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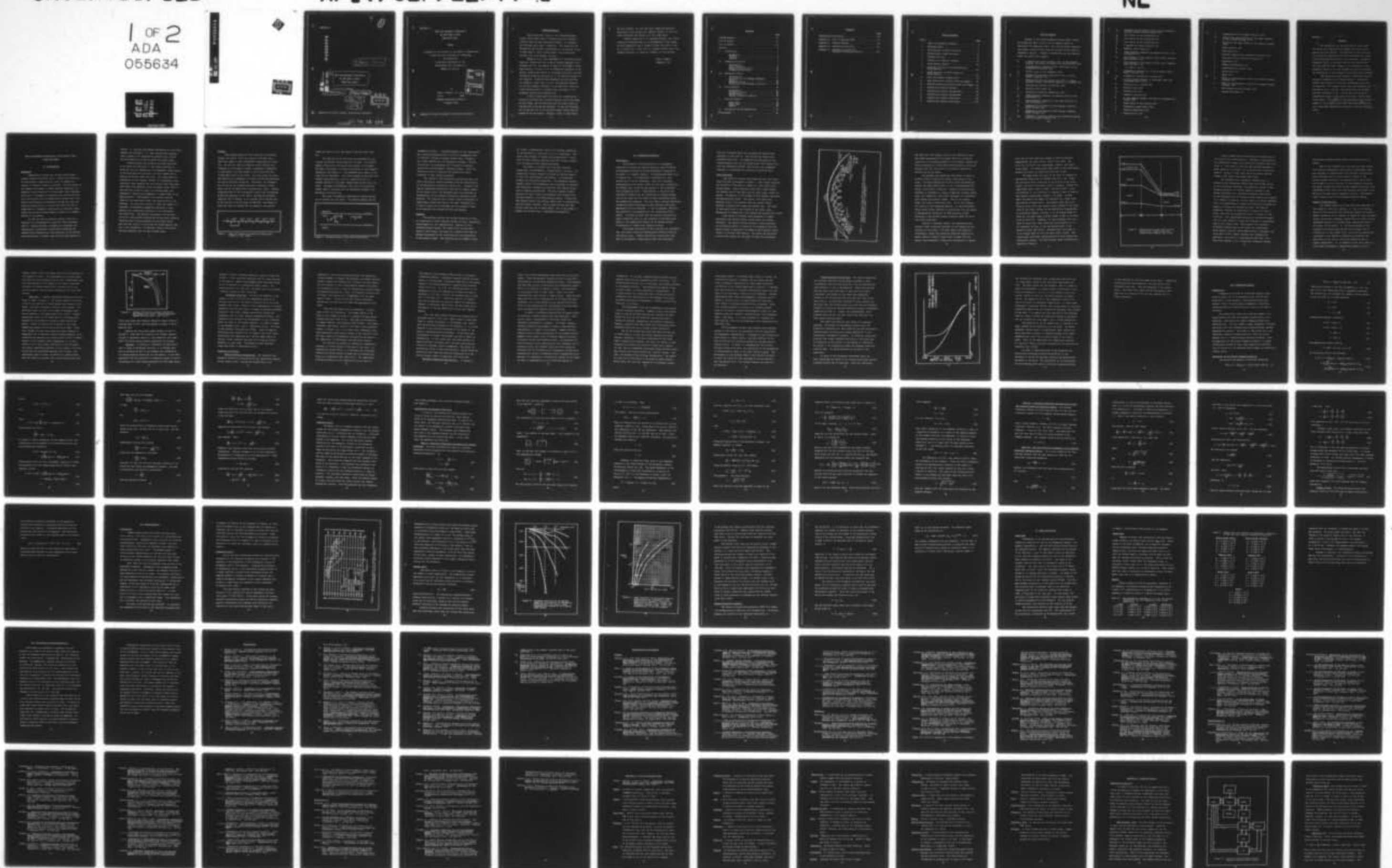

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BELOW THE OCEAN.

THESIS

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10 Ruth B. Kaplan
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VERY LOW FREQUENCY PROPAGATION
IN THE EARTH'S CRUST
BELOW THE OCEAN

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by
Ruth B. Kaplan, B.S., B.A.
2d Lt USAF

Graduate Engineering Physics
December 1977

Acknowledgements

This project was unique in its interdisciplinary nature, which meant that it required more from everyone involved than the more specialized theses. To everyone who willingly gave more, I thank you. All credit for the formulation and original coordination of the project belong to Capt James E. Lord, without whom I would never have started, much less finised, the work.

Thanks go to Dr. Phil Hansberger for obtaining several important translations and original Russian-language source documents for me. My sponsor at Rome Air Development Center, Capt Kenneth E. Wilson, is to be thanked for agreeing to the project, getting me started in the proper direction, and then letting me follow my instincts as to the specific conduct of the research. Professor Donn Shankland not only provided the computer library used to solve the waveguide problem, but he also assumed virtually a co-advisor role, which was a most welcome source of guidance and assistance in the waveguide analysis and computer work.

I wish to thank Capt Bill Davis for accepting the position of advisor for a project that was still very shaky at that stage, and for providing just the right amount of constructive criticism and guidance. He had the foresight not to push me, but to let me drive myself toward goals he helped me set for myself. Finally, I want to thank Molly and Bill Bustard, not only for their highly professional assistance in the library and computer center, but also for their friendship and support over the rough spots.

Special thanks go to Dr. Meryland Nestell, who, after teaching me advanced math as an undergraduate, then taught me more geophysics than I thought I would ever need to use. As it turned out, I used both to a greater extent than I had imagined possible, in doing the research on this project.

Ruth B. Kaplan

December, 1977

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List of Symbols

Because of the interdisciplinary nature of this study, an attempt was made to find a set of symbols usable by physicists and engineers alike. This was not always possible and usually conflicts were resolved in favor of the author's background, physics. Numbers in parentheses are the equation where the symbol first appears.

$\bar{A}$	A generalized vector quantity (10); in the computer program, the matrix of conductivity coefficients (106).
A	Electromagnetic impedance (27); coefficient of the conductivity function (96).
A_o	Initial value of the impedance (63).
B	Conductivity function coefficient (96); in noise theory, bandwidth (97).
C	Conductivity function coefficient (96); in communications theory, information capacity of a system (98).
D	Conductivity function coefficient (96).
$\bar{E}$	Electric field vector (1).
E	Conductivity function coefficient (96).
E_x	Depth-dependent component of electric field in the x-direction (1).
E_z	Depth-dependent component of the electric field in the z-direction (1).
E_+	Component of the electric field having a positive phase constant (56).
E_-	Component of the electric field having a negative phase constant (56).
E_{x+}	Component of electric field in the x-direction having a positive phase constant (61).

E_{x-}	Component of the electric field in the x-direction having a negative phase constant (61).
$\bar{e}_x$	Unit vector in the x-direction (1).
$\bar{e}_y$	Unit vector in the y-direction (2).
$\bar{e}_z$	Unit vector in the z-direction (1).
f	A generalized scalar quantity (10).
$\bar{H}$	Magnetic field vector (2).
H_y	Depth-dependent component of magnetic field in the y-direction (2).
H_+	The component of the magnetic field with a positive phase constant (50).
H_-	The component of the magnetic field with a negative phase constant (50).
i	-1 = exp i(/2) (1).
k	Propagation constant (1); in noise theory, Boltzmann's constant (50).
k_o	Propagation constant for a vaccum (77).
$\bar{L}$	In the computer program, an arbitrary lower left triangular matrix (107).
N	Total noise in a system (98).
N_r	Receiver noise (99).
N_t	Thermal noise (97).
P	Algebraic constant (87).
$\bar{S}$	In the computer program, the matrix of conductivity values (106).
S	Signal power at the receiver (98).
S_o	Transmitted signal power (100)
T	Absolute temperature (97).
u	Phase function (33).

y	Imaginary part of the phase function (90).
YS	Value of the pahse function at the upper boundary in the computer program (104).
$\bar{Z}$	Matrix for the depth values in the computer program (106).
α	Phase constant (53).
δ	Skin depth (42).
ϵ	Electric permittivity (dielectric constant) (4).
ϵ'	Real part of the dielectric conetant (5).
λ	Eigenvalue (41).
μ	Magnetic permeability (6).
ξ	Proportionality constant (33).
σ	Conductivity (3).
Φ	Phase (11).
Φ_+	Phase of electromagnetic field with a positive phase constant (50).
Φ_-	Phase of electromagnetic field with a negative phase constant (50).
$\varkappa$	Real proportionality constant (75).
	Angular frequency (1).

 E sub x/H sub y,

Abstract

The feasibility of using the earth's crust under the oceans as a communications channel for very low frequency waves was studied. The structure of the crust and its electrical properties were used to evaluate the conductivity-depth profiles found in the literature. Using the impedance, E_x/H_y, a new phase function was defined that not only made the phase changes at the boundaries of the waveguide explicit, but also allowed the use of a computer for calculation of the propagation and attenuation constants.

The system noise was assumed to come from two main sources: atmospherics and thermal effects. Calculation showed that beneath the ocean the atmospheric noise could be neglected. The thermal noise within the waveguide was calculated to be -162 dBm. The attenuation for the TM_{10} mode was calculated to be -1.35 dB /km, thus allowing a transmission range of only about 163 km for 1 kW of transmitted power. The conslusion was that despite the aesthetic appeal of the idea the crust under the ocean was feasible as a long-range communications channel at VLF for the TM_{10} mode.

TM sub 10

c

not

VERY LOW FREQUENCY PROPAGATION IN THE EARTH'S CRUST BELOW THE OCEANS

I. Introduction

Background

Communication systems are the key links between command centers and control units. Without the continuity of uninterrupted communications, unity of command and control of resources cannot be achieved. With the advent of the nuclear environment in modern wartime situations, the potential total disruption of conventional radio communications due to ionospheric disturbances has created the need for a more secure form of communications system (Ref 1:20). Direct electromagnetic transmission through the crust provides the possilility of a system that would not only be independent of ionospheric conditions but also have transmitter and receiver hardened against attack as an inherent feature of the system.

In 1961 the idea of using the earth's crust as a waveguide for electromagnetic waves was first introduced (Ref 2). Numerous studies, attempting to determine the feasibility of using such a hypothetical waveguide for communications purposes have been published in the succeeding sixteen years. However, they have two main aspects in common: 1) they all deal almost exclusively with the crust beneath the continents; 2) they conclude that although such a system is not precluded by present data, neither can the feasibility of such a system be clearly shown.

Because present war scenarios envision operations on at least two continents, it has become important to study not only the feasibility of lithospheric communication on the North American continent, but also between North America and Europe, under the ocean. Two years after the publication of the original concept of lithospheric communication, there appeared the only article found that dealt exclusively and explicitly with the oceanic crust (Ref 3). This was more along the lines of a concept paper, and presented no theoretical background to support much of the data presented. Unfortunately this article, like the others on the continental crust, was inconclusive in its findings. The only other article to treat the subject of suboceanic lithospheric propagation mentioned it only passing, as a contrasting situation to the continental case (Ref 4:34). One possible explanation for the lack of work on this specific problem may be that until recently there has been no data available on the oceanic crust, and even now, there is little data for depths greater than one or two kilometers. For whatever reason, the problem has been neglected over the last sixteen years.

Problem

The primary purpose of this study was to determine whether the oceanic crust can sustain a VLF wave over a sufficient range to make lithospheric communications feasible. The VLF and lower LF range was chosen because this frequency is low enough to permit lithospheric propagation to some extent, but high enough to avoid noise from the natural ELF fields in the earth. The crust under the ocean was modelled as a waveguide of infinite horizontal dimensions and finite vertical dimensions. Vertically, the waveguide was defined by the seawater-saturated sedimentary strata above, and by the Mohorovicic discontinuity, below. Lateral discontinuities in the lithospheric strata were disregarded, as was the curvature of the earth. Although the frequency range for VLF is defined to be 3-30 kHz, some work was done in the low end of the LF range (30-300 kHz) (see Figure 1). Since the ocean of concern was the Atlantic, the desired

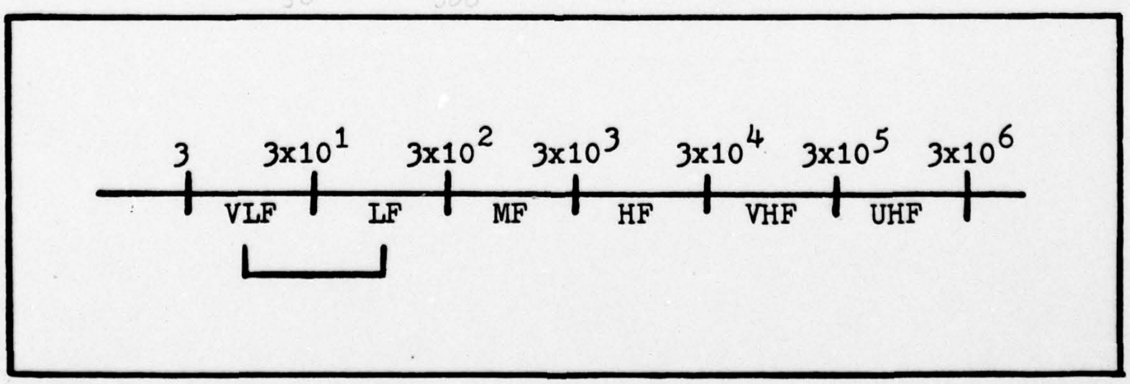

Figure 1. Scale of frequency categories showing range treated in this study.

range was taken to be on the order of 4500 km (about 2800 mi).

The conductivity of the crust was modelled as a continuous but rapidly varying function of depth. The electromagnetic waves within the guide were assumed to be planar TM waves, travelling in a direction parallel to the waveguide boundaries (see Figure 2). The waveguide had a depth on the order of one wavelength. The lower boundary of the guide was defined electrically by a rise in conductivity due to thermal effects of the higher temperatures deeper within the crust. Although not documented, this rise in conductivity seemed often to coincide with the geological boundary, the Mohorovicic discontinuity.

The total lithospheric communications system problem can be divided into two parts: the antenna problem and the

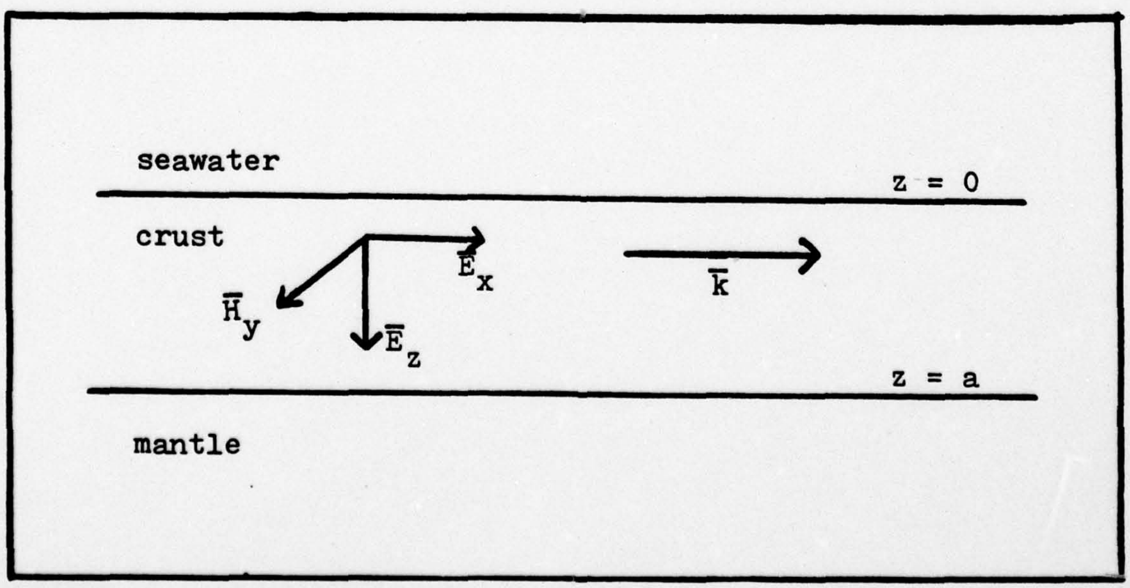

Figure 2. Waveguide model of the crust and TM wave.

propagation problem. A detailed analysis of the transmission and receiving antennas would be futile if propagation were not feasible through the medium between them. Therefore this study treated only the propagation problem. The key factors were the propagation and attenuation constants derived from electromagnetic waveguide theory. These constants were used to calculate the transmission power necessary to make reception possible.

The results of the attenuation calculations were, by their very nature, heavily dependent upon the peculiarities of the particular conductivity profile used. Because of the lack of dependable conductivity data for the deeper regions of the oceanic crust, the waveguide model was developed as independently of the specific conductivity profiles as was possible. The objective was to enable future researchers to simply apply newly-found data to the model developed here, so that it would not be necessary for the waveguide theory to be reworked just because the data was changed.

Approach

This problem involved the use and evaluation of data and techniques in three different fields of study: geophysics, electromagnetics, and communications. Because of this interdisciplinary nature, this report will discuss these topics in more detail, and often on a simpler level than is usually encountered by the individuals who are specialists in the various fields. The intention was to attempt to give the reader a comprehensive view of the problem, regardless of the profession in which she or he is a specialist. The report also attempts to enable the non-specialist to read only the less technical portions and still obtain a comprehensive summary of the research performed.

The report is divided into four main sections: geophysical, electromagnetic, communications, and data. The Geophysical Analysis chapter discusses the various aspects of the crust that affected the problem: its structural, thermal, and conductive properties. The Waveguide Analysis chapter derives the mathematical tools necessary to calculate the attenuation constants and describes the computer method used to perform calculations. The Noise Analysis chapter presents the basic theory of atmospheric and thermal noise, and their effect on the communications system. Finally the Data chapter details the precise numbers used in calculations, and the results obtained. Entire books can and have been written about any one of these topics; this is an attempt to present the problem from a comprehensive perspective.

