REMOTE SENSING OF ABANDONED MINE WORKS USING DOWNHOLE RADIO IMAGING TECHNIQUES[1]

David F. List,[2] James G. Schotsch,[3] and Gennaro G. Marino[4]

Abstract: Because of the potential for surface subsidence, electromagnetic radio imaging method or RIM was employed to identify old (prior to 1928), mine workings in a 300-foot deep by approximately 5-foot thick coal seam below a proposed construction site near Carlisle, Indiana. Cross-borehole RIM delineated the worked regions in the coal seam between pairs of boreholes using distinct variations in the measured signal strength (i.e., attenuation) of continuous radio waves transmitted at three different frequencies (422.5, 532.5, and 612.5 kHz). At the Carlisle site, 33 holes spaced 113 feet to 293 feet apart were drilled within an approximately 900,000 square-foot area. The holes were specifically positioned to calibrate signal attenuation for worked and unworked sections of the seam and then to verify the original mine workings map. Of the 43 pairs of holes measured, 36 clearly showed the presence or absence of mining using single-frequency data. In the remaining 7 cases, multiple-frequency data provided clear answers. In 3 areas, mine workings were detected that were not indicated on the original map.

Introduction

Unmapped abandoned mines are hazards for underground mines, surface mines, and surface structures. Mining operations risk employee safety, flooding, decreased reserves and loss of revenue, if old workings are not predetermined. Surface structures can incur damage ranging from cracked foundations to a total loss of the structure. Mine engineers and architects can avoid risks by delineating unmapped mine works and adjusting operations accordingly (Schotsch and Sutton 1991). One method for delineating unmapped mine works is the radio imaging method or RIM.

RIM is an electromagnetic method that generates a subsurface image by mapping variations in wave transmission. To date, we have successfully used RIM in a variety of settings for a variety of reasons. We used in-mine RIM across production panels in coal, trona, and potash mines to image geologic features, including sandstone scours, faults, collapse structures, and lithological variations (Fry, et al. 1985, Hill 1984, Miller and Schreiber 1990, Stolarczyk and Fry 1989). We used cross-borehole RIM in proposed mining zones to provide long-term planning information (Miller, et al. 1986, Miller and Schreiber 1990). In the case study presented here, we used cross-borehole RIM, as an alternative to costly, closely spaced drilling, to locate abandoned mine works.

In this study, the survey site was targeted for building the Wabash Valley Correction Institution (WVCI) near Carlisle, Indiana. Because of the uncertainty of a mine map made in 1928 and the potential for subsidence above worked zones, RIM was employed to delineate worked and unworked areas of the seam. RIM measurements made at the site verified the accuracy of the map in all but three areas. In these areas, RIM detected mine workings not indicated on the original map.

Radio Imaging Method - Theory

[1]Paper presented at the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, April 24-29,1994.

[2]David F. List, Geophysical Engineer, RIMtech, Inc., Westminster, CO, USA

[3]James G. Schotsch, P.E., RIMtech, Inc., Lexington, KY, USA

[4]Gennaro G. Marino, Ph.D., P.E., Gennaro G. Marino Engineering Consultants, Champaign, IL, USA

Proceedings America Society of Mining and Reclamation, 1994 pp 29-38
DOI: 10.21000/JASMR94040029

https://doi.org/10.21000/JASMR94040029

The cross-borehole RIM, as used at Carlisle, works by transmitting an electromagnetic (EM) or radio wave at a specific (radio) frequency from a transmitting antenna in one drill hole to a receiver antenna in a second hole. The antennae are free hanging and, for the Carlisle survey, were lowered to a depth within the coal seam. Coal is typically much less electrically conductive than the surrounding roof and floor rock. This conductivity contrast or layering confines the wave, preventing most of the wave energy from vertically escaping the coal seam and extending the horizontal range of transmission. In this regard, the coal seam acts as and is called a *waveguide*.

Wave guide transmission offers two unique benefits to RIM and the problem of locating abandoned workings in coal seams. First, as state above, the confining of the signal in the layer allows for longer wave transmission than would occur if there were no a waveguide. And, second, because it is confined, the radio wave is very sensitive to electrical conductivity variations within the wave guide (i.e., the contrast between worked and unworked regions).

Single Frequency

Figure 1 shows a schematic of a RIM signal transmitted through a coal seam, the electric property of the coal seam, and how we analyze the recorded signal. Figure 1-A cartoons a continuous, single-frequency EM signal that is emitted from transmitter T_x and travels through the coal seam waveguide to receiver R_x, where the amplitude of the signal, A, is recorded. In the figure, the line representing the wave thins from T_x to R_x; this is an indication of the loss in signal amplitude.

