

RADC-TR-77-108
Final Report
March 1977

Scientific Report No. 23

MODAL CHARACTERISTICS OF SINGLE AND DUAL WIRES
LOCATED OVER A DISSIPATIVE EARTH

by

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March 1977

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ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER RADC-TR-77-108	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Final Report on MODAL CHARACTERISTICS OF SINGLE AND DUAL WIRES LOCATED OVER A DISSIPATIVE EARTH		5. TYPE OF REPORT & PERIOD COVERED Final Report 1 Nov. '75 - 30 Sept. '76
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) David C. Chang		8. CONTRACT OR GRANT NUMBER(s) 19628-76-C-0099
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Electrical Engineering University of Colorado Boulder, Colo. 80309		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 21530401
11. CONTROLLING OFFICE NAME AND ADDRESS Deputy for Electronic Technology (RADC/ETEP) Hanscom AFB, Massachusetts 01731 Monitor/Walter Rotman		12. REPORT DATE March 1977
		13. NUMBER OF PAGES 19 pp.
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Single and dual wires Goubau-line over earth Open waveguide Mode propagation Mode excitation		
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continued #20.

been given to the development of excitation schemes for low attenuation modes, to the problem of mode conversion due to irregularities in the immediate vicinity of a guiding structure and to the calculation of radiation loss in the presence of bends among others.

MODAL CHARACTERISTICS OF SINGLE AND DUAL WIRES
LOCATED OVER A DISSIPATIVE EARTH

1. Introduction

The objective of this research project is to investigate the characteristics of discrete guided wave modes supported by open structures near a dissipative earth. Possible engineering application is found in radar traffic control, airport surveillance and other similar problems. Since the beginning of this contract, considerable progress has been made towards a better understanding of electromagnetic propagation on thin-wire structures located above earth in general, and the characteristics of guided modes on a single or dual line of bare-wires and dielectrically-coated wires in particular. Attention also has been given to the development of excitation schemes for low attenuation modes, to the problem of mode conversion due to irregularities in the immediate vicinity of a guiding structure and to the calculation of radiation loss in the presence of bends among others.

2. Summary of Work Completed

In this section we shall summarize work conducted under this contract for the entire funding period from November 1, 1975 to October 31, 1976. Detailed description of this work is given either in the form of technical reports and papers published previously under the contract, or in the appendices of this report.

2.1 Modal Representation of a Horizontal Wire Above a Finitely Conducting Earth

A general formulation for the excitation of discrete modes by an arbitrarily-oriented electric or magnetic dipole is found rigorously in this work. The derivation is extended to include an aperture field of arbitrary form in the transverse plane. As a consequence, we are able to prove that the current on a thin wire parallel to a conducting half space may be uniquely decomposed into discrete and continuous modal components, and that any of the discrete modes may be excited with arbitrarily high efficiency and to the exclusion of the other modes by appropriately matching an aperture field to that of the desired mode. This means that even though the radiation or continuous type currents must eventually dominate the discrete modal currents on the wire in a lossy environment, the discrete components however can be made to dominate over an arbitrarily long portion of the wire, so that the concept of modal representation will still have important utility in practical applications. Moreover, the modal representation is always rigorous and the attendant orthogonality properties are useful in solving problems wherein the wire is not infinite or possesses discontinuities, as straightforward generalizations, at least in principle, of closed waveguide techniques. The dependence of the modal propagation constants of the discrete modes upon various physical parameters is then investigated numerically in detail for a single Goubau-line over a typical earth, and the possibility for mode degeneration is demonstrated. Field plots of the discrete modes in a cross-sectional plane further indicates the qualitative differences between the two modes commonly known as the transmission-line mode and the earth-attached mode. It is observed that the attenuation constant of the earth-attached mode is generally smaller than the transmission-line mode

at low heights, say, less than a quarter wavelength, but the opposite is true for heights greater than a free-space wavelength. Degeneracy of the two modes is also shown to be possible for some selective heights as well as coating parameters of a Goubau line. Detail discussion of this work is given in Interim Technical Report RADC-TR-76-287, September 1976.