II. Geophysical Analysis

Introduction

The problem of the feasibility of a lithospheric communication system was studied using two types of models. The mathematical model of the electromagnetic waveguide is discussed in a separate chapter. The geophysical models will be treated here. The importance of geophysics to this problem should not be overlooked. Only with a thorough understanding of the earth's crust can the basic conductivity and thermal data be derived and applied to the electromagnetic propagation model. Unfortunately, a review of the literature revealed that the electrical and thermal properties of the crust are the source of much controversy within the geophysical community. For this reason, several hypotheses concerning factors affecting the data obtained from actual experiments will be discussed. A list of geologic terms has been provided in the Appendix for the convenience of the reader. It should be noted that the theories discussed are highly simplified here, in the interests of providing background in the geophysical aspects of the problem without overwhelming the reader with technical details.

The primary motivation of this study was the assumption that the oceanic crust was significantly different from the continental crust. Several feasibility studies have been done on lithospheric communication under the continents.

Only one conceptual paper has discussed the subsea crust, published in 1963 (Ref 3). The continental studies were published since then. By examining the structures of the subcontinental crust and the subsea crust, this chapter will show the differences between them and give the background necessary to understand the conductivity profiles used.

Crust Structure

One theory of overall earth structure and crust formation has been illustrated in Figure 3. This theory considers the structure of the earth in terms of a very slowly circulating system. Large convection cells have formed between the central core of the earth and the outer crust, within the mantle. Circulation is the product of both thermal convection and gravitational forces. The hotter, less dense rock material rises to the surface while the cooler, denser material is pulled down toward the central core. The crust is the cooled shell on the outside of the earth, which emerges and is reabsorbed in the circulation process (Ref 5:228).

This theory of internal earth processes is highly consistent with another theory, which models the crustal processes. The theory of plate tectonics, known popularly as "continental drift," is based on the assumption that the earth's crust is conposed of a number of solid plates, which "float" on the more fluid mantle. The plates are theorized to move quite slowly--on the order of about one centimeter

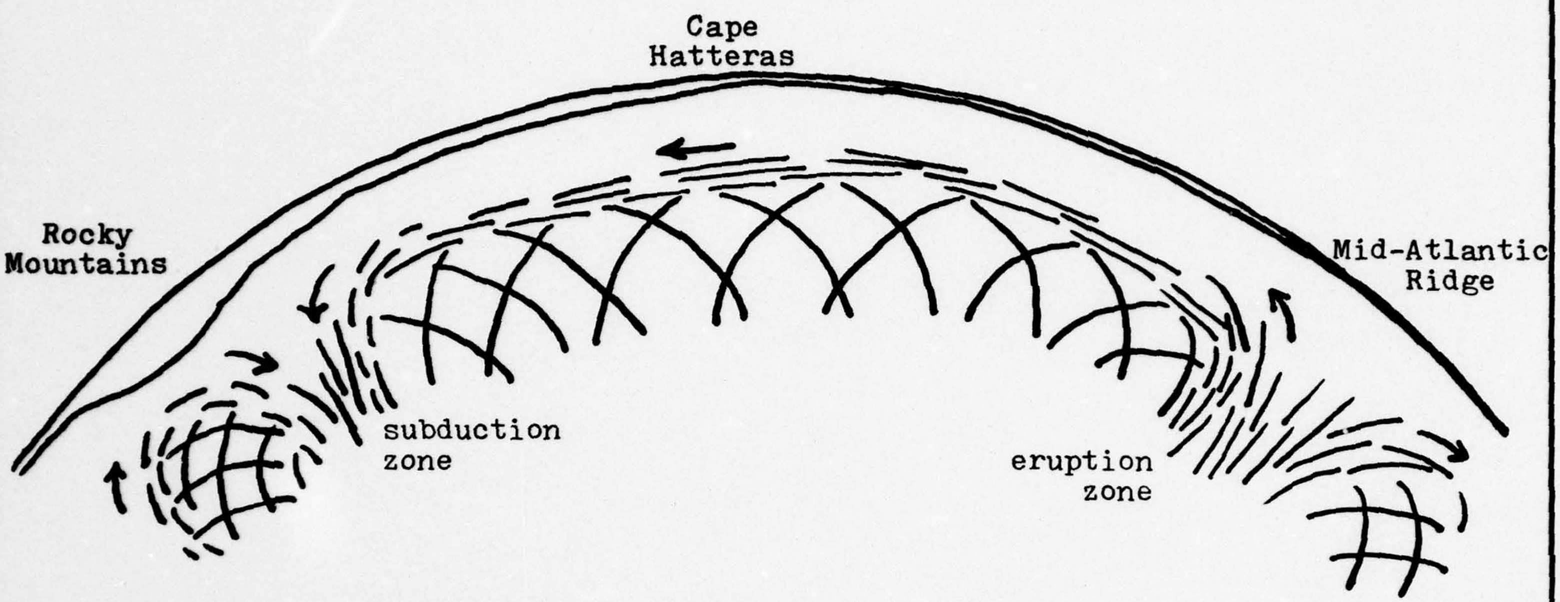

Figure 3. Cross section of earth structure showing eruption and subduction zones (vertical exaggeration about four times actual relative depth). (Ref 6:531)

per year--from the eruption zones to the subduction zones. The former corresponds to the areas where two convection cells meet, both pushing material to the surface, whereas the latter corresponds to areas where both convection cells pull material from the crust down to the mantle, towards the central core of the earth.

The eruption and subduction zones model is based on evidence found in some of the oldest rocks found in the crust. The exact explanation is still quite controversial; however the above models serve to aid in understanding the nature of the crust's structure. Eruption zones have been observed to correspond to oceanic ridges and volcanic island arcs. The subduction zones often correspond to continental rift valleys and mountain ranges. Thus in the oceanic areas, the crust is relatively thin, due to the "pulling out" action of the spreading seafloor. In the continental areas, where crustal material is pulled down into the mantle, a corresponding "piling up" of crust material occurs, producing a much thicker crustal structure under the continents (Ref 6:228,289).

Because of extensive seismic and compression wave studies, there is general agreement on the composition and structure of the crust. The three basic rock types are sedimentary, formed from materials deposited primarily by water; igneous, formed by lava flows of magma from the mantle; and metamorphic, formed from sedimentary or igneous rock that has been radically changed in form by pressure, temperatures, and other forces, deep in the earth. The crust can be divided into continental, oceanic, and transitional areas. The transitional areas refer to the continental margins both above and below sea level (Ref 7:238).

The upper layer over most of the crust is composed of sedimentary strata with an average depth of 1-2 km. Under the continents these strata may be as thick as 10 km; under oceans, they may be altogether absent in places. However the usual depth under oceans is about 1 km (Ref 3:324). Below the sediments on the continents is located a layer of granite that becomes increasingly basaltic with depth. In some areas the branite and basalt are separated by a sharp break call Conrad's discontinuity. The granite layer may be as thick as 20 km, while the basaltic layer extends to the lower limit of the crust, defined by the Mohorovicic discontinuity. In continental regions, the Moho is at an average depth of 35-40 km, but under large mountain ranges it may lie as deep as 80 km (Ref 8:8). Undersea, the thin sediments rest on a layer of basic rock, which often has little granite in it, but resembles the base of the continental crust in its basaltic nature (Ref 3:324). The Moho under the ocean is at an average depth of 10-15 km (Refs 3:324, 5:199). The transitional areas have characteristics of both oceanic and continental regions. All three general crust structures are depicted in Figure 4.

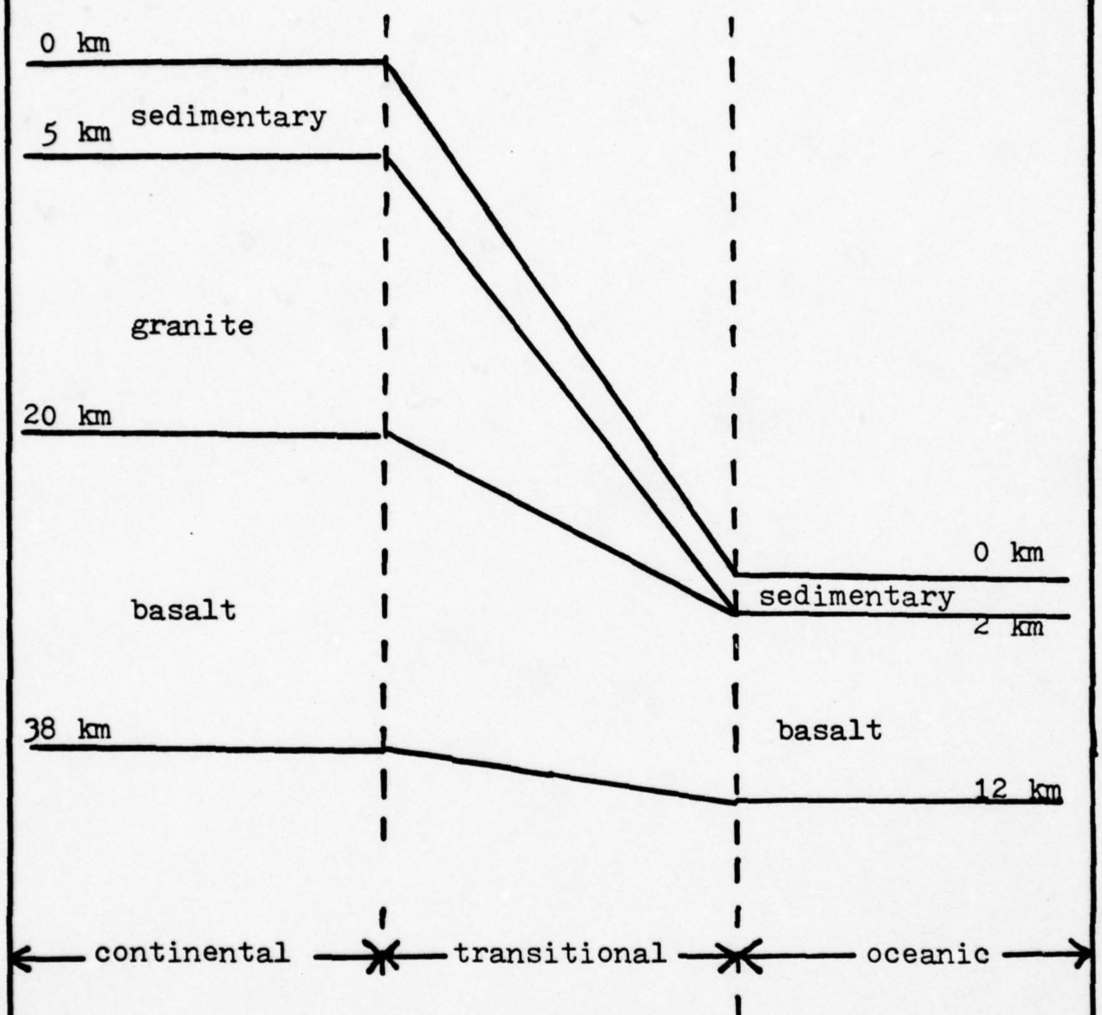

Figure 4. Characteristic depth structure for continental, transitional, and oceanic crust regions (Ref 3:324).

Little is known about the Mohorovicic discontinuity or the nature of the rock around it. The Moho is characterized by a significant change in the velocity of seismic waves that cross it. One theory is that the rock material undergoes a phase change at this depth, due to pressure and temperature effects. Another is that there may be an actual chemical change in the rock at that depth (Ref 5:198).

The waveguide for lithospheric communication is bounded by the sedimentary strata above and the Moho below. In the continental structure, the dielectric center is then primarily granitic to vitreous basaltic, whereas in the oceanic structure it is crystalline basaltic (Ref 3:324). If the characteristics of silicon dioxide (quartz) are assumed to be similar to granite, of which quartz is a major component, then it is interesting to compare the dielectric constants of quartz in vitreous and crystalline form. The relative dielectric constant of fused quartz is about 3.75 (Ref 9: F-55), while for the crystalline form it is about 4.5 (Ref 10:9-111). This significant variation in dielectric properties is a good reason to reject the extension of continental data to the oceanic case. Additionally, the dielectric difference between granite and basalt are considerable. Where granite contains coarse-grained quartz, feldspars, and micas (Ref 11:166), basalt contains only feldspars and pyroxenes, which are in a finer-grained form (Ref 11:31). Thus there appears to be a substantial difference between the proposed waveguide media under the continents and the oceans.

Most of the information on the crust has been deduced from indirect measurements using seismic (earthquake) waves and soundings of compressional waves produced by explosions. Thus, although there is little direct evidence of the precise crustal structure, the general outline given above was assumed to be the structure of the waveguide considered. The upper boundary was formed by the seawater-saturated, thin, sedimentary layer, while the lower boundary was formed by the Moho and the upper mantle composed of dunite. The basaltic region between acted as the proposed waveguide medium.

Thermal Characteristics

The thermal properties of the crust were important to this study for three main reasons: 1) one of the driving forces of the convection cell system was thermal circulation. Warmer substances have a tendency to expand and their decreased density gives them a buoyancy, making them rise, while cooler substances contract to a denser state, making them tend to the bottom of the system. 2) The lower boundary of the waveguide was electrically defined by an assumed rise in conductivity in the crustal rock. This rise in conductivity (discussed in the section on conductivity profiles) was attributed to the rise in electronic conduction due to higher temperatures. 3) A component of the noise power in the overall lithospheric communication system is due to thermal effects within the system (this will be discussed in the chapter on noise). The temperature of the crust under the ocean has been estimated with the aid of geothermal heat flow measurements at the surface of the crust, along with estimates of thermal conductivity, radioactivity in the crust and mantle, and frictional heating in the crust (Ref 12:227).

Heat Flow. A typical temperature-depth curve for the earth is shown in Figure 5. The concave shape of the curve is due to the addition of three primary heat sources in the earth: radioactive elements, friction, and pressure. The principal source of heat is the decay of naturally radioactive elements in the upper mantle (ref 13:211). Another significant cource in the lower crust is frictional heat produced by the movement of tectonic plates across the mantle. These two sources add to produce a very steep temperature gradient in the first 200 km of depth. Below this, though, the much less steep and linear increase in temperature due to pressure effects becomes dominant, since convection and radiation are minimal (Refs 13:223, 14:264-6). Because of the slightly deeper emplacement of the heat sources, due to the thicker overburden on the continents, the oceanic temperature gradient is less steep in the first 100 km than the continental gradient (Ref 13:220). The continental areas of crust, in addition to being thicker than the oceanic are cooler, due to their being older rock.

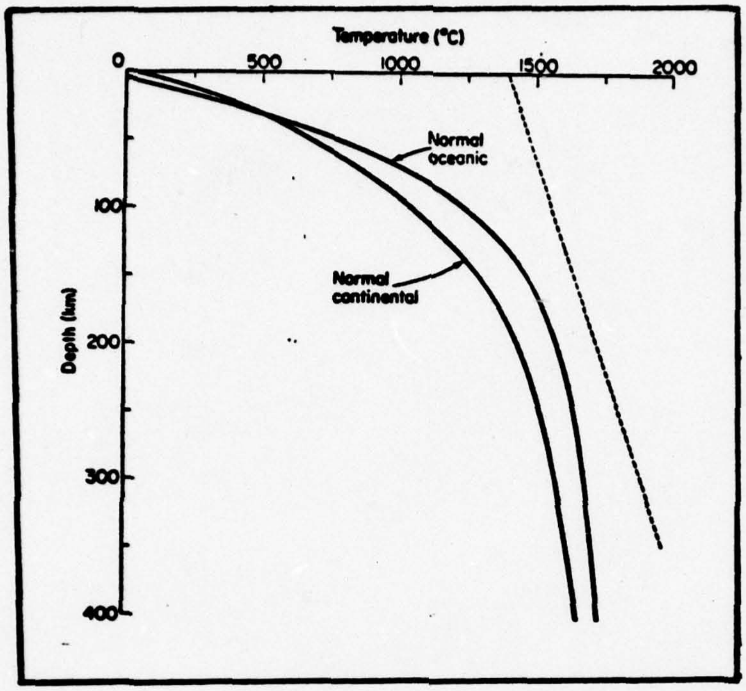

Figure 5. Thermal profiles for typical continental and oceanic heat flows. Dashed line shows assumed melting curve.. (Ref 13:217)

It has been shown that seafloor sediments become cooler as they age (Ref 12:227), and this appears to apply to continents as well.

Typical heat flow rates range between 0.6 and 2.4 cal/cm^2-s. High heat flow levels at the surface indicate an area of geotechnic activity, since these are also areas where the hotter mantle material approaches the surface.

Friction. In addition to conduction of radioactive heat in areas of geotechnic activity, it is thought that heat is produced as part of the movement and reabsorption of crustal material across and into the mantle. It has been calculated that the conversion of potential energy to heat in the process of a plate being reabsorbed into the upper mantle produces a finite, although indefinite, amount of heat (Ref 12:229). It has also been theorized that hot areas are left in the wake of a plate being dragged across the upper mantle as it is absorbed in a mountainous region nearby. The resulting frictional heat melts the upper mantle and produces a volcanic island arc (Ref 12:228-30).

Temperature Profiles. The heat flow measured at the surface can be used to find the temperature gradient by dividing heat flow by the thermal conductivity of the crust material (Ref 15:24). However, direct measurements of thermal conductivity extend down only to a depth of several kilometers. Thus below this depth, thermal conductivity figures are estimates, based on other indirect measurement methods. This uncertainty has produced some disagreement in the literature about the value of the thermal gradient. As shown in Figure 5, the gradiant above 50 km is essentially linear. The value of the gradient given here was 15^{o}/km. Values as high as 20^{o}/km have been reported for the oceanic crust (Ref 2:190). Continental crust gradients are, for the reason mentioned earlier, lower, although they also are as high as oceanic gradients in some areas. Continental thermal gradients range from 9^{o}/km to 24^{o}/km (Ref 16:177).

