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Horizon Sensor for Advanced Coal Extraction (ACE)

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Abstract

In the early 1980s, the Jet Propulsion Laboratory (JPL) investigated the automation problem in advanced coal extraction (ACE). Studies conducted in underground mines determined that manufacturers of state-of-the-art continuous and longwall machines had created mining equipment that could be transformed into semi-autonomous machines. Their study also determined that the slow pace of automation and unexpected increases in mining cost in computer-assisted control of machines was related to technology limitation beyond the expertise of the manufacturers. Anomalous geology and the difficulty of communicating control data between essential parts of complex machines were at the heart of the problem. JPL determined that the anomalous geology problem could be overcome by remote sensing; however, coal seam imaging and horizon sensing along margins of sandstone channels were beyond the remote sensing state of the art. JPL envisioned a NASA type of deep space vehicle employing a real-time semi-autonomous control system communicating via radio links to a supervisory computer. The radio links and operating system were judged by JPL to be within the state of the art.

This paper describes the development history of horizon sensor technologies. Evidence now exists that a new type of drum-mounted horizon sensor featuring a Resonant Microstrip Patch Antenna (RMPA) sensor will measure uncut coal thickness under fractured roof and sandstone channels. The sensor enables real-time control of the machine’s electrohydraulic systems. Semi-autonomous continuous miners and shearers can stay in an undulating coal seam. The sensor can limit the cut so that the contaminated boundary coal layer with higher ash, sulfur, and heavy metals will be abandoned in the mine. Most importantly, the sensor reduces mine personnel dust exposure.

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Background

Beginning in 1977, JPL began working with several US mining companies in identifying technologies needed in Advanced Coal Extraction (ACE). The influence of NASA-JPL deep space vehicular design was evident in their vision of the ACE mining machine. Unmanned deep space vehicles are designed to be controlled by earth-based supervisory computers that feature visualization (monitoring) and flight data recording. The supervisory computer communicates by radio data links with a semi-autonomous deep space vehicle. The unmanned vehicles are designed with onboard navigation sensors, memory loaded with predetermined flight trajectory parameters, and real-time control/diagnostic algorithms that process data from navigation and propulsion system sensors. The radio links feature very narrow band transmission of data. This allows the communications systems to overcome the very high radio signal path loss associated with very long distant transmission. NASA believed that a similar narrow band radio system would overcome the high path attenuation encountered in transmission through geology and along metallic structures that serve the utility needs of mining machines. The NASA-JPL study determined that mining machine manufacturers were designing and manufacturing state-of-the-art machines for the underground mine environment. These computer-assisted machines have achieved remarkable improvements in both safety and productivity. Bessinger, in his Ph.D. dissertation, describes a 20 percent productivity improvement in the Consol automated longwall. Although manpower has not been reduced, tons per man shift has increased because the shearer can be operated in a more efficient manner. The manpower was shifted to more cost-effective support functions outby the dust plumes associated with the shearing operations. The benefits of reduced dust exposure to mine personnel and cost-effective support were achieved with the automated mining machine. The vision of the NASA-JPL semi-autonomous machine has not been realized in coal seams where anomalous geologic structure prevails. Oftentimes, computer-assisted mining machines experience unexpected increases in mining cost. Anomalous geologic conditions must be detected and imaged in advance of mining to detect faults, magmatic intrusions (sills and dykes), burned-out coal, rapidly thinning coal, and paleo channels. Paleo channels and differential compaction cause roles in the coal seam. Along the margins of the paleo channels, the sedimentary roof rock changes from mudstone/shale/limestone to sandstone. The immediate roof is oftentimes fractured. Mining into the roof rock increases the potential for ground control problems. The NASA-JPL study concluded that the technology limitations to semi-autonomous machine design were related to geology. These limitations were beyond the expertise of the machine manufacturer—in fact, beyond the state of the art.

The NASA-JPL identified advanced coal extraction (ACE) technologies needed in semi-autonomous machine designs as:

Sensor category:

- Imaging of coal seam anomalies in advance of mining, and
- Navigation sensors for vertical and lateral steering.

Real-time operating systems:

- Hardware for radio data transmission between machines,
- Hardware for computerized, command, control, and monitoring (C^3M), and
- Real-time machine control and diagnostic algorithms.

NASA-JPL stated that the first two ACE technologies in the sensor category were beyond the state of the art in 1980. NASA-JPL was confident that the technologies needed in real-time operating systems were within the art. NASA developed similar systems for their state-of-the-art machines.

Prior to the NASA-JPL study, the British Coal Board developed their own vision of the mine automation problem. Sensor category technology featuring seismic wave tomography image was developed for mapping anomalous geology ahead of mining. The British work expanded and improved prior German work in the coal seam seismic wave imaging. The navigation sensor work resulted in the development of a horizon sensor based upon the detection and counting potassium-34 decay emissions from sedimentary rocks bounding the coal seam. Because the gamma sensor could not make real-time measurements at the point of cutting, the Coal Board was forced to develop a longwall operating system featuring a last pass memory (LPM). The LPM operating system included a predication algorithm to determine the machine electrohydraulic control signals for the next cut sequence.

