RADIO COMMUNICATION IN MINES

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Declaration

I hereby declare that the dissertation accompanying this letter is entirely my own, unaided work. All material obtained from other sources has been acknowledged within the text. The research work reported herein was done while the author was employed in the Electronics Division of the Chamber of Mines of South Africa Research Laboratories in Johannesburg.

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ABSTRACT

The effect of the electrical properties of rock on the propagation of electromagnetic energy are investigated, particularly from the point of view of using laboratory determined values in predicting the attenuation characteristics of the rock medium and its variation with frequency. It is shown that the curve representing this characteristic increases with frequency as expected and exhibits higher attenuation than that predicted from laboratory sample values. The effect of a surrounding dissipative medium on antenna performance is examined, and the characteristics of the two representative elemental antenna types discussed from the point of view of their comparative effectiveness when operating within the lossy medium. The electrical properties of a small loop antenna are presented.

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NOMENCLATURE

A	=	area (m^2)
a	=	radius of spherical cavity (m)
B	=	magnetic vector potential
b	=	radius of loop (m)
C, C_1, C_2	=	capacitance (F)
c	=	radius of permeable core (m)
D	=	directivity of antenna
d	=	diameter of loop antenna (m)
dA	=	elemental area (m^2)
dl	=	elemental length (m)
E, $\underset{\sim}{E}$, E_ϕ	=	electric field intensity (v/m)
f	=	frequency (Hz)
G	=	gain of antenna
G_T	=	transmitting antenna gain
G_R	=	receiving antenna gain
$\underset{\sim}{H}$, H_o	=	magnetic field intensity (A/m)
h	=	maximum linear dimension of antenna (m)
I, I_a, I_b, I_{loop}	=	current (A)
$\underset{\sim}{J}$	=	current density (A/m^2)
$\underset{\sim}{J}m$	=	magnetic current density
j	=	complex operator ($\sqrt{-1}$)
K, k	=	constants of proportionality
K_1	=	effective area factor
L	=	inductance (H)
l	=	length of linear antenna (m)
M	=	magnetic dipole moment (Am^2)

N	=	number of turns
P	=	power (w)
P_E		power due to electric dipole (w)
P_M		power due to magnetic dipole (w)
P_r	=	power at receiving antenna terminals (w)
P_t	=	power at transmitting antenna terminals (w)
P'	=	porosity
p	=	loss tangent
Q	=	quality factor
R	=	radial distance (m)
R_l	=	antenna loss resistance (Ω)
R_r	=	antenna radiation resistance (Ω)
R_p	=	loss resistance due to proximity effect (Ω)
R_o	=	loss resistance without proximity effect (Ω)
r	=	radius of wire (m)
s	=	spacing between wires (m)
t, t'	=	time (s)
V	=	voltage (v)
V_r	=	voltage at receiving antenna terminals (v)
V_t	=	voltage at transmitting antenna terminals (v)
v	=	velocity of propagation (m/s)
x, y, z	=	co-ordinate directions
Z	=	impedance (Ω)
Z_D	=	dynamic impedance (Ω)
Z_0	=	impedance of free space (Ω)
Δz	=	incremental impedance (Ω)
α	=	attenuation constant (nepers/m)
β	=	phase constant (rad/m)

γ	=	propagation constant
ω	=	angular frequency (rad/s)
μ	=	permeability (H/m)
μ_0	=	permeability of free space ($4 \pi \times 10^{-7}$ H/m)
μ_r	=	relative permeability
σ	=	electrical conductivity (s/m)
ϵ	=	permittivity (F/m)
ϵ_0	=	permittivity of free space ($8,85 \times 10^{-12}$ F/m)
ϵ_r	=	relative permittivity
λ	=	wavelength (m)
λ_0	=	wavelength in free space (m)
π	=	3,1416
τ	=	metallic skin depth (m)
η	=	efficiency
η_T	=	efficiency of transmitting antenna
η_R	=	efficiency of receiving antenna
θ, ϕ	=	angles relating to antenna field components (deg.)

CHAPTER 1

INTRODUCTION

It is the intention in this dissertation to examine the feasibility of using radio techniques in order to communicate over useful distances within an underground mining environment. In order to do this a review of the relevant literature was undertaken which unearthed a wealth of material, (see List of References), dealing with both the theoretical and practical aspects of the problem. A number of techniques exist for the propagation of electromagnetic signals throughout the confines of the mine, and it was thus necessary to examine all of these from the point of view of their suitability to the South African gold mining industry initially, but not restricting their application to just this one mining area.