Although the signal is essentially confined by the coal seam waveguide, transmission is not lossless. Some of the signal is lost or radiated into the surrounding rocks and some of the signal is absorbed by the waveguide media. Radiation loss into the surrounding rock is minor and we neglect it. As a result, the amplitude of the signal at R_x depends on the intrinsic absorption or attenuation rate of the transmission path and the distance between T_x and R_x (i.e., termed "geometric spreading" which we discuss later).

Figure 1-B shows a representative attenuation rate of a coal seam waveguide. The shaded region represents the flooded mine workings and, since water has a relatively high electrical conductivity, it has a much higher attenuation rate than the unworked coal seam.

Attenuation rate in a coal seam waveguide is a function of the electrical conductivity of the coal and the contrast in conductivities between the coal and surrounding rocks (Hill, 1984, Stolarczyk and Fry 1989, Stolarczyk, 1990). The greater the electrical conductivity of the coal, the greater the attenuation rate. The greater the conductivity contrast, the smaller the attenuation rate. For analysis purposes, we calculate attenuation rate in units of decibels or dB per 100 feet.

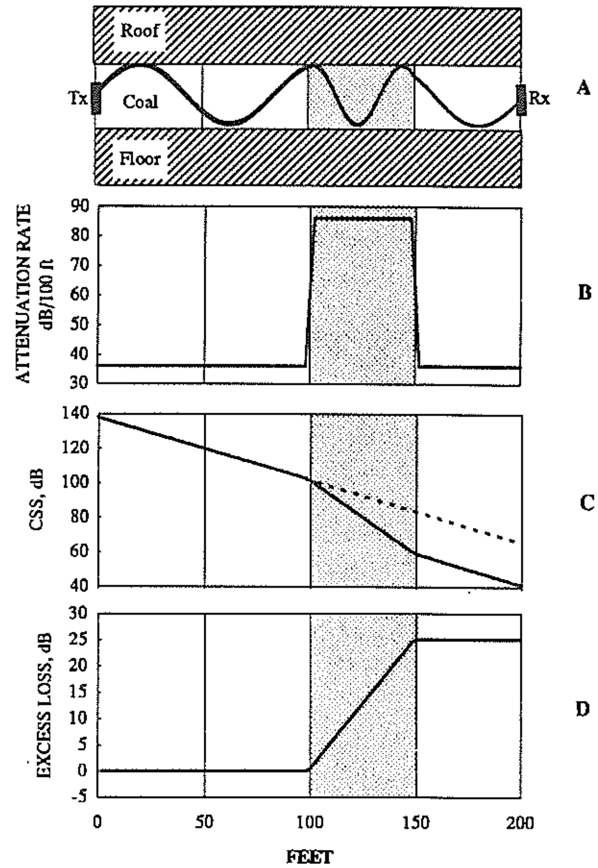

Figure 1. Diagram of the RIM transmission and analysis curves in a coal seam with water filled void (shaded area). A) EM wave in a coal seam, width of line indicates decreasing signal amplitude. Antennae are denoted by T_x and R_x. B) Attenuation rates in coal seam and mine void. C) CSS, corrected signal strength of the EM wave as it passes through seam with workings present (solid line) and in absence of workings (dashed line). D) Excess loss of the EM wave in the seam.

[Note: dB = $20\log_{10}(A/A_o)$, where A_o is a reference amplitude, which we define as 1 nano-volt].

Figures 1-C and 1-D show the results of the analysis of the measured signal strength at R_x. The signal is processed to provide the corrected signal strength (1-C) and the excess loss (1-D). The corrected signal strength or CSS is the measured signal strength corrected for geometric spreading. Geometric spreading is the reduction of signal amplitude with increased distance from the transmitter and its effect must be removed from the data. It occurs because the wave radiated by the transmitter horizontally spreads over an increasing wave front or area within the waveguide as the wave travels to the receiver. In the coal seam, the spreading is a linear function of the T_x-R_x antenna separation when amplitude is cast in dB. The results of the removing geometric spreading is showed by the solid line, the corrected signal strength (CSS) in Figure 1-C.

In addition to the solid line, Figure 1-C shows a dashed line. This line is the projection of corrected signal strength in the absence of the increased attenuation rate due to the flooded, worked coal seam. We term the difference between the solid and dashed lines the excess (signal) loss. Excess loss is an indicator of the presence of the mine workings. If the ray path does not cross mine workings, the excess loss will be negligible; if mine workings are crossed, the excess loss will be high.