Conductivity Profiles

Factors Affecting Conductivity. The basis for the waveguide attenuation calculation was the conductivity profile of the oceanic crust. Because the conductivity is so dependent on the various structure factors and properties, it was necessary to examine the geologic and thermal profiles before studying the conductivity. In fact, the main reason why this problem is still being debated sixteen years after its conceptualization is that the conductivity profiles cannot be measured directly (or, rather, for financial reasons, have not been), thus leading to a disagreement over the exact shape of them. A review of the main factors affecting conductivity in the crust will make the uncertainties more clear.

There are two basic forms of conduction: electrolytic (ionic) and electronic. The former refers to the flow of ionic charge carriers in a solution of electrolytes (dissociated ions) (Ref 17:11). This type of conductivity is highly dependent upon frequency (Ref 18:348). The latter, electronic conduction, refers to the flow of free electrons either in metallic ores, or in other ionic substances, when high temperatures have already broken up the ions Ref 17:11). The basic theory of lithospheric conductivity was based on the combination of electrolytic and electronic effects.

The conductivity profile is affected by temperature, pressure, and water content of the rock in the crust. At temperatures around 450°C, it is theorized that electronic conductivity effects become dominant and the conductivity rises at a significant rate (Ref 4:8-9). The significance of pressure effects on the conductivity is not quite as well-defined, since pressure effects seem to counteract temperature effects. Assuming a constant density of crust material, the pressures at various depths may be calculated. Adding to the density pressure is pressure from stresses within the crust: at 10 km, the density pressure is 0.27 gigapascals, while the combination of stress and density pressure is 0.67 GPa; at 30 km, the pressures are 0.81 GPa and 1.2 GPa (Ref 5:15). There does seem to be evidence that the counteraction of pressure effects on temperature effects is nontrivial (Ref 19:158), but the nature of the interaction of the two effects has not yet been clearly defined.

The other major factor affecting the conductivity is the water content of the rock. Water occurs in three main forms in mineral structures: 1) as hydroxyl ions, locked into the molecular structure of the minerals; 2) as a free solution in the pores and fractures of the rocks; 3) as films in capillary-sized microcracks. In the first case, the presence of absence of hydroxyl ions has no effect on conductivity. In the second case, the water serves as a weak electrolyte of mineral ions, and thus raises the conductivity by several orders of magnitude. The effect of interstitial films is very controversial; however there are indications that they also raise the conductivity of the rock by several orders of magnitude (Ref 19:159-160).

<u>Methods of Measuring Conductivity.</u> To depths of

about 3 km, direct measurements have been made on the lithosphere. These measurements usually are made in deep boreholes produced by petroleum exploration wells. Unfortunately, few have been drilled in areas with thin sedimentary layers, down to the granitic and basaltic layers, since petroleum is not usually found in these areas. Fewer still such boreholes have been drilled in oceanic areas. There are also many questions about interpretation of the data from these boreholes, due to such factors as the conductivity of the fluid in the borehole and the anisotropy of the rock formations containing the borehole (Ref 19:154-155).

In order to determine conductivities of deeper levels in the crust, indirect methods have been developed. There are two types: measurements on the crust itself and laboratory measurements on samples. The former category includes soundings using magneto-telluric, four-electrode, long antenna, or magnetic loop methods. Magneto-telluric methods involve surface measurements of the natural electromagnetic field along a line of constant magnetic latitude (distance from the north magnetic pole). By measuring the field fluctuations and subtracting out the components due to external cuases, the internal fields are left, giving an indication of the distribution of lithospheric conductivity. Although this method is frequently used in geophysical prospecting, its usefulness in conductivity studies is not clear, as there is disagreement as to how the data should be interpreted. In any case, magneto-telluric methods provide maximum values for the conductivity (Ref 20:405-407). The four-electrode method, one of the oldest, has similar problems to the magneto-telluric. Long antennas and magnetic loops are also useful, but their precesion is questionable. All of these methods are useful when their results are used in conjunction with previous data on the geology of the area and other techniques of measurement. However they are very difficult to use alone.

The measurements that can be performed in the laboratory are virtually unlimited. Samples of rock from drilled cores or rock of the same minerals and structure as those within the crust can be tested for conductivity under a variety of pressure, temperature, and humidity conditions. However, questions have been raised as to how similar these simulated conditions are to actual crustal conditions.

One of the reasons that doubt has been cast upon all of these methods, is that the results obtained are widely variant, resulting in the basic controversy of the lithosperic communication problem. The ideal, of course, is that assuming the conductivity profile is stable over a period of time, various measurement techniques should produce convergent results that would indicate the "correct" values. However, the obtained values diverge substantially. The reason for this lies in the nature of the material being studied. Rocks within the crust are composed of an extremely complex three-phase system: the mineral matrix which is porous, the interstitual solution of mineral ions and water, and gas. Thus a laboratory reproduction if these exact conditions is difficult if not nearly impossible to achieve. It becomes even more difficult to interpret measurements taken when only some of the lithospheric conditions are reproduced. Whereas measurements taken using electromagnetic soundings are not nearly as accurate and do not have nearly the resolving power needed to determine conductivities accurately. Moreover, sounding methods are based on an extremely simple model of the earth's natural electromagnetic field--one that ignores cracks and fissures, stratifications, and inhomogeneities. Once again, it is very difficult to interpret the data obtained, even with the knowledge of the simplifications used (Ref 8:20).

This discrepancy between data obtained from different sources is the crux of the controversy over the feasibility of lithospheric communication. Assessment of this feasibility, particularly in oceanic regions, was made difficult by the lack of data and the conflicts between the existing data on conductivities. It cannot be overemphasized that without reliable conductivity data, any calculation of the propagation of electromagnetic waves in the crust becomes suspect. The development of this problem seems to have reached the point at which the theory has been developed as far as possible with the present data. For further advance, new data will be necessary.

Actual Conductivity Profiles. The lack of appropriate and reliable conductivity data became a problem in this investigation when the need arose for a set of conductivity-depth profiles to use in calculations. There were only two profiles found that were based on data from the oceanic lithosphere (see Figure 6), and these were composites, derived as two alternatives from the same data base by the same authors. An additional drawback of these profiles was that they were over fifteen years old, from the only available attempt to discuss the specific problem of oceanic lithospheric communication (Ref 3). Despite the disadvantages, these profiles were used for the very reason that they were the only oceanic profiles found.

The other five profiles were chosen for comparison purposes. As profiles of continental conductivity, the attenuation parameters for these profiles had been calculated, using boundary conditions and methods appropriate to the continental lithospheric waveguide. By using the continental profiles with oceanic boundary conditions it was hoped that an evaluation of the effects of the changes on attenuation due solely to the calculation method and boundary conditions could be made. All these profiles are included in the Appendices.

In spite of the widespread controversy about the exact mechanisms and values of the conductivity-depth profile, a general profile may be described. Below the continents,

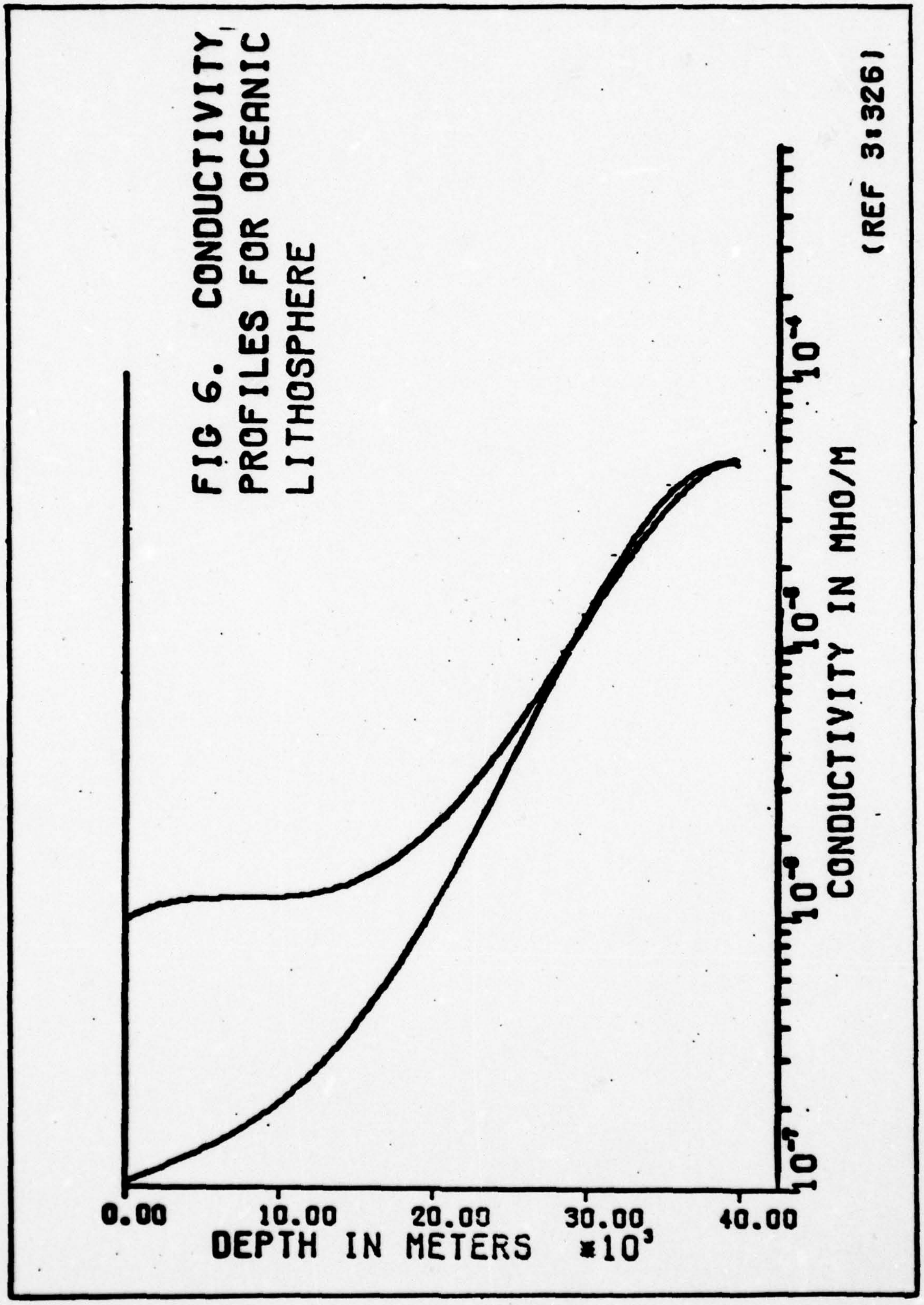

FIG 6. CONDUCTIVITY PROFILES FOR OCEANIC LITHOSPHERE

the conductivity decreases from a relatively high value due to a high water content in the rock pores and cracks (Ref 4:8). The exact reason for the decrease, down to a depth of about ten kilometers, is a major source of contention in the field of geophysics. One view is that pressure closes the cracks, drying the rock out, and thus lowering the conductivity. The opposing view is that temperature effects are the major factor in decreasing conductivity: at depths where electrolytic conduction effects start being curbed by electronic conduction effects, the net conductivity decreases (Ref 21:334). In any case, it is agreed that the conductivity does decrease down to a depth at which the electronic conduction dominates and the conductivity rises again, due to rising temperature.

The conductivity of the subsea crust is limited at the upper surface by the conductivity of sea water. The water-saturated sediments have a significantly lower conductivity which then holds constant or decreases slightly with depth, depending upon which view of water content of the rock is taken. Then, at the depth where the temperature increases to a point to effect electronic conductivity, the conductivity increases (Ref 12:230).

In order to understand much of the background and controversy concerning conductivity profiles, it was necessary to review the geologic structure and geotechnical processes in the crust. The calculation of the attenuation of the electromagnetic waves in the crust required profiles of the conductivity over the depth of the crust. Despite the controversy over these profiles, the ones found in the literature were used. Only two pertained to the oceanic crust. The other five, taken from the continental crust, were used for comparison with the work already done by other researchers.

III. Waveguide Analysis

Introduction

Assumption of the use of a vertical monopole transmitting antenna led to the assumption that only TM modes would exist in the waveguide. The waveguide medium was treated as flat and horizontally homogeneous, neglecting stratifications and discontinuities as well as the earth's curvature.

The conductivity within the crust was assumed to be significantly less than the boundary conductivities, thus producing a continuous but rapidly changing conductivity-depth function. For this reason a phase integration technique was chosen over both boundary-value matching methods and WKB approximation methods. The former is best-suited for a discontinuous conductivity-depth function, while the latter applies best to a slowly-varying continuous function. Thus an application of the phase-integration method to a simple horizontally stratified crust would require some modification to account for the extremely rapid changes in conductivity between strata.

Derivation of the General Impedance Equation

The electric and magnetic fields were defined as

$$\bar{E}(x,z,t) = [\bar{e}_x E_x(z) + \bar{e}_z E_z(z)] \exp i(kx-\omega t) \quad (1)$$

$$\bar{H}(y,t) = \{\bar{e}_y H_y(z)\} \exp i(kx - \omega t) \tag{2}$$

(Symbols are defined in the List of Symbols, p. vii) The $\exp(-i\omega t)$ time dependence will be suppressed hereafter. The conductivity and therefore the complex electric permittivity was taken to be depth-dependent:

$$\sigma = \sigma(z) \tag{3}$$

$$\epsilon = \epsilon(z) \tag{4}$$

$$= \epsilon' + \frac{i\sigma}{\omega} \tag{5}$$

Starting with Maxwell's equations

$$\nabla \times \bar{E} - i\omega\mu\bar{H} = 0 \tag{6}$$

$$\nabla \times \bar{H} + i\omega\epsilon'\bar{E} = \bar{E} \tag{7}$$

$$\nabla \cdot \mu\bar{H} = 0 \tag{8}$$

$$\nabla \cdot \epsilon\bar{E} = 0 \tag{9}$$

and applying the vector identity

$$\nabla \times (f\bar{A}) = \nabla f \times \bar{A} + f(\nabla \times \bar{A}) \tag{10}$$

the following relation was obtained:

$$\nabla \times \bar{E} = \nabla \times \{\bar{e}_x E_x(z) + \bar{e}_z E_z(z)\} \exp i\phi \tag{11}$$

$$\begin{aligned} &= \{\bar{e}_z \frac{dE_z}{dz} \exp i\phi + ik\bar{e}_x E_x(z) \exp i\phi\} \times \bar{e}_x \\ &+ \{\bar{e}_z \frac{dE_z}{dz} \exp i\phi + ik\bar{e}_x E_z(z) \exp i\phi\} \times \bar{e}_z \end{aligned} \tag{12}$$

where

$$\nabla \times \bar{e}_x = \nabla \times \bar{e}_z = 0 \tag{13}$$

and

$$\phi = kx \tag{14}$$

Thus

$$\nabla \times \bar{E} = \bar{e}_y \{ \frac{dE_x}{dz} \exp i\phi - ikE_z \exp i\phi \} \tag{15}$$

Substituting into Eq (6)

$$\frac{dE_x}{dz} = ikE_z + i\omega\mu H_y \tag{16}$$

To obtain a similar expression for the magnetic field, the identity Eq (10) was applied to the definition Eq (2), and the following was obtained:

$$\nabla \times \bar{H} = \nabla(H_y \exp i\phi) \times \bar{e}_y \tag{17}$$

$$= -\bar{e}_x \frac{dH_y}{dz} \exp i\phi + ik\bar{e}_z H_y \exp i\phi \tag{18}$$

Substitution of Eq (18) into the Maxwell equation (7), when the definition for the complex permittivity, Eq (5), was applied, yielded

$$\nabla \times \bar{H} + i\omega\epsilon\bar{E} = -\bar{e}_x \frac{dH_y}{d\,z} \exp i\phi + ik\bar{e}_z H_y \exp i\phi$$

$$+ i\omega\epsilon\{E_x\bar{e}_x + E_z\bar{e}_z\} \exp i\phi \tag{19}$$

$$= 0 \tag{20}$$

Thus, Eqs (19) and (20) produced

$$-\bar{e}_x \frac{dH_y}{dz} + \bar{e}_z ikH_y + i\omega\epsilon\{E_x\bar{e}_x + E_z\bar{e}_z\} = 0 \tag{21}$$

So that

$$-\frac{dH_y}{dz} + i\omega\epsilon E_x = 0 \tag{22}$$

and

$$ikH_y + i\omega\epsilon E_z = 0 \tag{23}$$

since the coefficients of orthogonal vectors must individually equal zero, if their sum is to equal zero. Eq (23) produced

$$E_z = -\frac{k}{\omega\epsilon} H_y \tag{24}$$

Substitution into Eq (16) yielded

$$\frac{dE_x}{d\,z} = i\omega\mu \{1 - \frac{k^2}{\omega^2\mu\epsilon}\} H_y \tag{25}$$

If Eq (22) was expressed in the form

$$\frac{dH_y}{d\,z} = i\omega\epsilon E_x \tag{26}$$

then Eqs (25) and (26) were the two basic equations to be solved for the fields and propagation constant. For ease of calculation the function A was defined

$$A = \frac{E_x}{H_y} \tag{27}$$

Thus the derivative became

$$\frac{dE_x}{dz} = \frac{dA}{dz} H_y + A \frac{dH_y}{dz} \tag{28}$$

$$= i\omega\mu\{1 - \frac{k^2}{\omega^2\mu\epsilon}\} H_y \tag{29}$$

where the definition of the field, Eq (2) was applied. Substituting Eq (26) into Eq (28), the equation of Eq (28) to Eq (29) gave

$$\frac{dA}{dz} H_y + A(i\omega\epsilon E_x) = i\omega\mu\{1 - \frac{k^2}{\omega^2\mu\epsilon}\} H_y \tag{30}$$

Applying the definition of A, Eq (27), the equation

$$H_y \{\frac{dA}{dz} + i\omega\epsilon A^2\} = i\omega\mu\{1 - \frac{k^2}{\omega^2\mu\epsilon}\} H_y \tag{31}$$

was obtained. Thus

$$\frac{dA}{dz} = i\omega\{-\epsilon A^2 + \mu - \frac{k^2}{\omega^2\epsilon}\} \tag{32}$$

Normally, this equation would have been solved by direct integration. However, attempts to do so were hindered by the presence of singularities in the function A(z). These singularities were removed by setting

$$A = \frac{1}{\xi} \tan u \tag{33}$$

Substitution into Eq (32) produced

$$\frac{dA}{dz} = i\omega\{-\frac{k^2}{\omega^2\epsilon} - \epsilon\frac{1}{\xi^2}\tan^2 u + \mu\} \tag{34}$$

$$= \frac{1}{\xi}\sec^2 u \frac{du}{dz} \tag{35}$$

where the latter was obtained from the definition, Eq (33). Thus the final equation for the phase function, u, was

$$\frac{du}{dz} = - \frac{i\omega\epsilon}{\xi} \sin^2 u - i\xi \cos^2 u \left\{\frac{k^2}{\omega\epsilon} - \omega\mu\right\} \qquad (36)$$

This was the equation solved by numerical integration techniques.