2.2 Characteristics of Discrete Propagation Modes on a System of Horizontal Wires over Dissipative Earth

The question whether a dual line can be used more effectively than a single line for the application in a radar detection system is a particularly worthwhile one to investigate. In this work the equation for determining the propagation constants of the discrete modes on a system of m parallel lines above a dissipative earth is derived. By first deriving approximate expressions for the Sommerfeld integrals involved in the modal equation that are accurate for a typical earth, we have calculated the propagation constants for a dual line of identical bare wires. We find that there are two monofilar modes and one or two bifilar modes depending on the spacing between the wires. Typically the electromagnetic field associated with a bifilar mode can be more confined to the region between the two wires while the field of a monofilar mode can be more spread out into the region outside the wire. The earth-attached monofilar mode is usually less attenuated than the transmission-line-like bifilar mode for spacings larger than the wire height; however for very small spacings the bifilar mode has the lower attenuation. On the other hand, attenuation of the transmission-line-like monofilar mode usually increases initially as the spacing decreases until it is approximately equal to the wire height. After this point, it starts to decrease and approaches the value of the single wire mode. This mode seems always to have an attenuation constant

much larger than the other ones. The fourth mode, i.e. an earth-attached bifilar mode, exists only where the spacing between the two is at least equal to several wavelengths in full-space. However, degeneracy of the two bifilar modes is observed for certain wire heights. Detailed discussion of this work is given in an RADC Interim Technical Report (pending approval).

2.3 Time Causal Characteristics of Leaky and Surface Waves

Since the thin-wire structure of interest in this research supports either a surface-wave or a leaky-wave type of modes, the time-causal properties of these modes are investigated. For leaky modes, the field increases exponentially in the transverse plane and at the same time attenuates axially. Thus, there exists a critical cone spatially outside of which the radiation condition is not satisfied. For surface-wave modes, the field is radially attenuated in the absence of losses. But to provide the energy absorbed in the lossy space the radial characteristics also involve an incoming radial wave feature. Although there is no critical cone in this case the situation is not unlike that of the leaky wave in that the surface wave merges with the source radiation, which eventually takes over at large distances, and satisfies the radiation condition at infinity. For an idealized model of a thin-wire characterized by a constant reactive surface, our analysis shows that both the leaky wave and the Goubau surface wave, taken in isolation without consideration of other fields that would be present when generated by a finite source, indeed possesses a time precursor when a time-harmonic source is initially switched on. However since the structure of these waves is frequency-dependent and since all frequencies are generated by switching on, individual modes of this kind can not be taken in isolation when one considers the transient response of a source-related problem.

2.4 Thin-wire Approximation in Analysis of Wave Propagation Along a Wire over a Ground

Since the analysis of wave propagation along a wire structure can be greatly simplified by the use of the so-called thin-wire approximation which assumes no azimuthal variation of surface current on the wire, validity of this approximation has been carefully examined. The investigation is carried out by first formulating the problem of wave propagation along a perfectly conducting cylindrical wire parallel to a plane interface between two dissimilar materials rigorously, and then expressing the modal equation for discrete propagating modes retaining only the zero-order and first-order terms in the azimuthal variation. Comparison of the first-order terms with the zero order ones then yields a criterion for the determination of the error incurred in the thin-wire approximation. Validity of the approximation is discussed for two cases; one corresponds to the case of a wire height much smaller than the skin-depth of earth and the other for height greater than several free-space wavelengths. In both cases, the use of the thin-wire approximation seems to be justified for typical parameters chosen. It is also shown that the first order current becomes more significant as the height decreases before the propagation constant is significantly modified. Detailed discussion of this work is given in RADC-TR-76-373.

2.5 Excitation of Current on a Horizontal Wire Above Earth by an Electric Dipole Source

As a first step leading to the study of the mode conversion in the presence of an anomaly, the problem of dipole excitation is investigated. An expression for current on the wire due to a vertical dipole located directly above the wire is first derived and a closed-form expression for the case where the dipole is electrically distant from the wire, is

obtained. Current distribution along the wire is then computed numerically for an arbitrarily-located dipole, including the case of interest where the dipole source is right on the earth surface and away from the wire. Detailed discussion of this work will be given in an Interim Technical Report under preparation and a paper entitled "The Excitation of Current on an Infinite Horizontal Wire above Earth by a Vertical Electrical Dipole" by R.G. Olsen and M.A. Usta which is supported in part by this project.

2.6 Radiation Loss of a Curved Goubau-Line

To understand quantitatively the effect of bends in the waveguiding structure in actual installations, effort has been expended in determining the continuous radiation loss of a surface-wave propagating along a curved Goubau-line in free space. A general scheme for calculating the change in the complex propagation constant of a surface-wave mode on a general open waveguide structure is presented. It is shown that the loss formulas require knowledge only of the fields and propagation constant of the corresponding straight waveguide mode, and the value of the radius of curvature of the waveguide axis. As the radius of curvature decreases, the total radiation loss over a curved section of fixed angle and finite length (in decibels) increases initially like $kR^{\frac{1}{2}}\exp(-kR\alpha)$ where k is the wavenumber and R is the radius and α is a constant usually dependent upon how closely the surface-wave is confined to the line. Detailed description of this work is given by a paper entitled "Radiation and propagation of a surface-wave mode on a curved open waveguide of arbitrary cross section" by D.C. Chang and E.F. Kuester, and in Appendix A where the specific case of a dielectrically-coated thin wire is discussed. Radiation from a bend between two straight sections of open waveguide is treated by Maley in a report to be written soon.

