ELECTROMAGNETIC WAVE DETECTION AND IMAGING TECHNOLOGIES (EDIT) FOR REDUCING ASH, SULFUR, AND HEAVY METALS IN RUN-OF-MINE COAL

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ABSTRACT

The historical development of longwall and continuous miner automation began with principal goals of improving safety and productivity in the mining of coal. From the mid 1970s to the present time, computer-assisted mining machine technology development and enhanced machine designs have resulted in high productivity machines with very low downtime. This paper suggests that the technology roadmap leading from today's computer-assisted to tomorrow's semi-autonomous machine designs will cause further increases in productivity while achieving significant gains in reducing ash, sulfur, and heavy metals in run-of-mine (ROM) coal. Oftentimes the thin layer of seam boundary coal contains higher percentages of ash, sulfur, and heavy metals. A drum-mounted sensor that measures uncut coal thickness in real time will prevent mining through the contaminated coal layer and into the roof/floor boundary rock. Remote seam mapping of anomalous geology would also reduce ROM coal contamination, improve mine planning, and decrease the risk of unexpected increases in mining cost. The reduction in emissions from the Nation's electric power utilities will be gained by applying newly developed remote sensing technology.

INTRODUCTION

Apollo 17's successful landing on the surface of the moon and subsequent moon walk by Astronaut Harrison H. "Jack" Schmitt proved that man and his semi-autonomous machine could be accurately guided to a remote location and acquire geologic information. Being the son of a famous mine geologist, it was natural for this Harvard-trained geologist to wonder why NASA's semi-autonomous machine technologies could not be applied in mining (1). In 1975, Schmitt was successful in establishing the Advanced Mineral Extraction Technology project at the Marshall Space Flight Center (MSFC). In an agreement with the Department of Interior (DOI), this project was to initially focus on the coal mine automation problem (2). Ed Moore and Harry Elkins of Kaiser Steel's coal mine near Raton, New Mexico, cooperated in the initial NASA demonstrations of coal interface detection sensors required in mine automation. In October of 1977, the project was transferred from the DOI US Bureau of Mines (USBM) to the Department of Energy (DOE). The Coal Division of DOE entered into an agreement with the Jet Propulsion Laboratory (JPL) to continue mining machine automation research. JPL scientists developed the Advanced Coal Extraction (ACE) project in cooperation with engineers at Utah Power and Light (now InterWest Mining Company), US Steel, Lee Engineering, and Joy Manufacturing to determine what technologies were needed to transform mining machines into semi-autonomous machines (3). The JPL study determined that five ACE technologies were needed in the building of a "NASA"-like semi-autonomous machine (4):

- Sensor required for semi-autonomous machines
  - Remote seam imaging in advance of mining
  - Real-time guidance and navigation sensors for mining in an undulating coal seam (horizon sensor and lateral guidance)
- Real-time operating systems for computer-assisted mining
  - Data communications between machine subsystems and the supervisory computer (shield and pan-line advance, shear tram and ranging arm control)
  - Real-time machine control algorithms (face alignment, last cut memory)
  - Self-diagnostic algorithms (fault and failure diagnostics).

In 1982, JPL judged the first two sensing technologies to be beyond the state of the art and in need of development. The three remaining technologies were within the art and could be integrated in mining machine design.

A snapshot of today's state-of-the-art machines shows that machine manufacturers have steadily improved the building of electrohydraulic-controlled machines that now exhibit high productivity and very low downtime. Bessinger and Nelson (5) at CONSOL proved that a well-conceived industry-directed development and adaptation plan could integrate real-time operating systems on a longwall machine, creating a computer-assisted mining machine. This was a remarkable achievement in terms of cooperation in technology development during production in a mine with high productivity goals. Prior to CONSOL's work, the British Coal Board pioneered the development of technologies needed in computer-assisted mining (6)(7)(8)(9)(10). Following the NASA-JPL studies and occurring in the same time frame as CONSOL's work, the USBM developed a computer-assisted continuous miner in a laboratory-like underground mine environment (11). Because this program was not industry driven, the USBM work did not find its way into practical mining; however, parts of the USBM work were adapted by Arch Technology in their highwall miner.

The JPL study was correct in its assessment that remote sensing and navigation were tough problems beyond the state of the art. Because real-time remote sensing and imaging technologies were not available to work with the real-time operating system, the National Coal Board, CONSOL, and others were forced to settle for "last pass" memory (12)(13). The last cut memory control algorithm is based upon the measurement of prior cut machine control parameters. These data are processed in a prediction algorithm to determine the next machine cut control parameters. A subsystem for machine operator interdiction was required to reset the machine parameters to maintain cutting within the coal seam. Even though these pioneers failed to achieve semi-autonomous machine operation, productive enhancements of tens of percent were achieved in everyday mining. Additional savings were achieved in maintenance and consistency of the cut. Although the NASA/JPL assessment of the mine automation problem was conducted from the perspective of improving productivity, today's national concern over emissions from coal-fired electric generation stations adds an environmental perspective to the machine automation problem.

During the period of time that Government-sponsored and industry research and development focused on the upstream computer-assisted machine design problem, the DOE focused its R&D work on the downstream problem. The government, through the DOE's fossil fuels program, has invested along with industry in development and demonstration of clean combustion technologies. For private and a \$200-million government investment, US sales of this technology are \$6 billion—\$2 billion coming from foreign sales—a handsome payoff for upstream environmental investment. Since the industrial revolution, environmental concerns over emissions from coal combustion have persisted. Today, US coal-fired generation emissions meet and exceed regulatory standards. A 1970-vintage boiler rarely resembles the state-of-the art designs of today. Emissions of SO_2 and NO_X from new plants have declined despite a doubling of coal-fired generation. Acid rain, along with the buildup of heavy metals such as mercury in our National waterways, continues to be a national concern. Clean air regulations have caused utilities to switch to compliance coal with lower sulfur dioxide per million British Thermal Units (BTUs). Disposal of ash with heavy metals is now evident on the Environmental Protection Agency (EPA) radar screen. Environmental concerns force the coal mining companies to develop mining methods to increase run-of-mine (ROM) coal quality. On average, coal contains 10,338 BTU/pound, 9.36 percent ash, and less than 1.17 percent sulfur. Yearly combustion releases a minimum of 4.68 million tons of sulfur dioxide into the atmosphere. Emission controls result in 34.4 million tons of fly ash. Utilities assume a \$3 per ton liability for disposal cost.

It should be recognized that there is more to be gained in emissions reduction by working on the upstream problem (inby the portal) and solving the tough remote sensing and imaging problems identified by NASA/JPL. The next step in enhanced mining technology would transform today's computer-assisted machine design to a semi-autonomous machine with industry benefits of increased productivity, optimized coal reserves, and improved quality of run-of-mine (ROM) coal.

The potential for reducing emissions with upstream R&D follows from the chemical and biological studies of the peat-forming process in deltaic depositional environments (14)(15)(16). These studies of depositional geology suggest that thin boundary layers of coal are oftentimes contaminated by much higher percentages of ash, sulfur, and heavy metals when compared to the rest of the seam. The contaminated coal layer is obvious to miners working in today's modern mines. The contaminated boundary layer occurred in the peat-coal swamps where vegetation rapidly developed adjacent to the distributary channels. The atmosphere in the inland drainage area was oxygen-rich where oxides of the heavy metals formed and then were carried along with the sediments into the delta swamp. The swamp, being a reducing environment, caused sedimentation of the heavy metals, and subsequent subsidence caused the microbial accumulation to change from aerobic to anaerobic bacterial strains. The metabolic process changed from carbon dioxide to hydrosulfide/methane gas generation. The reduction and biological processes produce pyritic and organic sulfur in the peat-coal. The depositional episode of burial and compaction caused 7 to 14 feet of peat to be compressed into a thin (oftentimes less than 1 foot) contaminated boundary layer of coal. In Southwestern Pennsylvania, mine operators are interested in leaving approximately 6 inches of floor coal that contains higher percentages of sulfur than are near the center of the coal seam. As stated above, the existence of the contaminated layer is known to mine personnel; however, because ROM coal quality is measured in bulk samples of coal, contaminate stratification information is not available for most coal deposits. The impact of the contaminated coal layer on ROM quality is exacerbated by the greater density of the contaminated layer when compared to the seam coal. When the contaminated layer is mined along the seam coal, the coal quality is significantly reduced. Figure 1 illustrates the contamination.

