ELECTROMAGNETIC SEAM WAVE MAPPING OF ROOF ROCK CONDITIONS ACROSS A LONGWALL PANEL

Larry G. Stolarczyk, President,
and
Gerald L. Stolarczyk, Vice President and Senior Systems Engineer
Stolar Horizon, Inc., and Raton Technology Research, Inc.
848 Clayton Highway, P.O. Box 428, Raton, New Mexico 87740 USA
Phone: (505) 445-3607; fax: (505) 445-9659; email: stolarhorizon@stolarhorizon.com

ABSTRACT

The mining industry would benefit greatly by imaging geologic conditions well in advance of mining. In layered deposits such as coal, trona, quartz, and potash, natural waveguides form and enable electromagnetic seam waves to travel great distances. In the early 1980s, the Radio Imaging Method (RIM) was developed to capitalize on electromagnetic seam wave propagation in the assessments of seam conditions in longwall panels. The initial applications of RIM tomography and comparisons to in-mine mapping of geologic conditions proved that faults, paleochannels, and rapidly thinning coal could be detected and imaged with seam waves. This paper describes the application of electromagnetic seam waves in mapping the margins of a paleochannel crossing a longwall panel and the interesting possibility of adopting the newly developed Full Wave Inversion Code (FWIC) (Newman 1995) to significantly improve imaging resolution. When tomography images are combined with ground control science, a significant reduction in cost, roof fall potential, and waste rock in underground mining may be realized.

INTRODUCTION

In the mid 1970s, theoretical studies of electromagnetic wave transmission phenomena in underground mines determined that the already installed electrical conductors, such as ac power cable, hydro/air pipe, and conveyor belts, form natural waveguides for low attenuation rate transmission of radio signals (1)(2). During our development and demonstration of an inductive radio communications system in the York Canyon Mine near Raton, New Mexico, we discovered that coal seams also form a natural waveguide for low attenuation rate transmission of radio signals (3). Subsequent tests showed that electromagnetic seam waves also form in trona, potash, and quartz deposits. Radio communications distance in coal seams exceeded 700 feet and confirmed the 1962 prediction by Jim Wait that natural waveguides exist in the layered earth (4). The natural waveguide exists because the resistivity of the bounding sedimentary rock layers is oftentimes three orders of magnitude less than the resistivity of coal, trona, quartz, or potash (10,000 ohm-meters)(5). Our rediscovery of the natural waveguides led to the idea of applying electromagnetic seam waves in the detection and imaging of geologic anomalies ahead of mining (6)(7)(8)(9)(10)(11)(12)(13).

Because a full seam fault crosses the York Canyon Mine main entries, a confirmation experiment was set up to measure the electromagnetic wave propagation phenomena of transmission reflections near a geologic anomaly. A transmitter was located outby the fault, and a hand-carried receiver was used to measure electromagnetic seam wave intensity in the outby entry and through the fault. The seam wave spreading (amplitude decay with distance) was determined to be to the half power of distance. If the seam waveguide were not present, the decay would have been measured to be the first power of distance. This confirmed the existence of a seam wave. The decrease in spreading factor makes a dramatic difference in instrumentation design requirements because less transmit power would be required to reach a measurements receiver. Approaching the fault from the transmitter side, the receiver measurement of the magnitude of the total electromagnetic wave (sum of the incident and reflected wave) rapidly increased in front of the fault and significantly decreased inby the fault. This experiment proved that electromagnetic seam waves were reflected back toward the transmitter by the fault. Seam waves could be used to detect faults ahead of mining. Although faults were a definite mining problem, the Raton Basin coal deposit exhibited a number of other difficult mining problems. Because the coal-peat formed in a delta region, paleochannel flow during the seam burial episode cut into the mudstone sedimentary layer overlying the coal seam. Oftentimes, these sandstone channels scoured into the coal seam resulting in partial to full seam washouts. Because of the meandering nature of paleochannels, it was impossible for the mine geologists to predict where high-energy cutbanks and scouring would occur. The difficult mining condition is illustrated in figure 1.

