Abstract

The Radio Imaging Method (RIM) is based upon electromagnetic (EM) wave propagation in the coal seam waveguide. The radio geophysics theory underlying RIM was developed by Dr. David Hill of the National Institute for Science and Technology. Recent advances in radio geophysics instrumentation have increased the operating range in the coal seam waveguide to almost 3,000 feet. This paper describes RIM longwall panel reconnaissance scans and tomography results. The paper also describes the flameproof instruments approved by Mine Safety and Health Administration (MSHA) for insertion into horizontal boreholes.
Introduction

RIM has been successfully used for coal seam imaging for two decades. As a result of Stolar’s expertise in radiophysics science and engineering, a 21st century RIM system has been developed that includes significant conceptual, electrical, and mechanical improvements that have elevated RIM performance and field ruggedness. The current system (termed RIM-IV) was a 2004 recipient of the R&D 100 Award as one of the most technologically significant new products in industry worldwide. In comparison with the earlier versions of RIM, the improved capabilities of RIM-IV include: 1) greater distance of signal transmission (this feature enables surveys of wide panels), 2) greater receiver sensitivity for improved signal measurement, and 3) detection of signal phase shift that produces greatly enhanced and higher-resolution tomographic and three-dimensional (3-D) images of coal seams.

A steady application of RIM-IV within the industry, combined with detailed groundtruthing studies, has shown RIM-IV to be is a viable detection and imaging instrument that aids in the development of new and more efficient mine planning and mitigates the effects of difficult and complex geology. Several recently conducted surveys confirm the added value to mining management of high-resolution geologic images, which enable better mine planning to reduce risks and improve production performance.

The RIM-IV systems, including Down-Hole and In-Mine configurations, have been applied to many different types of geologic regimes and imaging scenarios in the United States, Canada, Mexico, the United Kingdom, and Australia. For example, the RIM-IV In-Mine system was used to image sandstone channels, clay dikes, faults, and coal seam intrusions, as well as metaliferous ore bodies. RIM-IV system has also been used to image voids associated with old mine workings (both In-Mine and Down-Hole).

In-Mine RIM-IV Survey Equipment

The RIM-IV instrumentation consists of a transmitter (TX) unit and a receiver (RX) unit. The two units are not connected by any type of cable or wire. The In-Mine system is the most basic representation of the RIM-IV equipment. The In-Mine version is small, light-weight, and entirely man-portable. The In-Mine TX is intended to be operated from the headgate of a longwall panel, while the In-Mine RX section must remain in the tailgate. Figure 1 shows the RX unit operated in a tailgate entry between cribbing timbers.
In-Mine RIM-IV Case Study Survey

A Radio Imaging Method™ (RIM) survey was performed at the Bowie Resources Mine near Paonia, Colorado, to investigate geological conditions on B-Seam Longwall Panel #3 (Figure 2). The No. 3 longwall panel, which includes the BU1 and BU2 coal seams, is known to possess intermittent sandstone problems in the roof strata that have been encountered during entry development. The adjacent longwall block, Panel #2, was surveyed previously and the RIM tomogram detected areas in the panel with poor roof conditions. Like Panel #2, the objective of this current RIM survey was to help Bowie’s geologists and mine engineers understand the scope and severity of its geologic mining hazards.
The Panel #3 longwall block is 650 feet wide and had 6100 feet of mineable length remaining during the RIM survey. A 4800-foot survey grid was possible between the current longwall face and to a point 1300 feet inby the planned finishing line (at 0+00).

The goal of the Bowie Mine survey was to develop high-resolution radio-wave images of the #3 longwall panel. These images are designed to investigate changes in the coal seam conductivity that may be related to waveguide thinning from intrusion of roof material. Additionally, it is important to identify other serious, but undetected, anomalies ahead of mining that could impede or disrupt entry development and longwall production, adversely impacting mine profitability. The RIM survey images could also help develop a better understanding of the scope and severity of the known geologic mining hazards in Panel #3. During gate road development, several areas of poor roof conditions were intersected in the coal seam, and some undulation in the seam was observed.

With the invaluable assistance of Bowie Resource mine personnel, the calibration, reconnaissance, and tomography surveys were completed during two days of underground work effort (roughly 8 survey-hours per day, excluding travel and setup time).

Survey Logistics

The primary objective of the survey was to develop high-resolution, two-dimensional (2-D) tomographic images of the #3 longwall panel at the Bowie Mine. This was only possible by creating a high-density pattern of radio-wave transmission from the headgate to the tailgate of the block. This pattern of radio waves was created using standard tomographic techniques whereby a RIM transmitter (TX) unit was carried down the headgate entry (h/g) while a RIM receiver (RX) unit ran adjacent through the tailgate entry (t/g) at variable offsets. Hundreds of transmissions from the TX were received via the RX, and 2-D images were generated from the resulting high-frequency data sets. This process is analogous to a medical CAT scan.