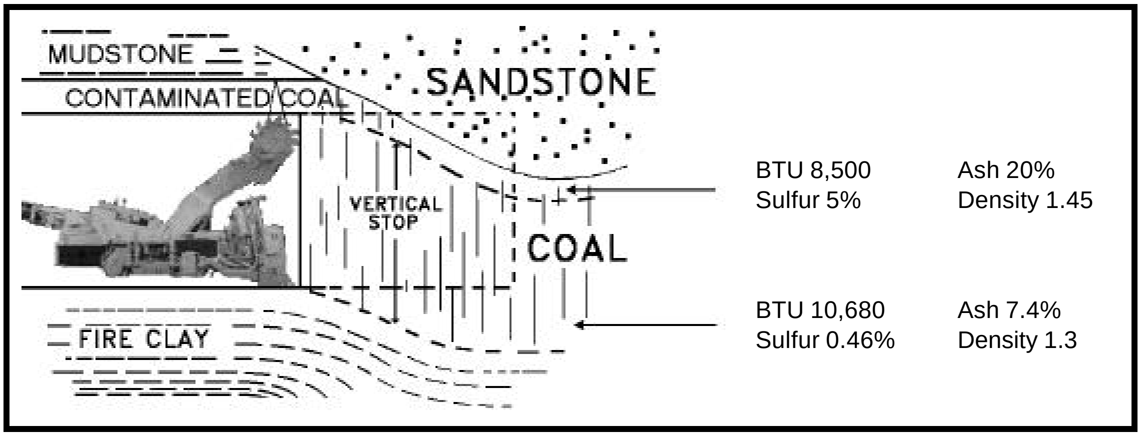


Figure 1. *Vertical cross section illustrating Electromagnetic wave Detection and Imaging Technology (EDIT) horizon sensing and the sump-cut cycle*

An example of the improvement in coal quality is illustrated in the figure. If the entire seam is cut, the ROM coal quality is 10,338 BTU, 1.1 percent sulfur, and 9.36 percent ash (the average ROM delivered to the electric power generation industry). If the contaminated layer is left behind, mining produces compliance coal with a BTU value of 10,680 BTUs, 0.46 percent sulfur, and 7.4 percent ash. In this example, the uncut coal thickness reduces organic sulfur by more than 50 percent.

Because coal seams dip (roll) under paleochannels, the machine cutting drum horizon must be lowered for the machine to remain in the coal. This requires a drum-mounted sensor.

In today's snapshot of the mining process operating mine personnel are in close proximity to the machine. The operator is required to visually establish a frame of reference for the cutting horizons (usually a marker band) to follow in order to prevent mining into roof and floor sedimentary rock. Leaving bottom coal in a longwall wall or continuous mining section is a notoriously difficult task. The frame of reference or cutting horizon is lost when the machine is on top of the contaminated coal layer. When cutting into the sandstone, Mine Safety and Health Administration (MSHA) dust regulations become more stringent as silicon dust increases. Mining into sandstone roof rock creates large quantities of quartz dust. Cutting may produce flying sparks, which could ignite methane gas. This exposes the machine operator to high levels of dust and acoustical noise and, in deep mines, coal fragment outburst. MSHA regulates dust and acoustical exposure. Dust exposure gives rise to the occupational "black lung" disease. High acoustical noise level causes hearing loss; mine personnel are compensated for hearing loss. In the 1969 Coal Mine Health and Safety Act, Congress called for a formula to be developed to lower the amount of respirable dust in the mine below what is normally allowed (2 mg/m^3) whenever the quartz level in the dust is greater than 5 percent. This was based on the recognition that the toxicity of coal dust increases when higher levels of quartz are present. In the past, it has been difficult to make quartz measurements. MSHA enforcement people have been provided with a new infrared instrument for making quartz measurements. Mining companies attempt to comply with MSHA regulations and control dust by spraying water to reduce dust plumes, reducing the cutting rate of coal shearing machines and increasing fresh air flow to disperse dust particles. In large mines, maintaining adequate ventilation air velocity to disperse dust becomes a serious problem. In these mines, compliance with dust regulations requires a reduction in cutting height along with less resource recovery. Cutting into the fire clay floor causes efficiencies of the wash plant to decrease. The waste rock in some ROM exceeds 30 percent.

HORIZON SENSING

Researchers around the world have accepted the grand technology challenge of developing remote sensing technology called horizon sensing. Sometimes this technology is called coal-rock interface detection (CDI). CDI is not the problem to be solved in NASA/JPL's vision of a semi-autonomous machine—this type of sensing is too late to avoid contamination of the ROM coal. In examining the historical development of horizon sensing technology, one must be impressed by the fact that almost every known physics principle has at least been explored and some were even developed to the demonstration stage. The real-time uncut coal thickness problem is easy to define and hard to solve. An effective sensor must measure uncut coal thickness in real time and be positioned on the mining machine so that it can be effective in controlling the cut horizons in an undulating coal seam. Furthermore, the sensor must be effective in coal seams where bounding rock changes from mudstone/shale to sandstone associated with paleochannels. The sensor is especially needed along the margin of paleochannels where rolls in the seam begin and the machine cut horizon must rapidly change with advance of the machine. These requirements suggest that the horizon sensor must be located on the surface of the drum instead of on the body of the machine. This mounting position brings with it extreme withstanding requirements of vibration, abrasion, and shock associated with the drum pick's cutting of coal. Measurement of roof and floor coal layer thickness in real time requires that the measurement be completed in a 6-degree arc centered on the vertical center line of the cutting drum, as shown in Figure 2.

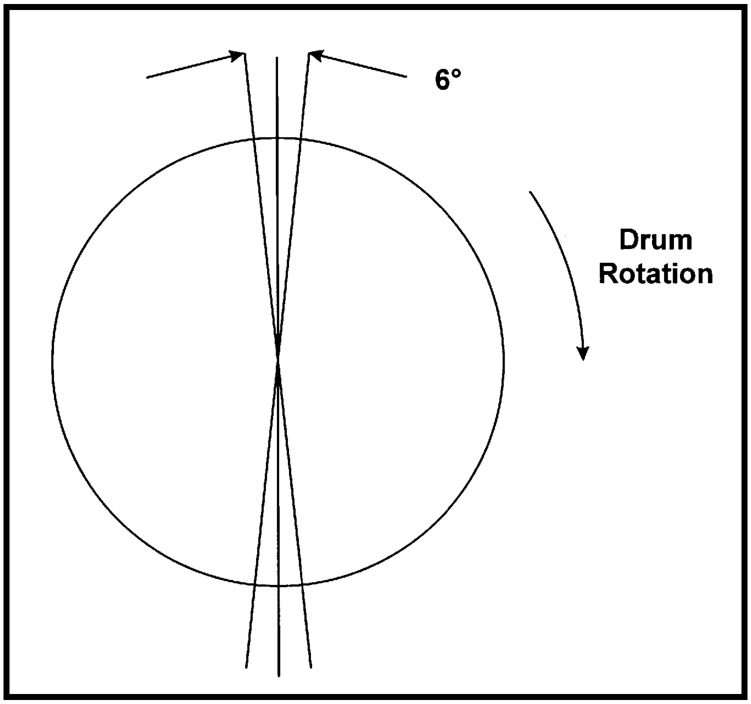


Figure 2. *Cross section of the drum*

With a nominal drum rotation of 60 rpm, the measurements must be computed in 16.7 milliseconds. To compound the problem, the computer-controlled electronics must be integrated into a cutting drum where electrical power and data communication means are not available and physical space is limited. Therefore, in addition to very tough measurement requirements, self-power generation must also be integrated into the design of the drum-mounted instrument. The entire system must be designed to intrinsic safety standards or enclosed in a MSHA-certified flameproof enclosure.

