In Situ Determination of Bulk Electric Properties of Coal

In-situ Determination of Bulk

Electric Properties of Coal

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by David C. Chang and E.F. Kuester
775 Linden Ave.
Boulder, Colorado 80302

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16. Abstract

A survey of in-situ methods for determining bulk electric properties of coal is given. Largely because of the strong dependence of coal's properties on operating frequency, different sensing methods have to be adopted for different applications. Evaluation of both established and feasible methods is made in this report from the viewpoint of physical set-up, probing depth, and the type of inversion involved.

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- FOREWORD -

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This report is a summary of the work recently completed as part of this contract during the period March 1, 1977 to July 30, 1977. This report was submitted by the authors on August 3, 1977.

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TABLE OF CONTENTS

IN SITU DETERMINATION OF BULK ELECTRIC PROPERTIES OF COAL

Summary

The result of our survey clearly indicates that there is no single in situ measurement method which can be used universally for measuring bulk conductivity and permittivity of coal in a typical mining situation. Largely because of the strong dependence of coal's electrical properties on operating frequency, one must first determine the frequency range of interest before any particular method can be adopted. Equally clear from our survey is the fact that, while numerous electric methods and techniques exist in the literature, very few of them are suited for coal mine application. An optimum technique in this regard, should be one which can provide a reasonably accurate result and at the same time, is easy to install, stable to operate and gives measured data that are suitable for interpretation. A non-contact and remote technique is therefore superior to a contacting one which requires the drilling of bore holes. Similarly a method which allows direct analytical inversion of measured results is better than one which requires graphical interpretation by matching the measured pattern with pre-calculated theoretical curves, or one which needs a large amount of on-site data processing.

For low frequency detection up to a few kilohertz, most in situ probing methods are based upon the diffusion phenomenon of conduction current into the medium to be probed. Measured results can therefore be hampered by the

lack of good contact between the electrodes and the coal. However, it would appear that the electrode (galvanic resistivity) method, when properly installed, can provide reliable information concerning the apparent conductivity of the coal medium. The inversion from measured data can be done analytically and the physical set-up does not require drilling boreholes into the coal surface (section 3.1).

As frequency increases to the intermediate range of a few kilohertz to a few megahertz, the detection methods also become more reliant on inductive than resistive coupling. This eases the contact problem, even though some of the methods still require drilling into the coal medium. One which requires neither drilling nor contact is the two-loop induction method (section 4.1). Inversion of measured mutual coupling between the two loops to apparent properties of coal can still be done analytically in the lower frequency range (say, below a few hundred kilohertz) under the quasi-static assumption, although the same may not be true at a higher frequency range.

It is worthwhile to note that probing methods designed for the low and intermediate frequency ranges detect only the apparent conductivity of coal, since the displacement current (which affects the permittivity) is usually negligible in these ranges. From a user's point of view, the fact that its effect can be ignored also means that it is relatively unimportant as to whether it can be determined accurately or not. Moreover, the two methods mentioned above measure basically the near-field coupling between the source and the receiver. Thus, the resultant apparent conductivity represents in principle the average conductivity of coal within a sounding depth (or sounding volume) comparable to the separation of the two.

When the operating frequency exceeds a few hundred megahertz (10^8 Hz), electromagnetic waves can be radiated from antenna structures with a launching efficiency determined by both the geometry of the antenna and the electric properties of the surrounding medium or media. Thus, one may deduce the apparent conductivity and permittivity simply by measuring the change in the impedance of a resonant antenna. On the other hand, because the wavelength of waves in this frequency range is of the order of a meter or less, one can also deduce the needed information by measuring the propagation and attenuation characteristics of a waveguiding structure. Thus, detection methods developed in this range usually require only a monostatic scheme consisting of a single antenna or waveguide element. However, beause the electromagnetic coupling between the structure and the surrounding medium (or media) is more complicated, interpretation of measured data can be carried out only graphically in most instances. Our study shows that while some of the established techniques require boreholes and good contacts with the coal, there exist at least three feasible methods which do not have such requirements (aperture coupling method, section 4.5; resonant loop and dipole methods, section 5.3; guided wave propagation method, section 5.4). Particularly, in the case of the guided wave propagation method, simple analytic inversion of measured data is also possible when the guiding structure is that of a long, bare conducting wire located at the coal-air interface.

Measuring the apparent conductivity and permittivity of coal in the frequency range between a few megahertz (10^6 Hz) to a few hundred megahertz (10^8 Hz) appears to be difficult mainly because the wavelength in this case is too long for any antenna or wave guiding structure to be used effectively, while too short for the concept of electric and magnetic dipoles (used in the intermediate frequency range) to apply. It is conceivable that the two-loop method (section 4.1) can be generalized to the electromagnetic interference method (section 4.2) and be extended to perhaps up to a few tens of megahertz (10^7 Hz). The aperture coupling and buried antenna methods (sections 4.5 and 5.3) on the other hand can be lowered to a similar range.

Sensitivity of the methods, however, is expected to decrease from the higher-frequency case since the resonant property can no longer be utilized.

Various radar techniques are available for frequencies of operation above 1 GHz (10^9 Hz). Measurement of the reflectivity of a plane wave incident onto the coal surface using these techniques (section 5.6) usually yields data suitable for a direct inversion to coal parameters for both the monostatic and bistatic arrangements. Wave interaction with antenna structures can also be separated in this frequency range because of the far-field, high-gain condition prevailing in such an operation. On the other hand, direct transmission methods (section 5.5) are useful only when a path of transmission in coal is easily accessible. In either case, because the conduction current and hence, the conductivity is smaller in this frequency range, what one detects is then the apparent permittivity of coal, in direct contrast with the very low frequency case.

A brief summary of all the methods considered has been assembled for ease of reference. The useful frequency range, some general characteristics of the physical set-up, and an indication as to whether the method is established or merely feasible, as well as whether graphical or direct analytical inversion is needed are given. The section number refers to the location in Chapters 3-5 where more detailed information on a particular method can be found.

SUMMARY TABLE OF METHODS

Method	Frequency Range	Physical Set-up	Application
Electrode methods (§3.1)	DC to 1 KHz	Remote; contacting; portable (battery source)	Established technique graphical interpretation
Electrode well logging methods (§3.2)	DC to 1 KHz	Requires borehole (well) drilled into medium; contacting	Established technique (commercially available); direct analytical inversion or graphical interpretation
Magnetotelluric method (§3.3)	ELF (10^{-3} to 10^{3} Hz)	Remote; non-contacting; natural source, portable sensor	Established technique; analytical or graphical interpretation
Telluric current method (§3.4)	ELF (10^{-1} to 10^{3} Hz)	Remote; contacting; natural source; portable sensor	Established technique; graphical or analytical interpretation
Two-loop induction methods (§4.1)	10 KHz to 10 MHz	Remote; non-contacting; can be portable	Established technique (commercially available); graphical interpretation or direct analytical inversion
Radio frequency interferometry method (§4.2)	1 MHz to 50 MHz	Remote, non-contacting	Established technique; graphical interpretation
Induction logging methods (§4.3)	10 KHz to 10 MHz	Requires borehole (well) drilled into medium; non-contacting	Established technique; graphical interpretation or analytical inversion
Ground wave methods (§4.4)	LF-HF (30 KHz to 30 MHz)	Remote; non-contacting	Established technique; direct inversion, sometimes graphical interpretation

SUMMARY TABLE OF METHODS (continued)

Method	Frequency Range	Physical Set-up	Application
Aperture coupling method (§4.5)	30 MHz to 300 MHz	Remote; non-contacting	Potentially feasible technique; graphical interpretation
Buried dipole methods (§4.6)	10 MHz to 300 MHz	Requires bore hole drilling; contacting	Established technique; graphical interpretation
Open-wire transmission line (OWL) method (§5.1)	100 MHz to 1 GHz	Intrusive (requires penetration into medium); contacting, portable	Established technique; direct analytical inversion
Resonant buried monopole method (§5.2)	100 MHz to 1 GHz	Intrusive; contacting	Established technique; graphical interpretation
Resonant loop or dipole methods (§5.3)	100 MHz to 1 GHz	Remote; non-conctacting	Potentially feasible technique; graphical interpretation
Guided wave proparation method (§5.4)	100 MHz to 10 GHz	Remote; non-contacting	Potentially feasible technique; direct interpretation
Direct transmission method (§5.5)	300 MHz and up	Contacting or non-contacting	Direct interpretation; established technique but has limited application
Reflectivity methods (§5.6)	1 GHz and up	Remote; non-contacting	Established technique; direct interpretation or graphical interpretation

CHAPTER 1

INTRODUCTION

The objective of this work is to provide a comprehensive survey on the use of electromagnetic schemes for the *in situ* probings of the electric properties of a coal seam. Our purpose is to identify plausible measurement techniques which can adequately determine the bulk conductivity and permittivity of coal in a volume immediately behind the working face of a coal seam. A full knowledge of the coal properties in this case is not only important for the design of mine tunnel communication systems, but also essential for monitoring the size of the uncut portion of a coal seam, the roof thickness and other pertinent information in a mining operation.

As one might expect, the electrical properties of coal vary according to its carbon and ash content; the moisture contained therein, and the microscopic layering in a coal seam. In Chapter 2 a summary of the coal properties, as measured from coal samples in laboratory-controlled environments, is given. The fact that coal properties can indeed vary drastically from one coal mine to another, or even from one place to another place in the same mine, further demonstrates the need of developing measurement techniques capable of measuring the electrical properties of coal on site. One can see that in this regard, a successful measurement technique is not only one which could provide accurate results, but also one which is easy to install, stable to operate, and gives measured data suitable for interpretation without excessive on-site computation.

To present the results of our survey in a systematic manner, various measurement techniques are grouped together according to their applicable frequency ranges. Thus, in Chapter 3 we shall be concerned mainly with low and very low frequency methods (d.c. to 10 KHz), in Chapter 4 with intermediate frequency methods (10 KHz to 100 MHz), and finally in Chapter 5 with high and very high frequency methods (100 MHz to 10 GHz). Grouping of different techniques in this manner is obviously not unique, as many of those can readily be extended from one range to another with or without further modification. In many situations, a particular in situ scheme can also be achieved with more than one technique. However, the grouping does serve the purpose of emphasizing the fact that the success of a measurement technique is usually dependent upon the operating frequency one uses. Moreover, it is not at all unusual that the electric properties of coal itself have a strong dependence on frequency. Thus one really cannot select a particular measuring technique without first having a prior knowledge of the operating frequency of the communication system under consideration.

Then there is the question of sounding depth and sounding volume for any given measurement technique. In the case of low frequency detection where the skin depth of the electromagnetic wave is large, it is generally valid to say that the sounding depth and hence the sounding volume are comparable to the separation between the source and the observation points. Thus, in the electrode method, it is the distance between the current and voltage electrodes; in the two-loop induction method, it is the distance between the transmitting loop and the receiving loop, etc. In the case of high frequency detection however, the sounding depth and the sounding volume are more of a function of the skin-depth and/or the effective wavelength in the medium being sensed, both of which can vary as a result of changing the operating frequency. Consequently, one needs to determine what is the desirable sounding depth or volume, before a particular frequency range can be chosen.

The problem of determining the bulk conductivity and permittivity of coal is further compounded by the fact that in many instances, the medium is not homogeneous within the volume specified by a particular sounding technique. In addition to localized inhomogeneities such as sulphur balls which may scatter electromagnetic waves and hence distort the measured result, other complications can also arise as a result of wave penetration into the overburden material which usually has a very different conductivity as well as permittivity. Thus, the "apparent" electric properties of coal determined from one frequency can actually differ from those of another frequency, or even from one sensing method to another at the same frequency because of the different depths of penetration. When the discrepancy does arise, one may find that it is more appropriate to use the values determined from a method which is compatible to the propagation scheme of the communication system under consideration. For instance, a measurement scheme which is based upon the propagation characteristic of waves along the interface would be preferred over one which is based upon the reflection of a normally-incident wave. It is noteworthy that many of the measurement schemes discussed in our survey are actually capable of determining the electrical properties of coal modeled by a layered medium, instead of the apparent properties as modelled by a homogeneous one.

In describing each measurement technique in subsequent chapters, we shall first characterize the technique physically as to whether it is one which needs direct contact with the coal or one which is remote from the coal surface. From the viewpoint of installation, it is obvious that a non-contact one is superior to the one which requires contact, and a remote one is superior to the one which requires drilling into the coal surface. We shall then comment on the extent of difficulty in the interpretation of the measured result. A direct inversion from the electromagnetic quantities to the coal properties is obviously better than one which can be inverted only graphically with a cut-and-try process. Finally, before we proceed with the detailed description of the method, we shall identify the method as being an established one which has been applied to a similar situation, or one which is potentially feasible. Also included in each section is an evaluation of the method involved, typical results that can be obtained by the method, and references related to that method. For general background information on various methods of measuring earth conductivity (particularly of those applicable to frequency below a few hundred megahertz) readers may refer to the references lists as follows:

1. G.V. Keller and F.C. Frischknecht, Electrical Methods in Geophysics Prospecting, Oxford; Pergamon Press, 1966.

2. J.R. Wait (ed.) Electromagnetic Probing in Geophysics, Boulder, Colo: The Golem Press, 1971.

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4. R.J. Lytle, "Measurement of earth medium electrical characteristics, techniques, results, and applications," IEEE Trans. Geosci. Elec., vol. 12, pp. 81-101, 1974.

   Also an extensive bibliography on work done before 1968 was listed in the Appendix of the paper

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While every attempt has been made to include every class of measurement techniques, no such attempt has been made to compile exhaustive bibliographies for them. Representative references have been included, and further references can usually be found in these. The omission of a particular paper or book, however, is in no way intended as a commentary on its usefulness.

