PROPAGATION IN A DIELECTRIC SLAB

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University of Cape Town, October 2008

DECLARATION

This is to certify that this thesis is my own, unaided work. All assistance taken has been properly acknowledged and all information drawn from other sources has been referenced and acknowledged.

The thesis is being submitted as a partial fulfillment for the **Degree of Bachelor of Science in Electrical Engineering** at the University of Cape Town. It has not been submitted for any degree or examination at any University.

Signature...

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21st October 2008

ABSTRACT

There has been regular reports, of methane gas explosions in coal mines. This methane gas remains traped in voids of coal seams. This thesis focuses in launching and propagation of Electromagnetic (EM) waves to probe ahead of the drill that drills in the coal seam to extract methane gas. A model is used to simulate seam-rock waveguide to study the behaviour of EM waves in the seam. Another program is used to investigate the loss in the path of these waves.

ACKNOWLEDGMENTS

First and fore most I would like to thank God for giving me life. I would also like to thank Prof. M.R Inggs for always assisting for everytime I experienced some problems.

I acknowledge the Radar remote sensing group(RRSG) for their support during the completion of this report. In particular I would like to thank Jonathan and Gunther for their consistent assistance and patience, especially towards the deadline of the project.

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List of Symbols

c — Speed of light
E — Electric field intensity
H — Magnetic field intensity
k — wave number
α — Attenuation Constant
β — Phase Constant
μ — Permeability
ϵ — General Permittivity
ϵ_c^* — Complex Permittivity of Coal
ϵ_r^* — Complex Permittivity of Bounding Rocks
σ — Conductivity
η — Intrinsic Impedance

Glossary of Acronyms

EM — Electromagnetic
TE — Transverse Electric
TM — Transverse Magnetic
TEM — Transverse Electromagnetic
EA — Excess attenuation
AR — Attenuation rate
RF — Radio frequency
E — Electric field
H — Magnetic field

Chapter 1

INTRODUCTION

1.1 Background

There is need for electricity in everyday life to facilitate efficient operation of industries and other utilities. Coal is the most used form of energy to drive generators that produce electricity in the world[12]. According to [13], coal is the highest source of Greenhouse gases. A much cleaner and reliable source of energy has been sought to support, if not replace, the already existing source(coal). Methane gas has now caught the attention of many African countries, mainly to support the existing source. There is currently an ongoing project in Botswana to build the third Methane gas station in the world [14].

Coal may be defined as *a heterogeneous mixture of organic compounds, together with a certain amount of organic material in the form of moisture and mineral impurities*[15], and it is found in seams. The degree of metamorphosis (coal rank or classification), the physical, chemical technological properties of coal constituents, combined, contribute to the properties of the seam as a whole. Generally, coal seams are usually saturated with methane gas that is kept adsorbed in the coal by water's hydrostatic pressure. According to [16]and [17], there has been a need to extract methane gas from the seam to reduce the hazards that it brings to the safety of workers or even to be used to drive generators.

Coal seams differ according to the geographical position and the time of formation. Over time, these seams develop fault lines due to the movement of Earth's plates, and thus introducing mud in the seam, making coal mining a hustle. Clay is believed to be the most abundant and the widely-spread mineral occurring in coal seams [18].

A drill is used to drill through the coal seam, to extract methane. This can be done by horizontal drilling [19]. Horizontal drilling needs borehole surveying to probe ahead of the drill, as to increase mining productivity and indicate the amount of coal between the upper and lower floor of the seam. Surveying will indicate the thickness of the seam, and is therefore a powerful tool for locating faults, clay-veins and sand channels.

1.2 Problem Definition

Interest has developed in propagation of EM waves in coal seams, to probe ahead of a borehole drill that is extracting methane gas from the seam. The project is to investigate the launching and propagation of these waves in various grades of the seam sandwiched by host rocks. Of great interest is the effect of changes in thickness of the coal seam, and the presence of the fault that cuts off the seam by dislocation. In this project, *a coal seam is idealised as a resistive slab bounded by more conductive rocks*[20], which are termed as host rocks. EM waves are taken to be sourced by a vertical electric dipole.

1.3 Project Objectives

The objectives of this thesis are:

- to solve the boundary conditions at the coal seam and the host rock,
- to simulate boundary conditions and plot the mode (TM and TE) solutions,
- to see how the EM waves behave in the less conductive coal seam,
- to conclude on the findings.

1.4 Project Scope

This thesis uses some open source FD-TD codes generated as a GUI in Matlab or C+ + (platform-independent). These GUIs will be used to launch EM waves and observe their propagation in dielectric slabs of different thickness, so as to model a coal seam and its host rocks.

The main emphasis is in:

- investigating how the presence of faults affect the propagation,
- investigating how change in thickness affects the propagation.

1.5 Limitations

Just like any other project time will always be a limiting factor. 3-dimentional problems will not be looked into because of the available time frame.

1.6 Plan of Development

This thesis starts with background research that is required to understand the problem at hand, and the tools needed to proceed with the rest of the project. The drilling system is looked into to reinforce the process of extracting methane gas from coal seams, then literature of existing researches is reviewed to reflect how others have approached the problem theoretically.

Chapter 3 presents the geology and classification of coal. Dielectric properties of coal will be discussed.

Chapter 4 presents sedimentary rocks that may bound the coal seam. Dielectric properties of these rocks will also be prensented. Coal seams are normally bounded by sandsteones or shale with occasional limestones.

Chapter 5 presents a brief theory about dielectric waveguide.

Chapter 6 outlines the procedure followed to meet the objectives of the project.

Chapter 7 presents the overall results with relevant discussions.

Chapter 8 draws conclusions based on the results and makes recommendations for future developments.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Close to half a century ago, Wait (1963)[9] speculated that a natural waveguide may exist in the earth's crust through which electromagnetic (EM) waves may propagate as guided waves. The Earth's crust is usually considered to extend to the depths ranging from 10 to about 50km. The structure of the crust is actually very complicated. For example, just below the surface there may be a relatively thin film of soil covering the sedimentary rocks. There is then granite, below the sedimentary rocks , which extends to some depth towards the core of the earth for a couple of kilometres. This granite is thought to have a low conductivity compared to the sedimentary rocks. Further down towards the core, an increase in conductivity is again experienced due to the increase in temperature [9].