Horizon sensing technologies have been under development for more than 30 years. The ideal horizon sensor must be able to measure both roof and floor coal thickness (0 to 16 inches) and not require frequent or elaborate calibration. The sensor must provide real-time signals for the machine's electrohydraulic controls to enable semi-autonomous mining in an undulating coal seam. The following table describes the many sensor technologies investigated for the horizon sensing problem.

Technology	Function	Evaluation by Industry
Natural background radiation	Measure natural gamma radiation flux emanating from shale; thickness determined by reduction in count from 100s of counts per second	Will not work under sandstone. Gamma radiation is not uniform in mudstone; not a point sensor.
Sensitive - pick	Pick rock vibration sensor	Too late; not real time
Nucleonic	Interface response to a radiation source	Too risky if source lost in cave-in
Electromagnetic pulse radar	Step frequency mono-pulse radar	Reflections from air-coal interface predominate reflection from coal-rock interface when coal thickness is less than 24 inches.
Magnetic spin resonance	Measures free electrons in coal, but not in shale	Not a proven technique; gradational bound problem.
Acoustics	Detect reflected ultrasonic echoes from coal shale boundary	Mining environment acoustically noisy
Thermal infrared	Response to bit heating	Too late; not real time
Hydraulic drill	Mechanical measurement technique	Not real time
Reflectometer	Light sensitive detector technique to measure differences in surface reflectivity	Unsound technique
Penetrometers	Acceleration profile indicates coal or non-coal	Cannot apply to cutting drum
Vibration sensor	Measures vibration of cutting drum	Too late; coal interface already hit
Bureau of Mines - electromagnetic moving microwave antenna	Mechanical stepped antenna and synthetic pulse	Not real time; mechanical antenna may not survive harsh mining environment
DOE/STL electromagnetic step frequency	Synthetic pulse radar (FM-CW)	Real-time information, can be adapted to fit on cutting drum; most practical for look-ahead radar
Video cameras	Change of contrast	Too late

The National Coal Board (now British Coal) developed gamma radiation sensing technology as part of their machine automation program (17)(18)(19)(20). This sensor employed a large scintillating sodium iodide crystal. This detector was physically large and required the use of high-voltage photomultiplier tubes. A cadmium telluride detector was introduced by Bessinger and Nelson into a gamma radiation type of horizon sensor while they were at CONSOL (21)(22)(23)(24)(25). This sensor is now available commercially from American Mine Electronics (AME) (26). The gamma sensor limitation includes the difficulty of making measurements under sandstone where potassium-34 and uranium gamma emissions are oftentimes of very low intensity. This sensor would not be useful in controlling a machine under a paleochannel. Natural gamma emissions in the coal layer itself limit thickness measurement to a few inches. Gamma sensor counts in the order of hundreds per second disqualify this sensor in real-time drum measurements. This sensor is effective when placed on the cutting machine body and applied in uniform shale/mudstone bounded seam. Because of these problems, the National Coal Board and CONSOL were forced to adapt and develop the last pass memory machine control algorithms.

When researchers are faced with the detection of geologic objects that cannot be seen, some form of radar is always proposed and evaluated (27). Radar has been applied in the measurement of uncut coal thickness by the US Bureau of Standards (Boulder, Colorado). A unique stepped-frequency radar developed by the DOE has been evaluated in measuring rib thickness. The functional block diagram of the stepped-frequency radar is shown in Figure 3.

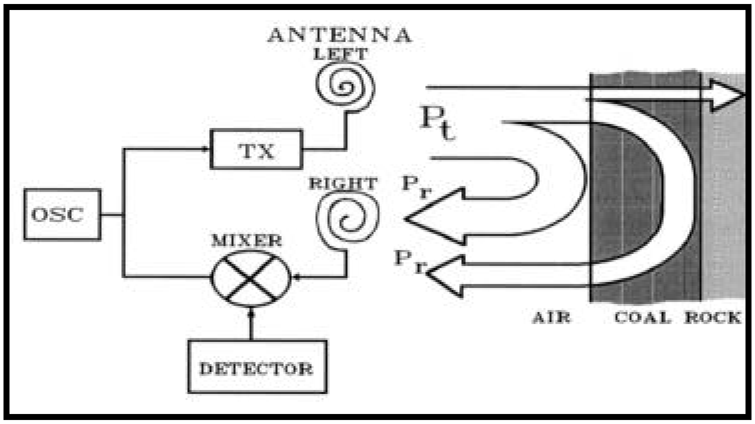


Figure 3. *Block diagram of the stepped-frequency radar*

The transmitter (TX) and its antenna transmit an incident electromagnetic (EM) wave that is partially reflected (P_r) at the air-coal interface and partially transmitted through the coal layer. At the coal-rock (air) interface, a second reflected EM wave (P_r) is returned through the first air-coal interface. The receiver antenna (right) and receiver (mixer) determine the time it takes for the EM wave to travel through the coal layer. The DOE stepped-frequency radar was used to acquire the data shown in Figure 4.

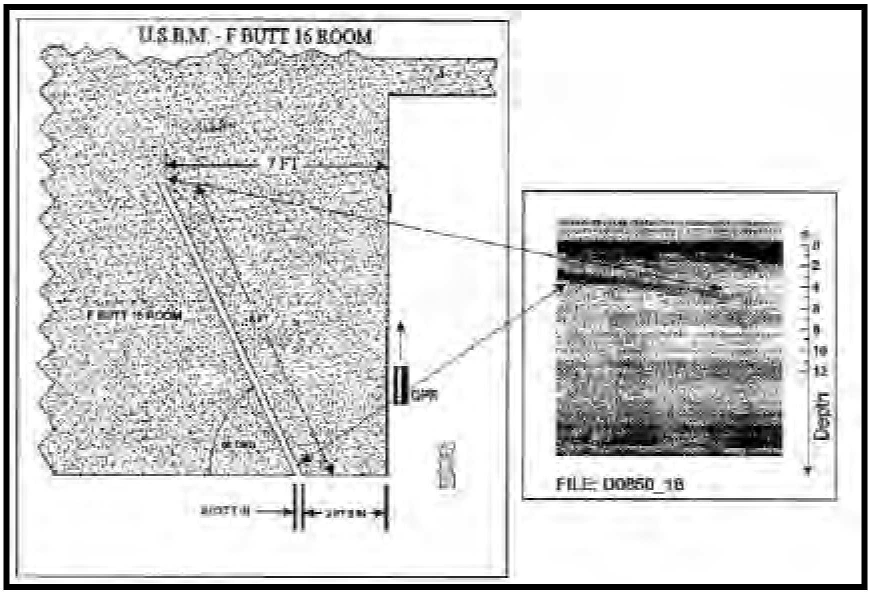


Figure 4. *Radar thickness measurement*

The stepped frequency radar data show that the measurement resolution is poor for coal thickness of less than 2 feet. Radar can determine thickness to more than 4 feet. This limitation occurs because radiowave energy travels approximately 1 foot in 3 nanoseconds. This high velocity causes the reflection from the coal-rock interface to occur during the ring-down time of the microwave antenna, which causes EM wave interference between the incident wave and the reflected wave, preventing thin layer measurements. Even when the layer is sufficiently thick, extensive computer processing time is required in a real-time system.

