Recommended Reading on Underground Mine Radio Communications

Topics: Leaky Feeder Technology, Propagation in the UHF and Medium Frequency Bands, Through-the-Earth Transmission and Electromagnetic Noise.

Over the last 35 years much has been learned about radio communications in the underground mine environment. The U.S. Bureau of Mines funded an intense study of the topic in the 1970's and 80's and laid the foundation for much that is currently known. There are hundreds of peer reviewed papers and contract reports on the topic. Hence the following list can only be a starting point. Most of these documents have a bibliography for further reading.

Leaky Feeder Technology Two old but useful papers by D.J.R. Martin – "Leaky-Feeder Radio Communication: A Historical Review" and "Cost-Effective Leaky-Feeder Radio Systems" give a good review. The Martin papers also provide references to the theoretical work on this technique. There are numerous vendors now routinely installing these systems in mines and tunnels. The document by Steve Luzik (MSHA) lists several manufacturers of leaky feeder systems as well as other communication technologies MSHA has investigated.

UHF Propagation The paper by A.G. Emslie "Theory of the Propagation of UHF Radio Waves in Coal Mine Tunnels" and contract report by ADL entitled "Propagation of Radio Waves in Coal Mines" provide extensive background on the theory and measurements on UHF in mine tunnels.

Medium Frequency Propagation Three papers provide an extensive background on this topic. Modeling and Data Analysis of 50 To 5000 Khz Radio Wave Propagation In Coal Mines, Robert L. Lagace et. al., Propagation of EM Signal in Underground Mines by Terry S. Corry, and Emergency and Operational Low and Medium Frequency Band Radio Communications System for Underground Mines by L.G. Stolarczyk.

Through-the-Earth Transmission The paper by Walter E. Pittman, Jr. et. al. "Through-The-Earth Electromagnetic Trapped Miner Location Systems. A Review" gives a good overview with an extensive bibliography. A detailed technical treatment is given in "Detection of Trapped Miner Electromagnetic Signals Above Coal Mines" by Robert L Lagace et. al.

Electromagnetic Noise Much of what is known about noise in coal mines and often quoted derived from original work done by the National Bureau of Standards (now NIST). Three reports (Electromagnetic Noise in Itmann Mine; Electromagnetic Noise in McElroyMine, Electromagnetic Noise in Robena No. 4 Coal Mine) provided the data.

References and Abstracts

(References proceeded with * are included on CDROM)

***Leaky-Feeder Radio Communication: A Historical Review, Martin, D.J.R., 34th IEEE Vehicular Technology Conference, Volume: 34, pp 25- 30, May 1984.**

Abstract - Problems of radio communication in mines, tunnels and other confined spaces are being increasingly solved by the use of leaky-feeder techniques. As first described in 1956 these comprised a simple open-braided coax or a twin-lead connected to one or more standard VHF base stations: nowadays they incorporate remarkably simple and inexpensive line-powered signal boosters or 'repeaters' to compensate for line losses as they occur and can provide virtually unlimited range without dependence on linking land-lines. For use in coal mines the entire system can be made intrinsically safe, since the power drawn by a typical present-day signal booster need be only a few milliwatts of DC.

***Cost-Effective Leaky-Feeder Radio Systems, Martin, D.J.R., 31st IEEE Vehicular Technology Conference, Volume: 31, pp 137-141, April 1981.**

Abstract - Leaky-feeder systems for artificially propagating VHF radio signals underground are highly developed in the UK for application in coal mines. Techniques now in regular use provide two-way communication using one-way repeater-amplifiers or 'signal boosters' in conjunction with small linepowered frequency converters. Examples of these devices are described. Although of low power and designed to be intrinsically safe for coal mine use, the equipment and techniques are applicable to other fields of application such as underground passenger transportation.

***Theory of the Propagation of UHF Radio Waves in Coal Mine Tunnels, Emslie, A.G., IEEE Transactions on Antennas and Propagation, V. AP-23, No. 2, March 1975.**

Abstract - The theoretical study of UHF radio communication in coal mines, with particular reference to the rate of loss of signal strength along a tunnel, and from one tunnel to another around a corner is the concern of this paper. Of prime interest are the nature of the propagation mechanism and the prediction of the radio frequency that propagates with the smallest loss. The theoretical results are compared with published measurements. This work was part of an investigation of new ways to reach and extend two-way communications to the key individuals who are highly mobile within the sections and haulageways of coal mines.