It is within this low conductivity granite that EM waves could be propagated in the manner of a waveguide. The variation in conductivity constricts the EM waves within[1] the granite. For carrying out analytic studies, a model similar to the one in figure 2.1 is usually developed.

In this chapter, literature of studies that analysed the propagation of EM waves in a natural waveguide is reviewed in a theoretical sense. The chapter starts by giving a brief review of the methods of mining coal and then focuses on the review of literature that was aimed at investigating EM waves propagation in coal seams, detection of coal seam anomalies, extraction of methane gas or water (that accumulates in voids), and/or location of abandoned coal mines. This is of major importance in the mining industry [21] [4].

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[1] Some EM waves may leak into the more conducting sedimentary rocks and decay away exponentially.

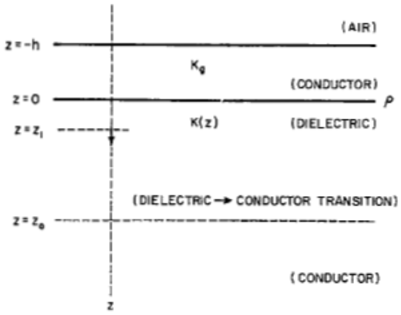

Figure 2.1: Model of the Earth's Crust [9]

2.2 Coal Mining Methods [1]

Coal is mined from coal seams using different methods. Surface and Underground mining are the two methods that are used depending on the geological position of the coal seam in the earth. Figure 2.2 illustrates these different methods.

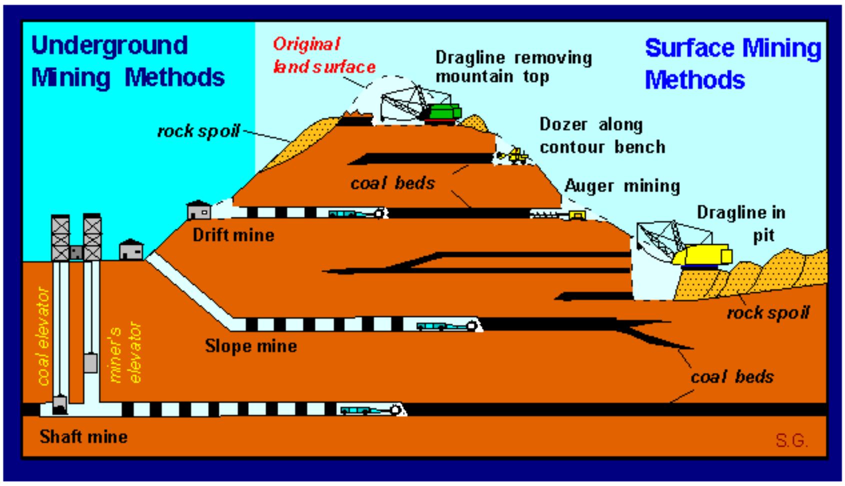

Figure 2.2: Methods of mining[1]

Surface Mining

This kind of method is used when coal seams are close to the surface of the earth. It is commonly deployed in open hilly terrain areas where an overburden (rocks that cover the coal) is removed to mine coal and then later put back into the pit. Contour mines are used for this method and the coal that cannot be mined by this type is drilled out.

Underground Mining

This method involves mining coal underground. There are different modes of access into the ground (figure 2.2). After access, different types of the method are deployed to do the actual mining of coal from the coal seams. These types include room-and-pillar and long wall.

Room-and-pillar is self explanatory. Miners continually cut rooms into the seam as they proceed further into that coal bed/seam, and alternate these rooms with pillars behind (the rooms) to support the roof of the mine. This type is very common.

Long wall is a more efficient type than room and pillar, but it does not suit all the geological circumstances. In this type, as the extraction of coal continues, roof bolts from temporary hydraulic-powered pumps are implemented to support the roof from collapsing.

2.3 Propagation Of Electromagnetic Waves In A Natural Waveguide

There are different natural waveguides in existence and when EM waves propagate through these waveguides, they usually attenuate because of the losses in the dielectric[2] waveguide. These EM waves propagate at a certain frequencies and their propagation loss is usually due to the properties (e.g dielectric constant) of the dielectric. Certain modes (TM,TE or TEM) of propagation are able to propagate in a certain dielectric because of the properties of the bounding media. These propagation modes result from the boundary conditions that could be solved using Maxwell's equations.

2.4 Electromagnetic Wave Propagation In A Coal Seam

A coal seam is a natural waveguide of concern in this project. Methane gas and water usually accumulate in seam voids. EM waves are propagated in the seam[3], bounded above and below by sedimentary rocks, for detection of voids and fault zones which pose threats to safety in coal mining. This involves borehole drilling at the centre of the seam.

The seam is characterised by a complex permittivity, $\epsilon_c^* = \epsilon^{'} - j\epsilon^{''}$, magnetic permeability, μ, and conductivity, σ. Where $\epsilon^{'}$ is the real part of permittivity representing the measure of the amount of polarisation in the seam and $\epsilon^{''}$ is the imaginary part representing losses in the seam [6][8].

Formulation

2.4.1 Symmetric Coal Seams [2]

To start the propagation of EM waves in a coal seam, there should be some form of dipole excitation (source) to excite modes of propagation in the bed. This excitation could be vertical or horizontal with respect to model depicted in figure 2.1, where the dielectric region is analogous to the coal seam. Vertical and horizontal refer to the orientation of the the dipole (figures 2.3 and 2.4).

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[2] Because of the low conductivity

[3] Because of the low conductivity of the coal seam relative to the sedimentary/ bounding rocks

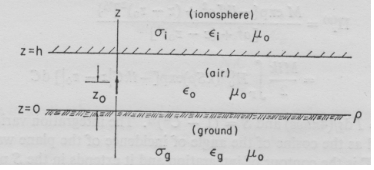

Figure 2.3: Vertical dipole excitation[10]

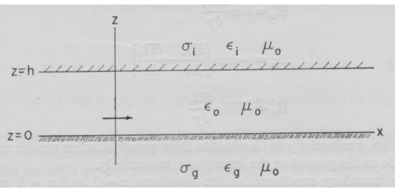

Figure 2.4: Horizontal dipole excitation[10]

The arrows represent orientation of excitation and region $0 \leq z \leq h$ could in essence be regarded as the coal seam thickness where $z \geq h$ and $z \leq 0$ are bounding region.