Multiple Frequencies

The previous example discussed single-frequency RIM. RIM can also be done in a multiple-frequency mode. In practice, a multiple-frequency RIM survey consists of a series of single frequency RIM measurements, each operated at a different frequency. However, analysis of the multiple-frequency RIM data gives more information than simply the direct sum of information from the individual frequencies. The information gain allows for predicting, not only the presence of anomalous features in a coal seam, as with single frequency data, but also the type and location of the features. This is important because for a setting in which mine workings run parallel to, but are offset from, the direct line between the measuring holes may appear in single frequency data to be the same as mine workings that cross the direct line. With multiple-frequency data, these two configurations of mine workings can be differentiated.

As implied above, signals transmitted between T_x and R_x are influenced not only by features along the direct line between the antennae (termed the "ray path"), but also by features near the ray path. The zone surrounding the ray path that influences the signals is called the zone of influence. In planar or map view, this zone is an ellipse with T_x and R_x as foci and the ray path as the major axis. The zone of influence ellipse, also termed the "scattering ellipse," is the outer boundary where signal amplitude is great enough to travel from T_x, hit a perfect reflector (i.e. 100% reflection) at this boundary, and still be detectable at R_x. The size of the ellipse is a function of geometric spreading, signal strength, but most important for RIM, frequency and attenuation rate. Higher frequency signals attenuate more readily and have smaller ellipses than lower frequencies. Overlaying scattering ellipses from different frequencies and eliminating the common region of both ellipses results in an elliptical annulus. This is the basis of multiple-frequency RIM surveys.

By comparing one frequency signal with another frequency signal, features within the elliptical annulus can be detected and isolated. To make this comparison, we define an attenuation index at two frequencies,

$$\text{Index} = [\alpha(f_2)/\alpha(f_1) - \alpha_s(f_2)/\alpha_s(f_1)]*100, \tag{1}$$

where $\alpha(f_i)$ is attenuation rate at frequency f_i, $\alpha_s(f_i)$ is the standard attenuation rate at frequency f_i, and f_1 and f_2 are the two frequencies of the analysis. The standard attenuation in equation (1) is defined at the attenuation under uniform conditions (i.e., no anomalous features within the zone of influence of either frequency f_1 or f_2).

Multiple-Frequency - Theoretical Case Studies

The utility of multiple-frequency data for detecting and distinguishing abandoned mine working configurations is depicted in Figure 2. Figure 2 shows the four possible configurations between the mine workings and the ray paths. To determine which case exists in the survey data, we determine values of excess loss and the attenuation index. The characteristics of ray paths and zone of influence for two frequencies of each case in Figure 2 are discussed below:

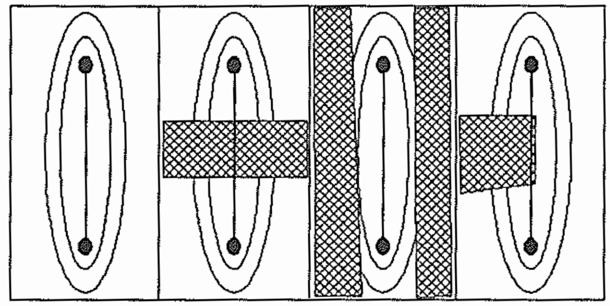

Figure 2. Map view schematic of four possible mine workings (hatched areas) ray path (solid line) configurations. Circles represent antennae locations. The larger ellipse surrounds the zone of influence in the coal seam for the lower frequency signal. The smaller ellipse surrounds the zone of influence for the higher frequency signal. A) Case A - unworked seam. B) Case B - workings crossing ray path. C) Case C - workings parallel and offset to ray path. D) Case D - workings into but not traversing ellipses.

Case A Ray paths in a uniform coal seam, characterized by low excess loss on both frequencies. Since neither zone of influence for the two frequencies encounter anomalous areas,the index is approximately equal to 0.

Case B Ray paths crossing mine workings, characterized by large excess loss. High frequencies are more affected than low frequencies, leading to a positive attenuation rate index.

Case C Ray paths close to but not crossing workings, characterized by elevated excess loss since the workings are in the zone of influence. Low frequencies are more affected by the workings more than the higher frequencies, which leads to a negative index.

Case D Mine working crossing the ray path and ending, characterized by slightly higher excess loss than case C, but lower than case B. The larger zone of influence of a low frequency signal can propagate around the disturbance easier than the smaller high frequency zone leading to a positive index.

Survey Site and Operations

Mine No 1.

The proposed WVCI site is in the northwest corner of the Illinois Basin just north of Carlisle in southwestern Indiana near the Indiana-Illinois border. Extensive coal mining took place here over the past century. The coal mine beneath the site was called the Mine No. 1 and was operated by the Carlisle Coal Mining Co. (Marino, 1990). The operation appears to have begun in 1908 and was abandoned in 1928 (Marino, 1990).