However, the basic structures of mines differ in many respects meaning that a communication system adapted to one environment may not be ideally suited to another. This restriction applies more specifically to radio techniques which propagate their energy via air spaces, and thereby perform basically independently of the surrounding medium. As might appear obvious, this technique would have limited application in a highly irregular and multi-level mine environment but does find use, particularly in the U.S.A. in certain coal mines. (Lagace and Parkinson, 1972).

From experience gained over a number of years within the Chamber of Mines of South Africa Research Laboratories with radio communication systems used underground, it has been shown that propagation of electromagnetic energy is possible directly through the rock strata. In view of the success gained in this area, considerable time and effort has been expended within the laboratories in developing suitable radio equipment. The basis for this work was a paper prepared by T.L. Wadley (1949) of the then Telecommunications Research Laboratory, now the National Institute of Telecommunication Research of the C.S.I.R. In it Wadley examined the possibilities of transmitting signals via the rock by considering the effect which the electrical characteristics of the rock would have on electromagnetic energy, particularly from the point of view of frequency dependence. In his work he measured, in the laboratory, characteristics using typical samples of rock common to gold mining areas. He was thus able to calculate the attenuation which would be suffered by an electromagnetic wave in propagating through this medium. In addition he considered the effect of using a small antenna, since portable applications were a necessity, and discussed the frequency characteristics of these.

From this information Wadley presented data on the optimum frequency of transmission through a particular homogeneous geological medium for a maximum transmission distance which he showed was limited by the total system loss, being made up of rock attenuation and antenna dissipation due to the lack of radiation efficiency incurred by the use of small antennas at low frequencies.

This information has proved invaluable, however, certain elements of doubt still remained and it was felt worthwhile to investigate the mechanism of direct through rock propagation again. It was at this point that the literature survey unearthed a wealth of useful information, and stressed particularly that no reliance should be placed on laboratory determined values for rock electrical characteristics since the <u>in situ</u> conditions, which can be immeasurably complex, modify these and hence any predictions resulting therefrom.

Further investigation has also shown that the effect of a dissipative medium surrounding an antenna is very marked on the antenna's performance, hence free space antenna characteristics either do not hold, or are modified in lossy media.

With these limitations in mind, this study was made, and the emphasis was placed on attempting to equate the theory developed in the literature with the results as measured in practice over a wide frequency range in a typical gold mining environment.

As would be expected in a study of this nature, many complications arose, particularly from the point of view of suitable equipment but the attenuati[illegible]racteristics of this medium were measured and were show[illegible] greater than those predicted by Wadley, as was to be expected. It was possible also to estimate the typical conductivity prevailing in the test area, which was again greater than laboratory sample values, as predicted.

Assessment of the antenna and the effect of the environment on it proved difficult. This was due to the fact that measurements involving the antenna's characteristics are complicated by the complex nature of the fields which exist in its immediate vicinity, and that no single antenna could easily be used over the more than four octave range of frequencies examined in this study, thus making comparison difficult.

More work remains to be done in this area, particularly since the antenna is such an integral part of the system, both in the technique under discussion here, and in the field of cable guided communication where metallic conductors, running throughout an operational mining area, can be used to convey the signals, re-radiating and receiving them along their length, and thereby to increase communication range.

Practical experiments underground have shown this mode to be of inestimable value in longer range communication and is an area deserving of thorough study, particularly in view of the results obtained from using existing metal objects which span the areas, such as power lines, pipes and rails, rather than the specially installed transmission lines, of one type or another, which have been employed in British and European mines, (Martin, 1970).

This dissertation thus presents a review of the theory pertaining to electromagnetic energy propagation in a dissipative medium. In so doing, those electrical characteristics of the rock which affect this propagation, namely conductivity, σ, and permittivity, ϵ, are made evident, and the dependence of these on the physical properties of moisture content, non-homogeneity, temperature, pressure and frequency are examined. The discrepancy between propagation predictions based on laboratory determined values of σ and ϵ, and those measured <u>in situ</u>, is highlighted. Experimental results obtained in the laboratory and underground, are presented to confirm this, and, since a system, involving both the environment and electronic equipment is involved, the effect of the surrounding lossy medium on antenna performance is examined, and the form of an optimum antenna configuration is presented.