CHAPTER 2

ELECTRICAL PROPERTIES OF COAL

Before setting out to evaluate the merits of any given remote sensing technique, it is important to know the ranges of dielectric constant and conductivity (or loss tangent) one can expect to have to measure for actual coals. Thus, data for various coals and at various frequencies should be available which are obtained under controlled laboratory conditions, rather than from one of the probing methods under consideration. Even though the latter, performed in situ, could be expected to be more representative of coal properties as they will be encountered in actual mines, we must consider them to be potentially unreliable because they cannot be checked except to a limited degree.

The electrical properties of coal have been studied experimentally by a number of researchers,[1,2] but the techniques used and the condition of the samples must sometimes be sought in the original literature. Thus, many early low-frequency measurements are made on samples which have been ground into a powder.[3-6] This, in particular, tends to give a smaller value for conductivity at low frequencies than measurements made on solid samples.[7-15] It is also found that water content, especially at lower frequencies, can significantly increase both conductivity and dielectric constant. Finally, the carbon and ash content is also quite important. It is not surprising, then, to see a graph of resistivity such as Fig. 1— in this case vs. ash content— contain a range of seven orders of magnitude. Though less dramatic, the variation in dielectric constant can also be significant as shown in Fig. 2.

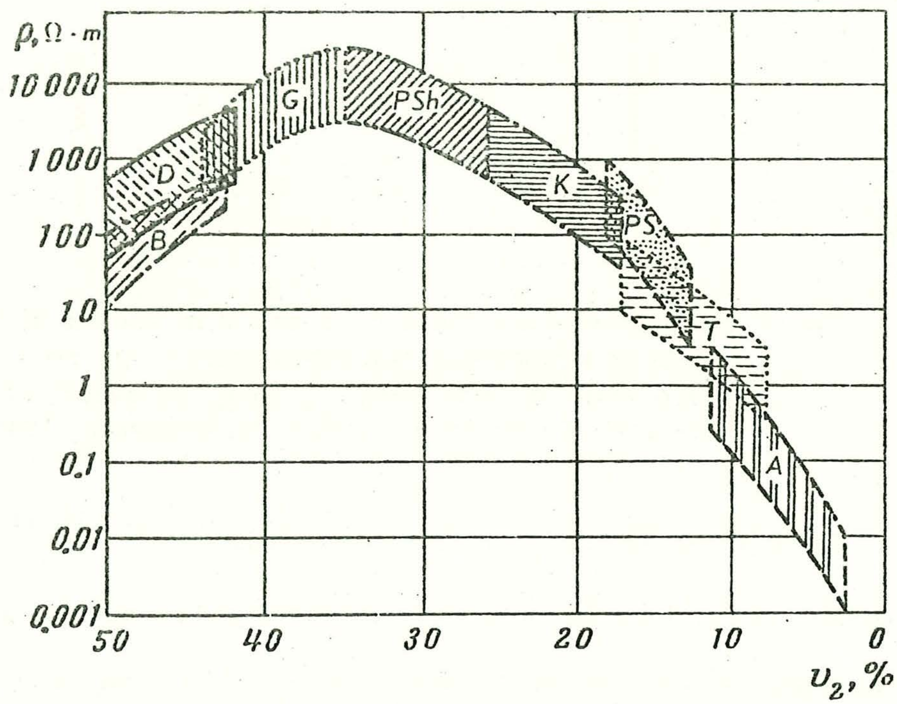

Fig. 1. Graph of the most probable values for the resistivity of coals of various grades as a function of quality. The ash content is plotted along the abscissa. (After Parkhomenko, 1967.)[1]

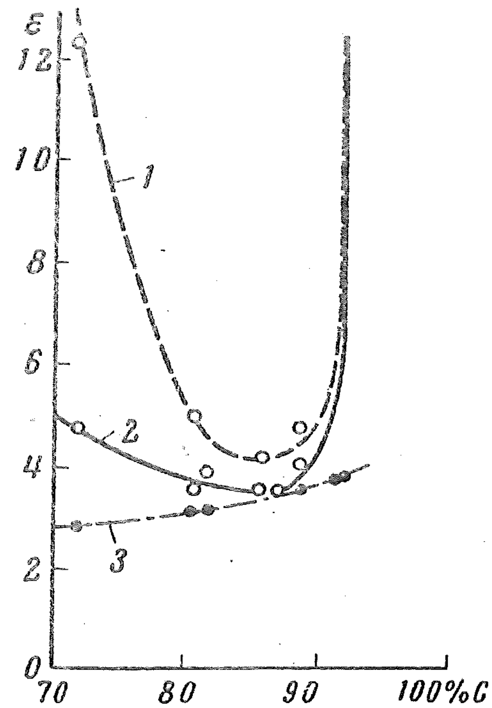

Fig. 2. Variation of the dielectric constant in wet and dry coals as a function of the cabon content: (1) air-dried coal, (2) absolutely dry coal, (3) square of the index of refraction. (After Parkhomenko, 1967.)[1]

These properties are also sensitive to frequency[4-7,10,11,15] and as a result, the coal can be anything from a very good conductor with negligible displacement currents, at low frequencies up to about 1 MHz, to a lossy dielectric tric at VHF frequencies. Thus, either permittivity or conductivity may be most important to measure. Measurements at microwave frequencies are few,[15-17] but indicate an only slightly lossy dielectric whose loss tangent is primarily that of the moisture contained therein, and whose dielectric constant is rather smaller ($\sim 2 - 4$) than at lower frequencies. Table 1 provides some typical results.The microscopic (relative to a wavelength) layering of coal as it occurs in a coal seam causes most coals to have an effective anisotropy in dielectric constant and, particularly, in conductivity at low frequencies.[2,7,10,11,13,15] The conductivity and dielectric constant in the direction normal to the coal bedding are smaller than in a direction parallel to the seam. The anisotropy factor (ratio of parallel to normal values) for dielectric constant is usually less than 2 (although Tonkonogov and Veksler[7] indicate the possibility of a value up to 5). The anisotropy factor for conductivity is typically larger, as high as 5 or 10 (see Table 1; again, however, Tonkonogov and Veksler[7] indicate higher values, possibly up to 100). Balanis et al.[15] give measurements showing that anisotropy is less pronounced, but still significant at microwave (X band) frequencies.

Table 1

Some VHF Electrical Properties of Pittsburgh Coal (After Cook, 1970)[10]

Conditions, freq.	Permittivity κ	Resistivity ρ_2 ohm-m	Attenuation Length D for 60 db
E parallel to beds 1 sample)			
1 Mhz	3.19	21,400	1,400 m
5 Mhz	2.89	4,600	288 m
25 Mhz	2.64	1,260	75 m
100 Mhz	2.47	545	31 m
E normal to beds 3 samples)			
1 Mhz	2.16-2.56	78,000-175,000	4,570-10,200 m
5 Mhz	2.13-2.45	30,700- 36,200	1,680- 1,980 m
25 Mhz	2.12-2.30	7,200- 7,850	398- 435 m
100 Mhz	2.06-2.22	1,270- 1,820	62.8-72.7 m
Powders 2 samples)			
1 Mhz	2.35-2.90	68,500-160,000	4,250-10,200 m
5 Mhz	2.34-2.64	15,500- 24,000	925- 2,000 m
25 Mhz	2.29-2.43	3,540- 8,600	202- 476 m
100 Mhz	2.12-2.30	1,130- 1,470	63-78.5 m

The relative magnetic permeability of a typical coal seems to differ from unity by an amount on the order of 10^{-6}, and so the permeability of coal may be taken as that of free space with no appreciable error.[14]

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CHAPTER 3

LOW AND VERY LOW FREQUENCY METHODS

3.1 Electrode methods (Galvanic resistivity methods)

Frequency Range: DC to 1 KHz

Physical Set-up : Remote; contacting; portable (battery source)

Application: Established technique; graphical interpretation

DESCRIPTION: In this technique, a potential field is set up in the medium to be probed by forcing current through a pair of electrodes contacting the surface of the medium. A second pair of contacting probes is then used to measure the potential gradient thus produced at one or more sets of points on the surface. A number of arrangements for the four electrodes are commonly used: the Wenner array (Fig. 1a), the Schlumberger array (Fig. 1b), and the polar dipole array (Fig. 1c). A further variant (which minimizes mutual inductance between transmitter and receiver) is the right-angle array (Fig. 1d). The measured data is interpreted by matching it to resistivity curves computed from theoretical analysis of a particular model of the unknown medium. If the model is taken to be a homogeneous, isotropic halfspace, the resulting value is called the apparent resistivity, regardless of the actual composition of the medium. Thus, Fig. 2 shows the apparent resistivity curves for a Schlumberger array for a two-layer medium with slab thickness h vs. the electrode spacing a, for various ratios (not shown) of substratum to slab resistivity ρ_2/ρ_1. The apparent resistivity in this case is normalized to the resistivity ρ_1 of the top layer. Measured data (the circles) is shown matched to the curve $\rho_2/\rho_1 = \infty$, and h and ρ_1 are then found from the raw (unnormalized) data. Analytical inversion for the apparent resistivity can be carried out in a straightforward manner, particularly in the case when one of the voltage electrodes and one of the current electrodes are removed to infinity. The conductivity is simply given by $(2\pi\rho R)^{-1}$ when R is the measured resistance and ρ is the separation between the current and the voltage electrode.

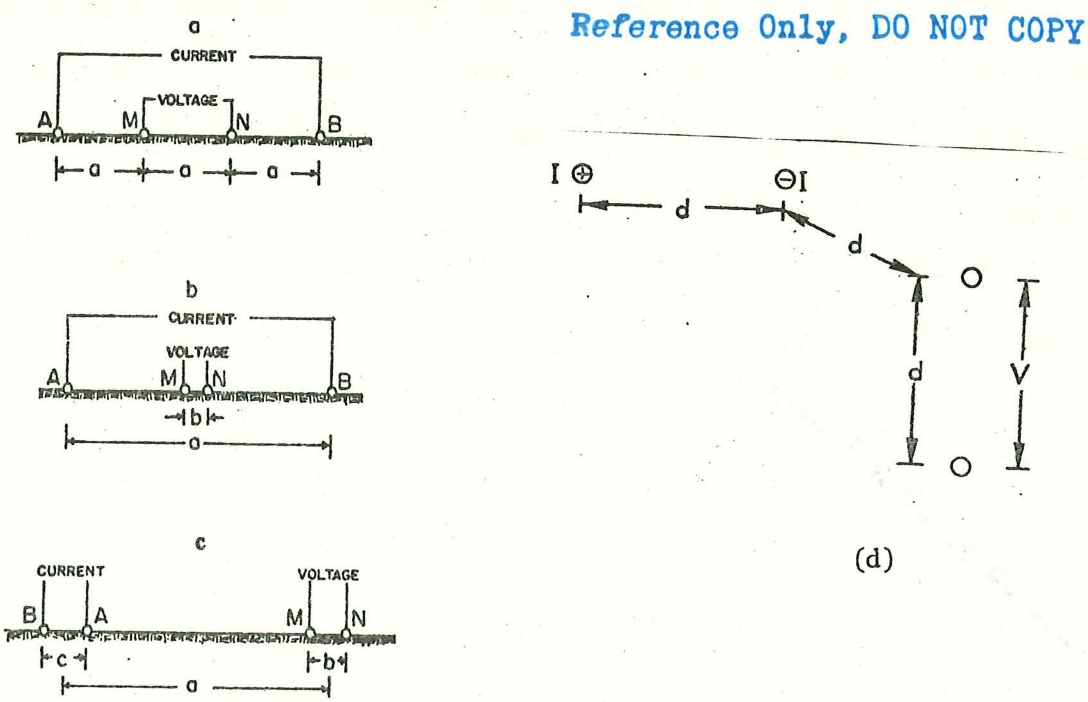

Fig. 1. a) Wenner array; b) Schlumberger array; c) polar dipole array; d) right-angle array. (After Keller and Frischknecht, 1966 and Lytle, 1974)

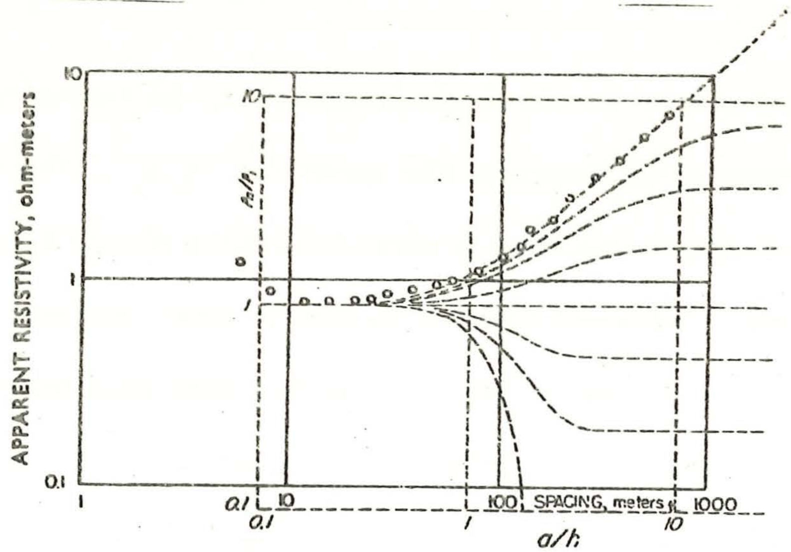

Fig. 2. Example of the interpretation of a field curve by superposition with a set of two-layer (single-overburden) resistivity curves. (After Keller and Frischknecht, 1966.)