Development of ACE Technologies

Beginning in 1980, the Radio Imaging Method (RIM) was discovered and developed to map anomalous geology ahead of mining. RIM capitalizes on the coal seam being a natural waveguide for transmission of low and medium frequency radio waves. RIM has proven to be cost effective in detecting and imaging anomalous geology ahead of mining. RIM is used to map the geology ahead of 70 percent of the Australian longwall. As the longwall panels became wider (550 ft to more than 700 ft), image resolution limitations emerged. The high attenuation encountered in transmission through 700 ft longwall was reduced by decreasing the imaging frequency from 300 kHz to 50 kHz. The image resolution decreases at lower frequency. An advanced RIM System III technology was developed to improve receiver sensitivity and imaging resolution. Sandia National Laboratories (SNL) developed new non-linear tomography inversion algorithms for processing total electromagnetic wave (EM) field data measured by the RIM III. The new algorithms overcame the straight-ray path limitation required in the RIM II algebraic reconstruction technique (ART) algorithms. RIM III measures scattered waves from multiple anomalies and forms higher resolution images with fewer artifacts. Dr. Greg Newman of SNL provided a significant improvement in high resolution imaging in anomalous coal seams. This technology greatly reduces the geologic risk in underground mining.

The lateral navigation technology breakthrough was made by Honeywell in their adaptation of the ring laser gyro (RLG) in mining. The RLG was originally developed for military applications by Honeywell. The RLG is the critical element in the navigation of rapid development and highwall mining machines. The drift problem associated with RLG is being minimized with new software development. Radar capable of monitoring uncut coal web thickness is being investigated by a number of research organizations. In the US, a unique stepped frequency radar developed by the Department of Energy (DOE) has proven effective in measuring rib thickness. The functional block diagram of the stepped frequency radar is shown in Figure 1.

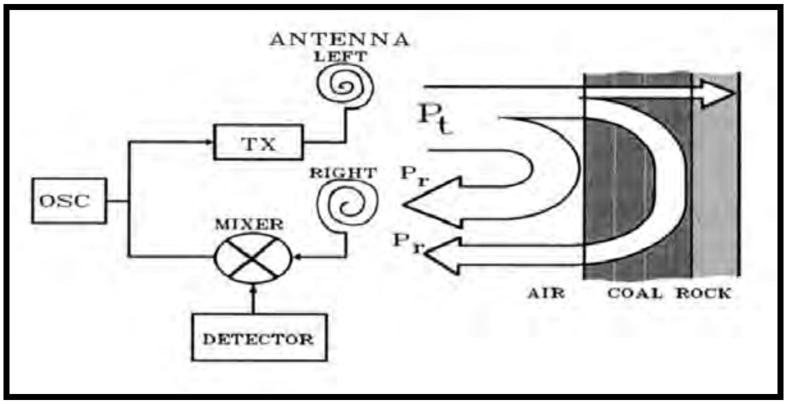

Figure 1. *Block diagram of the stepped frequency radar*

The transmitter (TX) and its antenna transmits an incident 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) determines the time it takes for the EM wave to travel through the coal layer. The radar was used to acquire the data shown in Figure 2.

