A SPATIAL/SPECTRAL DOMAIN MICROWAVE COAL SEAM IMAGING SENSOR–PROGRESS IN SIGNAL PROCESSING

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Abstract-The paper, "An Electromagnetic Roof and Rib Thickness Sensor" presented at The 12th WVU International Mining Electrotechnology Conference in 1992, presented the results of roof coal thickness measurements in underground mines and rib coal thickness measurements in highwall mines. The microwave sensor described uses a unique spatial modulation scheme created by antenna motion, along with frequency domain signal processing, to solve the problem of media, target, and antenna dispersion. This paper further describes the advantages of the unique frequency domain signal processing technology chosen by the U.S. Bureau of Mines in extending previously reported one-dimensional thickness measurement technology to the generation of a full three-dimensional underground image of the underground environment.

The electromagnetic signature of a media, whether it is coal or other geological material, is its permeability and permittivity and the effect on the velocity and amplitude of an electromagnetic wave as it passes through. High-quality imaging cannot occur without the identification of, and correction for, the permittivity and permeability of each layer of a multilayer geological deposit. Clutter, or any signal that can interfere with target discrimination, usually comes from objects in the field of view for which there is no design control. These are nuisance targets with possibly very high contrasts compared to the real target. The only proven tool to reduce clutter is to increase spatial, spectral, and polarization diversity. This paper will describe some techniques being used by the U.S. Bureau of Mines to increase the information content of both single-dimensional and three-dimensional imaging systems through the identification of media distortion mechanisms made possible by the use of spatial/spectral sensor technology. These techniques will permit high quality imaging in an environment where the data is corrupted by dispersion and clutter.

INTRODUCTION

Parseval's relation states that frequency is just a time derivative. This has resulted in two sets of Maxwell's equations, one set for the time domain (TD) and an equivalent set for the frequency domain (FD). There are no physical phenomena or variables in one domain that do not have corresponding physical phenomena or variables in the other domain. A TD sensor, like pulse radar, senses reflections vs. time. An FD sensor, like a synthetic pulse sensor, measures a number of frequencies and integrates the reflection data to theoretically get the same reflections vs. time as does the TD radar. However, in a practical sense, we must ask, Are these two hardware architectures equal? For subterranean imaging, FD sensors have an overwhelming advantage over TD sensors for the following reasons:

1. The true imaging objective is the spatial distribution of permittivity and permeability, not reflection amplitude vs. time. In a subterranean media, electromagnetic time-space is not linear. High-quality imaging cannot occur without the identification of and correction for permittivity and permeability.

2. Subterranean imaging is a complex problem requiring large data files and complex signal processing. FD sensors produce more object plane data with more degrees of freedom than TD sensors.

3. FD sensors produce data in a format compatible with theory. TD data must be transformed into the FD before dispersion corrections can be made. Windowing data in preparation for a transform will cost about a third of the data.

4. Spectral bandwidth is equivalent to information. But for TD sensors, limited by analog to digital converter (ADC) sample rate, a smaller pulse-width means less information. As a result, FD sensors can produce more bandwidth than equivalent TD sensors.

5. All antennas are dispersive. If a TD sensor and an FD sensor use the same antenna, the FD sensor will get more than twice the bandwidth out of the same antenna than does the TD sensor.

GENERAL

Subterranean Imaging

The electromagnetic signature of a media is its permeability and permittivity and the effect on the velocity and amplitude of an electromagnetic wave as it passes through. The reason so many of the boundaries in a TD image look like ringing and are blurry, is because of the difference of permittivity (dispersion) at the boundary of materials having different dielectric constants. In TD processing the dispersion is almost impossible to sort out, but in FD processing the problem is a straightforward inverse scattering problem.

Processing Complexity

There are many problems with imaging and identifying the permittivity of underground targets. The antenna, media, and target are all dispersive; the media are usually inhomogeneous and lossy, and the target may have very little dielectric contrast compared to the bulk media in which it is buried. Sometimes the targets are either lying on the surface or are buried just below. Therefore, the surface reflections can never be completely separated from the target in the TD.

We can postulate that multipath in TD, is the same as dispersion in FD. If two or more paths are too close to be separated by time (i.e., not enough bandwidth is available for separation) they can still be separated in the FD if the dispersion signature is known.

In addition, the surface acts like a reflector and the antenna sees itself as a target. Like the old multimeter problem where the meter impedance was part of the measurement, antennas interact with the unknown ground impedance. To make matters worse, the measurement is distorted by antenna and media dispersion.

Clutter, or any signal that can interfere with target discrimination, usually comes from objects in the field of view for which there is no design control. These are nuisance targets with possibly very high contrasts compared to the real target. The only proven way to reduce clutter is to increase spatial, spectral, and polarization diversity (i.e., reduce the antenna beamwidth, use a range gate, and improve E field spatial purity).