The USBM developed a different type of radar that requires sequential movement of the antenna and stepping the radar through more than 100 frequencies at each distance step (28). This radar, developed by Robert Chufo of the USBM, received the prestigious IR100 award and has the capability of accurately measuring coal thickness. Because the stepped-frequency radar must make measurements at 100s of discrete frequencies and then process the measured data through a Fourier transform algorithm, the processing time can be expected to be in the 100s of milliseconds time frame. It is not a candidate for real-time sensing on the cutting drum.

Sensitized picks, vibration, and infrared sensors have been demonstrated in mine experiments (29)(30)(31)(32)(33)(34).

It is interesting to note that both Harvard and NASA have played pivotal roles in the solution of the tough remote sensing problem, although neither Harvard nor NASA are members of the mining industry. This is not the first time that breakthroughs have been made by researchers outside of the mining industry. Joseph (Joe) House of General Mills developed the LIX process, which led to the successful application of the solvent extraction electrowinning process.

EDIT UNCUT COAL THICKNESS SENSOR

David Chang, in work on his Ph.D. dissertation under R. W. P. King of Harvard, investigated a microwave frequency band resonance phenomena that could practically measure layer thickness without needing extensive computations as required in the radar-based technologies (35). This research was concluded in 1967 and not recognized as a possible uncut coal thickness physics principle until proposed by Drs. Chang (now President of Polytech Institute of New York) and James Wait (Professor Emeritus at University of Arizona)—both distinguished scientists and Fellows of the Institute of Electrical and Electronics Engineers (IEEE) (36). Even though their breakthrough research work was funded by the USBM, for some reason their theoretical formulations were not developed into a demonstration project until the discovery by the author (1986) in an obscure French technical publication. In the years following the discovery of the French paper, Ken Perry of InterWest Mining Company, Dr. Dicky Arndt of NASA, and our research staff developed the Chang-Wait sensor into a practical sensor (37)(38)(39).

Although the Chang-Wait sensor operates in the microwave frequency band, it is not a radar (40). The sensor capitalizes on its resonant impedance sensitivity to changes in coal thickness.

The vertical cross section of the Resonant Microstrip Patch Antenna (RMPA) sensor is shown in Figure 5. The RMPA sensor can be modeled as a high Q cavity that capitalizes on its resonant sensitivity such that a distinct advantage is obtained over a non-resonant radar type of sensor. The wall of the high Q cavity is formed by the circular copper patch and the ground plane. The E-field within the cavity is excited/sensed by a vertical "probe" at the feed point. The TM_{11} mode E-field within the cavity and the fringing E-fields are illustrated in Figure 5. The magnetic (H) fields are not shown; however, they are orthogonal to the E-fields and form the magnetic wall enclosing the cavity. The fringing E-fields (and H-fields) play an important part in the RMPA. The fringing EM fields are the coupling mechanisms between the internal cavity fields and the external fields.

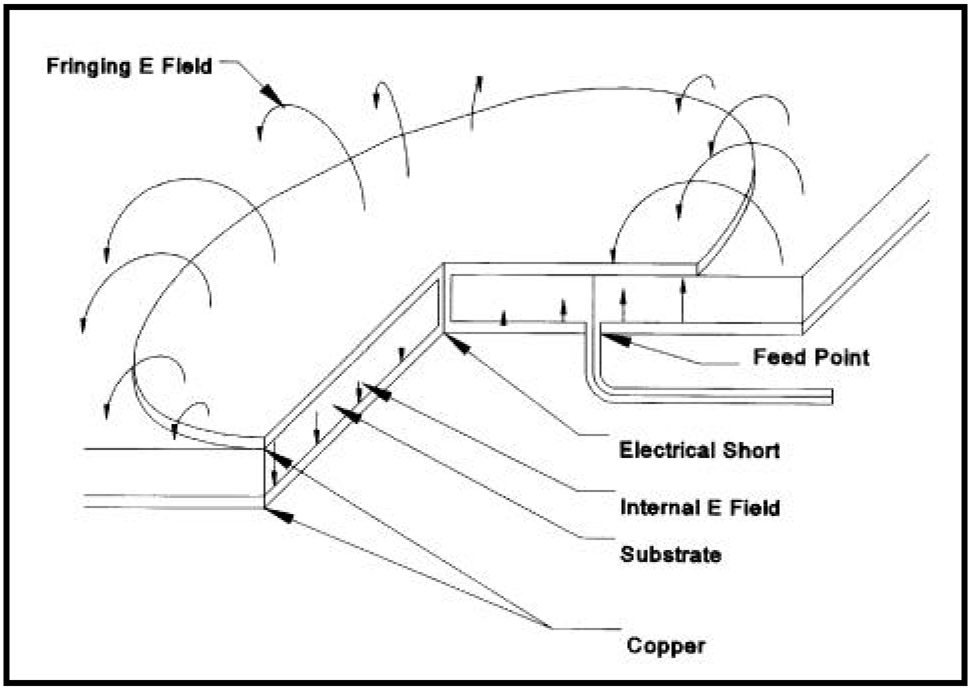


Figure 5. *Vertical cross section of the RMPA sensor including the electric field lines*

As illustrated in Figure 6, the fringing E-fields cause a polarized electromagnetic field to propagate upward from RMPA and into the coal layer. At a distance of 0.15 meter, the E-field is predominately polarized along the axis through the feed point and electrical short (see Figure 5). The radiation pattern is null at right angles to the axis. Approximately 30 percent of the incident energy is reflected at the air-coal interface.

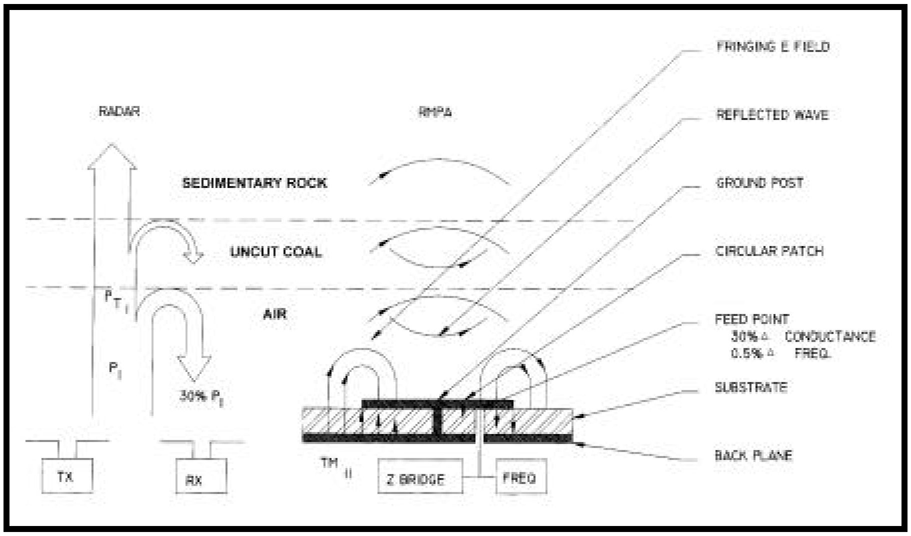


Figure 6. *A cross section of the uncut coal thickness measuring problem. For comparison purposes, a GPR system is illustrated on the left and RMPA is illustrated on the right.*

By way of comparison, this return reflected wave shown on the left side of the above figure would be detected by the receiving antenna in a ground penetrating radar (GPR). The reflected signal from the coal-rock interface is only 1 to 2 percent of the incident wave. The single high Q RMPA on the right side of the above figure transmits primary EM fields and senses the reflected and scattered fields through its altered resonant condition. A continuous wave is emitted from RMPA that is partly reflected and partly transmitted at the air-coal interface. The transmitted portion of the wave is reflected from the coal-rock interface due to the discontinuity in conductivity and dielectric constant. The reflected wave is again partly reflected and transmitted at the air-coal interface.

