AN ELECTROMAGNETIC SPATIAL/SPECTRAL SENSOR FOR GEOLOGICAL MEASUREMENTS

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ABSTRACT

The U.S. Department of Energy Pittsburgh Research Center,[1] has developed and field tested a spatial, spectral sensor for measuring the thickness of mineral deposits. Knowledge of the dielectric constant of the material is not necessary because the electrical properties of the media are determined automatically along with the thickness or distance measurement. The technology was developed to measure the thickness of coal remaining in the roof and floor of a mine or the thickness of a coal pillar remaining between two mining entries for the purpose of guiding a mining machine. However, field tests have shown the new technique is equally valuable for measuring the thickness of each layer in a multilayer manmade structure such as highway paving or building foundations and the thickness of geological deposits other than coal, such as, salt, granite and sandstone. The noncontacting electromagnetic technique uses spatial modulation created by moving a simple dipole 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 and enables frequency domain signal processing to solve the problem of media, target and antenna dispersion. The technique overcomes the problem of multipath reflections from nearby metal structures and avoids the use of radio frequency absorbing material. In its present form the system measures material thickness of zero to over 3 m to within ±2.5 cm accuracy. The system parameters are variable to suit the application but for most applications default values of 40 cm antenna motion with measurements made at 401 frequencies from 0.6 to 1.4 GHz at each of 32 antenna positions with a power level of 0 dBm or less are more than adequate to provide a satisfactory signal-to noise ratio. In the range of 0 to 10 m the system operates in the continuous wave mode and by simply turning off the transmitter for ranges beyond 10 m the problems of time domain processing are entirely avoided. The technique can be implemented with a vector network analyzer, a servo controlled L-band antenna positioner, an IEEE488 bus controller and a process computer. An electronics package designed and constructed to operate in the harsh mining environment and providing 1, 2 or 3 dimensional image presentation is being evaluated as a replacement for the network analyzer.

Key words: Ground penetration radar, Spatial, Spectral

INTRODUCTION

Ground penetration radar technology has to deal with two fundamental problems: penetration and focus. Low-frequency electromagnetic waves penetrate the media but do not clearly image small objects. When the transmitted energy does penetrate the media, the returning signal appears to be scrambled and out of focus. The problem is caused by dispersion. Media dispersion coupled with antenna and target dispersion cause problems too complex to resolve in the time domain. It is much easier to solve these problems in the frequency domain. The theory supporting the Radar Coal Thickness Sensor technology is in the frequency domain but the signal processing architecture uses both frequency domain and time domain signal processing. In the future, all the signal processing will be in the frequency domain. A time domain graphics plot of the transformed frequency domain data is provided to visualize the reflected signal.

The thickness measurement technique uses a continuous-wave (CW) signal with a single antenna for simultaneously transmitting and receiving. The antenna is moved perpendicular to the surface whose layers are being investigated. The antenna movement is in 32 discrete steps over a distance of 40 cm. At each step, CW signals are transmitted in 401 increments from 600 to 1,600 MHz. The amplitude and phase of the reflected signal are recorded. When the antenna has completed its motion, all of the recorded data are analyzed by a computer. The result of the analysis shows the location and thickness of layers of material with different dielectric constants. The boundaries between air and coal, coal and shale, etc., can be measured with an accuracy of ±2.5 cm to a depth of at least 3 m. Field experience with the sensor has provided the confidence to envision that this sensor technology can be a general solution that will satisfy other underground imaging and thickness measurement requirements. These requirements include the detection of tunnels and the detection of mining hazards such as water-filled voids and fractures that may be particularly dangerous to the mining process. The present technology has been implemented as a one-dimensional (1-D) sensor and 2-D sensor. The theory

[1]This work originated under the U.S. Bureau of Mines prior to transferring to the U.S. Department of Energy on April 4, 1996.

for developing this same concept into a 3-D imaging sensor has been developed for implementation and field testing.