CHAPTER 2

PROPAGATION OF ELECTROMAGNETIC ENERGY THROUGH THE EARTH - A REVIEW

2.1 Introduction

Since an underground mine consists of a maze of shafts, tunnels, passages and other air spaces all interlinked to some extent, the possibility of using these as propagation paths cannot be overlooked. However, on closer examination many problems are found to exist and their usefulness is thus limited. Before examining those factors which affect propagation via rock strata, the mechanism of propagation via tunnels will be reviewed.

2.2 Waveguide and beamed transmission

If the surrounding rock medium is to be ignored, then an indefinitely short wavelength would have to be used in order that no air-rock interference effects occurred at the interface. This method would then allow effective radio communication over an indefinite distance. However, any irregularity in the path such as bends and curvature in the tunnel, variation in dimensions or obstructions intruding into the path would result in signal attenuation. Since these limiting factors are very much part of a mine environment, this type of communication would have limited practical application. (Wadley, 1949). However, in an ordered mine environment such as is found in a bord and pillar coal mine, the use of ultra-high frequency (UHF) techniques is feasible for providing communication over a roughly 200 m square area. (Lagace and Parkinson, 1972).

The air spaces within a mine may be regarded as air-filled waveguides. In order to propagate, a wavelength approximating the cross-sectional dimensions of the tunnel would have to be used. Any deviation in tunnel direction will result in attenuation by reflection and refraction of energy at the air-rock interface since the electrical characteristics of the rock differ from those of the air dielectric. Similarly any change in tunnel dimensions will alter the "waveguide" mode characteristics and if it is assumed that the initial cross-sectional dimensions favoured dominant mode propagation, any change in these will cause attenuation of the signal. In the event of the tunnel becoming small in cross-section the excitation frequency might now be below the cut-off frequency of the guide, resulting in no energy propagation since the mode has become evanescent. Energy might propagate via higher order modes to some extent, but with loss of coupling efficiency and energy transfer since these higher order modes always propagate with more attenuation than the dominant mode. (Wadley, 1949; Terman, 1955 and Delogne, 1976).

In a waveguide with walls of infinite conductivity and of uniform cross-sectional dimensions along its length with no curvature, then no attenuation occurs in the direction of propagation, (Jordan, 1964). However, mine tunnel walls are irregularly shaped and of complex geological nature having finite conductivity thus resulting in the electromagnetic energy being attenuated exponentially with distance in the direction of propagation.

These objections to propagation underground using beamed or guided transmissions would immediately render them unsuitable for mining applications. However, an even more meaningful objection, which would remain just as valid even if signal propagation were possible over vast distances via tunnels and underground workings, would be that in the event of an emergency in the mine, which resulted in the blocking of access routes, then communication systems relying on these methods would be inoperative, just at the time when they would be most desirable.

It is with this possibility in mind that a radio system, capable of propagating through dense geological material is a necessity and it is for this reason that the mechanism affecting it is to be studied in this dissertation.

2.3 Cable guided transmission

A technique of signal propagation which is being applied in Britain and Europe (Martin, 1970) particularly, relies for its effectiveness on the use of transmission lines which are laid throughout the area of mining activity. The lines have a lossy energy transfer characteristic which means that transmitters and receivers in their vicinity are able to induce energy into or receive energy from these lines respectively. These transmission lines are referred to as "leaky feeders" and increasing use is being made of them in conjunction with H.F. and V.H.F. portable transceivers, in the overseas coal mines (Martin, 1970). Their effectiveness is well proven but their use in South African Mines would be problematical due particularly to the likelihood of damage by falls of ground, which are fairly frequent in gold mines, and the resulting necessity of skilled artisans being available to effect repairs.

2.4 Direct radiation through rock

A mathematical analysis of a linearly polarized wave propagating through a lossy medium, such as rock, characterised by its permeability μ, conductivity σ and permittivity ϵ yields a fundamental wave equation from which an insight may be obtained into the electromagnetic attenuation characteristics of the medium. This wave equation, for the electric field component E in the positive y direction is given by:

$$\frac{\partial^2 E_y}{\partial x^2} - \left(j\omega\mu\sigma - \omega^2\mu\epsilon \right) E_y = 0 \qquad 2 - 1$$

(Kraus, 1953)

where $\gamma^2 = j\omega\mu\sigma - \omega^2\mu\epsilon$ is the propagation constant, or wave number, of the medium, ω is the angular frequency of operation, and j the complex operator $\sqrt{-1}$.

Now this propagation constant may be expressed as follows:

$$\gamma^2 = (\alpha + j\beta)^2 \qquad 2 - 2$$

where α is the attenuation in nepers/m,

and β is the phase shift in radians/m.

