Geosci. Instrum. Method. Data Syst., 5, 561–566, 2016
www.geosci-instrum-method-data-syst.net/5/561/2016/
doi:10.5194/gi-5-561-2016

Geoscientific Instrumentation Methods and Data Systems
Open Access

Electromagnetic system for detection and localization of miners caught in mine accidents

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Received: 29 June 2016 – Published in Geosci. Instrum. Method. Data Syst. Discuss.: 2 August 2016
Revised: 7 November 2016 – Accepted: 9 November 2016 – Published: 9 December 2016

Abstract. The profession of a miner is one of the most dangerous in the world. Among the main causes of fatalities in underground coal mines are the delayed alert of the accident and the lack of information regarding the actual location of the miners after the accident. In an emergency situation (failure or destruction of underground infrastructure), personnel search behind and beneath blockage needs to be performed urgently. However, none of the standard technologies – radio-frequency identification (RFID), Digital Enhanced Cordless Telecommunications (DECT), Wi-Fi, emitting cables, which use the stationary technical devices in mines – provide information about the miners location with the necessary precision. The only technology that is able to provide guaranteed delivery of messages to mine personnel, regardless of their location and under any destruction in the mine, is low-frequency radio technology, which is able to operate through the thickness of rocks even if they are wet. The proposed new system for miner localization is based on solving the inverse problem of determining the magnetic field source coordinates 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 the inverse problem solution. As a result, a working model of the system for miner's beacon search and localization (MILES – MIner's Location Emergency System) was developed and successfully tested. This paper presents the most important aspects of this development and the results of experimental tests.

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.

As an example, in Ukraine, 3120 people were injured from 1994 to 2003. In Russia, 1822 people were fatally injured during the same period. China has the highest number of accidents in 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 (Xiaohui and Xueli, 2004). In US mines, 36 people were killed in 2012 (Mineweb, 2016).

Among the main causes of fatalities in underground coal mining enterprises are the untimely alert of rescue teams and the lack of information concerning the actual location of the miners after the accident. There are standard technologies for transmitting information, communicating, scheduling and monitoring staff. These technologies use the stationary technical devices in mines, such as DECT, Wi-Fi, emitting cable, etc., but there is almost always underground infrastructure destruction after an accident. In these cases the most efficient system for detecting people behind a massive layer of rock is the low-frequency electromagnetic (EM) system. Such systems have been under development for almost half a century in many countries with mining industry (Hill and Wait, 1974; Powell, 1976; Lagace et al., 1980; Curry et al., 1984; Webb et al., 1984; Pittman Jr. et al., 1985). As the most well-known examples of the available EM systems, the GLON–GLOP and GLOP2 systems produced in Poland are mentioned. It is claimed that they can detect and localize the miner at a distance of up to 25 m. However, the re-

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sults of laboratory tests of the 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 at 16 m when the beacon orientation is known; otherwise, this error can reach 26 %. Another example is the 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; therefore, the system does not have the required distance determination range while working through the layer of wet rock. Finally, Helian Underground safety system, which is developed by Mine Radio Systems Inc., Canada (Farjow, 2010), is claimed to be operable up to 25 m. However, no information about the error of target localization is available.

The main problem in 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 $1\,\mathrm{S\,m^{-1}}$ (mines in rock saturated by salt solution) (McNeill, 1980; Durkin, 1984; Ishankuliev, 2007). Although the systems mentioned operate more or less reliably in dry mines, in wet mines with high conductivity of the medium (0.01–$1\,\mathrm{S\,m^{-1}}$) no substantial progress related to the localization of personnel at a distance of at least 20–30 m through rock has been reached until now, as our short survey shows.

The aim of our study was to develop a system that can reliably operate in the highest range of environment conductivities, 0.01–$1\,\mathrm{S\,m^{-1}}$, with an error of no more than the maximally allowable ~ 2 m.

