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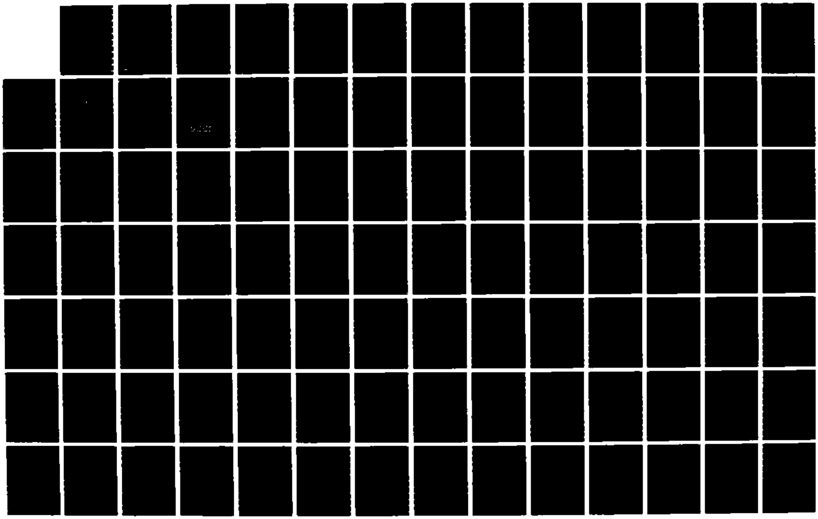

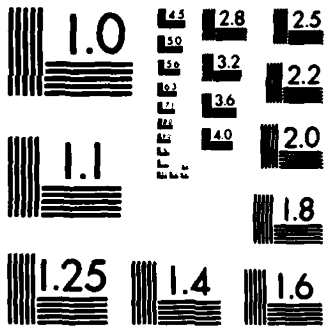

MICROCOPY RESOLUTION TEST CHART

AD-A171 991

SRI International

Final Report

April 1980

UHF PROPAGATION IN VEGETATIVE MEDIA

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Prepared for:

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ABSTRACT

The status of experimental and theoretical work dealing with UHF propagation in vegetative media has been investigated. The area of particular interest is work that is applicable to spread-spectrum communication.

A literature search revealed that a number of experimental investigations of UHF propagation in vegetative media have been conducted, but that there have been very few wideband experiments that are relevant for spread-spectrum communications.

A vast literature exists on the theory of wave propagation in random media in general, but specific application to UHF electromagnetic wave propagation in forests appears to be lacking.

An outline of the application of propagation-mechanism theory is included together with a brief discussion of the characterization of a vegetative medium.

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ILLUSTRATIONS

I INTRODUCTION

A. General

An investigation has been made of the propagation of ultra-high-frequency (UHF) radio waves through vegetative media. The general objective was to provide information for quantifying spread-spectrum communications capabilities in ground-vegetated environments in the frequency band from 400 MHz to 2000 MHz. The following specific tasks have been designated in the statement of work for accomplishing this general objective:

(1) Literature Search--Perform a literature search on both experimental and theoretical investigations of UHF radio-wave propagation through vegetative media to provide a basis for determining the appropriate model for describing propagation in the frequency range from 400 MHz to 2000 MHz.

(2) Propagation Mechanism--Utilize available theories of wave propagation in random media to investigate, conceptually understand, and definitize the propagation mechanisms responsible for phenomena reported in the literature for this frequency range. The first question to be answered is whether propagation over the entire frequency range of interest can be treated with a model that deals with an inhomogeneous propagation medium or whether a slab model with a homogeneous propagation medium is valid over a portion of the frequency range of interest.

(3) Characterization of the Medium--Determine the physical parameters of vegetation needed to characterize this mode of UHF propagation using the appropriate propagation model(s).

(4) Recommendations--Recommend experiments for verifying these relevant parameters.

