Theoretical grounds for the propagation of electromagnetic waves of low-frequency (URL) in low-resistivity rocks

D S Kudinov, O A Maykov, E A Kokhonkova and V V Romanov
Siberian Federal University, 79, Svobodny pr., Krasnoyarsk, 660041, Russia

E-mail: markuss86@mail.ru

Abstract. The article describes and estimates the method of wireless data transmission through rocks using a long dipole antenna, and also describes the effect on the propagation of low-frequency electromagnetic low-resistivity inclusions in the form of non-ferrous metal deposits. Estimates of the methods from other articles and their assessment in the presence of such bodies are given. A numerical analysis of the proposed system was also made for given parameters of the field source and rocks with a special configuration of antennas.

1. Introduction
When developing the reserves of non-ferrous metal ore deposits and other minerals, there are both open methods represented by quarries and closed methods in the form of shafts and mines. In the second case, there is a need to provide personnel with a general alarm system and an individual call. With a constantly changing topology of mine horizons and in order to reduce costs, only the main working and transport horizons are provided with wire methods and microwave channels. Some of the workings are not equipped with communication systems and power lines. To maintain contact between the dispatcher and the miners, it is necessary to use the method of ensuring widespread emergency alarm and an individual call to personal receiving RFID tags. The article will examine the potential of the method of data transmission using electromagnetic waves of low frequency (ULR), which have less attenuation in the conditions of inclusion in the rocks of low-resistance ore minerals with low resistivity. An analysis will also be made of the electrophysical properties of rocks most characteristic of mines for the extraction of copper-zinc ores.

2. The influence of the geological structure of mines and the topology of mine workings on the propagation of electromagnetic waves of very low frequency
The fundamental factor affecting the propagation of EM fields in rocks is their electrical conductivity \( \sigma \), or the inverse of the resistivity \( \rho \). This parameter to a greater extent affects the damping constant \( \alpha \), which also depends on the frequency of the signal and the electrophysical properties of the medium (electrical conductivity, dielectric and magnetic permeability) [1]. This parameter shows the degree of signal attenuation in a medium with distance (figure 1):

\[
\alpha = \omega \sqrt{\frac{\mu \varepsilon}{2}} \left(\sqrt{1 + \tan^2 \delta} - 1\right),
\]

where \( \mu \varepsilon \) and \( \varepsilon \) are the relative magnetic and dielectric permittivities of the medium, respectively; \( \omega = \]
$2\pi f$ is the angular frequency of EM waves propagating through rocks; $tg\delta=\sigma/\omega\varepsilon$ is the dielectric loss tangent; $\sigma$ is the electrical conductivity of the medium.

It must be taken into account that for $tg\delta<<1$, $\alpha\rightarrow0$, nd in the case of $tg\delta>>1$, $\alpha = \sqrt{\frac{\sigma\omega}{\mu}}$ [2].

![Figure 1](image)

**Figure 1.** Dependence of the attenuation parameter on electrical conductivity for various frequencies of the EM field. Frequency step - 2 kHz.

The geology of non-ferrous metal mines is characterized by the porphyry structure of the host rocks, with small crystalline inclusions. Such rock-forming host minerals have low electrical conductivity $\sigma=10^{-3}–10^{-12}$ S/m. Ore bodies include one or more types of ore mineral stacked with a host rock. Most pure ore minerals (galena, pyrite, chalcopyrite, etc.) have ionic conductivity in the range $\sigma=1–10^5$ S/m, however, in ore deposits, these minerals are presented in the form of grains and veins, which reduces the overall electrical conductivity of the deposit [1].

The shape of the ore bodies and the angle of inclination affect the structure of the mine, its length and depth, as well as the propagation of the EM field. Thus, deposits in the form of elongated formations with a small angle of inclination provoke the laying of workings with a large length in one direction, because of which the horizons are not located one under the other, which complicates the installation of communications and covering the mine field. Wide deposits in the form of lenses of various thicknesses have strong shielding properties, since ore minerals absorb the EM field. Typically, the electrical conductivity of ore bodies and host rocks differs by several orders of magnitude, which contributes to the absorption of currents by the reservoir, which excludes their contribution to the formation of a useful signal.