For the Panel #2 survey, two RX units were used to measure each TX broadcast, creating two ray paths of radio-wave signal through the longwall block for transmission. Each ray path provided a measurement of
received signal strength unique to the origin and termination of the ray path and the condition of the coal seam through which the signal propagated. A ray-path plot is an idealised representation of the path taken by the RIM signal as it travels from the TX antenna to the RX antenna. The travel path, however, is not a straight line in reality, but rather an ellipse whose width is a maximum directly between the units. To ensure that any anomalous features would be adequately imaged, the block was mapped from just outby the longwall face (60+60 footage marker) down to a point inby the finishing line (13+00 footage marker). The Panel #3 tomography survey plan and ray path plots are shown in Figure 3.

![Complete LW-B3 Tomographic Ray Path Pattern 13+00 to 60+60](image)

**Figure 3.** Diagram of the Bowie LW Panel #3 survey plan showing ray-path pattern and density from 60+60 to 13+00.

The points of transmission and reception along the block, termed measurement stations, were prepared on 20-foot intervals. This survey plan provided 241 possible measurement stations on each side of the panel. However, depending on the ray path orientation, stations intervals of 40-foot were common. Over the length of the survey area (4800 feet) a total of 1203 ray paths were generated.
The data collection was performed at a single imaging frequency of 290 kHz. This frequency, the highest possible with the current in-mine system, was selected based on its high propagation signal levels as determined during the calibration survey.

**Calibration Survey**

Complete RIM calibration surveys were conducted during the Panel #2 work in November 2005. These data were collected along the inby corner of the #2 longwall tailgate and were close enough to the #3 longwall (implying similar waveguide properties) that no additional calibration data was needed. The Panel #2 calibration surveys indicated the overall range of the RIM signal, specifically at a preferred operating frequency of 290 kHz (1200 feet), was more than adequate for the block being imaged (650 feet). It is important to image at the highest frequency possible, while maintaining high received signal strength at long ray-path lengths.

The calibration parameters for Panel #3, including the standard attenuation rate (SAR) and the effective transmitter power (C-Factor), are unique to the electrical and stratigraphic characteristics of the mine’s coal seam waveguide and must be measured directly in the seam being surveyed. As shown in Figure 4, the Panel #3 calibration survey for the 290-kHz signal produced a SAR of 0.057 dB/ft (5.7 dB/100ft) and a C-Factor of 152 dB (+2 dBm).

![290 kHz Calibration (t/g)](image)

**Figure 4.** 290-kHz Calibration Survey results at Bowie LW Panel #3 showing standard computed attenuation rate on the inby end of the panel (5.7 dB/100ft) and range to the lowest signal measurement through the panel (1200ft).

**Reconnaissance Profiles**

The process of collecting tomographic data sets involves a series of measurement sweeps down the longwall panel. These sweeps, as seen in the ray-path plot of Figure 3, consist of direct ray paths and diagonal ray paths. Direct ray paths are perpendicular to the rib wall and travel to stations having the same footage markers at either gate road. Analyzing these direct ray paths as a reconnaissance survey is an initial method of assessing waveguide quality and detecting areas likely to contain coal seam anomalies. By plotting signal levels versus RX position for each direct ray-path, a Reconnaissance Profile is created for reference. The profile shows areas of signal variation along the longwall block. If signal drops, the attenuation rates through...
that part of the seam are increasing due to waveguide degradation. The areas of high signal level are the “cleanest” parts of the coal seam.

Figures 5 through 7 show Reconnaissance Profiles from the 290-kHz data set: Direct Reconnaissance Profile for Panel #3, a comparison of the Reconnaissance Profile’s for Panels #2 and #3, and the Reconnaissance Tomography Map for Panel #3, respectively. The comparison plot (Figure 6) shows the direct ray path attenuation rates (dB/ft). This is necessary since the measured signal strengths for the individual panels can not be readily contrasted due to significant magnitude offset (Panel #2 is wider, thus its signal levels were lower). By using attenuation rates, where the ray path distance is normalized, a direct comparison is possible.

![Figure 5. 290-kHz Direct Ray Path Reconnaissance Profile of Panel #3 from 60+60 to 13+00.](image-url)
The Panel #3 reconnaissance profile in Figure 5 shows that signal strength for the direct ray paths ranged between 100 and 118 dB (-50 to -68 dBm). Given the 200-ft shorter ray path lengths, the increase over Panel #2-magnitudes (62 to 89 dB) appears normal. The average measured signal strength is around 110 dB (-60 dBm), with higher levels inby and lower levels out by (similar to Panel #2). There are three regions of above-normal signal level along the profile indicating normal to exceptional waveguide quality. However, there are at least three major troughs (low dips in signal) which may represent in-seam anomalies or changing roof conditions.