B. Historical Highlights

It is appropriate to introduce the subject by mentioning a few historical highlights and some of the more general sources of information on the subject. It appears that the earliest experimental measurements on UHF propagation in a vegetative medium were carried out by Trevor (A*-32) in July and November of 1939 and the results were published the following year. He measured the attenuation of a 500 MHz signal resulting from propagation through 500 ft of woods and underbrush in New York state. A greater loss in field strength was observed in the summer when the trees were in full leaf.† No great difference was found between horizontal and vertical polarization.

Measurements of the diffraction and absorption of UHF signals by a single isolated tree were first reported by McPetrie and Ford (A-18) in 1946 and much later by LaGrone and Chapman (A-15).

The earliest work on jungle communications using radio waves was carried out during World War II by Herbstreit and Crichlow (B-22) in Panama and New Guinea; their results, however, were not published until 1964. Their measurements were all at frequencies below 100 MHz. In 1955 Saxton and Lane (A-23) reported on some previously unpublished work by McPetrie and Ford on the effects of trees and obstacles on VHF and UHF reception. They noted that the rate of attenuation for propagation through forests increases with frequency and that the loss of field strength behind opaque obstacles could be explained by Fresnel diffraction theory.

A very extensive research program on electromagnetic-wave propagation in jungle environments was conducted under U.S. Army Electronics Command and Defense Advanced Research Projects Agency sponsorship in Thailand in the 1960s. Much of the work in the UHF band was performed by the Jansky and Bailey Engineering Department of the Atlantic Research Corporation (see Section III). A four-volume final report plus twelve semiannual reports on this work (A-25 through A-28, B-45 through B-55) provide a wealth of information on the subject. A review paper entitled

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*The letter denotes the appendix in which the reference will be found, the number, its order in the listing.

†A quantitative summary of relevant portion of results from these measurements is given in section III of this report.

"Electromagnetic Propagation in a Tropical Environment" was published by Doeppner, Hagn, and Sturgill (B-12) in 1972 but most of the emphasis was on HF and VHF rather than the UHF band. Another general reference on the subject is the proceedings (edited by J. R. Wait, A-33), of the Workshop on Radio Systems in Forested, and/or Vegetated Environments, which was held at Fort Huachuca, Arizona in February 1974. Here again most of the most of the papers deal with frequencies below UHF. Some of the more recent experimental works are by Frankel (A-9), LaGrone (A-14), Murray (A-20), and Swarup and Tewari (A-29).

There does not appear to be any theory describing UHF propagation in vegetative media. The well-known theoretical work by Tamir (B-10) is valid primarily below 100 MHz. There is an extensive literature on wave propagation in random media that is related in a general way, but specific application to UHF in forests is lacking.

C. Organization of Report

The organization of this report follows the order of the work statement. Section II describes the literature search. A summary of the important findings from the search is contained in Section III. A discussion of the propagation mechanism is found in Section IV. This is followed in Section V by thoughts on how to characterize a vegetative medium for UHF propagation. Conclusions and recommendations are presented in Section VI. Three appendices contain references and abstracts. Two additional appendices contain an author index and a subject index.

II LITERATURE SEARCH

The literature search was an important part of this investigation. It provided a basis for assessing the status of both experimental and theoretical work on UHF propagation in vegetation.

The search made use of the DIALOG Information Retrieval Service, which is provided by the Lockheed Missiles and Space Company, Inc., Palo Alto, California. SRI International, Menlo Park, California, has a computer terminal that provides access to the DIALOG data bases. The following databases were searched:

(1) INSPEC, Files 12 and 13 (1969 through 1979, issue 18)
This is the on-line version of the science abstract family of abstract journals, indices and title bulletins. The on-line INSPEC file corresponds to the printed Physics Abstracts, Electrical and Electronics Abstracts, and Computer and Control Abstracts.

(2) COMPENDEX, File 8 (1970 through September 1979)
This is the on-line equivalent of the Engineering Index.

(3) NTIS, File 6 (1964 through 1979, Issue 21)
The National Technical Information Service report contains announcements of government-sponsored research, development, and engineering.