1.1 Estimation of the system's main parameters with environment conductivities of 0.01–1 $\mathrm{S\,m^{-1}}$

For the magnetic dipole with given magnetic moment, it is rather easy to determine the parameters of the electromagnetic radiation at any distance. However, the solution of the inverse problem – to determine the distance to the miner equipped with the EM beacon using a rescue team search facility allowing measurements of the parameters of the magnetic field created by the beacon – has significant 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, which is no more than 2 m at a distance of at least of 20–30 m. The calculations showed that the measurements of the magnetic field created by the beacon needed at least two points with a known distance between them in order to be carried out. Based on this, a system has been proposed that includes a miner's responder beacon (MRB) that has both a transmitter and a receiver to switch on the transmitter with a command to save energy. The system also includes rescue team instrumentation (RTI) consisting of a transmitter to switch on the MRB and a receiver allowing the MRB signal to pass through rock with any given conductivity. This way the RTI receiver has to measure all three components of the EM signals transmitted by the MRB minimum at two points. The detailed description of such a system is given below; here we describe the mathematical fundamentals of its operational algorithm.

The first problem is to create the MRB as a field source whose parameters are independent of the parameters of the environment at low frequencies. For this, the coil with maximum possible size and minimum cross section of the winding (such as a hoop) is the most appropriate. The coil's field source is well described within the magnetic dipole approximation at distances 3–5 times greater than its diameter. Due to the low-frequency approach, the electric field component for the required distance, about 30 m, is very small and can be neglected. Magnetic field components of such sources in Cartesian coordinate system x, y, z are described by the following expressions (Dudkin and Kalashnikov, 1986):

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

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

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

where

$$|B_\mathrm{r}| = \mu_0 M\,z\left(2\pi r^4\right)^{-1} A\,C,$$

$$|B_\theta| = \mu_0 M\left(x^2+y^2\right)^{0.5}\left(4\pi r^4\right)^{-1} B\,C,$$

$$A = \left(1+2^{0.5}\,|kr|+|kr|^2\right)^{0.5},$$

$$B = \left(1+2^{0.5}\,|kr|+|kr|^2+2^{0.5}|kr|^3+|kr|^4\right)^{0.5},$$

$$C = \exp\left(-2^{-0.5}\,|kr|\right), \quad |k| = (\omega\mu_0\sigma)^{0.5},$$

$$r = \left(x^2+y^2+z^2\right)^{0.5},$$

where $M = I\,S$, I is current in the coil, S is equivalent area of the coil, $\mu_0 = 4\pi\,10^{-7}\,\mathrm{H\,m^{-1}}$, $|k|$ is wave number module, $\omega = 2\pi f$, f is frequency and σ is 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 system operating frequency range should be limited by the condition of close $|kr| \ll 1$ or intermediate $|kr| \sim 1$ radiation zones (Dudkin and Kalashnikov, 1986).

The next important factor is the choice of field source radiation pattern in order to make field source detection possible regardless of its orientation. In order to do 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 it possible to detect the field source regardless of its orientation in the worst case scenario (in the upper part of the frequency range or higher medium conductivity).

Considering the convenience of the MRB 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 30 m from the field source, depending on the weight of coil m, consumed power W, and the conductivity of the medium σ (for the angle $\theta = 90°$ between the coil axis and the radius vector drawn from the reception point to the geometric center of the coil), is shown in Fig. 1. Figure 2 presents the directional pattern of this circular loop with a diameter of 0.2 m and power dissipation of 3 W for the distance of 30 m, depending on the conductivity of the medium and operational frequency. From these considerations we may select the optimal operating frequency that allows obtainment of the isotropic field source radiation pattern, even when the exponential decay factor in the medium begins to affect it. It should be noted that in case of an increase in 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 that limit the detection distance and localization precision. Therefore, the operating frequency of 500 Hz was selected for higher conductivity values.

These calculations allowed us to solve the most important problem – selecting the parameters of the MRB transmitter. According to the system description given above, the system should also include RT equipment that contains a transmitter and a two-point receiver. The following main parameters of these units were determined from practical considerations and modeling results:

- MRB transmitting coil or field source: coil with a weight of ∼ 200 g, diameter of ∼ 20 cm and power consumption of ∼ 3 W;
- MRB receiver to switch on the RTI transmitter: one component induction magnetometer with a length of 4–5 cm and the noise spectral density of no less than 0.25–0.4 pT Hz$^{-0.5}$;
- RTI transmitting coil to switch on the MRB transmitter: three-component coil with a weight of ∼ 9 kg, diameter of ∼ 0.5 m and power consumption of ∼ 20 W;
- RTI receiver to measure the MRB signals at two points: two three-component induction magnetometers with the length of each component as ∼ 20 cm and a noise spectral density of 0.05 pT Hz$^{-0.5}$.