Numerical Method

The method used to integrate equation (36) and obtain values for the complex propagation constant k had two primary functional units: a minimizer and an integrator. A detailed description of all the various program units used has been placed in the Appendix. The initial and final boundary conditions for the waveguide, derived in the following section, were input to the minimizer, along with an arbitrary initial value and range values for k. The integrator used an eighth-order predictor-corrector method to calculate the value of the phase function at the lower boundary of the waveguide. This value was compared with the boundary value given to the minimizer. The minimizer then produced a new value of k, attempting to make the difference between the integration results and the boundary condition as small as possible. The successive values of k were based on random, gradient, average, and jump steps. After the desired number of trials, the best value was output, giving the complex propagation constant. Both the minimizer and the integrator were library programs, run on the ASD computer system, a CDC CYBER 74.

Verification and Boundary Conditions

In order to test whether the computer program was actually doing the desired calculations, three special cases of the waveguide problem were used. In each of the three cases, the boundary conditions had to be derived, and the values of the propagation constant calculated from known waveguide theory. The boundary value expressions were used in the computer program, and the resulting k was compared with the theoretical value. In all three cases the agreement was within 2%.

Case I: Infinitely Conducting Boundaries With Perfect Dielectric. We first considered the case of a lossless, dielectric-filled waveguide with two parallel and infinitely conducting boundaries. As

$$\sigma \to \infty , \qquad \frac{\sigma}{\omega \epsilon'} >> 1$$
$$\epsilon \to \frac{i\sigma}{\omega} \tag{37}$$

Substitution in Eqs (25) and (26) yielded

$$\left.\frac{dH_y}{dz}\right|_{\sigma\to\infty} = i\omega \{\frac{i\sigma}{\omega} E_x\} = -\sigma E_x \tag{38}$$

$$\left.\frac{dE_x}{dz}\right|_{\sigma\to\infty} = i\,\omega\mu\{1 - \frac{k^2\omega}{i\,\omega^2\mu\,\sigma}\} H_y$$
$$= i\omega\mu H_y \tag{39}$$

Eqs (38) and (39) were expressed in matrix form and solved as an eigenvalue equation:

$$\frac{d}{dz}\begin{pmatrix} E_x \\ H_y \end{pmatrix} = \begin{pmatrix} 0 & i\omega\mu \\ -\sigma & 0 \end{pmatrix}\begin{pmatrix} E_x \\ H_y \end{pmatrix} \tag{40}$$

The characteristic equation was solved for the eigenvalue λ :

$$\lambda^2 + i\omega\,\mu\sigma = 0 \tag{41}$$

$$\lambda = \pm\sqrt{\frac{\omega\mu\sigma}{2}}\,(-1 + i) = \pm\frac{i - 1}{\delta} \tag{42}$$

where δ was defined as the skin depth. This resulted in the eigenvector

$$\begin{pmatrix} \lambda \\ -\sigma \end{pmatrix} = \begin{pmatrix} \pm\frac{i - 1}{\delta} \\ -\sigma \end{pmatrix} \tag{43}$$

Thus, if the wave was assumed to attenuate as exp $\mp(z/\delta)$, the eigenequation became

$$\begin{pmatrix} E_x \\ H_y \end{pmatrix} = \text{const.}\begin{pmatrix} \pm\frac{i - 1}{\delta} \\ -\sigma \end{pmatrix}\exp \pm\frac{i - 1}{\delta}z \tag{44}$$

Then for

$$\begin{aligned} \mathrm{Re}(\lambda) < 0, \quad \frac{E_x}{H_y} &= \frac{\omega\mu\delta}{2}(1 - i) \\ \mathrm{Re}(\lambda) > 0, \quad \frac{E_x}{H_y} &= \frac{\omega\mu\delta}{2}(i - 1) \end{aligned} \tag{45}$$

For the initial condition the wave must decay as it travels in the (-z) direction. Thus

$$\text{Re}(\lambda) > 0, \quad \lambda = \frac{-(i - 1)}{\delta} \tag{46}$$

was chosen. Thus the initial condition was

$$A\Big|_{\sigma \to \infty} = \frac{\omega \mu \delta}{2}(i - 1) \tag{47}$$

When the conductivity was assumed to be infinite the initial condition tended to zero. Using this as an initial condition the integration of Eq (32) was performed. Equivalently, the initial condition for u in Eq (36) was set to zero. Since the waveguide medium was a perfect dielectric, the dielectric constant was taken as

$$\epsilon = \epsilon' \tag{48}$$

since the conductivity was

$$\sigma = 0 \tag{49}$$

However, to check the final value of the impedance function at the lower boundary of the waveguide, another derivational method was used. The depth dependence of the electromagnetic fields was considered as a function of $\exp(\pm \alpha z)$, where it was desirable to obtain, first, an expression for α. The magnetic field was expressed as

$$\bar{H} = (H_+ \exp i\,\phi_+ + H_- \exp i\,\phi_-)\,\bar{e}_y \tag{50}$$

where

$$\phi_{\pm} = kx \pm \alpha z \tag{51}$$

From the identity, Eq (10), $\nabla \times H$ was calculated using

$$\nabla(\exp i\,\phi_{\pm}) = (\exp i\,\phi_{\pm})\, i\nabla\,\phi_{\pm} \tag{52}$$

and

$$\nabla\,\phi_{\pm} = \bar{e}_x k \pm \bar{e}_z \alpha \tag{53}$$

Thus

$$\nabla \times \bar{H}_{\pm} = i(\bar{e}_x k \pm \bar{e}_z \alpha) \times \bar{e}_y H_{\pm} \exp i\,\phi_{\pm} \tag{54}$$

$$= i(\bar{e}_z k + \bar{e}_x \alpha) H_{\pm} \exp i\,\phi_{\pm} \tag{55}$$

Using the complex form of the dielectric constant, the Maxwell equation (7) became

$$\bar{E}_{\pm} = \frac{-1}{i\omega\epsilon} \nabla \times \bar{H}_{\pm} \tag{56}$$

Substitution of Eq (55) into (56) yielded

$$\bar{E}_{\pm} = \frac{-1}{\omega\epsilon}(\bar{e}_z k \mp \bar{e}_x \alpha) H_{\pm} \exp i\,\phi_{\pm} \tag{57}$$

Using the Maxwell equation (6), this became

$$H_{\pm} = \frac{1}{\omega^2 \mu \epsilon} (k^2 + \alpha^2) H_{\pm} \tag{58}$$

The parameter   was thus obtained:

$$\alpha = \sqrt{\omega^2 \mu \epsilon - k^2} \tag{59}$$

Since the electric field was expressed in terms of the magnetic field, the electric field could also be defined as

$$\overline{E} = \overline{E}_{+} \exp i\phi_{+} + \overline{E}_{-} \exp i\ \phi_{-} \tag{60}$$

Thus the impedance

$$A = \frac{E_x}{H_y} = \frac{E_{x+} \exp i\ \phi_{+} + E_{x-} \exp i\ \phi_{-}}{H_{+} \exp i\ \phi_{+} + H_{-} \exp i\ \phi_{-}} \tag{61}$$

At the upper boundary, $\phi_{+} = \phi_{-} = 0$, so that

$$A\Big|_{z=0} = \frac{\alpha H_{+} - \alpha H_{-}}{\omega\epsilon (H_{+} + H_{-})} \tag{62}$$

where Eq (57) was substituted for the electric field. Thus, H_{+} and H_{-} are related by

$$H_{+} = \left[\frac{\frac{\alpha}{\omega\epsilon} + A_o}{\frac{\alpha}{\omega\epsilon} - A_o} \right] H_{-} \tag{63}$$

where A_o was the field impedance at the upper boundary. Using Eq (57) for the electric field, Eq (63) for the magnetic field, Eq (59) for α , and Eq (62) for A_o, the general expression for the impedance within the waveguide was

$$A(z) = \frac{\alpha}{\omega\epsilon} \left[\frac{(A_o + \frac{\alpha}{\omega\epsilon}) \exp i\alpha z + (A_o - \frac{\alpha}{\omega\epsilon}) \exp -i\alpha z}{(A_o + \frac{\alpha}{\omega\epsilon}) \exp i\alpha z + (\frac{\alpha}{\omega\epsilon} - A_o) \exp -i\alpha z} \right] \tag{64}$$

Because the boundaries were infinite conductors, the zero initial condition was used in Eq (64) to obtain the impedance at the lower boundary,

$$A(a) = i(\frac{\alpha}{\omega\epsilon}) \tan \alpha a = 0 \qquad . \tag{65}$$

where a was the waveguide depth. Using the definition, Eq (33), this suggested

$$\frac{1}{\xi} = i\left(\frac{\alpha}{\omega\epsilon}\right) \tag{66}$$

$$\alpha z = u(z) \tag{67}$$

For the impedance to be zero,

$$\alpha a = m\pi = u(a) \tag{68}$$

Thus, while expression of the boundary condition in terms of A produced an ambiguity as a result of the complex argument of the tangent function, the expression in terms of u gave the boundary condition at the bottom of the waveguide explicitly, and it is valid even for other values of the constant ξ . For the TM_{10} mode, the boundary conditions for Eq (36) become

$$u(0) = 0 \quad \text{and} \quad u(a) = \pi \tag{69}$$

The expression, Eq (64), also could be used to check the integration by the computer. Since the direct integration solution was mathematically identical to the method of deriving Eq (64), the values obtained by each for a given k should be identical. The check on the minimization procedure in the program was performed using the value of k from waveguide theory (Ref 22:185):

$$k = \sqrt{\omega^2\mu\epsilon - \left(\frac{\pi}{a}\right)^2} \tag{70}$$

This was compared with the final value of k produced by the computer program.

Case II: Infinitely Conducting Boundaries With Small But Finitely Conducting Waveguide Medium. The primary difference between the first case and this one was that the dielectric constant of the waveguide medium became complex:

$$\epsilon = \epsilon' + \frac{i\sigma}{\omega} \tag{71}$$

Thus k became complex. However, Eq (47), the upper boundary condition, remained zero. The lower boundary condition remained π, since Eq (68) still held. Once again Eqs (64) and (70) were used to check the values produced by the computer program. The internal conductivity was defined as

$$\sigma = 10^{-3}\omega\,\epsilon' \tag{72}$$

Case III: Finitely Conducting Boundaries with Perfectly Dielectric Waveguide Medium. The initial condition for this case was obtained from the same equation as that for the infinitely conducting boundaries:

$$A_o = \frac{\omega\mu\delta}{2}(i - 1) \tag{47}$$

However, the difference was that since the conductivity was not infinite,

$$\delta \neq 0 \tag{73}$$

Thus

$$A_o = \sqrt{\frac{\omega\,\mu}{2\,\sigma}}\,(i - 1) \tag{74}$$

Additionally, A_o had to be converted to the phase function form, u_o, since the differential equation had been converted to a function of u. In order to effect the conversion, it became necessary to solve for the proportionality constant, ξ. Since ξ was purely imaginary, a real constant,

$$\chi = -i\xi \tag{75}$$

was defined. Then Eq (36) became

$$\frac{du}{dz} = -\frac{\omega\epsilon}{\chi}\left\{\sin^2 u + \frac{\mu\chi^2}{\epsilon}\left[1 - \frac{k^2}{\omega^2\mu\epsilon}\right]\cos^2 u\right\} \tag{76}$$

χ was chosen for ϵ real and $k = k_o$, such that

$$\frac{\mu}{\epsilon'}\left[1 - \frac{k_o^{\,2}}{\omega^2\mu\epsilon'}\right]\chi^2 = 1 \tag{77}$$

where

$$k_o = \sqrt{\omega^2\mu\epsilon' - \left(\frac{\pi}{a}\right)^2} \tag{78}$$

and

$$\chi = \frac{\omega\epsilon'}{\sqrt{\omega^2\mu\epsilon' - k_o^{\,2}}} \tag{79}$$

Thus for this situation

$$\frac{du}{dz} = \frac{-\omega\epsilon'}{\chi} = \text{const.} \tag{80}$$

or

$$u = \frac{\omega\epsilon'}{\chi} z + u_o \tag{81}$$

which was the linear depth dependence desired. The phase function, at the top of the waveguide (+), or at the bottom (-), could be expressed

$$u = \tan^{-1}(iA\chi) \tag{82}$$

$$= \tan^{-1} \{\pm\chi\sqrt{\frac{\mu\,\omega}{2\,\sigma}}\,(-i - 1)\} \tag{83}$$

$$= \tan^{-1} \{\pm\chi\sqrt{\frac{\mu\omega}{\sigma}}\ \exp i\pi/4\} \tag{84}$$

Using a series expansion on Eq (82), this was expressed

$$u \approx iA\chi - \frac{(iA\chi)^3}{3} + \frac{(iA\chi)^5}{5} - \frac{(iA\chi)^7}{7} \tag{85}$$

Factoring out (iAχ), and using Eq (84),

$$u = \pm\chi\ \frac{\mu\omega}{\sigma}\ \exp i\pi/4\ \{1 - \frac{\mu\omega\chi^2}{3\sigma}\,i - \frac{(\mu\omega\chi^2)^2}{5\sigma^2} + \frac{(\mu\omega\chi^2)^3}{7\sigma^3}\,i\} \tag{86}$$

The function P was defined

$$P = \chi\sqrt{\frac{\mu\,\omega}{\sigma}} \tag{87}$$

Also the expression

$$\exp i\pi/4 = \frac{1 + i}{\sqrt{2}} \tag{88}$$

was used. Thus

$$u = \pm P\ \frac{(1 + i)}{\sqrt{2}}\ \{\ 1 - \frac{P^2 i}{3} - \frac{P^4}{5} + \frac{P^6 i}{7}\ \} \tag{89}$$

Therefore, if

$$u = x + iy \tag{90}$$

then the upper boundary conditions were, taking the (+)-sign in Eqs (83) - (89),

$$x = \frac{P}{\sqrt{2}}\{1 + \frac{P^2}{3} - \frac{P^4}{5} - \frac{P^6}{7}\} \quad (91)$$

$$y = \frac{P}{\sqrt{2}}\{1 - \frac{P^2}{3} - \frac{P^4}{5} + \frac{P^6}{7}\} \quad (92)$$

Thus expressions (91), (92), and (87) were used as initial conditions.

Assuming a TM_{10} mode, the boundary conditions at the lower boundary were, taking the (-) sign in Eqs (83)-(89)

$$x = -\pi - \frac{P}{\sqrt{2}}\{1 + \frac{P^2}{3} - \frac{P^4}{5} - \frac{P^6}{7}\} \quad (93)$$

$$y = -\frac{P}{\sqrt{2}}\{1 - \frac{P^2}{3} - \frac{P^4}{5} + \frac{P^6}{7}\} \quad (94)$$

The $-\pi$ difference in the real part accounted for the phase change across the waveguide for the lowest mode. It should be noted that P must be much less than unity for these boundary conditions to hold. For certain material parameters, it would be necessary to decrease the chosen value of for this expansion to be valid.

The theoretical k-values for a relatively low-loss case were (Ref 22:184, 192):

$$k = \sqrt{\frac{\omega^3\epsilon^2\mu}{2\sigma a^2\{\omega^2\mu\epsilon - (\pi/a)^2\}}} - i\sqrt{\mu\omega^2\epsilon - (\pi/a)^2} \quad (95)$$

These were compared with those obtained from the computer calculation.

<u>Actual Problem</u>. The actual problem involved the boundary conditions (91)-(94) with a complex conductivity.

The conductivity profiles discussed in the geophysics section were converted to functional form by a curve-fit routine on the computer. A detailed description of the process has been placed in the Appendix. The functional polynomial then served as the imaginary part of the permittivity

$$\mathrm{Im}\,(\epsilon) = \frac{1}{\omega} \exp\,(Az^4 + Bz^3 + Cz^2 + Dz + E) \qquad (96)$$

Because no previous work of this nature has been found on this particular problem, no real comparison of the final results could be made for verification.

IV. Noise Analysis

Introduction

Surface communications must deal with three main noise sources, other than noise inherent to transmitting and receiving devices: atmospheric noise, produced by electrical thunderstorms; cosmic noise, produced by radio stars and solar electrical activity; and man-made noise produced by other transmitters (Ref 3:327). The primary appeal of thru-the-earth communications is that the last two noise sources can be totally neglected and that the first one may be attenuated enough to be virtually neglected (Ref 2:189).

Thus, there are only two external noise sources in the subsurface waveguide: atmospheric noise propagating down through the crust from the surface, and thermal noise due to high temperatures within the crust. The original motivation for investigating the feasibility of lithospheric communication was the hypothesis that increased attenuation of transmitted signals in the crust might be more than compensated for by attenuation of the atmospheric noise by the upper lithospheric strata, to quite low levels (Ref 4:v). A lower noise level than at the surface might then enable the signals to propagate over a significant range. This hypothesis was, of course, the subject of this study.

