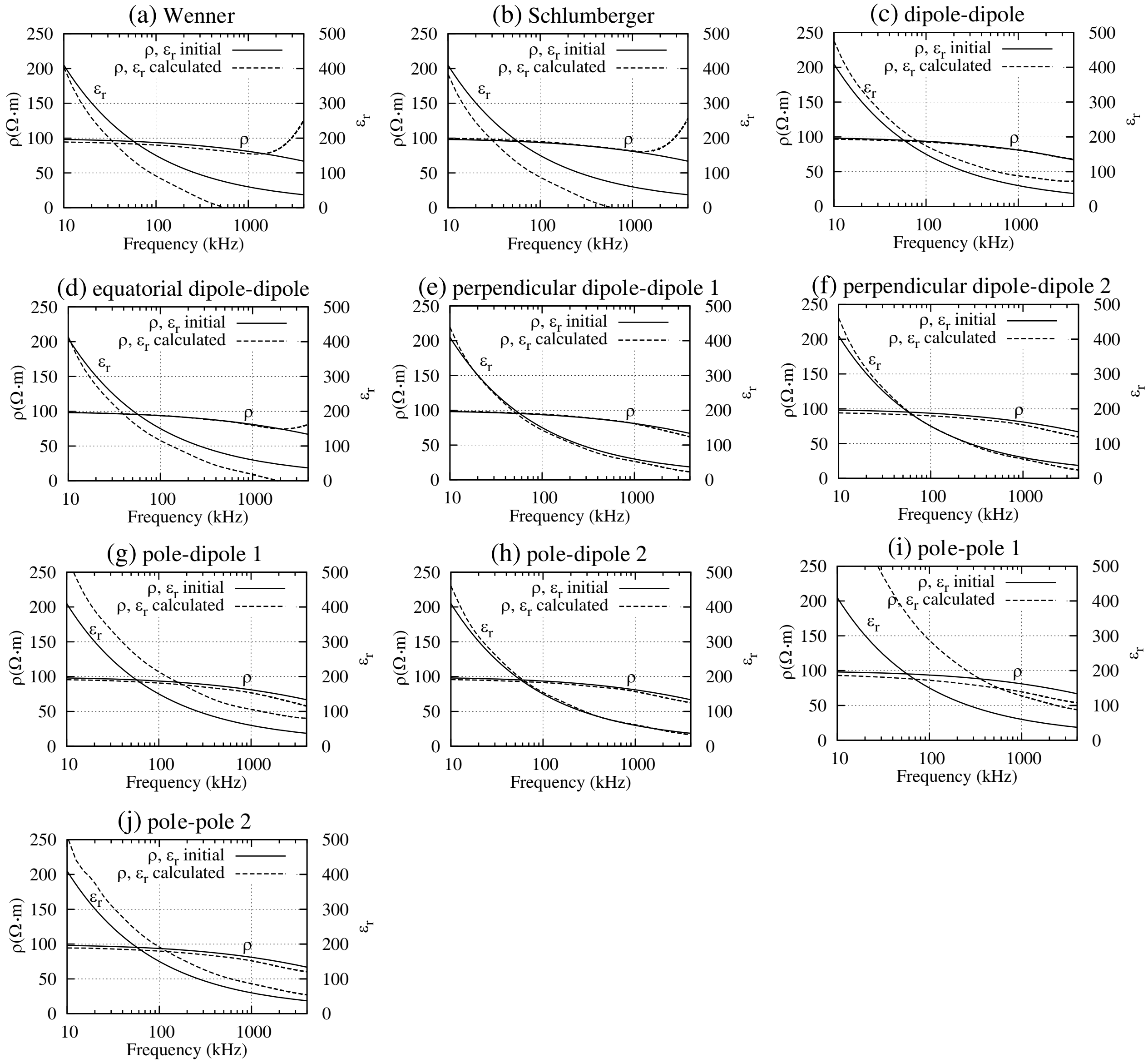

Figure 4. Calculation results. $\rho_0 = 100\,\Omega \cdot \mathrm{m}$.

3. VOLTAGE BETWEEN POTENTIAL RODS

The higher the voltage is between potential rods for the particular current, the less the powerful source is needed (and simpler the measurements). In order to estimate the voltage between potential rods, voltage values from the above calculations are presented here.