3. Research analyses on methods for wireless data transmission in mines

Wireless methods of data transmission and communication can be divided into high-frequency (HF) and low-frequency (LF). VHF systems are always combined with wired communication methods in the form of a cable connected to transmitting stations operating in direct visibility zones; instead of such stations, radiating cables in the form of a feeder antenna located along the tunnel can be used. In this direction, the most famous company is the PBE Group, USA-Canada (M Farjow W) [3, 4].

Among the low-frequency systems for transmitting data through rocks (Through-the-Earth Communications), near-field magnetic communications operating in the range of 30–100 kHz are distinguished. The communication channel is implemented using a pair of magnetic frames with current or coils (transmitting and receiving antennas) mounted on the surface of the earth and in the mine tunnel. According to the studies [5, 6], with a transmitter power of 7–10 kW, the device reaches a signal transmission range of 300 m through the rock mass. This type of communication channel is designed for installation in control centers on the surface and in mine workings, as the transmitter and receiver have large overall dimensions.
In this area, the results of works published in one of the last articles, where a group of scientists analyzed the propagation of EM signals in the frequency range 400 Hz - 9 kHz are also of interest [7]. The article analyzes the propagation of waves of this frequency range in the presence of long metal structures (rails, long beams, metal pipes), which allowed to increase the distribution range of the useful signal in the mines.

The article [8] presents an analysis of the propagation of natural noise electric and seismic fields in rocks. An analysis of the measurements shows that the intensity and amplitude of these noise fields is negligible to act as intense noise interference fields when registering a useful signal.

A wide range of scientific research and scientific and technological developments in the field of mine communication systems operating in various ranges (from 300 Hz to 10 MHz) and presented in the scientific press confirms the significance of this research area.

4. Model of EM field propagation in rocks

To reduce the effect of the shielding properties of ore deposits, the quality of the radiating antenna is estimated using an electric dipole, one end of which is grounded on the surface of the earth (grounding 1), the other end is laid along the mine shaft and the mine, where it is grounded (grounding 2). This type of emitter covers a large space of the mine field underground and allows the signal to spread both from top to bottom and in the workings between deposits [8, 9]. Analyze the electromagnetic field of the antenna in the form of a cable of length \( L \) and current \( J \), which is visually divided into 2 parts (figure 2). The model is one end of the antenna with grounding 1 at point 0 (0,0), the other end with grounding 2 at point 1 \((x_1, z_1)\). The RFID tag with the receiving antenna is located at point \( M(x_3, z_3) \). In the presence of ore bodies with a large electrical conductivity \( \sigma_2 \), which differs from the electrical conductivity of the host rocks by 3-5 orders of magnitude, the current flowing between the groundings is not taken into account as an EM field source, since it is localized in the deposit.

The calculation can be performed both in the space of the host rocks with approximately homogeneous electrodynamic parameters, and with the presence of an ore body represented as a sphere with electric conductivity \( \sigma_2 \) of the ore body centered at point \( S(x_2, z_2) \), in this case, at the first stage, it is calculated the field between the grounding points and the sphere at a distance \( r_1 \) and \( r_2 \), in the second stage, the intensity of the secondary field created by the sphere from the ore body at a distance \( r_3 \) between the center of the sphere \( S \) and the measurement point \( M \) is calculated.

Figure 2. Model for calculating the field intensity at the measurement point in the presence of an ore body.

The electric field of the antenna grounding points at point \( M \) under the condition of homogeneous enclosing rocks is calculated through the formula [2] (Figure 3):

\[
E_x = \frac{J}{\sigma_1 2\pi} \cdot \left( \frac{x_3}{r_1^3} \pm \frac{x_1 - x_3}{r_2^3} \right) \cdot e^{-\alpha_1 r_1} \cdot e^{-\alpha_1 r_2},
\]

(2)

where \( J \) – antenna current; \( \sigma_1 = 10^{-3} \) – electrical conductivity of the host rocks; \( x_1 \) – the distance from 0 to ground point 1 along the x axis; \( x_3 \) – distance from 0 to the measurement point along the x axis; \( r_1, r_2 \) – distance between the ground points and the measurement point.
The distance between the grounding 1, 2 and the measuring point is calculated from the expression:

\[ r_1 = \sqrt{(x_0 - x_2)^2 + (z_0 - z_2)^2}, \quad r_2 = \sqrt{(x_1 - x_2)^2 + (z_1 - z_2)^2}, \]  

(3)

Figure 3. Dependence of the electric field intensity of the antenna grounding on the distance at J=16 A, \( \sigma_1=10^{-3} \) S/m, f=1000 Hz, grounding 1(0, 0), grounding 2(1000, 800).