Because the regions(upper →middle→lower) are of different conductivity and permittivity, boundary conditions will exist at the interfaces. It is firstly assumed that the bounding regions are of equivalent/similar properties. As it was mentioned in section 2.3, these boundary conditions are solved using Maxwell's equations. The geometry of a uniform coal seam is shown in figure 2.5.

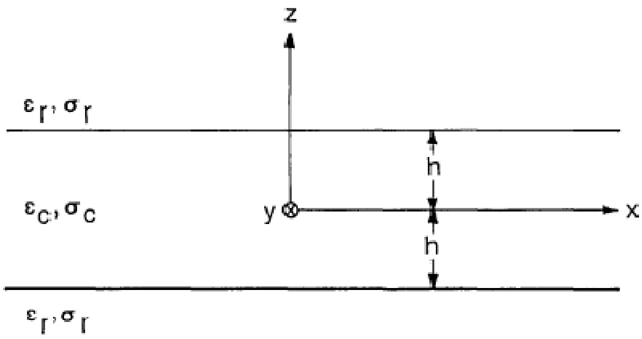

Figure 2.5: Geometry of a uniform coal seam of thickness 2h[2]

The formulation that follows is for a symmetric coal seam, and the electric field is vertically polarised with nearly transverse electromagnetic (TEM) mode, quesi-TEM [2].

Free space permeability, μ_o, is assumed everywhere and the thickness of the seam is 2h with permittivity and conductivity of ϵ_c and σ_c respectively. The bounding rocks have permittivity and conductivity of ϵ_r and σ_r

respectively[4]. The wave numbers for the seam and the rocks, $k_c$and k_r, are given by

$$k_c = \omega\sqrt{\mu_o\epsilon_c^*}\, and\, k_r = \omega\sqrt{\mu_o\epsilon_r^*} \tag{2.1}$$

where $\epsilon_c^* = \epsilon_c^{'} - j\epsilon_c^{''}$; $\epsilon_r^* = \epsilon_r^{'} - j\epsilon_r^{''}$; and $\omega = 2\pi f$ is the EM wave propagation frequency.
The lowest order(dominant) mode (guided wave) is the transverse magnetic (TM), and the magnetic field intensity in the y-direction H_y (with propagation in the x-direction as in figure 2.5) must satisfy the following Helmholtz equation:

$$(\nabla^2 + k_c^2)H_y = 0\, if \;\mid z \mid < h \tag{2.2}$$

$$(\nabla^2 + k_r^2)H_y = 0\, if \;\mid z \mid > h \tag{2.3}$$

Since the seam is assumed to be symmetric, the lowest order is even in z (figure 2.5). With the current orientation, H_y will propagate in x-direction and satisfy equation 2.4.1. For in-seam propagation [2](| z |< h),H_y will be:

$$H_y = H_o e^{-jk_cSx} cos(k_cCz) \tag{2.4}$$

where H_o is an arbitrary constant, S is the normalised propagation constant from mode equation (eq. 2.4.1) and $S^2 + C^2$ =1.
The electric field in the y-direction $E_y = 0$, so by Maxwell's equations:

$$E_x = -jC\eta_c H_o e^{-jk_cSx} sin(k_cCz) \tag{2.5}$$

$$E_z = -S\eta_c H_o e^{-jk_cSx} cos(k_cCz) \tag{2.6}$$

where $\eta_c = \sqrt{\frac{\mu_o}{\epsilon_c^*}}$.
For $z > h$, outside the seam[5], the same procedure is followed with a requirement that H_y decay as $z \to \pm\infty$. So, for the latter condition:

$$H_y = Ae^{-jk_cSx}e^{-juz} \tag{2.7}$$

where u = $\sqrt{k_r^2 - k_c^2S^2}$ with Im(u) < 0 and A being an unknown constant. Maxwell's equations again result in:

$$E_x = \frac{uA}{\omega\epsilon_r^*} e^{-jk_cSx}e^{-juz} \tag{2.8}$$

$$E_z = -\frac{k_cSA}{\omega\epsilon_r^*} e^{-jk_cSx}e^{-juz} \tag{2.9}$$

At the boundaries, $z = h$, $H_y$and E_x are required to be continuous by Maxwell's equations. This leads to a mode equation that can be solved for C by Newton's method [2]

$$jk_cCtanh(jk_cCh) + ju\frac{\epsilon_c^*}{\epsilon_r^*} = 0 \tag{2.10}$$

---

[4] Similarity of parameters of top and bottom rocks is assumed for simplicity

[5] The region $z < h$ will have similar results because of assumed similarity in parameters

with a complex propagation constant of

$$\gamma = jk_cS = jk_c\sqrt{1-C^2} = \alpha + j\beta \tag{2.11}$$

where Re(γ) $>$ 0 (i.e $\alpha > 0$).
Attenuation rate/coefficient (AR) of the seam is given by 8.686α in $dB.m^{-1}$. The phase velocity may provide extra information about the AR [5] because it accounts for vertical inhomogeneity in the rock medium $|z| > h$. As expected, AR will increase with frequency as it does with plane wave in an infinite rock medium. Nevertheless, the frequency cannot be too low. This is because in remote sensing, the resolution and antenna efficiency decreases with frequency. The trade-off between AR and antenna efficiency results in a frequency of 500kHz [2]. The figures below depict AR relationship with characteristic parameters (h, σ_c, σ_r) of the seam and rocks.

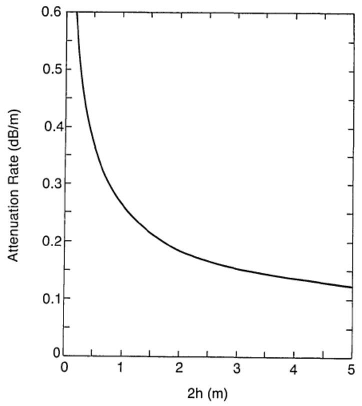

Figure 2.6: AR as function of seam thickness ($2h$)[2]

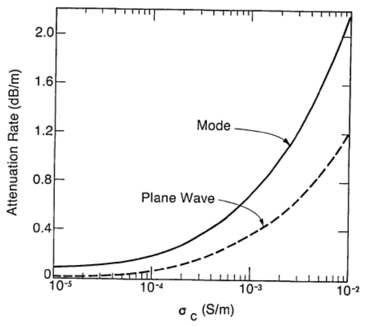

Figure 2.7: AR as a function of coal conductivity (σ_c)[2]