(4) AGRICOLA, File 10 (1970 through 1978)
This file contains the catalogue and index database of the National Agricultural Library. It was searched for possible Forest Service radio-communication information.

In addition to these computer-aided searches, a Defense Documentation Center search was obtained, and other references (such as some of the earliest references) were obtained from miscellaneous sources.

The large number of titles and abstracts that were obtained were sorted according to relevance to the project. Irrelevant abstracts were disposed of, and the relevant abstracts were divided into three lists that are contained in Appendices A, B, and C. Appendix A contains references that are directly related to UHF propagation in vegetative media. Appendix B is made up, primarily, of less directly related papers on experimental measurements, including experiments in adjacent frequency bands.

Appendix C has related theoretical papers, many of which are on the general topic of wave propagation and scattering in random media. Each is arranged in alphabetical order by author, except when no author is given; in those cases the corporation name is used instead.

This division of the literature into three lists was, of course, somewhat arbitrary. For example, the four final reports by Sturgill et al. on the extensive work by the Jansky and Bailey Engineering Department of Atlantic Research Corporation are all listed under Sturgill in Appendix A even though his name does not appear on all four volumes. Likewise the twelve semiannual reports on the same work are listed under Sturgill in Appendix B.

Abstracts are included for most of the references. Key words, descriptors, and identifiers are also included when available. Different formats are used for the different DIALOG databases. As a consequence, these differences are reflected in the appendices.

An attempt (not always successful) was made to obtain copies of all the papers and documents in Appendix A and the most relevant items from Appendices B and C. It was beyond the scope of the project to obtain and read all of the references, particularly references cited within the literature in the three lists. As an example, the second volume alone of the two-volume work, "Wave Propagation and Scattering in Random Media" by A. Ishimaru, cites over 400 references.

III PRINCIPAL FINDINGS FROM THE LITERATURE SEARCH

Most of the experimental investigations of the propagation of UHF radio-wave signals in the frequency range from 400 MHz to 2000 MHz in the presence of vegetation tend to be divided into two broad groups (with a few experiments in other related areas). In both groups of experiments, line-of-sight propagation is prevented by foliage.

A. Foliage-Coverage Obstacles

In the first group of measurements the transmitting and receiving antennas are generally not immersed in the vegetation and much of the propagation is through free space. Typically the propagation is over irregular terrain with line-of-sight propagation being prevented by foliage-covered obstacles. Figure 1 illustrates this situation.

Satisfactory theoretical explanations of the experimental results of these experiments are provided by applying Fresnel diffraction theory to the propagation of radio waves over the obstacle. More specifically, diffraction of UHF waves by a totally absorbing knife edge explains the results. (A brief discussion of Fresnel diffraction theory is included at the end of this section.) It is generally reported that the effective height of the knife edge is frequency-dependent with waves of frequency near the low end of the band penetrating deeper into the foliage than the higher-frequency waves. That is, the effective height of the knife edge corresponds closely to the physical height of the foliage for frequencies above roughly 1000 MHz (solid line on Figure 1); a somewhat lower height (dashed line on Figure 1) must be used at lower frequencies to obtain agreement between theory and experiment.* This is a relatively

*Quantitative expressions of this relationship have not been reported. LaGrone and Chapman (A-15) state that "more measurements of the type reported here would have to be made before the interrelationship of the variables could be put on an empirical basis."