Solving the wave equation for α and β yields the following results:

$$\alpha = \omega \left[\frac{\mu\varepsilon \left\{ \left(1 + \frac{\sigma^2}{\omega^2\varepsilon^2}\right)^{\frac{1}{2}} - 1 \right\}}{2} \right]^{\frac{1}{2}} \qquad 2 - 3$$

$$\beta = \omega \left[\frac{\mu\varepsilon \left\{ \left(1 + \frac{\sigma^2}{\omega^2\varepsilon^2}\right)^{\frac{1}{2}} + 1 \right\}}{2} \right]^{\frac{1}{2}} \qquad 2 - 4$$

Only one of the quantities, the frequency, is a design parameter. Of the others, μ may be assumed to be equal to the free-space permeability $\mu_0 = 4\pi \times 10^{-7}$ H/m. (Ames, et al, 1963; Smith and King 1974; Geyer and Keller, 1976), and thus α and β are dependent on ω, ε and σ.

This last relationship is of fundamental importance since it illustrates particularly the complex nature of the propagation medium and the interdependence of the quantities involved.

At this stage the concept of loss tangent is introduced, and is obtained from

$$\gamma^2 = j\omega^2\varepsilon\mu\left(\frac{\sigma}{\omega\varepsilon} + j\right)$$

where $\frac{\sigma}{\omega\varepsilon} = p \qquad 2 - 5$

is the loss tangent of the medium, which defines very accurately the electrical characteristics of the medium since it is in fact equal to the ratio of conduction current to displacement current in that medium, and is thus an indicator of the medium's performance as a conductor, quasi-conductor or dielectric.

σ and ϵ, the complex characteristics of the medium, may be related as follows (Ames et al, 1963):

$$\epsilon - j\frac{\sigma}{\omega} = \epsilon_o\epsilon_r\,(1 - jp) \qquad 2-6$$

where $$(1 - jp) = \{f(p) - jg(p)\} \qquad 2-7$$

$$f(p) = \left[\frac{\left(1 + p^2\right)^{\frac{1}{2}} + 1}{2}\right]^{\frac{1}{2}} \qquad 2-8$$

and $$g(p) = \left[\frac{\left(1 + p^2\right)^{\frac{1}{2}} - 1}{2}\right]^{\frac{1}{2}} \qquad 2-9$$

$\epsilon_o = 8{,}85 \times 10^{-12}$ F/m, the permittivity of free space and ϵ_r is the relative permittivity of the medium.

Most cases of electromagnetic energy propagation through dissipative media encountered in practice can be related to simplifications of the above expressions when p is small or large compared to unity. (Ames et al, 1963, Wundt and Boots, 1964).

For $p \leq 0{,}6$

$$f(p) \doteq 1 \text{ and } g(p) \doteq \frac{p}{2} \qquad 2-10$$

and $p \geq 10$

$$f(p) \doteq g(p) \doteq \sqrt{\frac{p}{2}}$$

Use of these simplifications gives expressions for α for the two values of p, viz.

$$p \le 0,6 \qquad \alpha = \frac{1,64 \times 10^3 \sigma}{\sqrt{\epsilon_r}} \quad dB/m \qquad 2 - 11$$

$$p \ge 10 \qquad \alpha = 0,545 \sqrt{f(kHz)\ \sigma} \quad dB/m \qquad 2 - 12$$

It is interesting to note that in the determination of α only a knowledge of σ is required for the case $p \ge 10$, whereas both σ and ϵ_r must be known when $p \le 0,6$.

It is thus shown that any investigation of electromagnetic energy propagation through dissipative media requires a knowledge of the loss tangent of that medium and particularly of its dependence on frequency, the environmental factors of temperature, pressure, moisture and mineral content of the region.

2.5 The effect of the environment on the physical quantities σ and ϵ_r.

The factors involved in the expression for loss tangent, namely σ and ϵ_r can both be determined by laboratory measurements on representative rock samples. However, these handbook values so obtained, are misleading and not representative of the values which would be measured *in situ*. (Ames *et al*, 1963; Keller, 1963; Fritsch, 1963; Scott *et al*, 1967).

2.5.1 Moisture content

The conductivity of rock is greatly affected by the presence of pore spaces within it since these are invariably filled with water of high mineral content. This effect of porosity on conductivity may be expressed as follows :

$$\sigma = ke^{P'} \qquad 2 - 13$$

where k is a constant, and P' the porosity. (Ames et al, 1963).