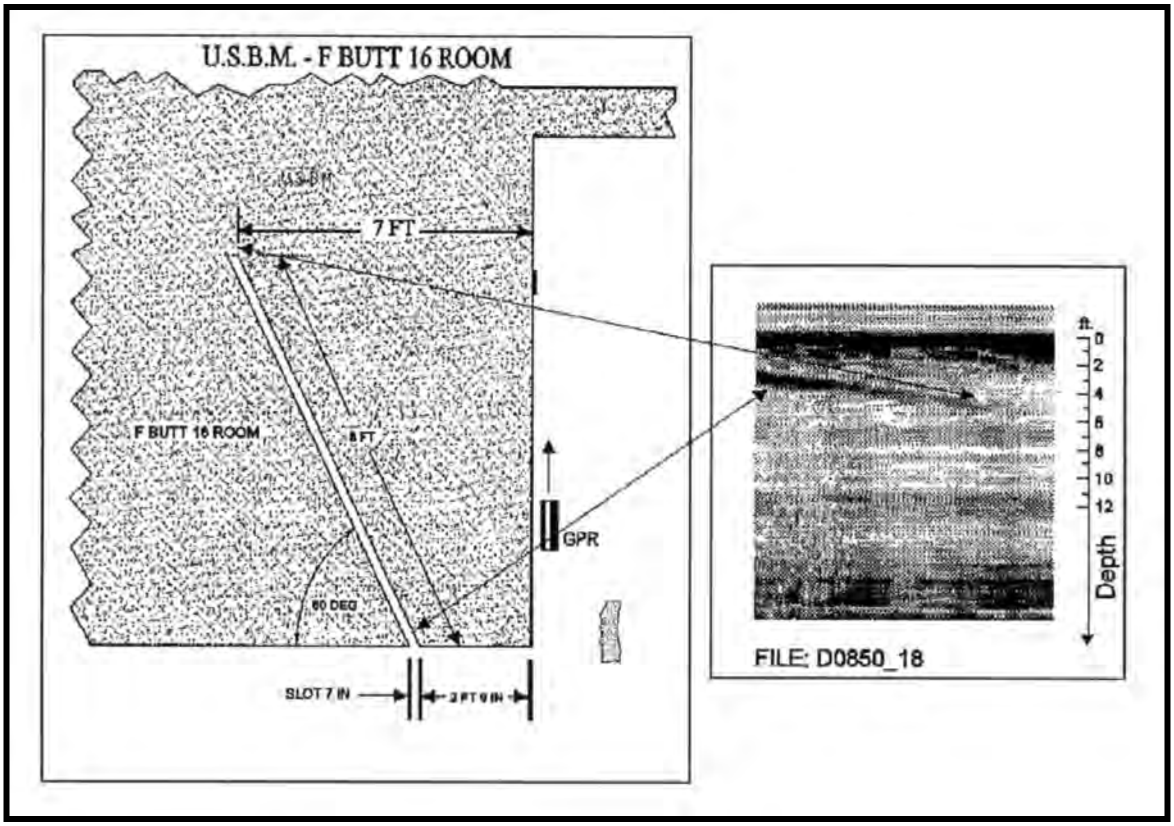

Figure 2. *Radar thickness measurement*

The stepped frequency radar data shows that the measurement resolution is poor for coal thickness of less than 2 ft. Radar can determine thickness to more than 4 ft. In highwall mining, radar will be a good complement, but not a substitute for the Honeywell RLG.

The USBM developed a radar that requires a moving antenna operating at multiple frequencies. The radar has the capability of accurately measuring coal thickness.

The horizon sensing part of the navigation problem has been under development for more than 30 years. The ideal horizon sensor would be located at the point of cutting, be able to measure both roof and floor coal thickness (0 to 16 inches), perform measurements in real time, not require frequent or elaborate calibration, and must not be limited because of the type of roof/floor sedimentary rock. The sensor must provide real-time signal for the machine's electrohydraulic controls to enable semi-autonomous mining in an undulating coal seam.

The table below summarizes the technologies that have been developed for sensing the coal-rock interface and measuring uncut coal thickness.

TABLE 1. *COMPARISON OF COAL-ROCK INTERFACE SENSING TECHNOLOGIES*

Technology	Function	Evaluation by Industry
Natural background radiation	Measure natural radiation flux	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, not in shale	Not a proven technique. Gradational bound problem.
Acoustics	Detect reflected ultrasonic echoes from coal shale boundary	Mining environment too 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	Unsound technique
Penetrometers	Drill saws	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	Not real time

The physics principles of detection vary from mechanical devices that vibrate (resonate) when bits cut through the coal layer and into the rock to electronic sensors that can measure thermal infrared (TIR) emissions from bits that strike the rock interface. Video cameras mounted on the machine have been used to observe mudstone marker bands as well as change in contrast of the residual dust.

The natural gamma radiation (NGR) from the decay of potassium-34 isotope in shale and mudstone layers is absorbed by the uncut coal thickness layer. Decreasing count is related to increasing thickness of uncut coal. Because coal is argillaceous (contains clay), the coal layer itself has a natural gamma count that limits thickness measurements to 12 inches. Because the sensor gamma radiation acceptance angle is wide, it averages the gamma emissions from a wide aperture. This, coupled with the fact that the sensor cannot be mounted in a cutting drum, prevents its usage in a real-time operating system. This is the reason that the LPM operating systems were developed by the British Coal Board.

The search for a practical sensor technology that could measure uncut coal thickness in real-time was initiated in 1986. Our search discovered a research paper by Drs. David Chang (now president of Polytech Institute of New York) and James R. Wait (Professor Emeritus at University of Arizona). Both distinguished scientists are fellows of the Institute of Electrical and Electronics Engineers (IEEE). Under US Bureau of Mine sponsorship, they investigated a sensor constructed with a resonant circular loop of wire that was positioned directly over coal and rock layers. Mathematic formulations described the dependence of resonant frequency and resonant impedance (measured at the feed point of the loop of wire) on coal layer thickness. Reviewers of this breakthrough work must have wondered how the combination of Bessel functions, Lommel-Weber functions, and a circular piece of wire would find practical applications in coal mining. Incidentally, Wait should be given credit for his analytical formulations and predication of natural waveguides in the layered earth, the physics principle upon which the RIM coal seam imaging process is based. The resonant wire loop concept was originally formulated by David Chang during his doctoral dissertation at Harvard under Dr. R. W. P. King (1968). It is interesting to note that the technical paper describing the 1977 Chang-Wait sensor concept was “lost” when the DOE took over the machine automation research and development initiative from the USBM and the NASA Marshall Space Flight Center.