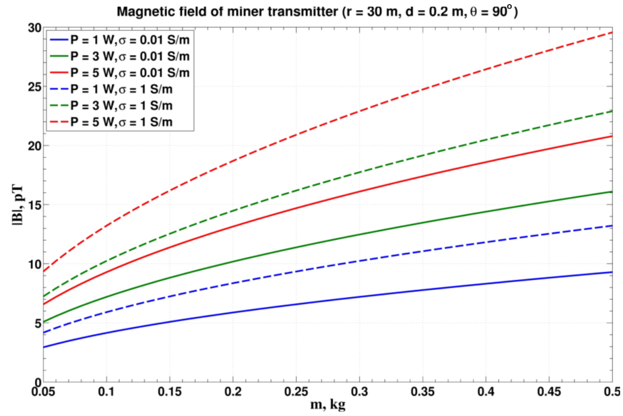

Figure 1. The magnetic field modulus at a distance of 30 m from the field source (circular loop with a diameter of 0.2 m) depending on the weight of the coil m, consumed power W and the conductivity of the medium σ.

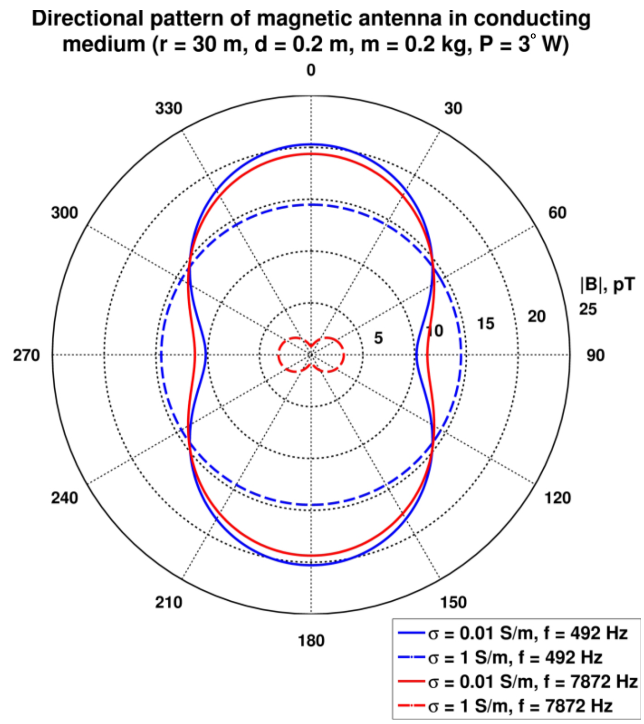

Figure 2. The directional pattern of the circular loop with a diameter of 0.2 m and power dissipation of 3 W for the distance of 30 m depending on the conductivity σ and operation frequency f.

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

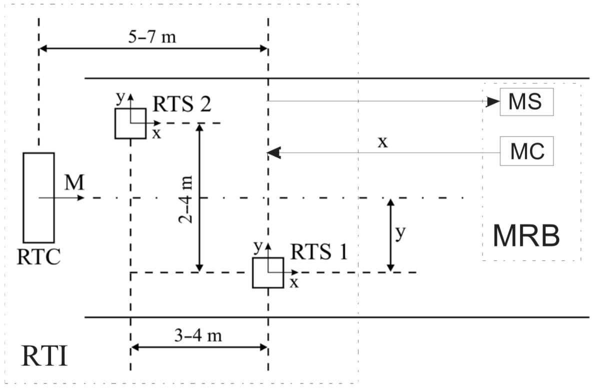

Figure 3. Miner's location emergency system (MILES) functional diagram.

2 Description of the system for miner beacon search and localization

For the experimental verification and testing of the proposed operation algorithm, a model of the system for miner's 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 Fig. 3.