A variant of the instrumentation is shown in Fig. 3. This technique is known as the bridge and substitution, where an impedance bridge and precision resistor and capacitor are used to improve the accuracy of the measurement. Some improvement in results, especially at small electrode spacings, can be expected. Also, recent variants of the electrode array have been proposed[7] which offer somewhat more flexibility than do conventional arrays.

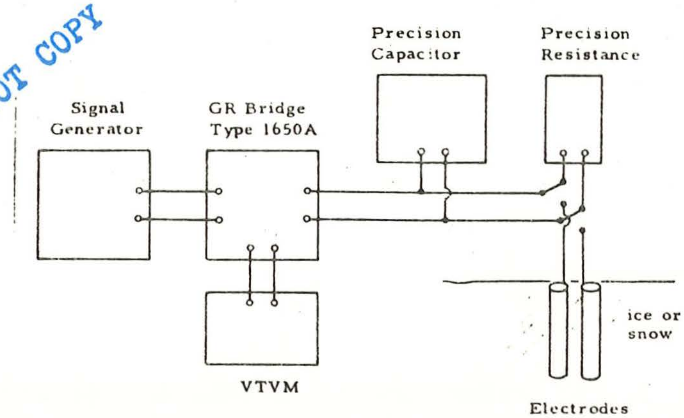

Fig. 3. Bridge and substitution method for measuring conductivity and dielectric constant. (After Watt and Maxwell, 1960)

EVALUATION: In common with the telluric current method, this approach suffers from uncertainty about electrode contact resistances with the medium, which makes absolute measurements of resistivity less reliable, depending upon such factors as ground moisture, etc. In the case of an inhomogeneous half-space, the measured resistivity value usually represents the average of the resistivity for the medium in between the two probes. The depth which is probed by this technique is of the same order of magnitude as the electrode spacing. Thus, for a spacing of a meter, for example, only the properties of the medium to a depth of a few meters will influence the measured results. This method is also incapable of detecting anisotropy (resistivity different in the horizontal and vertical directions), and will in fact present an apparent resistivity equal to the geometric mean between two values. It is, however, capable of detecting anomalies (i.e., changes from background resistivities). The analysis is strictly a d.c. one. Hence the permittivity of the coal, which is responsible for producing the displacement current is completely ignored. Such a technique is useful only in the very low frequency range.

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6. A. D. Watt and E. L. Maxwell, "Measured electrical properties of snow and glacial ice," J. Res. NBS v. 64D, pp. 357-363 (1960).

7. M. A. Ralston and J. R. Wait, "Theory of low frequency ground conductivity measurements--with application to probing of roof structures in coal mines," EM Rept. No. 2, CIRES, Univ. of Colo. (Bureau of Mines Contract No. GO155054), 1977.

3.2 Electrode well logging methods

Frequency Range: DC to 1 KHz

Physical Set-up: Requires borehole (well) drilled into medium; contacting

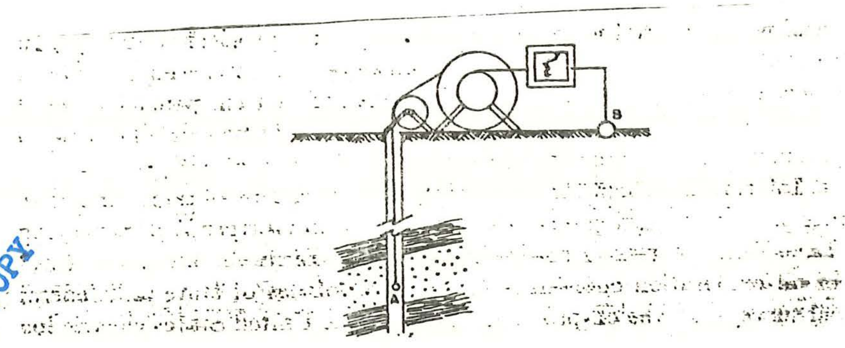
Application: Established technique (commercially available); direct analytical inversion or graphical interpretation

DESCRIPTION: These methods are similar to galvanic electrode methods, but give more information, especially about localized electrical anomalies buried at some distance below the surface. This is accomplished by lowering one or more of the electrodes down into a borehole, electrical contact with which is assured by filling the hole with water or mud. As with galvanic surface methods, a number of electrode configurations are available:

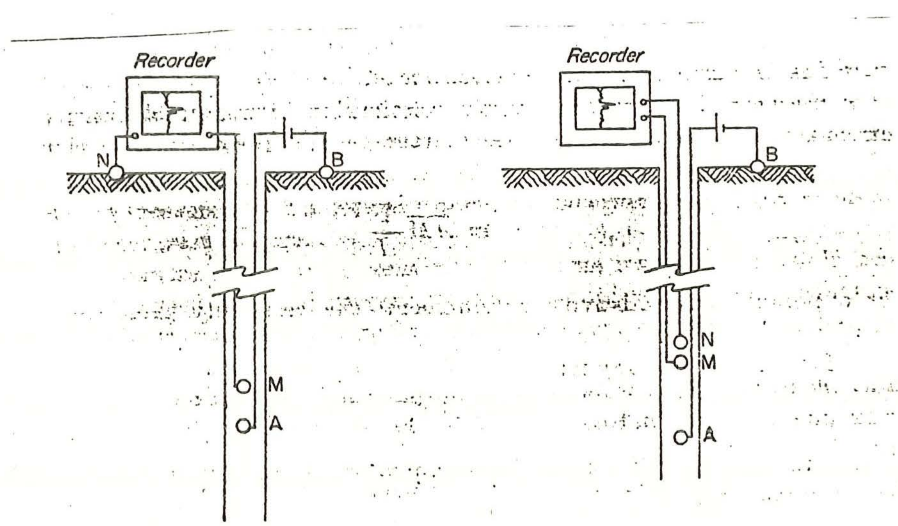
a) single-electrode resistance logs
b) multi-electrode spacing logs
c) focused-current logs
d) micro-spacing and pad logs

In method (a), a single electrode is lowered into the hole, and the resistance is measured to some point on the surface (Fig. 1(a)). In this case, if the medium can be assumed homogeneous, an analytic inversion to obtain the resistivity is possible. If the medium is non-homogeneous, a value of apparent resistivity is obtained, and it is difficult to relate this to the actual parameters unless other information is available.

In method (b) (Fig. 1(b) or 1(c)) one or more additional electrodes is lowered into the borehole, and like the four-electrode galvanic arrays, two of the electrodes provide a current excitation while the remaining ones measure the potential. Once again an apparent resistivity is obtained, and to provide an accurate picture of the actual situation, many different logs must be run with different spacings of the electrode array, or the log must be supplemented with data from a surface electrode measurement. These data must be interpreted graphically from a set of curves such as in Fig. 2.



(a)



(b) (c)

Fig. 1 (After Keller and Frischknecht, 1966)

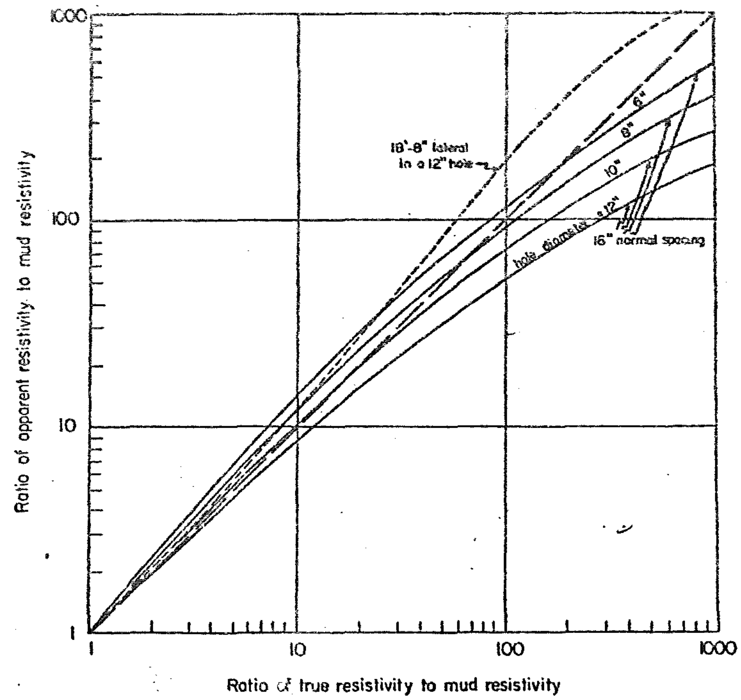


Fig. 2. Departure of apparent resistivity from the true resistivity of the rock around a well as a function of the contrast between rock resistivity and mud resistivity. The solid curves are calculated for a 16-in. normal spacing, while the dashed curve is calculated for a 224-in. lateral spacing. (After Keller and Frischknecht, 1966.)

Method (c) is a modification of method (a) or (b) in which the electrode shape is tailored to focus the current along a thin horizontal slab at the level of the electrode. The above statements on interpretation apply to this method as well. Method (d) uses electrodes mounted on a pad which is spring-loaded to hold against the wall of the bore. This method is identical in principle to (a) or (b) above, but can generally detect a greater number of fine layers.

EVALUATION: The contact problems associated with electrode methods are present (but to a lesser degree because of the water - or mud-filled hole) here along with the consequent uncertainty regarding absolute values of measured resistivity. Moreover, the need for a well makes this technique undesirable for locations where drilling is inconvenient or impossible (it is, of course, impossible to fill a hole in the roof of a mine with mud or water). The method however is a more general one capable of probing the profile variation in the medium. The depth of penetration away from the electrodes into the medium is, as in the galvanic resistivity methods, on the order of the electrode spacing.

REFERENCE:

1. G.V. Keller and F.C. Frischknecht, Electrical Methods in Geophysical Prospecting. Oxford: Pergamon Press, 1966, chapter 2.

3.3 Magnetotelluric method

Frequency Range: ELF (10^{-3} to 10^{3} Hz)

Physical Set-up: Remote; non-contacting; natural source, portable sensor

Application: Established technique; analytical or graphical interpretation

DESCRIPTION: Natural electromagnetic fields in the ELF range are produced by thunderstorms around the world (10^{0} - 10^{3} Hz) and by micro-pulsations in the earth's magnetic field (10^{-3} - 10^{0} Hz). If the source distribution is known (typically assumed to be a plane wave) then sounding curves for the surface impedance of the field (ratio of tangential E to tangential H) can be produced. Actual measured data, taken at one or more frequencies, is then matched against the sounding curves for interpretation, allowing conductivity (and heights of layers, if included in the model of the earth) to be inferred. As with many other methods, an apparent resistivity can be obtained by analytic inversion.

EVALUATION: The method depends upon a knowledge of the form of the source fields. If this is unavailable, discrepancies come in which can resemble those produced by anisotropic conductivity. Moreover, since it utilizes the natural sources, it may not be a particularly practical one in a mining situation. The frequencies involved are such that depths on the order of kilometers are sensed. Since the electric fields involved are of small amplitude ($\sim 1\mu$ V/m), detector sensitivity and noise are likely to be problems as well.

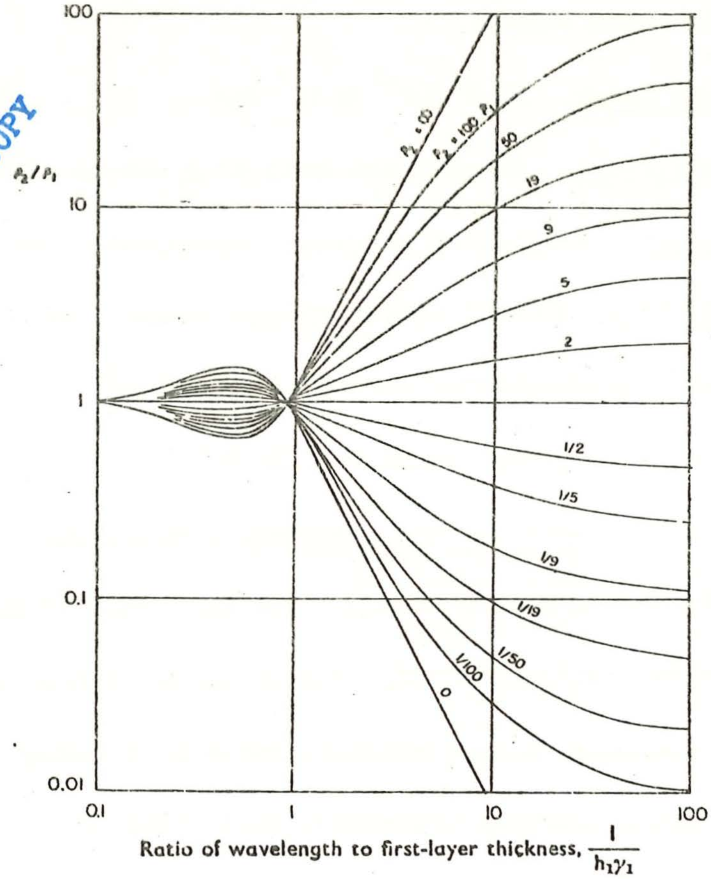


Fig. 1. Apparent resistivity calculated from magnetic-telluric measurements over a two-layer earth. (After Keller and Frischknecht, 1966).

REFERENCES:

1. J. R. Wait, "Theory of magneto-telluric fields." J. Res. NBS vol. 66D, pp. 509-541 (1962).

2. G. V. Keller and F. C. Frischknecht, Electrical Methods in Geophysical Prospecting, Oxford: Pergamon Press, 1966, chapter 4.