Although several coal seams exist beneath the site, only the Springfield No. 5 Coal seam was exploited (fig. 3). The seam's depth ranges from about 290 feet to 310 feet below the surface. The water table is 7 feet to 19 feet below the surface. The average thickness of the seam is 4.3 feet and is bound above by a thin black sheety shale overlain by limestone and below by fire clay or black shale. The only available map of the mine (fig. 4) indicates extensive mining in the southern half the site.

Survey Design and Field Operations

The goal of this RIM survey was to verify the 1928 mine map. The analysis procedure requires distinguishing ray paths crossing worked versus unworked. To do this we designed 45 ray paths into 3 groups: a calibration group with ray paths that crossed worked areas, a second calibration group away from worked areas, and a third group to verify the original mine map. We positioned 9 ray paths to cross mapped-worked areas and they are referred to as the **worked** ray path group. We positioned 10 more far away from worked areas and they are referred to as the **unworked** ray path group. We positioned the final 26 to verify the map and are referred to as the **verification** ray path group. Figure 4 gives the numbering of the ray paths and their separations.

To measure the 45 ray paths, 33 boreholes were drilled into the Springfield No. 5 Coal Seam. The data collection took 3 days to complete at a rate of 2 ray paths per hour.

Data collection for each ray path follows a prescribed sequence to maintain consistency. The first step is to center the antennae, operating at 422.5 kHz, in the coal seam at locations giving the maximum amplitude. This is done by by lowering the R_x to the center of the coal seam then moving T_x to the depth of maximum signal amplitude. The T_x is then fixed and R_x moved to find the maximum signal amplitude depth. Keeping the antennae at these depths, the amplitude and phase of the signal are recorded at three different frequencies (422.5 kHz, 532.5 kHz, and 612.5 kHz).

Results

Of the 45 ray paths attempted at the site, two in the **unworked** group could not be recorded because the signal was below the noise level. This occurred because the ray path distances were too long for the frequencies. The two ray paths were 22 and 43 and had distances of 284 feet and 293 feet, which is 50 feet longer than the next longest path and well above the average ray path distance of 170 feet.

The remaining 43 ray paths were processed to obtain CSS for the three frequencies recorded. These values for ray paths in the **unworked** group were plotted versus ray path distance and a least squares regression line fit to them. The least squares line is the line from which excess loss was calculated (i.e. dashed line in Figure 1C). The y-intercept was 145 dB and the slope was 42.0 dB/100 feet for the 612.5 kHz signal. Using the regression lines, excess loss, and attenuation rate,

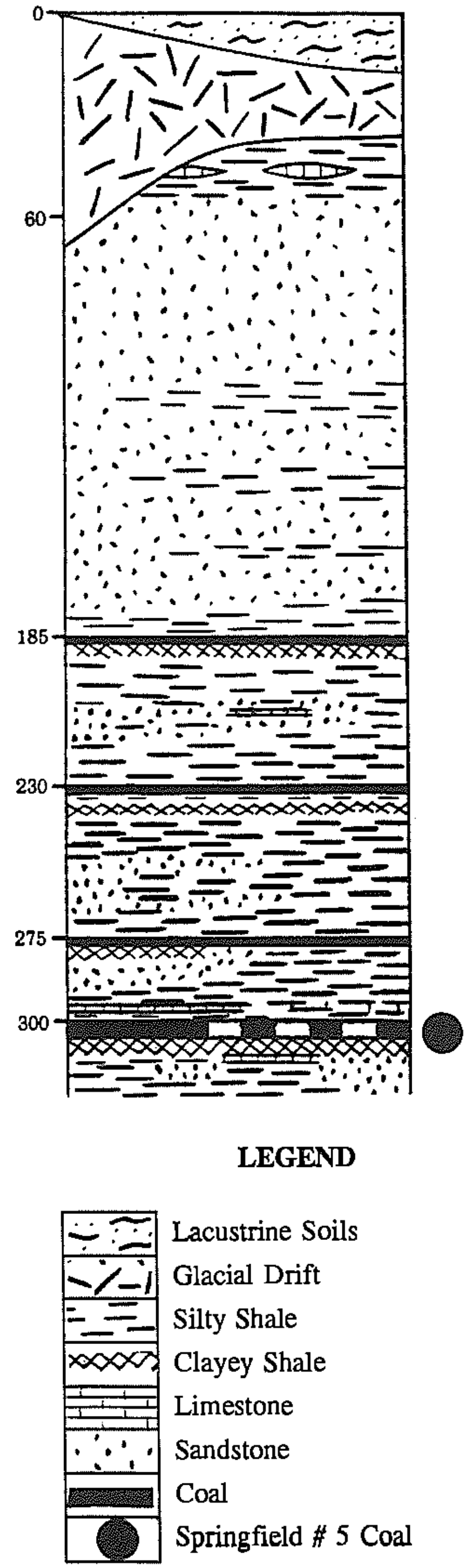

Figure 3. Generalized geologic column beneath the Wabash Valley Correctional Institution site near Carlisle, Indiana.

we calculated attenuation rate indices for all the ray paths.