Laboratory investigations by Raton Technology Research, Inc. (RTR) and NASA Johnson Space Center, showed that a RMPA sensor exhibited similar resonant frequency and impedance changes as that of the wire loop in the Chang-Wait analysis. New Mexico Research and Development Institute (NMRDI) and a sponsoring mining company sponsored a series of projects that lead to the development of associated microcomputer-controlled electronic measuring circuit for the RMPA sensor application in coal. The vertical cross section of the RMPA sensor is shown in Figure 3.

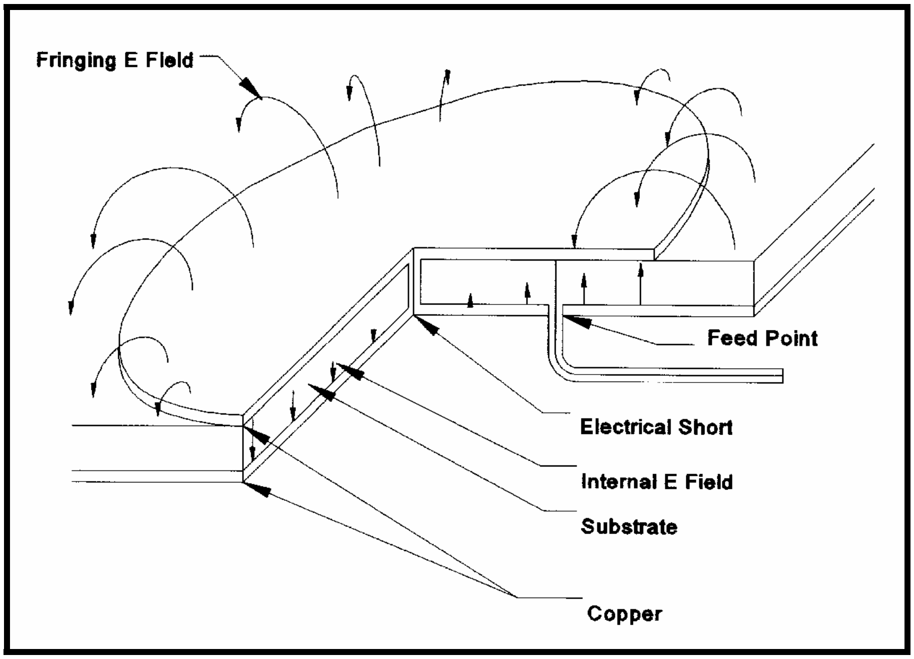

Figure 3. *Vertical cross section of the RMPA sensor including the electric field lines*

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 EM wave 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 3 above. 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 external fields.

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 3). The radiation pattern is null at right angles to the axis. Figure 4 illustrates the physics of the RMPA sensor. In a continuous wave (CW) ground penetrating radar (GPR) or RMPA system, the primary field energy propagates upward from the antenna. Approximately 30 percent of the incident energy is reflected at the air-coal interface.

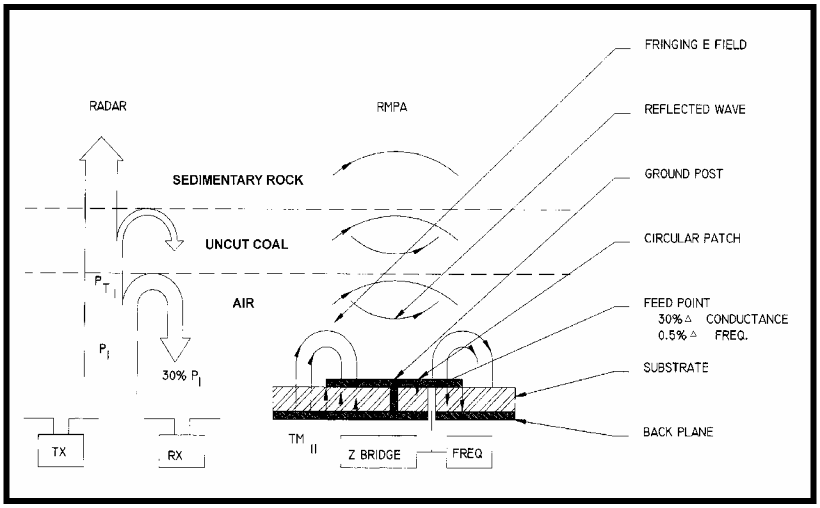

Figure 4. *A cross section of the uncut coal thickness measuring problem. For comparison purposes, a GPR system is illustrated on the left and RMPA is illustrated on the right.*

The single high Q RMPA 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 changes the frequency until the measured impedance is real. The resonant impedance measured at the feed point 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. Figure 2 suggests that GPR cannot sense coal layer thicknesses of less than 2 ft. 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 is presented in Figure 5.

