Estimation of the optimal frequency range of EM waves for the implementation of a wireless channel of charge activation during drilling and blasting operations

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Abstract. The article analyzes the methods of wireless detonation of underground charges during drilling and blasting operations. The technologies considered are intended mainly for disrupting the integrity of rocks during tunneling and extraction of mineral resources in mines and quarries, as well as for the controlled demolition of buildings. The methods presented in the scientific press do not provide sufficient accuracy of time synchronization between the moment of the explosion and the command to launch the operator of the explosive machine, which is a necessary requirement for seismic exploration, and are also based on the use of magnetic antennas for wireless activation of detonators located at a depth of 30 m. The article, by the authors, on the basis of the analytical solution of equations and computational modeling, considers the physical processes of propagation of electromagnetic fields and currents induced by a grounded electric dipole, which is an alternative method of transmitting radio signals to a linear group of detonators. The most favorable operating frequency range of the channel is also analyzed based on the absorbing properties of the medium.

1. Introduction
The bulk of seismic technologies, using an explosive charge placed in an open hole up to 25 m deep to generate elastic waves in the ground, use wire methods for transmitting an activating signal by removing the contact group from the wellhead [1, 2]. A modification of this method is the connection of a cable to a microwave transceiver, for the organization of partially wireless channels intended for work in quarries when a large area of rocks is undermined [3–7]. Fully wireless channels, with a variety of communication algorithms between the explosive machine and detonators, are based on the method of magnetic communication through loop transmitting antennas of various sizes (from small ones with a diameter of up to 2 m, to large ones covering a large area and covering several wells). Also, to increase the maximum depth of the channel, all known BDZ complexes operate in the VLF (300 Hz - 3 kHz) and ULF (3–30 kHz) ranges [8–19].

In the considered methods of BDZ and wireless signal transmission through continuous conductive media, it is possible to distinguish several technologies:

- Channel with activation by individual number [9–18].

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• Duplex channel using RFID technology and tracking the signal of underground detonators according to the individual frequencies of the recorded signal, the loss of which from the spectrum indicates the successful activation of the charge [8].
• Channel with retransmission of the signal of the explosive machine between detonators under the surface of the earth [19].
• Channel for blasting operations in underground mines, working with a magnetic loop as a radiating antenna, stretched through a closed tunnel located above the place of charge activation [6, 9, 11].

Also known are works in the field of wireless data transmission through rocks for the purpose of general notification of mine personnel, based on long-length radiating antennas located on the surface of the earth or in an underground tunnel, and grounded to the metal structure of the mine. This method of low-frequency communication allows you to provide a large coverage area of the radio channel [20–23].

All presented methods and technologies are not intended for seismic exploration and do not meet the requirements for quality indicators, such as time deviation accuracy. In addition, when operating at low frequencies of 1–8 kHz, the channel has redundancy in the depth of penetration of the EM field into the conductive medium, which is an advantage when working in mines, but is not suitable for shallow ground boreholes with low electrical conductivity compared to ore minerals. Negatively affecting the EM field.

Magnetic loop transmitting antennas are not optimal for activating long line profiles for seismic surveys involving multiple wells. The method of radiation using a long-length electric dipole grounded in the ground, which is actively used for electrical exploration of polymetallic ore deposits near the earth's surface, seems to be more suitable for this purpose. The article investigates the energy potential of transmitting a useful signal through layered media using a grounded dipole, and substantiates the optimal frequency range. The study was carried out taking into account the electrodynamic properties of soils. A comparative analysis of the direct solution of the electrodynamic problem and computational modeling by the finite element method is also implemented.

2. Material and methods

It is customary to determine the properties of soil as a current conductor by its specific electrical resistance $\rho$, or the reciprocal value - electrical conductivity $\sigma$. The value of the resistivity $\rho$ depends on the type of soil, moisture content, the content of alkalis, salts and acids, and temperature. Also, this parameter is influenced by the properties of natural solutions that fill pores and cracks. For example, natural waters, depending on the salts dissolved in them, have a resistance of $0.07–600 \ \Omega\cdot m$.

An increase in the content of dissolved substances in the soil, total moisture content, compaction of its particles, and an increase in temperature (at constant moisture content) lead to a decrease in $\rho$. Soil impregnation with oils and oil, as well as freezing, significantly increase the resistivity index. Because analytical calculation of the factors influencing $\rho$ is an extremely difficult task; obtaining soil parameters remains the result of direct measurements. For the task of assessing the absorbing properties of the medium, it is necessary to estimate the value of the resistivity $\rho$ ($\Omega\cdot m$), according to reference data.