The highest level of electric field intensity observed in the area of the antenna grounding, with increasing distance, the \( E_x \) intensity decreases exponentially under the influence of scattering and attenuation in the rocks.

An electromagnetic field with the presence of a deposit is calculated by a two-stage method. At the location of the deposit \( S(x_2, z_2) \), it is necessary to calculate the electric field intensity \( E_x \) radiated by the antenna ground [2].

\[ E_x = \frac{J}{\sigma_1 2\pi} \left( \frac{x_2 \pm x_1 - x_2}{r_1^3} \right) \cdot e^{-\alpha_1 r_1} \cdot e^{-\alpha_1 r_2} \]

To determine the secondary electric field emitted by the reservoir, the dipole moment of the reservoir is determined [2]:

\[ P = \frac{-2\pi E_x \cdot e^{-\alpha_2 R}}{\rho_1}, \]

\[ K_{ot} = \frac{\rho_2 - \rho_1}{2\rho_2 + \rho_1}, \]  

(6)  

(7)

where \( R \) – the radius of the sphere from the ore body; \( K_{om} \) – the reflection coefficient; \( \alpha_2 \) – M field attenuation coefficient for a sphere from an ore body with \( \sigma_2 \); \( \rho_1, \rho_2 \) – electrical resistivity of the host rock and ore body, respectively.

Since the sphere has an electrical conductivity exceeding this parameter of the host rocks by 3-5 orders of magnitude, the main contribution to the attenuation \( \alpha_2 \) is made precisely by the parameter \( \sigma_2 \) and the radius of the sphere \( R \), which correlates with the size of the ore deposit located between the emitter and the measurement point. The intensity of the magnetic and electric fields at the measuring point M is determined by the formulas [2]:
The calculation of the voltage at the output of the antenna at the measurement point is made according to the formula [9]:

\[ U_x = \omega \cdot \mu_0 \cdot H_x \cdot S_{\text{ef}}, \]  

\[ r_3 = \sqrt{(x_2 - x_3)^2 + (z_2 - z_3)^2}. \]

The calculation of the voltage at the output of the antenna at the measurement point is made according to the formula [9]:

\[ U_j = \omega \cdot \mu_0 \cdot H_j \cdot S_{\text{ef}}, \]  

where \( S_{\text{ef}} = \mu_{\text{cpr}} \cdot S_{\text{cpr}} \cdot n_p = 4 \text{ m}^2 \) – effective area of the receiving antenna; \( \mu_{\text{cpr}} \) – magnetic permeability of the core; \( S_{\text{cpr}} \) – the cross-sectional area of the core; \( \mu_0 = 4\pi \cdot 10^{-7} \text{ Гн/м} \) – magnetic constant; \( n_p \) – the number of turns of the receiving antenna; \( H_j \) – magnetic field intensity.

In addition to the EM grounding field \( E_x \), the field of the cable itself with the current \( J \) forming the transmitting antenna is induced on the RFID antenna. Since the presented antenna has a bend at the transition point between the shaft of the mine and the beginning of the mine and in the workings themselves, when calculating each cable is divided into 2 segments, the field of which is calculated at the measurement point and summed with the ground field. The magnetic of each part of the cable and the voltage at the output of the receiving antenna is calculated using the formulas [10]:

\[ H_M^x = \frac{p}{4\pi r_3^3} \cdot e^{-a_1 r_3}, E_M^x = \frac{2\rho_p p}{4\pi r_3^3} e^{-a_1 r_3}, \]  

\[ r_3 = \sqrt{(x_2 - x_3)^2 + (z_2 - z_3)^2}. \]  