The return signal to the RMPA serves as an inductive and capacitive mutual coupling between the upper layers and the RMPA. The return signal is coupled through the fringing field and alters the E-field at the feed point. The RMPA microprocessor-controlled electronics measure the impedance at the feed point, which changes by a significant amount when the coal layer thickness changes.

GPR relies on a low Q antenna(s) to measure the voltage changes that are proportional to the reflected and scattered fields. Resonant impedance changes at the high Q cavity feed point appear substantially larger than corresponding GPR voltage changes. Therefore, RMPA has a significant increase in sensitivity to reflected fields.

The real (R) and imaginary (X) values of the RMPA feed-point impedance were measured over a range of frequencies with an HP 4191A RF impedance analyzer. The measured data are presented in Figure 7.

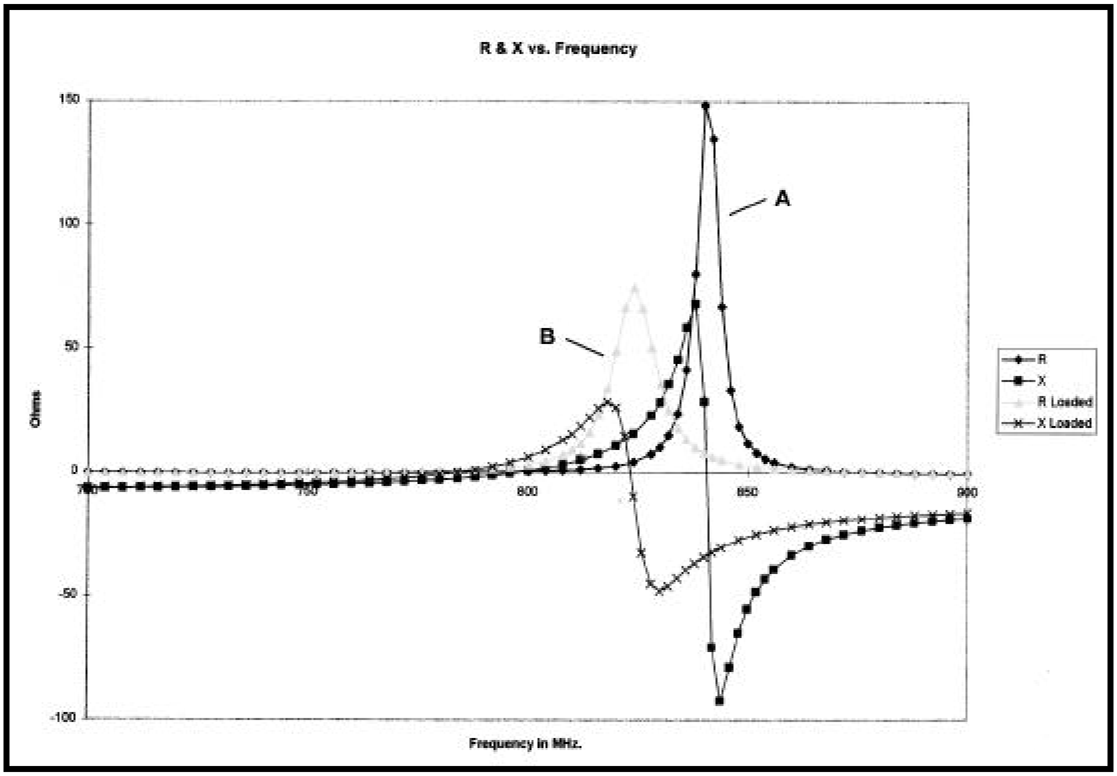


Figure 7. *Measured 850 MHz RMPA sensor feed-point impedance versus frequency*

The resonant impedance (ohms) curve to the upper right (A) was measured with the RMPA sensor radiating into free space. The lower left curve (B) was measured when RMPA was pressed against a sandstone layer. The real (R) component (resistance in ohms) of the feed-point impedance versus frequency curve illustrates the resonant characteristics of the high Q cavity. The resistance rapidly changes on each side of the resonant frequency. The imaginary component (x) rapidly changes in the neighborhood of resonance.

NASA Johnson Space Center developed a RMPA for conformal installation on the surface of missiles and space vehicles. Laboratory tests show that RMPA exhibited impedance changes similar to that of the wire loop in the Chang-Wait analysis. This extremely rugged antenna survives space crash re-entry as well as the drum cutting environment. The feed-point resonant frequency and impedance dependence on the electrical parameters have been determined with a commercial software program (Sonnet). The change in resonant condition caused by coal thickness change is seen in the impedance diagram (Figure 8).

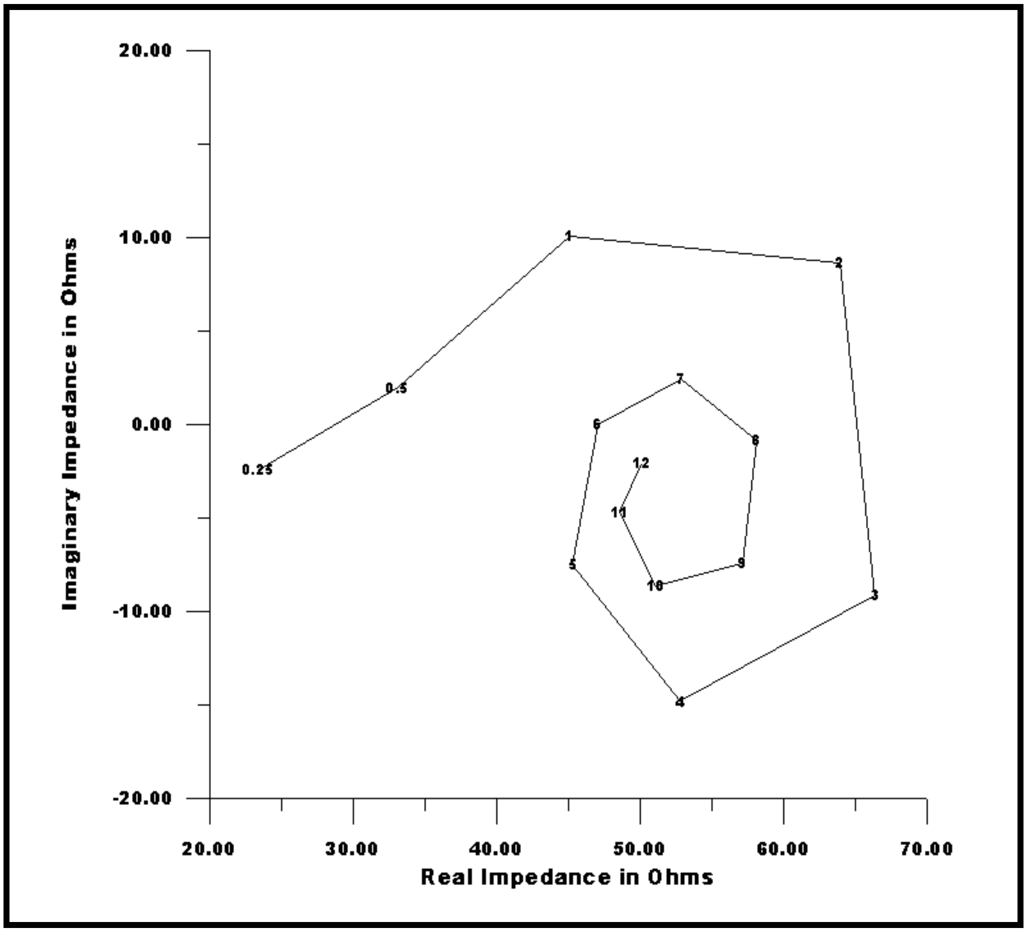


Figure 8. *Imaginary versus real impedance for a square patch antenna (F_o= 450.4 MHz). Antenna is flush with coal layer. Coal layer properties are e_r = 6, s = 0.0001. Rock layer properties are e_r = 10, s = 0.1. Data represent an increasing coal layer thickness from 0.25 inches to 12 inches.*