A comparison of the Panel #2 and #3 reconnaissance profiles show that relative variations in the direct ray path attenuation rates occur at similar locations along the length of the two longwall panels (Figure 6). Were troughs occur at the same footage markers, the wave guide anomaly which creates them is roughly linear (running from Panel #2 to #3) and has a trend perpendicular to longwall long-axis. If the peaks are shared between profiles, but have some footage offset, the degree of offset can be related to the angle of the shared anomalies trend away from the longwall perpendicular. For instance, a significant broad trough is seen in Panel #2 at 51+00, and seen again in Panel #3 at 49+00. This 200-foot offset in the outby direction implies the trend of the feature is also outby on the Panel #3 side. Like Offset Ray Paths Reconnaissance Profiles (many done for Panel #2), these trends indicate waveguide variations which are not perpendicular to the panels’ long axes or are not continuous down the entire panel.

The data from the direct ray path reconnaissance data set can be used to generate a 1-D tomogram of attenuation rate viewable in plan view as a Reconnaissance Map for the Panel #3 survey grid. This tomogram, shown in Figure 7, uses a standard range of attenuation rates in the color scale: the coolest color (blue) is the lowest decay rate sampled while the hottest color (red) is the highest decay rate. In the case of this initial Panel #3 tomogram, the range was set from 0.048 to 0.073 dB/ft.
The Panel #3 Reconnaissance Map (Figure 7) illustrates three distinct types of waveguide behavior (seen previously within Panel #2). These are characterized by:

- **Normal**: normal waveguide conditions with very small signal variation (3–9 dB). Occurs from 58+00 to face, 48+00 to 53+00 and 32+00 to 37+00.

- **Moderately Anomalous**: weakening waveguide condition with abnormal signal decreases (10–20 dB). Occurs from 53+00 to 58+00, 37+00 to 48+00, and between 14+00 and 19+00.

- **Significantly Anomalous**: abnormal seam condition based on discrete, well-defined, attenuation increase. Occurs from 32+00 to outby end of survey section (does drop to moderate levels between 14+00 and 19+00).
Figure 7. Direct Ray Path Reconnaissance Map of Panel #3 (attenuation rate tomogram).
Tomography Images

While the Reconnaissance Profiles are helpful in determining both the repeatability of the data and the general waveguide condition of the survey area, only tomographic reconstruction can identify the severity and shape of in-seam structure based on all the data collected. This reconstruction is done using the Simultaneous Iterative Reconstruction Technique (SIRT) inversion algorithm. While beyond the scope of this report, it should be noted that the velocity model used was Maximum Velocity (MVM) and that the algorithm was limited to three iterations.

Figure 8 shows the survey ray path density and the 290-kHz tomographic image (tomogram) created for the Panel #3 data set using the SIRT algorithm. The tomogram shows the attenuation rates in two dimensions throughout the longwall block. The headgate footage markers are shown along the left axis. The attenuation scale for the tomogram is given in the lower-right corner of the figure.

The tomogram uses a standard range of attenuation rates in the color scale: the coolest color (blue) is the lowest decay rate sampled while the hottest color (red) is the highest decay rate. In the case of this initial tomogram, the range was set from 0.046 to 0.068 dB/ft. The waveguide, as indicated in the tomogram, does appear moderately disturbed in the areas with green color codes. In these areas attenuation rates have increased slightly over background levels. However, the area of highest attenuation rate change is in the outby section and indicates some type of distinct coal seam stratigraphic change. The attenuation rates in these areas are significantly higher than the inby and central portions of the panel. This anomaly is broad and gradual on its inby side, and very abrupt on its outby side.

In general, with a total attenuation rate range of only 3 dB/100ft (4 to 7 dB/100ft scale), the Panel #3 tomogram does not show the significant in-seam discontinuity of any major coal seam disturbances. These would generally result in 6 to 10 dB/100ft increases (at 290-kHz). The level of increased attenuation in the data is considered moderate and is most often indicative of seam thinning or increased pore-space moisture. The increase may also result from “out-of-seam” characteristics such as roof rock change or sandstone encroachment on the seam. This phenomenon was encountered in Panel #2 and correlated well the tomogram features (subjectively described by Bowie geologists).

However, as discussed in the previous survey report, the “waveguide” results from all the coal seam layers in the immediate stratigraphic column. The radio-wave energy is greatest in the sub-seam nearest the RIM antennas but the signal does travel within all the smaller “dependent” wave guides made up of BU1, BU2, etc., and is sensitive to variations in all these seams and inter-seam layers. Since the Panel #3 survey was conducted near the top of the sequence, the survey results are dominated by the upper seam condition and changes in roof geology are detectable by this method, however, the thickness of the waveguide below mining floor level will dilute the sensitivity of the signal to “roof” features alone.
Figure 8. 290-kHz Tomogram (and ray path plot) of Panel #3 showing attenuation rates throughout the longwall block. Indications of waveguide quality are given for each of the primary color indicators.