3. M. N. Berdichevskii, Electrical Exploration with Telluric Currents, Translated in Quart. Colo. School Mines v. 60, no. 1, 1965.

3.4 Telluric current method

Frequency Range: ELF (10^{-1} to 10^{3} Hz)

Physical Set-up: Remote; contacting; natural source; portable sensor

Application: Established technique; graphical or analytical interpretation

DESCRIPTION: Except that the currents induced in the earth are probed rather than the surface impedance, this is basically the same as the magneto-telluric method. Since the strength of the source field is not known, the absolute value of resistivity can thus not be determined without supplementary information. However, by measuring voltages between spaced electrodes planted into the earth, the relative variations in resistivity from one location to another can be measured. Data must be interpreted from theoretical curves appropriate to some assumed geometry or, if the geometry is simple enough, be analytically inverted.

EVALUATION: This method has the limitations both of the magneto-telluric method and of the electrode methods, except that it is not so plagued by noise and sensitivity problems as the former. It is moreover unable to determine resistivity alone. As with the electrode methods, and to an even greater degree, this method is best suited to the detection of anomalies (i.e., localized changes from ambient properties) rather than absolute values of electrical properties.

REFERENCES:

1. G.V. Keller and F.C. Frischknecht, Electrical Methods in Geophysical Prospecting, Oxford: Pergamon Press, 1966, chapter 5.

2. W.M. Telford, L.P. Geldart, R.E. Sheriff, D.A. Keys, Applied Geophysics, Cambridge, Cambridge Univ. Press, 1976, pp. 468-489.

3. M.N. Berdichevskii, Electrical Exploration with Telluric Currents, translated in Quart. Colo. School Mines. v. 60, no. 1, 1965.

3.5 Evaluation of Methods

Although most of the low frequency methods were developed for probing profile variations and anomalies in the medium, the use of these techniques for the determination of apparent conductivity of bulk coal can be carried out in a straightforward manner. Except in the case of the magneto-telluric method, surface preparation and/or drilling are usually required. Accuracy in measured results can be hampered by the lack of close contact between the electrodes and the sensing medium. Among all these established methods, it would appear that the electrode (galvanic resistivity) method, when equipped with proper brush contact or with electrodes nailed down to the coal surface, is the most suited to a typical mining environment. The apparent conductivity determined by this method usually represents an average property of coal located between the two voltage electrodes in a four-electrode method, and between the voltage and the current electrodes in a two-electrode method.

CHAPTER 4

INTERMEDIATE FREQUENCY METHODS

4.1 Two-loop induction methods

Frequency Range: 10 KHz to 10 MHz

Physical Set-up: Remote, non-contacting; can be portable

Application: Established technique (commercially available); graphical interpretation or direct analytical inversion.

DESCRIPTION: As a general class, induction methods are characterized by an excitation of the medium being probed by a VLF to MF source, typically an electrically small antenna such as a loop. Using theoretically determined sounding curves for the fields induced by such a source, the measured data as a function of either operating frequency or separation of the two loops are matched to these curves to obtain the electrical parameters of the medium.

In two-loop methods, the fields are measured by a second, generally multi-turn loop antenna. It is common, instead of the fields, to measure directly the mutual impedance between the loops, and match these data against appropriate theoretical sounding curves. A typical set of sounding curves for a homogeneous isotropic half-space is shown in Fig. 1. Extensive tables and graphs of sounding data are found in Ref. 6. There are four typical mutual arrangements between the loops above a layered half-space--horizontal coplanar (apparently the most commonly used in practice), perpendicular, vertical coaxial, and vertical coplanar. As with the electrode methods, regardless of whether the half-space is actually homogeneous and isotropic, the values of resistivity and permittivity obtained by matching with a sounding curve for a homogeneous isotropic half-space are called apparent values. The measurement of an anisotropic medium requires at least two distinct orientations of sending and receiving loop.

A portable two-loop sensor operating at 39.2 kHz and powered by batteries is manufactured by Geonics Limited of Toronto, Canada.

EVALUATION: As can be seen from Fig. 1, the determination of apparent conductivity and dielectric constant depends upon the separation of the loops, and sensitivity can be a problem. However, with proper selection of operating parameters, this problem can be avoided. The Geonics unit mentioned above, for example, measures conductivity accurately up to 200 m mho/m. Although dielectric constant is less reliably determined, this is primarily due to its negligible effect on wave propagation at this frequency in any case.

As with the galvanic resistivity methods, the two-loop methods are sensitive to medium parameters at depths comparable to loop separation. If the latter is 1 m, then a probing depth of a few meters might be expected.

It has been noted[2] that the vertical magnetic field of a horizontal loop antenna over an anisotropic half space in the quasistatic approximation depends only on transverse resistivity. Other field components of this and otherwise oriented sources typically depend only on either transverse or vertical resistivity, or on some fixed combination of the two.[2,4] For a single measurement, different loop orientations may give rise to different apparent resistivities, which may be a drawback for some specific applications.

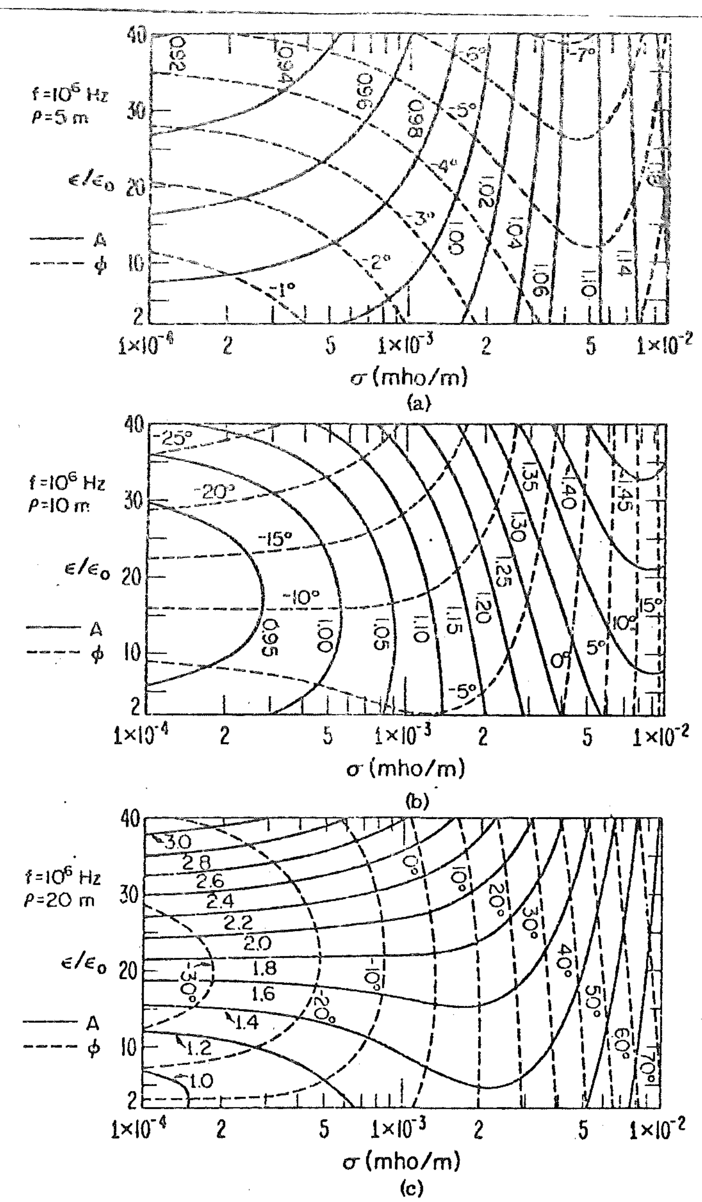


Fig. 1. Curves of equal amplitude and phase of the mutual impedance ratio Z/Z_o as a function of σ and ϵ/ϵ_o. $Z/Z_o = Ae^{-i\phi}$. (After Wait and Spies, 1972.)

Since the method is based upon the inductive coupling through different media, near-by machinery and lead wires can be significant in causing distortion of the magnetic flux lines thereby affecting the measured result. Such interference does seem to impose a limitation on the separation of the transmitting and receiving loops, as well as the upper limit of the frequency one can use. Also at frequencies higher than one megahertz, a more accurate formulation of the problem in terms of the so-called Sommerfeld integral has to be adopted instead of the quasi-static approximation normally used to simplify the inversion process. As a consequence, only graphical interpretation of the measured data can be carried out. (Fig. 2)

Misalignment problems in this method depend on the particular configuration being used. For the two horizontal loops, for instance, a small angular deviation from horizontal will not change the coupling substantially since the coupling between vertical and horizontal components is much smaller.

REFERENCES:

1. G.V. Keller and F.C.Frischknecht, Electrical Methods in Geophysical Prospecting, Oxford: Pergamon Press, 1966, chapter 6.

2. L.L. Vanyan et al., Electromagnetic Depth Soundings. New York: Consultants Bureau, 1967.

3. G.W. Hohmann, "Inductive electromagnetic methods at lunar surface," in Electromagnetic Exploration of the Moon (W.I. Linlor, ed.) Baltimore: Mono Book Corp., 1970, pp. 171-190.

4. J.R. Wait, "Electromagnetic fields of a dipole over an anisotropic half-space," Canad. J. Phys. v. 44, pp. 2387-2401 (1966).

5. J.R. Wait and K.P. Spies, "Note on determining electrical ground constants from the mutual impedance of small coplanar loops," J. Appl. Phys. v. 43, pp. 890-891 (1972).

6. F.C. Frischknecht, "Fields about an oscillating magnetic dipole over a two-layer earth, and application to ground and airborne electromagnetic surveys," Quart. Colo. School Mines v. 62, no. 1, pp. 1-326 (1967).

7. J.R. Wait and M. Ralston, "Low-frequency EM coupling of loops as a probe to measure roof thickness," Prelim. Rept. to U.S. Bureau of Mines, Project No. G0155054, Dec. 1976.

8. J.R. Wait and J.A. Fuller, "Argand representation of electromagnetic coupling of loops on a two-layered earth," Geoexploration, v. 10, pp. 221-227 (1972).

9. W.L. Taylor, "Effective ground conductivity measurements at radio frequencies using small loop antennas," Conf. Environmental Effects on Antenna Performance, v. 1, pp. 186-189 (Boulder, Colo., 1969).

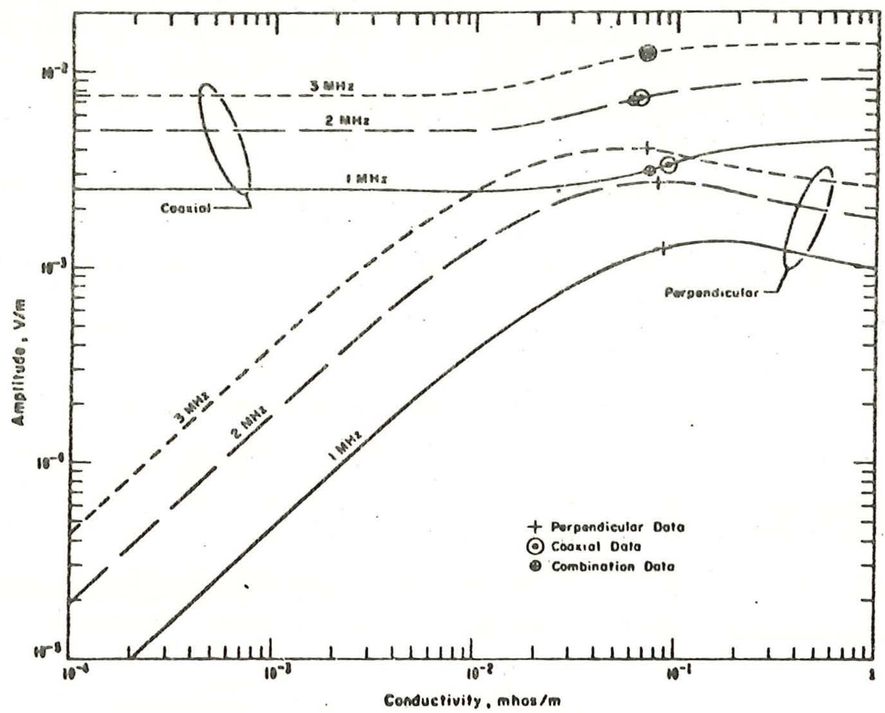


Fig. 2 Amplitude of receiving loop versus conductivity for coaxial and perpendicular loops (After Taylor, 1969).

4.2 Radio frequency interferometry method

Frequency Range: 1 MHz to 50 MHz

Physical Set-Up: Remote, non-contacting

Application: Established technique; graphical interpretation

DESCRIPTION: This method is basically an extension of the two-loop induction method to higher frequency range. Because the launching efficiency is higher at these frequencies, the source usually is a horizontal, electrically-short dipole antenna instead of a loop, and in principle, any component of the field can be used for probing purposes. The coupling between the source and receiver is now electromagnetic in nature, instead of coupling by induction. When the transmitting antenna is placed on the coal surface, an interference pattern with the original field arises as a result of the field penetration and scattering by the coal medium. In this case, interpretation is then made through precalculated curves based upon the so-called Sommerfeld integral formulas, which of course are more difficult to compute numerically without making the same quasi-static approximation as in the two-loop method. To demonstrate the use of this method, Fig. 1 indicates the calculated and the measured pattern of the vertical magnetic field due to a horizontal electric dipole. The electric parameters for the theoretical curves in this case are computed for conductivity = 3.3 and permittivity = 0.016 millimhos and thereby we are provided the information about the sensing medium.

