Hybrid receiving dipole for broadband electric field measurement

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SUMMARY

High-frequency electric field measurements with a regular receiving dipole with poor electrode contact are greatly influenced by capacitive leakage between the wires and the ground. At the same time, noncontact receiving lines are not generally suitable for low-frequency electric field measurements. We introduce a novel hybrid galvanic-capacitive receiving dipole, which could be used for broadband electric field measurement even with high contact resistance of grounded electrodes.

Keywords: poor electrode contact, capacitive leakage, ECR-effect.

INTRODUCTION

In electrical prospecting there are two ways to measure the electric field in the ground, that is, the contact, or “galvanic” method, and the noncontact or “capacitive” one. In the first case, the field sensor is a receiving line connected to a pair of grounded electrodes, while in the second case the receiving line includes special capacitive electrodes or just a pair of ungrounded wires. The galvanic method shows the best results when working at very low frequencies (up to ~100 Hz) and is widely used in resistivity methods, induced polarization (IP) and magnetotelluric (MT) sounding. The capacitive method shows best performance at very high frequencies (>1 kHz) and is successfully used in noncontact modifications of resistivity methods (Gruzdev et al. 2020; Kuras et al. 2006) and in radio-MT (RMT) exploration (Shlykov et al. 2020).

Unfortunately, the application of either of the indicated electric field sensors for carrying out measurements at both low and high frequencies is associated with serious difficulties. In particular, a conventional grounded array, as applied in the audio-MT (AMT) method, with a frequency ranging from ~1 Hz to ~10 kHz, requires very low grounding resistance values (<1 kΩ). Otherwise, the arising parasitic electrode contact resistance (ECR) effects may result in large distortions of the high-frequency parts of the sounding curves (Zonge and Hughes 1985). At the same time the non-contact technique is not applicable for frequencies well below ~1 kHz. This problem severely limits the applicability of such methods as AMT when working on frozen, sandy, or stony soils, rocks, etc.

Below we present a novel electric field sensor, which allows taking broadband measurements without any excessive requirements for the contact resistance of the grounded electrodes.

CLASSIC RECEIVING DIPOLE

The classic version of the receiving electric line and its simplified equivalent circuit are shown in Figure 1 (Vishnyakov and Vishnyakova 1974; Zonge and Hughes 1985). The following symbols are used in the figure: R_M (R_N) is the grounding resistance of the electrode M (N); C_M (C_N) is the capacitance between the cable M (N) and the ground; Z_0 is the complex input impedance of the receiver; D is the distance between the grounded electrodes; E is the electric field in the ground; and U_0 is the observed voltage at the receiver’s input. U_0 and E are related as follows:

$$U(\omega) = \left(\frac{0.5 + \frac{0.25}{1 + i\omega R_M C_M} + \frac{0.25}{1 + i\omega R_N C_N}}{1 + \frac{Z_{MN}(\omega)}{Z_0(\omega)}} \right) DE(\omega),$$

where ω stands for the angular frequency; i stands for the imaginary unit; $Z_{MN} = Z_M + Z_N$ is the complex contact impedance of the dipole MN; $Z_M = R_M/(1 + i\omega R_M C_M),\ Z_N = R_N/(1 + i\omega R_N C_N)$.

Separating in this expression the coefficient K_{MN} due to wire-to-ground capacitive leakage from the coefficient K_0 due to voltage division at the receiver’s input, we get:

$$U_0(\omega) = K_0(\omega) K_{MN}(\omega) DE(\omega), \qquad (1a)$$

$$K_0(\omega) = \frac{Z_0(\omega)}{Z_0(\omega) + Z_{MN}(\omega)}, \qquad (1b)$$

$$K_{MN}(\omega) = 0.5 + \frac{0.25}{1 + i\omega R_M C_M} + \frac{0.25}{1 + i\omega R_N C_N}. \qquad (1c)$$

For a perfectly grounded dipole Equation 1 yields $K_{MN} \equiv K_0 \equiv 1$, and the observed voltage U_0 is related to the measured electrical field E with a simple expression:

$$U_0(\omega) = DE(\omega). \quad (2)$$

In a real grounded dipole, the voltage recorded by the receiver is always less than the expected value (2), and the degree of bias is governed by the values of complex coefficients K_{MN} and K_0.