Our calculations showed ray path excess loss values at 612.5 kHz ranged from -8.6 dB in unworked areas to 42.6 dB on ray paths crossing worked areas (fig. 5). These excess loss values were used in the single-frequency interpretation discussed below. Attenuation rate indices were calculated between the 612.5 kHz and 422.5 kHz data

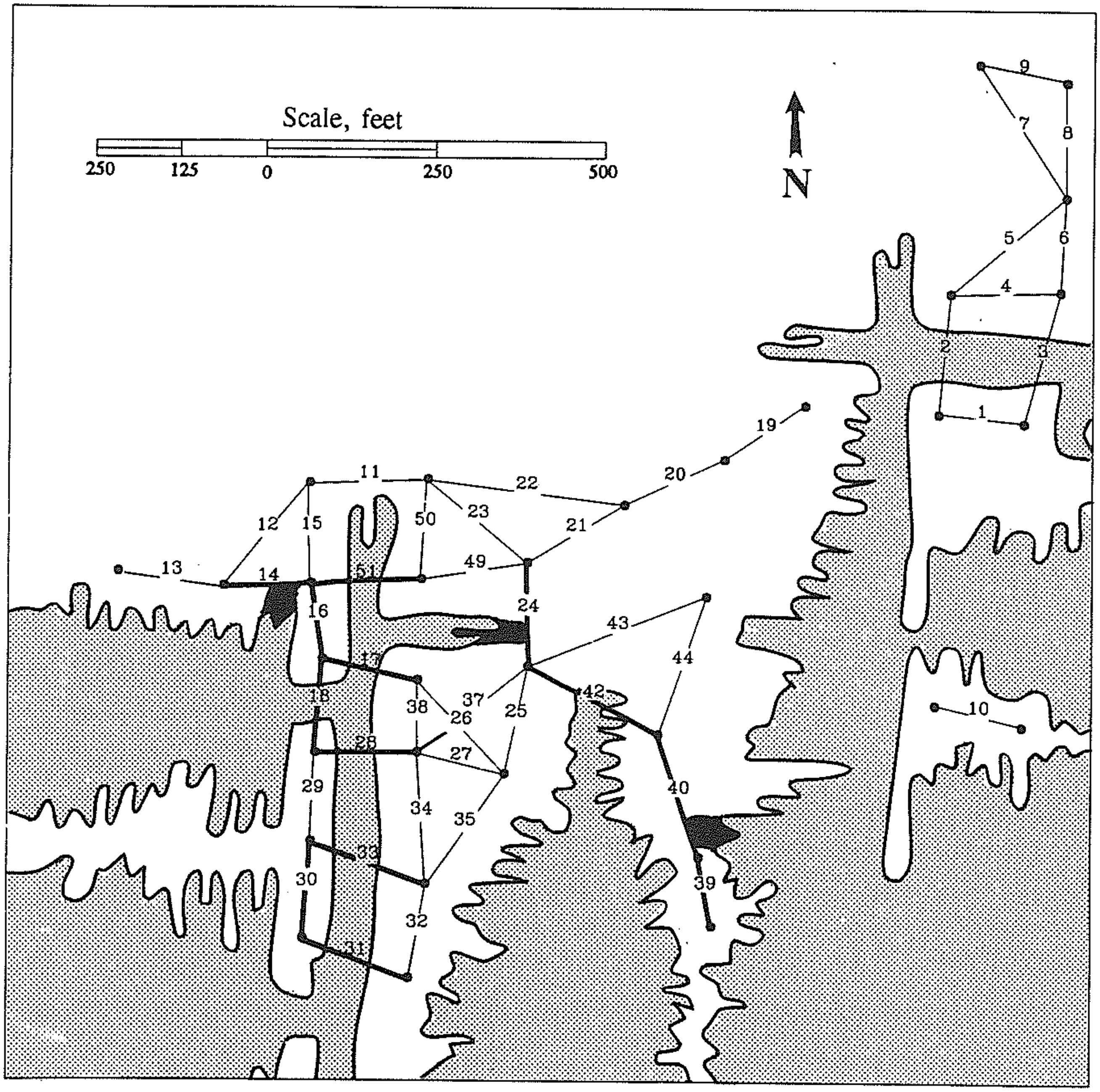

Figure 4. Map showing mine outline of the Carlisle Coal Mining Co. Mine No. 1, interpreted from the original 1928 map, and the RIM survey. Solid lines show ray paths identified by number. Shaded areas represent believed worked areas. Small circles are boreholes drilled through the coal seam. Multiple-frequency analysis ray paths are bold lines. Solid areas are mining identified by RIM and not on original map.