When the spectral bandwidth of a TD sensor increases, the information content decreases because the hardware limits the maximum data sampling rate. If the TD hardware is optimum, then only one pulse can be sampled because only one pulse is returned from the stationary target in the object plane. When TD people talk about averaging, they are talking about overcoming the moving clutter within the transmitter and receiver. One cannot talk about KTB noise, (the "noise floor" where K = Boltzmann's constant, T = noise temperature in degrees Kelvin, and B = noise bandwidth in hertz) which is random and can be averaged, because the object plane is so close to the antenna and the transmitter power level is so high that KTB noise should never show up in subterranean imaging.

Theory

Increasing the information content of an image will not help unless all the distortion mechanisms are also identified. Equations written in the FD are preferred to TD equations because FD equations more easily characterize distortion caused by dispersion and clutter.

Spectral Bandwidth

When the sensor is a ground penetrating radar (TD sensor), the typical means of increasing the bandwidth is to reduce the pulse width. This usually makes things worse because antenna dispersion, coupled with media and target dispersion, causes time and space distortion problems too complex to sort out in the TD.

It is interesting to hypothesize that more frequency diversity (i.e., a shorter equivalent pulse) can be achieved by either (1) modifying the antenna design so that the phase center, in FD phase space, moves in the direction of propagation to counteract the dispersion delay (the phase of $S_{01}S_{10}(f)$) within the antenna, or (2) the phase of each frequency, for the stepped CW data, can be shifted at the output of the receiver to counteract the dispersion delay. For all common dispersive and anisotropic targets, the two techniques are the same. However, due to the finite dynamic range of the receiver, the two techniques are not the same for antenna gain correction. Phase can be corrected in the software, but gain must be corrected by attenuating the transmitter midband power output before the receiver reference power splitter. Attenuating transmitter power will not degrade system performance by adding noise to the system as received signal strength is in excess of the noise floor. In fact, there is merit in reducing the transmitter power below the present 0 dBm level to further reduce any clutter generated by the third harmonic of the transmitted signal. Transmitter power in the FD system is not an issue as signals returned from the target are well above the noise floor.

In addition to the external clutter, there are serious problems with internal clutter. Internal clutter is multipath within the sensor or paths between antenna and outside sensor parasitics for which there is some design control but have not fully mitigated or understood. Internal clutter is difficult to measure and is usually overlooked because designers have evoked the linear transform principle to declare that any unknown but fixed internal multipath will affect the target and nuisance target equally. Research has shown that this assumption is incorrect. The antenna parasitic can produce quasi-harmonic couples with the media that cannot be solved with linear techniques.

When the antenna cross-section coefficient is tested (see fig.1) one finds that the error terms have a missing harmonic. This passive cross-section is caused by the antenna parasitic and the asymmetry of the impinging field and its effects are quasi-harmonic and much more complex than a single power series. Fig. 2 shows how the wave might reflect from the parasitic on the first bounce but enter the coaxial cable on the second bounce. The usual problem is that some of the backplane or reflector will act like a mirror to the half space but not excite the antenna on the first bounce.

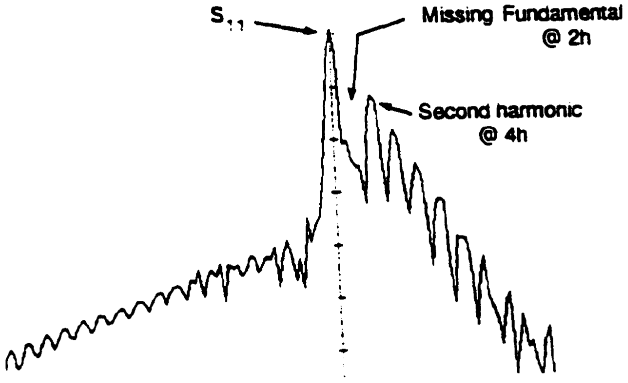

Fig. 1. Antenna Cross-Section (coefficient) with Parasitic Errors.

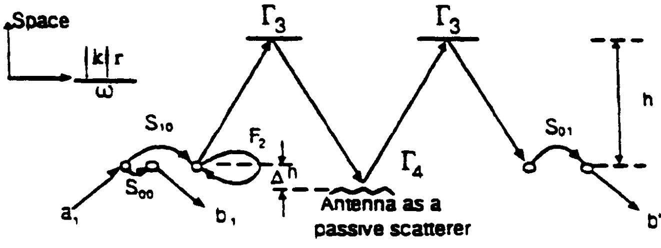

Fig. 2. Monochromatic Phase-Space for a Passive Scatterer.

Antenna Dispersion

Fig. 3a shows spatial Bessel data (and spectral data a through e) of a single target before and after antenna normalization. Each polar plot is the spatial history for one frequency. The top row (600-1400 MHz) is how the data would appear at the ADC if only the S_{00} reflection was removed. The bottom row is the same data after compensation for the two-way antenna gain $S_{01}S_{10}$.