\[ H_1^y = \frac{J}{2\pi \tau_{k1}} \cdot e^{-a_1 \tau_{k1}}, H_2^y = \frac{J}{2\pi \tau_{k2}} e^{-a_1 \tau_{k2}}, \]

\[ U_1 = \omega \cdot \mu_0 \cdot H_1 \cdot S_{\text{ef}}, \quad U_2 = \omega \cdot \mu_0 \cdot H_2 \cdot S_{\text{ef}}, \]

where \( \tau_{k1}, \tau_{k2} \) – distance between current cable and measuring point \( M \).

The magnetic field of the cable, as well as the grounding field, is also subjected to extremely strong attenuation in the environment of the host rocks and ore bodies located on the propagation paths, which should be taken into account when installing this type of system. Figure 3 shows the distribution of the magnetic field of the cable forming the radiating antenna in a homogeneous environment of the enclosing rocks. This type of radiation is characterized by a decrease in the magnetic field at the ends of the radiating cable, as well as its exponential decrease with distance under the influence of the attenuation parameter in the medium.

![Figure 3](image)

5. Conclusion

From the above, it can be concluded that the installation of TTE systems of the presented type should be carried out individually for each type of mine, in order to take into account the shielding properties of elongated and lenticular deposits and cover the largest part of the mine field, as the magnetic field of the cable with a current covers the sections of the mine, shielded from the ground field. In addition to the location of the deposits, it is necessary to take into account their mineral composition, which

\[ \sigma_1 = 10^{-3} \text{ S/m}, \quad f = 1000 \text{ Hz}, \quad \text{grounding } 1(0, 0), \quad \text{grounding } 2(1000, 800): \]

\[ a \] – field of the first cable segment; \( b \) – field of the second cable segment.
determines their electrophysical properties and the attenuation parameter. A small signal-to-noise ratio caused by absorption of a useful signal by an ore body can be partially increased by several approaches:

- use of different configurations of the radiating antenna;
- lowering the operating frequency of the data transmission system, since the attenuation parameter is highly dependent on this parameter;
- application of modulation methods (PSK) that are more effective in low-signal conditions;
- increase in the accumulation time of the useful signal;
- increase in transmitter power.

Acknowledgements
The reported study was supported by grant of the Russian Science Foundation (project No. 18-79-00137).

References
[1] Physical properties of rocks and minerals (petrophysics): Geophysics Reference ed N B Dortman 1948 (Moscow:Nedra) p 455
[2] Zhdanov M S 1986 Electrical Intelligence: Textbook for High Schools (Moscow:Nedra) p 316
[3] Kamruzzaman S M, Fernando X, Jaseemuddin M and Farjow W 2017 Reliable communication network for emergency response and disaster management in underground mines Smart Technologies for Emergency Response and Disaster Management pp 42-84
[4] Farjow W, Raahemifar K and Fernando X 2015 Novel wireless channels characterization model for underground mines Applied Mathematical Modelling 39(19) 5997-6007
[5] Lin S-C, Alshehri A A, Wang P and Akyildiz I F 2017 Magnetic Induction-Based Localization in Randomly Deployed Wireless Underground Sensor Networks IEEE Internet of Things J. 4(5) 7986987 1454-65
[6] Akyildiz I F, Wang P and Sun Z 2015 Realizing underwater communication through magnetic induction IEEE Communications Magazine 53(11) 7321970 42-8
[7] Ralchenko M, Roper M, Samson C and Svilans M 2016 Coupling of very low frequency electromagnetic signals to long man-made conductors SEG Technical Program Expanded Abstracts pp 2154–58
[8] Potylitsyn V, Kudinov D, Shaidurov G, Kokhonkova E and Romanov V 2019 Analysis of the frequency-time characteristics of seismic and electromagnetic fields over a gas condensate field 24th European Meeting of Environmental and Engineering Geophysics (Sept 2018)
[9] Bova N T and Reznikov G B 1982 Antennas and microwave devices (Kiev:Vyshshaya Shkola)
[10] Khomich V I 1963 Ferrite Receiving Antennas:Textbook (Moscow)