Calculation results for $1000\,\Omega \cdot \mathrm{m}$ soil corresponding to the arrays in Fig. 1 are presented in Fig. 7; cases (g) and (i) are not included as they are similar to (h) and (j). From the results it can be seen that the maximum voltage values increase in this order: dipole-dipole arrays, pole-dipole array, Schlumberger and Wenner arrays, pole-pole array.

Thus, the pole-dipole array (h) provides not only accurate results but also relatively high voltage between potential rods (below it is shown, however, that with the particular allocation of measurement wires, other arrays might be more preferable).

Of course, the comparison could also be made using geometric factors: according to Equation (5), they are inversely proportional to voltages, with a remark that the voltages from the Fig. 7 include the

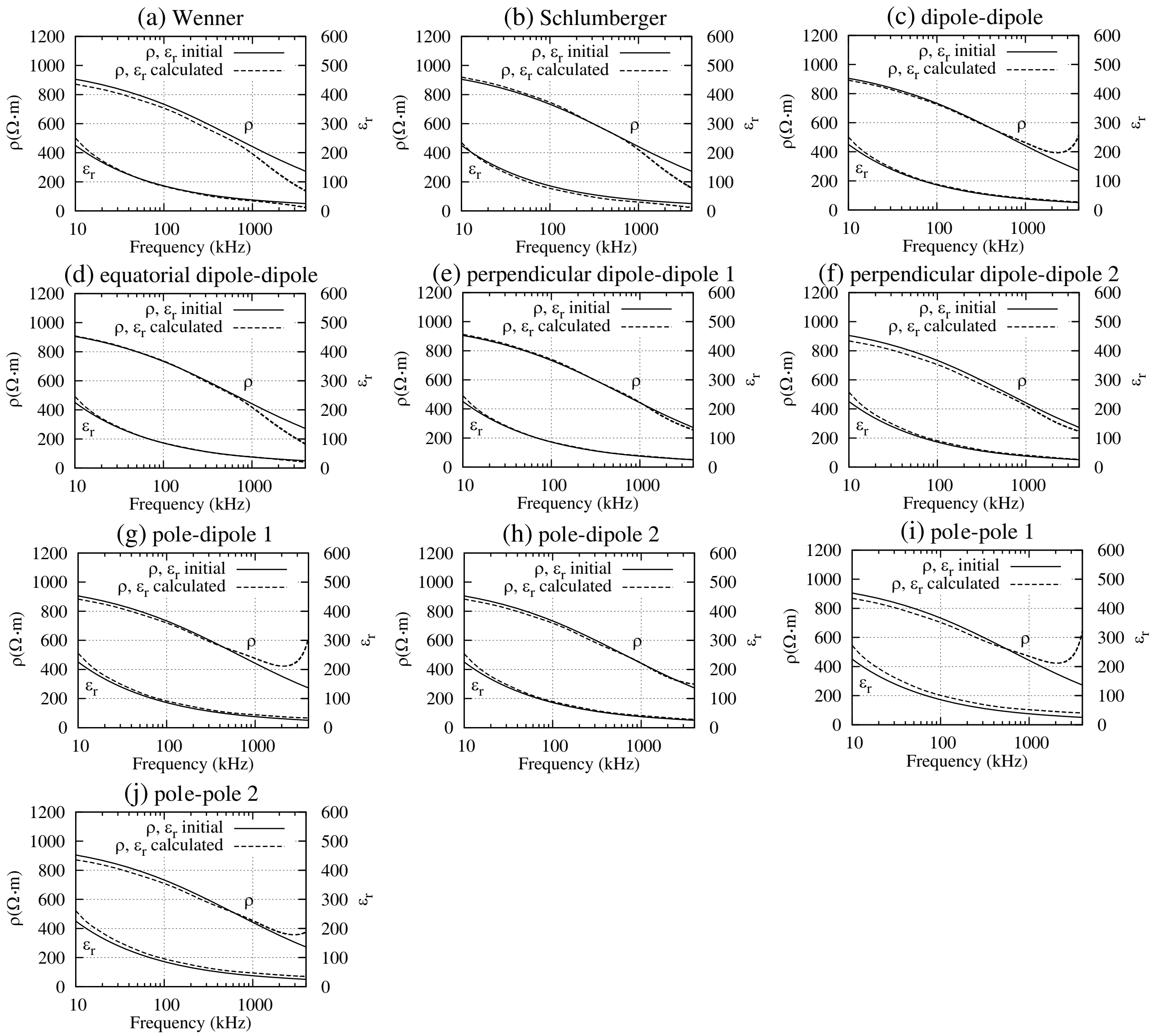

Figure 5. Calculation results. $\rho_0 = 1000\,\Omega \cdot \mathrm{m}$.

influence of the EM coupling and the capacitive effect of the soil.

