AN ELECTROMAGNETIC NONCONTACTING SENSOR FOR THICKNESS MEASUREMENT IN A DISPERSIVE MEDIA

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Abstract

This paper describes a general purpose imaging technology developed by the U.S. Bureau of Mines (USBM) that, when fully implemented, will solve the general problem of "seeing into the earth." A first-generation radar coal thickness sensor, the RCTS-1, has been developed and field-tested in both underground and highwall mines. The noncontacting electromagnetic technique uses spatial modulation created by moving a simple sensor antenna in a direction along each axes to be measured while the complex reflection coefficient is measured at multiple frequencies over a two-to-one bandwidth. The antenna motion imparts spatial modulation to the data that enables signal processing to solve the problems of media, target and antenna dispersion. Knowledge of the dielectric constant of the media is not necessary because the electrical properties of the media are determined automatically along with the distance to the target and thickness of each layer of the target. The sensor was developed as a navigation guidance sensor to accurately detect the coal/noncoal interface required for the USBM computer-assisted mining machine program. Other mining applications include the location of rock fractures, water-filled voids, and abandoned gas wells. These hazards can be detected in advance of the mining operation. This initiating technology is being expanded into a full three-dimensional (3-D) imaging system that will have applications in both the underground and surface environment.

Introduction

Early research investigated various high-frequency radar sensor systems using pulse, impulse, FM-CW, or synthetic pulse. Electromagnetic waves penetrate coal, rock, and earth, but when the energy penetrates the media, the returning information content appears to be scrambled and out-of-focus. The problem is dispersion: Media dispersion, coupled with antenna and target dispersion, cause problems too complex to analyze in the time domain. These problems are much easier to resolve in the frequency domain. Both the time domain and frequency domain are transforms of only one variable, so either approach is legitimate. However, it is very difficult to work problems in both domains at the same time. The theory supporting the present research is in the frequency domain, but the resulting architecture for signal processing uses both. The concept being used is the spatial-domain technique (i.e., moving the antenna to create a modulation on the radar output). This concept has been applied to advantage to reject unwanted reflections and help cancel out media dispersion and antenna dispersion.

The problems of designing an underground imaging sensor were solved by utilizing a sensor model created from one-dimensional, spherical wave, scattering matrix theory. By separating surface reflections from single-layered media reflections, laboratory and field testing confirmed the validity of the one-dimensional imaging model. The model, based on fundamentals, allows the use of a wide range of design architectures.

Rather than devoting project time to hardware development, emphasis was placed on the data processing scheme required to derive coal thickness and dielectric constant from network analyzer measurements of the reflection coefficient of the target media. The sensor data were taken at a wide range of frequencies and antenna positions (e.g., 401 frequencies between 600 and 1,600 MHz and 32 equally-spaced positions over a distance of 16 in). This was accomplished with a vector network analyzer connected to an antenna that was moved in space by a linear positioner. Data processing provided a direct measurement of the thickness of underground media and also the electrical characteristics of the media. Prior knowledge of the characteristics of the media is not necessary.

Measurements made of coal, rock, concrete, granite, and salt have shown that the technique can measure thickness from 0 to over 5 ft in single and multilayer media. The accuracy of the technique is not affected when the material is rough or wet. These results and parallel applications such as the measurement of the depth of hidden tunnels, the thickness of multilayer highway pavement, and the location of buried nuclear waste, unexploded ordnance, and cultural artifacts, have provided the technical incentive to further develop this unique technology to take advantage of its broad potential, including full 3-D imaging of the underground environment.

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Experimental Measurement Technique

The original development of the radar coal thickness sensor measurement technique started with Kerns plane wave theory [1] and solved for each of the scattering coefficients in the matrix with a standard antenna calibration technique. However, when the antenna was within two wavelengths of the material being measured, diffraction became too strong an effect for a plane wave model. A solution was sought in simple plane wave theory but the cost was the necessity of an explicit solution for the coefficients of the model. Several approximation techniques for linear calibration were tried and it was found that a solution was possible. The coefficients did not vary when the antenna was closer than two wavelengths to a metal calibration plate. This was called the linear reduction method [2] and it worked quite well except for some second-order problems. It was assumed that these problems were nonlinear multipath effects that were not accounted for in the calibration procedure. The math model was then expanded to include the higher order effects and named the "quick reduction method." Many of the higher order coefficients were lumped together to accommodate a metal plate calibration technique preformed with a 4-ft-square metal plate placed between the sample and the antenna. This in-situ calibration technique corrected for signals returned from reflectors beyond the edges of the calibration plate. In an underground mine these reflections would be from material similar to the target coal but outside the measurement area. Presently a self-calibrating technique is being evaluated that will improve upon the metal plate calibration technique.