The basic noise problem was threefold: to calculate the atmospheric noise field in the suboceanic waveguide and to analyze its effects on the reception of signals, to calculate the thermal noise in the waveguide and its effects on reception, and to calculate the signal-to-noise ratio and the data rate possible for the calculated noise levels. These calculations, along with the propagation constants calculated from waveguide theory in Chapter III, gave an estimate of the feasibility of using the suboceanic crust as a communications channel.

Atmospheric Noise

One of the major differences between the subcontinental waveguide and the suboceanic waveguide was revealed in the analysis of the attenuation of the atmospheric noise as it propagates down to the waveguide. Although the overburden of sedimentary strata on the continental waveguide serves as a rather effective insulator from atmospheric noise, the combined effects of several kilometers of seawater and a shallow sedimentary overburden on the oceanic waveguide are as much as eight times the insulator as the continental overburden (Ref 3:328).

The noise density spectrum at the surface has been measured by E.L. Maxwell for various geographic locations (see Figure 7) (Ref 23:641). Using these values and assumed constant conductivity values for various materials (seawater, granite, sedimentary rock), Maxwell also calculated the variation of the noise spectrum with depth to 300 meters.

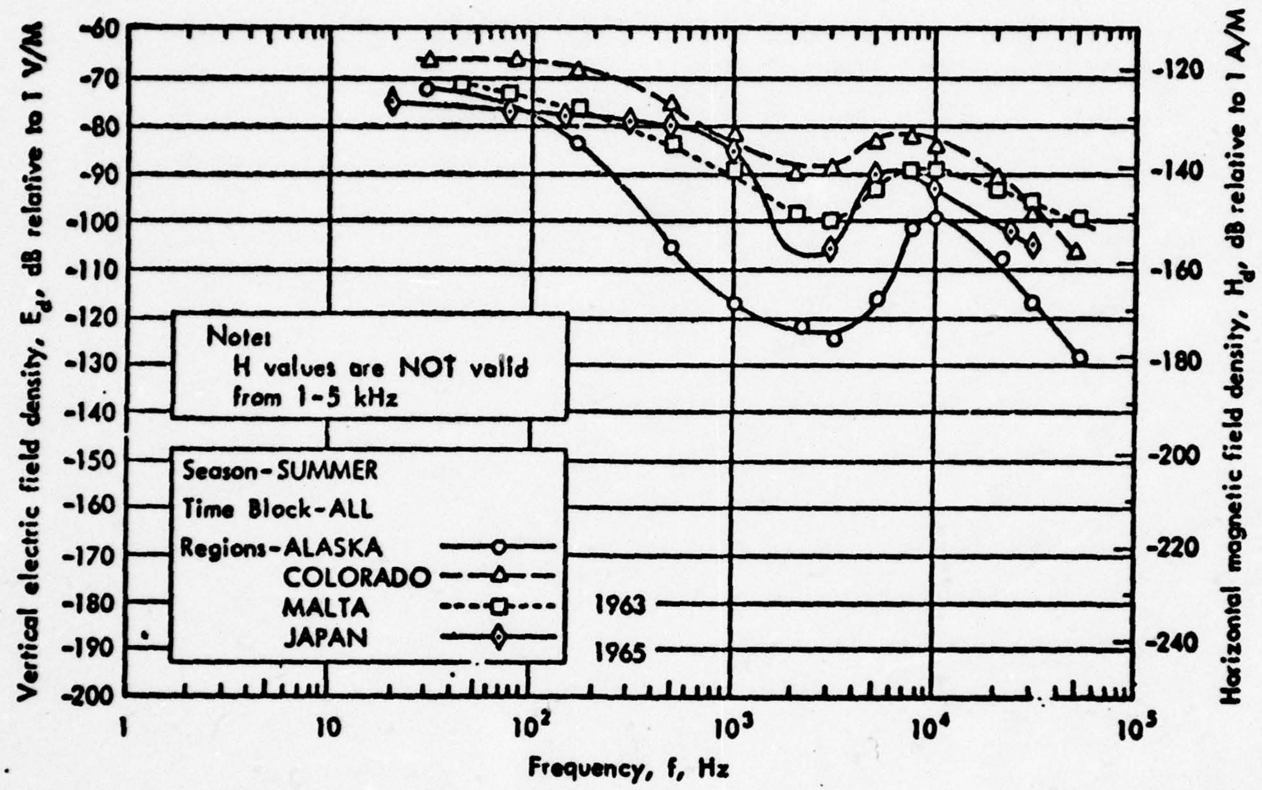

Figure 7. Noise density spectra for surface-level atmospheric noise in four geographic locations (Ref 23:461).

Extrapolations of these curves (see Figure 8) produced similar results for attenuation values at 1 km depth as those given in an earlier study (see Figure 9) (Ref 3:328). Using these extrapolations to a depth of 4.7 km, the average depth of the oceans, the atmospheric noise at a frequency of 10^4 Hz, on the seafloor, was calculated to be on the order of 10^{-2641} times the magnitude of the noise at the surface. Thus it was considered negligible at the ocean floor, and even more negligible within the waveguide, 10-20 km below the surface of the crust. Based on these calculations, the atmospheric noise was totally neglected in the signal attenuation calculations for the waveguide.

Thermal Noise

The second source of noise in the waveguide is due to the effects of high temperatures. The relationship between available noise power and the temperature of a resistance in a circuit may be calculated using the Norton or Thevenin equivalent circuits and Nyquist's Theorem:

$$N_t = kTB \tag{97}$$

(Ref 24:469-470,481). By treating the waveguide medium's thermal properties as a resistor in a circuit, the thermal noise may be calculated, using Eq (97) and the thermal profiles discussed in the Geophysical Analysis chapter.

Detailed analysis and calculations of the noise power have been performed, which take into account the directivity

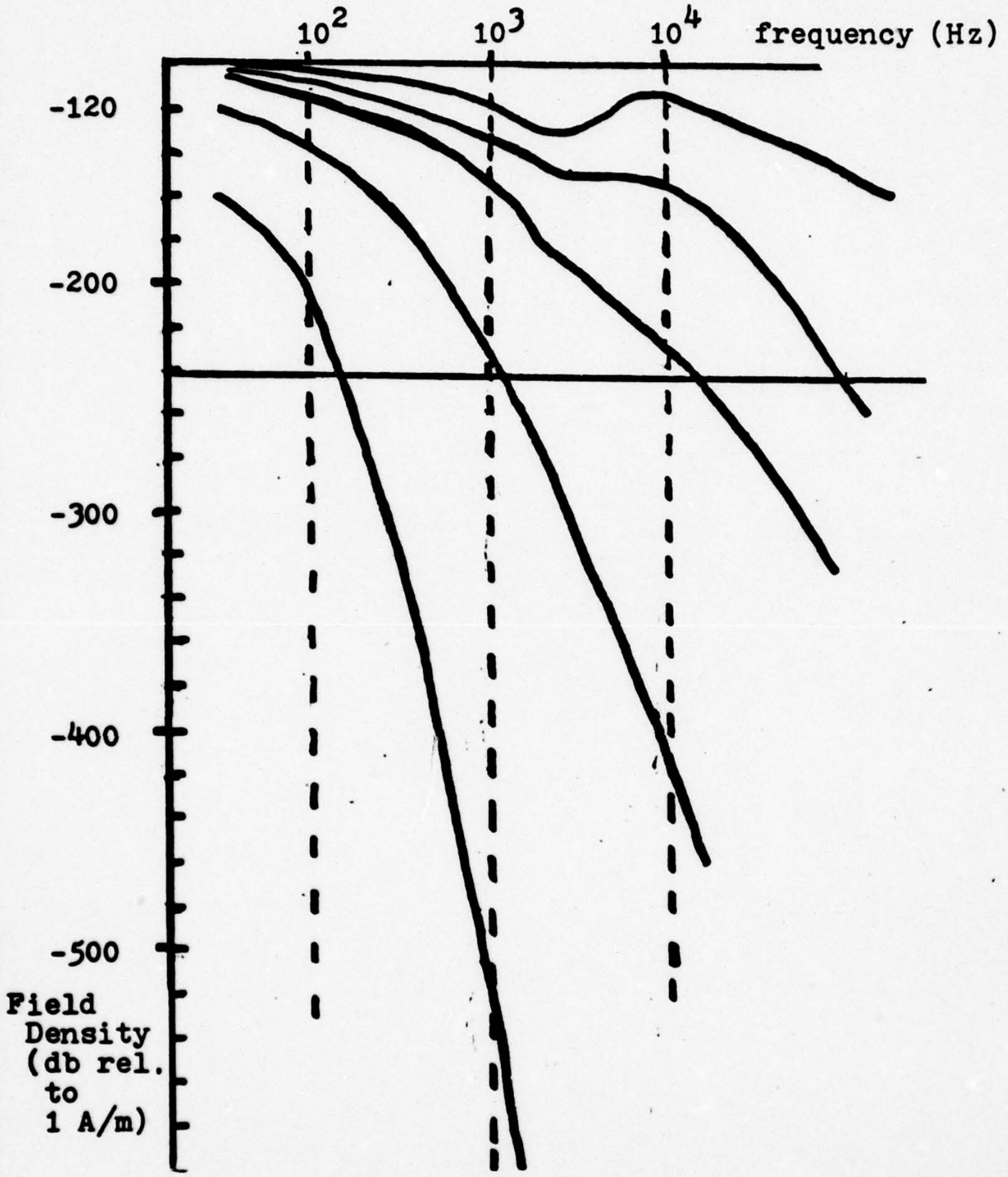

Figure 8. Frequency variation of horizontal magnetic field density of atmospheric noise spectra with oceanic depth (conductivity assumed to be 4 mho/m) (Ref 23:644).

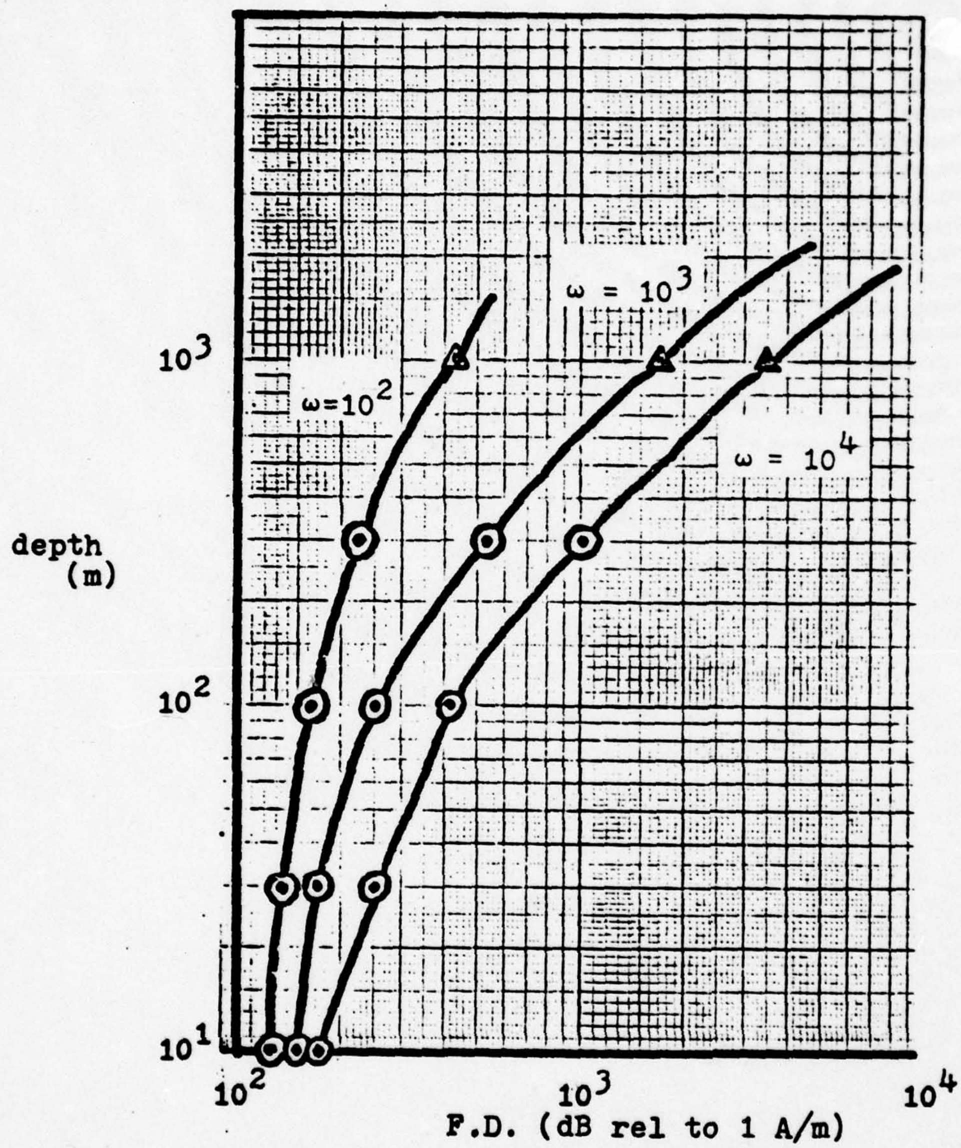

Figure 9. Depth variation of horizontal magnetic field density of atmospheric noise spectra with frequency. Circles are taken from Figure 2 (Ref 23:644), and triangles from Ref 3:328. Shows the corroboration of the two sources.

of the antenna and thermal contributions from the surrounding medium (Ref 25:4-6). However these detailed results vary only by one or two decibels from the results of Eq (97) (Ref 4:25). Thus Eq (97) was used to calculate the noise power in the waveguide.

The thermal noise power was calculated using a thermal profile deduced from heat-flow measurements performed at the seafloor in a high heat-flow region (Ref 13:221). The receiving antenna was assumed to reach to a depth of 15 km, where it encountered a temperature of 540°C. Using the same bandwidth as in the atmospheric noise measurements, 6 Hz, the noise power in this worst case was calculated to be -162 dBm. Since the thermal noise dominated the atmospheric noise, the thermal noise was used to determine signal-to-noise ratios at the receiving antenna. However, as often occurs in communications systems, the thermal noise in the receiver was considered to dominate even the thermal noise in the waveguide, and the sum was arbitrarily set at -160 dBm. This is still a significant improvement over the noise situation in surface communications, where receiver thermal noise is often dominated by atmospherics and external thermal noise (Ref 3:328).

System Information Capacity

The details of pulse-code modulation (PCM) of a signal in a communications system will be discussed here. Interested readers are referred to the excellent description in

Ref 26:138-163. It is sufficient to state that the information capacity of a system is dependent on the minimum response time of the system and the number of distinguishable voltage levels in the coding scheme. Using the average power over a large interval, the maxiumum rate of information transmission is

$$C = B \log_2 (1 + \frac{S}{N}) \tag{98}$$

where S/N is the signal-to-noise ratio (SNR) for the system (Ref 26:150). The required SNR cannot be determined without assuming certain factors about the communication devices. Given a desired bandwidth and data rate capacity for the above equation, the required SNR can be calculated. For a rate of one bit/second and bandwidth of one hertz, the SNR should be at least unity. In practice, the SNR often must be several dB above the limit given in Eq (98) (Ref 25:24).

The results of the waveguide calculations, the noise power, and the information capacity can be used to calculate the necessary transmitted power to obtain an assumed data transmission capacity. Since the total noise power is the sum of the thermal and receiver noise, let

$$N = N_t + N_r \tag{99}$$

and the receiver signal power can be related to the transmitted power by

$$S = S_o \{\exp -2 \, \mathrm{Im}(kx)\} \tag{100}$$

where S_o is the transmitted power. The required signal power at the transmitter is

$$S_o = \{\exp 2\, \mathrm{Im}(kx)\}\, (N_r + N_t)(2^{C/B} - 1) \qquad (101)$$

for a given information rate and bandwidth. In this way, it was at least theoretically possible to calculate the feasibility of transmitting a signal of sufficient power to be received and decoded after travelling a desired range, x.

V. Data and Results

Input Data

Performance of the calculations for the attenuation coefficient required the use of two fundamental values: the magnetic permeability , and the real electric permittivity of the waveguide medium. The magnetic permeability was assumed to be identical to that of free space, since the materials of not only the waveguide medium but also of the boundaries were assumed non-magnetic (Ref 32:2). The value of the electric permittivity used in calculation varied in the literature. The value used in this study was 10^{-10} farad/meter (Ref 10:5-137), since the suboceanic waveguide medium seemed to be composed primarily of basalt. The depth of the waveguide varied from one conductivity profile to another, due to the nature of the computer routine LOOKAT. This program stopped calculations at the depth when the conductivity had increased from its minimum value to one where the imaginary part of the dielectric constant was within an order of magnitude of the real part. In other words, the calculation stopped when conductor losses became large enough to prevent propagation in the waveguide. For the shallow oceanic profile, this occurred in the vicinity of 30 km.

The conductivity profiles were input into the program in the form of a polynomial, Eq (96). The coefficients of this polynomial, calculated by the program FIT, are listed in Table I, with further details given in the Appendix.

Output Data

Because of severe time constraints, only the shallow oceanic profile was treated fully for the TM_{10} mode. Calculation of the final propagation and attenuation constants for one wavelength value involved perfoming successive computer runs, adjusting the upper and lower limits on k, until the values began to converge, with as small an error from the boundary conditions as possible. Then a final run was made, using a large number of convergent steps, to calculate a final value of k. The values calculated for the shallow oceanic profile are listed in Table II. These values were then used to calculate the attenuation within the waveguide, when used as a communications system.

Results

Using a quadratic curve-fit procedure, described in the Appendix, the minimum attenuation was calculated to be 1.5547×10^{-4} nepers/meter at a frequency of 1.3×10^{4} Hz. Assuming a transmitted power of 1 kW for the planar wave

Table II. The propagation constant, $k = \beta + i\alpha$, for various frequencies, and the respective error in the calculation.