An alternate version of the Panel #3 tomogram is shown in Figure 9 with a tight contouring interval and a slightly different color code. This tomogram better illustrates the absolute shape, scale, and trend of the attenuation rate features. The contoured tomogram is shown with the original tomogram for comparison.
The geologic implications of the attenuation rate scale in Figure 9 can best be described as follows:

- 0.040 to 0.052 dB/ft = Low Attenuation Levels: normal coal seam conditions: thickest continual portion of coal seam, thinnest interbedding, low in-seam moisture, competent and electrically conductive bounding rock

**Figure 9. Additional 290-kHz Tomograms of Bowie Longwall Panel #3.**
• 0.056 to 0.068 dB/ft = Moderate Attenuation Levels: moderately anomalous: variable bounding-rock stratigraphy, moderate seam thinning, intrusion of roof material, roof undulations

• 0.068 dB/ft and higher = High Attenuation Levels: significant waveguide anomaly: changing bounding-rock stratigraphy, seam thinning, increased banding-interbedding thickness, increased coal seam moisture

In general, the Panel #3 tomograms are of high quality and the types of features expected in the seam based on the Reconnaissance Profiles were effectively delineated with a greater degree of “lateral” resolution, which is parallel to the rib.

Groundtruth Evaluations

The average signal loss for the Panel #3 seam thickness (in a non-anomalous part of the seam) can be discussed as the “standard rate” of between 0.045 to 0.057 dB/ft. If the seam thickness changes, or geologic anomalies are introduced into or near the coal seam, then the attenuation rate through that area increases. Comparing the RIM-IV results to groundtruth establishes the imaging capabilities for this mine site and imaging frequency. The two main sources of groundtruth provided by the Bowie were roof sedimentary structure maps and seam thickness maps (developmental projections, not mining history). In the following sections, these resources are used to compare the RIM tomograms from Panel #3 to known, or suspected, coal seam structure.

The color-coded tomogram from Figure 9 can be separated into three sections (inby, center, and outby) and compared to the panel’s structure map. This comparison is given in Figure 10 using Bowie’s B-Seam Sedimentary Structure Map. This Figure shows a significant correlation between attenuation rate highs in the RIM tomogram and the edges of known or suspect rock channels in the roof geology.

Section 1, Inby 1600 feet of Panel #3: The inby-third section of this tomogram constituting abnormal attenuation rates, described as Moderately Anomalous in a previous paragraph, is apparent on the mine map of Figure 10. Occurring between 49+00 and 45+00, this area is considered to possess waveguide disturbances which strongly correspond to the rock channel as mapped in the Sedimentary Structure Map. The orientation of the contour lines for the high attenuation rate anomaly at 49+00 and 45+00 does indicate a trend which parallels the channel projection into the #3 panel. This trend could be referred to as having an outby angle with respect to the h/g side of the panel.

In addition, there is also attenuation features observed in close proximity to the tailgate rib from 59+00 moving inby to at least 60+00. These features are primarily isolated to the tailgate side of the panel, although some minor extension of the contours does move across to the headgate. These subtle features inby of the main anomaly at 49+00 may also result from a roof channel system but in general, the areas inby show normal seam conditions outside of this highlighted area.

Section 2, Central 1600 feet of Panel #3: The central-third section of the tomogram shows two (2) survey areas possessing abnormally high attenuation rates on the mine map. Occurring between 45+00 and 35+50 (actually it extends inby to 49+00), this area is considered to possess waveguide disturbances which again correspond to the edges of the rock channel in the roof. The trend of the contours continue to parallel the channel projections from t/g to h/g but there is an extension of the feature towards the headgate to a point at 45+00 (h/g). This extension is not seen in the roof channel projection from the Sedimentary Map.

Between 38+00 and 33+00 the coal seam appears fairly benign, indicated by normal attenuation rates. However, starting at 33+00 the tomogram shows a broad, gradual increase in attenuation levels to the outby end of this section. The contour lines indicate that inby side of the approaching anomaly roughly parallel to
the direct ray paths but are shifting to an inby angle (referenced to h/g). This is a slight rotation in the
predominate trend of the attenuation features with respect to the roof channel anomaly seen inby (39+00 to
49+00).

Section 3, Outby 1600 feet of Panel #3: The outby-third section of the tomogram also shows two (2) areas
possessing abnormally high attenuation rates on the mine map. Occurring between 29+00 and 17+50, the
largest anomaly (in both size and severity), shows the same gradual increase moving outby and culminates in
a peak ridge running from t/g:19+50 to h/g:23+50. The trend of this attenuation ridge has a distinct inby angle
(referenced to h/g) but does not correlate with any contour lines on the Sedimentary Map, but is rather
perpendicular. The contour lines indicate that the outby side of this anomaly is abrupt and seam conditions
return to normal within 200 feet of the ridge axis.