Measurements of the conductivity of dry and wet core samples show its dependence on moisture content very clearly. An example quoted by Parkhomenko (1967) illustrates this in Figure 2.1. (resistivity ρ in Ω cm is used in this example, however, $\rho = {}^1/\sigma$).

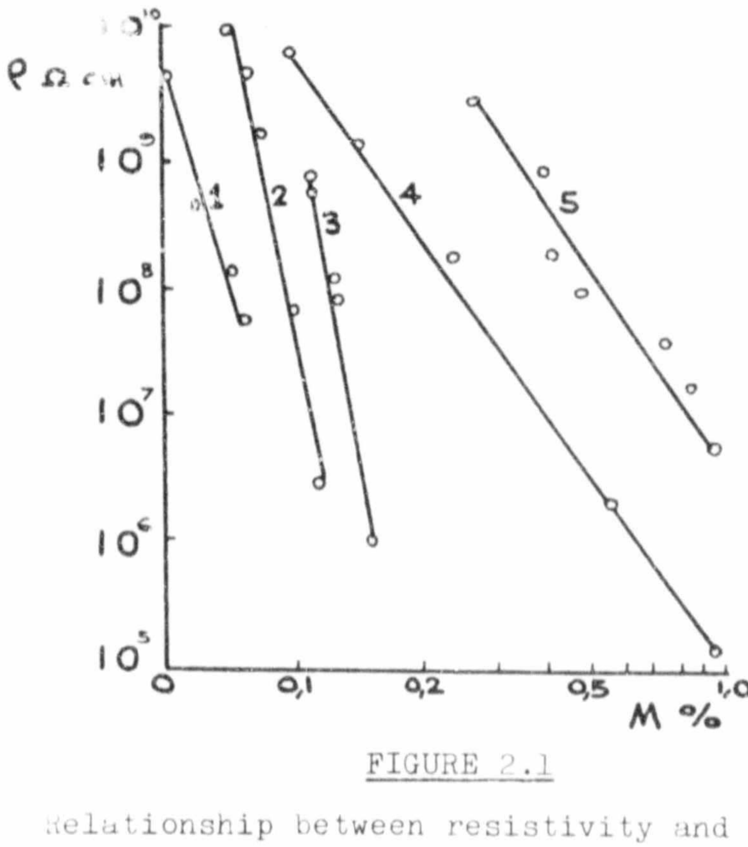

FIGURE 2.1

Relationship between resistivity and moisture content (1) andesite-basalt, (2,3) granite, (4) dolomite, (5) basalt, (Parkhomenko 1967)

The presence of water in rock has a pronounced effect on the permittivity, (Keller and Licastro, 1959). A moisture content of 0,38 per cent increases the permittivity of dolomite by 13 per cent over the dry sample value. (Parkhomenko, 1967). This is due to water having a permittivity of about 80, thereby increasing the permittivity of rock many times. As in the case of conductivity, many mixing rules exist, but none satisfactorily yields the permittivity, least of all in water-saturated samples (Howell and Licastro, 1961). The amount of water needed to raise the permittivity is very small. A dry sample of rock, exposed to the atmosphere, gradually increases its permittivity, presumably by the adsorption of water (Howell and Licastro, 1961), even though the amount of water taken in is too small to measure by weighing the rock sample.

The dependence of the rock electrical characteristics on the presence of water within pore spaces and cracks is thus obvious, and so, any prediction relating to in situ conditions, not taking cognisance of this will be in error.

2.5.2 Non-homogeneity

A further invalidation of laboratory measurements would be due to the non-homegeneous nature of the medium encountered in any mining environment. Various rock types, with differing electrical properties must exist in an area, and the resulting complex geology raises the overall or "bulk" conductivity above the laboratory or "handbook" values. (Ames, Frazier and Orange, 1963). This resulting aggregate of individual components has electrical properties which are dependent on the resistivity and permittivity of the constituent parts, and on their relative volumes. Several mixing theories can be used to calculate these properties of the aggregate, but this is hardly a practicable solution, considering the variety of geological situations which occur in a mining environment. Also values of conductivity calculated in this way apply only to d.c. on low a.c. conditions, which could limit their usefulness. (Fritsch, 1963).