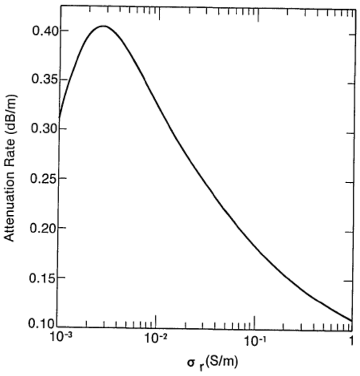

Figure 2.8: AR as a function of rock conductivity (σ_r)[2]

Magnetic and Electric field distributions are symmetric (figures 2.9, 2.10 and 2.11) and the normalisation field E_o is given by

$$E_o = \eta_c S H_o \tag{2.12}$$

All the field components decay exponentially in the rocks and the decay rate is most rapid for large values of σ_r. H_y and E_z are dominant in the coal seam allowing efficient vertical electric dipole or horizontal magnetic dipole excitation (or reception). This proves independence of position of transmitter and receiver within the coal seam [2]. Anomalies can be illuminated from the coal seam.

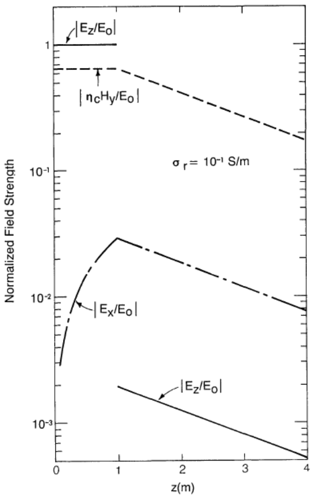

Figure 2.9: Field distribution in the coal seam[2]

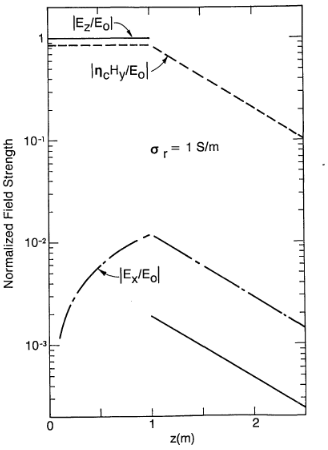

Figure 2.10: Upper bounding rock field distribution [2]

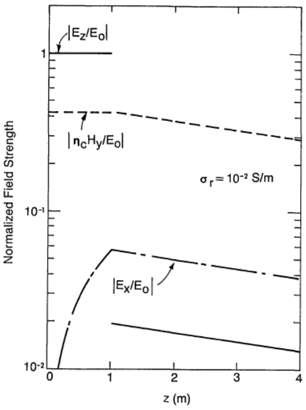

Figure 2.11: Lower bounding rock field distribution [2]

2.4.2 Asymmetric Coal Seams [3]

The bounding sedimentary rocks could have different electrical properties [3]. Free space permeability μ_o is assumed everywhere, again. The top and bottom bounding rocks have different permittivity and conductivity (figure 2.12).

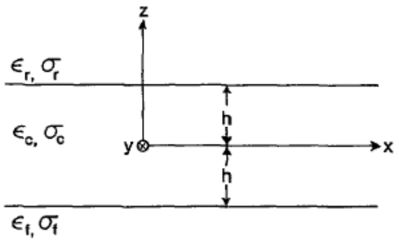

Figure 2.12: Coal seam geometry with dissimilar bounding rock parameters [3]

The coal seam formulation has an extra term, relative to equation 2.4.1. The seam model is still symmetric. Coal seam magnetic field becomes

$$H_y = [H_e cos(k_c C z) + H_o sin(k_c C z)] e^{-jk_c S x} \tag{2.13}$$

where H_e is an unknown constant.
The upper and lower rocks have H_y similar to that of equation 2.4.1, but with different (symbolically and/or numerically) unknown constants [3].
At $z = \pm h$(i.e the boundaries, figure 2.12) after solving Maxwell's equations for boundary conditions, the mode equation for C becomes

$$f_e + f_o = 0 \tag{2.14}$$

where

$$f_e = jk_c tanh(jk_c Ch) + \frac{j\epsilon_c^*}{2}\left(\frac{u_r}{\epsilon_r^*} + \frac{u_f}{\epsilon_f^*}\right)$$

and

$$f_o = \frac{-j tanh(jk_c Ch)\left[\epsilon_c^*\left(\frac{u_r}{\epsilon_r^*} + \frac{u_f}{\epsilon_f^*}\right)\right]^2}{tanh(jk_c Ch)\frac{\epsilon_c^*}{2}\left(\frac{u_r}{\epsilon_r^*} + \frac{u_f}{\epsilon_f^*}\right) + k_c C}$$

For the special case when upper and lower rock parameters are equal, $f_o = 0$. This consistent with equation 2.4.1. The attenuation rate within the seam is reduced, and asymmetry is more evident in the field decay in the upper and lower rocks.

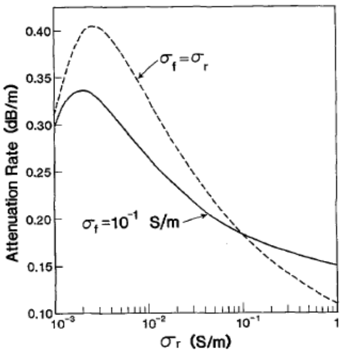

Figure 2.13: Attenuation rate as function of rock permittivity σ_r[3]

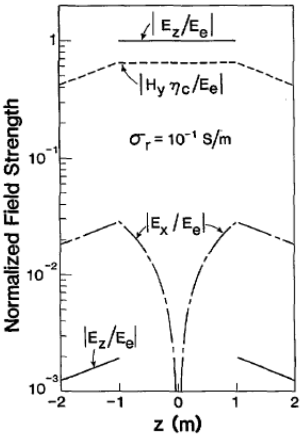

Figure 2.14: Field distribution of $\sigma_r = \sigma_f$ [3]

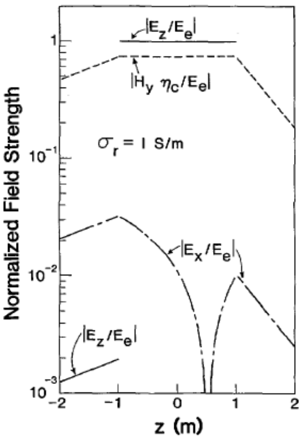

Figure 2.15: Field Distribution of Upper rock $\sigma_r = 1[S/m]$[3]

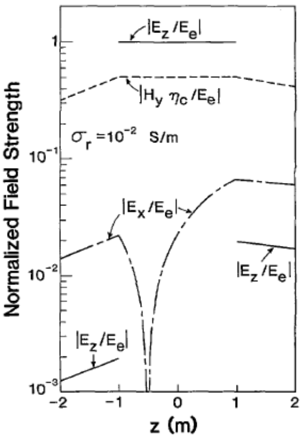

Figure 2.16: Field distribution of upper rock $\sigma_r = 10^{-2}[S/m]$[3]

Even with different bounding rocks E_z and H_y are still dominant in the coal seam.