Propagation of Radio Waves in Coal Mines, Robert L. Lagace, Martin L. Cohen, Alfred G. Emslie, Richard H. Spencer, Arthur D. Little, Inc., Cambridge, Massachusetts 02140, Task F, Task Order 1, Contract No. H0346045, October 1975, U.S. Department of the Interior, Bureau of Mines. (No abstract available)

***Modeling and Data Analysis of 50 To 5000 Khz Radio Wave PropagationIn Coal Mines, Robert L. Lagace, Alfred G. Emslie, Michael A. Grossman, Arthur D. Little, Inc., Cambridge, Massachusetts 02140, Final Report Contract No. H0346045, February 1980, U.S. Department of the Interior, Bureau of Mines. [H0346045.pdf]**

Abstract - Simple theoretical models are formulated to characterize medium frequency (MF) radio wave propagation in underground room and pillar coal mines for the purpose of predicting the most favorable operating frequencies and maximum communication ranges for portable radios with loop antennas. For conductor free areas, a three layer propagation model with a transmission line formulation for the propagation constant has been developed and verified experimentally. The mode of propagation takes the form of a parallel plane (0,0) TEM transmission line type of mode with the electric field vertical and the magnetic field horizontal within a planar coal seam in which the tunnels can be ignored and which is bounded above and below by higher conductivity rock. The model fits the data best over the 200 to 1000 kHz frequency band and exhibits a region of optimum performance, with respect to maximizing radio communication range, between 300 and 700 kHz. Maximum communication ranges are strongly dependent on the signal attenuation rate, and therefore on the electrical conductivities of the coal seam and surrounding rock. These ranges vary from about 75 to 100 meters in a high loss seam such as the Herrin No. 6 to about 300 to 400 meters in a low loss seam such as the Pittsburgh for portable intrinsically safe radios. The results are based on the comparison of theory and experiment for eleven mines in seven coal seams. For areas where a conductor such as a power cable, is present a model has been developed for the coupling of loop antennas to a low loss coaxial TEM transmission line mode in which the cable acts as the inner conductor and the rock above and below acts as the outer conductor. The electric and magnetic fields for this mode are approximately transverse to the cable and fall off exponentially with distance in the transverse plane. The principle of reciprocity is used to simplify the analysis. More experimental data are needed to help resolve discrepancies between the theory and the limited data available to date.

Propagation of EM Signal in Underground Mines, Terry S. Corry, Collins Commercial Telecommunications Group, Circuit Systems Switching Division, Cedar Rapids, Iowa 52406, Final Report Contract No. H0366028, Open File Report 136-78, September, 1977 U.S. Department of the Interior, Bureau of Mines.

Abstract – This report is a comprehensive summary, of the results of the propagation measurements program conducted for the U.S. Bureau of Mines under contract HO366028. Data was gathered in the MF frequency range from a cross sample of six

mines representative of the industry having typical wireless requirements. From the raw data which was gathered, a logical method of data reduction is presented which culminates in a set of average attenuation characteristics for all mines visited. These characteristics define a typical MF wireless system when the communication range requirements are known. Direct through-the-earth propagation and the range enhancement mechanisms due to coupling on and off conductors are evaluated and related to the planning of a typical wireless communications system.

***Emergency and Operational Low and Medium Frequency Band Radio Communications System for Underground Mines, Stolarczyk, L.G., IEEE Transactions on Industry Applications. Vol. 21, No. 4, July/August 1991**