2.5.3 The effect of temperature

According to Keller (1963), the conductivity of rock at high temperatures (greater than 10^3 °C) is an intrinsic property of the material, varying little from sample to sample. However, at temperatures lower than this (obviously more representative of a mining environment) the conductivity is sensitive to the structure of the sample and to its thermal history, and does not reproduce well. This is known as the region of extrinsic conductivity. Brace, Orange and Madden (1965) quote an example of granite at a pressure of 10^5 kPa measured at d.c., having a conductivity of approximately $2{,}5 \times 10^{-5}$ S/m at 20 °C, which increases to approximately $6{,}7 \times 10^{-5}$ S/m at 60 °C.

The effect of temperature on the permittivity of quartzite has been quoted by Parkhomenko (1967), and illustrates that over the temperature range of interest (20 °C < t < 100 °C) the permittivity is to all intents and purposes constant. This is shown in Figure 2.2.

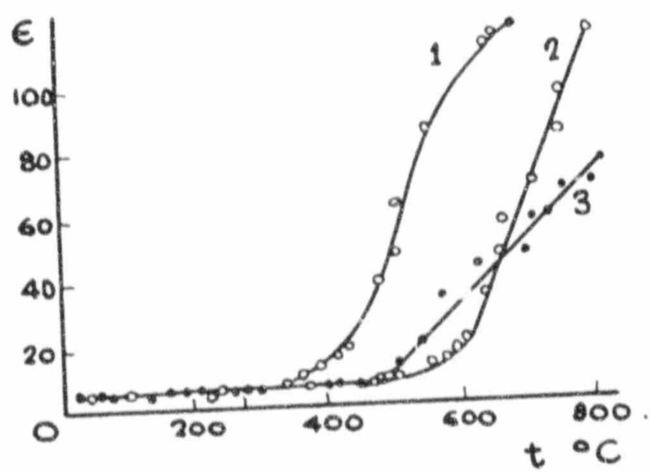

FIGURE 2.2

Temperature dependence of permittivity:
(1) sandstone; (2) quartzite; (3) vein quartz, (Parkhomenko, 1967).

2.5.4 The effect of pressure

The effect of pressure on the conductivity of rocks to depths of some tens of kilometres is shown to be negligible by Keller (1963). At a pressure of 10^6 kPa, which represents a depth below the earth's surface of about 35 km, the conductivity should decrease only by about 25 per cent below the zero pressure value. The increase in pressure with depth results in partial closure or compaction of cracks and pores in the rock, but sufficient water is still present, even at very high pressure, to affect conductivity. (Ames, Frazier and Orange, 1963).

However, Brace, Orange and Madden (1965), quote examples of the variation in conductivity for various rock types with pressure which show a decrease of about an order of magnitude for a pressure increase from zero to 3×10^5 kPa, which is a value typical of deep level mining. For example, quartzite in salt solution at 20 °C shows a decrease in conductivity from about $2,5 \times 10^{-3}$ S/m at zero pressure to about $1,7 \times 10^{-4}$ S/m at 3×10^5 kPa. Above a pressure of approximately 2×10^5 kPa the rate of conductivity decrease is much more gradual, decreasing to about $2,5 \times 10^{-5}$ S/m at 10^6 kPa. The initial rapid decrease in resistivity is due to the change in rock porosity and crack geometry (Brace and Orange, 1968), since most cracks are closed at pressures of 3 to 4×10^5 kPa (ibid).

The conductivity at <u>all</u> pressures is determined by pore geometry and pore fluids, since even pressures of 10^6 kPa to $1,5 \times 10^6$ kPa are clearly insufficient to lower the conductivity of saturated rock to within orders of magnitude of the dry sample values of 10^{-11} S/m (Parkhomenko, 1967, Brace and Orange, 1968). It is reasonable to expect some decrease in conductivity with depth below surface of 5 to 6 km. This may be of an order of magnitude or so. Since this depth range _might_ be typical of mining environments of the future, it is of interest in this investigation. The more gradual variation in conductivity at greater depths need not concern us here.

The effect of pressure on the permittivity of rocks is the least documented of all parameters affecting rock electrical characteristics (Parkhomenko, 1967). However, it has been shown that an increase in relative permittivity results from an increase in pressure. For example, in granite a pressure change from about 10^4 to 2×10^4 kPa results in a 10 - 20 per cent change in relative permittivity, which then increases more slowly as the pressure is elevated further. Figure 2.3 illustrates the effect for samples of sandstone (1), syenite (2) and granite (3 - 5).