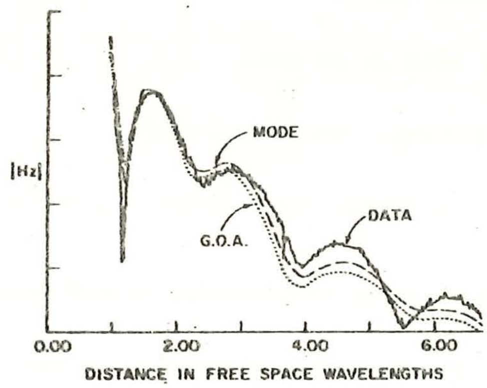


Fig. 1. Set of Athabasca data taken at 2 MHz, site 3 compared with theoretical results obtained with mode approach and geometrical optics approach. Theoretical results are calculated for layer of ice with dielectric constant $3.3\,\epsilon_0\,(1 + i0.15)$ and depth $1.2\lambda = 180$ m. Scale is 8 dB/division. (After Kong et al., 1974)

EVALUATION: Pattern measurement usually has to be carried out by varying the separation between the source and the observation point at a fixed frequency, although the extension to varying operating frequency for a fixed distance can be carried out. At the higher operating frequencies, the approximation of an antenna of finite size as a short dipole becomes less accurate, and a more complicated inversion taking this effect into account is needed (see § 5.3 on resonant antenna methods). Moreover, at these frequencies, the separation distance and operating wavelength no longer scale together simply, so that a much larger set of interpretation curves may be needed. Finally, the probing depth is now no longer simply related to the loop separation, but involves wavelength and skin depth parameters as well. In order to take advantage of the additional information provided by this method, separations of at least a wavelength are desirable, making application in confined coal-mine environments less convenient.

REFERENCE:

J. A. Kong, et al., "Geophysical surface probing with radio frequency interferometry," IEEE Trans. Ant. Prop., vol. 22, pp. 616-620 (1974).

4.3 Induction logging methods

Frequency Range: 10 kHz to 10 MHz

Physical Set-up: Requires borehole (well) drilled into medium; non-contacting

Application: Established technique; graphical interpretation or analytical inversion

DESCRIPTION: Induction logging methods, in common with electrode logging methods, require the presence of at least one, and sometimes two or three, boreholes drilled into the medium into which probes and sources can be lowered. In contrast with the latter, however, contact with the wall of the hole is not required. For the single hole method, the principle is similar to the two-loop induction method: a source and receiver, which are considered to be dipoles, separated by a known distance, are lowered into the hole and the mutual impedance between them is measured as a function of depth. Using a simple theory, a graphical (or sometimes analytical) interpretation is made, giving an apparent resistivity vs. depth.

As with two-loop induction methods, this technique can be extended to frequencies up to 10 MHz if a more precise theory is used for interpretation. This can also be accomplished by drilling two holes and measuring the transmitted signal between the two. Transmitter and receiver are raised and lowered independently, and many different propagation paths can be taken into account if desired[3,5] (see Fig. 1). The data can then be processed and a profile determined. A third alternative is to drill a third hole[2,4] and place receivers in two adjacent holes. The differential transmission between the two holes can then be interpreted in terms of phase and attenuation factors of the medium by direct analytical inversion.

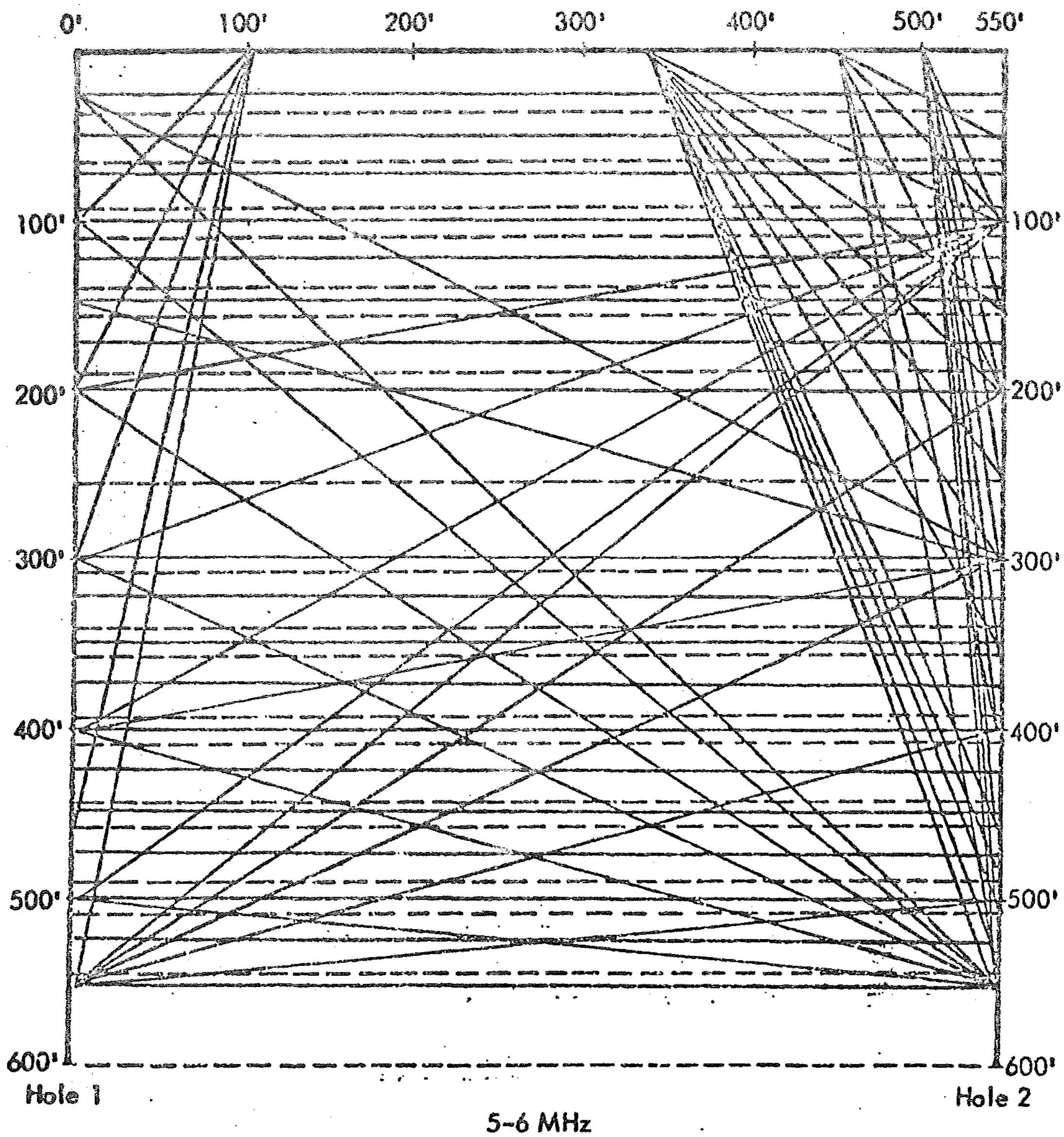


Fig. 1. Propagation paths for two-hole logging (After Lytle, 1974)

EVALUATION: The usefulness of this method is primarily in the detection of isolated anomalies buried in coal, where only the contrast in electrical properties is required. Although these methods ameliorate the contact problems (especially by eliminating the need to fill the hole(s) with mud or water) associated with the electrode logs, the necessity of holes, sometimes more than one, is still a disadvantage in a coal mine environment. Moreover, the two-hole variant described above requires extensive data processing to eliminate the effects of differing antenna properties. If holes of small depth can be tolerated, the three-hole (differential transmission variant) offers the simplest inversion and is therefore the most attractive of the three methods described here. This technique has the drawback, however, of requiring rather large separations between the holes (on the order of a skin depth) which makes application in a mine inconvenient as compared to essentially local measurement techniques.

REFERENCES:

1. G.V. Keller and C.F. Frischknecht, Electrical Methods in Geophysical Prospecting. Oxford: Pergamon Press, 1966, chapter 2.

2. R.N. Grubb and J.R. Wait, "In situ measurements of the complex propagation constant in rocks for frequencies from 1 MHz to 10 MHz," Electron. Lett. v. 7, pp. 506-507 (1971).

3. R.J. Lytle, "Measurement of earth medium electrical characteristics: techniques, results, and applications," IEEE Trans. Geosci. Elec. v. 12, pp. 81-101 (1974).

4. R.N. Grubb et al., "Borehole measurements of conductivity and dielectric constant in the 300 kHz to 25 MHz frequency range," Radio Science v. 11, pp. 275-283 (1976).

5. R.J. Lytle et al., "Determination of the in situ high frequency electrical properties of permaforst rock," Radio Science, v. 11, pp. 285-293 (1976).

4.4 Ground wave methods

Frequency range: LF-HF (30 kHz-30 MHz)

Physical Set-up: Remote; non-contacting

Application: Established technique; direct inversion, sometimes graphical interpretation

DESCRIPTION: Ground wave methods may be thought of as versions of the magneto-telluric technique using man-made sources. A known source (an electrically small transmitting antenna, say) located above a semi-infinite medium sets up a field at the surface of the medium. If the measurement point is located at least a free-space wavelength from the transmitter, the incident field is locally a plane wave. Measurements can thus be made:

a) of the surface impedance $(E_z/H_\phi$ or $E_\phi/H_z)$,

b) of the "wave tilt" E_ρ/E_z or H_ρ/H_z, where ρ is the radial direction from the transmitter and z is perpendicular to the surface of the medium,

c) of the variation in field strength as a function of source or receiver height above the surface (height gain measurements).

The E measurements can typically be made with a short linear antenna (electric dipole), while the H measurements are made with a small loop (magnetic dipole), whose axes are oriented parallel to the desired field component. For a homogeneous half-space, analytical inversion is possible, and in other cases graphical interpretation of data has been done.

EVALUATION: An advantage of this technique over the magneto-telluric approach is the control which is exerted over the source, permitting the noise problems to be reduced. The possibility of analytical inversion is also a favorable aspect. In common with the magneto-telluric approach, the measurements are made practically independent of the source location.

This contrasts with the two-loop methods, which are essentially mutual induction techniques, and whose low frequency analogs are the electrode methods. This independence from the source is the clearest advantage of ground wave methods. The necessity of separating source and receiver by a wavelength (300 m at 1 MHz) is a distinct disadvantage in a coal mine. Moreover, the idealization of a coal surface in a mine as a half-space geometry is poor at these frequencies; to correct either of these drawbacks would require extensive numerical computation and necessitate graphical interpretation.

REFERENCES:

1. J.R. Wait, Electromagnetic Waves in Stratified Media, Oxford: Pergamon Press, 1962.

2. R.J. King, "Crossed-dipole method of measuring wave tilt," Radio Science v. 3, pp. 345-350 (1968).

3. S.W. Maley, "Radio wave methods for measuring the electrical parameters of the earth," in Electromagnetic Probing in Geophysics (J.R. Wait, ed.). Boulder, Colo: The Golem Press, 1971, pp. 77-107.

4.5 Aperture coupling method

Frequency Range: 30 MHz to 300 MHz

Physical Set-up: Remote, non-contacting

Application: Potentially feasible technique; graphical interpretation

DESCRIPTION: When the open end of a waveguide is placed directly in front of the coal surface, the near-field coupling with the coal medium can cause a change in the reflection coefficient of the propagating mode insde the waveguide. Thus, by measuring this change, one can in principle extract information regarding the electrical properties of coal in the immediate vicinity of the waveguide open wing. In the case when the waveguide structure propagates a TEM-mode with no low frequency cut-off, say a parallel-plate waveguide[1] or a flushed-mounted coaxial cylindrical horn,[2] the method conceivably can be used for frequencies below 100 MHz when most other waveguides or antenna structures would not be effective. On the other hand, at higher frequencies, this method reduces to the reflectivity method discussed in section 5.6.

Figure 1 shows the calculated magnitude $|B_o|$ and phase (Arg B_o) of the reflection coefficient of an unflanged parallel-plate waveguide as a function of conductivity and permittivity of the sensing medium ($k_o = 2\pi/\lambda$ and λ is the free-space wavelength).