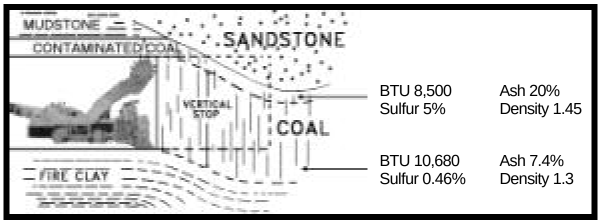

Figure 1. *Vertical cross section illustrating a paleochannel scour, roll, and vertical cut stop limit in a coal seam.*

Along the margins of the channel, the mudstone sedimentary rock is fractured by the mechanics of differential compaction occurring during burial. Fracturing leads to weak roof and rock falls. Waste rock increases in the run-of-mine (ROM) coal. Because mining machines are not equipped with cutting-edge sensors on the drum, machine operators cannot judge the distance to the roll and, therefore, cut into the sandstone roof rock. This causes out-of-seam dilution, decreases ROM coal quality, and introduces silicon dust into the ventilation airstream.

Although it was a simple in-mine demonstration problem to show that faults can be detected with electromagnetic seam waves, it was another and more challenging matter to show/prove that paleochannels and the associated fractured roof margins could also be detected with electromagnetic seam waves. To approach the solution to this detection problem, theoretical studies were conducted by David Hill, which resulted in the determination that seam wave attenuation rate strongly depends on roof/floor rock resistivity. These data are shown in figure 2 (14).

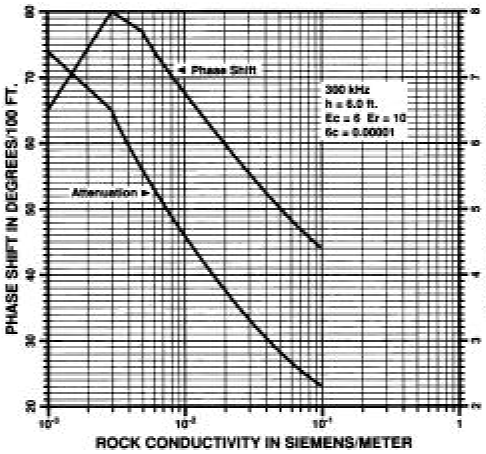

Figure 2. *Seam wave attenuation rate versus boundary rock conductivity (after Hill).*

Hill graphically illustrated that the attenuation rate rapidly increases under sandstone roof rock where sandstone resistivity is approximately 100 ohm-meters as compared to mudstone with 10 ohm-meters. Electrical conductivity used by Hill in figure 2 is the inverse of resistivity and has been given the designation of Siemens per meter (S/m). Now that the theoretical possibility of detecting paleochannels in advance of mining was advanced by Hill, it was left to in-mine trials to validate the use of electromagnetic seam waves in mapping paleochannels ahead of mining.

DATA COLLECTION AND INTERPRETATION

Instrumentation was developed for electromagnetic seam wave data collection. First, in-mine instruments were developed and then followed by down-the-hole instruments. The application of these instrument configurations is illustrated in figure 3.