and used for the multiple-frequecy interpretation. The indices varied between +10 and -13. We found erratic values for the index on ray paths with measured signal strengths close to the noise level. [**Note**: Due to the success in processing the amplitude data, the phase data were not processed at this time.]

Interpretation

Scheme

We interpreted the results in a two-fold scheme. The first was a single-frequency approach that focused on the **worked** and **unworked** calibration groups to determine an excess loss value to use to separate ray paths in the **verification** group into those definitely not near mine works (low excess loss) and those that may be (elevated excess loss). The second step of the scheme was to take the ray paths in the **verification** group that may be near mine workings and apply multiple-frequency analysis to determine the position and possible type of anomalous feature causing the elevated excess loss.

Single-frequency

From the excess losses of **worked** and **unworked** ray path groups we identified an excess loss discrimination level for the **verification** group. We recognized that this value should be less than excess loss in the **worked** group but greater than any in the **unworked** group. We determined a value of 10 dB with one exception. Figure 5 shows all but one ray path in the **worked** group to have excess loss values greater than 14 db and all in the **unworked**

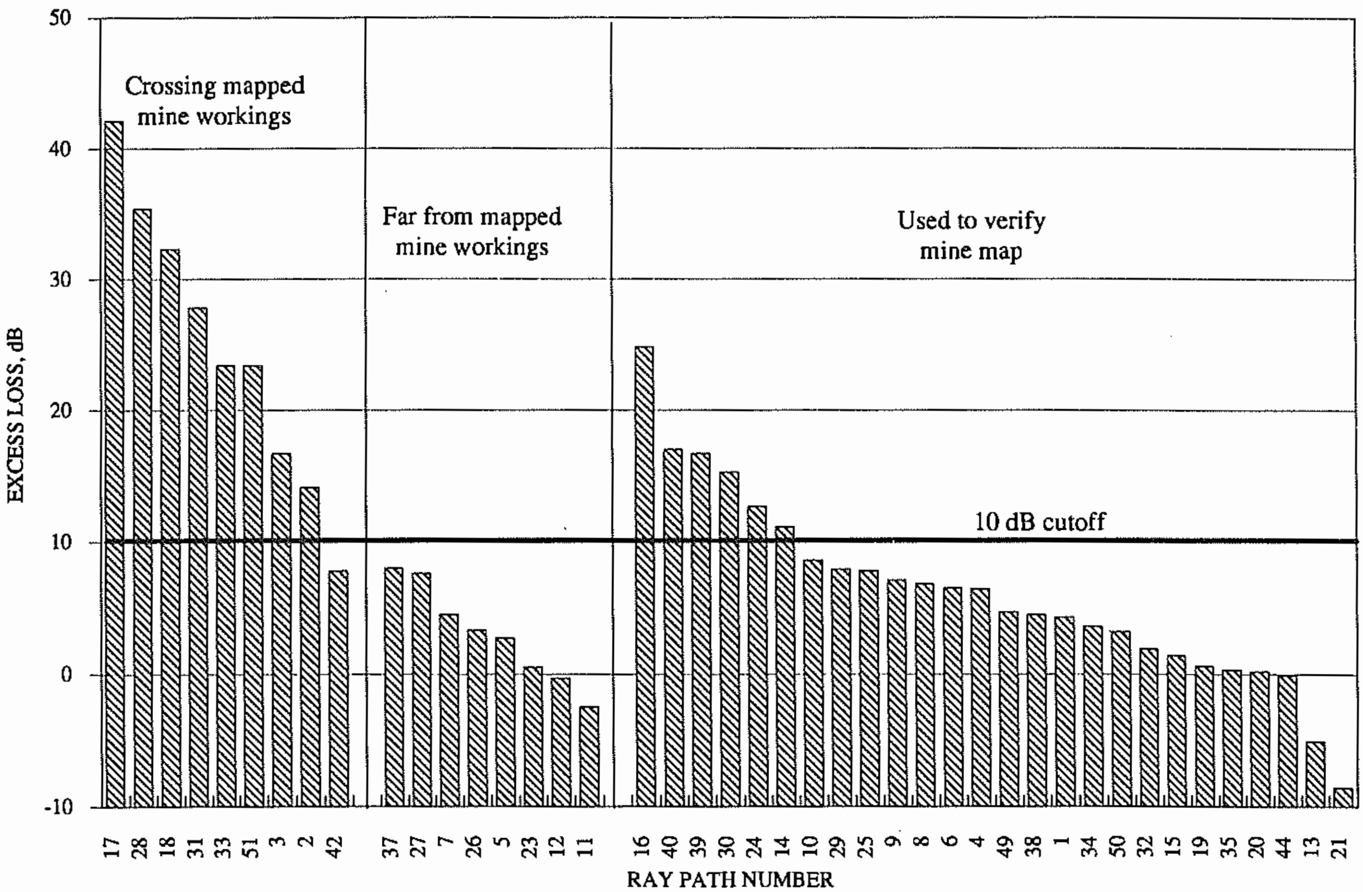

Figure 5. Excess loss of ray paths collected at the proposed Wabash Valley Correctional Institution.

group to be less than 8 dB. Ray path 42 (fig. 5) in the **worked** group is the exception with an 8-dB excess loss. This ray path only crosses the very end of a mapped-mine working (fig. 4), which explains the anomalous low excess loss.

Using the cutoff of 10 dB excess loss, we examined the ray paths in the **verification** group. Of the 26 ray paths, six have excess loss greater than 10 dB (nos. 16, 40, 39, 30, 24, and 14; fig. 4) indicating they are crossing or close to anomalous areas of the seam. We then investigated these six ray paths using the multiple-frequency approach to determine possible causes of the anomalous excess loss. Seven ray paths from the **worked** group were also analyzed in the same manner to provide calibration data for the interpretation. The seven **worked** group ray paths came from the same area as the anomalous **verification** group ray paths. These 13 ray paths are highlighted on Figure 4.

Multiple-frequency

In the multiple-frequency analysis of the six anomalous **verification** ray paths, we separated the ray paths into one of the four theoretical case studies presented earlier. We then adjusted the mine map, if necessary, to be consistent with this interpretation. First ray paths in the **worked** group were examined; then the anomalous ray paths in the **verification** group.