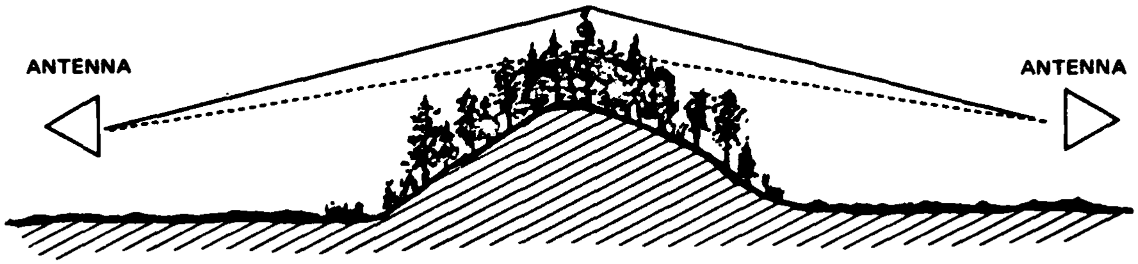

FIGURE 1 UHF PROPAGATION OVER FOLIAGE-COVERED OBSTACLES

minor detail. What is important, is that the experimentally observed variation in received signal with antenna heights and distances from the obstacle can be predicted by Fresnel diffraction theory. Thus the propagation is interpreted as primarily being a diffraction over the foliage-covered obstacle rather than through the foliage.

Figures 2 and 3, which are taken from a paper by LaGrone (A-14), illustrate this point. Horizontally polarized signals were measured as a function of height above local ground and of distance behind a grove of live oak and hackberry trees in full leaf. The wooded area was flat for several hundred meters in the direction of the transmitters. Tree-trunk diameters 1 m above ground varied from 15 cm to 45 cm. No number count was made of the trees per unit area. Propagation from the transmitters was through free space until the ray path encountered the grove of trees. The zero-dB reference for each run was taken to be the measured signal level with the receiving antenna at a height of 18.3 m. For Run 4, the receiving antenna was located 66 m behind the edge of the grove of trees. The corresponding distance for run 5 was 111 m. Almost all of the measured points fall within the calculated knife-edge diffraction envelope. Agreement with the calculated smooth-spherical-earth predictions was obtained only for antenna heights above 14 m, which was well above the tops of the trees, which were approximately 9-m high.