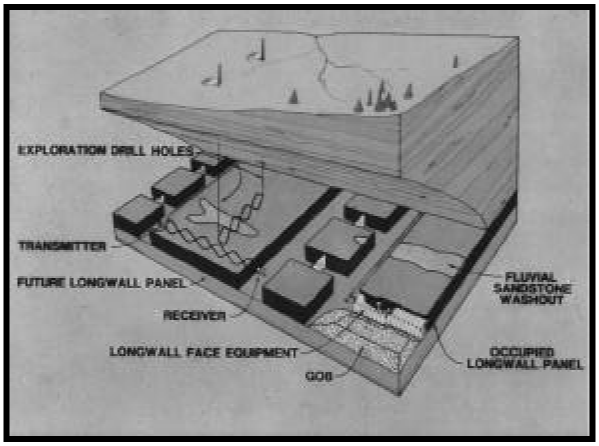

Figure 3. *Adaptation of the Stolar-RIM instrumentation in a longwall mine.*

The transmitter features a loop antenna that initiates electromagnetic seam wave. The seam wave is broadcast (propagates) through the coal layer and appears as an attenuated electromagnetic wave at the receiver location in the tailgate entry. The quasi transverse electromagnetic (TEM) wave is polarized by the waveguide to have a vertical electric (E) field component and a horizontal magnetic (H) field component. There is a third electric field component that is horizontally polarized and reaches maximum value at each coal-sedimentary rock boundary. In a uniform seam, this horizontal electric field has zero value in the center of the seam. The horizontal electric field component is not measured in routine surveys, although it can be made a diagnostic tool in assessing roof rock stability conditions along an entry. This possibility could lead to a simple method of assessing the potential for rockfall in developed entries in a layered deposit.

The mapping of a paleochannel across a longwall panel was achieved by conducting a tomographic survey in a longwall panel as indicated in figure 3.

Measurements made at multiple receiver stations were processed in the Algebraic Reconstruction Technique (ART) tomographic algorithm to map the radiowave attenuation rate in the plan view plane of the block of coal. The ART algorithm assumes that the radiowave energy travels along a straight path between the transmitter and receiver. Although the assumption is not valid in a highly disturbed geologic zone, slightly anomalous zones in an otherwise uniform coal seam are accurately mapped with RIM. The image of a roof rock fracture zone under a paleochannel in a longwall panel of coal is illustrated in figure 4.

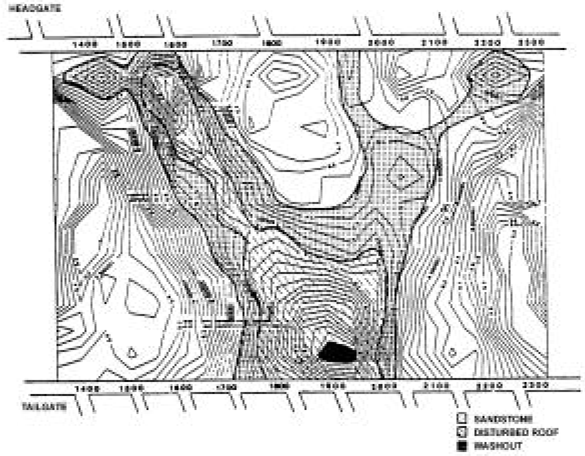

Figure 4. *Reconstructed tomography image illustrating constant attenuation rate (in decibels per 100 feet) contours of a geologically disturbed zone in a 600-foot (181-meter) wide retreating longwall coal panel.*

Early detection of anomalous seam conditions prior to mining has proven to be cost effective in mine design, planning to ensure a smooth-running mine, and enhancing ROM coal quality. The EM field propagation constants along each path were determined by measuring the magnitude and phase shift at each receiver location. The measured data was subsequently processed in the ART tomography algorithm that first divides the geologic image zone into pixels (plan view two-dimensional image). The tomography algorithm then determines the attenuation rate and phase shift occurring in each pixel based upon the measured data. Applying a contouring program, an image of attenuation rate or phase shift variations throughout the longwall panel illustrates the geologically disturbed zone. The plan view longwall panel image illustrates contours of constant attenuation rate of the seam wave propagating in the coal seam waveguide. To interpret the image, the fractured coal seam waveguide allows energy in the electromagnetic wave to leak out of the waveguide and into the surrounding fractured rock as predicted by Hill. If water is contained in the pore space of the overlying sandstone, its leakage into the coal fractures causes the coal's electrical conductivity to increase. Both conditions cause the attenuation rate of the seam wave traveling through the anomalous zone to increase. The rapid change in attenuation rate (gradient) illustrates the margin of the river channel and the location of fractured roof rock. A "roll" in the coal seam begins along the margin of the channel. The black region of very high attenuation rate locates a zone of rapidly thinning coal. High energy flow in the paleochannel has scoured the coal, producing a localized washout in the seam.