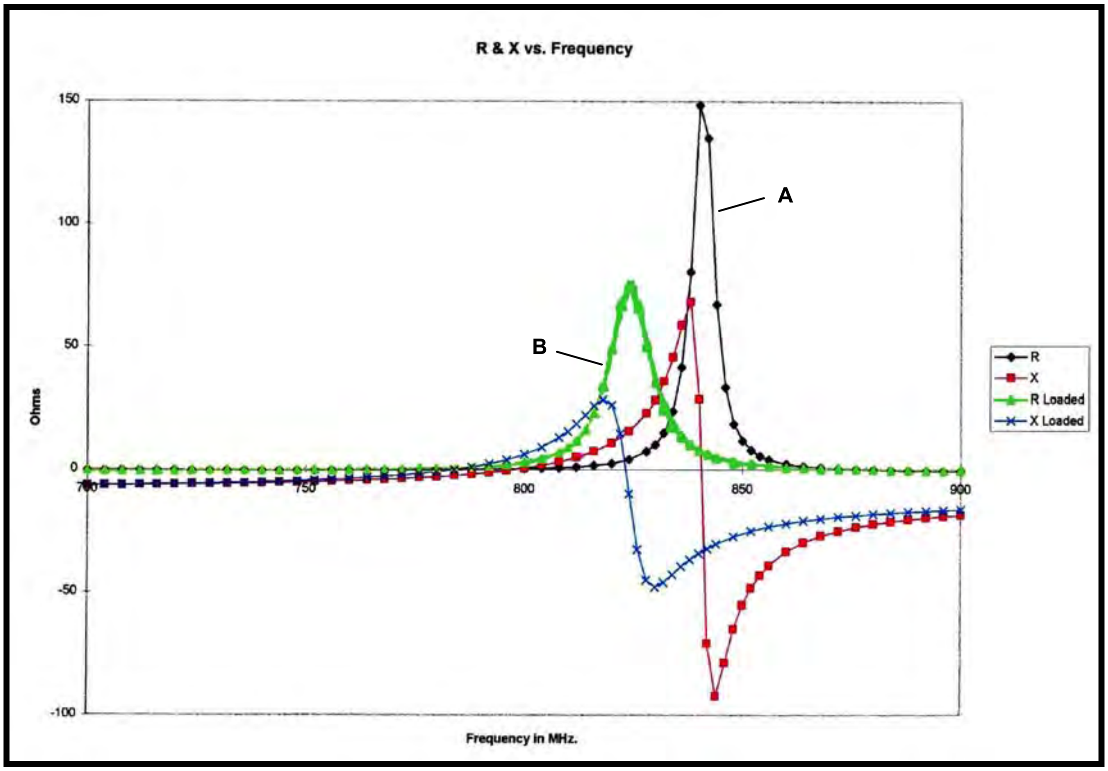

Figure 5. *Measured 850 MHz RMPA sensor feed-point impedance versus frequency*

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.

The feed-point resonant frequency and impedance dependence on the electrical parameters have been determined with a commercial software program (Sonnet). A Green’s function analysis of the circular patch antenna with multiple layers was also used in modeling. The analytical software programs determined that the resonant frequency and impedance exhibited a damped sinusoidal variation as the sensor or as layer thickness was varied. The theoretical simulations were in agreement with laboratory and field data. Studies conducted by Bob Kelly at Los Alamos National Laboratories suggested that the time average energy density of the standing wave closely followed both the modeling and measured data. The energy density versus layer thickness is illustrated in Figure 6.

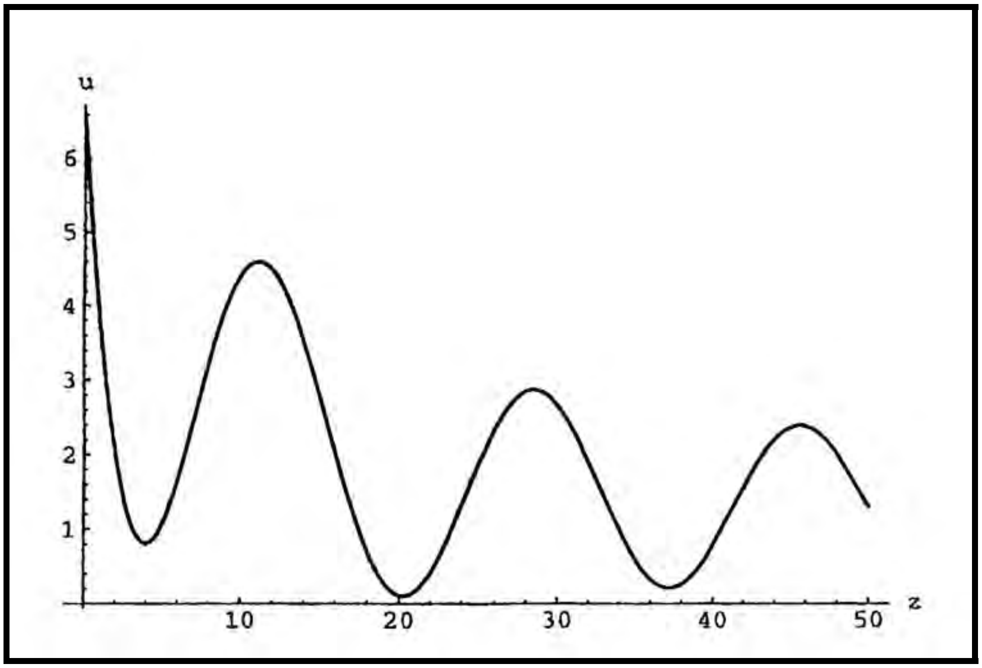

Figure 6. Energy density versus coal layer thickness (after Bob Kelly, LANL)

