



Electromagnetic system for detection and localization of the miners caught by accident in mine

Vira Pronenko, Fedir Dudkin

Lviv Centre of Institute for Space Research, Lviv, 79060, Ukraine

5 *Correspondence to:* Vira Pronenko (pron@isr.lviv.ua)

Abstract. The profession of a miner is one of the most dangerous in the world. Among the main causes of the fatalities in the underground coal mines is the untimely alerting of the accident, as well as the lack of information for the rescuers about the actual location of the miners after the accident. In an emergency situation (failure or destruction of underground infrastructure), personnel search behind and beneath of blockage should be provided urgently. But none of the standard technologies (RFID, DECT, WiFi, emitting cable), which use the stationary technical devices in mines, provides the information about the people location caught by accident with necessary precision. The only technology that is able to provide guaranteed delivery of messages about the accident to the mine personnel, regardless of their location and under any destruction in the mine, is low-frequency radio technology able to operate through the thickness of rocks even if it is wet. The proposed new system for miners localization is based on solving the inverse problem that allows the magnetic field source coordinates determining using the data of magnetic field measurements. This approach is based on the measurement of the magnetic field radiated by the miner's responder beacon using two fixed and spaced three-component magnetic field receivers and next the inverse problem solution. As a result, the working model of the system for miner's beacon search and localization (MILES - miner's location emergency system) was developed and successfully tested. The paper presents the peculiarities of this development and the results of experimental tests.

20 **1 Introduction**

The coal mine is a complex engineering structure with hazardous working conditions where sudden changes in geological conditions, combined with abnormal operating conditions, the lack of appropriate control equipment and safety violations, may lead to accidents with serious consequences.

25 As the examples, in Ukraine 3120 people are injured for the period 1994-2003. In Russia 1822 persons are fatally injured for the same period. China is the absolute leader in the number of accidents in the mines. Despite the fact that it owns about 35% of world coal production, the number of accidents with fatalities is more than 80% of the world total amount (Xiaohui and Xueli, 2004). In US mines 36 people were killed in 2012 (Mineweb, 2016).

Among the main causes of the fatalities in the underground coal mining enterprises is untimely alerting of rescue team about the accident, as well as the lack of information for the rescuers about the actual location of the miners after the accident.



There are standard technologies for transmission of information, communication, scheduling and monitoring of staff, which use the stationary technical devices in mines, such as DECT, WiFi, emitting cable etc. But after the accidents the underground infrastructure destruction happens practically always. In these cases the most efficient system for the search and detection of people across a massive layer of rock is the low-frequency electromagnetic (EM) system. Such systems are under development almost half a century in many countries dealing with mine industry (Hill and Wait, 1974; Powell, 1976; Lagace et al., 1980; Curry et al., 1984; Webb et al., 1984; Pittman et al, 1985). As the most known examples of the available EM systems a GLON – GLOP and GLOP2 systems produced in Poland may be mentioned. It is claimed that it can detect and localize the miner at the distance up to 25 meters. But the results of laboratory tests of more advanced GLOP2 system (Burnos and Gajda, 2010), show that, starting from a distance of 12 m, the error in determining the distance to the beacon sharply increases and reaches ± 3 m at 16 m when the beacon orientation is known, otherwise, this error can reach 26%. Another example is L-3 Location Tracking System for Underground Coal Mines (www.ingortech.ru) designed in 2007-2009 by L-3 Global Security & Engineering Solutions (US). This system operates at high frequencies; due to this the system does not have the required distance determination range while working through the layer of wet rock. Finally, Helian system which is developed by Mine Radio Systems Inc., Canada (Farjow, 2010) is claimed to be operable up to 25 m. But any information about the error of target localization is not available.

The main problem at the development of such systems is that, as measurements show, the conductivity of rocks in various coal mines can range 5 orders of magnitude - from 10^{-5} (dry mines) to 1 S/m (mines in the saturated by salt solution rock) (McNeill, 1980; Durkin, 1984; Ishankuliev, 2007). If for dry mines the mentioned systems may operate more or less reliably, in wet mines with high conductivity of the medium (0.01 - 1 S / m), as our short survey shows, no substantial progress related to the localization of personnel at a distance at least of 20-30 meters through the rock is reached till now.