Abstract-A minewide low- and medium-frequency radio system has been developed and installed in coal and metalliferous mines. The radio system establishes reliable emergency communications between mine personnel on the surface, in working areas, or traveling in designated escapeways. The system also provides operational communications to improve coordination among working groups in the underground mining complex. The radio system utilizes two robust radio signal transmission modes to establish underground radio coverage areas. The seam transmission mode occurs when layers of coal, trona, potash, quartzite, or gilsonite are surrounded by more electrically conductive sediment layers. The layering forms a natural waveguide for transmission of medium-frequency (MF) band (300 to 23 000 kHz) radio signals. The conductor transmission line mode waveguide occurs when electrical conductors, such as ac power distribution cable, conveyor belt structures, steel pipe, and rail are in place in mine passageways. The conductor transmission waveguide attenuation rate is lowest in the low-frequency band (30 to 300 kHz). Safety is inherent in the system design since robust radio signal transmission modes are likely to survive events such as rock falls, fire, or explosion. Since the conductor utilities are necessary parts of the underground mine infrastructure, transmission line installation and maintenance cost can be avoided in the radio system. The conductor transmission line automatically expands with the development of the mine. This paper describes the development history of MF and technology during the past five decades in South Africa, Europe, and the United States. Electromagnetic (EM) wave theory relating to radio signal coupling and transmission along the in-place conductors is set forth. This paper describes how EM wave theory guided the design and development of the conductor transmission line repeater network and associated mobile radio equipment. Safety and cost reduction benefits of a practical radio system are also described in this paper.

***Through-The-Earth Electromagnetic Trapped Miner Location Systems. A Review, Walter E. Pittman, Jr., Ronald H. Church, and J. T. McLendon, Tuscaloosa Research Center, Tuscaloosa, Ala., Open File Report: 127-85, U.S. Department of the Interior, Bureau of Mines. Circa 1981.**

Abstract - In its role of providing technical assistance to the mining industry, the Bureau of Mines' Tuscaloosa Research Center has conducted research to develop

trapped miner location systems which would aid in locating miners trapped by underground mining disasters. Efforts to produce electromagnetic systems for the location of trapped miners underground and to communicate with them were surveyed, from the 1920's to 1981. Theoretical studies of through-the-earth electromagnetic transmissions are described as well as studies of the electrical characteristics of various rocks, minerals, and soil. Several trapped miner locationsystems are reviewed including the Westinghouse systems, the DEVELCO system, and an automated three-dimensional location system, and the phase difference of arrival technique. Tangential research, relevant to trapped miner location systems is described. A comprehensive bibliography covering all aspects of trapped miner, through-the-earth electromagnetic location and communications systems is appended.

***Detection of Trapped Miner Electromagnetic Signals Above Coal Mines, Robert L Lagace, James M. Dobbie, Thomas E. Doerfler, William S. Hawes, Richard H. Spencer, Arthur D. Little, Inc., Cambridge, Massachusetts 02140, Final Report Contract No. J0188037, July 1980, U.S. Department of the Interior, Bureau of Mines.**

Abstract - This report assesses the expected detectability, on the surface above mines, of electromagnetic signals produced in the frequency band of 630 to 3030 Hz by a rescue transmitter activated by miners trapped underground. This assessment is based on a statistical analysis of experimental signal and noise data taken at a representative sample of coal mine sites well distributed over the United States underground coal fields. Regression analyses are performed to characterize the signal transmission behavior of overburdens as a function of depth and frequency. The predicted signal behavior is then combined with experimentally based distributions of the background noise, and aural detection characteristics of signals in noise, to generate curves of the expected probability of detection for trapped miner signals versus overburden depth and operating frequency. The implications of these results, and associated recommendations, are presented regarding the detectability of trapped miners, sensitivity analyses and confirmatory tests, and operational utilization considerations for the trapped miners and the search and rescue team on the surface.

***Bensema, W.D., M. Kanda and J.W. Adams. "Electromagnetic Noise in Robena No. 4 Coal Mine." U.S. National Bureau of Standards Technical Note 654, April 1974. (U.S. Bureau of Mines Contract H0133005)**

Abstract - Two different techniques were used to make measurements of the absolute value of electromagnetic noise in an operating coal mine, Robena No. 4, located near Waynesburg, Pennsylvania. One technique measures noise over the entire electromagnetic spectrum of interest for brief time periods. With present instrumentation, the spectrum can be covered from 40 Hz to 400 kHz. It is recorded using broad-band analog magnetic tape, and the noise data are later transformed to give spectral plots. The other technique records noise envelopes at several discrete frequencies for a sufficient amount of time to provide amplitude probability

distributions. The specific measured results are given in a number of spectral plots and amplitude probability distribution plots. The general results are that at frequencies below 10 kHz, power line noise within the mine is severe. Impulsive noise is severe near arcing trolleys, and at lower frequencies near any transmission line. Carrier trolley phone signals and harmonics are strong throughout the mine whenever the trolley phone is in operation. Additional information beyond that included in this report may be obtained from the authors, who are with the Electromagnetics Division of the National Bureau of Standards.