Between the ridge of the large anomaly, and the outby end of the survey area, the coal seam returns to
normal. However, the tomogram shows a significant attenuation rate anomaly at the h/g corner of the survey
grid (16+00 to 13+00). Although truncated on two sides, this anomaly shows the same basic inby trend as the
major ridge feature.
Figure 10: Panel B3 color-coded tomogram with sedimentary structure overlay.
The sedimentary map does provide evidence that attenuation rates in the survey tomogram correlates to roof structure, in particular, roof channels. The additional form of groundtruth provided by Bowie are the coal seam contour maps. The topography of the two major upper sub-seams have been provided in the form of contour maps for the BU1 and BU2 seams, as well as the interbedding between these seams. Figure 11 shows the full length 290-kHz tomograms (13+00 to 60+60) with an overlay of the sub-seams’ thickness (and interbedding thickness).

The key object in comparing tomograms to these contour maps would be to identify any areas of correlation between attenuation rate change and sub-seam thickness change. The data provided shows that the BU1 seam thickness is fairly consistent over the length of the panel, with the exception of the outby third of the survey area. In this region, the BU1 seam thickness indicates a slight curvature in the dip of the seam. This region also corresponds to the large attenuation feature (with inby-trending ridge). While these two features do overlap, the curvature of the thickness contour does not realistically correlate to the severity of the attenuation rate anomaly. The same can be said of the interburden thickness between BU1 and BU2. There is some subtle correlation between interburden variation and attenuation change as shown by the overlap of the anomaly and the interburden contour map.

The best look at total seam stratigraphy is given in Figure 11 with a contour of total distance between the top of BU and the bottom of BU2. This figure shows that total waveguide thickness is variable along the length of Panel #3 and that some correlation with attenuation rate is apparent. The anomaly near the center of the survey area matches well with the contour lines of the thickness map. The central contour ridges of each map (tomogram and thickness map) nearly overlap while the down-dipping feature on the inby side tracks well with attenuation rate peaks that curve around to run parallel in close proximity to the t/g rib. The outby attenuation rate anomaly also possesses a trend which parallels the thickness contours. Figure 11 shows a definite correlation between attenuation and thickness of the waveguide stratigraphy. This is a significant conclusion and a key graphic in the report.
In-Mine Case Study Survey Conclusions

The Panel #3 RIM survey performed at the Bowie Mine provided high-quality measured signal strengths and superior tomogram quality highlighting the width, trend, and severity of waveguide disturbances in the panel. With a total attenuation rate range of only 3 dB/100ft (4 to 7 dB/100ft scale), the Panel #3 tomogram does not show the significant in-seam discontinuity of a major coal seam disturbance. The level of increased attenuation in the data is considered moderate and does not result from any type of “major” in-seam anomaly, at least not one completely within the coal seam. The increases most probably result from “out-of-seam”
characteristics such as rock channels encroaching into the roof of the seam. This phenomenon was encountered in the Panel #2 RIM survey and correlated well with the panel’s respective tomogram features (as subjectively described by Bowie geologists).

The tomograms are of greater quality than from the Panel #2 survey due to the increased ray path density and addition of higher incident angle ray paths. The coal seam features were effectively delineated with a greater degree of “lateral” resolution in diagonal directions within the panel than with Panel #2, which displayed more cross-panel biasing (parallel to direct ray paths) due to the lack of high-angle ray paths (>20 degrees).

The sedimentary maps do provide evidence that attenuation rates in the Panel #3 tomograms correlate well to sedimentary structure, in particular, roof channels. Comparing the tomograms to the coal seam contour maps also showed a definite correlation between attenuation and thickness of the waveguide stratigraphy. The waveguide includes all the coal seam layers in the immediate stratigraphic column. The radio-wave energy is greatest in the sub-seam nearest the RIM antennas but the signal does travel within all the smaller dependent wave guides made up of BU1, BU2, etc., and is sensitive to variations in all these seams and inter-seam layers. Since the Panel #3 survey was conducted near the top of the sequence, the survey results are dominated by the upper seam condition and changes in roof geology are detectable by this method, however, the significant thickness of the waveguide below mining floor level will dilute the sensitivity of the signal to roof features alone.

Bowie geologists are currently conducting a more empirical study of mining history and seam condition for both Panel #2 and #3 as mining progresses.

Crosswell RIM-IV Instrumentation

A Crosswell RIM-IV imaging system is available for surface and in-mine borehole applications for coal mining. While more complicated to deploy than the In-Mine system, the new RIM-IV system includes smaller tool diameter, longer borehole depth capability, mobile transport platforms and generators, onboard PDA-based data collection and processing displays, and several key MSHA approvals for in-mine usage. This imaging system has been field tested in both coal and metaliferous boreholes with never-before-seen range and resolution capabilities.

To facilitate the deployment of the borehole tools in horizontal (+/- 30 degree dip) drill holes, a method by which to propel the tool from the top-of-hole (TOH) to the end-of-hole (EOH) was needed. A water-pressure system was developed and tested for this purpose. This system uses 2-inch diameter, flush-joint PVC pipe as a liner for the horizontal boreholes. The TOH is capped by a special coupler which pressurizes the liner with water while allowing the tool, and its fiber optic cable, to pass fluidly through a sealed barrier and down the borehole. The EOH of the lining is capped with a perforated sleeve which allows the water to exit and flow back out of the drill hole along the outside of the PVC liner. With as little as 10psi of water pressure (controlled by the operator at the TOH coupler) the RIM probes can be accurately deployed down the horizontal borehole while monitoring position through the graphical user interface.