The above figure shows that the impedance measured at various coal layer thicknesses can be graphically constructed to form a mathematical function that resembles Cornu's spiral. The function is used to determine uncut coal thickness from the measured data. An algorithm in the sensor creates the Cornu's spiral from the calibration data. The measured data are then compared to the Cornu's spiral calibration data to determine the uncut coal thickness.

The integration of the horizon sensor on the drum of a mining machine eliminates the bottleneck in building a semi-autonomous machine (Figure 9).

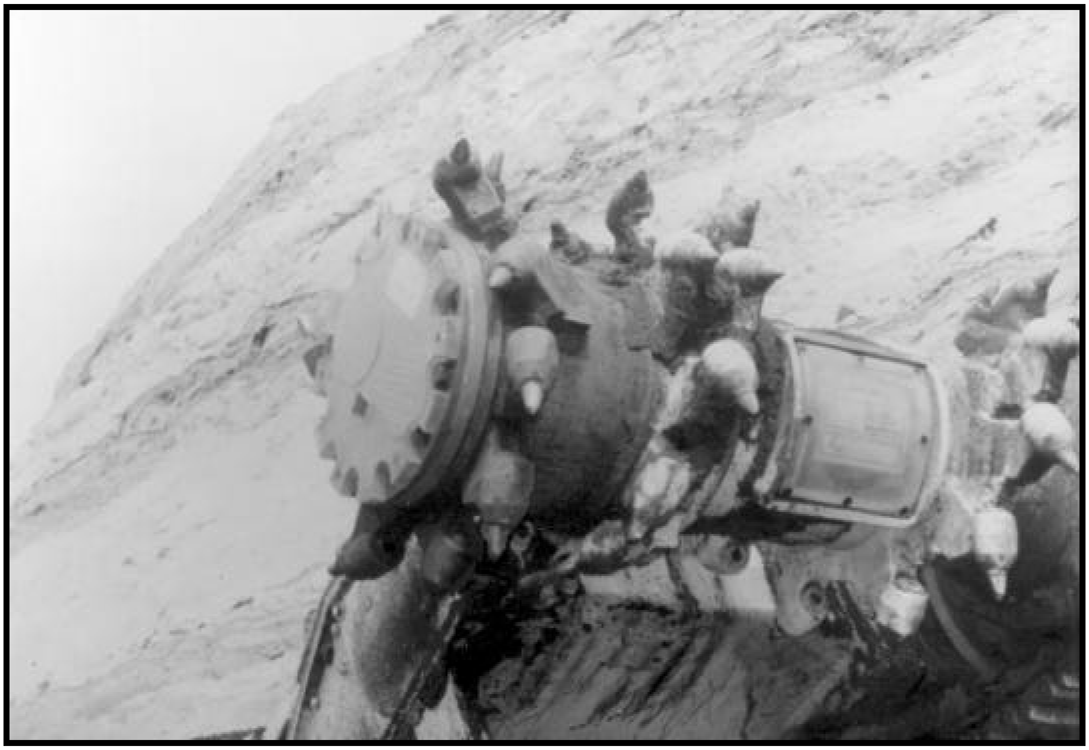


Figure 9. *Installation of EDIT horizon sensor on a cutting drum*

The MSHA-approved flameproof enclosure is installed in the left side of the drum. The sensor mounting location is shown on the surface of the drum. Measured data are transmitted by a radio link back to a companion receiver display enclosure mounted on the body of the machine. Although developed for drum mounting, the sensor can be adapted for mounting on a ripper shank shoe, buckets of shovels, or on cleaning blades used in surface mining.

REMOTE SEAM MAPPING

The successful deployment of tomorrow's semi-autonomous machine requires high-resolution geologic assessment of the coal seam geology ahead of mining. Complete seam geologic information is required to determine production rates, machine cutting parameters, and maintenance schedule. ROM coal quality rapidly decreases when cutting through geologic disturbance zones. The most common geologic anomalies are faults, dikes, paleochannels, splay, and sills. Burned-out coal and abandoned mine workings are also included in the mining problem.

Coal mine geologists develop geologic models for the property based upon the analysis of exploration drill hole information and logging data. This information is combined with depositional modeling to give a preliminary assessment of minability and provide information for the initial mining plan. Entry development and seam mapping during mining provide geologic information for improving the geologic model.

To improve upon the accuracy of geologic information ahead of mining, technology for remote seam mapping has been developing over the past twenty years. Improving the accuracy of seam geologic information is in reality tied to the methods of data collection. Data acquisition relied initially (and it still does) on in-mine geologic mapping. Following World War II, the Germans adapted oil field seismic instrumentation to detect and locate faults ahead of mining (41). Seismic data were gathered from roadways within the mine. Seismic methods were introduced into the United Kingdom and further developed by Buchanan *et al.* in support of the National Coal Board's automation project (42)(43)(44)(45). Later, Hatherly in Australia improved upon the cross panel tomography method of the coal seam seismic imaging (46). As development along the technology roadmap continued, it was obvious that horizontal drilling being developed for methane draining ahead of mining coal could also be used in acquiring additional geologic information. The practice of horizontal drilling has gradually increased in importance since the early 1980s. Advanced drilling has added directional drilling control by designing offset drillhead and rotation of the drillstem during drilling. Instrumentation has been developed to acquire real-time directional drilling information that is used in guiding the drill within the coal seam. The improvements in directional drilling enabled probing the roof and floor to determine coal seam height and determine the throw of the fault.

In the early 1980s, the Radio Imaging Method (RIM) was developed in industry-driven cooperative R&D projects at Utah Power and Light Company mining division (now InterWest Mining) and American Electric Power Miggs mining division (47)(48). Although these mining companies had already applied the coal seam seismic wave technology, a method requiring less logistical support and higher detection sensitivity, especially for paleochannel scouring, was sought. Seismic surveys are conducted in a number of ways. The best known is the reflection survey where recordings are made of seam waves reflected from non-coal interfaces. Analysis of the reflected wave indicates the location of the reflector. Reflection surveys are conducted by firing many single shots underground from entries on the mining face and recording the signals with detectors (geophones). Typically 40 to 50 single shots are fired and up to 1,200 individual geophone records are obtained. Transmission surveys may also be conducted that are initiated at the face and travel to distant boreholes. Tomographic surveys are a special type of transmission survey. The logistics for these surveys require drilling into the coal rib for shot holes and geophones. Setup for a survey can take one or more weeks. The seismic surveys have produced good results in locating full seam displacement faults; however, the detection sensitivity degrades in partial seam displacement faults. Seismic surveys were not effective in the detection of scouring under paleochannels. Early in-mine demonstration of RIM in these mines confirmed that paleochannels and scouring could be imaged. RIM technologies include:

- instrumentation,
- data processing software to form images of anomalous geologic structures,
- interpretation know-how of the mine geologist.