2.7 Analysis of Semi-infinite and of Finite Thin-Wires Above the Earth

To investigate the standing wave produced by the truncation of an infinite wire, the problem of a semi-infinite wire is solved using Wiener-Hopf techniques. It is found that the end effect can be expressed as a single reflection parameter which is a function of the height of the wire, and the electrical properties of the earth for points not very close to the end of the wire. Representation of the end effect in this manner leads to a simple theory for long finite horizontal antennas similar to that found in transmission line problems. Input conductance changes as a function of earth parameters for a resonant and an antiresonant antenna are then presented. Detail discussion of this work is given in a technical paper entitled "Analysis of semi-infinite and finite thin-wire antennas above a dissipative earth" by R.G. Olsen and D.C. Chang, which is supported in part by this project.

2.8 Microwave Model Study of a Goubau-line Above a Simulated Earth

We have also conducted an experimental investigation of electromagnetic waves on a Goubau-line over a conducting half-space in a laboratory-scaled model at microwave frequency (8 - 12 GHz). Employing basically the concept of an open resonator, a swept-frequency technique was developed in which the propagation constant of waves existed on an electrically-long Goubau-line (several tens of free-space wavelengths) located between two vertical metallic screens, can be determined from measurements of the resonant frequencies of several consecutive resonances. This technique is proven to be a very effective one whenever the open resonator made up by the Goubau-line and the two metallic screens, has a high Q-factor and

thus, sharp resonances. Experimental results thus obtained are shown to be in agreement with theoretical calculation in the case of an isolated Goubau-line and the case when the line is located above a highly-conducting earth. However, due to limitation in the performance of the swept-frequency generator and the overall sensitivity of the detection system, less than satisfactory results are obtained for a low-Q resonator as the external line resonances and the fluctuation in the input frequency response becomes significant. Consequently, only limited a degree of success has been achieved so far in the case when the Goubau-line is located very close to dissipative earth material. A more detailed description of the experimental work is given in Appendix B.

3. List of Personnel Involved in the Research

Principal Investigator:

Dr. David C. Chang, Professor of Electrical Engineering

Associate Investigators:

Dr. Leonard Lewin, Professor of Electrical Engineering

Dr. Samuel W. Maley, Professor of Electrical Engineering

Dr. Edward F. Kuester, Research Assistant Professor

Visiting Research Scientists:

Dr. Robert G. Olsen, Assistant Professor of Electrical Engineering
Washington State University

Dr. Ronald J. Pogorzelski, Associate Professor of Electrical
Engineering, University of Mississippi

Graduate Research Assistants:

Mr. Ahmed Abul-Kassem

Mr. Steve Plate

Mr. Ahmed Hoorfar

4. List of Publications

E.F. Kuester and D.C. Chang, "Modal Representation of a Horizontal Wire above a Finitely Conducting Earth," Interim Technical Report RADC-TR-76-287, Rome Air Development Center, Griffiss AFB, New York 13441, Sept. 1976.

L. Lewin, "Some Comments on the Time-Causal Characteristics of Leaky and Surface Waves," Interim Technical Report RADC-TR-76-374, Rome Air Development Center, Griffiss AFB, New York 13441, Nov. 1976.

R.J. Pogorzelski and D.C. Chang, "On the Validity of the Thin Wire Approximation in Analysis of Wave Propagation along a Wire over a Ground," Interim Technical Report RADC-TR-76-373, Rome Air Development Center, Griffiss AFB, New York 13441, Nov. 1976.

S. Plate, D.C. Chang and E.F. Kuester, "Characteristics of Discrete Propagation Modes on a System of Horizontal Wires over a Dissipative Earth," Interim Technical Report, Rome Air Development Center, Griffiss AFB, New York 13441 (submitted for approval).

D.C. Chang and E.F. Kuester, "Radiation and Propagation of a Surface Wave Mode on a Curved Open Waveguide of Arbitrary Cross Section,"* Radio Science, Vol. 11, No. 5, 449-457, May 1976.

R.G. Olsen and D.C. Chang, "Analysis of Semi-infinite and Finite Thin-wire Antennas above a Dissipative Earth,"* Radio Science, Vol. 11, No. 11, November 1976.

R.G. Olsen and M.A. Usta, "The Excitation of Current on an Infinite Horizontal Wire above Earth by a Vertical Electric Dipole,"* submitted to Radio Science for Publication.

*Supported in part by this project.