The thickness measurement process begins with a measurement of the input reflection coefficient of an antenna in close proximity to the coal surface. This measurement is taken at a wide range of frequencies and positions (e.g., 401 frequencies between 600 and 1,400 MHz, and 32 positions between 4 and 20 in from the coal. This is accomplished using a vector network analyzer connected to an antenna moved in space by a linear positioner. The measurement plane is then electrically moved from the instrument measurement plane to the plane of the antenna. Figure 1 shows the instrumentation setup.

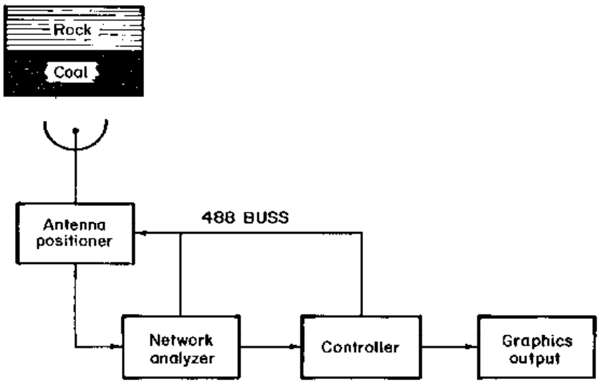

Fig. 1. Instrumentation

Data

The data from this measurement are a function of both frequency and position. The data contain both amplitude and phase information. Transforming the data to the time domain at this point in the process and inspecting the time domain history for this one antenna position shows the absence of any sharp peaks around the antenna, indicating that the information for the coal surface is corrupted by other effects such as the antenna dispersion, diffraction, and multipath. These effects must be characterized and accounted for by considering the frequency domain history at each antenna position.

Antenna Transfer Functions

To characterize the antenna, a separate test is run with a metal surface substituted for the coal surface; the same frequencies and positions are used. This provides data from a known reflection surface to obtain the antenna transfer functions. These functions are used in removing antenna dispersion from the data taken at the corresponding antenna position.

Removing Antenna Dispersion

When the antenna transfer functions are accounted for in the data, the result is the product of the antenna-to-surface-to-antenna distance, represented by the spatial delay and the coal surface reflection coefficient. It is the reflection coefficient that contains the information for the coal thickness. Other reflections (i.e., multipath) are also present in the resulting transfer function.

Shifting Image Plane to Coal and Removing Diffraction

Dividing the reflection coefficient expression by the spatial delay shifts the image plane from the antenna to the surface of the coal and removes diffraction. With the antenna-to-surface-to-antenna distance a known quantity, the true reflection coefficient in the frequency domain can be determined.

Integrating Space

By performing a spatial integration, the multipath can now be decorrelated. Since spatial integration is coherent with the coal but not coherent with any other spatial distances, the multipath will become zero sum or at least small compared with the surface reflection.

Transforming to the Time Domain and Range Gating

Transforming the data to the time domain and range gating, removes unwanted reflections from the data by gating out all the information on either side of the desired peak. However, the data as presented in the results section of this paper have shown that range gating is unnecessary as the signal return from the dielectric interfaces between the coal and rock are sufficiently distinct to make the interface easily discernible. If range gating were used, transforming the reflection coefficient back to the frequency domain would yield the composite reflection coefficient for just the reflections within the range gate.

Validation of the Model

An earlier method [2] for determining the thickness transformed the time domain reflection coefficient back to the frequency domain so that the measured reflection coefficient could be correlated with theoretical reflection coefficients for various thicknesses and dielectric constants. The theoretical reflection coefficient that correlated best, provided a statistical determination of the thickness and dielectric constant of the coal being measured. For example, the theoretical reflection coefficient that correlated best with the measured reflection coefficient was for a coal thickness of 5.3 in (for a relative dielectric 4 and loss tan of .03). The actual thickness of the rough wet coal measured in this underground test was a nominal 6 in. This result provided the encouragement to refine the model and proceed with the development of a method to directly measure the coal thickness from data acquired by the network analyzer frequency domain measurements.