(Hz)	β (n/m)	α (n/m)	Error(rel)
9.0×10^{3}	6.3787×10^{-5}	5.7673×10^{-4}	5.6215×10^{-1}
1.1×10^{4}	8.4795×10^{-5}	2.4229×10^{-4}	4.8118×10^{-3}
1.5×10^{4}	6.4953×10^{-5}	3.4329×10^{-4}	7.4953×10^{-4}
1.9×10^{4}	1.3162×10^{-4}	4.5394×10^{-4}	7.7851×10^{-5}

Table I. Coefficients for conductivity polynomial, calculated in FIT, for the different conductivity profiles.

Mott & Biggs (deep)

$A = -7.8826 \times 10^{-18}$
$B = 4.4923 \times 10^{-13}$
$C = -3.1180 \times 10^{-9}$
$D = 6.3691 \times 10^{-5}$
$E = -1.6087 \times 10^{1}$

Mott & Biggs (shallow)

$A = -9.6638 \times 10^{-18}$
$B = 7.0805 \times 10^{-13}$
$C = -1.2495 \times 10^{-8}$
$D = 8.4344 \times 10^{-5}$
$E = -1.3861 \times 10^{1}$

Housely (EUS)

$A = 2.6085 \times 10^{-17}$
$B = -3.5396 \times 10^{-12}$
$C = 1.7246 \times 10^{-7}$
$D = -3.2968 \times 10^{-3}$
$E = 1.5213 \times 10^{-1}$

Housely (BR)

$A = 8.1033 \times 10^{-17}$
$B = -7.4797 \times 10^{-12}$
$C = 2.7101 \times 10^{-7}$
$D = -4.0537 \times 10^{-3}$
$E = 1.8119 \times 10^{0}$

Levin (dry)

$A = 3.1109 \times 10^{-17}$
$B = -2.8981 \times 10^{-12}$
$C = 1.1069 \times 10^{-7}$
$D = -1.7696 \times 10^{-3}$
$E = -5.8058 \times 10^{0}$

Levin (wet)

$A = 9.4523 \times 10^{-17}$
$B = -6.6532 \times 10^{-12}$
$C = 1.5513 \times 10^{-7}$
$D = -1.4071 \times 10^{-3}$
$E = -6.7000 \times 10^{0}$

Keller

$A = 5.6825 \times 10^{-17}$
$B = 9.8938 \times 10^{-12}$
$C = -1.2703 \times 10^{-7}$
$D = -5.0319 \times 10^{-4}$
$E = -9.2258 \times 10^{0}$

traveling down the waveguide, a transmitted power of 60 dBm was produced. The noise within the guide, -160 dBm, was treated as the required signal level at the receiver, in order to obtain a minimum SNR of unity. The minimum attenuation, 1.5547×10^{-4} nepers/meter, was calculated to be -1.35 dB /km. Therefore the maximum range of the system, under these circumstances, is 163 kilometers.

Attempts to calculate the attenuation using a continental profile were unsuccessful. Because of time constrainst on the study, the errors preventing this set of calculations, as well as those for the quasi-TM_{00} mode were not eliminated.

VI. Conclusions and Recommendations

This report has attempted to summarize the work perfomed in a study of the earth's crust under the ocean as a very low frequency communications channel. The study was broken into three parts: a geophysical, waveguide, and noise analysis. The goephysical analysis examined the effects of structural, thermal, and electrical properties on the conductivity-depth profile of the crust. This profile was then applied to an analysis of the electromagnetics of the crust as a waveguide, to derive and calculate the attenuation constant for a TM_{10} planar mode. The atmospheric noise was neglected due to its attenuation by the overlying ocean, and the thermal noise due to temperature effects in the waveguide was calculated to be -162 dBm. The combined receiver and thermal noise was chosen to be -160 dBm.

The attenuation in the waveguide was calculated to be -1.35 dB /km, which produced a maximum range of about 163 km for a minimum signal-to-noise ratio of unity. It should be noted that these results neglect receiver noise, and therefore represent an upper limit on range. The attenuation found here was corroborated by several other sources (Refs 3:326, 4:33, 32:54), to within an order of magnitude. On the basis of these results, it is not feasible to think in terms of using the earth's crust for a very low frequency communications system.

Although the limitations to this study could be used to justify further feasibility studies on this subject, this is not recommended. In fact, there have already been enough studies of the various aspects of the lithospheric communications problem from the waveguide perspective to justify discarding the idea altogether. The reason the idea has persisted over the years since its introduction is its aesthetic appeal, as well as the fact that it fills a very real need. However, this system may well be compared to the early trans-Atlantic cables--because of technical problems, the initial concept of simply a telegraph wire across the Atlantic did not work. The system simply was not feasible until the later innovations in insulation and repeater technology came about. Therefore, rather than persisting in trying to make a lithospheric waveguide communications system work by "brute force" as in this study, it would be better to start with the basic idea of a hardened system, and develop it along more innovative lines. There may indeed be a way to use the earth's crust for communications, but the indications are that a very low frequency waveguide is not one of them.

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Appendix A: List of Geologic Terms

Source: Nelson, A. and K.D. Nelson. Dictionary of Applied Geology, Mining, and Civil Engineering. New York: Philosophical Library, Inc., 1967.

Augite. Silicate of calcium, magnesium, iron, and aluminum, $(CaMgFeAl)_2(AlSi)_2O_6$. Composition is variable. Greenish black to black in color.

Basalt. A fine-grained, often partly glassy, basic igneous rock occuring mainly as dykes, sills, and lava flows; essential minerals are plagioclase and augite. Dark grey to black in color.

Basic Rock. Igneous rock containing between about 52% and 45% silica, with a high proportion of dark minerals and no free quartz.

Borehole. A hole drilled into the ground, from the surface or from underground workings, to secure geological information; also used for the extraction of water, oil, natural gas, salt, sulphur, and for many other mining purposes. A borehole may range from an inch or so to well over 12 inches in diameter and drilled at any angle to many thousands of feet depth.

Core. The cylindrical piece of rock obtained during drilling with a diamond drill or shot drill. The core is recovered from the core barrel and may be from less than an inch to 20 feet or so in length.

Crystalline Form. A mineral is crystalline when the atoms are arranged in a definite geometrical pattern. There are six principal crystal systems and these are specified by the relative lengths and angular relationships of their crystallographic axes.

Dunite. A variety of peridotite consisting of almost pure olivine.

Dyke. A wall-like mass of igneous rock that fills a fissure in pre-existing rocks; often form a group or swarm in which each member is roughly parallel.

Feldspar. A family of rock forming minerals consisting of aluminous silicates of potassium, sodium, calcium, or barium. Greyish-white to red in color.

Fissure. An extensive fracture, crack, or break in rock formations.

Formatinn. A group of rocks which have certain characteristics in common and which were deposited about the same geological period and constitute a convenient unit for description.

Fracture. A break, crack, or any kind of discontinuity in a mass of rock, coal or orebody. It may be produced by tensile stress or shear stress.

Granite. An important and widely distributed igneous rock; coarse-grained, mostly deep-seated or plutonic. It consists of quartz, orthoclase feldspar, and mica. Whitish-grey, grey, reddish to pink in color.

Igneous Rock. A rock formed by the solidification of molten matter (magma) from the earth's interior.

Lustre. The appearance of the surface of a mineral in reflected light. The lustre may differ in degree and kind on different crystal surfaces.

Magma. Molten masses of igneous rock before they have crystallized; silica is the dominant component. On cooling, the other oxides of the magma combine with the silica to form the minerals known as rock-forming silicates.

Metamorphic Rock. A sedimentary or igneous rock which has been altered to such an extent as to erase all resemblance to the original deposit.

Mica. Original constituent of plutonic and volcanic rocks; composed of complex silicates of aluminum and potassium. Distinguished by its splendent pearly lustre, softness, and brown-black or silvery-white color.

Olivine. Magnesium iron orthosilicate, $(MgFe)_2SiO_4$, in which Fe replaces part of the Mg. Shades of green and brown in color.

Orthoclase. Potassium aluminum silicate, $KAlSi_3O_8$. White to pink to grey in color.

Overburden. The barren soil, rock or waste overlying coal, or an orebody at a mine.

Oxides. Compounds of oxygen with another element.

Peridotite. A coarse-grained ultrabasic igneous rock composed dominantly of olivine. Dark colored.

Plagioclase. Silicates of aluminum with calcium and/or sodium. Colorless to white, yellow, red, green, or grey in color. Important mineral in many plutonic and volcanic rocks.

Plutonic Rock. A major group of deep seated, coarse-grained igneous rocks. These rocks solidified at depth below the surface.

Pyroxenes. A group of silicate minerals which similar in certain chermical and physical characteristics. The dark-colored minerals are silicates of iron, calcium, and magnesium, sometimes with aluminum.

Quartz. Oxide of silicon, SiO_2. Colorless to white.

Rock-forming Minerals. The minerals which constitute the treater part of a rock and are necessary to give it its character as a whole.

Sedimentary Rock. A rock produced by the weathering and denudation of pre-existing rocks, and the deposition of the sediment in water or on land. On the basis of origin, a sedimentary rock may be mechanically, chemically, or organically formed.

Seismic Wave Method. A geophysical prospecting method which measures the velocities of shock waves when passing through different rocks. The survey data are interpreted by geophysicists in terms of the nature and structure of the rock formation in depth. The velocities of shock waves vary with the elastic constants and densities of the rocks penetrated. The method is used to locate faults, various geologic structures, and assist in mining.

Silica. Silicon dioxide, SiO_2, a colorless or white mineral; hard and insoluble; very abundant in nature.

Sill. A sheet of igneous rock of considerable lateral extent with fairly uniform thickness.

Stratification. The arrangement of the deposited sediments, and eventually the rocks, in regular layers or beds.

Tectonics. The physical forces which are operative in the earth's crust and their results; closely allied to structural geology.

Ultrabasic Rock. An igneous rock containing less than about 45% silica.

Vitreous. A lustre resembling that of broken glass. Magma which has cooled rather rapidly at the earth's surface is usually vitreous or glassy, or partly glassy and partly crystalline.

Appendix B: Computer Methods

Waveguide Integration

In order to solve Eq (36) for the phase function u, it was necessary to integrate the expression on the right-hand side. A standard library integration subroutine was used, while the main program and the supporting subroutines and functions were original. The chart on the next page shows the general relationships between the various program units, although it is not intended as a formal flow chart. Program listings have not been included, as they were important only in producing the data, not in the method of its production, nor in determining the final system feasibility.

Main Program: NIAM. The main program served primarily to input initial data and to output results. Among the values input by NIAM were the initial parameters for the minimizer, MINUM; values for the frequency, intrinsic dielectric constant, magnetic permeability, and the depth of the waveguide; the initial value of the complex propagation constant, k, and estimated upper and lower limits to the possible values for it; and algebraic and arithmetic constants, calculated from physical constants, to simplifiy later calculations. Many of these parameters and constants were passed to other program units by common storage. The main program then called MINUM. When MINUM returned with the

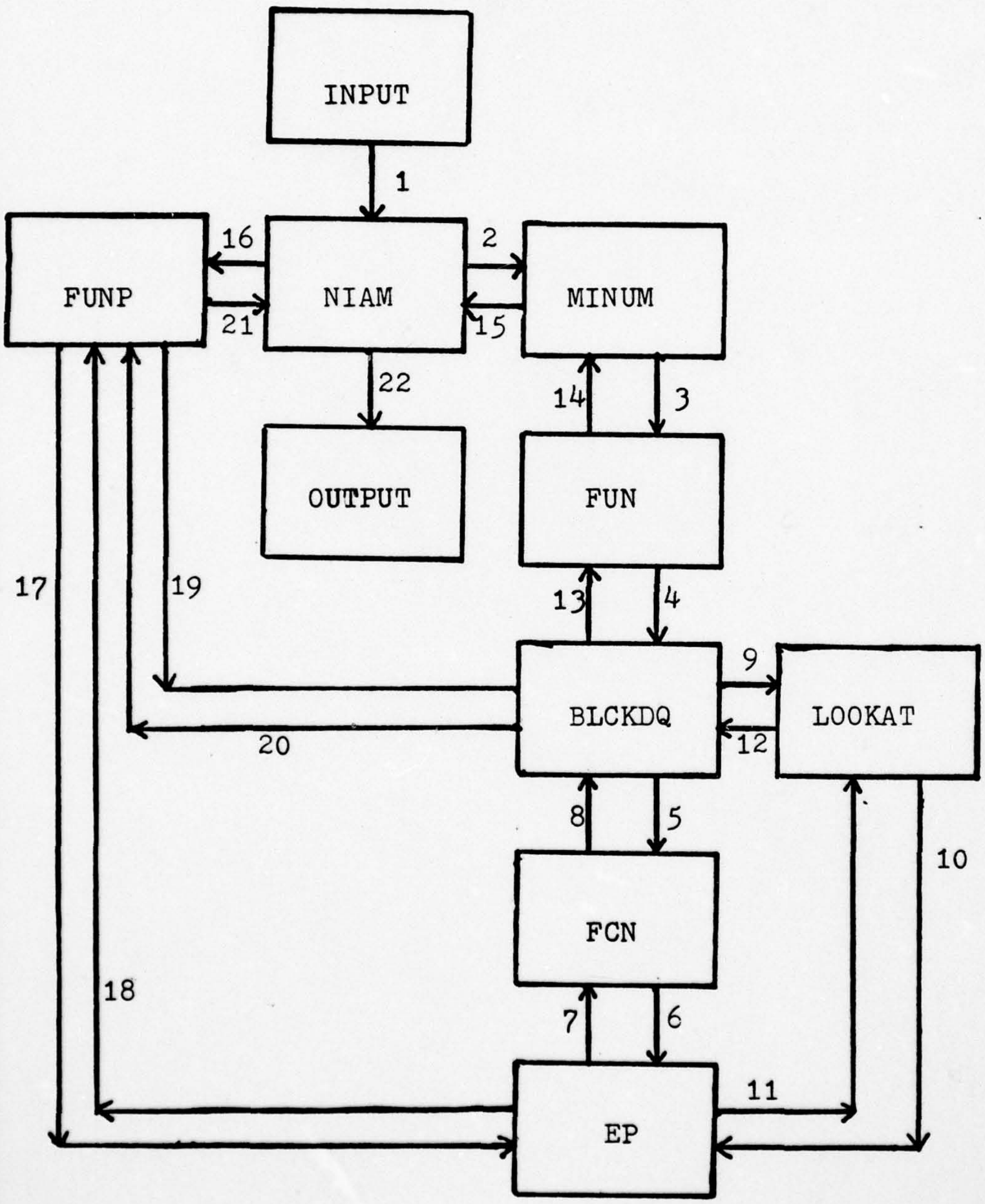

Figure 10. Data Flow Between Program Units (Numbers reflect order of paths)

best values of the k-parameters, NIAM called FUNP, which calculated the best value of k and the phase profile and printed both of them out

Subroutine MINUM. This library routine worked in terms of two parameters that varied between zero and one as the value of k varied between its given limits. The parameters were set to 0.5 in NIAM, in order to start k in the middle of its given range. FUN was then called, which calculated the variance between the value of the phase function at the bottom of the waveguide and the value given by the boundary condition. MINUM attempted to minimize this variance by changing the parameter (and thus k) values in random, gradient, average, and jump step increments. The random steps were determined by a random parameter input in NIAM. The last random numbers used were output for use in the next program run, in order to assure a new set of truly random numbers.

Subroutine FUN. This original subroutine performed several functions. First, the parameters passed from MINUM were converted to k-values using

$$K = KRL + PM(1)(KRU-KRL) + i\{KIL + PM(2)(KIU - KIL)\} \quad (103)$$

This K-value was then used to calculate the initial value of the phase function at the upper waveguide boundary. Then BLCKDQ, the integrator, was called, which returned a final value for the phase function at the lower boundary. FUN

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recalculated the boundary conditions for the lower boundary and compared this value of the pahse function with that returned by BLCKDQ:

$$FUN = \left(\frac{Re(YS - US)}{Re(US)}\right)^2 + \left(\frac{Im(YS - US)}{Im(US) + Re(US) \times 10^{-5}}\right)^2 \quad (104)$$

This function was used, rather than simply subtracting the real and imaginary parts of YS and US, because of the difference in magnitude between the real and imaginary parts of the values. It was necessary to normalize the parts and insure that the values to be minimized would always remain positive. Thus FUN calculated the upper and lower boundary conditions, called BLCKDQ, and calculated the variance of the value of the final integrated phase function from the boundary value.

Subroutine BLCDQ. This library subroutine started with the initial boundary values, calculated in FUN, and solved the complex first-order, ordinary differential equation down to the lower boundary of the waveguide. The integration proceeded from the initial conditions using a starting scheme modelled after Picard's method of successive substitutions and an eighth-order predictor-corrector formula to perform the integration. Error control was effected using local polynomial fit and derivatives determined by the differential equation. Tolerances were relaxed as the solution passed a zero, but not when it tended towards one. Thus BLCKDQ integrated down from the upper boundary condition to the lower one, and output the value of the phase function at the lower boundary condition.

Function FCN. BLCKDQ used this original function subroutine to define the function to be integrated. Because u, the phase function, was complex, the problem was solved as two ordinary differential equations corresponding to the real and imaginary parts of u. As BLCKDQ integrated through the waveguide, FCN was called to calculate the value of du/dz at each given depth.

Function EP. This original function served to define the complex dielectric constant, ϵ. It was defined separately so that the various conductivity profiles could be used to obtain different permittivity functions. The conductivity profiles were expressed in polynomial form, which will be discussed below. In the final forms, after verification of the program had been completed, a logical IF-statement was added to define the discontinuity at the upper boundary. Thus for the expressions defining the upper boundary conditions, a negative argument was used, leading to a definition of the conductivity in terms of the conductivity of seawater-saturated rock. Then for any zero or positive depth, the conductivity function was defined by the polynomial form.