APPENDIX A

Expression for the continuous radiation loss of a surface-wave on a curved Goubau-line in free-space was previously derived in [1,2]. In this Appendix, some numerical results are given for G-lines. Using small argument expansions for Bessel functions appropriate for wires that are thin compared to a wavelength, we can re-express the attenuation constant of a surface-wave, i.e. (30) of [1] as

$$\alpha/k_o = c/k_o p = \left(\frac{\pi}{k_o R}\right)^{\frac{1}{2}} \frac{e^{-2\tau_o} [1 + \lambda_o^2 \sin^2 \phi_o]}{4v_o} \frac{\lambda_o^{5/2}}{2\left(\frac{n^2-1}{n^2}\right) \ln(b/a) - \lambda_o^2 - \left(\frac{n^2-1}{n^4}\right) \kappa_o^4 k_o^2 b^2 [\ln(b/a)]^2}$$

where

k_o = wave number in free-space = $2\pi f/c$ where f is the operating frequency and $c = 3 \times 10^8$ is the speed of light in free-space;

ϕ_o = polarization of the field with respect to the bending axis (minimum attenuation occurs at $\sin^2 \phi_o = 0$);

n = refractive index of the coating material;

a = radius of the wire;

$b - a$ = thickness of the dielectric coating;

R = radius of curvature of a curved line

v_o = propagation constant of the surface-wave on a straight line;

$\lambda_o = (v_o^2 - 1)^{\frac{1}{2}}$ and $\kappa_o = (n^2 - v_o^2)^{\frac{1}{2}}$.

Thus, the power carried by a given surface-wave mode attenuates as $\exp(-2\alpha R \phi)$ where ϕ is the total bending angle.

In Fig. 1, the value of $\Delta = 2\alpha R \phi$ is plotted as a function of the radius of curvature for the polarization where $\phi_o = 0$; $a = 1.587$ cm, $b = 1.908$ cm, $n = 1.581$ and $f = 100$ MHz. For this case we find $v_o = 1.01028$,

$\lambda_0 = 0.14373$, $k_0 = 1.2161$. It appears that more than 10% loss in power occurs when the normalized radius of curvature $k_0 R$ is 1640 or $R = 260\lambda$, and a 30% loss occurs for $R = 158\lambda$. The radiation loss formula loses validity when $\lambda_0^3 k_0 R$ becomes comparable to or smaller than one; radiation loss is still expected to increase, but should behave qualitatively more like a sharp angle junction. Some experimental work in this parameter range has appeared in the literature [3], as well as for a related structure, the image line [4] but some discrepancy appears to exist with other theoretical [5-8] and experimental [7,8] work on sharp angle bends. According to [5-8], the power loss for a small angle ϕ of bend is predicted to be proportional to

$$P_{\text{ang}} \propto \left(\frac{\phi}{\lambda_0}\right)^2$$

and virtually all power is lost for a bend of $\phi = 90^\circ$ (see [6]). As frequency increases, the surface wave becomes more tightly bound, λ_0 increases and hence the power loss decreases.

The effect of doubling the thickness of the dielectric layer is shown in Fig. 2; here $b = 2.23$ cm (again at 100 MHz). In this case

$$v_0 = 1.075$$

$$\lambda_0 = 0.39442$$

$$k_0 = 1.1593$$

and it can be seen how the loss is reduced because of the well-bound surface mode. This same line, operated at $f = 76$ MHz is shown in Fig. 3. That the mode is less well bound at this frequency is evident, but clearly the loss is increased much more by reducing the thickness of the coating as in Fig. 1.