Field Test Results

The purpose of this research was to develop a coal and rock thickness sensor of sufficient accuracy to provide vertical and horizontal guidance of both room-and-pillar and highwall mining machines. In order to validate the theory developed for thickness measurement, extensive underground and surface mine testing was performed. Over a period of 2 years, tests were conducted in mines with a variety of geological and environmental conditions. Test areas of both freshly mined and aged coal from 3 to 60 in thick were measured. The areas measured ranged from very dry to extremely wet with water dripping from the roof test area. The wet coal did not affect the thickness measurement. Coal seams with clay and metal vein intrusions of iron pyrite could be imaged and the distance from the coal surface to the intrusion was accurately measured. Surface roughness and cleating was not a problem. The average thickness of rough cleated surfaces was measured accurately. Accurate measurements were obtained even when water filled the cracks between the cleats.

Roof Tests

Roof thickness tests were made in production mines and in the Safety Research Coal Mine at the USBM Pittsburgh Research Center. Figure 2 is a representative measurement of roof coal thickness. On the vertical axis, the plot shows the amplitude of the reflected signal in decibels; time in nanoseconds is shown on the horizontal axis. The large peak on the vertical axes represents the reflection from the first interface, the air/coal interface. Signals plotted to the left of the large peak represent discontinuities internal to the measurement equipment and between the antenna and the coal surface. These reflections are reduced to at least 30 dB below the air/coal reflection by the calibration and spatial integration scheme. To the right of the air/coal reflection are reflections from discontinuities internal to the coal and shale being measured. The printout on the left is the thickness of coal between the air/coal interface and the coal/shale interface. Measurements have identified both the thickness of the coal and the thickness of the next layer, usually shale, above the coal roof. At the L-band frequencies presently used, the depth of penetration is usually about 10 ft. Future roof thickness measurement research will attempt to provide a direct readout of the thickness of each layer of geological material within the penetration range of the signal. At the present time, the power level of the transmitted signal is 0 dBm (1 mW). This signal level, or less, is adequate to produce a good signal-to-noise ratio for the return signal measurement. The hardware will permit an increase in transmitted power of 20 dB to determine if greater penetration is best achieved through increased signal power or through the use of a lower transmitter frequency. Both the hardware and software will operate from 300 kHz to 3,000 MHz.

Rib Tests

Figure 3 is a plot of actual data taken at an operating highwall mine in West Virginia.

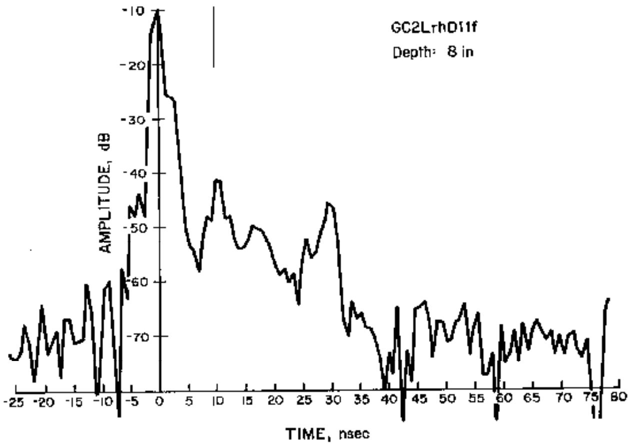

Fig. 2. Roof Coal Thickness

Measurements were made in freshly mined entries immediately following the mining machine. The determination of rib thickness can usually be interpreted both visually from the FFT data in the figure and from the numerical readout from the automatic thickness measurement software. A large dielectric contrast is seen at the first air/coal interface and a somewhat smaller but still pronounced reflection can be seen as the signal exits from the coal rib at the coal/air interface in the adjacent drift. The vertical bar to the right of the main peak at the first interface as the signal enters the rib indicates that the rib thickness is 35 in. The dielectric constant and loss in decibels per meter is also indicated above the rib thickness measurement printout at the left of the plot. Rib measurements were also made in underground mines over the range of 18 to 50 in. The thickness in these test ribs could be determined to within 1 or 2 in.