***Bensema, W.D., M. Kanda and J.W. Adams. "Electromagnetic Noise in Itmann Mine." U.S. National Bureau of Standards NBSIR 74-390, June 1974. (U.S. Bureau of Mines Contract H0133005)**

Abstract - Two different techniques were used to make measurements of the absolute value of electromagnetic noise in and above an operating coal mine, Itmann No. 3 Mine, located near Mullens, West Virginia. The electromagnetic environment created by 250-volt-dc and 550 and 950 volt-ac machinery in two longwall panels was measured and is reported. One technique measures noise over the entire electromagnetic spectrum of interest for brief time periods. It is recorded using broadband analog magnetic tape and the noise data is later transformed to give spectral plots. The other technique records noise amplitudes a t several discrete frequencies for a sufficient amount of time to provide amplitude probability distributions. The specific, measured results are given in a number of spectral plots and amplitude probability distribution plots.

***Kanda, M., J.W. Adams and W.D. Bensema, "Electromagnetic Noise in McElroy Mine." US. National Bureau of Standards NBSIR 74-389, June 1974. (U.S. Bureau of Mines Contract H0 133005)**

Abstract - Two different techniques were used to make measurements of the absolute value of electromagnetic noise in and above an operating coal mine, McElroy Mine, located near Moundsville, West Virginia. 300-volt-dc and 480-volt-ac machinery was measured to see the electromagnetic environment it created. One technique measures noise over the entire electromagnetic spectrum of interest for brief time periods. It is recorded using broadband analog magnetic tape and the noise data is later transformed to give spectral plots. The other technique records noise amplitudes a t several discrete frequencies for a sufficient amount of time to provide amplitude probability distributions. The specific, measured results are given in a number of spectral plots and amplitude probability distribution plots.

Other References of Interest

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square brackets enclose file name on disc)

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2. *Analytical Investigations of Electromagnetic Location Schemes Relevant To Mine Rescue, Part I - Executive Summary and Part II - Collected Reprints, James R. Wait and David A. Hill, Institute for Telecommunication Sciences Office of Telecommunications, U.S. Department of Commerce, Boulder, Colorado 80302, Final Report Contract No. H0122061, December 1974, U.S. Department of the Interior, Bureau of Mines. [H0122061.pdf]

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5. *Propagation of UHF Radio Waves in Limestone Room and Pillar Mines, Robert L Lagace, Alfred G. Emslie, Arthur D. Little, Inc., Cambridge, Massachusetts 02140, Final Report Contract No. J0387217, January 1979, U.S. Department of the Interior, Bureau of Mines. [J0387217.pdf]

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8. *Propagation of EM Signals in Underground Metal/Non-Metal Mines, Terry S. Cory, P.E, 2857 Mount Vernon Rd. S.E., Cedar Rapids, Iowa 52403, Final Report Contract No. J0308012, August 1981, U.S. Department of the Interior, Bureau of Mines. [J0308012.pdf]

9. *Electromagnetic Detection of Trapped Miners, J. Durkin, IEEE Communications Magazine, February 1984 Vol 22, No. 2. [Electromagnetic detection of …..pdf]

10. *Adaptive-Noise-Cancellation Techniques For Through-The-Earth Electromagnetics, Frederick H. Raab, Ph.D, Green Mountain Radio Research Company, 50 Vermont Avenue, Fort Ethan Allen, Winooski, Vermont 05404, Final Report Contract No. J0318070, February 1984, U.S. Department of the Interior, Bureau of Mines. [J0318070 – VOL 3 of 3.pdf]

11. *EM Rescue (Location) System for Deep Mines, Phase II - Build and Test Breadboard Equipment, F.B. Curry, T.C. Moore, L . H . Rorden, I.D. Schleicher, Develco, Inc., 404 Tasman Drive, Sunnyvale, CA 94086, Final Report Contract No. J0199009, October 1984, U.S. Department of the Interior, Bureau of Mines. [J0199009.pdf]

12. *Apparent Earth Conductivity over Coal Mines as Estimated From Through-the- Earth Electromagnetic Transmission Tests, J. Durkin, Report of Investigations 8869, 1984, U.S. Department of the Interior, Bureau of Mines. [RI 8869.pdf]