The practical application of ground control science can be improved when combined with electromagnetic seam wave imaging. The impact on mining under paleochannels can be significantly reduced by leaving a bridge coal layer thickness of 12 inches along the channel margins. This will minimize the waste rock caused by rock fall into the ROM product. Additional roof support should be added in the ground control plan where the gradient increases across the entries.

CONCLUDING REMARKS

Several hundred RIM surveys have been conducted since 1983. This practical experience resulted in the recognition of technical limitations that, if overcome, would create an effective seam mapping technology. Since the original development of electromagnetic seam wave technology, longwall panels have increased in width from 500 feet (152 meters) to more than 1,000 feet (304 meters). To achieve greater operating range, the RIM operating frequency was reduced from 500 kHz to 50 kHz, which decreased image resolution. To overcome the limitation, the instrumentation has been redesigned to include synchronous detection, which significantly increases the receiver threshold sensitivity. The increase in sensitivity restores operation at 500 kHz.

The application of RIM in seams with multiple anomalies and larger blocks of coal produced images with *poor* resolution. In the case of multiple anomalies, the straight ray path assumption was invalid resulting in detection failure. Full-Wave Tomography Inversion Code (FWIC) processing algorithms are currently under development by industry, university, and national laboratory researchers. These FWIC tomography algorithms do not require the straight ray path assumption and can resolve multiple anomalies in the anomalous zone. Because these algorithms require accurate amplitude and phase measurements along with the measurement of multiple radiowave field components (caused by the scattered wave), a new instrumentation system is required—called Stolar-RIM. Our company and Sandia National Laboratories are participating in a Cooperative Research and Development Agreement (CRADA) in the development of the Stolar-RIM instrumentation, which features synchronous detection and FWIC interpretation algorithms.

The limitations in RIM technology have been overcome by state-of-the-art improvements in instrument design and the development of the FWIC software (15). The limitations in the ART tomography as well as the significant improvements in the FWIC tomography are illustrated in figure 5. In this geologic simulation model, the Stolar-RIM transmitter's stations are located on the left side of the image and the Stolar-RIM receiver measurement stations are located on the right side of the reconstructed image. The model to be imaged represents a sandstone washout and is shown in the upper left illustration. Present-day ART imaging results in image distortion in the direction of wave propagation as shown in the upper right corner of figure 5. The early ART images had very poor lateral resolution, therefore, predicting the exact location of washout or faults heading perpendicular to the mining face would not be possible. The lower right FWIC tomography image shows the significant improvement in resolution and the possibility of detecting faults and paleochannels perpendicular to the face with a heading. FWIC appears to be a quantum leap forward in coal seam imaging. We anxiously await in-mine data collection with Stolar-RIM instrumentation and processing of collected data to confirm the improvement in imaging.

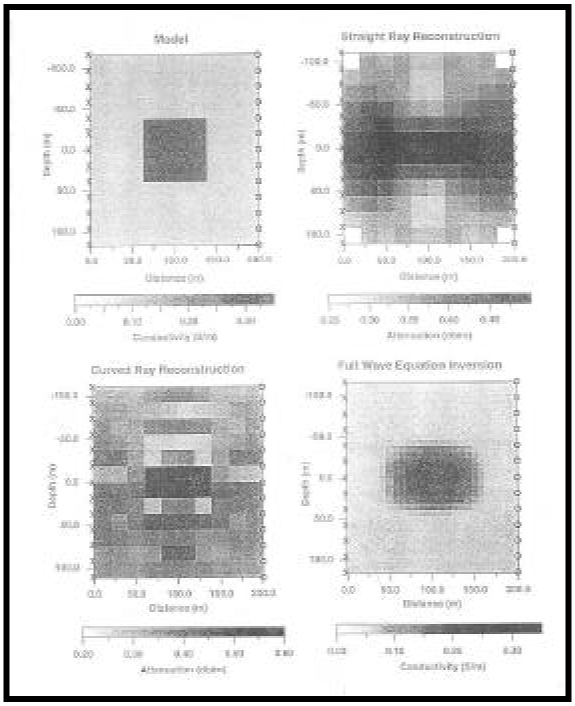

Figure 5. *Comparison of reconstructed tomography images using straight ray path assumptions and the state-of-the-art full wave inversion technique developed by Gregory Newman.*

ACKNOWLEDGEMENT

We would like to dedicate this paper to the memory of James R. Wait for his many contributions to the development of our understanding of how electromagnetic waves propagate in the earth.