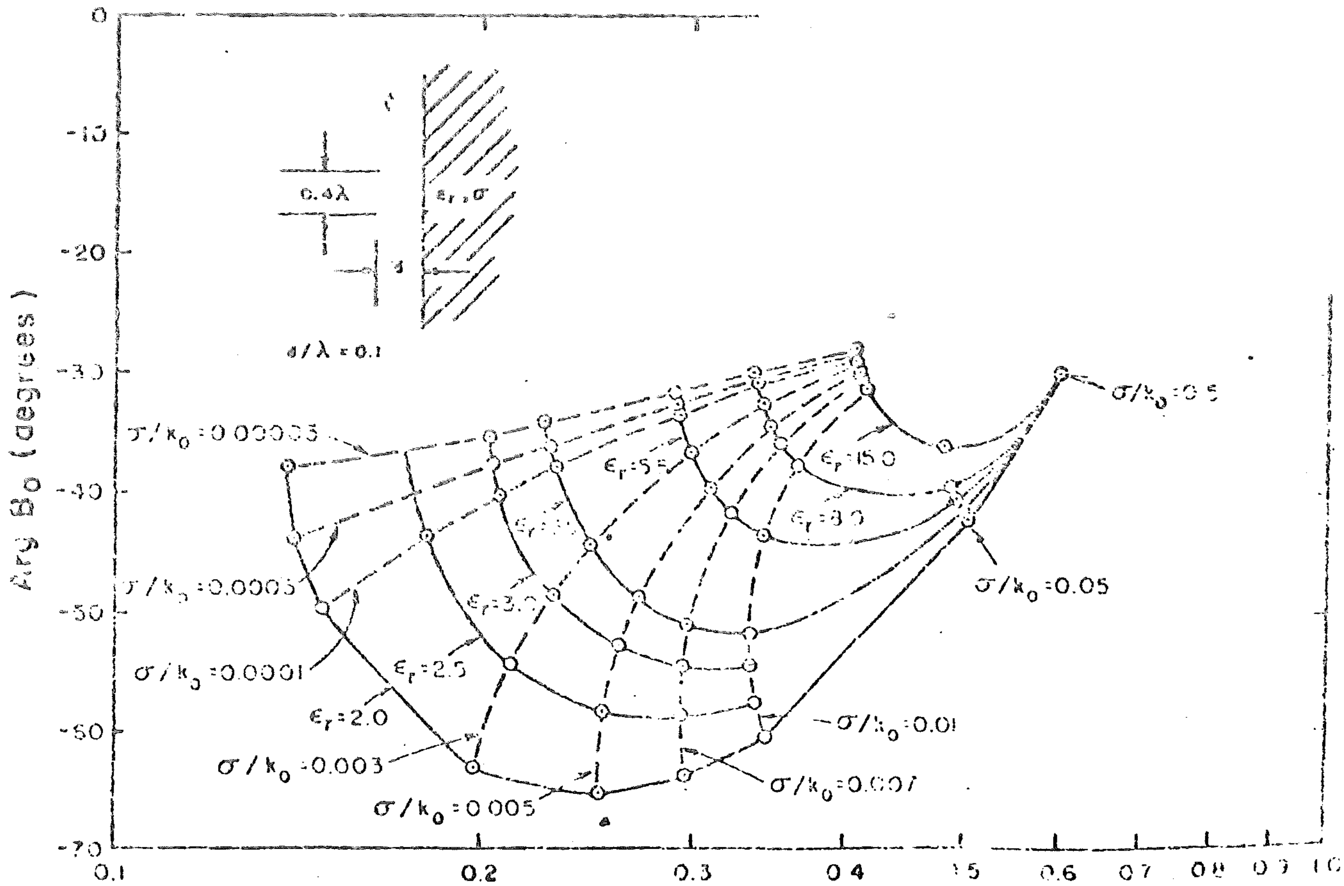


Fig. 1. Matched Reflection Coefficient of a Parallel Plate Waveguide Radiating into a Dielectric Half Space as a Function of the Dielectric Parameters (after Montgomery and Chang, 1974)

EVALUATION: The method, as applied at lower frequencies only has a limited sounding range proportional to the dimension of the aperture, rather than the skin-depth of the operating frequency. At higher frequencies, say 300 MHz, the method is comparable to the resonant antenna method both in terms of the complexity involved in the theoretical analysis, and the physical set-up. A flanged aperture actually has the added advantage of minimizing external interference. However the analytical work is not well developed at present. Although no data is available, the alignment problem appears to be less severe because only a single aperture is involved.

REFERENCES:

1. J.P. Montgomery and D.C. Chang, "Solution of electromagnetic problems using the modified residue calculus and function-theoretic techniques," Tech. Rept. no. 8, Electromagnetics Lab., Dept. of Elec. Eng., Univ. of Colo., Boulder, Colorado (1974).

2. D.C. Chang, "Input admittance and complete near field distribution of an annular aperture antenna driven by a coaxial line," IEEE Tran. Ant. and Prop., vol. AP-18, pp. 610-616 (1970).

4.6 Buried dipole methods

Frequency Range: 10 MHz-300 MHz

Physical Set-up: Requires bore hole drilling; contacting

Application: Established technique; graphical interpretation

DESCRIPTION: The self-impedance of an electrically-short buried dipole antenna can be influenced by the electrical properties of the surrounding medium.[1-3] Thus, by measuring the input resistance and/or reactance of the short bare-wire or insulated antenna probe, one can in principle determine the conductivity and permittivity of the coal medium. Alternatively, one can also use an insulated monopole placed in a bore hole with a finite ground screen lying on the coal surface. The arrangement is then the same as the resonant monopole method (section 5.2) except that the non-resonant property of a short probe is utilized.

Mechanical considerations for the design of such probes are discussed in the IEEE Standard 356-1974.[2]

EVALUATION: Both the buried dipole and monopole methods need to be placed in a bore hole inside the coal medium. Unlike the induction logging methods (section 4.3), good contact is necessary in either the insultated or the bare-wire arrangement. For low frequency application, these methods usually have a higher sensitivity than the aperture coupling method, but like all other contact methods they are more difficult to set-up physically. The buried monopole can alleviate some of the problems encountered in the design of a balanced, center-fed buried dipole antenna.

REFERENCE:

1. C.K.H. Tsao and J.T. deBettencourt, "Conductivity measurements in dissipative media with electrically short probes," IEEE Trans. Instrum.Measurement, vol. IM-16, pp.242-246 (1967).

2. J.T. deBettencourt, et al., IEEE Guide for Radio Methods of Measuring Earth Conductivity, (IEEE Standard 356-1974).

3. R.W.P. King and K. Iizuka, "An experimental study of the properties of antennas immersed in conducting media," Sci. Rept. No. 2, Cruft Lab., Harvard Univ., Cambridge, Mass. (Contract AF 19(604)7262), 1961.

4.7 Evaluation of methods

In the intermediate range up to a few megahertz, the two-loop induction method appears to be best suited for probing the bulk conductivity of coal. Not only is the physical set-up remote and noncontacting, but the inversion from measured data to coal parameters is also direct, and the technique has been successfully demonstrated at least in lower frequency operation. Only when frequency is high enough that displacement current in the coal medium can no longer be ignored, is there a need to modify the theoretical model with a quasi-static assumption, and even then, one only has to replace the direct inversion of measured data by a graphical interpretation. Thus, the only major restriction in extending the method to a higher frequency range would be the approximation of a physical loop of a finite size by a magnetic dipole. The sounding depth of a two-loop induction method is comparable to the separation between the two loops.

For an operating frequency above a few megahertz, the two-loop method reduces essentially to a special case of the more general electromagnetic interference scheme (section 4.2), as the coupling between the transmitter and receiver is becoming more complicated. Because the detailed make-up of the field components at the observation point is strongly dependent on the local characteristics of the medium being probed, one may argue that the measurement of the surface impedance or the wave tilt using composite probes (section 4.4) is a more effective way to determine the electric constants of the medium. However, the far-field requirement of the method severely limits its direct usage in a coal mine environment.

In addition to the bistatic arrangement which is based upon the mutual coupling of the transmitter and the receiver such as the two-loop method, the monostatic scheme using only a single probe can also be used when the frequency is above 30 MHz, The aperture-coupling method (section 4.5) appears to be an attractive alternative to the contacting buried dipole, or monopole (section 4.6).

CHAPTER 5

HIGH FREQUENCY TECHNIQUES

5.1 Open-wire transmission line (OWL) method

Frequency Range: 100 MHz-1 GHz

Physical Set-up: Intrusive (requires penetration into medium); contacting, portable

Application: Established technique, direct analytical inversion

DESCRIPTION: In this technique, a section of two-wire transmission line is inserted into the coal, and the input impedance is measured with both an open-circuit and a short-circuit termination. Since the characteristic impedance is $Z_o = \sqrt{Z_{oc} Z_{sc}}$ (where Z_{oc} and Z_{sc} are the open- and short-circuit impedances respectively), the characteristic impedance of the line in the coal can be determined from surface measurements. In the event that it is not possible to short the line in the earth, two open circuit measurements, the second with a section of line twice the length of the first, can be made. In this case, $Z_o = \sqrt{Z_{oc}(2Z_{oc2} - Z_{oc})}$ where Z_{oc2} is the second open circuit measured impedance. In either case, Z_o can in turn be simply related to the conductivity and permittivity of the coal. A typical result for a soil medium is shown in Fig. 1.

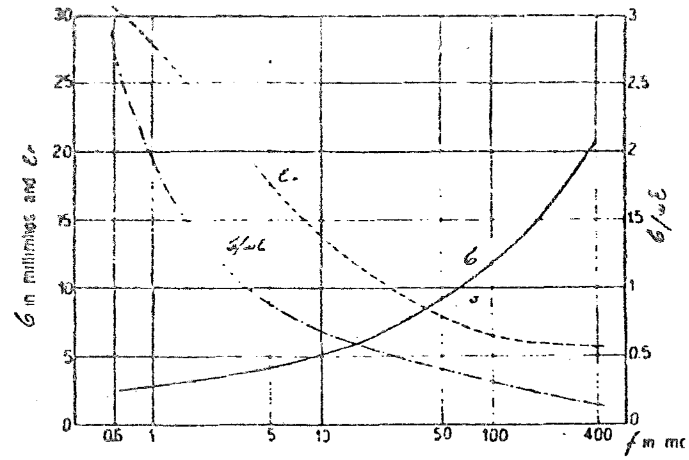


Fig. 1. Curves of the earth's conductivity, relative dielectric constant and dissipation factor as functions of frequency. (After Kirkscether, 1960)

EVALUATION: The main attractiveness of this method would appear to lie in the simplicity of inversion of the measured data. Impedance measurements on transmission lines can be done in a straightforward manner and can even be automated. On the other hand, not only is drilling required, but the wires of the line must make complete contact with the medium along their entire length. Any air gaps between the wires and the coal can drastically distort the results. Although correction for this effect is possible, it would sufficiently complicate the inversion scheme that only a graphical inversion could be done.

REFERENCES:

1. E. J. Kirkscether, "Ground constant measurements using a section of balanced two-wire transmission line," IRE Trans. Ant. Prop. v. 8, p. 307-312 (1960).

2. S. W. Maley, "Open- wire transmission line techniques," in Electromagnetic Probing in Geophysics (J. R. Wait, ed.) Boulder, Colo: The Golem Press, 1971, pp. 83-84.

5.2 Resonant buried monopole method

<u>Frequency Range</u>: 100 MHz - 1 GHz

<u>Physical Set-up</u>: Intrusive; contacting

<u>Application</u>: Established technique; graphical interpretation

<u>DESCRIPTION</u>: The probe consists of a coaxially driven monopole immersed in the medium, and operating at resonance. The measurable quantities are the resonant length normalized to the free space wavelength of the operating frequency (h_r/λ_o), and the input resistance (R_r) at resonance. These two quantities are expressible in terms of the relative dielectric constant and the loss tangent and are solved for graphically (see Fig. 1). Reasonable agreement between the results of soil measurements <u>in situ</u> and in the laboratory using a sample holder were demonstrated.

<u>EVALUATION</u>: Similar to the open-transmission-line method, good contact between the probe and the medium is most essential to the success of the measurement. If the borehole were filled with a liquid to ensure good contact, the arrangement would act as a coaxial line, and then, except for the special case when the electrical properties of the liquid are very similar to that of the surrounding media, the resonant length of the antenna would become less sensitive to the external medium.

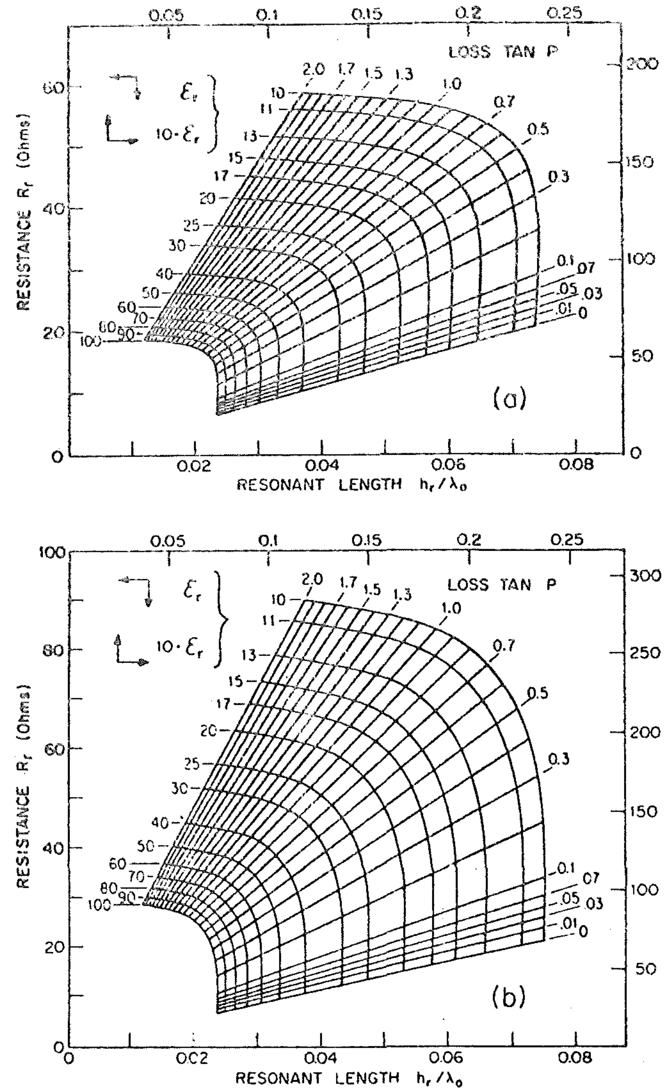


Fig. 1. Parametric representation for the resonant length and resistance at resonance of a cylindrical dipole antenna in a dissipative medium for fixed values of relative permittivity ϵ_r and loss tangent p with (a) $\Omega = 2 \ln(2h/a) = 8.0$ and (b) $\Omega = 11.0$. (After Smith and King, 1974)

REFERENCE:

1. G. S. Smith and R. W. P. King, "The resonant linear antenna for measuring the in situ electrical properties of geological media." J. Geophys. Res. v. 79, pp. 2623-2628.