Subroutine LOOKAT. Since it was necessary to have a mechanism that stopped the integration by BLCKDQ, this routine was called at several points in the integration. LOOKAT was used in two forms: a library version that tested whether the given final depth value had been reached, and an original version that also tested whether the conductivity ahd reached a value high enough to prevent wave propagation within the guide (it was assumed that the conductivity decreased within the waveguide region before becoming large once again at greater depths). The latter version of LOOKAT allowed the depth of the waveguide to be determined mainly by the conductivity profile.

<u>Subroutine FUNP</u>. This subroutine, called by NIAM after the return of MINUM, was essentially identical to FUN except that it ran only once. The best parameters returned by MINUM were converted to k-values by FUNP and printed. FUNP also called BLCKDQ in a DO-loop, so that the integration was performed in a series of sixty equal steps. The values of the phase function and depth were printed at each step, providing a phase plot of the impedance function.

<u>Summary</u>. A typical program cycle started with MINUM choosing a set of parameters for k. The propagation constant was then calculated by FUN, and BLCKDQ was called. The function defined by FCN was integrated using the initial conditions from FUN, in accordance with the conductivity-depth profile in the function EP. When LOOKAT determined that the bottom of the waveguide had been reached, BLCKDQ returned the final phase function values to FUN. The variance from lower boundary conditions was calculated by FUN, which then returned to MINUM for a new set of k-parameters.

When the designated number of trials had been made, MINUM called FUNP, which calculated and printed the best value of k. FUNP also printed the real and imaginary parts of the phase function as a function of depth. By adjusting the upper and lower limits on k, in successive program runs, the variance of the phase function from the boundary conditions was made as small as possible, usually on the order of 10^{-2}. This "fine-tuning" enabled accurate results for the best value of k.

Conductivity Data: Program FIT

The conductivity data was obtained from published curves of empirical data, in the form of a set of discrete values. To facilitate input to the function EP, it was necessary to compute a functional form to fit these discrete values. A fourth-order polynomial

$$Az^4 + Bz^3 + Cz^2 + Dz + E = \ln \sigma \tag{105}$$

was used. The set of equations in this form, derived from the discrete data were expressed as a matrix equation

$$\overline{Z} \cdot \overline{A} = \overline{S} \tag{106}$$

where $\overline{A}$ was the coefficient matrix, which was unknown, $\overline{Z}$ was a square, symmetric, positive-definite matrix of the known depth values, and $\overline{S}$ was the conductivity matrix. A standard library subroutine, MESCHP, was used to decompose

$\overline{Z}$ by the method of Choleski into the form

$$\overline{Z} = \overline{L}\overline{L}^T \tag{107}$$

where $\overline{L}^T$ was the transpose matrix of $\overline{L}$ and $\overline{L}$ was lower-left triangular. Thus

$$\overline{L} \cdot \overline{y} = \overline{S} \tag{108}$$

and

$$\overline{L}^T \cdot \overline{A} = \overline{y} \tag{109}$$

were solved by forward and backward substitution. Thus $\overline{A}$ was obtained, which contained the coefficients used to form the conducitivty-depth function. A set of plots were made for each set of data and the corresponding functions, showing the accuracy of the functional fit to the actual data. These plots are in the Appendix following.

Appendix C: Conductivity Profiles

Contained herein are the computer-generated plots of the conductivity data taken from empirical curves in the literature, and their corresponding curve-fit functions. Except for the first two, they are all applicable to the crust under the continents, either because the sources stated that they were measured on the continental crust, or because the geophysical discussion accompanying them in the literature indicated a continental crust. These are included because of the age of the oceanic profiles available and because there are only two specifically oceanic profiles that could be found.

Figures 11 and 12: Profiles from H. Mott and A.W. Biggs (Ref 3:324-326). These are composite oceanic profiles, based on two other profiles, obtained by different methods. The near-surface values for both were taken from studies made by Garland and Webster on basement rock in western Canada (Ref 20:27). The method used involved comparison of magnetic and electric field components of the natural geomagnetic field. From 10-60 km the data was based on experimental measurements by Hughes, performed on olivines at various temperatures (Ref 28). The curves themselves required an assumed linear temperature-depth gradient of 19^{o}/km (Ref 3:324).

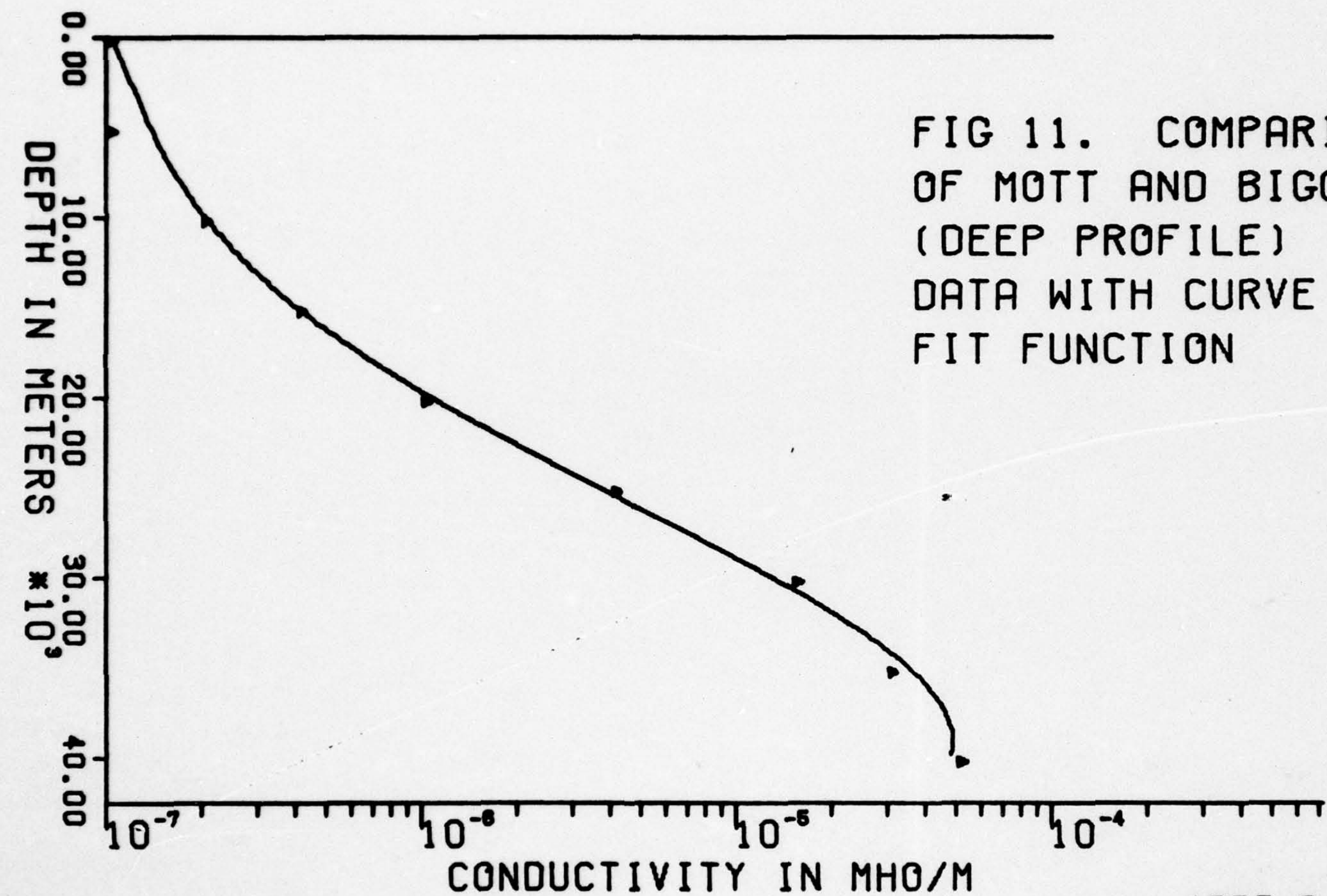

FIG 11. COMPARISON OF MOTT AND BIGGS (DEEP PROFILE) DATA WITH CURVE FIT FUNCTION

(REF 3:326)

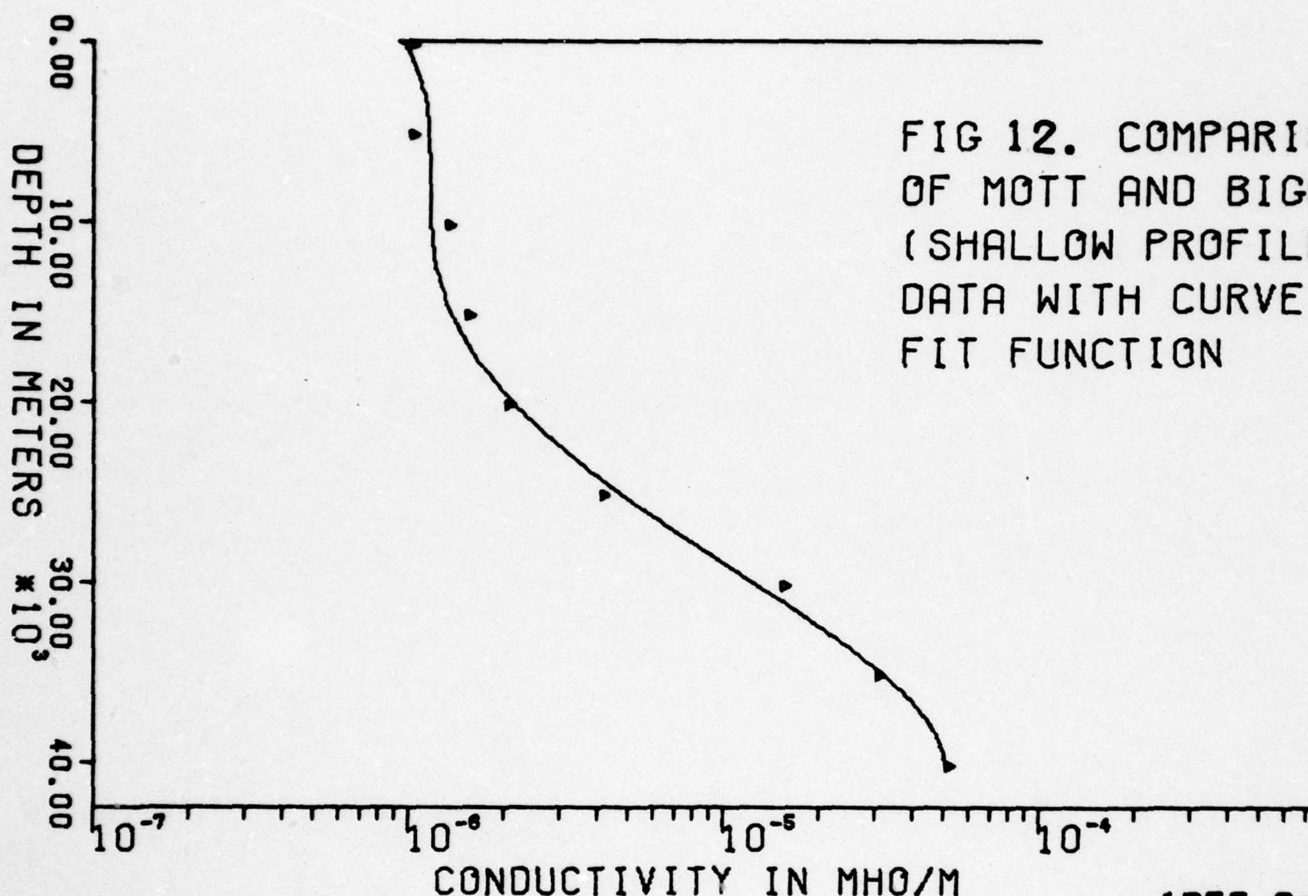

FIG 12. COMPARISON OF MOTT AND BIGGS (SHALLOW PROFILE) DATA WITH CURVE FIT FUNCTION

(REF 3:326)

Figure 13: Profile by Keller From Gallawa and Haidle (Ref 25:44). This continental profile was based on the average of well log measurements at two locations, separated by about fifty miles and in differenct rock formations. The lower part was derived from in-laboratory dry rock sample measurements. A thermal gradient of 16^{o}/km in the crust was assumed. As this profile was originally contained in a private communication, it was first published by Gallawa and Haidle, even though it was authored by Keller.

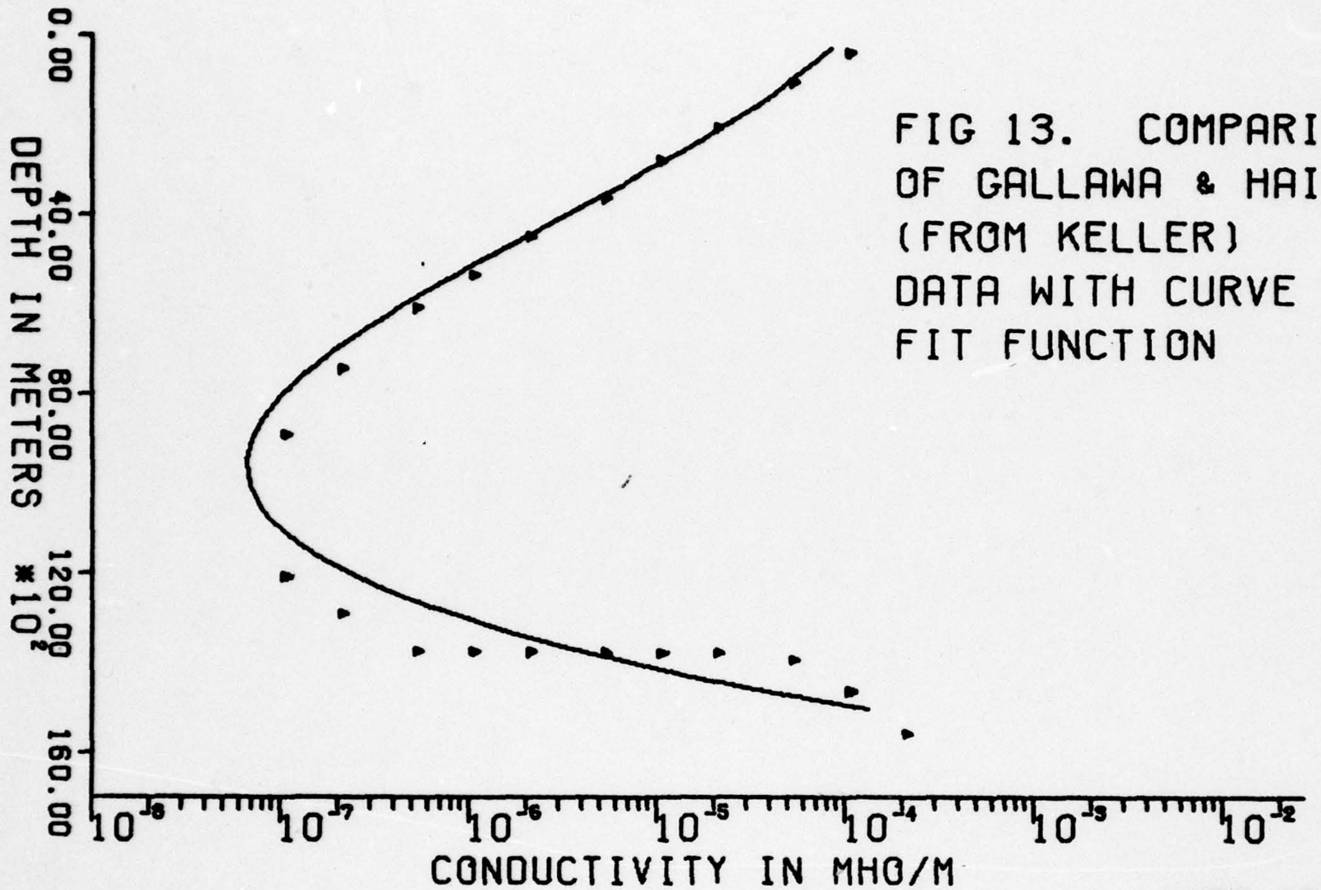

FIG 13. COMPARISON OF GALLAWA & HAIDLE (FROM KELLER) DATA WITH CURVE FIT FUNCTION

(REF 25:44)

Figures 14 and 15: Profiles by Simmons, Housely, and Forin (Ref 29) from Field and Dore (Ref 4:10-12). These two continental profiles were the results of laboratory measurements based on two relatively new and controversial concepts: 1) that fluid-filled microcracks are present in rock removed from deep in the earth, and cannot be closed by reapplying pressures and temperatures comparable to those in the rocks' original locations. Thus laboratory measurements resulted in significantly higher conductivities than may be present within the earth. 2) The partial pressure of oxygen, different for deep in the earth from at the surface, has an effect on laboratory conductivity measurements. The two profiles vary due to different thermal gradients: BR, 24^{o}/km; EUS, 14^{o}/km.