The system operates as follows. Rescue team instrumentation (RTI) triggers the rescue team coil (RTC), which sends a code sequence of pulses every 20 s to switch on the miner's responder beacon (MRB), which has a personal code number, and then switches off. This signal is received by the miner's receiver or sensor (MS), amplified, decoded and then it is processed by the microcontroller. In case of an accident the code sequence microcontroller switches on the miner's transmitting coil (MC), which sends a signal for 20 s and then turns off. This signal is received by RTI, which has two three-component rescue team sensors, RTS-1 and RTS-2, placed at a known distance relatively close to each other. The signal is then amplified, digitized and processed by the computer using the specially developed software. The calculated coordinates and the position of the MRB are shown on a display. To minimize the error, this procedure may be repeated several times. Then the cycle is repeated for the MRB with the next number.

MILES equipment works with two operating frequencies: in a mine with normal conditions (dry or wet rock, soaked in fresh water), an operating frequency in the region of 10 kHz should be selected. In a mine with rock soaked in salt solutions the lower operating frequency (500 Hz) should be selected. The main parameters of the MRB prototype are given in Table 1, and RTI prototype main parameters are given in Table 2.

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

Miner's transmitting coil	
Antenna type	loop
Power consumption	3 W
Dimensions	150 × 100 × 30 mm
Weight	300 g
Miner's sensor	
Number of measured magnetic field components	1
Transformation coefficient for the central frequency	$540\,\mathrm{mV\,nT^{-1}}$
Magnetic noise level for the central frequency	$\leq 30\,\mathrm{fT} \times \mathrm{Hz}^{-1/2}$
Supply voltage	$+(3.4 \div 4.5)$ V
Current consumption	3 mA
Operation temperature range	$-10° \div +50\,°\mathrm{C}$
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 × 500 × 110 mm
Weight	3 kg
Rescue team sensors (two pieces)	
Number of measured magnetic field components	3
Transformation coefficient for the central frequency	$540\,\mathrm{mV\,nT^{-1}}$
Magnetic noise level for the central frequency	$\leq 20\,\mathrm{fT} \times \mathrm{Hz}^{-1/2}$
Supply voltage	$+(3.4 \div 4.5)$ V
Current consumption	15 mA
Operation temperature range	$-10° \div +50\,°\mathrm{C}$
Dimensions of the one sensor	145× Ø15 mm
Weight	200 g

3 Results of MILES testing

3.1 MILES testing in a bomb shelter

The test was performed in a bomb shelter on the land of the 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, MRB was located at a distance of up to 40 m in the next room behind concrete walls in terms of direct and indirect visibility. In the second case, rescue team instrumentation was installed inside the bomb shelter,

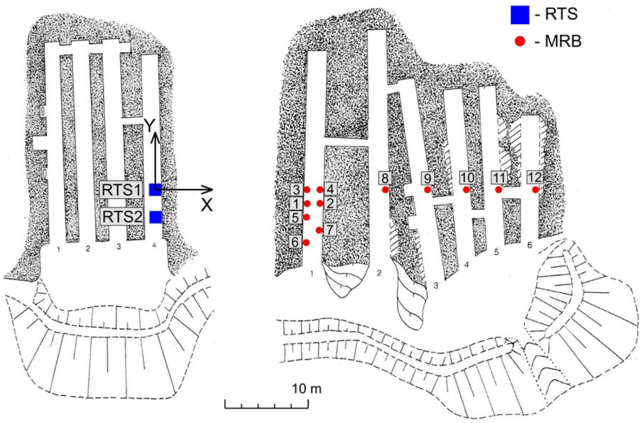

Figure 4. Cave plans.

while the MRB was at the surface at distances of 10–70 m. The thickness of the soil and bomb shelter ceiling was approximately 5 m.

The system tests showed that even under an extremely high level of electromagnetic interference in the working plant and inside the room, with a lot of ferromagnetic objects that were shielding the signal from the miner's responder beacon, the system reliably recorded the alarm signal at a distance no less than 50 m for a single measurement. In order to investigate how the precision will be increased with statistical averaging, a set of 10 measurements were made at each location. The final results showed that the errors of the distance determination and of the MRB position location were both in the limit of about 1–1.5 m in every case – for single and ten-fold procedures. More repetitions were not used because of time limitations during real rescue procedures – it is not possible to spend very much time on the measurements in real rescue conditions.