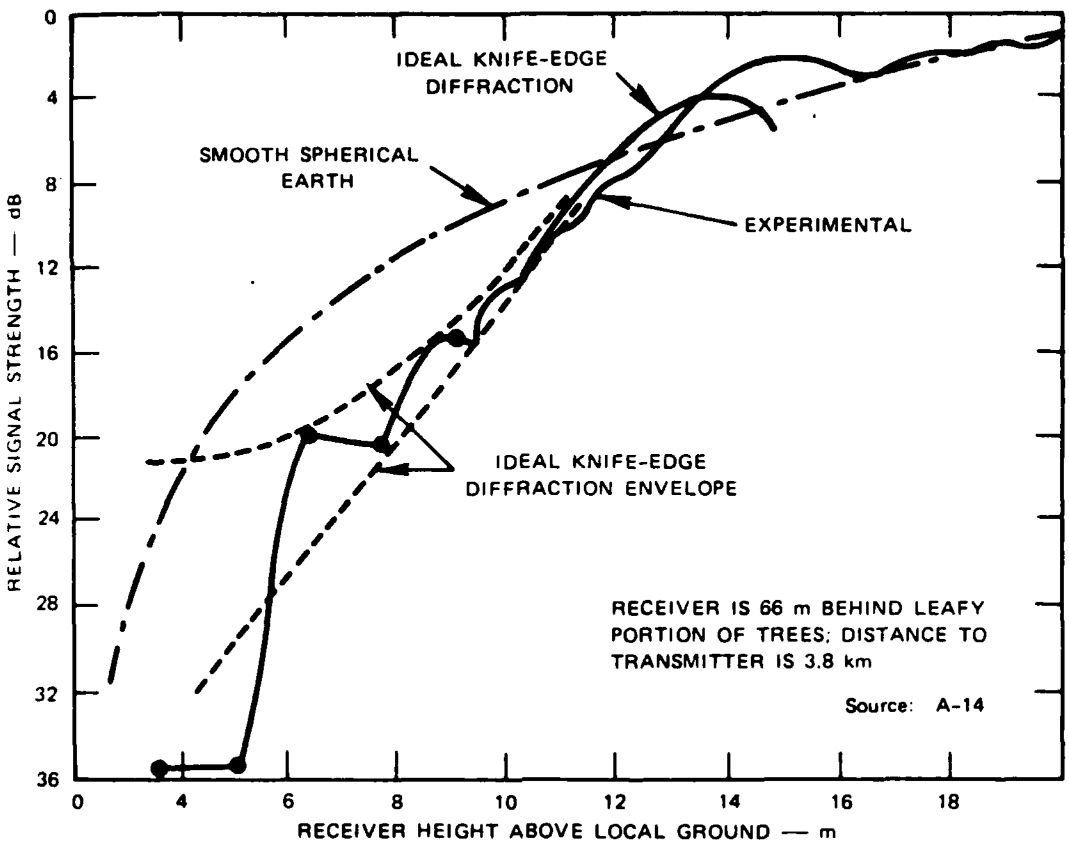

FIGURE 2 COMPARISON OF MEASURED SIGNAL WITH THEORETICAL SIGNALS AT f = 1280 MHz, RUN 4

Fresnel diffraction theory* is appropriate whenever either the source location or the point of observation is at a finite distance from the diffracting obstacle. An outline of Fresnel theory, as applied to a knife edge, is as follows. Consider the geometry shown in Figure 4. The knife edge (which is perpendicular to the plane of the paper) is the top of an obstacle that is opaque to radio waves. Thus, a two-dimensional geometry will be used. A wave is incident from the antenna at the left as shown in the figure. By Huygens' principle, each element of the incident wavefront that coincides with the knife edge acts as point emitter of a new wave. The amplitude and phase of the new wave are the same as that of the incident wave at that point. For the case

*Sommerfeld, A., "Optics," (Academic Press, 1954).