2.4.3 Disrupted Coal Seams[4]

It has been observed that signal strength is reduced when ray-paths go through disturbed zones which can be located [22]. The transmitter-receiver arrangement is as depicted in figure 2.17

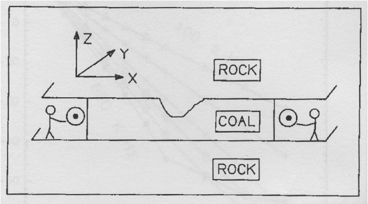

Figure 2.17: Transmitter-receiver configuration [4]

The conductivity is assumed to be isotropic. An examination on how interruption by anomalies affect attenuation of the EM waves propagating in the coal seam is imposed. Excess Attenuation (EA) is the difference in dB between the spectral amplitude for a model and the amplitude when no interrupt zone (fault) is present. It represents the loss caused by the disrupted zone. Figure 2.18 implicate the modelled faults.

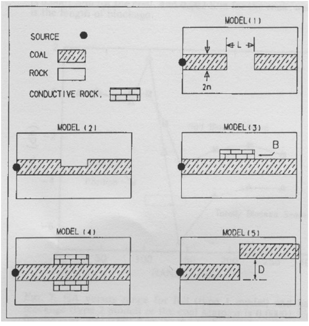

Figure 2.18: Cross section of fault zones [4]

It was shown that the amount of loss that occurs in going through disturbed/ fault zones is highly dependent on the conductivity (which is so sensitive upon pore geometry, clay content, and contained water conductivity) of the coal seam and the bounding rocks. The loss that the waves undergo when propagated via the disturbed zones is the combination of reflection and scattering loss and higher attenuation rates in the zones [4].

2.4.4 Inhomogeneous Coal Seams and Rock walls[5]

Again, this problem was analysed by an idealised slab model. The objective was to determine the complex propagation constant of the dominant TM mode which propagates in a coal seam. Most of the formulation is similar to the ones above, and the both agree. The difference is that phase velocity (accounting for vertical inhomogeneity) has been included for analysis.

2.5 Conclusion

This chapter was aimed at introducing the reader with theoretical background of solving the problem at hand, by the review of previous work. It has been shown that EM waves can be used to detect anomalies in a coal seam, and the dominant mode is TM mode. Attenuation of propagating EM waves at faults regions provide useful information, and phase velocity information can also be used to analyse the condition of the seam. The amount of loss that occurs in going through disturbed zones is highly dependent on the conductivity of the coal seam and EA will not be very sensitive to frequencies between 100kHz and 500kHz.

Chapter 3

COAL GEOLOGY AND CLASSIFICATION

3.1 Introduction

Coal is a natural mineral which is mined mainly for energy generation purposes. It is important to know the electrical properties of coal before launching electromagnetic into coal seams, to investigate their behaviour while propagating.

This chapter will present brief historical formation of coal and will also present the dielectric properties of coal.

3.2 Coal geology

Even though they are made up of material that is distinct, both chemically and petrographically, from other rocks, coal seams are still integral parts of more diverse sedimentary accumulations. Some seams may be found as laterally extensive layers of uniform thickness and quality in a regular sequence of other equally extensive rock units, but others are made up of irregularly distributed subsections of different coal types, and many contain discrete beds or lenses of non-coal materials. Individual seams may thicken, thin or pinch out in a variety of ways or split and coalesce with one another due to contemporaneous sedimentary activity.

The processes associated with peat (initial stage of coal) formation, together with the physical and chemical properties of the coal and non-coal strata at different stages of rank advance, are responsible for the development of a number of unusual geological features in and around coal seams.

Lateral tracing of a coal seam in the field sometimes shows it to become divided, over a relatively short distance, by a wedge-shaped body of non-coal sediment to form two distinctly separate coal beds.Figure 3.1 shows the possible splits in coal seams. [11].

Clastic dykes are wedges or sheet-like bodies of sedimentary material that cut across the bedding of another unit. When found in coal they are commonly joined to a coal seam with similar lithology in the roof of the seam, which may partially thin out in the area above the injection zone. The clastic material may be almost perpendicular to the bedding of the seam, or at some oblique, often shallow angle. The dykes are generally thought to represent the infilling of fractures. The infilling material is mostly sand and clay [11].

Apart from the more common clastic sediments, such as sandstone and shale, a number of unusual rock

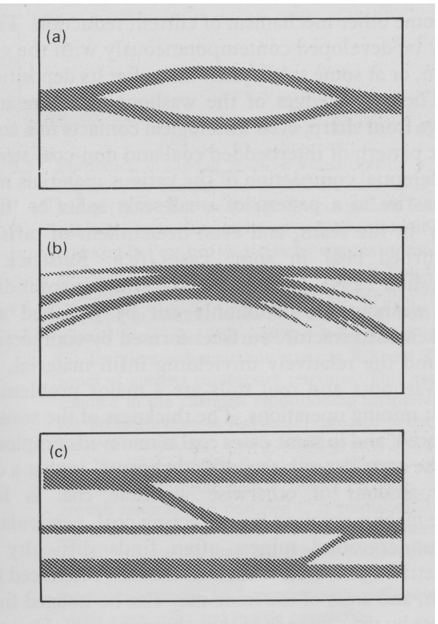

Figure 3.1: Cross section showing forms of splitting. (a) Simple splitting. (b) Progressive splitting. (c) Zig-zag splitting [11]

types are often found within or closely associated with coal seams.These include kaolinite-rich materials, such as flint clays and underclays, siliceous materials, such as chert and gannister, and ferruginous deposits, such as sideritic mudstones or clay-ironstone deposits [11].