The task of our study was to develop a system which can reliably operate in the highest range of environment conductivities 0.01 - 1 S/m with the error no more than maximally allowable ~ 2 meters.

2 Estimation of the system main parameters with the environment conductivities 0.01 - 1 S/m

For the magnetic dipole with given magnetic moment it is rather easy to determine the parameters of the electromagnetic radiation at any distance. But the solution of inverse problem - to determine the distance to the miner equipped with the EM beacon using a rescue team search facility allowing measurements of parameters of the magnetic field created by this beacon - is connected with important difficulties (Kalashnikov et al., 1980, Hill and Wait, 1974). The main idea of the proposed method is to arrange the rescue team instrumentation in such a way that it would be possible to collect as much information as possible to find the miner's location with allowed error – no more than 2 meters at a distance at least of 20-30 meters. The calculations showed that for this the measurements of the magnetic field created by the beacon necessary to carry out at least in two points with known distance between them. Basing on this, it is proposed to construct a system which includes miner's beacon (MB) having both transmitter and receiver to switch on the transmitter by a command to save energy, and rescue team (RT) equipment consisting from transmitter to switch on MB and receiver allowing to get MB signal passed through



the rock with given conductivity. By this, the RT receiver has to measure all three components of EM signals transmitted by MB minimum in two points. The detailed description of such a system is given below; here we describe the mathematical fundamentals of its operation algorithm.

First problem is to create the MB as a field source which parameters are independent on the parameters of the environment at the low frequencies. For this, the coil with maximum possible size and minimum cross section of the winding (such as hoop) is the most appropriated. Its field source is well described within the magnetic dipole approximation at distances greater than 3 - 5 of its linear dimensions. Due to the low-frequency approach, the electric field component for the required distance about 30 meters is very small and can be neglected. Magnetic field components of such source in Cartesian coordinate system x, y, z are described by expressions (Dudkin and Kalashnikov, 1986):

$$|B_x| = |B_r|xr^{-1} + |B_\theta|xz\left(r(x^2 + y^2)^{0.5}\right)^{-1},$$

$$|B_y| = |B_r|yr^{-1} + |B_\theta|yz\left(r(x^2 + y^2)^{0.5}\right)^{-1},$$

$$|B_z| = |B_r|zr^{-1} - |B_\theta|(x^2 + y^2)^{0.5}r^{-1},$$

$$\text{where } |B_r| = \mu_0 Mz(2\pi r^4)^{-1} AC, \quad |B_\theta| = \mu_0 M(x^2 + y^2)^{0.5}(4\pi r^4)^{-1} BC, \quad A = (1 + 2^{0.5}|kr| + |kr|^2)^{0.5},$$

$$B = (1 + 2^{0.5}|kr| + |kr|^2 + 2^{0.5}|kr|^3 + |kr|^4)^{0.5}, \quad C = \exp(-2^{-0.5}|kr|), \quad |k| = (\omega\mu_0\sigma)^{0.5}, \quad r = (x^2 + y^2 + z^2)^{0.5},$$

$M=IS$, I – current in the coil, S – equivalent area of the coil, $\mu_0 = 4\pi 10^{-7}$ H/m; $|k|$ – wave number module, $\omega=2\pi f$, f – frequency, σ – specific electrical conductivity of the medium.

From these expressions it follows that the wave processes in an environment with high losses are absent (because of the strong exponential decay), that is, the field is practically damped at a distance comparable to the theoretical wavelength $\lambda=2^{1.5}\pi/|k|$. Therefore, the choice of the system operating frequency range should be limited by the condition of a near $|kr| \ll 1$ or intermediate $|kr| \sim 1$ radiation zones (Dudkin, Kalashnikov, 1986).

Next important factor is the right choice of the field source radiation pattern in order to make possible the field source detection regardless of its orientation. For this it is necessary to form a spherical radiation pattern of a magnetic dipole source in the conductive medium. The condition for this is $|kr| \approx 1.87$ (Kalashnikov et al., 1980). This makes possible to detect the field source regardless of its orientation in the worst case (in the upper part of the frequency range or higher medium conductivity).