Fig. 3b are data that have had the reflection and gain removed after the ADC, and it can be seen that the 600 MHz data are noisy compared to 800 MHz (antenna resonance) data. This is because the bulk of the dynamic range was used to remove reflection and gain before the first receiver amplifier. With an antenna normalization circuit (synthetic interferometer) there will be a uniform signal-to-noise ratio for all frequencies.

Consider a synthetic switch hypothesis. Most monostatic radar designers use a transmit/receive switch at the input to the receiver to gate out the antenna reflection $S_{00}(f)$. This allows maximum dynamic range for target response in the receiver. However, this condition occurs at only one frequency, and if the antenna is too close to the target the switch must be very fast. This hypothesis assumes that there exists a passive antenna network that will cancel all antenna reflections into the receiver for all frequencies, thus eliminating the need for the transmit/receive switch or the minimum-distance-to-target requirement.

An antenna normalization circuit solves two problems, (1) it corrects the antenna dispersion plus any other distortions found in calibration, and (2) it allows a receiver architecture to be designed without a switch.

CONCLUSION

The imaging goal of measuring the permeability and permittivity of a target, whether it is coal or other geological material, is best met with FD sensor technology. High-quality imaging should be done with the measurement technology that provides the greatest amount of information about the object plane. Frequency domain measurement technology has the most degrees of freedom and has a data-gathering format compatible with image-processing theory. With high quality data, the boundaries of materials having different dielectric constants and the resulting dispersion that causes blurry images can be easily resolved.

Nomenclature

A	Area of a spatial modulation spiral area.
a	Vectorial spectrum for E of incident field.
a_0	Incident wave-amplitude in antenna feed transmission line.
b	Vectorial spectrum for E of scattered or radiated field.
b_0	Emergent wave-amplitude in antenna feed transmission line.
e	Constant (2.718281828).
f	Frequency.
j	Imaginary number $(j^2 = -1)$.
k	Wave number ($2\pi/\lambda$, free space).
M_{11}	Measured input reflection coefficient.
R	Recursive reflection terms.
S	Scattering matrix parameter.
S_{00}	Antenna reflecting characteristic into coaxial cable.
S_{01}, S_{02}	Antenna receiving characteristic from free space to coax.
S_{10}, S_{20}	Antenna transmitting characteristic from coax to free space.
S_{11}	Antenna reflecting characteristic from space to space.
T	Vector spatial delay with diffraction.
t	Time.
v	Velocity.
Z	Distance of antenna to dielectric.
Z_0	Characteristic impedance.
λ	Wave length.
Γ	Reflection coefficient.
θ	Angle.
e^{-jkr}	Spatial delay factor.

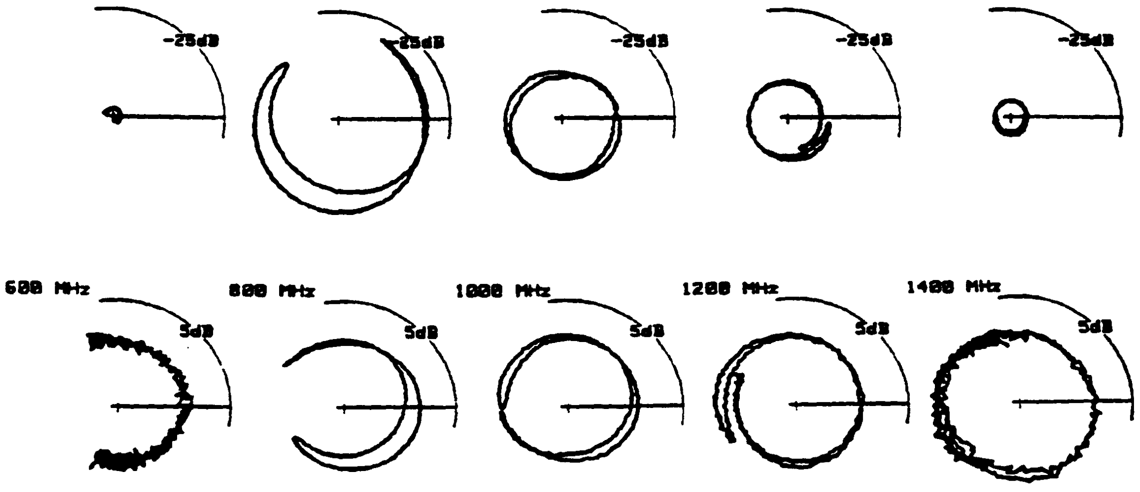

Fig.3. Antenna Normalization in Gain and Phase: top row, with S_{00} reflection removed, bottom row, after two-way antenna gain compensation.