3.3 Coal Classification and Rank

Coal is classed according to order of alteration. It starts of as peat, then after a considerable amount of time, heat and burial pressure, it metamorphose to lignite. Lignite is a more mature peat but immature form of coal because it is still somewhat light in colour and soft. As time passes,lignite increase maturity into sub-bituminous. This is a darker and a little harder (relative to lignite) form of coal. As this process of burial and alteration continues, more chemical and physical changes occur and the coal is classified as bituminous. The next mature form of coal is anthracite, which is the last in-terms of maturity, and is very hard and shiny. Figure 3.2 shows different classes of coal.

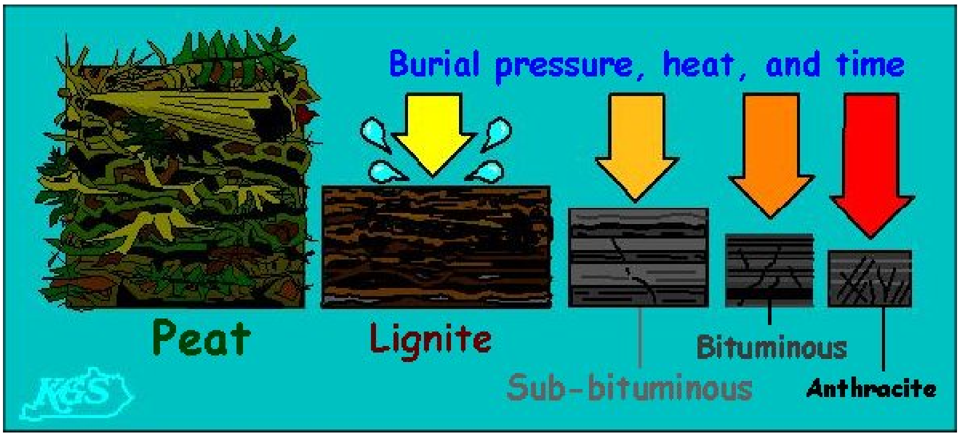

Figure 3.2: Classes of coal [1]

The degree of metamorphism that occurs as coal matures from peat to anthracite is known as coal rank. The degree of metamorphism also indicate the amount of energy that is contained in the coal. Lignite and sub-bituminous have lower energy content relative to bituminous and anthracite [1].

3.4 Dielectric Properties of coal [6]

In a dielectric, conduction normally involves transport mechanisms (such as ionic diffusion and ionic replacement in the neighbouring solid-like interface) introducing a phase difference between the transport current density and the electric field. The conduction also undergoes total partial ionic retention processes, resulting again in an additional phase difference between the current density and the applied field [23]. As a consequence, the electrical conductivity and dielectric constant are, in general, complex quantities. The electric permittivity (dielectric constant) expresses the ability of a dielectric to be polarised. The relationship between the real and imaginary parts is expressed as the loss tangent, which represents the fraction of stored energy lost per period of field oscillation [6].

$$tan\delta = \frac{\epsilon_c^{''}}{\epsilon_c^{'}} \tag{3.1}$$

The dielectric properties of coal depends on a number of factors, which includes: coal rank, moisture content, mineral composition, temperature and frequency of radiation of EM waves that may be propagation in the coal seam. Electric permittivity has been shown to decrease with increasing temperature. To analyse coal dielectric properties, coal has been grouped in two groups by [6]. Group 1 is the mid-seam coal and group 2 is the power-station feed coal. It was done so to give a more realistic account of coal preparation plant product and generally exhibit an increased mineral matter content.

The moisture in a coal may occur in four possible forms [15]:

1. Surface moisture - water held as films on the surface of the coal particles,
2. Hydroscopic moisture - water held inside the capillaries of the coal substance,
3. Decomposition moisture - water incorporated in some of the coal's organic compounds,
4. Mineral moisture - water which forms part of the crystal structure of clays and other minerals present in coal.

3.4.1 Dielectric properties of coal for varying temperature

Measurements of dielectric properties were recorded on intervals of 20^oC on the range of $40^oC - 180^oC$, during the heating and cooling cycles. During the heating cycle, between 80^oC and 180^oC, a sharp decrease in the dielectric constant is observed. Nevertheless, the cooling cycles showed a contrast behaviour by having a relatively constant dielectric constant. The decrease, is believed to be because of reduction in moisture content in the coal.

3.4.2 Dielectric properties of coal at selected frequencies

Dielectric measurements carried out at three different frequencies show that there are no significant changes in dielectric properties with frequencies tested even though a certain frequency will be required for excitation of modes (Section 2.4.1).

Table 3.1 shows the measured dielectric constant behaviour in varying frequencies.

Table 3.1: Coal dielectric constant dependence on frequency[6]

Coal	Bulk Coal ϵ_c^*at 0.615Ghz		Bulk Coal ϵ_c^*at 1.413Ghz		Bulk Coal ϵ_c^*at 2.216Ghz		Volatile Matter $_{dmmf}$(%)
	$\epsilon_c^{'}$ 60^oC	$\epsilon_c^{''}$ 60^oC	$\epsilon_c^{'}$ 60^oC	$\epsilon_c^{''}$ 60^oC	$\epsilon_c^{'}$ 60^oC	$\epsilon_c^{''}$ 60^oC	
F-1	2.91	0.1630	2.89	0.1433	2.93	0.1657	4.8
F-2	2.47	0.0443	2.46	0.0402	2.49	0.0539	13.4
F-3	2.30	0.0543	2.31	0.0534	2.34	0.0818	29.8
F-4	2.80	0.1951	2.75	0.1810	2.77	0.2087	37.6
F-5	2.40	0.1381	2.34	0.1317	2.32	0.1389	38.7
F-6	2.88	0.1494	2.84	0.1489	2.86	0.1564	40.4
F-7	2.50	0.1150	2.45	0.1188	2.45	0.1252	41.6
F-8	3.63	0.3792	3.52	0.3191	3.51	0.3153	45.1

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3.4.3 Dielectric variation with coal rank

The mineral matter content and composition depends upon geological age of the coal and its proximity to seam boundaries. To determine the dielectric properties on the coal rank, group 1 coals of various ranks were selected. Medium ranked coals exhibit lower dielectric constant values. Moisture content is shown to significantly increase the coals dielectric constant [6].