HYBRID RECEIVING DIPOLE

The proposed hybrid "galvanic-capacitive" line and its simplified equivalent circuit are shown in Figure 2. It consists of an ordinary grounded dipole, supplemented with two more wires of the same length connected to each of the electrodes and stretched in different directions, as shown in Figure 2 (the far ends of the additional wire sections are insulated). Since the centers of the resulting M and N cables coincide with the grounding points of the corresponding electrodes, the effective length D of the hybrid dipole at very low frequencies ("galvanic mode") equals to that at very high frequencies ("capacitive mode"). As a result, the measured electric field in the ground is related to the observed voltage at the receiver's input as follows:

$$U_0(\omega) = K_0(\omega) DE(\omega), \qquad (3a)$$

$$K_0(\omega) = \frac{Z_0(\omega)}{Z_0(\omega) + Z_{MN}(\omega)}. \qquad (3b)$$

Comparison of Equations 1 and 3 shows that, irrespective of the contact resistivity of grounded electrodes, the electric field measurements with a hybrid receiving dipole are not vulnerable to the wire-to-ground capacitive leakage coefficient K_{MN}, and the only remaining source of possible distortion is the coefficient K_0 due to voltage division at the receiver's input. The influence of the latter could be minimized by using a receiver or pre-amplifier with sufficiently large input impedance Z_0 or by taking broadband *in situ* measurements of the complex contact impedance Z_{MN} at every observation site and correcting the acquired electric field data with the help of Equation 3.

CONCLUSIONS

Unlike conventional grounded or ungrounded electric field sensors, hybrid receiving dipoles are capable of performing equally well in galvanic, capacitive, and mixed operating modes. At very low frequencies this dipole behaves like a classic grounded line, at high frequencies – like a classic ungrounded line, and at intermediate frequencies there is a smooth transition from one mode of operation to another without changing the effective length of the receiving dipole. Thus, the hybrid setup successfully combines the advantages of grounded and ungrounded lines without showing their main drawbacks. The principal advantage of the hybrid dipole is its potential ability to record unbiased data in an unlimited frequency bandwidth, even under poor grounding conditions. At the same time, the way of its practical implementation proposed in our research is rather simple, requires minimal additional labor and, therefore, should not lead to a noticeable rise in the costs of field work.

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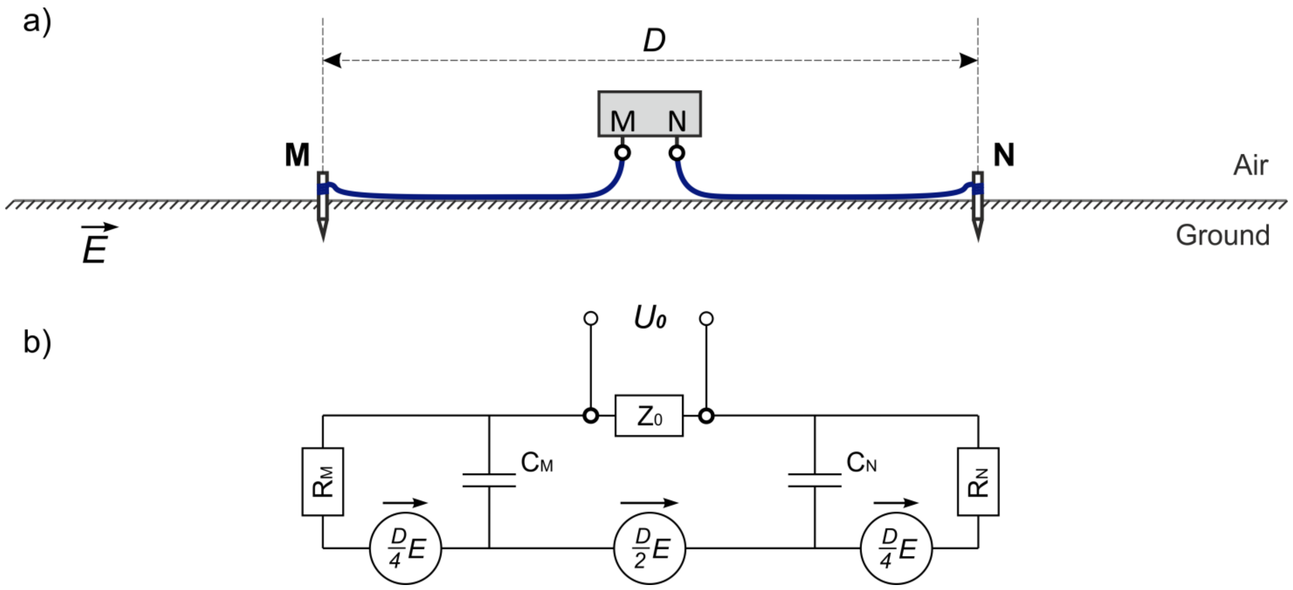