Crosswell Electronics

The RIM development team has finalized the mechanical design of the antenna, battery packs and electronics probes. These designs include cylindrical (borehole probe) flameproof enclosures with specialized end-apters. The tasks to secure MSHA approval for the RIM probes are in their final stages. The last of the approvals are pending in the near-term. Flameproof testing has been successfully completed and only the advanced notification on the intrinsically safe certification (I.S.) of the battery packs and antennas is outstanding.
Stolar has tested the instrumentation in their laboratory as well as in a controlled mine testing. The system has proven to be fully functionality and operation capabilities. The electronics assemblies (receivers and transmitters) are fully functional and field-ready, as shown in Figure 12; these include primary and backup electronics. The receiver sensitivity and operational bandwidth exceeds capabilities of the prior prototype system.

![Figure 12. Croswell 3-D RIM electronics assemblies based on RIM-IV prototype design (transmitter and receiver pairs). These electronic chassis are the commercial version shown here before packaging.](image)

Antenna assemblies, as shown in Figure 13, have been built at the following frequencies: 90, 190, 290 kHz (including primary and backups). Battery packs are also built into probe housings using D-cell batteries and current trip boards (important to I.S. approval). Additional testing has been done to ensure the system is environmental sealed and robust enough for field use.

![Figure 13. The Crosswell 3-D RIM system uses one of four antenna assemblies (30, 90, 190, and 290 kHz) and rechargeable Nickel Metal Hydride battery packs. Stainless steel end-adapters are used with pin-and-socket connectors on each probe-end.](image)
**Crosswell Hoists**

The crosswell equipment is operated with fiber optic hoists (electric operation) to pull the TX and RX probes out of the boreholes during field use. The hoists have a depth encoder that measures the position of the probe within the borehole for each measurement. The fiber optic hoists built for the newest crosswell system have 2100 feet of fiber optic cable on their spools. Figure 14 shows the build up of the Crosswell 3-D RIM system early in its testing program.

![Hoist frame complete with fiber optic spool, motor controllers, and stock depth counter.](image)

**Local Field Testing**

Once the hoist build-up was complete the electronic probe assemblies were added and local field testing of the Crosswell system was begun. This testing involved surface-based calibration surveys at a test site near Raton, New Mexico. These tests involved assembling the probe sections on site and moving the TX and RX probes through a range of distance, frequency, and gain setting to establish communication stability, calibrator settings, and measure the air-wave attenuation rates for each imaging frequency. This testing is shown in Figures 15 and 16.
Figure 15: Local field testing of the Crosswell 3-D RIM system (TX and RX Hoists) immediately after initial build-up (and before actual mine-site surveys).

Figure 16: Field testing set-up included RX hoist during probe deployment (top), assembled RX probe (center), and prototype RX graphical user interface (bottom).

MSHA Approvals

The MSHA approval process needed to have the Crosswell 3-D RIM system entirely certified for methane-air use is completed. The components involved in the approval include:

1. Electronics Tubes are approved Explosion-Proof (X/P) housings.
2. Display enclosures are approved Explosion-Proof (X/P) housings.

3. Battery pack and antenna are approved as Intrinsically-Safe (I/S).

The explosion-proof evaluations are complete. The electronics are approved for use in an explosion-proof enclosure (stainless steel) with the proper end-adaptors (titanium).

**Advanced Hardware Upgrades**

Two new hardware components were recently integrated into the Crosswell RIM system to replace outdated prototype units. These are the components related to hoist’s depth display and the Graphical User Interface (GUI). In light of recent developments in the availability and commercial software for person digital assistants (PDA), Stolar changed from the prototype display to a smaller, cheaper, more reliable PDA GUI. These units use HP Pocket-PC handhelds to control the RIM electronics over a wireless link. The PDA is currently used in a dust-proof housing to simplify field surveys. An approved X/P housing is available but only used under mandatory regulation in non-fresh air entries.