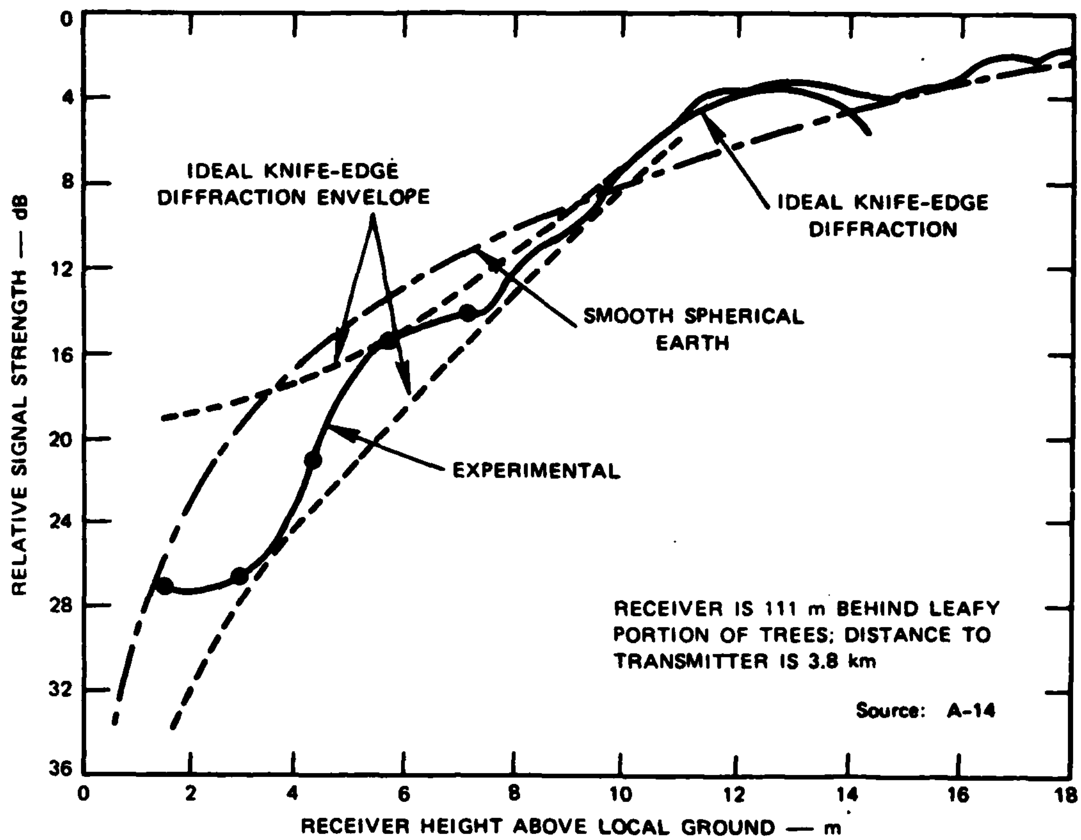

FIGURE 3 COMPARISON OF MEASURED SIGNAL WITH THEORETICAL SIGNALS AT f = 1280 MHz, RUN 5

being considered here, the amplitude and phase will be constant across the wavefront indicated in the figure. An integration of the received amplitudes (at the antenna to the right) of waves from each element of the indicated wavefront gives the diffracted signal at the receiving antenna. This integration involves the Fresnel integrals C(w) and S(w), which are defined by

$$C(w) = \int_0^w \cos\left(\frac{\pi\tau^2}{2}\right) d\tau$$

$$S(w) = \int_0^w \sin\left(\frac{\pi\tau^2}{2}\right) d\tau$$

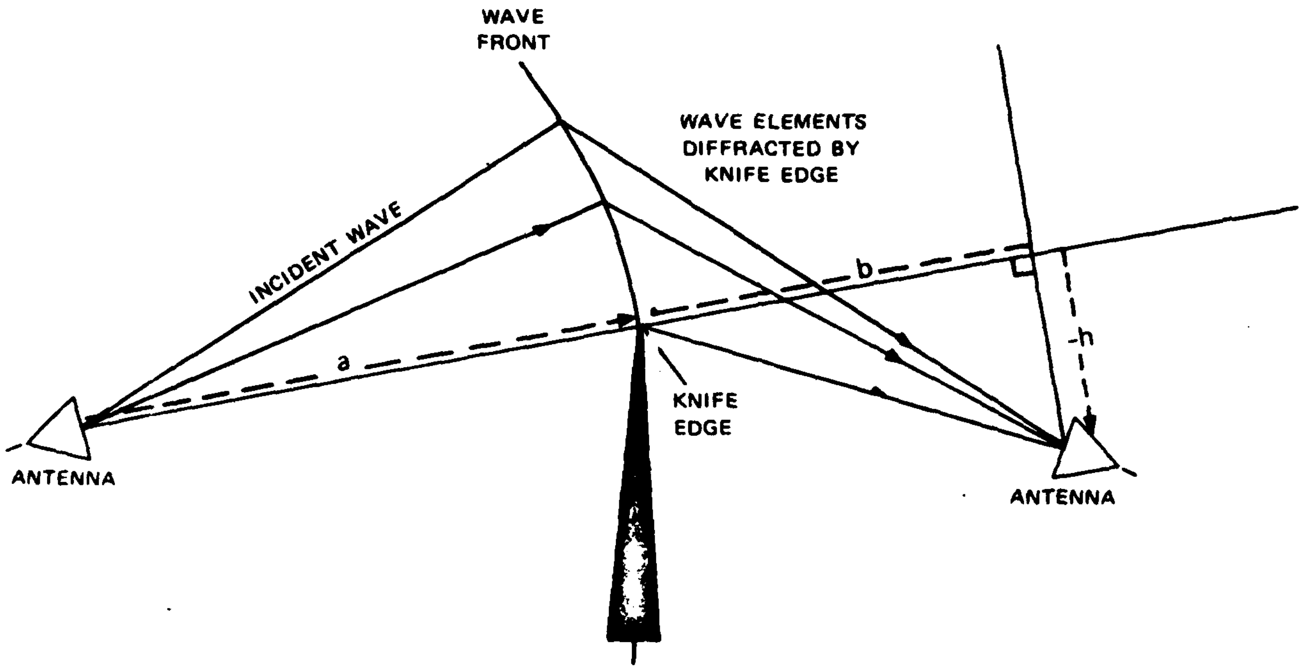

FIGURE 4 KNIFE-EDGE DIFFRACTION GEOMETRY

For the geometry shown in Figure 4 the relative amplitude of the diffracted signal* is given by