5.3 Resonant loop or dipole methods

Frequency Range: 100 MHz - 1 GHz

Physical Set-up: Remote, non-contacting

Application: Potentially feasible technique; graphical interpretation

DESCRIPTION: A horizontal loop or dipole antenna of finite dimensions is placed in the air above the coal surface. The influence of the medium on the antenna response can be accounted for accurately from the solution of an integral equation for the antenna current. Optimum sensitivity to the unknown medium parameters is obtained when the antenna is operating near resonance, and when its height above the medium is electrically small. The Argand diagram for the input admittance of a near-resonant loop placed 0.1 wavelength above the surface, and operating at a frequency for which the circumference of the loop is one wavelength, is shown in Fig. 1. By measuring the input admittance, the value of the conductivity and permittivity of the coal near the surface can be obtained directly from such a diagram.

Useful information can also be extracted by measuring the resonant frequency (at which the input conductance attains a maximum) and the Q-factor at this resonance. In this case, the cosinusoidal component of the current distribution is dominant, and simplification of the analysis occurs to such an extent that it may be possible to invert the measured data analytically to the coal properties rather than using an Argand diagram.

A similar antenna structure which can also be used effectively is that of a resonant horizontal dipole. While the analysis differs somewhat from the loop, the principle of operation is the same in both cases. A typical response of input resistance vs. antenna height normalized to the wavelength is shown in Fig. 2 for several values of permittivity. An Argand diagram similar to Fig. 1 can, in principle, be obtained for this structure as well.

In addition, a vertical dipole antenna is also an alternative arrangement. The influence of the coal properties on the antenna response is usually not as strong as in the horizontal case, and thus the vertical arrangement is somewhat less attractive.

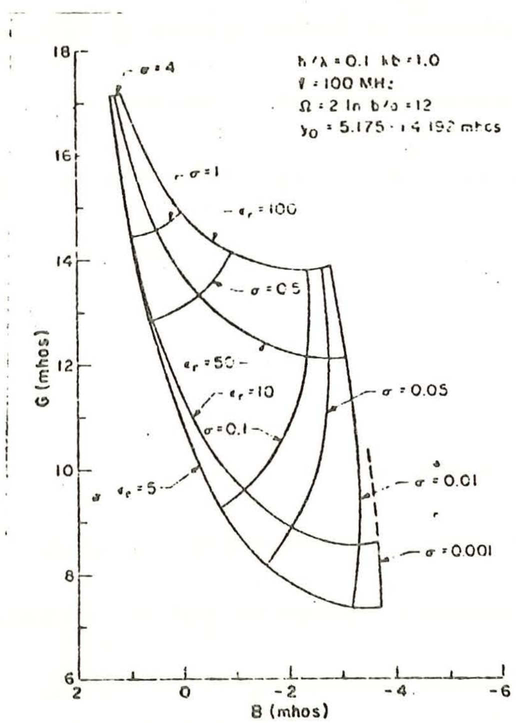


Fig. 1 Argand diagram for input admittance (G + iB) of resonant loop over homogeneous earth. (After Chang, 1973)

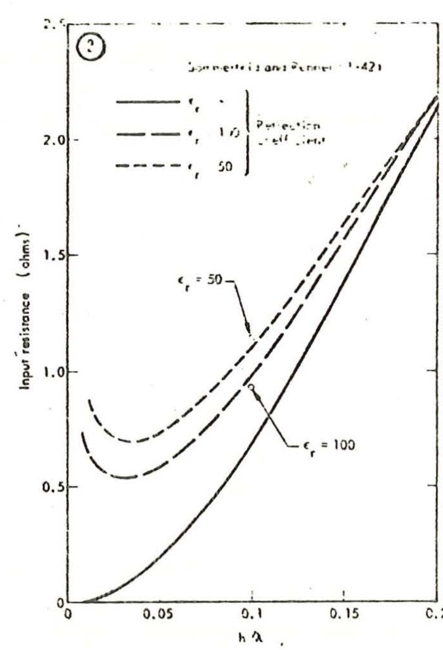


Fig. 2 Input resistance of horizontal dipole 0.1λ long located a distance h above a purely dielectric ground (dielectric constant ϵ_r). (After Miller et al. 1972.)

EVALUATION: Although the accuracy of the resonant antenna techniques has not been experimentally verified, they do appear to be viable both from the viewpoint of ease of installation and from that of measurement sensitivity. Compared to both the monopole technique (Section 5.2) and the open-wire line method (Section 5.1), the major advantage seems to be the fact that no direct contact with the coal surface is necessary. The impedance (or admittance) measurement is once again straightforward, and can be automated.

Because of its greater sensitivity, the horizontal configuration also offers the least susceptibility to errors in alignment.

REFERENCES:

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2. E.K. Miller et al., "Analysis of wire antennas in the presence of a conducting half-space," Canad. J. Phys. v. 50, pp. 2614-2627 (1972).

3. R.F. Proctor, "Input impedance of horizontal dipole aerials at low heights above the ground," Proc, IEE (London), part III, v. 97, pp. 188-190 (1950).

4. R.G. Olsen and D.C. Chang, "Analysis of semi-infinite and finite thin-wire antennas above a dissipative earth," Radio Science v. 11, pp. 867-874 (1976).

5. D.C. Chang and J.R. Wait, "Theory of a vertical tubular antenna located above a conducting half-space, IEEE Trans. Ant. Prop. v. 18, pp. 182-188 (1970).

5.4 Guided Wave propagation method

Frequency Range: 100 MHz - 10 GHZ

Physical Set-Up: Remote, non-contacting

Application: Potentially feasible technique; direct interpretation

DESCRIPTION: The propagation characteristics of a wave guiding structure can be strongly influenced by the coal properties even if it is only placed in parallel to the air-coal interface. Thus by measuring the propagation constant (β) and the attenuation constant (α) of such a structure, one can in principle extract the information regarding the conductivity (σ) and permittivity (ε) of coal. In particular, if the structure of a long thin-wire located in the interface is used,[1-3] the complex propagation constant of the wire, $\beta - j\alpha$, is given approximately by an average between the wave numbers of the air and the coal, $\beta - j\alpha = 1.48 \times 10^{-2} f [1 + \varepsilon - j1.8 \times 10^{4} \sigma f^{-1}]^{\frac{1}{2}}$ where f is the operating frequency in MHz. Thus, the inversion of the measured data to the electric properties of coal is immediate. Simple results can also be expected for a two-wire transmission line located on the coal surface.

At least three measurement schemes can be used conveniently for determining α and β. The first one employs the so-called FM-CW technique which we will discuss in some detail in section 5.6. By using a thin wire of adjustable length, one in principle can determine the β-value from the frequency shift in a spectrum analyzer when the reflected signal is beat against the incoming signal at the input end of the wire using a crystal mixer. The α-value on the other hand is obtained from the relative magnitude of the beat signal. The success of such a technique has been demonstrated when used to detect roof thickness in a coal mine environment provided internal resonance of the measuring system can be eliminated.

The second technique employs basically a homodyne system.[4,5] The quantity to be measured, as in the FM-CW measurement, is the propagation constant of the wire. In this technique, however, a signal is fed to the wire, which is scattered by a modulating scatterer which is movable along a section of the wire. The wire itself is terminated with a matched load. The scattered modulated signal returns and is mixed with a reference unmodulated signal, detected and measured through a VSWR meter, (Fig. 1). The phase constant is determined by the separation between nulls in the output as the scatterer is moved, while the attenuation constant is found from the slope of the envelope of the peaks, (Fig. 2).

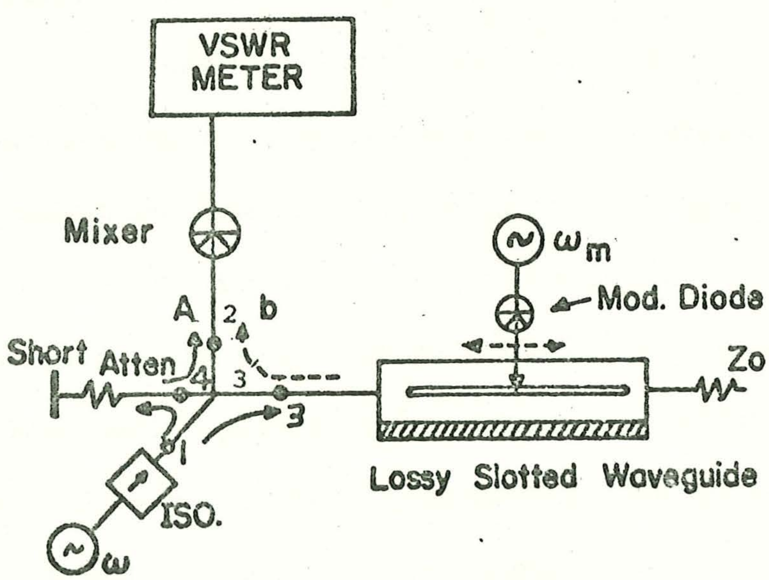

Fig. 1. Pseudo-double channel coherent system for measuring the attenuation (α) and wavelength (λ_g) in a lossy waveguide. (After King and Knudson, 1976)

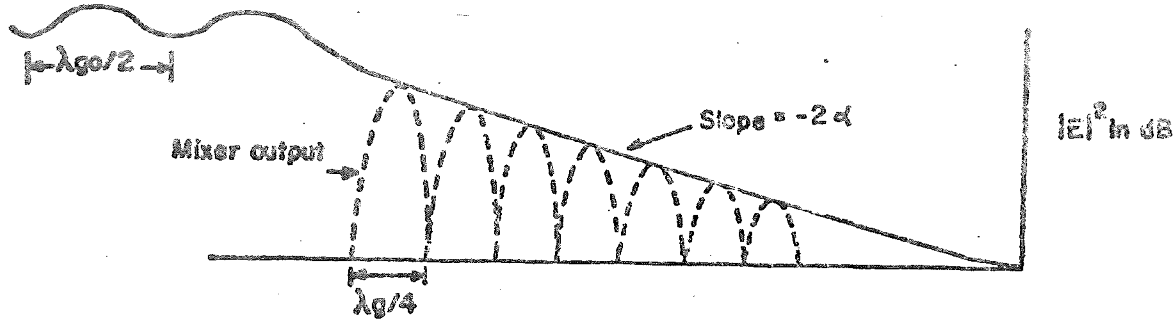

Fig. 2. Electric field distribution inside the lossy waveguide, and a typical output of the coherent detector versus position of the scattering modulated probe. (After King and Knudson, 1976)

No experimental data on this configuration are available, although the application to a closed metallic waveguide for the detection of the electric properties of a lossy dielectric sample appears to be successful. Some difficulty is to be expected in obtaining a matched load on the end of the wire, since the characteristic impedance is quite sensitive to the properties of the coal, which are, of course, unknown. However, instrumentation appears to be simpler than the FM-CW technique, and less sensitive to system noise problems.

A third technique[6] is that of wire-guided transients in a closed loop recirculation circuit (Fig. 3). Here a pulse generator sends out narrow pulses around a closed loop of the wire, and another is sent out only when the previous pulse is detected. The resulting feedback loop has a pulse repetition rate determined by the time delay of the pulse traveling around the loop. If the length L of loop is known, then a group phase constnat β_g at the pulse center frequency f_c can be calculated directly from the measured repetition frequency f_r as

$$\beta_g = \left(\frac{2\pi}{L}\right)\left(\frac{f_c}{f_r}\right)$$

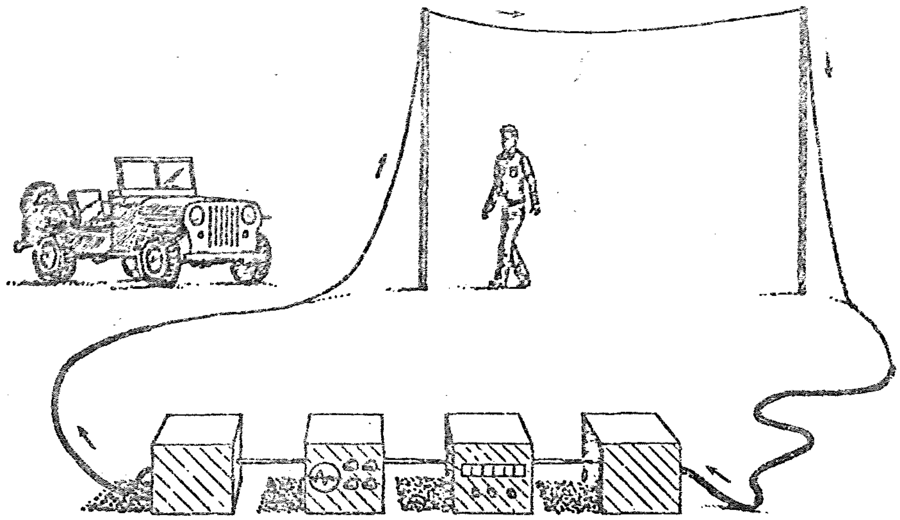

Fig. 3. Sketch of a closed-loop pulse rate sensing device. The propagation speed of recirculating transients on an unshielded sensing wire is changed by material objects that approach the sensor. The signal travels from a 2 V source, over the sensor line to a detector amplifier (arrows) where it triggers a new signal. A frequency counter indicates signal repetition rate changes, caused by a car or a person. (After Gerharz, 1977)

If the dispersion of the medium can be neglected (or if a particular dispersion model can be assumed, such as one of constant conductivity) this gives β (or, respectively, a relation between β and α). By an amplitude measurement at the detector, α can be determined as in the other technqiues. The slightly more complicated inversion for a dispersive medium could be a drawback, but the additional complexity for the conductivity model is not impossible to deal with.