Usually, the voltage can be increased by reducing the distance between one of the current rods and one of the voltage rods (if a smaller depth of investigation is sufficient) or by increasing the distance between two current rods (or two voltage rods).

4. REDUCING THE EM COUPLING ERROR

In some cases, it is possible to reduce the EM coupling error by increasing the distance between parallel parts of measurement wires that contribute to the EM coupling error. Examples with the Wenner and equatorial dipole-dipole arrays are presented here (see Fig. 8). These arrays were chosen because they provide relatively high voltages between potential rods and have a possibility to decrease EM coupling error.

Calculation results for the arrays are shown in Fig. 9. Comparing to the previous calculation results (cases (a) and (d) in the Figs. 4–6), one can see that the error significantly decreased. Even though these arrays have parallel wires, EM coupling error cancels out due to the symmetry; and those parts

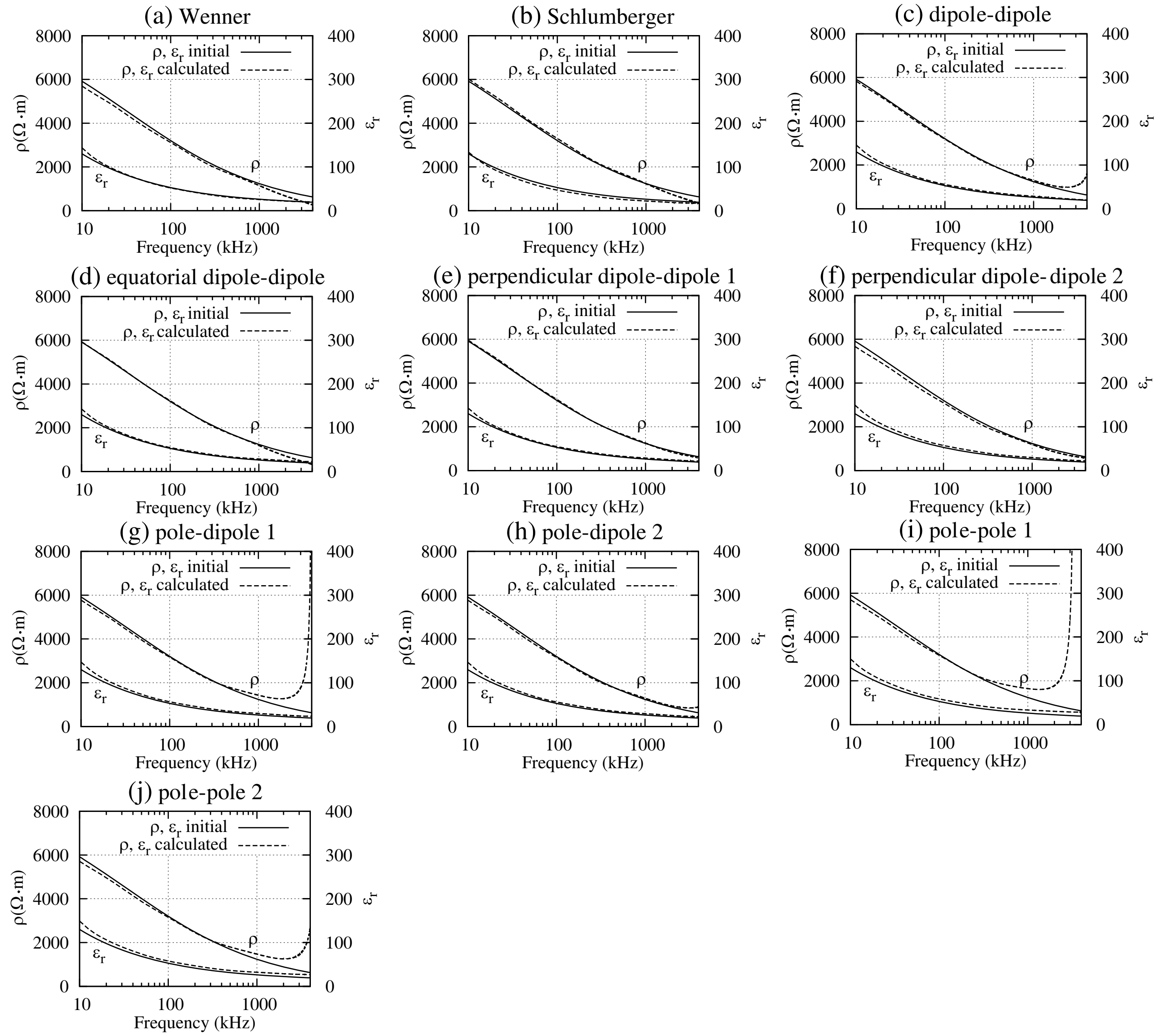

Figure 6. Calculation results. $\rho_0 = 9000\,\Omega \cdot \text{m}$.

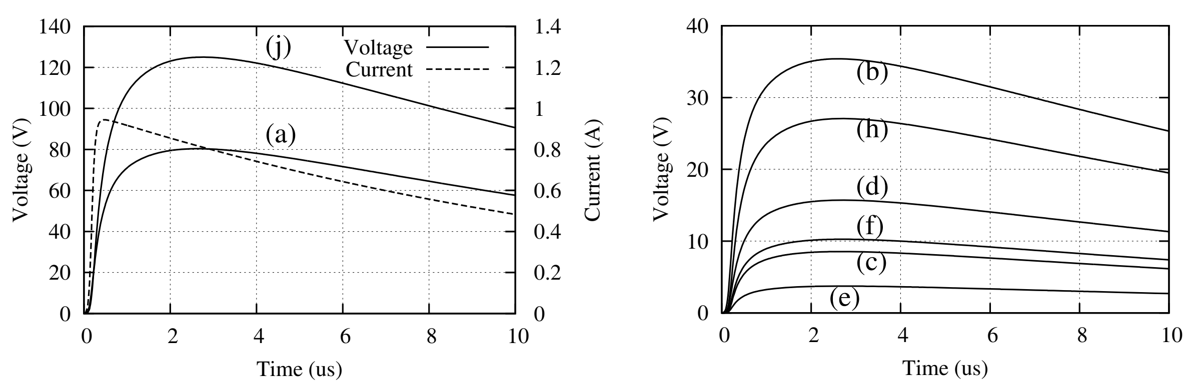

Figure 7. Voltages for the array configurations (a)–(f), (h), (j) and source current.

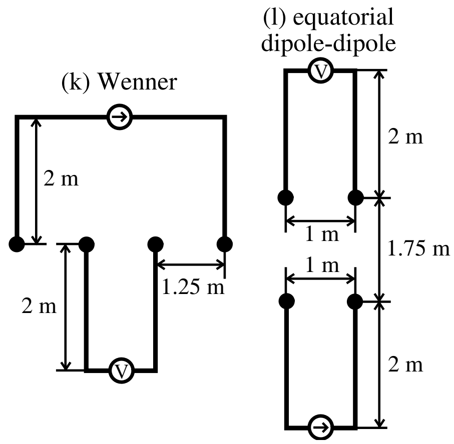

Figure 8. Examined arrays. Top view.