DESIGN APPROACH

Equipment

Early in this development effort it was decided that the thickness measurement scheme would be implemented in software that could control off-the-shelf radio frequency (RF) test equipment. This approach was taken to insure that no resources were devoted to the expense of hardware design and development and the associated development risk. Consequently, the program effort went into the development and validation of software to gather and process the measurement data. The antenna is a simple dipole with a polarized screen reflector and matching balun. The antenna positioner that moves the antenna to produce the spatial modulation is constructed entirely of common hardware store PVC tubing. A stepper motor is enclosed in the base of the positioner and drives a nonmetallic screw to position the antenna with sub-millimeter accuracy. The positioner assembly includes limit switches that interrupt the data collection software if antenna positions beyond the range of travel are entered into the computer data statements. Originally it was thought that the antenna positioner should be constructed of nonmetallic components, and with the exception of the stepper motor at the far end of the assembly and the small limit switches, the positioner is nonmetallic.

The instrumentation used is a HP8753 network analyzer[2] a HP R/382 68040-based computer controller, and a general purpose IEEE488 bus controller for driving the stepper motor. A fiber optic IEEE488 data link is used when it is desired to locate the control computer in a sheltered location away from rock falls and the mining machinery. The computer code is written in Rocky Mountain Basic (RMB).

FIELD TESTS

The initial 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 conducted over a period of 2 years in mines with a variety of geological and environmental conditions. Test areas of both freshly mined and aged coal from 7 cm to 150 cm 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 could be 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.

Measurements were made on mine roof coal, mine rib coal, granite, sandstone, and salt. The data output plot shows the amplitude of the reflected signal in decibels vs time in nanoseconds and distance in meters. A large peak on the vertical axis represents the reflection from the first surface. Signals plotted previous to the first surface reflection represent discontinuities internal to the measurement equipment and between the antenna and the first surface. These reflections are reduced to at least 30 dB below the first interface reflection by the calibration and spatial integration scheme. Peaks following the first reflection are reflections from discontinuities internal to the media being measured. A table lists the calculated real part of the dielectric constant, the loss in decibels-per-meter, and the thickness of the target material. 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 3 m. The present roof thickness measurement research provides a direct readout of the thickness of each layer of geological material within the penetration range of the signal along with the permeability and permittivity. A transmitter power level of 0dBm (1mW) is adequate to produce a good SNR for the return signal measurement and increased power levels are not necessary. Both the hardware and software will operate from 300 kHz to 3,000 MHz.

Similar results are obtained when the sensor is used to measure the thickness of concrete or asphalt paving. Multiple layers of paving can be detected and the thickness and electrical characteristics of each layer measured.

FUTURE PLANS

An electronics package has been constructed that will replace the off-the-shelf test equipment that has been used on the tests described in this paper. This second-generation effort has resulted in a small portable instrument that will greatly ease the problems associated with transporting the laboratory test equipment to the various test sites and into and out of operating underground and surface coal mines. The sensor package, including the antenna, are packaged so that it can be installed on an operating highwall mining machine to measure the thickness of the coal rib separating the active cut from the previous cut. This information will be used for automated machine guidance so that a rib thickness of 1 m to 1.5 m can be maintained for roof support. The actual thickness maintained will be determined by the conditions at each mine site.

[2]Reference to specific products does not imply endorsement by the U.S. Department of Energy Pittsburgh Presearch Center.

This sensor will measure multilayer targets in 1-D with a spatial modulator that moves the antenna on an axis perpendicular to the target. A new antenna positioner moves the antenna in the necessary two or three dimensions as required to scan the target to produce a 2-D or 3-D image. A low-cost electronics package was designed and constructed to replace the function of the laboratory network analyzer. The frequency synthesizer included in the new analyzer package covers a three-to-one bandwidth with sub-microsecond coherent switching between programmed frequency steps. The success of the system depends on the accuracy and speed of the frequency synthesizer, the data processing speed and data acquisition, and transmission rate. For low-frequency ground probing applications, it is now possible to construct an all-digital programmable receiver and transmitter at low cost.

CONCLUSIONS

An electromagnetic, noncontacting thickness sensor has been designed, constructed, and field tested. The results were of sufficient accuracy to justify continuing with the engineering work necessary to develop a practical sensor that can be mounted on mining machines for the determination of roof, floor, and rib thickness. The equipment operates in the presence of nearby and adjacent metal structures and will be packaged as a portable instrument that can be used for other applications for measuring the thickness of rock and concrete and measuring the size and depth of tunnels. The technology when fully developed appears to be usable as a general solution to the problem of locating and imaging underground artifacts.

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