The new depth counter uses smaller and more modern circuitry than the original encoder LED display. The depth counter module, termed the Junction Box, also serves as a communications hub for the PDA, probe, land-link, and depth encoder. In this hub all the RS-232 communication links for the subsystems (both TX and RX) are multiplexed for a single wireless link to the Bluetooth modem in the PDA. The Depth counter software counts to a maximum of 10,000 feet and shows the rate of probe movement up to 2.0 feet per second either going up or down. The probe depth is updated on the LED display module of the junction box every 0.1 feet. On start-up the counter will display either the last depth measurement before power-down or using a PRESET value (usually probe length). The display electronics includes LED modules with a logic driver, a thumbwheel switch to preset the depth, and a buzzer to let you know that the depth is less than 100 feet. The junction box and PDA display are generally mounted on the top of the unit hoist (one for both RX and TX) as shown in Figure 17. Both units are within view of the hoist operator.
Horizontal Survey Methodology and Equipment

During standard down-hole RIM surveys in vertical boreholes the method of probe insertion and extraction is aided entirely by gravity. For this project the RIM probes will be used in horizontal borehole. This is a new process that will make deployment of the probes difficult without a method to insert the probes deep into the boreholes, measure precise location, and safely withdraw the probe during the survey. For this application special equipment was developed, built and tested to propel the probe deep into the borehole, under very fine control, using water-pressurized. This was accomplished by designing a PVC lining and metal pressure-coupler that could be used in a borehole with water input from the mine. The coupler allows the probe to be inserted through it while sealing around the fiber optic cable so sufficient water pressure is developed in the lining to apply a propulsive force against the end of the probe housing. Pressure is controlled with an input valve on the coupler and monitored on a gauge at the water input.

The location of the probe in the lined hole is then monitored with the standard depth counter at the hoist operator’s station near the borehole. The methodology and equipment needed to deploy the RIM probe is entirely mechanical, it meets the MSHA requirements for use underground. However, the hoist must be located in fresh air, generally outby the last open crosscut. The fiber-optic cables that trail from the probes must not be damaged during the insertion or extraction of the tool from the lining and coupler.
The Crosswell 3-D RIM in-seam propulsion system hardware has been designed and built. The system consists of perforated PVC lining and a steel coupler-head for water hook-up, pressure control, and fiber-optic cable entry. Field testing of the coupler device is ongoing. The lining material itself is a 3-inch PVC tubing (Schedule 80) with a 2.5-inch internal diameter. The lining is assembled with 10-foot sections at flush-joint threaded connections. Any length of liner is conducive to the process provided that the lining at the end of the hole be open to allow water to escape. To do this effectively, the lining uses a perforated tube at the end of the liner string to allow water passable while keeping material out of the tube. The liner also uses a tapered end-cap, shown in Figure 18, to improve the insertion of the liner into the borehole. Once the survey is complete, the liner is extracted and dismantled for re-use at another borehole.

![Figure 18. The lining material is 2.5-inch, schedule 80, PVC with a perforated tip to allow water leakage under pressure. Using 10-foot PVC sections, any borehole length of 20 feet to 2000 feet is possible.](image)

The in-seam propulsion system hardware has been tested on the surface to ensure adequate pressure control and probe movement. These field tests involved deploying 1000 feet of PVC lining and a pressure-coupler. A RIM RX probe was fitted into the coupler and the fiber optic cable sealed with the grommet kit. A water supply line was connected to the couple and the water-pressure increased until the probe began to move down the lining tube. This field test is shown in Figure 19.
Tomography Processing Models

Stolar has spent significant time creating analytic models with tomographic RIM images. However, these models are constantly being improved, so the team has continued to review the current portfolio of models available (ART, SIRT, and other least squares techniques) for creating images and, more importantly, correlating with ground truth. This work has involved using data from recent RIM field tests to evaluate different tomographic modeling algorithms (creating 2-D and 3-D images) and optimize the procedure of analysis for RIM tomography.

Using several RIM-IV data sets, along with older data sets collected in the last 3 years, an evaluation of several popular tomographic reconstructive algorithms has been completed. These commercially available algorithms include: Algebraic Reconstruction Technique (ART), the Simultaneous Iterative Reconstruction Technique (SIRT), the Conjugate Gradient Least Squares (CGLS) method, and the Least Squares iteration (LSQR) algorithm.

The Algebraic Reconstruction Technique (ART) is a standard technique for solving large sparse linear systems that arise in medical tomography. This technique was introduced for seismic inversion and has become the standard method in geophysics. The Simultaneous Iterative Reconstruction Technique (SIRT) is a modification of the ART algorithm. Used in the modern era for geophysical tomographic inversion, this method improves the convergence problem encountered using the ART method. The Conjugate Gradient Least Squares (CGLS) method is also an iterative method that has been used in geophysical tomography. This method solves a normal least squares equation and produces a favorable minimum norm least squares
solution. The Least Squares QR (LSQR) algorithm is another iteration method for solving large sparse matrix system. LSQR algorithm is a combination of special iteration methods and the CGLS method.

WVU and Stolar have generated tomographic images of 3 known targets that have been surveyed by in-mine RIM instruments in the past year. These images were created using all four tomographic models. Using ground-truth information provided after the survey area was mined; an assessment of the models resolution, accuracy, and inversion convergence was done. When cross-correlating RIM images to known geologic conditions (based on mining history and ground-truth) it was determined that the SIRT algorithm best demonstrated image characteristics related to actual seam parameters. These parameters include bench thickness, seam undulation, and seam intrusion or discontinuity. This groundtruthing study was conducted by WVU Mining Engineering Department in 2003 and presented at the 22nd International Conference on Ground Control in Mining and the 2004 SME Conference. This paper describes the comparative details of various tomographic inversion algorithms for a survey performed at Consol’s Mine Eighty-Four.