EVALUATION: The main attractiveness of these techniques appear to be their ability to invert directly the measured data to the electrical parameters of coal. Since one measures basically the accumulated propagation effect along the line, local variation tends to be averaged out. It is also most compatible to the actual communication systems that might be adopted in this frequency range (for instance, the leaky coax). Although some preparatory work on the coal surface may be necessary in order to position the wire properly, it does not have the kind of installation problems that any non-remote, contacting scheme like the open transmission line method (section 5.1) has. However, instrumentation could be more complicated than the impedance measurement.

Since the relationship of measured data to coal parameters is insensitive to the geometrical parameters, this method could offer great immunity to differences in orientation, but no measured data are yet available to confirm this.

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1. B.L. Coleman, "Propagation of electromagnetic disturbances along a thin wire in a horizontally stratified medium." Phil. Mag. ser. 7, v. 41, pp. 276-288 (1950).

2. J.R. Wait, "Theory of wave propagation along a thin wire parallel to an interface," Radio Science v. 7, pp. 675-679 (1972).

3. D.C. Chang and J.R. Wait, "Extremely low frequency (ELF) propagation along a horizontal wire located above or buried in the earth," IEEE Trans. Commun. v. 22, pp. 421-426 (1974).

4. R.J. King and R. Knudson, "Attenuation and wavelength measurement of lossy waveguides," Electron. Lett. v. 12, pp. 560-562 (1976).

5. R. Knudson and R.J. King, "A microwave system for measuring complex dielectric constants," Rept. ECE-77-1, Dept. Elec. Eng. Comp. Eng., Univ. of Wisconsin, 1977.

6. R. Gerharz, "Wire-guided transients as remote sensing agents for material objects," Int. J. Electron. v. 42, pp. 449-455 (1977).

5.5 Direct transmission method

Frequency Range: 300 MHz and up

Physical Set-up: Contacting or non-contacting

Application: Direct interpretation; established technique but has limited application

DESCRIPTION: An electromagnetic wave propagating through a finite thickness of medium suffers attenuation and delay which can be related directly to the conductivity and permittivity of the medium if the thickness is known. Provided two sides of the medium are accessible, (for instance one frequently encounters pillars of finite length in a typical coal mine environment), transmitting and receiving horns can be set up at each end, and, after suitable calibration, measurement of the attenuation constant (α) and the propagation constant (β) be made. Since coal in this frequency range acts more like a dielectric material with a very small loss tangent, the conductivity of coal is then directly obtained from the expression $\alpha/(\epsilon_0 \pi)$, and the permittivity from $.048 f^{-1} \beta$ with f being the operating frequency in GHz. In some cases, a finite transmission path can be established by burying both the transmitter and the receiver in coal.[2] The scheme then becomes a non-remote one very much the same as the logging methods used in the low and intermediate frequency ranges. (See Sections 3.2 and 4.3)

Several measurement techniques can be employed in determining the propagation and attenuating constant. In a continuous-wave (CW) fixed frequency system, the magnitude and the phase of the transmission can be measured. In an FM-CW system, the magnitude and beat frequency of the transmitted signal can be measured (see section 5.6 for the description of such a system; the reference can be chosen as the incident signal). Finally, in the case of a time-pulse system, the time delay and the attenuation of the transmitted signal can be measured in the same way as in a TDR (time-domain reflectometer) system.[3] Broadband resistively-loaded antennas in this case can be used to replace the transmitting and receiving horns for operating frequencies below the gigahertz range.

EVALUATION: Although the method provides a direct inversion of the measured data, it is most attractive mainly in the case when the coal pillars are easily accessible. When used in a borehole situation, the scheme may suffer from contact or air gap problems similar to those encountered with the buried monopole (section 5.2) or open-transmission line (section 5.1) schemes. Degradation would then result from a failure to properly launch the electromagnetic wave. Another difficulty occurs with increasing thickness of the pillars. For a loss tangent of 0.1 and a pillar 10 m wide, an operating frequency of 100 MHz would be needed to limit the attenuation of the transmitted signal to - 10 dB. At such low frequencies, it becomes difficult to find antennas which will efficiently launch and receive the test signals.

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2. G.C. Rose and R.S. Vickers, "Transient response of resistively loaded cylindrical antenna," Int. J. Electron. v. 36, pp. 479-486 (1974).

3. G.D. Cormack and R.P. Manning, "Time domain reflectometer return loss measurements," IEEE Trans. Inst. Meas. v. 18, pp. 184-188 (1969).

5.6 Reflectivity methods

Frequency Range: 1 GHz and up

Physical Set-up: Remote, non-contacting

Application: Established technique; direct interpretation or graphical interpretation

DESCRIPTION:

A) Direct CW Reflectivity method: When an electromagnetic plane wave is incident from air onto the coal surface, part of the energy will be transmitted into the coal while the remaining part is reflected. Thus one may determine the electrical properties of coal simply from the measurement of the magnitude (R) and phase (θ) of the reflection coefficient of such a plane wave. For a normal incidence, the conductivity (σ) and permittivity (ϵ) of coal are obtained from the relationship, $(\epsilon - j18f^{-1}\sigma)^{\frac{1}{2}} = (1-\hat{R})/(1+\hat{R})$ where $j = (-1)^{\frac{1}{2}}$; $\hat{R} = R \exp(j\theta)$. A direct inversion is also possible for the case of oblique incidence, corresponding to a bi-static instead of a mono-static arrangement.

In the case when the radar transmitter has to be placed close to the coal surface, a near-field coupling effect of the coal with the antenna has to be accounted for in order to insure correct interpretation of the measured results. The method in this case essentially reduces to the near-field coupling method discussed in section 4.4.

B) Relative reflectivity method: Some of the near-field coupling problems can be alleviated when a relative change of reflectivity, instead of its absolute value, is measured. In the coal mine situation, it is typical that the coal seam usually is backed by a highly reflective material such as slate.

Table 5.6.1

Bruceton Mine

Test Area	Physical Thickness of Layer	Measured Dielectric Constant
1	17.8 cm	6.4
2*	27.9 cm	5.6
2*	27.9 cm	6.3
3	40.6 cm	5.6

*Different points in that test area

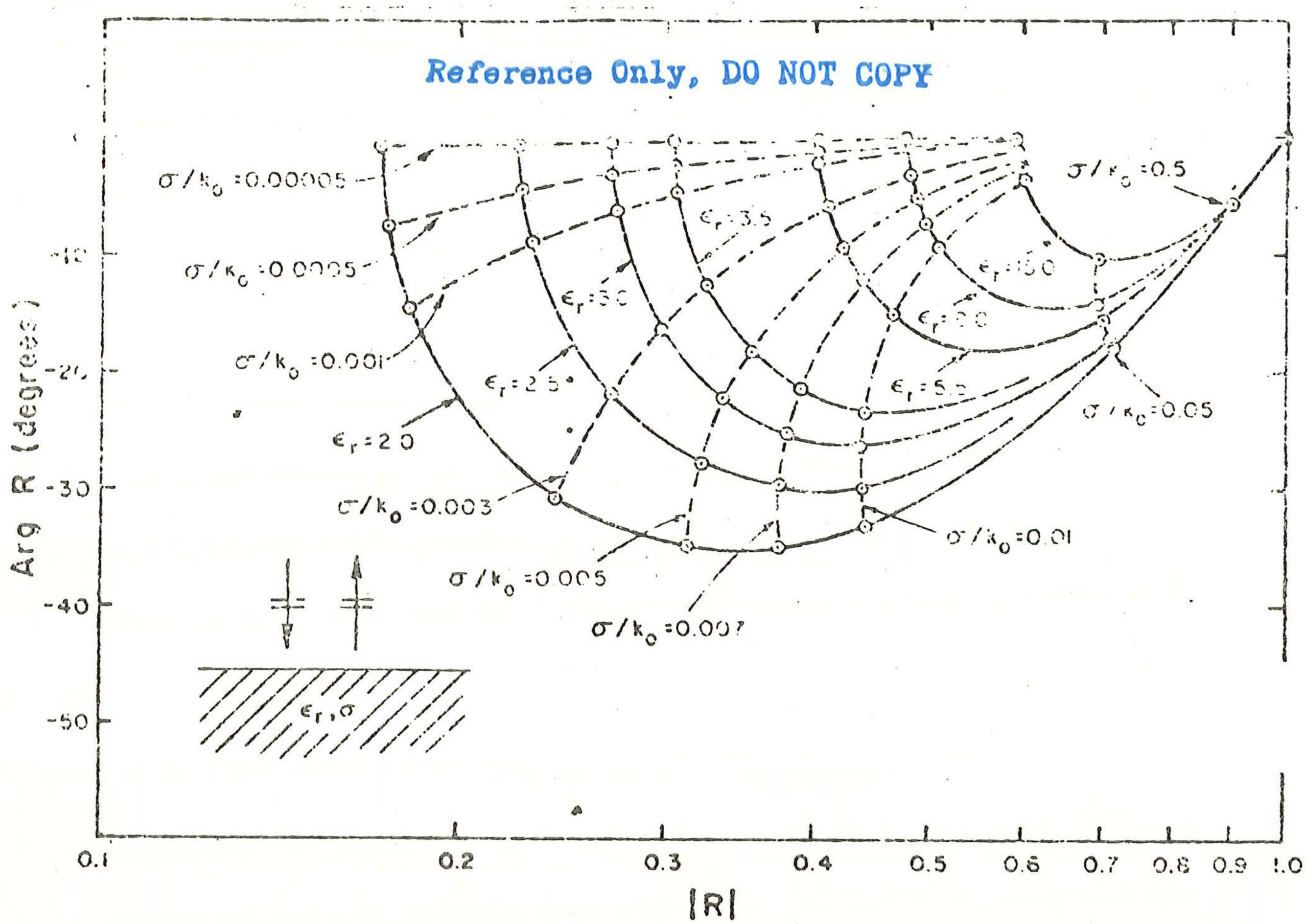

Fig. 1. Fresnel reflection coefficient for a plane wave of normal incidence (After Montgomery and Chang, 1974)

By comparing directly the delay and decay of return signals from coal seams of different thickness, one may deduce the permittivity and conductivity of coal from the known difference in the thickness. Such a measurement can be done on a real time basis with a TDR (time-domain-reflectometer), or on a frequency basis with an FM-CW radar or a sweep-frequency radar.

FM-CW System. Table 5.6.1 shows the measured dielectric constant of coal in Bruceton Mine by NBS personnel employing an FM-CW system.

The antenna arrangement consists of a system of bistatic electromagnetic horns. The sensing signal is obtained by sweeping linearly over the bandwidth (1-2 GHz) every 7.48 milliseconds. Half of the signal travels through a coaxial line directly to the mixer and serves as a reference while the other half radiates through the transmitting horn. The return signal arriving at the receiver horn is composed of the various reflected parts of the initial sensing signal. In the mixer the instantaneous rf-frequencies of the reference and the reflected sensing signals differ if the electrical lengths traveled are different. This results in a beat frequency proportional to the time-derivative of the reference signal times the difference between the electrical lengths traveled by the test signals and the reference. The latter is given as a product of the coal permittivity and twice the physical depth of the layer.

EVALUATION: While direct reflectivity methods provide a simple scheme for the detection of coal seam properties, a high-gain antenna operating at a reasonably large distance away from coal surface is needed in order to avoid elaborate calibration due to the near-field coupling effect. For a simple antenna such as a parallel-plate horn or a coaxial horn, a graphical interpretation is possible even when the antenna is placed right at the coal surface (section 4.4), and as in the direct transmission method, this method is relatively insensitive to angular misalignments.

The FM-CW radar and the sweep frequency radar allow the direct inversion of relative reflectivity measurements. However, these do need preparation on the coal surface in order to yield coal seams of different thickness.

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3. J.R. Lundien, "Determining presence, thickness and electric properties of a stratified medium using sweep frequency radar," Tech. U.S. Army Eng. Waterway Exper. Station, Vicksburg, Miss. (1972).

4. J.P. Montgomery and D.C. Chang, "Solution of electromagnetic problems using the modified residue calculus and function-theoretic techniques," Tech. Rept. no. 8, Electromagnetics Lab., Dept. of Elec. Eng., Univ. of Colo., Boulder, Colorado (1974).

5. C.T.A. Johnk, Electromagnetic Fields and Waves. New York: Wiley, 1973.

5.7 Evaluation of Methods:

Detection in the frequency range from 100 MHz to 1 GHz is highlighted by schemes that are based upon either a monostatic antenna arrangement: resonant buried monopoles (section 5.2), resonant horizontal loops and dipole antennas (section 5.3); or a guided-wave phenomenon: open transmission-lines (section 5.0), guided wave propagation (section 5.4); in contrast with basically bistatic arrangements in low frequency detection below MHz. While most of the established techniques (sections 5.1 and 5.2) require direct contact in a bore hole, a number of potentially feasible techniques (sections 5.3, 5.4) involve only remote detection above or on the coal surface. In the case of resonant loop and dipole antenna methods, inversion of measured data can be carried out only graphically by matching with predetermined curves obtained from the corresponding theoretical analyses. However, in the guided wave propagation method, direct analytic inversion of the measured data can be performed in a straightforward manner. Both methods are attractive when compared with the established contacting methods.

For frequencies higher than 1 GHz, most of the bi-static and/or monostatic radar techniques can be employed for the detection of either the transmission or the reflection of plane waves from the coal medium. While both schemes are noncontacting and remote, measuring the transmission of a plane wave is practical only in a situation when near-by coal pillars can be conveniently utilized. Inversion of measured data is typically direct and straightforward.