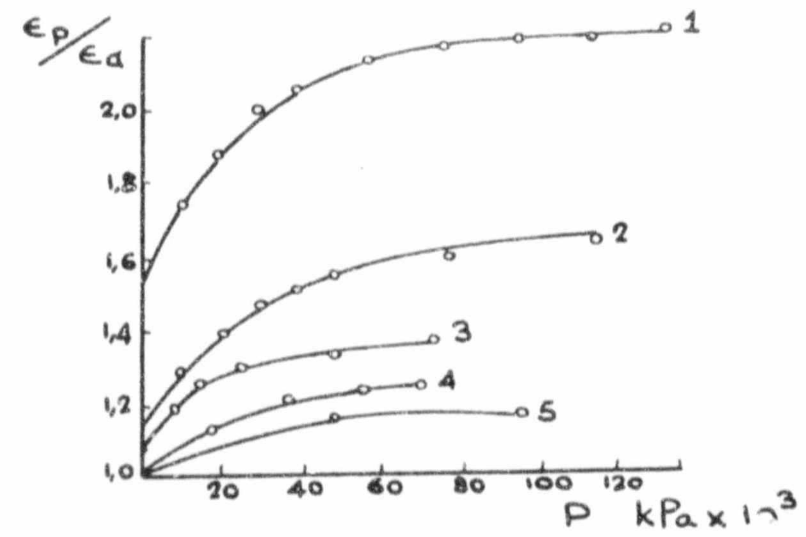

FIGURE 2.3

Relative permittivity ϵ_p at applied pressure p, to relative permittivity ϵ_a at atmospheric pressure. Adapted from Parkhomenko (1967).

At mining depths therefore a change in permittivity with change in depth is to be expected, as was the case with conductivity.

It is interesting to note that the loss tangent p decreases with an increase in pressure, and over the range of depths typical in South African deep level mining operations. This decrease should be particularly evident since the rate of change of conductivity and permittivity with depth is most rapid between surface and a depth of about 6 km. A decrease in loss tangent means, from 2 - 3, a decrease in attenuation, indicating therefore that given similar rock types, propagation should be more effective at depth than closer to surface. Whether this is realizable in practice, due to the variety of influencing factors, has yet to be established.

2.6 The effect of frequency on rock electrical properties

Since radio communication systems are very much frequency dependent, it is obvious that any investigation into the behaviour of geological substances under the effects of various physical phenomena would be totally incomplete without consideration being given to the effect of frequency on these.

The basic attenuation equation 2 - 3, (repeated here for clarity),

$$\alpha = \omega \left[\frac{\mu\epsilon \left\{ \left(1 + \frac{\sigma^2}{\omega^2 \epsilon^2} \right)^{\frac{1}{2}} - 1 \right\}}{2} \right]^{\frac{1}{2}}$$

illustrates the dependence of the attenuation constant α on frequency. What is not obvious, however, is that both conductivity σ and relative permittivity, $\epsilon_r = \epsilon/\epsilon_0$, are also frequency dependent. Any determination of α which does not take into account this dependence, but which relies on "handbook" values, measured at d.c., must be considerably in error. (Wadley, 1949).

2.6.1 Conductivity

The conductivity of a geological conductor generally increases with frequency. (Ryazantsev and Shabel'nikov, 1965; Scott, Carroll and Cunningham, 1967; Collett and Katsube, 1973; Cook, 1970; Keller and Licastro, 1952).

If the region is stratified the opposite result is also possible (Fritsch, 1963).

The depen. nce of conductivity on water content has been discussed above, however, a result of interest here is that of the effect of water content <u>and</u> frequency on this parameter. According to Parkhomenko (1967), and Keller and Licastro (1959), the lower the water content, in other words, the lower the conductivity, the greater is the rate of increase in conductivity with increasing frequency. In fact, dry rock exhibits an almost exponential relationship between conductivity and frequency over the range from 10 Hz to 10^8 Hz, whereas wet rock exhibits virtually no change over the same range. The low frequency value obtaining at 10^8 Hz, and, as in the case of permittivity, would appear to be influenced entirely by the presence of water within the pore spaces.

The range of conductivities encountered is considerable. An investigation in a mining environment necessitates cognisance being taken of a wide variety of rock types at depths varying from some tens of metres to many kilometres. In the shallower surface zone, extending to perhaps 10^3 m, the conductivities fall in the range from 1 to 10^{-4} S/m. In the intermediate zone, which covers depths extending well below the deepest mines (10 - 20 km), the expected conductivity lies in the range 2 x 10^{-5} S/m to 2 x 10^{-6} S/m. Below this depth, from about 60 km onwards, the conductivity is of the order of 10^{-1} S/m to 10^{-2} S/m, due to the very high temperatures prevailing at these depths (Parkhomenko, 1967).