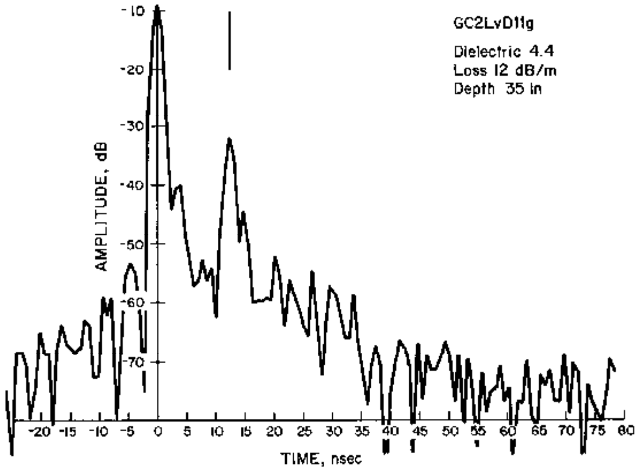

Fig. 3. Rib Thickness

Figure 4 is a plot of actual data taken at an operating highwall mine in Kentucky. In this case the software presented an amplitude vs range plot, an improvement over the amplitude vs time plot of figure 3. The data shown are for a rib thickness of 57.2 in with a dielectric constant of 3.97. The measured loss was 2.92 dB per wavelength. Also measured but not shown was the distance from the antenna measurement plane to the coal surface. This distance data could be used for control of the position of the mining machine.

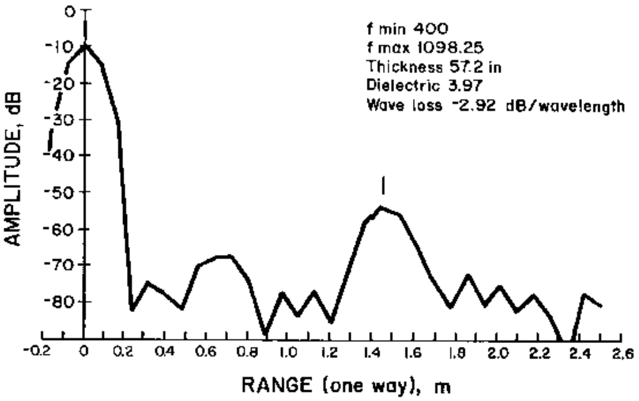

Fig. 4. Rib Thickness, Amplitude vs. Range

Thickness Measurement of Other Materials

The thickness of other materials has been measured with equal success. Granite, sandstone, and concrete ranging in thickness from 2 ft to over 4 ft have been measured to within 2% of their actual thickness. The thickness of each layer of multilayer pavement can be determined as can the location and orientation of steel reinforcing bars.

Conclusions and Recommendations

Field testing of the electromagnetic coal thickness sensor has produced results of sufficient accuracy (1 in for coal from 3 to 60 in thick) to justify continuing with the engineering work necessary to develop a practical sensor that can be mounted on a mining machine for the determination of roof, floor, and rib thickness. In addition, this research will be extended to the development of a full 3-D imaging system capable of "seeing into" the earth. Algorithms are presently being evaluated to simultaneously measure the azimuth, elevation, and range of targets in multilayered media such as coal and rock as well as for the location of buried ordnance and nuclear waste. Future plans are to minimize the size of the data set to reduce the software processing time now about 1 sec, and facilitate the construction of a compact sensor suitable for machine mounting or use as a general geological survey tool.

It was found that vertical E-field polarization penetrates thicker coal ribs than horizontal E-fields.

This is thought to be due to the thin horizontal ash layers having a higher loss than the coal.

The real part of the dielectric in coal varies very little from a value of 4 but the loss tangent varies a great deal. Wet, rough, or heavily cleated coal had little effect on the dielectric measurement.

The ash content may be related to the loss tangent of the dielectric measurement. This would be a helpful means to identify higher quality coal.

References

1. Kerns, D. M., Plane-Wave Scattering-Matrix Theory of Antennas and Antenna-Antenna Interactions, Nat. Bur. Stand., NBS Monogram 162, June 1981.

2. Chufo, R. L. and Walter J. Johnson, A Radar Coal Thickness Sensor, The 1991 IEEE Industry Applications Society Annual Meeting, September 28-October 4, 1991, Dearborn, MI.