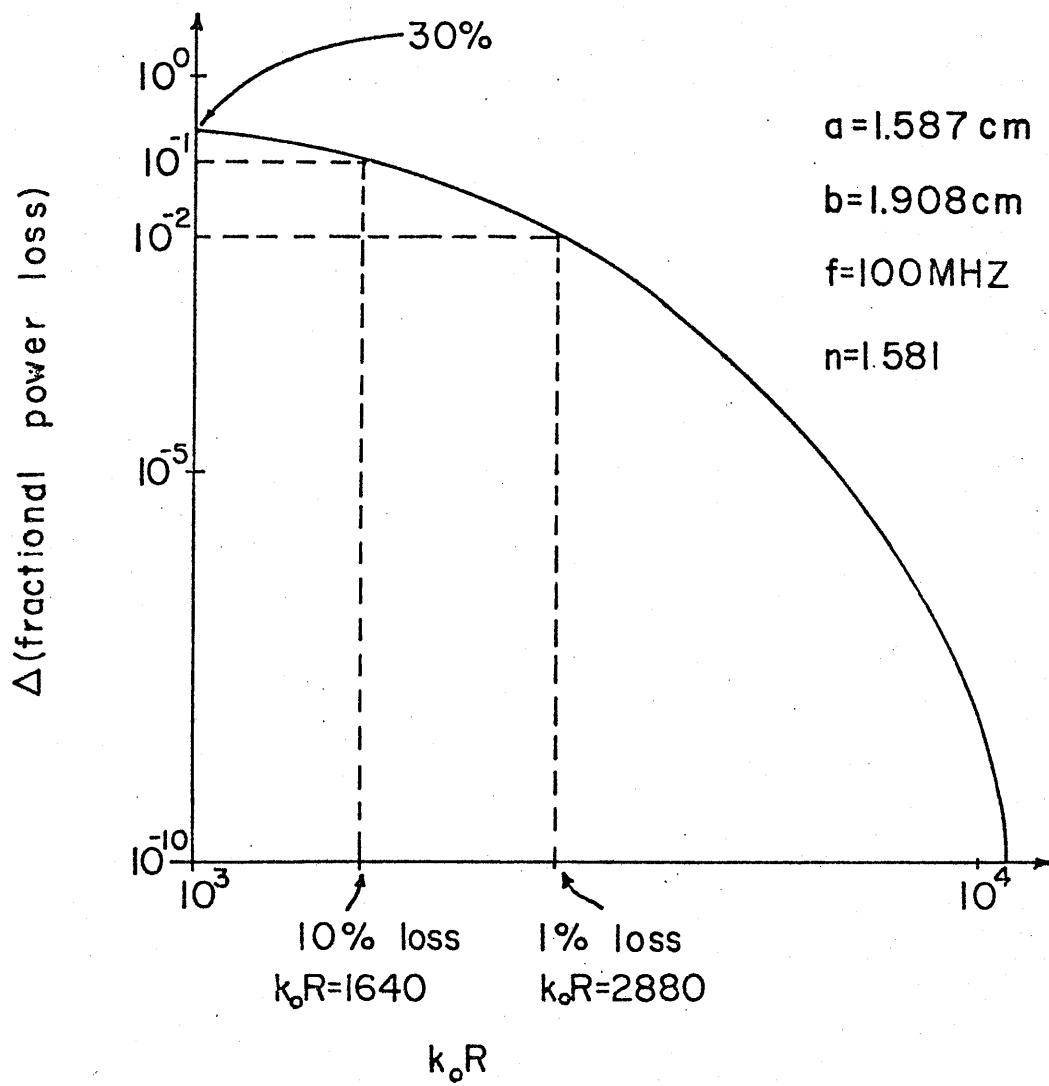


Figure 1

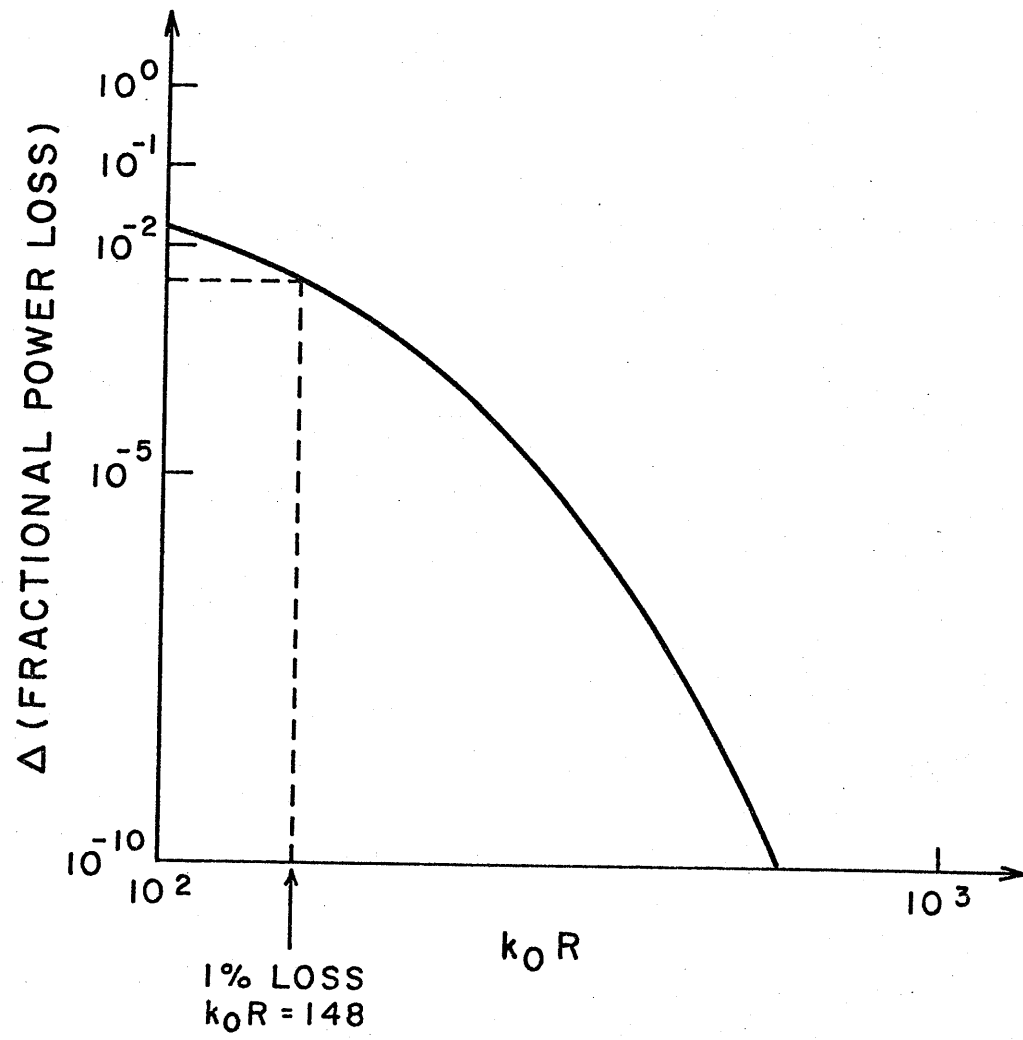


Figure 2

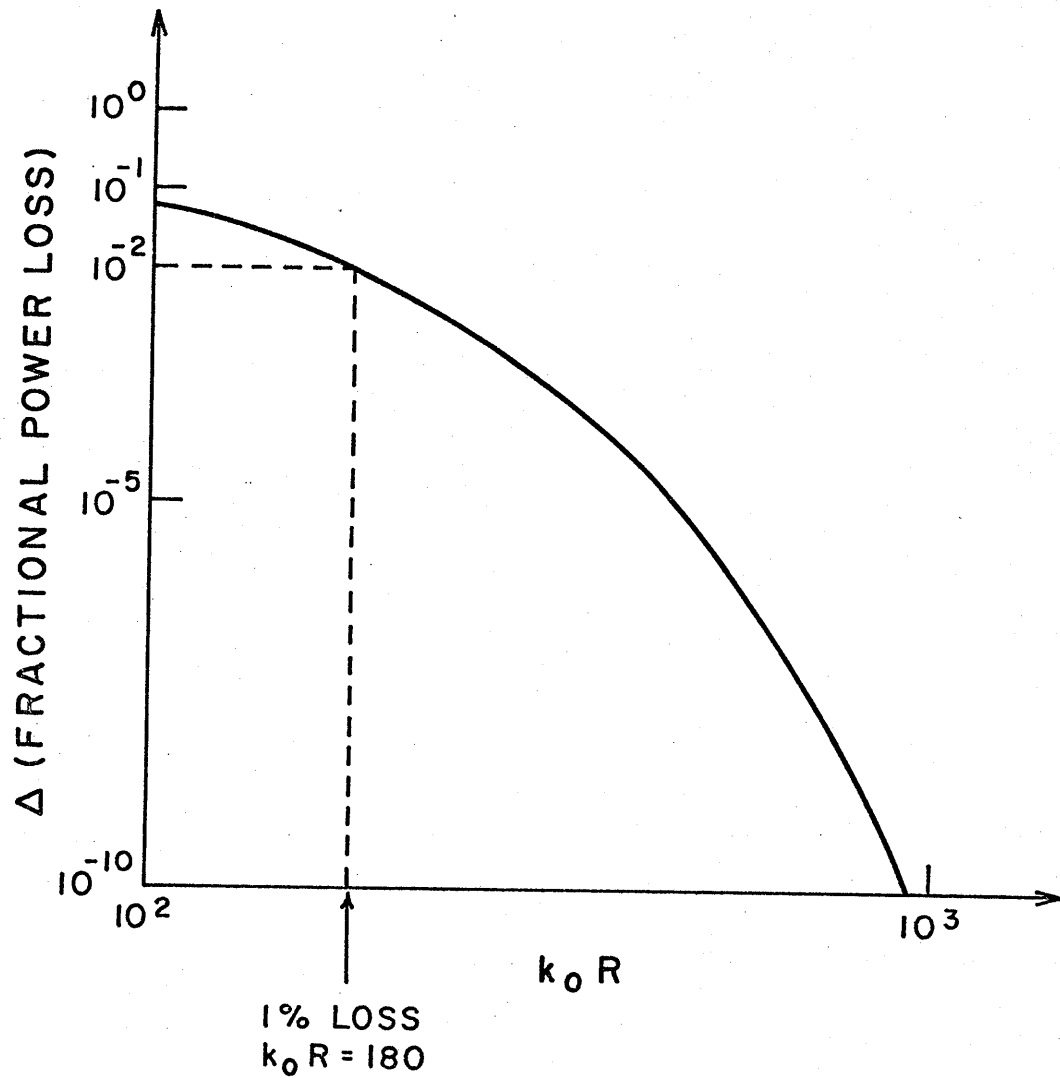


Figure 3

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APPENDIX B

EXPERIMENTAL INVESTIGATION

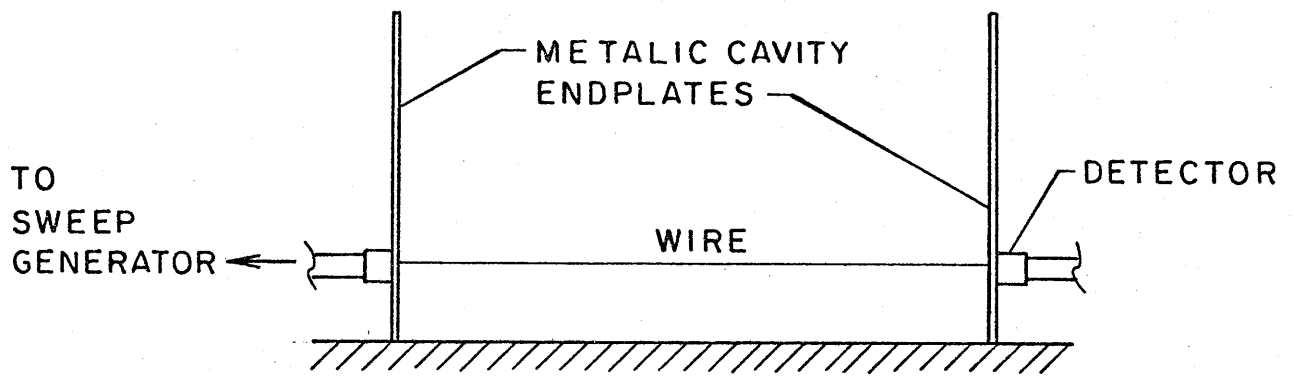
Experimental equipment was devised to permit the detection of the two modes that may exist on a wire parallel to the surface of the earth. The two modes are very nearly the same in most of their characteristics. One significant difference, however, is in their phase velocities. For the cases that were numerically studied, the difference was in the range of 0.2 to 1.0 percent. This would permit distinguishing the two modes by measurements of the resonant frequencies of a resonant cavity. An open cavity resonator of the type sketched below was constructed. The earth was simulated by various materials. In some cases, in which a very highly conducting earth was to be investigated, a metallic sheet was used. In other cases water was used and in still other cases water saturated sand was used. The height of the wire above the earth was made adjustable and the length of the cavity was adjustable. Furthermore there were two sets of cavity endplates made for use in different circumstances. The wire is usually connected to a sweep generator which should excite both of the modes that can exist (the wire is usually selected so that there is only one pair of modes, the transmission line like mode and the earth attached mode. For larger wires there could be additional pairs of modes of these types). The detector output can be displayed on an oscilloscope giving the spectral response of the cavity resonator. The length of the cavity can be made sufficiently long that the resonant frequencies for the two modes are sufficiently separated to be easily measured.

The first experimental measurements were an investigation of the electromagnetic field surrounding the wire to ascertain the efficiency of