From the considerations of the convenience of the MB arrangement in the standard miner's equipment (for example, inside a lamp battery housing) the field source was selected as a circular loop with a diameter of 0.2 m. The shape of the magnetic field modulus at the required maximal distance of 30m from the field source depending on the weight of coil m , consumed



power W , and the conductivity of the medium σ (for the angle $\theta = 90^\circ$ between the coil axis and the radius vector drawn from the reception point to the geometric center of the coil) is shown in Figure 1. Figure 2 presents the directional pattern of this circular loop with a diameter of 0.2 m and power dissipation 3 W for the distance of 30 m depending on the conductivity of the medium and operation frequency. From these considerations we may select the optimal operating frequency which

5 allows obtaining the isotropic field source radiation pattern, even in the case when the exponential decay factor in the medium begins to affect. It should be noted that in the case of the increase of conductivity of the rock, the magnetic field is sharply attenuated with frequency increase and the field source radiation pattern will change in an undesirable way (the maximum to minimum ratio of the field module will increase). Namely these two causes – signal decay and non-isotropic pattern of field source in the reception point – are the factors which limit the detection distance and localization precision.

10 These considerations allowed selecting the operation frequency for higher available conductivity values equal to 500 Hz. So, these calculations allowed us to solve the most important task - to select the parameters of the MB transmitter. According to the system description given above, the system should include also RT equipment, containing transmitter and two-points receiver. The following main parameters of these units were determined from practical considerations and modeling results:

- MB transmitter or field source: coil with weight ~ 200 g, diameter ~ 20 cm, power consumption ~ 3 W;
- 15 • MB receiver to switch on the transmitter at RT signal – one component induction magnetometer with a length of 4-5 cm and the noise spectral density of not less than $0.25\text{-}0.4$ pT / Hz $^{0.5}$;
- RT transmitting coil to switch on the MB transmitter: three-component induction magnetometer, weight ~ 9 kg, diameter ~ 0.5 m, power consumption ~ 20 W;
- RT receiver to measure the MB signals in two points- two three-components receivers including six induction
- 20 magnetometers with a length of 20 cm each and noise spectral density of 0.05 pT / Hz $^{0.5}$.

An operation algorithm using these equations was developed and the corresponding software in MathLab environment was compiled.

3 Description of the system for miners beacon search and localization

For the experimental verification and testing of the proposed operation algorithm, the model of the system for miner's

25 beacon search and localization was designed and manufactured. A geometry of the problem solution is clear from the functional diagram of the corresponding equipment - miners location emergency system (MILES) - presented in Figure 3.

The system operates as follows. Rescue team instrumentation (RTI) triggers the rescue team coil (RTC) which sends a code sequence of pulses within 20 seconds to switch on the miner's responder beacon (MRB) which has a personal code number and then switches off. This signal is received by miner's sensor (MS), amplified, decoded and then it is processed by the

30 microcontroller. In the case of coincidence of the code sequence microcontroller switches the miner's transmitting coil (MC) which sends a signal for 20 seconds and then turns off. This signal is received by RTI which has two 3-components rescue team sensors RTS-1 and RTS-2, placed at known distance relatively each other, amplified, digitized and processed by the



computer using the specially developed software. The calculated coordinates and the position of the MRB are shown at a display. To minimize the error, this procedure may be repeated several times. Then, this cycle is repeated for the MRB with the next number.

MILES equipment works with two operating frequencies: in the mine with usual conditions (dry or wet rock, soaked by fresh water) - in the region of 10 kHz; in the mine with rock soaked with salt solutions the lower operating frequency (500 Hz) should be selected. The main parameters of MB prototype are given in Table 1 and RT instrumentation prototype main parameters are given in Table 2.

4 Results of MILES testing

4.1 MILES testing in a bomb shelter

The test was performed in the bomb shelter on the territory of Kyiv Radio Plant, Kyiv, Ukraine. Two types of tests were made: measurements in the bomb shelter in terms of direct and indirect visibility, and measurements in terms of complete invisibility through a layer of concrete, ferroconcrete, and soil. In the first case, MB was located at a distance of up to 40 m in terms of direct and indirect visibility and in the next room behind the concrete walls. In the second case rescue team instrumentation was installed inside the bomb shelter while the MB was at the surface at distances of 10-70 m. The thickness of the soil and bomb shelter ceiling is approximately 5 m.