3.4.4 Dielectric Loss of coal as a function of temperature and frequency [7]

An experiment was conducted by [7] to show the dependence of loss tangent (equation 3.4) on temperature and frequency. The specimen was cut from a lump to a diameter of 55mm and thickness 5mm and directions along and across (relative to figure 2.5) the bedding were used.

Absorbed water greatly increased the loss tangent, $tan\delta$, for coal, since it increased the conductivity more rapidly than the permittivity, ϵ_c^*. The loss at audio frequencies for medium $tan\delta$decreased when the absorbed water exceeded 1%, whereas the RF (radio-frequency) loss increased. On the hand, absorbed water can reduce high $tan\delta$ at all frequencies [7].

It was also shown by [7] that the dielectric loss along the bedding in a dried coal exceeds that across the bedding by a factor of 10 - 100. The loss across the bedding is mainly of relaxation type , while conduction dominates $tan\delta$ along the bedding of coal (coal seam). Clearly $tan\delta$ depends on temperature and this dependence indicates that coal has a very open structure along the coal seam and that conduction dominates the loss in that direction [7].

3.5 Conclusion

From various undertaken researches it has been realised that temperature and water content affects the dielectric properties of coal seams. The effects are significant in the loss tangent, because it the affects the ability of the seam to be polarised by EM waves.

Chapter 4

SEDIMENTARY ROCKS

4.1 Introduction

The origin and accumulation of sedimentary rocks might, at first thought, seem relatively simple. Sands and muds are seen to form and carried by the rivers from the continents into the sea. The origin of sedimentary rocks, unlike that of many igneous and all metamorphic rocks, is apparently open to inspection and study [24]. The study of interpreting the history of a sedimentary rock is much more complex than that of an igneous or metamorphic rock. This follows from the more complex character of sedimentary rocks. There is a conventional separation of rocks into the traditional three categories - igneous, sedimentary, and metamorphic [24].

This chapter will introduce some types of sedimentary rocks, which are likely to bound coal seams, and present some dielectric properties at a particular frequency range.

4.2 Types Of Sedimentary Rocks

4.2.1 Sandstones

A sand consists primarily of a framework, which is the detrial sand fraction, and voids, which are the pores or empty spaces in the framework. The voids may, of course, be partially or completely filled. Sandstones vary from well-bedded to massive in character. The internal structure of the bedding unit is most significant [24].

4.2.2 Shale

Of the common sediments, shales are the most abundant. Despite their abundance they are not so well exposed as are the more resistant limestones and sandstones. And because of their fine grain they are not well known as the other sedimentary materials.

4.3 The Dielectric Constant of Sandstones, 60 kHz to 4 MHz [8]

In this paper, complex impedance data of eight sandstones at various levels of water saturation in frequency range of 5 Hz and 4 MHz was collected. Of principal interest, was the real part of the complex dielectric Re(ϵ_r^*) = $\epsilon_r^{'}$ dependence on frequency and the level of water saturation in the pore spaces of the sandstones. As it was mentioned in Section 2.4 that this quantity of the dielectric constant measure the amount of polarisation in a material, there can be a number of different polarising species of which each has a characteristic relaxation frequency and an associated dielectric dispersion centered around this relaxation frequency. The following results were obtained.

Table 4.1: $\epsilon_r^{'}$ of materials commonly encounted in formation evaluation [8]

Substance	$\epsilon_r^{'}$
Quartz	4.5 - 4.7
Calcite	7 - 8
Shale	13 - 15
Gas	1
Oil	2.2
Water	80

4.4 Conclusion

It has been presented that moisture content affects the dielectric constant of a material to some extent, especially the real part of the dielectric constant.

Chapter 5

DIELECTRIC SLAB WAVEGUIDE

An EM wave is able to propagate within a dielectric slab by multiple total internal reflections. The reflection is due to the strong contrast (difference in refractive indices) between the bounding media and the 'transport' dielectric medium. Dielectric slab on concern is a bounded. Surface waves of both TM and TE may be guided along a dielectric slab [25]. In Section 2.4, propagation of EM waves in a coal seam was looked into.

5.1 Closed Waveguides

A closed waveguide may be regarded as a waveguiding structure which is characterised by perfectly reflecting wall or boundaries. Most, if not all, fields are confined inside the boundaries which are taken as either perfectly electric or perfectly magnetic [26].

The modes that propagate in a dielectric are conventionally ordered according to the values of their cut-off frequencies. The lowest order is the one having the least cut-off frequency f_c and it is obviously the dominant mode since it can propagate, in a certain range of frequencies, when all modes are cut-off.

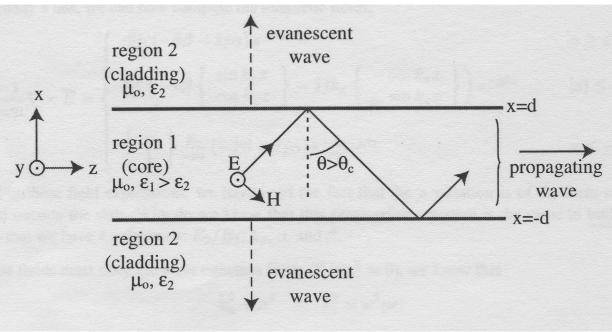

Figure 5.1: Dielectric slab waveguide of width 2d [27]

5.2 Attenuation in a closed waveguide

Power lost in the walls is a primary cause of signal attenuation in a waveguide. The walls are considered to have finitely higher conductivity compared to the guiding dielectric. Currents flowing in the walls (figure 5.1) will therefore be associated with power loss due to the finite resistance of the wall [26].

5.3 Phase, Group and Signal Velocities

When dealing with single frequency propagation in a waveguide a quantity of interest is the phase velocity. It is the velocity at which a point of constant phase moving axially down the guide. Phase velocity of a propagating mode is greater than the speed of light c, which contradicts the theory of relativity. On the other hand, it should be noted that this theory deals applies to physical velocities which, are velocities on of information and energy flow. The phase velocity is associated with a single frequency wave which carries no information and it is also different from the velocity of energy flow [26].

5.4 Mode Orthogonality

This an extremely import property of modes in waveguides. It plays a key role in solving problems of excitation and scattering in waveguides. Each mode carries its own power independently of the other modes. Orthogonality is valid for both lossless and lossy dielectrics. The dielectric material may be isotropic or anisotropic [26].