3.2 MILES testing in a cave

The test was performed in a cave complex located north of the city Mykolaiv in Lviv Oblast, Ukraine, in the natural landmark Bald Mountain. The cave plans are shown in Fig. 4, where RTI sensor locations are marked in blue and MRB locations are marked in red and numbered corresponding to numbers in the experiment.

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

4 Conclusion

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

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

This system may also be proposed for rescue team member tracking when they are clearing blockage or debris after explosions, earthquakes, etc.

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

Edited by: F. Soldovieri
Reviewed by: W. Schmidt and two anonymous referees

References

Burnos, P., Gajda, J., and Maj, P.: Digital system for detection and location of miners trapped in hard coalmines – GLOP2, Metrol. Meas. Syst., 17, 245–254, 2010.

Curry, F. B., Moore, T. C., Rorden, L. H., and Schleicher, I. D.: EM Rescue (Location) System for Deep Mines. Phase II – Build and Test Breadboard Equipment, U.S. Department of the Interior, Bureau of Mines, Pittsburgh, PA, Report No. J0199009, 108 pp., 1984.

Dudkin, F. and Kalashnikov, N.: Estimation of the electromagnetic field dipole radiators range limit in conducting media, Selection and transmission of information, a collection of works, Kiev, Naukova Dumka, 73, 61–65, 1986 (in Russian).

Durkin, J.: Apparent Earth Conductivity Over Coal Mines as Estimated From Through-the-Earth Electromagnetic Transmission Tests, U.S. Department of the Interior, Bureau of Mines, Pittsburgh, PA, Report No. 8869, 23 pp., 1984.

Farjow, W.: Technological Advancements for Safety in Confined Spaces, Advanced Mining Technologies Mining Magazine Congress, 2010.

Hill, D. A. and Wait, J. R.: Analytical investigations of electromagnetic location schemes relevant to mine rescue, U.S. Department of the Interior, Bureau of Mines, Pittsburgh, PA, Report No. H0122061, 170 pp., 1974.

Ingortech: Search system SPAS "MIKON" for people caught by accident, available at: http://www.ingortech.ru/index.php?option=com_k2&view=item&id=154, last access: 27 July 2016.

Ishankuliev, M. A.: Resistivity imaging of abandoned minelands at Huntley Hollow, Hocking County, Ohio, Ohio University, USA, MSc thesis, 76 pp., 2007.

Kalashnikov, N., Dudkin, F., and Nickolayenko, Y.: Fundamentals of marine electrical prospecting, Kiev, Naukova Dumka, 208 pp., 1980 (in Russian).

Lagace, R. L., Dobbie, J. M., Doerfler, T. E., Hawes, W. S., and Spencer, R. H.: Detection of trapped miner electromagnetic signals above coal mines, U.S. Department of the Interior, Bureau of Mines, Pittsburgh, PA, Report No. ADL-81978, 289 pp., 1980.

McNeill, J. D.: Electrical conductivity of soils and rocks, Geonics Ltd., Technical Note TN-5, 20 pp., 1980.

Mineweb: U.S. mining death toll surges with metal/nonmetals losses-MSHA, http://www.mineweb.com/uncategorized/u-s-mining-death-toll-surges-with-metalnonmetals-losses-msha/, last access: January 2014, 2016.

Powell, J. A.: An electromagnetic system for detecting and locating trapped miners, U.S. Department of the Interior, Bureau of Mines, Pittsburgh, PA, Report No. 8159, 17 pp., 1976.

Pittman, Jr. W. E., Church, R. H., McLendon, J. T.: Through-the-Earth electromagnetic trapped miner location system, A Review, U.S. Department of the Interior, Bureau of Mines, Pittsburgh, PA, Open File Report: 127-85, 57 pp., 1985.

Webb, W. E., Church, R. H., Pittman Jr., W. E., and Boyle Jr., J. R.: A Short-Range Locator System for Detecting Trapped Miners, U.S. Department of the Interior, Bureau of Mines, Pittsburgh, PA, Report No. 8844, 27 pp., 1984.

Xiaohui, Z. and Xueli, J.: Coal mining: Most deadly job in China, China daily, Updated: 13 November 2004.