$$A = \frac{1}{\sqrt{2}} \left| F(w) - F(-w) \right|$$

where $F(w)$ is the complex Fresnel integral defined by

$$F(w) = C(w) + i\ S(w)$$

and the parameter w is given by

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*It is assumed that the difference in propagation range of the new waves (from the indicated wave front to the receiving antenna) is small enough so that the received wave amplitudes are essentially equal. The differences in phase between the different received waves is not ignored because that is an essential part of the diffraction phenomenon.

$$w = \frac{a \arctan \frac{h}{a + b}}{\sqrt{\frac{\lambda b}{2 \left(1 + \frac{b}{a}\right)}}}$$

Note that h is negative in the shadow zone.

Figure 5 illustrates the knife-edge diffraction pattern. A relative amplitude of 1/2 is found at the edge of the geometric shadow (i.e., $h = 0$, $w = 0$). The amplitude decreases further as the point of observation is moved into the shadow zone (but does not fall to zero immediately as geometric wave theory predicts). It is of interest that there are a series of maxima outside of the shadow where the received signal is actually greater than would be the case in the absence of the obstacle. The first maximum (for $w \doteq 1.25$) gives a signal increase that is greater than 4 dB. The experimental results given in Figures 2 and 3 clearly show such an enhancement. This illustrates the importance of diffraction effects for propagation in the presence of obstacles.

B. Vegetative Propagation Path

In the second group of experiments the topography is not dominant. Rather, a flat, forested terrain is typical. In this case the transmitting and receiving antennas are immersed (or nearly so) in the foliage so the entire propagation path is occupied by vegetation. Figure 6 illustrates this situation. The results of these experiments have been generally expressed in terms of excess loss in dB/m that has arisen as a consequency of the vegetation; that is, the loss in signal strength beyond what would have taken place in the absence of the vegetation. These losses are found to increase with frequency (Saxton and Lane, A-23; Sturgill et al., A-25) and to be dependent of the characteristics of the vegetation. The rate of attenuation naturally varies with the density of the woods and the degree of undergrowth. It is greater for trees in full leaf than for bare trees (Trevor, A-32; Reudink, A-21) and increases when foliage is wet. Within the 400-MHz to 2000-MHz band, there is little