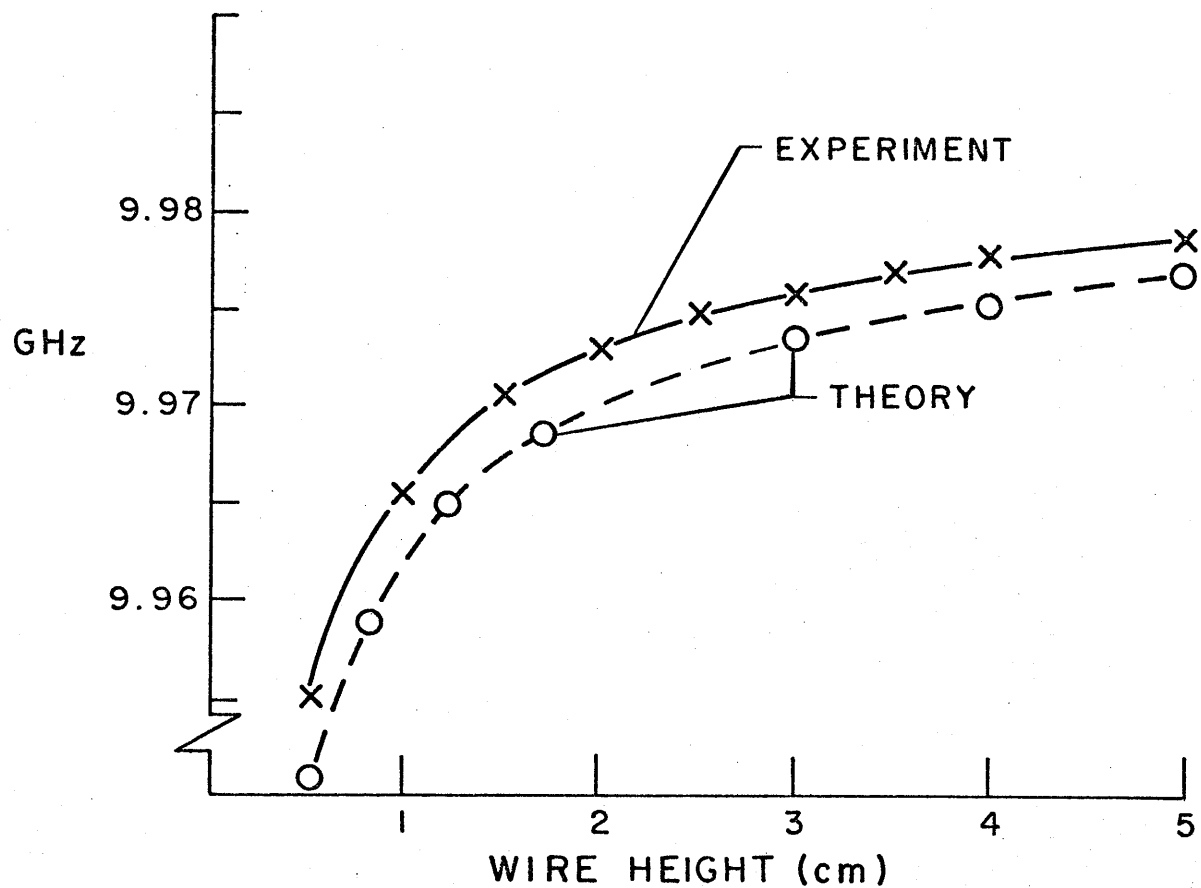
the feed structure of the cavity in exciting cavity modes that are guided by the wire. This was investigated by using a metallic plate for the simulated earth and by measuring the resonant frequency of the cavity as a function of the height of the wire above the metallic plate. These measurements were then compared with calculations. The comparison is shown below. It was felt the agreement was sufficiently close to assume that modes of the desired sort were being excited on the wire.

The next investigation involved the use of water for the simulated earth. In this case again the resonant frequency was measured as a function of the height of the wire above the surface of the water. The results of this series of measurements will be presented in a technical report now in preparation.

The experimental efforts were then directed toward measurement of resonant frequencies, as a function of height, with water saturated sand serving as the simulated earth. The dielectric constant and the loss tangent of the water saturated sand were measured and found to be very nearly the optimum values for this experimental investigation, (see table below). Such a simulated earth is reasonably convenient to use in the laboratory and it produces results which are repeatable from one day to the next. Extensive measurements were made of resonant frequencies as a function of height of the wire. A number of problems arose in the course of these measurements; they were primarily equipment problems. In some cases equipment malfunctions produced data of questionable value and in other cases equipment inadequacies were the primary problem. One previous problem results from the fact that practical electromagnetic structures have many resonances. The measurements system designed for this investigation measures all of them. It is difficult then to distinguish the resonances of interest



SKETCH OF OPEN CAVITY RESONATOR



RESONANT FREQUENCY AS A FUNCTION OF WIRE HEIGHT

from the extraneous ones. The results of this phase of the experimental investigation are not as satisfactory as was anticipated. A report on this work is now in progress.

Another type of experimental measurement was initiated to hopefully overcome some of the uncertainty of the measurements mentioned above. This was a measurement of the attenuation of a wave along a wire of fixed length as a function of height above the surface of the simulated earth. Again water saturated sand was used. This measurement was made at a fixed frequency and it could be made wither with or without the resonant cavity. The variation of the attenuation rates with height is significantly different for the two modes so this should provide a means for distinguishing between the two modes. Data resulting from these measurements will be included in the aforementioned report now in preparation.

TABLE

Material	Frequency GHz	Relative Permittivity	Loss Tangent
fine sand saturated with water	10.125	18.4	0.24
water	10.125	47.8	0.37
fine sand saturated with water	3.958	18.7	0.09
water	3.958	59.5	0.21