The z axis describes the coal layer thickness in inches and the u axis illustrates the energy density in the standing wave. This corresponds to resonant impedance measured at the feed point of the RMPA sensor. The damped sinusoidal characteristic is caused by a standing wave pattern in the coal layer. The sensor is placed against the coal layer (no air gap). Since the transmitter (PT) incident primary wave is coherent with the reflected secondary wave from the coal-rock boundary, a standing wave occurs in the coal layer. Theoretical and laboratory tests suggest that RMPA resonant conditions depend on the energy density of the standing wave at the RMPA location.

Improving Run-of-Mine Coal Quality

The concentration of coal contaminants in boundary layers of coal (up to 12 inches) is due to the peat-coal depositional environment. In deltaic deposits, stream borne sediments along with heavy metals were deposited over the peat-coal. During burial of the peat coal, microbial metabolic processes produced methane and organic hydrogen sulfide. These chemical processes, biological reactions, and compaction of the peat-coal during subsidence of the delta created the contaminated boundary layer of coal as illustrated in Figure 7.

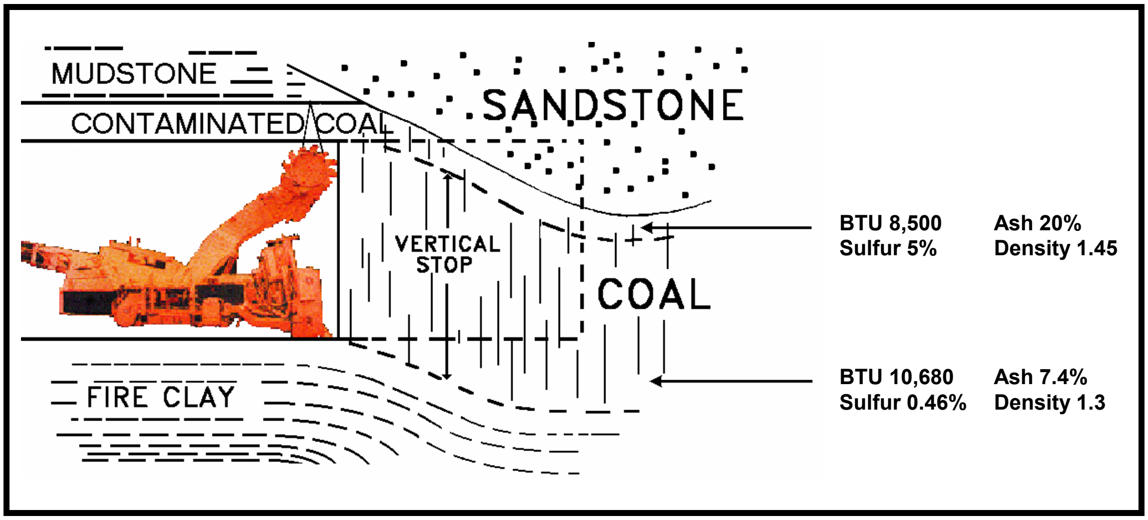

Figure 7. *Vertical cross section illustrating electromagnetic wave detection and imaging technology horizon sensing and the sump-cut cycle*

The real-time horizon sensor enables the machine to leave the contaminated layer of coal in place and improve run-of-mine coal quality. An example of the improvement in coal quality is illustrated in the figure. If the entire seam is cut, the run-of-mine coal quality is 10,338 BTU, 1.1 percent sulfur, and 9.36 percent ash (the average run-of-mine 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. The sensor reduces organic sulfur by more than 50 percent.

Because coal seams dip under paleo channels, the machine must lower the horizon of the cutting drum to remain in the coal seam. This requires a drum-mounted sensor.

Figure 8 illustrates the measured resonant frequency and resonant impedance dependence on coal layer thickness.