From these data it can be deduced that the bulk of the soils that make up the surface layer have a specific resistance $\rho$ of $1500–10 \ \Omega\cdot m$ and a dielectric constant $\varepsilon \ 10–30$. It should be noted that the most extensive part of the surface salt has a resistance of $500-100 \ \Omega\cdot m$, lower values of this parameter are rare, in the presence of water layers with high salinity, which can occur in the area of wet salt layers, but for most environments, typical such a low total resistivity of rocks is unusual for seismic surveys [23, 24].

Based on considerations of the practical application of the BDZ technology, the most expedient is dipole profiling with a radiating antenna size of the order of several hundred meters, which provides a sufficient penetration depth when operating at higher frequencies and is the optimal length for activating a linear group of borehole detonators.
Structurally, it consists of two long cable lines connected to the transmitter, stretched along the surface of the earth and connected to galvanically grounded electrodes. The electromagnetic field of a long line is formed under the influence of three factors [25]:

- galvanic spreading currents between grounding;
- capacitive currents of the wire line;
- induction currents excited in the ground by the magnetic field of the antenna.

Thus, the resulting electromagnetic field is formed with the participation of currents flowing both in the cable forming the dipole antenna (first component) and in the ground layers above (second component) and below the observation point (third component), which creates a complex structure of the electromagnetic field. To calculate currents and fields, in this case, it is necessary to divide the calculated conducting area into equivalent conductors Δz, through which elementary spreading currents flow.

\[ H = H_0 - \sum_{i=1}^{k_1} H_i + \sum_{i=k_1+1}^{k_2} H_i, \]  

where \( H_0 \) – field induced by current flowing in an antenna \( I \); \( k_1 \) – total number of elementary currents above the observation point \( (Δz - κ_1 ≤ z_1) \); \( k_2 \) – total number of elementary currents under the observation point \( (Δz - κ_2 ≤ z_1 + z) \); \( Δz \) – elementary conductor size; \( z_1 \) – observation point depth; \( z \) – overall depth.

The spreading current density in the Cartesian coordinate system has three components \( j_x, j_y, j_z \). Let us analyze a two-dimensional problem in the XZ plane [26]:

\[ \vec{j}_x = \frac{I}{2\pi} \left[ \frac{x}{(x^2 + y^2 + z^2)^{3/2}} - \frac{(L-x)}{(L-x)^2 + y^2 + z^2)^{3/2}} \right], \] (2)

\[ \vec{j}_z = \frac{I}{2\pi} \left[ \frac{z}{(x^2 + y^2 + z^2)^{3/2}} - \frac{z}{(L-x)^2 + y^2 + z^2)^{3/2}} \right], \] (3)

where \( \vec{I} \) – is current in the cable.

The current element is determined based on the cross-section of the equivalent conductor Δz, into which the computational domain is divided and the current density in this area [26].

\[ J_{i,z} = \frac{\pi d^2}{4}, \] (4)

where \( d \) is the cross-sectional diameter of the equivalent conductor.

The magnetic field of the current element is determined according to the Bio-Savart law [26]:

\[ H_i = \frac{1}{2\pi} \int \frac{dl_i \times \vec{j}}{r_i^3}, \] (5)

where \( dl_i \) – current element length \( \vec{l}_i \); \( \vec{j}_i \) – unit vector of radius vector \( r_i \); \( r_i \) – distance from current element to point \( M \); \( l_i \) – stream line; \( k' \) – the absorption coefficient of the EM field in the rock at the frequency \( f \).

The field of the ground-based current dipole \( H_0 \) is determined according to a different principle (figure 1). A dipole of length \( dl \) and connected to an alternating current source is directed along an arbitrary unit vector \( \vec{d} \). The dipole supplies alternating harmonic current \( I = I_0 e^{-i\omega t} \), with known electrodynamic parameters of the medium \( \sigma, \mu, \varepsilon \). It is necessary to find the value of the field components \( \vec{E} \) and \( \vec{H} \) at any point in space [24].
In the case when the dipole source is directed along the x axis, with a dipole moment \( \mathbf{p} \), the field components are calculated using the expressions [24]:

\[
H_z(x, y, 0) = \frac{ip}{2\pi \sigma \mu_0 r^3} \frac{1}{r} \left[ 3 - e^{ikr} \left( 3 - 3i k r - k^2 r^2 \right) \right] = \frac{3i p \sin(\theta)}{2\pi \sigma \mu_0 r^3} e^{ikr},
\]