Worked Group. The main purpose for examining the worked group was to provide calibration information to allow us to recognize ray paths that have the potential for crossing worked areas (case B). Ray paths that cross worked areas should have some minimum excess loss. Just as in the previous section where we defined a cutoff value for excess loss to detect ray paths that may be near mining, now one is needed to recognize ray paths that may be crossing workings. Once this cutoff is determined we can confidently put the six anomalous ray paths in the **verification** group into case B, C, or D using excess loss and attenuation rate index in the following manner:

Case B Excess loss above the cutoff value and a positive index.

Case C Excess loss above or below the cutoff value and a negative index.

Case D Excess loss below the cutoff value and a positive index.

The mine map predicts six ray paths (nos. 17, 28, 18, 31, 33, and 51; fig. 4) should be case B ray paths and one (no. 42) are in case D. The six ray paths crossing mapped mine works all have excess loss above 20 dB (Table 1). Thus, the cutoff value will be defined as excess loss larger than 20 dB.

All but ray path 51 has a positive attenuation index as predicted by case B (Table 1). The field notes were re-examined for this path and it was found that T_x calibration data taken from the borehole used for this path showed anomalous phase readings. This indicates the coupling between the T_x and coal seam was different for this path than all others. This may explain the discrepancy in the index from what was expected. Even though we do not understand the exact physics of this situation, we can recognize data exhibiting these T_x characteristics that may be providing misleading results using our current processing scheme.

Ray path 42 showed a much lower excess loss, 7.8 dB, (Table 1) than the six crossing mapped mine workings and a positive index, as expected if the mine map is accurate. This ray path demonstrates the utility of the multiple-frequency approach.

Verification Group. Using the 20 dB cutoff in combination with the attenuation rate index, the six anomalous ray paths in the **verification** group can be analyzed. Only ray path 16 exceeds the cutoff value (Table 1) indicating it could possibly cross worked areas. It, however, has a negative index placing it in case C. The map (fig. 4) is in agreement with this finding, which shows the ray path parallel to mine workings. Since the remaining five do not have excess loss greater than 20 dB, they cannot cross working areas and, therefore, must fall into either case C or D.

Ray paths 39 and 30, due to a negative index, fit the criteria for case C. These findings are in agreement with the mine map (fig. 4) that shows mine workings paralleling these ray paths on both sides within 50 feet.