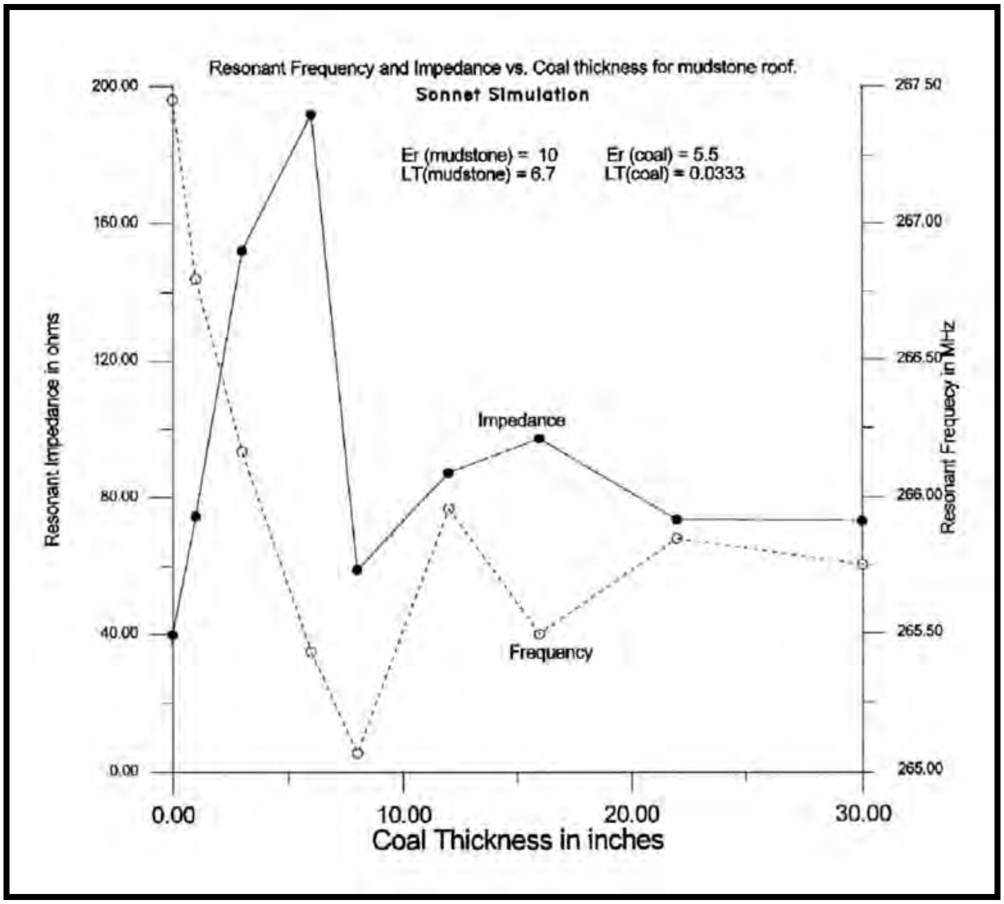

Figure 8. *Resonant frequency and impedance versus uncut coal thickness*

Field Demonstration

Field demonstrations of advanced navigation technologies were conducted at the sponsoring mining company located in southeastern Wyoming. Prior to the field demonstration, the mining company negotiated a Cooperative Research and Development Agreement (CRADA) with the DOE to demonstrate and evaluate the lateral navigation capability of the Honeywell RLG. Incidentally, the shutdown of the US Bureau of Mines resulted in the computer-assisted mining project being administratively managed under the DOE Department for Fossil Fuels. The scope of the demonstration was expanded to include the demonstration of an uncut coal thickness sensor and evaluate the potential for highwall mining in thick coal seams.

As part of the CRADA, the mining company provided a Joy Technology 12 CM11 continuous miner, which was transformed into a computer-assisted mining machine. The mining company uncovered a 30-ft thick seam of coal for what was called the Glass-Top Mine. Machine lateral navigation was demonstrated by cutting 5-ft deep 12-ft wide drives along the top of the exposed coal seam. The 12 CM11 continuous miner was guided by RLG control signals. Machine heading deviation and drift rate could be evaluated by surveying the cut headings. The tests were designed to evaluate the drift rate of the RLG. A later report on lateral navigation will be prepared by CRADA partners.

Horizon sensor navigation evaluation tests were added to the test program. The horizon sensor test focused on machine survivability and uncut coal measuring issues. The drum-mounted horizon sensor was installed in the drum of the Joy Technology's 12 CM11 continuous miner. Joy Technology's Price, Utah Service Center built the sensor enclosure for this project. The RMPA sensor drum mounting installation is shown in the photograph below (Figure 9).