Figure 1. Classic receiving dipole (a) and its equivalent circuit (b).

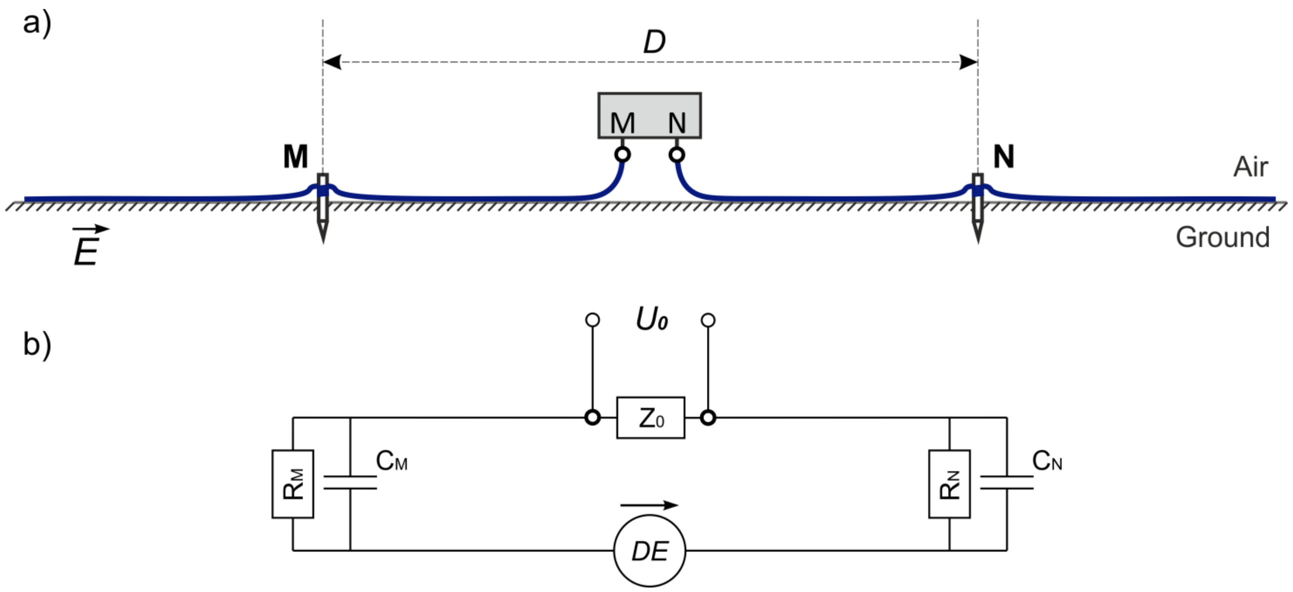

Figure 2. Hybrid receiving dipole (a) and its equivalent circuit (b).