Instrumentation was developed for in-seam imaging and, later, borehole tools were developed for crosswell applications. Most recently, a series of projects funded by the DOE and Sandia National Laboratories resulted in the development of RIM III technology. This new class of instrumentation acquires data for much higher resolution tomography reconstruction algorithms developed by Gregory Newman of Sandia National Laboratories.

RIM imaging transmits a radiowave in the coal seam waveguide to a distant receiver. The imaging method is shown in Figure 10 below.

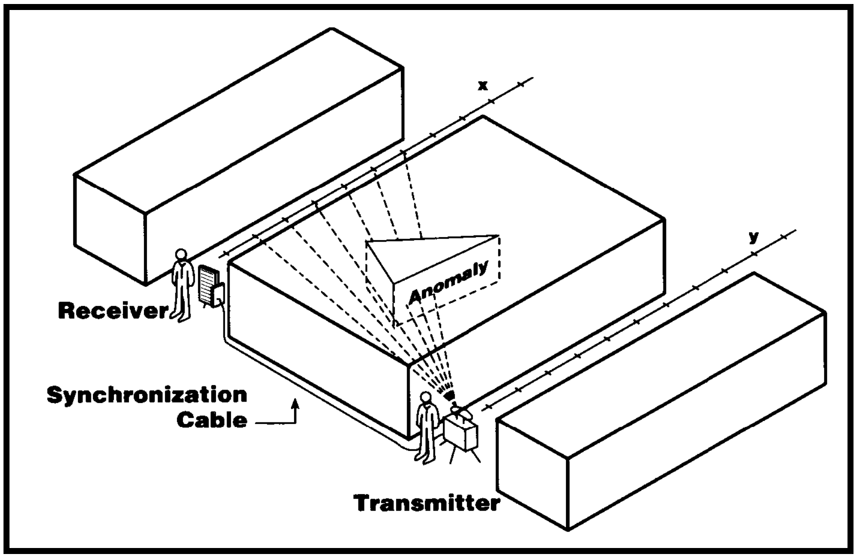


Figure 10. Sinusoidal radiowave signal paths in a coal seam

RIM capitalizes on the radiowave's sensitivity to changes in coal layer thickness as illustrated in Figure 11.

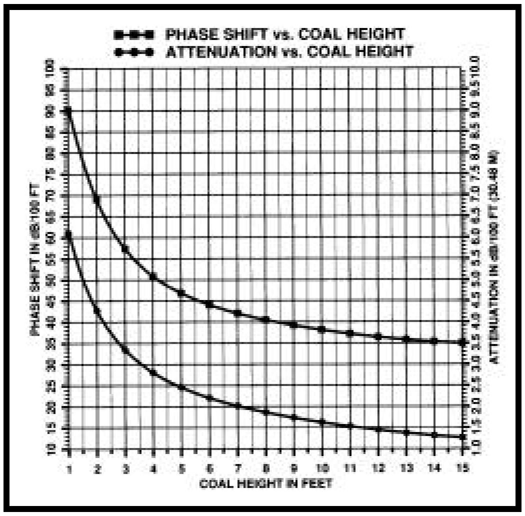


Figure 11. *Seam wave attenuation and phase shift dependence on seam height. The RIM instrumentation measures the attenuation and phase shift values shown in the above figure.*

Measurements made at multiple receiver stations are processed in the Algebraic Reconstruction Technique (ART) tomographic algorithm to map the radiowave attenuation rate throughout the block of coal. The 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, anomalous zones in an otherwise uniform coal seam are detected. The image of a roof rock fracture zone under a paleochannel is illustrated in Figure 12.

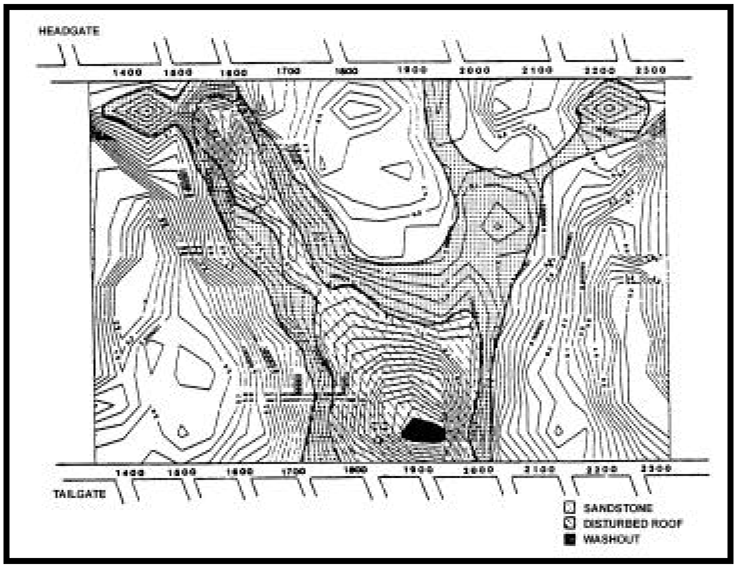


Figure 12. *Reconstructed tomography image illustrating constant attenuation rate (in decibels per 100 feet) contours of a geologically disturbed zone in a 600-foot (181-meter) wide retreating longwall coal panel*

Early detection prior to mining has proven to be cost effective in mine design, ensuring a smooth running mine and enhancing ROM coal quality. The image illustrates contours of constant attenuation rate of a radiowave propagating in the coal seam waveguide. To interpret the RIM data, the fractured coal seam waveguide allows radiowave energy to leak into the surrounding fractured rock. If water is contained in the pore-space of the overlying sandstone, its leakage into the coal fractures causes the coal seam electrical conductivity to increase. Both conditions cause the attenuation rate of the radiowave traveling through the anomalous zone to increase. The rapid change in attenuation rate (gradient) illustrates the margin of the river channel and fractured 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 radiowave imaging. The impact on mining can be significantly reduced when geologic problems are assessed prior to being intersected by the mining process.

Several hundred 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 RIM, longwall panels have increased in width from 500 feet to more than 1,000 feet. To achieve the greater operating range, the RIM operating frequency was reduced from 500 kHz to 50 kHz, which decreased image resolution.

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. Non-linear tomography-processing algorithms are currently under development by industry, university, and national laboratory researchers. These non-linear 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 RIM III. Our company and Sandia National Laboratories are participating in a Cooperative Research and Development Agreement (CRADA) in the development of the RIM III instrumentation and interpretation algorithms.

The instrumentation setup illustrated in Figure 10 determines the EM field propagation constants along the path by measuring the magnitude and phase shift at each receiver location. The measured data are processed in a tomography algorithm that first divides the geologic image zone into pixels (top view two-dimensional image) or boxels (three-dimensional image). The tomography algorithm then determines the attenuation rate and phase shift occurring in each pixel or boxel based upon the measured data. A contouring program is used to form an image of attenuation rate or phase shift variations throughout the geology in the image zone.

The limitations in RIM technology have been overcome by state-of-the-art improvements in instrument design and the development of the full wave (non-linear) tomography inversion software (49)(50)(51)(52). The limitations in the ART tomography as well as the significant improvements in full wave tomography are illustrated in Figure 13. In this simulation model the RIM transmitter's stations are located on the left side of the image and the 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 13. The early RIM images have very poor lateral resolution, therefore, predicting the exact location of the washout on the mining face would not be possible. If a fault heading was parallel with the panel ribs, it would not be detectable with RIM. The lower right full wave (non-linear) tomography image shows the significant improvement in resolution of a fault with a heading parallel and at right angles (actually any angle) to the sides of the image plane. Full wave tomography is a quantum leap forward in coal seam imaging.