5.5 Scattering at a Longitudinal Discontinuity

Dielectric waveguide may have dissimilarity or discontinuity along them. This does not exclude natural waveguides (e.g seam-rock or earth-ionosphere). For the well known natural waveguide, earth-ionosphere, the height of the effective reflecting layer of the ionosphere changes as the guide crosses the shadow region between day and night. A conical problem of interest in this respect in the sharp discontinuities in the waveguide. A gradual transition from one part to another is treated as a series of small sharp discontinuities in cascade [26].

Chapter 6

Methodology

6.1 Introduction

In the previous chapters, the theories relevant to this thesis were presented. In this chapter, the procedure followed to fulfil the research is based on the theories. The method of investigation will start by deriving bondary condition for a lossless dielectric slab, and the proceed to a lossy dielectric slab. Because it has already been mention that the dominant mode in a coal seam is TM (Section 2.4.1), TE will not be discussed. Some MATLAB coding will be done to plot some of the propagation modes.

6.2 Simulation of Coal-Rock Waveguide

The coal-rock simulation will be done using a virtual simulation tool based on Finite Difference Time Domain coding. The figure 6.1 shows the set-up.

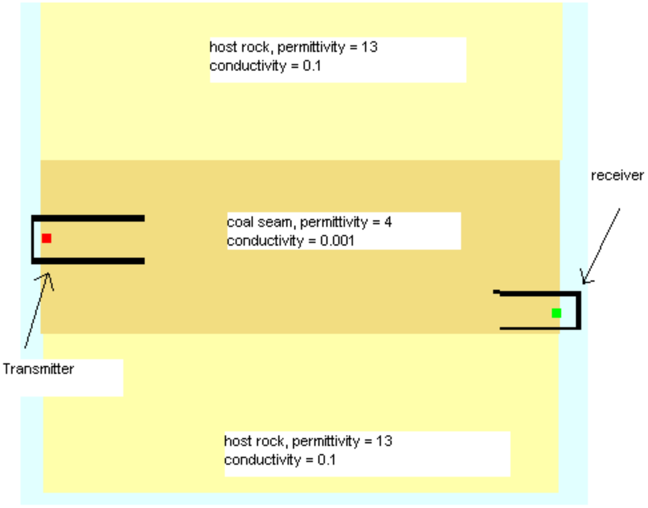

Figure 6.1: Simulation of coal-rock waveguide

The values were chosen based on table 4.1. The thickness of the model has to be changed to account for variation of thickness in the seam. More conductive (relative to coal seam) material will have to be introduced in the model during experiments to account for faults.

Chapter 7

Results

7.1 Propagation of EM waves

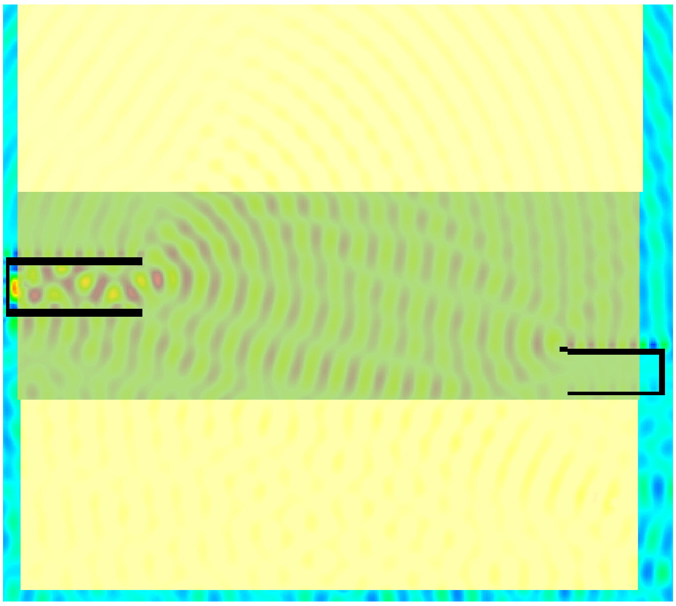

Figure 7.1: Simulation of EM waves

7.2 Ray-path loss

$\epsilon_c = 4$, $\epsilon_r = 13$, $\sigma_c = 0.0001$, $\sigma_r = 0.1$

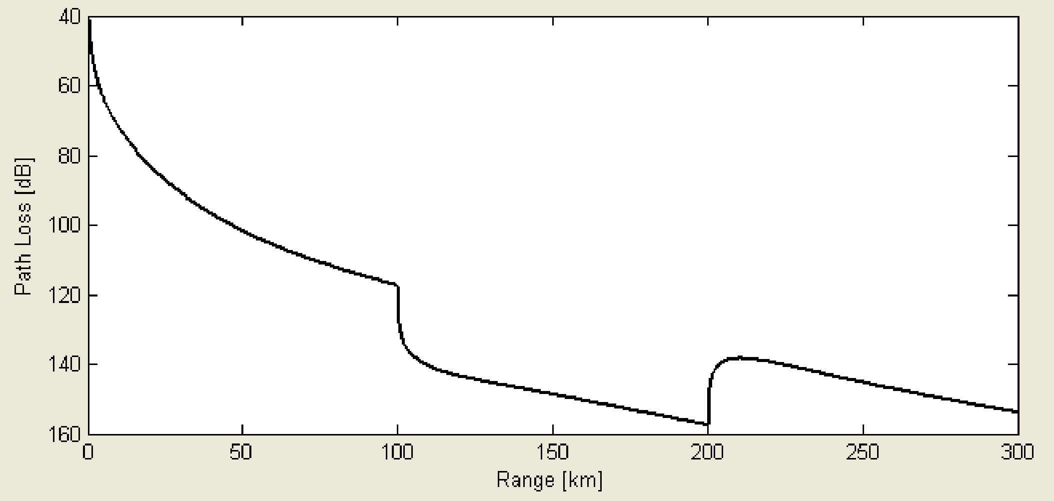

Figure 7.2: Ray-path loss

Chapter 8

Conclusions And Future Work

It has been shown from the literature that, EM wave propagation is affected by the moisture content in the minerals. This moisture content, increases the conductivity. If the conductivity of the coal seam increases, less attenuation is experienced.

Future work for this project may include:

- 3-D modeling of the coal seam to see dipersion,
- Construction of a device that can do the actual reading at the field

Appendix A

A Compact Disc with programs used for simulation. A copy of the report is also included.

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