The tests of the system showed that even under extremely high level of electromagnetic interference existing in working plant and inside the room with a lot of ferromagnetic objects which were shielding the signal from the miner's responder beacon, system reliably recorded the alarm signal at a distance no less than 50 meters for a single measurement. In order to investigate how the precision will be increased with statistical averaging, a set of ten measurements were made in each location. The final results showed that the errors of the distance determination and of the MB position location were both in the limit about 1 - 1.5 meters in every case – for single and ten-fold procedures. More repetitions were not used because of time limitations of real procedure – it is no possible to spend too much time for the measurements in real rescue conditions when time is very important factor.

4.2 Miner's location emergency system testing in a cave

The test was performed in the cave complex, located to the north of the city Mykolayiv, Lviv region, Ukraine in a natural landmark Bold Mountain. Caves plan is shown in Figure 4, where RT sensors locations are marked in blue, MB locations marked in red and numbered correspondently to a number of the experiment.

The testing result showed that the proposed system allows reliable recording of the signal from the miner's responder beacon for distances up to 44 m through the soil and detecting its location with an error about ~2 m for the furthest position 12 (see Figure 4). Again, both single measurements and ten-fold cycles were used with comparable results.

5 Conclusion



A new approach, based on the radiated by the MB magnetic field measurements by two fixed and spaced RT three-component magnetic field receivers and solution of the inverse problem using these measurements results, was proposed and the concept of the MILES equipment for MB search and localization were developed.

Laboratory test results showed that, even under extremely high level of electromagnetic interference and in the presence of
5 large ferromagnetic objects between the MB and the RT equipment, the MILES reliably records signal from the MB at a distance up to 70 m and can detect and localize MB at a distance up to 40 m with an admissible error.

This system may be also proposed to use for RT members tracking when they are clearing the blockage, ruinous buildings after the explosions, earthquakes etc.

So, after the preliminary tests described above it may be concluded that solving the problem of the detection and localization
10 of the MB position through the rock with several tens of meters thickness is possible using the low-frequency magnetic field transmitter – receiver system and inverse problem solution. Surely, final conclusion about MILES efficiency and resolution may be drawn only after the real tests in the natural conditions of wet mines. This is the task of further research.

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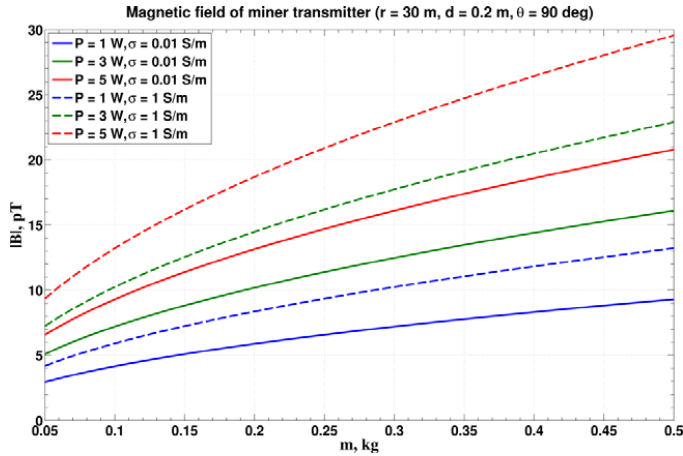
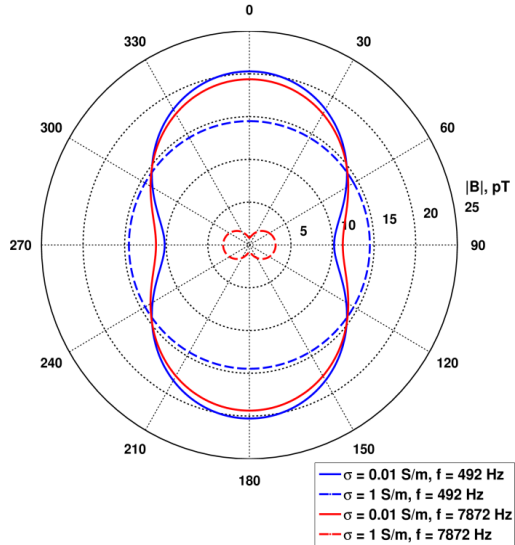


Figure 1: The magnetic field modulus at a distance of 30m from the field source (circular loop with a diameter of 0.2 m) depending on the weight of coil m , consumed power W , and the conductivity of the medium σ .