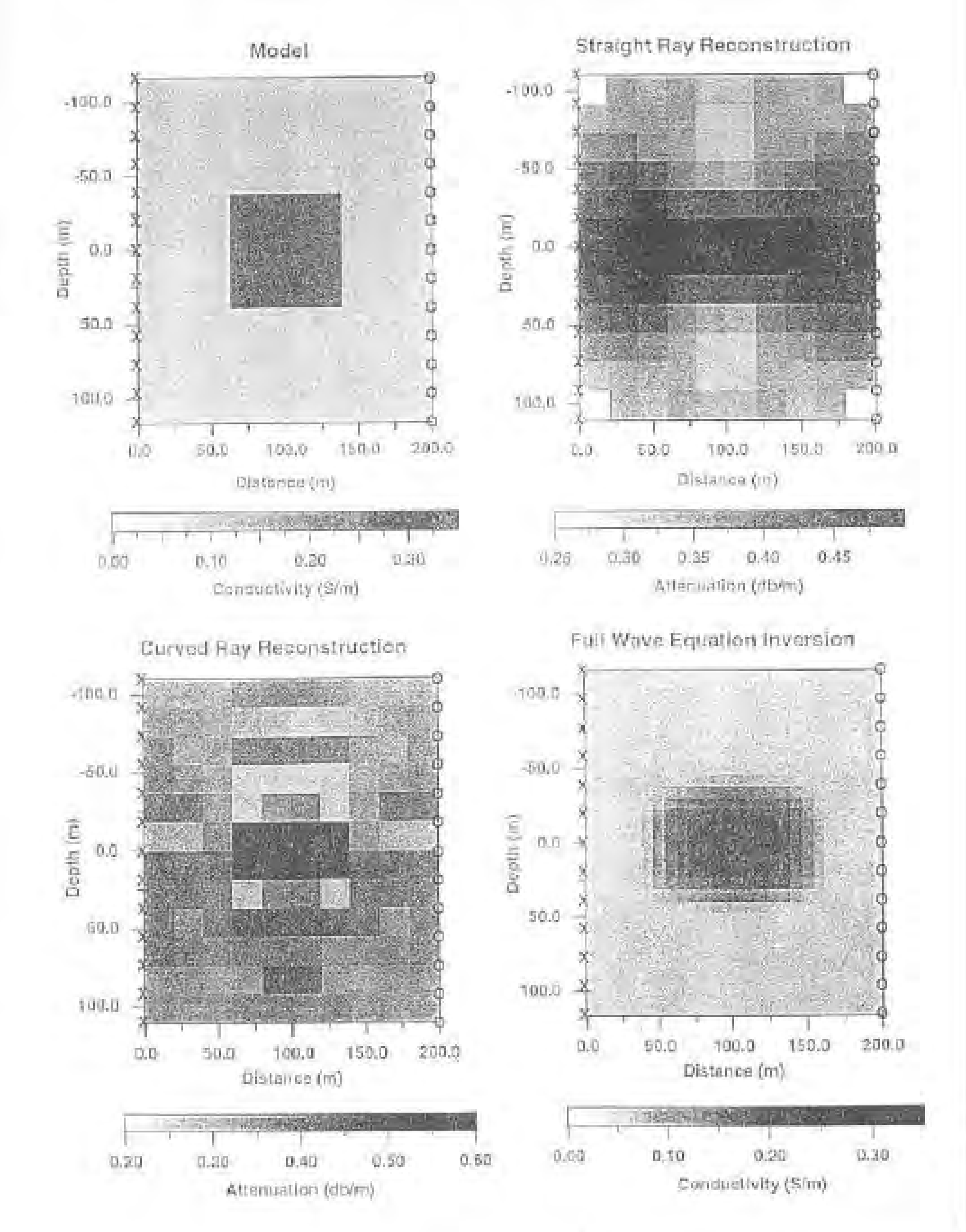
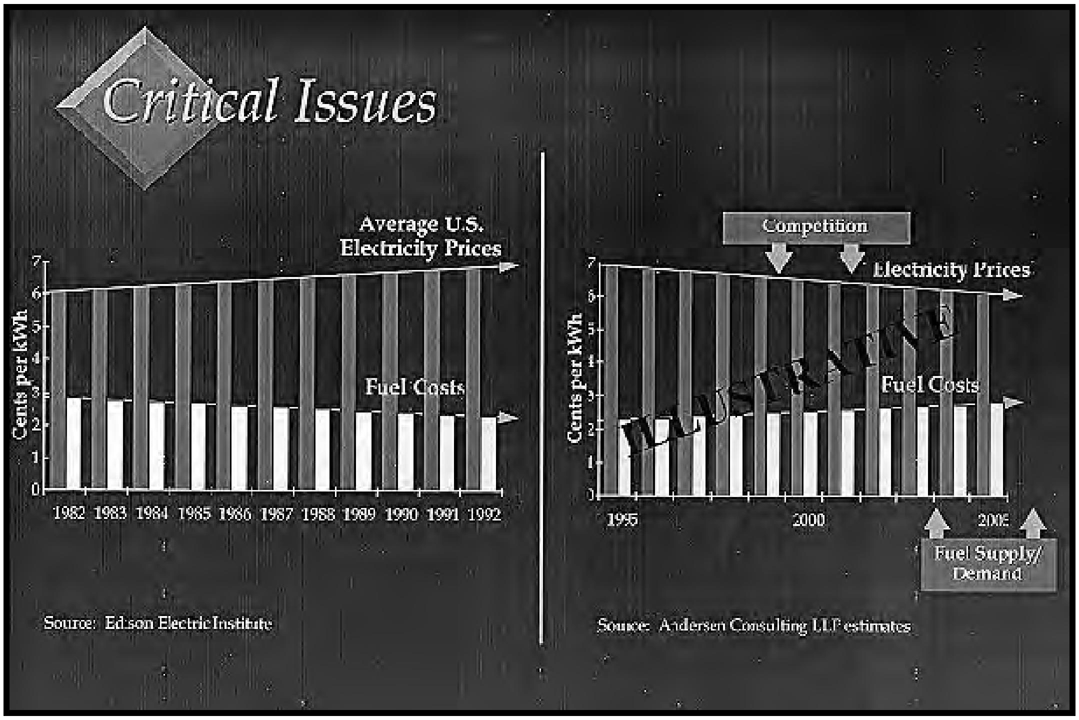


Figure 13. *Comparison of reconstructed tomography images using straight ray path assumptions and the state-of-the-art full wave inversion technique developed by Gregory Newman*

CONCLUDING REMARKS

Economic problems in the US coal mining industry and its dependent partner, the US electric supply utilities, are illustrated in Figure 14 below.



Source: Edison Electric Institute

Source: Andersen Consulting LLP estimates

Figure 14. *Fuel cost and electric rate versus time (provided by Glenn Wattley - Andersen Consulting, Boston, Massachusetts)*

Coal price has steadily decreased each year, and this year is no exception. Decreasing price has significantly reduced mine operating margins to the point that supply contracts are won and lost on differences in cents per ton. This trend in coal price is expected to reverse itself as minable US coal reserves are decreased because of mining cost and the clean air regulations. Energy price in the regulated utility environment has continued to rise; however, it is expected to reverse itself as deregulation causes competition in the electricity market.

To stay competitive and at the same time improve ROM coal quality, an industry-driven R&D program will be needed to achieve the NASA/JPL vision of a semi-autonomous mining machine. Along the technology roadmap described in this paper, a well-conceived adaptation plan will need to be developed that enables integration in an operating mine. Great benefit will be realized in developing cooperative upstream R&D projects with the national laboratories.

Emphasis should be placed upon the measurement of contamination stratification in US coal deposits. Achieving higher productivity and increased ROM coal quality will benefit both the mining industry and the electric utilities.

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