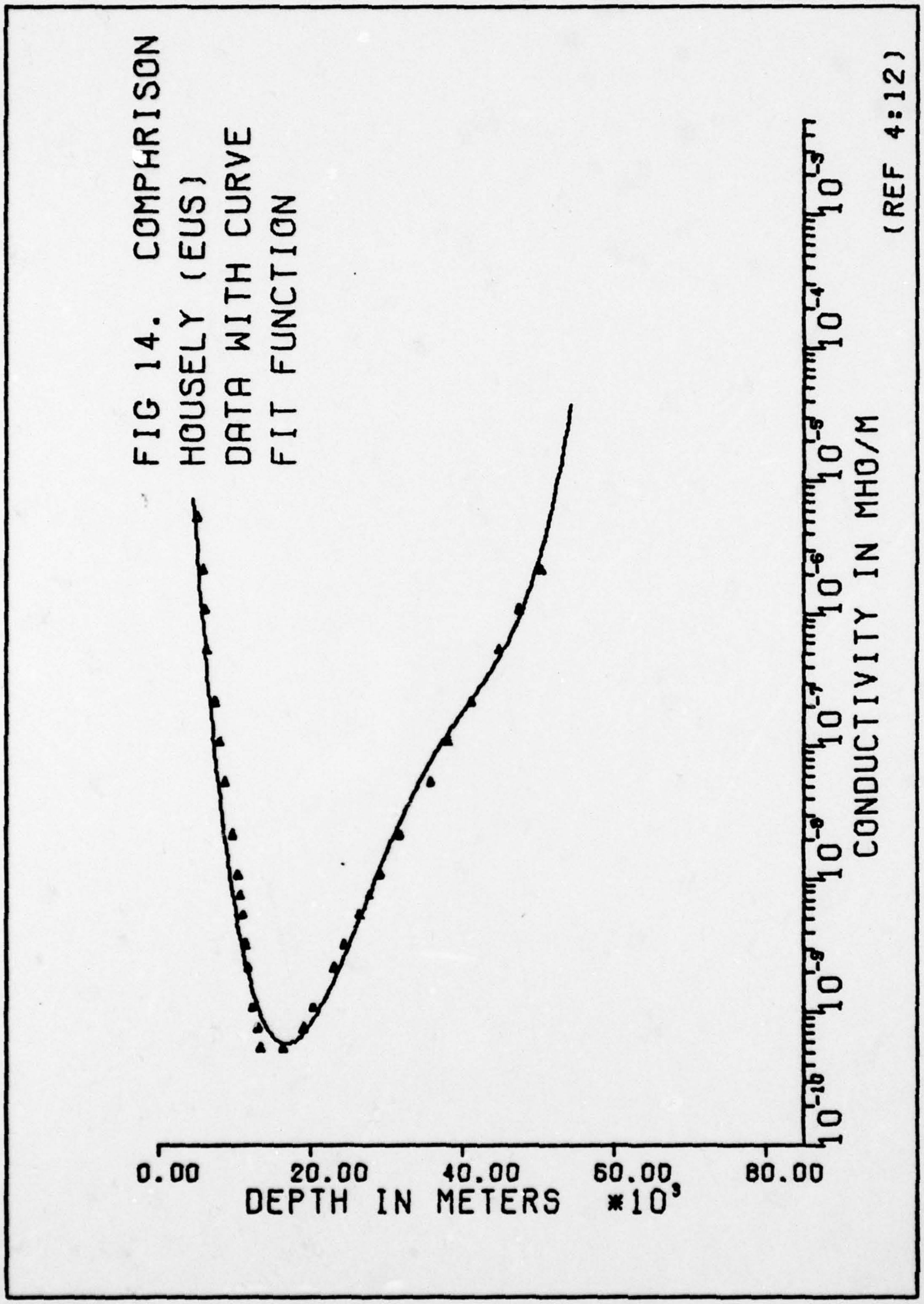

FIG 14. COMPARISON HOUSELY (EUS) DATA WITH CURVE FIT FUNCTION

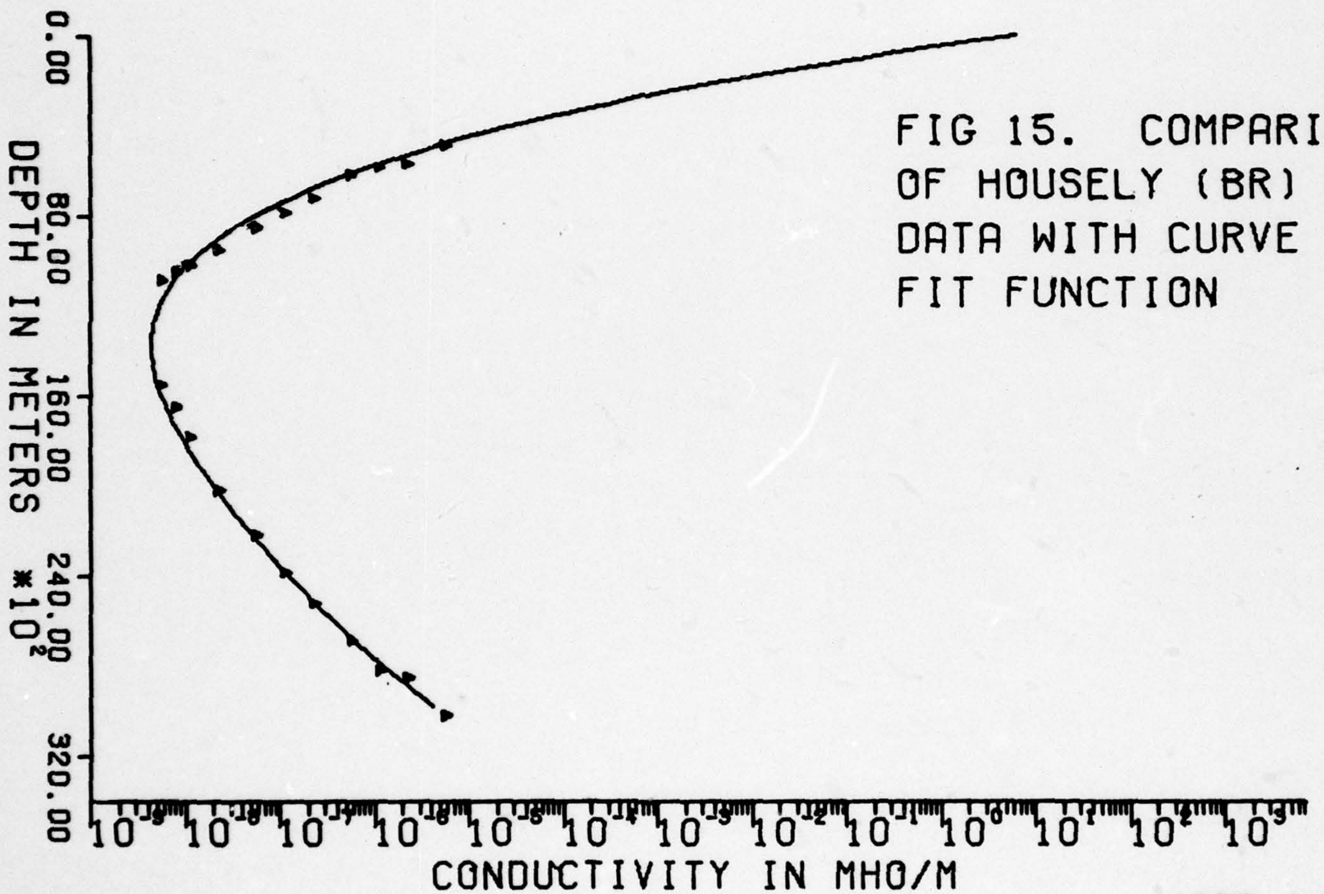

FIG 15. COMPARISON OF HOUSELY (BR) DATA WITH CURVE FIT FUNCTION

(REF 4:12)

Figure 16: Profile from Schwering, Peterson, and Levin (Ref 30), in Levin (Ref 21:334). This continental profile represents the concept of a two-part conductivity function. The upper segment has a decreasing conductivity as the water content decreases in the rock, due to temperature and pressure effects. This is the reason for referring to the profile as "dry". The lower segment, below ten kilometers, reflects the increasing temperature effects, which produce dominant electronic conductivity effects.

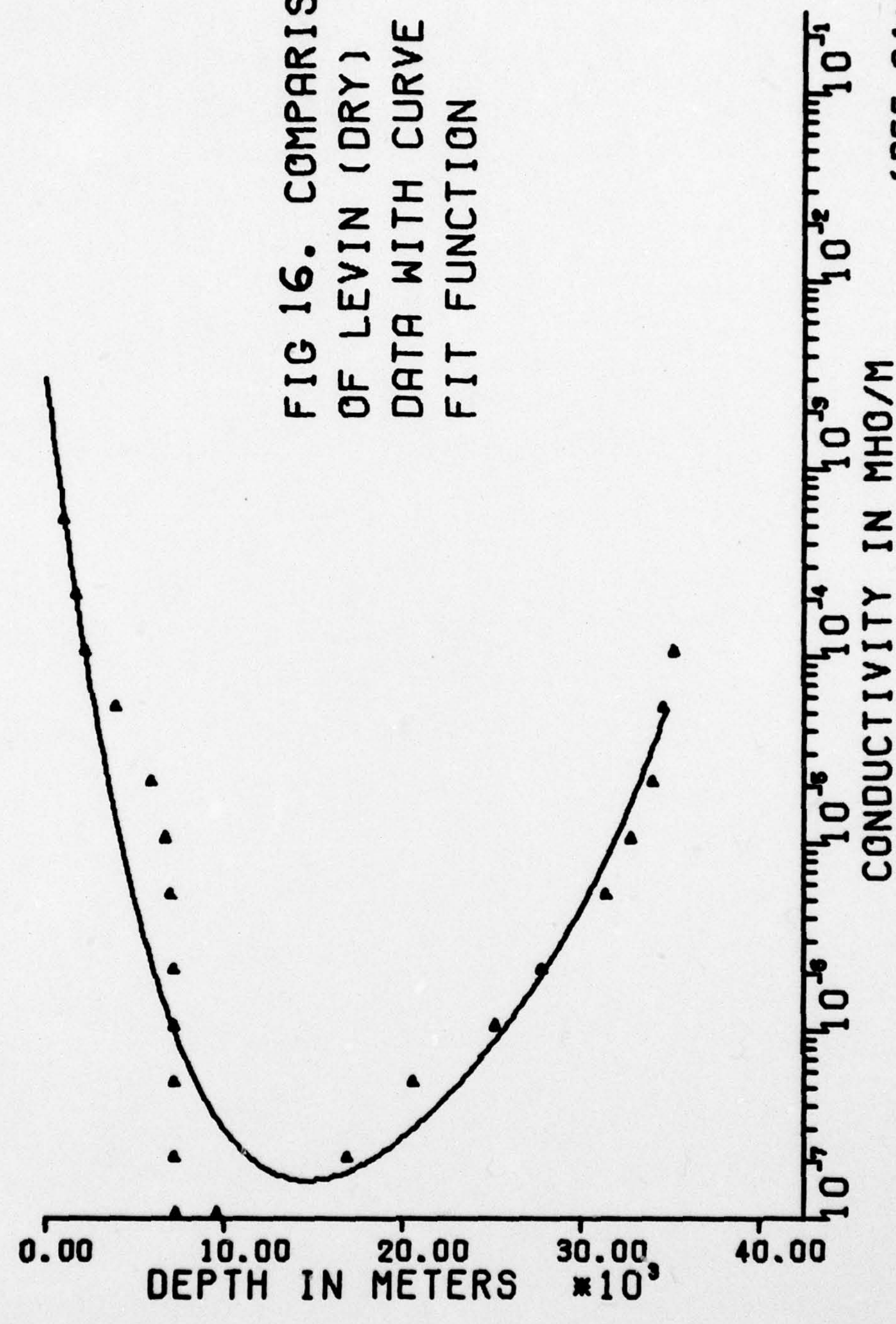

FIG 16. COMPARISON OF LEVIN (DRY) DATA WITH CURVE FIT FUNCTION

(REF 21:334)

Figure 17: Profile from Brace (Ref 31:10) in Levin (Ref 21:334). This continental profile was based on the concept that the electrolytic conductivity from interstitial fluids was the primary effect down to a depth of 30 km, where the electronic effects became dominant. The presence of a water content throughout the upper segment of the profile accounts for its being called "wet".

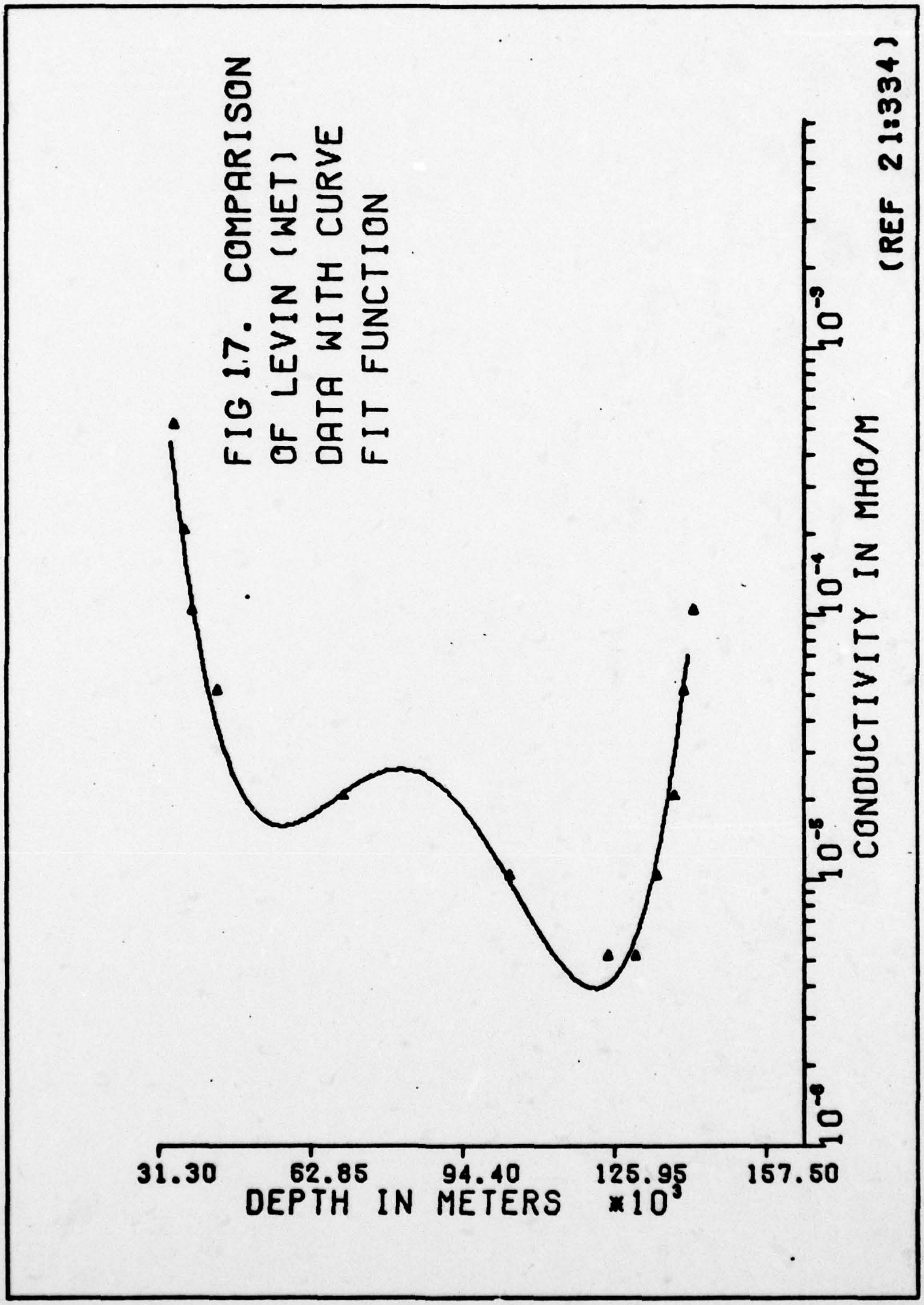

FIG 1.7. COMPARISON OF LEVIN (WET) DATA WITH CURVE FIT FUNCTION

Appendix D: Quadratic Curve-Fit For Attenuation-Frequency Function

The assumption was made that the attenuation, as a function of the logarithm of the frequency, could be expressed as a quadratic equation:

$$(\beta - \beta_o)^2 = 4a(\alpha - \alpha_o) \tag{110}$$

where

$$\beta = \log_{10}\omega \tag{111}$$

and where a is a constant and the minimum point of the semilog parabola is at (β_o, α_o). The method used to calculate the *minimum frequency* ω_o was as follows.

Given

$$(\beta_1,\alpha_1) \qquad (\beta_2,\alpha_2) \qquad (\beta_3,\alpha_3) \tag{112}$$

calculate

$$z_1 = \alpha_1(\beta_2 + \beta_3) \tag{113}$$

$$z_2 = \alpha_2(\beta_1 + \beta_3) \tag{114}$$

$$z_3 = \alpha_3(\beta_1 + \beta_2) \tag{115}$$

The minimum is

$$\beta_o = \frac{\{\beta_1\beta_2\beta_3\}_z}{2\{\beta_1\beta_2\beta_3\}_\alpha} \tag{116}$$

where

$$\{\beta_1\beta_2\beta_3\}_z = \frac{\{\beta_1\beta_2\}_z - \{\beta_2\beta_3\}_z}{\beta_1 - \beta_3} \tag{117}$$

and

$$\{\beta_1\beta_2\}_z = \frac{z_1 - z_2}{\beta_1 - \beta_2} \tag{118}$$

The minimum attenuation was obtained from the parabolic equation, Eq (110), above. The minimum value β_o was substituted from the first calculation, along with two sets of values from Table II. The constant a was then eliminated from the two equations, and the minimum value α_o was calculated.

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The feasibility of using the earth's crust under the oceans as a communications channel for very low frequency waves was studied. The structure of the crust and its electrical properties were used to evaluate the conductivity-depth profiles found in the literature. Using the impedance, E_x/H_y, a new phase function was defined that not only made the phase changes at the boundaries of the waveguide explicit, but also allowed the use of a computer for calculation

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) of the propagation and attenuation constants.

The system noise was assumed to come from two main sources: atmospherics and thermal effects. Calculation showed that beneath the ocean the atmospheric noise could be neglected. The thermal noise within the waveguide was calculated to be -162 dBm. The attenuation for the TM_{10} mode was calculated to be -1.35 dBm/km, thus allowing a transmission range of only about 163 km for 1 kW of transmitted power. The conclusion was that despite the aesthetic appeal of the idea, the crust under the ocean was not feasible as a long-range communications channel at VLF for the TM_{10} mode.