Directional pattern of magnetic antenna in conducting medium ($r = 30$ m, $d = 0.2$ m, $m = 0.2$ kg, $P = 3$ W)



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Figure 2: The directional pattern of the circular loop with a diameter of 0.2 m and power dissipation 3 W for the distance of 30 m depending on the conductivity σ and operation frequency f .

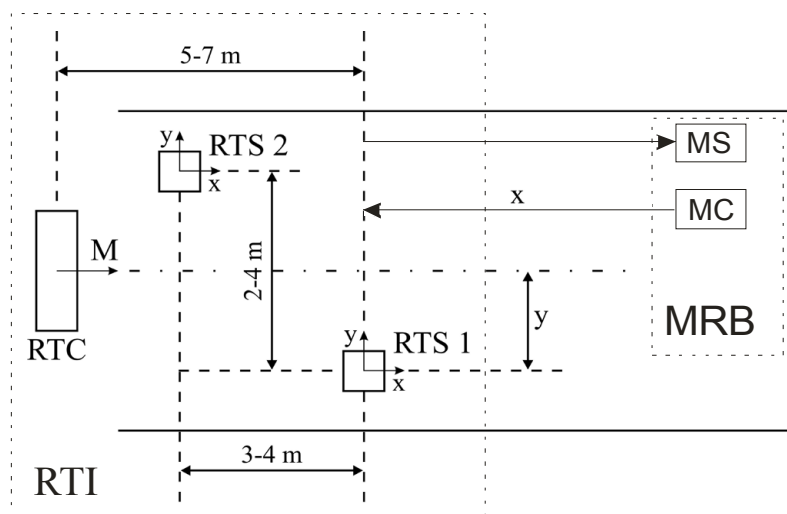


Figure 3: Miner's location emergency system functional diagram.

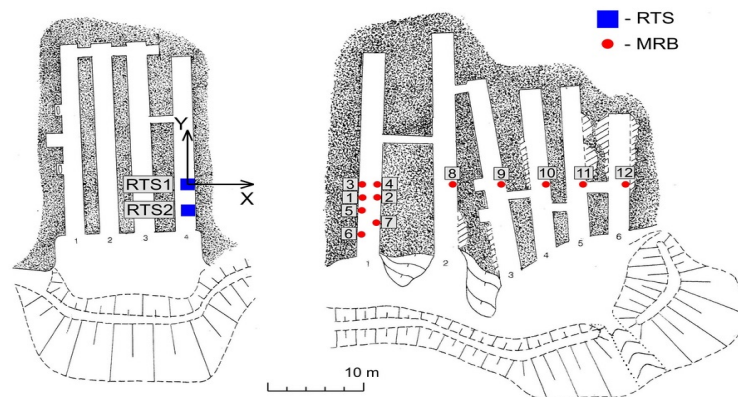


Figure 4: Caves plan.

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Table 1: Main parameters of miner's responder beacon prototype.

Miner's transmitting coil	
Antenna type	loop
Power consumption	3 W
Dimensions	150 x 100 x 30 mm
Weight	300 g
Miner's sensor	
Number of measured magnetic field components	1
Transformation coefficient for the central frequency	540 mV/nT
Magnetic noise level for the central frequency	$\leq 30 \text{ fT} \times \text{Hz}^{-1/2}$
Supply voltage	+(3.4 ÷ 4.5) V
Current consumption	3 mA
Operation temperature range	-10° ÷ +50°C
Dimensions	80 × Ø10 mm
Weight	50 g

Table 2: Main parameters of rescue team instrumentation prototype.

Rescue team transmitting coil	
Antenna type	loop
Power consumption	20 W
Dimensions	500 x 500 x 110 mm
Weight	3 kg
Rescue team sensors (2 pieces)	
Number of measured magnetic field components	3
Transformation coefficient for the central frequency	540 mV/nT
Magnetic noise level for the central frequency	$\leq 20 \text{ fT} \times \text{Hz}^{-1/2}$
Supply voltage	+(3.4 ÷ 4.5) V
Current consumption	15 mA
Operation temperature range	-10° ÷ +50°C
Dimensions of the one sensor	145 × Ø15 mm
Weight	200 g