\[
E_x(x, y, 0) = \frac{p}{2\pi \sigma r^3} \left( 1 - 3 \frac{y^2}{r^2} + (1 - ik r) e^{ikr} \right),
\]

\[
E_y(x, y, 0) = \frac{p}{2\pi \sigma r^3} \frac{3 x y}{r^2}
\]

where \( \mathbf{p} = i dl \mathbf{d}_k \) – the dipole moment of the current dipole oriented along the x-axis; \( dl \) – dipole length; \( \mathbf{d}_k \) – unit vector indicating x orientation; \( I_o \) – dipole current; \( x, y \) – coordinates; \( k_1 \) – wave number in the medium.

For a longitudinal current dipole, the calculation of the \( H_z \) component of the electromagnetic field in the near field is simplified, since at low frequencies, the distance between the receiving point and the antenna is small in comparison with the wavelength [26]:

\[
H_z = \frac{ip \sin(\theta)}{2\pi \sigma \mu_0 \varepsilon} \frac{1}{r^3} \left( -1 - k^2 r^2 + o(k^2 r^2) \right) \approx \frac{p \sin(\theta)}{4\pi r^2} e^{-kr},
\]

where \( \sin(\theta) = y/r \); \( o(k^2 r^2) \) – contribution of members with a degree higher \( (k r)^2 \).

Using analytical expressions (6, 7), the calculation of the strength of the component of the magnetic field \( H_z \) and the corresponding voltage on the receiver with a ferrite antenna with an effective area of 1 m² was realized. The analysis was carried out for the range of electrical conductivity of the medium \( \sigma = 1E-4 - 1E-1 \) cm/m when emitted by a magnetic and electric dipole without grounding into the ground, and also without taking into account the parameters of radiation efficiency and antenna matching, except for the dipole moment as the main parameter linking the antenna current and its electromagnetic fields.

3. Electric dipole parameters

Wire length (antenna arm) \( dl = 200 \) m; Antenna current \( I_o = 1 \) A.

For reception in a ground borehole, it is advisable to use a compact ferrite antenna designed to register a magnetic field [27]:

\[
U = \omega \cdot \mu_0 \cdot H \cdot S_{EF},
\]

Where \( S_{EF} = \mu_\text{SER} \cdot S_{SER} \cdot n_{PR} = 1 \) m² – effective area of the receiving inductive antenna; \( \mu_\text{SER} = 2000 \) – magnetic permeability of the core; \( S_{SER} = 1.25 \cdot 10^{-7} \) m² – cross-sectional area of the core; \( \mu_0 = 4\pi \cdot 10^{-7} \) H/m – magnetic constant; \( n_{PR} = 4000 \) – the number of turns of the receiving antenna; \( H \) – magnetic field strength.

Calculated estimates of the attenuation of the magnetic field of the dipole antenna at a depth of 30 m indicate a direct dependence of this parameter on the electrical conductivity of the medium (figure 2). At \( \sigma = 1E-4 - 1E-3 \) cm/m, the field level practically does not change with increasing frequency up to 100
kHz. With an electrical conductivity of 1E-2 cm/m, the field strength decreases with increasing frequency to 100 kHz, but the decrease in this parameter is 2.4 times. In this case, the voltage at the receiver rises to a frequency of 40 kHz and stably remains at the same level in the investigated frequency range. With an electrical conductivity of 1E-1 cm/m, the level of the magnetic field decreases by 3 orders of magnitude with increasing frequency. Such parameters of the environment give a maximum voltage at a frequency of 7 kHz, above which this characteristic decreases 22 times at a frequency of 100 kHz. Analysis of the attenuation of the EM field in a homogeneous environment indicates the possibility of using higher frequencies up to 60 kHz for the most difficult cases and up to 100 kHz for driest soils.

![Figure 2. Calculated values of the dependence of the magnetic field strength $H_z$ (a) and the voltage on the receiving antenna $U_z$ (b) on the frequency for an electric dipole.](image)

The need to evaluate the joint propagation and mutual influence of the electric dipole fields and elementary spreading currents in the soil makes the calculation using classical methods a multistage and technically difficult task, due to the need to divide the section of the conducting half-space into many elementary conductors for currents. In addition, this method does not allow assessing the distribution of magnetic fields in space with a sufficiently high accuracy. Solving the problem of the propagation of currents and electromagnetic fields in layered media, typical of surface soils, introduces additional restrictions into the calculation, which complicates the analysis of the interaction of currents and electromagnetic fields in media with many boundaries and different parameters.