All ray paths discussed up to this point have verified the mine map. The last three ray paths discussed (40, 24, and 14) show discrepancies. Each of the ray paths exhibit a positive index and excess loss less than 20 dB (Table 1) placing them in case D, ray paths approaching but not crossing the ray path. However, the map indicates these ray paths should either be in case A or case C. To honor the RIM data, the following modifications to the mine map were suggested:

1) The workings mapped south of ray path 14 may extend approximately another 50 feet to the north beyond the current mapped location.

2) The workings mapped west of ray path 24 may extend approximately another 50 feet to the west beyond the current mapped location.

3) The workings mapped east of and at the south end of ray path 40 may extend another 10 or 20 feet.

Table 1. Interpretation of ray paths that either cross abandoned mapped mine workings or show excess loss above 10 dB in southwestern area of survey.

Path	Loss	Index	Case
Worked ray path group			
17	42.1	8	B
28	35.4	10	B
18	32.2	4	B
31	27.8	6	B
33	23.4	1	B
51	23.4	-4	B
42	7.8	6	D
Verification ray path group			
16	24.8	-3	C
40	17.0	4	D
39	16.7	-13	C
30	15.3	-3	C
24	12.7	20	D
14	11.1	2	D

Conclusions

Multi-frequency radio imaging (i.e., single and multi-frequency analysis) was used to identify abandoned mine working in a 300-feet deep, 5-foot thick coal seam under the proposed building site of the Wabash Valley Correctional Institution near Carlisle, Indiana. Part of the motivation for the study was to verify an old (1928) map of the workings. The results of the study modified the map in three areas. In these areas, the RIM data indicated the worked area extended further than the map indicated. The RIM cross-hole program resulted in considerable financial savings since closely spaced drill holes would have been needed to verify the existing mine map.

For the study 33 holes with spacings between 113 feet to 293 feet were drilled in an approximately 900,000 square-foot area. The holes were specifically positioned to create calibration data for transmission thorough both worked and unworked sections of the seam that could be used to interpret data across sections of unknown mining history. Of the 43 pairs of holes measured, 36 clearly showed the presence or absence of mining using single-frequency data. In the remaining 6 cases, multiple-frequency RIM data analysis provided clear answers.

Verification of the mine workings, to the level obtained from the exploration program at the site, provided sufficient data to reduce the subsidence risk at individual structure locations. For example, without adequate proof, structures liable to be affected by mine subsidence would require designing for the worst case scenario. However with the subsurface information obtained, many combinations and magnitudes of ground displacement could be eliminated making the subsidence-resistant designs simpler and, in most cases, significantly less stringent. The total expense of this exploration effort was a fraction of the costs saved in foundation design under the worst case scenario.

References

Fry, R. C., J. G. Schotsch, and L. G. Stolarczyk, 1985. The radio imaging method (RIM) -a means of detecting and imaging anomalous geologic structures in a coal seam. p. 206-211. In Proceedings of the 4th Annual Conference on Ground Control in Mining. (Morgantown, WV).

Hill, D. A. 1984. Radio propagation in a coal seam and the inverse problem. NBS 89(5):385-394.

Marino, G. G. 1990. Investigation of subsidence potential of the Carlisle Mine No. 1 at the proposed Carlisle prison site. Report IN Dept. Administration, Public Works Div.

Miller, M. C., S. Doe, and L. G. Stolarczyk. 1986. Evaluation of buried coal seams using cross-hole radio imaging method. p. 137-142. In Proceedings of the 8th Annual WVU International Mining Electrotechnology Conference. (Morgantown, WV, July 30-August 1, 1986).

Miller, M. C. and B. S. Schreiber. 1990. Advancements in the RIM technique for identifying ground shifts and faults on longwalls. In Proceedings of AMC Convention. (Cincinnati, OH).

Schotsch, J. G. and T. Sutton. 1991. Remote detection of abandoned mine workings using radio imaging method techniques. In Proceedings of the 10th International Conference on Ground Control in Mining. (Morgantown, WV, June 10-12, 1991).

Stolarczyk, L. G. and R. C. Fry. 1989. Radio imaging method (RIM) for diagnostic imaging of anomalous geologic structures in coal, trona, gilsonite and quartzite seams. In Proceedings of the 118th Annual Joint SME-TMS Exhibit. (Las Vegas, NV, February 27-March 2, 1989).

Stolarczyk, L. G. 1990. Radio imaging in seam waveguides. Geotechnical and Environmental Geophysics, Vol. III: Geotechnical, p. 187-209.

http://dx.doi.org/10.1190/1.9781560802785.ch16