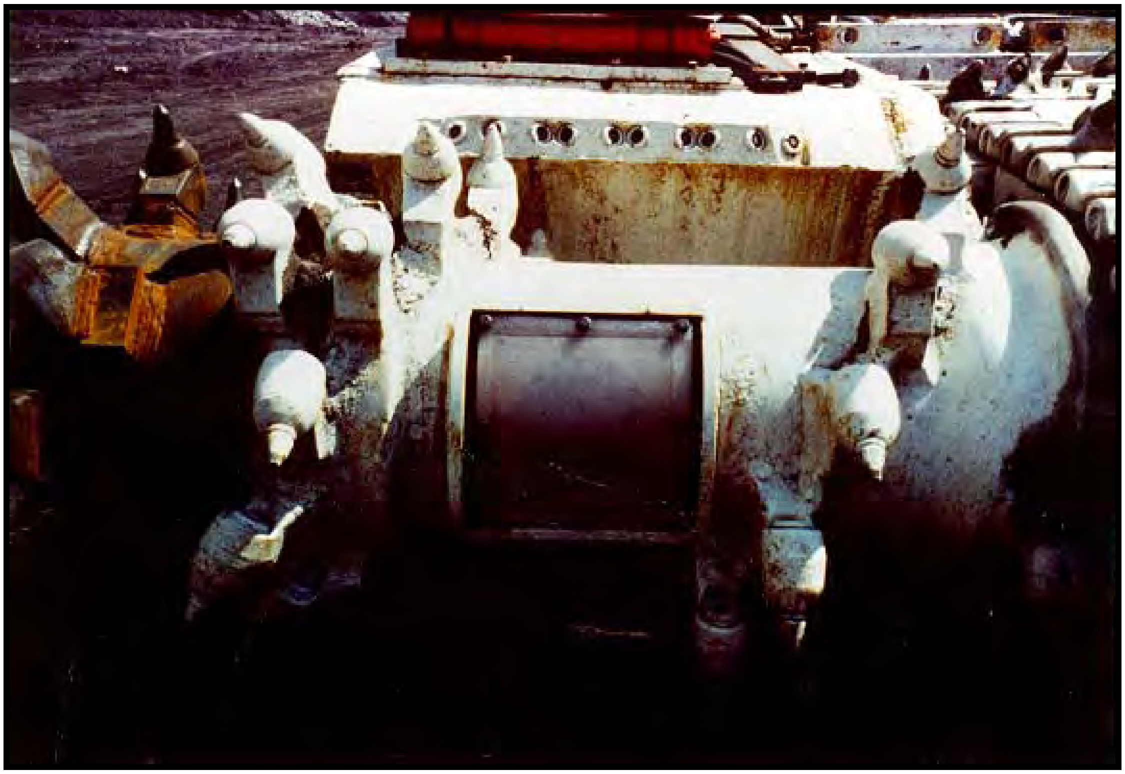

Figure 9. *Mounting of uncut coal thickness sensor on the surface of a cutting drum*

The RMPA sensor was conformally mounted in a machined cavity on a weld plate. The weld plate was conformally welded to the surface of the cutting drum. A Lexan cover plate protected the RMPA sensor from the abrasion in cutting. A coaxial cable was installed by drilling a 3/8-inch drillhole from the weld plate through to the inside of the end-of-drum cavity. An explosion-proof enclosure (EXP) welding ring was installed on the end of the drum. The EXP containing the horizon sensor electronics was inserted into the drum end cavity.

The EXP electronics includes an electrokinetic generator that provides electric power for the EXP electronics. The RMPA antenna was also used as a transmitting antenna communicating radio data to a companion receiving antenna on the machine. The machine receiving unit includes an RS-232 port for communicating with central control room. The computer-assisted mining machine was controlled from this room.

Because the coal seam was approximately 30-ft thick, a rock band in the coal seam had to be found. The rock layer simulated the floor of the glass-top mine. In later tests, the 12 CM11 continuous miner will be used to make cuts into the highwall to evaluate highwall mining potential in a 30-ft coal seam. The horizon sensor will be used to measure uncut coal roof coal next to the sandstone roof.

The uncut floor coal was measured each time the RMPA sensor rotated to the look-down position. The sensor resonant impedance was measured and used in a neural network to determine uncut coal thickness. The neural network was trained during calibration of the sensor by making measurements over a range of uncut coal thickness. The measured uncut coal thickness was displayed on a notebook computer operating in the x windows environment. The demonstration tests provided direct evidence that the sensor electronics will survive the vibration and shock of coal cutting. The sensor was able to measure uncut coal thickness in real time. Water spray did not affect the measurement values. The coal thickness measurement was limited in the glass-top tests. The measured data confirmed that thickness up to 12 inches of coal could be measured with RMPA technology.

Conclusions

The RMPA horizon sensor technology has been developed to a point that potential mine demonstrations can be conducted. The sensor will need to be installed on a continuous miner, evaluated, and improved for long-term reliable operation. The benefits to mining companies include consistent mining, reduced dust exposure to mine personnel, and increased productivity.

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Dr. Larry Icerman of the New Mexico Research and Development Institute provided the first development funds to explore the problem of actually building and testing the sensor. Dr. Dickey Arndt of NASA Johnson Space Flight Center contributed his knowledge of microstrip patch antenna theory that lead to the development of the Resonant Microstrip Patch Antenna (RMPA) sensor. In applying the RMPA to the shuttle ice detection problem, much practical experience was gained in the technology. The national laboratories also played a significant role in the RMPA development process. Dr. Billy C. Brock of Sandia National Laboratories developed RMPA theory to a greater understanding. Much credit must be given to Drs. Bob Kelly, Joe Mack, and Ron Moses of Los Alamos National Laboratory for developing, exploring, and expanding the detection and imaging physics of the RMPA high Q resonant cavity, especially its relevancy to the detection and imaging of non-metallic anti-personnel landmines. For the opportunity to prove that RMPA can be applied in the real-time measurement of uncut coal layer thickness, we must give special thanks to Bret Harvey, President of Interwest Mining Company (IMC), Dan Baker, Vice President of IMC and IMC managers, for their vision, encouragement, and financial support of this project. Without their support, the sensor could not have been developed to a practical demonstration point. To Mr. Ken Perry fell the tremendous responsibility of transitioning a totally new concept in drum-mounted sensing and imaging technology to a practical application in one of the most challenging and difficult problems in coal mining industry, the real-time measurement of uncut coal thickness.