For numerical estimates of the propagation of a magnetic field in a layered medium, computational modeling was carried out using the finite element method, which consists in splitting the computational three-dimensional model. In this case, the solution of the differential equations is given, occurs at the nodes of the elements, n which the model is broken down. In each element, an approximating function is additionally applied, the coefficients of which are selected from taking into account the numerical solutions of equations in neighboring elements. The accuracy of the numerical solution of a physical
model depends on the number of such elements and is limited by computing power, however, it gives a higher accuracy of the analysis.

Signal transmission during the simulation was carried out by means of an antenna in the form of an electric dipole with two parts in the form of cable lines stretched from the source in opposite directions and grounded by the ends into a conducting half-space to a depth of 1 m (figure 3 a):

- Length of one arm \( l = 200 \) m.
- Antenna supply voltage \( U = 50 \) V.
- Wire insulation – fluoroplastic.
- Frequency range of research \( f = 1–100 \) kHz.

The calculation of the current flow and the intensity of the EM field is carried out at the nodes of the grid elements, into which the model of soil layers is divided (figure 3 b).

![Figure 3. Design model of a grounded electric dipole and a two-dimensional section of the design model.](image)

The dipole is located in the air above a conductive half-space, imitating a geological section with a known layered structure, numbering 4 layers at the required depth of study of 30 m (figure 3 c). The calculation was carried out for three cases: dry soil (model 1); the top layer of sand moistened by rainwater (model 2); bottom layer of crushed stone moistened with groundwater (model 3). Layer parameters for computational models are shown in table 1.

**Table 1.** Electrodynamic properties of soils that make up the design models.

| Name of soil     | Model 1 | Model 2 | Model 3 |
|------------------|---------|---------|---------|
|                  | \( \sigma, \text{ cm/m} \) | \( \varepsilon_r \) | \( \sigma, \text{ cm/m} \) | \( \varepsilon_r \) | \( \sigma, \text{ cm/m} \) | \( \varepsilon_r \) |
| compacted sand   | \( 5 \times 10^{-4} \) | 6       | \( 5 \times 10^{-2} \) | 20      | \( 5 \times 10^{-4} \) | 6       |
4. Results

When simulating the propagation of the field of a grounded dipole in a layered medium, a calculation was carried out in models of soil media similar in geometric parameters and the parameters of the magnetic field strength at a depth of 30 m were obtained. The most favorable for the propagation of an EM field is model 1, which contains only dry soils. In this case, an 8-fold increase in the magnetic field level is noted with an increase in frequency to 100 kHz, similarly, the voltage at the receiver increases.

For model 2, which is characterized by the presence of two moist layers on the surface, the absorbing properties of the medium increase (figure 4). So, this model is the most difficult case of propagation of EM fields due to the shielding properties of the upper layer, however, with increasing frequency, the magnetic field strength also increases by 2 orders of magnitude when comparing 1 and 100 kHz. The most controversial case is presented by model 3 with the presence of groundwater in the lower layers in the presence of dry sand on the surface. The magnetic field strength for this case reaches its maximum at a frequency of 50–70 kHz, when this range is exceeded, a tendency to a drop in the field strength is noticeable (figure 4).

For model 2, the flow of currents opposite to the currents in the antenna is concentrated in the upper layers of moist soil, which provokes compensation of the antenna field by the field of spreading currents.
(figure 4a, 5). What makes this case the most difficult for EM wave propagation due to its strong shielding properties.

![Figure 5. Distribution of spreading currents in various computational model 2 and the level of the normalized magnetic field.](image)

5. Conclusion
The emitting antenna in the form of a horizontal electric dipole is the most optimized for activating a linear array of detonators widely used in seismic exploration. Analysis of the distribution of magnetic fields in the models shows the inhomogeneity of the distribution of fields and currents in layered media, as well as the different nature of the frequency characteristics. Modeling, in combination with calculated estimates, allows us to conclude that the most favorable frequency range for most surface soils under conditions of high humidity is the 40–80 kHz band. Modeling shows the predominance of the horizontal component of the magnetic field $H_x$, orthogonal to the antenna position. Based on these data, it is recommended to use compact ferrite antennas for signal reception from the surface, located horizontally and orthogonally to each other to receive the dominant field component.

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