REFERENCES

1. Wait, J. R., 1978, Electromagnetic Guided Waves in Mine Environments, Proceedings of a Workshop (Contract H0155008, Nat. Telecommunications and Inf. Admin., U.S. Dept. Commerce), *BuMines* OFR 134-78, May 31, 333 pp.; NTIS PB 289 742.

2. Wait, J. R., and D. A. Hill, 1976, Analytical Investigation of Electromagnetic Fields in Mine Environments (Contract H0155088, NOAA, U.S. Dept. Commerce), *BuMines* OFR 53-77, Nov. 15, 200 pp.

3. Stolarczyk, Larry G., 1991, Emergency and Operational Low and Medium Frequency Band Radio Communications System for Underground Mines, Reprinted from *IEEE Transactions on Industry Applications*, Vol. 27, No. 4, August, p. 780-790.

4. Wait, J. R., 1963, The Possibility of Guided Electromagnetic Waves in the Earth's Crust. *IEEE Transcript on Ant and Prop.*, Vol. AP-1, No. 3, May.

5. DeLonge, P., 1982, Leaky Feeders and Subsurface Radio Communications, *IEEE Electromagnetic Wave Series 14,* Peter Peregrinus, Ltd., Stevenage, U.K.

6. Stolarczyk, L. G., and R. C. Fry, 1990, *Radio Imaging Method (RIM) or diagnostic imaging of anomalous geologic structures in coal seam waveguides,* Transactions of Society for Mining, Metallurgy, and Exploration, Inc., Vol. 288, 1806-1814.

7. Gumbley, J., L. G. Stolarczyk, and S. Shope, 1987, The Radio Imaging Method (RIM) Evaluation of Longwall Panels in the East Huntley Coal Mine, Fifth Conference and Exhibition, Australian Society of Exploration Geophysics, Perth; February.

8. Lloyd, T. W., C. A. Semborski, and L. G. Stolarczyk, 1986, A Method of Predicting Coal Seam Discontinuities. SME preprint 86-28, SME Annual Meeting, New Orleans, March.

9. Miller, D., S. Doe, and L. G. Stolarczyk, 1986, Evaluation of Buried Coal Seam Discontinuities, SME Annual Meeting, New Orleans, March.

10. Shope, S. M., 1987, Electromagnetic Coal Seam Tomography, Ph.D. dissertation, Pennsylvania State University, p. 292.

11. Shope, S. M., R. J. Greenfield, and L. G., Stolarczyk, 1986, Use of Electromagnetic Waves for Coal Seam Tomography, Proceedings, Society for Exploration Geophysics, 56th Annual Meeting, Houston, TX.

12. Stolarczyk, L. G., 1986, US Patent No. 4,577,153, Continuous Wave Medium Frequency Signal Transmission Survey Procedures for Imaging Structures in Coal Seams, March.

13. Stolarczyk, L. G., G. Rogers, and P. Hatherly, 1988, Comparison of Radio Imaging Method (RIM) Electromagnetic wave tomography with in-mine geologic mapping in the Liddel, Bulli, and Wongawilli Seams, Sixth Conference and Exhibition, Australian Society of Exploration Geophysics, Adelaide, Vol. 19, No. 1/2, March/June, pp. 169-170.

14. Hill, D., 1984, Radio Propagation in a Coal Seam and the Inverse Problem, *Journal of Research,* National Bureau of Standards, Vol. 89, No. 5, Sept.-Oct.

15. Newman, G. A., 1995, Crosswell electromagnetic inversion using integral and differential equations. *Geophysics,* Vol. 60, 899-911.