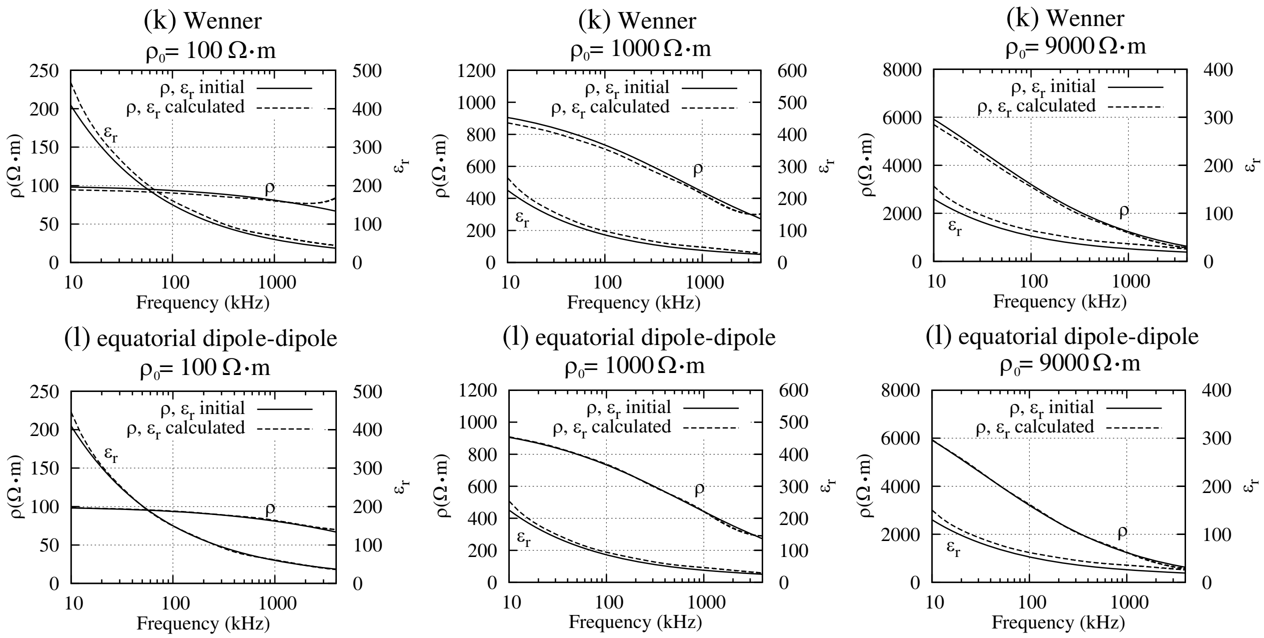

Figure 9. Calculation results for the array configurations (k) and (l).

of measurement wires that can cause the error, are far from each other. It can be seen, however, that the permittivity error is slightly increased (especially relative error for the $9000\,\Omega \cdot$ m soil). Probably, this can be taken into account in measurement results.

5. CONCLUSIONS

Location of measurement wires has a great impact on EM coupling for the frequency range above 1 MHz if the soil resistivity is high, and for the whole frequency range of interest if the soil resistivity is relatively low.

In most cases, arrays with perpendicular wire allocation provide more accurate results. However, for some array configurations the perpendicular wire arrangement does not necessarily provide accurate results: see array (j). Similar can be noticed for the parallel wires: even though it is a good practice to avoid the parallel wire arrangements during the measurements of the frequency dependent soil characteristics, there are cases, when parallel wires do not cause pronounced error: see cases (k), (l).

Depending on situation, following array configurations are proposed for the measurements: if the source provides sufficient voltage between potential electrodes, dipole-dipole arrays with perpendicular location of the dipoles are preferable, otherwise pole-dipole arrays can be a better option; with allocation of the measurement wires in a manner similar to that depicted in Fig. 8, Wenner or dipole-dipole array might be an even better alternative as they provide relatively high voltage and do not need remote earth (however, they need a special layout of measurement wires). If the soil resistivity is high and measurement frequency is lower than 1 MHz, most arrays give acceptable results.

One should not exclude that if the frequency dependent characteristics of a soil differ significantly from those that were considered in the article (but have the same low-frequency resistivity), there is a possibility that the EM coupling error can also be different. Usage of significantly different depth of investigation (resulting in a different distance between measurement wires), can also influence results. Thus, when choosing an array among those presented here, it is preferable to use configurations for which the EM coupling error is negligible.

Even though determination of the EM coupling error is more convenient by calculations, there are aspects for which experimental approach is preferable. For example, during measurements one can determine what kind of source is more convenient and what domain should be used for measurements: it is possible that conducting measurements in frequency domain might be more preferable than in time domain (i.e., conducting measurements with a limited set of frequencies using sinusoidal current and use the interpolation for the resulting data instead of using pulse current and applying fast Fourier transform).

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