Additional data sets are still being evaluated with variations of the SIRT method. One variation is commercially available (ImageWIN from CMTE Australia) and the second is being developed by the Mining Engineering Department at WVU. The implementation of more advanced Full Wave Inversion Codes (FWIC) is also on-going. Validation of the FWIC tomography algorithm will have been achieved by comparison with SIRT reconstruction of the same anomalous geologic zone in the coal bed. While Stolar controls and implements FWIC software, WVU is developing a tomography simulation program to be used as a supplementary tool for the FWIC program. This program is to simulate the effects of geological anomalies, the thickness and bending condition of the coal seam on the signal attenuation and phase changes. The benefits of this simulation program are: (1) to check the correctness, accuracy and sensitivity of FWIC interpretation, (2) to provide guideline for planning a RIM survey.

In addition to optimizing “off-the-shelf” tomographic algorithms, Stolar and WVU are evaluating specialized algorithms created by several leading researchers. WVU has formally structured a developmental program to create a physical modeling test bed for tomographic evaluation for both inverse and forward modeling. This work includes the fabrication of a physical modeling apparatus which serves as a miniature-scale longwall bed for tomographic evaluation for both inverse and forward modeling. This test bed is essentially a small scale waveguide stimulant with microwave imaging tools used over short distances within the waveguide in simulation to current RIM survey technique.

WVU is doing a feasibility study for building and conducting Radio Imaging Method (RIM) small-scale physical modeling. If feasible, many of the factors that will affect the EM wave attenuation, such as the changes of coal seam thickness, intrusion of sandstone channels, seam undulations, faults, contents of ash, S2, moisture content, etc. can be more studies more easily on laboratory small scale models. The following issues have been discussed with experts in the field:

- **Size of the models.** Since the sizes of the scale models are the first factor to be considered in the physical modeling. It depends on the antenna size of the radar used in the tests which in turn depends on the frequency. The equipment to be used in the study includes a radar system with a 1.2 GHz antenna on loan from NIOSH. Using this antenna, the size of the model should be between 4 and 6 ft. The other dimensions should be determined.

- **Radar antenna.** The NIOSH antennas are of the bowtie type, that is the transmitter and receiver antennas are tied together for the normal reflective studies. However, the physical modeling requires the testing EM wave being transmitted from one side to the other of the model. The transmitter and the receiver antennas should be separated. Steps are underway to secure the separate antenna types.
Shielding of the radar wave. Due to the relatively small size of the scale models, there is a high possibility for the EM signals to reach from the transmitter to the receiver through the surrounding air rather than through the model itself. In order to prevent this, the air path should be shielded out. Barriers are being built with Echo foam on both transmitter and receiver sides for this purpose.

Materials for the producing the stimulant rocks. How to produce the material layers in the scale models to represent the real rock strata is another important issue. NIOSH has used aluminum, carbon and iron powders in laboratory tests. Proper mixing of materials with various dielectric constants and conductivities should be tried and samples of these resultant materials should be tested on the EM property testing setup.

The goal of the physical modeling test bed to be better evaluation algorithm validity based on Image-to-Ground Truth correlation. These test bed evaluations are currently on-going.

Crosswell RIM-IV Field Surveys

Field surveys using commercial versions of the down-hole and crosswell RIM-IV system include tomography and reconnaissance in both coal and metal mines (Figure 20). These RIM surveys were performed at locations that had suspected geologic disturbances and some measure of groundtruthing. The RIM team conducted the surveys using standard practices and collected data with signal attenuation rate and signal phase shift. Stolar has worked with the mining companies to interpret the data and assist in mine planning. WVU has worked to analysis the mining and engineering risks that are implied by the RIM results. They are deciding how these results impact the current engineering plan the mine has in place and how any changes in planning would effect production and economics. Once the surveyed section is mined through, the actual impact feature on risk and economics are assessed and compared to estimates.

Consistent use of the Crosswell RIM-IV instrumentation provided three major benefits to the on-going improvements of the system. First, the survey work allowed the new instruments to be used in a real world environment where inefficiencies or failures in the mechanical and logistical operation of the system could be debugged and fine tuned. Secondly, the operational capabilities of the system were analyzed under a wide variety of geologic conditions so that performance specifications were quantitatively evaluated. These specifications include measurement and scanning speeds, data transmission and storage rates, transmitter coupling factors, receiver noise, operating range (distance), normal signal attenuation rates (geology dependant), resolution scale, and phase stability. The final developmental benefit of this field work has been in the acquisition of data sets needed to develop a tomographic algorithm evaluation plan. Analysis of this data was immediately reported to the mining companies for the purposes of geologic interpretation and mine planning.
Figure 20. Field survey data collection efforts with Crosswell RIM-IV.