2.6.2 Laboratory determined values of conductivity

It is interesting to quote examples of laboratory determined values of conductivity for various rock types typical of mining areas in order to gain some insight into the orders of magnitude of these dry, room temperature and atmospheric pressure samples. It is all too evident that these values are orders of magnitude lower than the values expected *in situ*, based on the arguments presented above. The examples quoted here, were obtained from the literature. At a later stage in this dissertation will be presented some results of the author's laboratory measurements on samples obtained from a variety of South African mines.

Wadley (1949) quotes values of conductivity for quartzite with frequency over the range 100 kHz to 3 MHz as in Table 2.1 :

TABLE 2.1

VARIATION OF CONDUCTIVITY WITH FREQUENCY OF QUARTZITE

FREQUENCY (kHz)	CONDUCTIVITY (S/m)
100	20×10^{-6}
300	40×10^{-6}
1 000	80×10^{-6}
3 000	200×10^{-6}

Dolomite, common in gold mining areas is quoted as follows by Collett and Katsube (1973), in Table 2.2:

TABLE 2.2

VARIATION OF CONDUCTIVITY WITH FREQUENCY OF DOLOMITE

FREQUENCY (kHz)	CONDUCTIVITY (S/m)
100	$0,5 \times 10^{-5}$
500	2×10^{-5}
1 000	4×10^{-5}
5 000	10×10^{-5}
10 000	33×10^{-5}

The conductivity of various coal samples is quoted by Cook (1970), and appear in Table 2.3:

TABLE 2.3

VARIATION IN CONDUCTIVITY WITH FREQUENCY OF COAL

FREQUENCY (kHz)	CONDUCTIVITY (S/m)
1 000	2×10^{-3} to 1×10^{-5}
5 000	5×10^{-3} to $1,66 \times 10^{-5}$
25 000	13×10^{-3} to 1×10^{-4}

The spread on values quoted here is due to coal samples from various United States mines being used, and also to the polarization of the electric field in the particular measurement system used.

2.6.3 Permittivity

The relative permittivity of dry rock is far less dependent on frequency than was the case for conductivity. Values from 2 to 15 are typical for most rock found in mining situations, and show only slight dispersion with frequency. (Scott, Carr 1 and Cunningham, 1967). This frequency dispersion is quoted by Ames and de Bettencourt (1963) as varying by a factor of 2 over a frequency range from 1 kHz to 20 kHz, which, although being two decades of frequency, is particularly low for the type of communication being considered in this study.

As mentioned previously (2.5.1), the presence of water in the rock has a pronounced effect on its relative permittivity. Parkhomenko (1967) quotes a variation from 100 to 8 for igneous rock over the frequency range 10^3 Hz to 10^7 Hz, for a moisture content of 0,09 per cent.

Howell and Licastro (1961) give the permittivity of sandstone with a 12 per cent moisture content as 3 000 at 10^2 Hz as against 4 at the same frequency when dry and tested under vacuum. At a frequency of 10^7 Hz the measured permittivities differed by less than a factor of two under the same test conditions.

Coal, with a large clay content, registered a permittivity greater than 25 at a frequency of 10^6 Hz, whereas a very dusty variety measured about 3 at the same frequency. At 10^8 Hz the two samples measured 7 and 2 respectively (Cook, 1970).

These high values of relative permittivity, measured in the laboratory, are considered to be in error due to electrolytic contact effects occurring at the measurement electrodes, and should thus not be relied upon. (Scott, Carroll and Cunningham, 1967; Collett and Katsube, 1973).

2.7 The loss tangent

Since the value of the loss tangent is of particular significance as far as the attenuation constant of a dissipative medium is concerned (see 2 - 11 and 2 - 12), it is informative to examine its dependence on the parameters already discussed. Of particular importance is the fact that the determination of the attenuation characteristics of the rock is dependent only on a knowledge of the medium conductivity if the loss tangent is greater than, or equal to 10, whereas a knowledge of both conductivity and permittivity is required when it is less than, or equal to 0,6.

Obviously "handbook" on laboratory measured sample values can be used in the determination of loss tangent, but since these values are likely to misrepresent the prevailing in situ conditions, the attenuation (and thus any propagation analysis based on it) will be in error.

Presented below in Table 2.4 are values of loss tangent at various frequencies, obtained by using Wadley's (1949) values for the conductivity of quartzite at those frequencies, and his value of 6 for the relative permittivity of the substance. He assumed this latter quantity remained constant over the frequency range quoted.