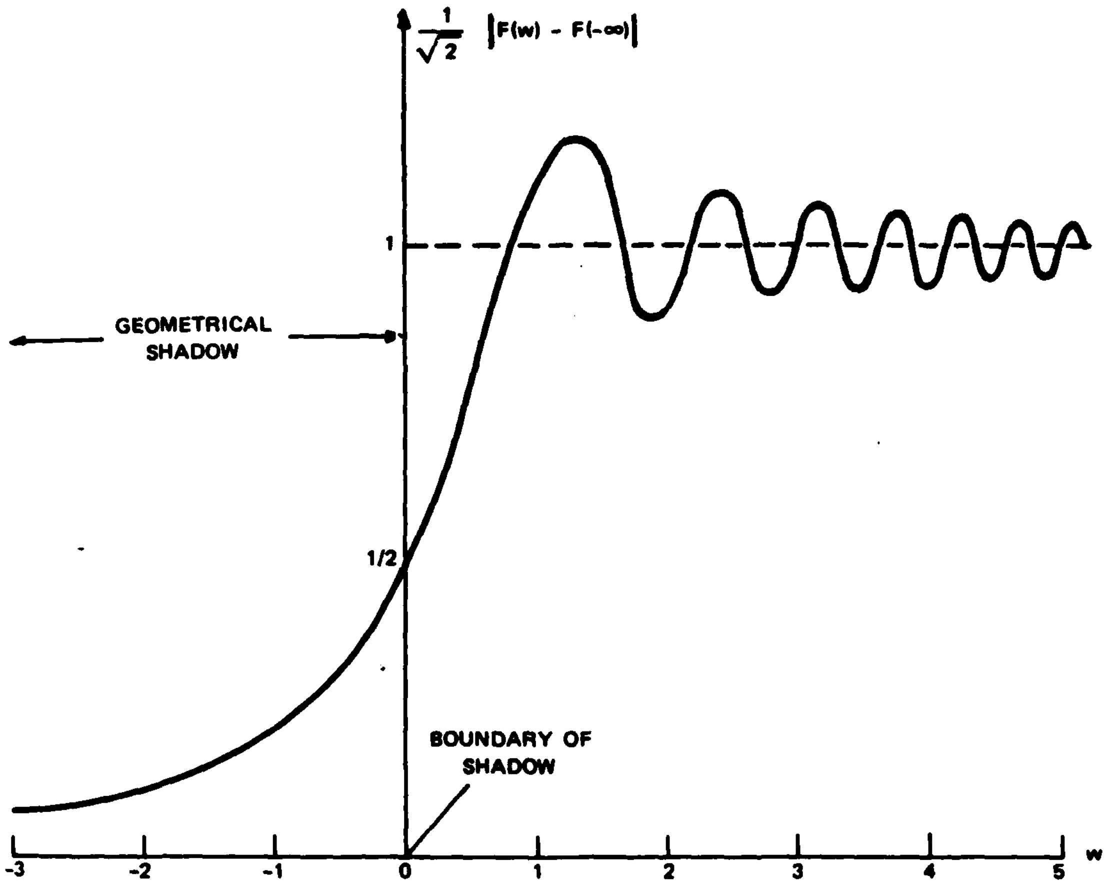

FIGURE 5 AMPLITUDE OF KNIFE-EDGE DIFFRACTION PATTERN

FIGURE 6 UHF PROPAGATION THROUGH A VEGETATIVE MEDIUM

difference in the loss rate between horizontal and vertically polarized waves; horizontal polarization is, however, slightly favored at the low end of the band.

Increasing the antenna height generally reduces the propagation loss (Baris, A-1).* This is particularly true, as is expected, when the height of both antennas exceeds the height of the foliage.

In addition to distance-related loss (i.e., dB/m loss rate times the distance of propagation through the medium), there is sometimes a more or less fixed loss† that appears to be associated with the immersion of the antennas in the medium. Such fixed losses can presumably be considered a consequence of a lossy medium being within the near field of the antenna, thereby reducing the antenna efficiency and distorting the antenna radiation pattern and reducing the gain.

A small sample of the loss-rate data versus frequency that have been reported is reproduced in Figure 7. The three curves labeled Sturgill et al. (A-25) were obtained from an extensive investigation of jungle propagation in Thailand. Data for the curve labeled Saxton and Lane (A-23) were derived from previously unpublished work by McPetrie and Ford (presumably in England) that was published by Saxton and Lane. The two points labeled Trevor (A-32) are based on measurements in a forest in New York State. The data labeled Frankel (A-9) were obtained on the peninsula south of San Francisco. Both the average and the standard deviation of these measurements are indicated.

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*There are special circumstances that can result in a lower propagation loss with lower antennas. For example, there can be a lower loss at tree-trunk level, in the absence of underbrush and short trees, compared with the loss through the heavy foliage of the trees.

†This result is inferred from the non-zero excess path loss that is obtained from extrapolation to zero path length of excess path loss versus path length. Data obtained by R. I. Presnell of SRI International on PLRS ground-to-ground propagation measurements for Contract MDA903-78-C-0126 for CENCOMS, CORADCOM.

There is a sizable spread in the reported loss rates but all in-igations show that the loss rate increases with frequency in the UHF nd. Saxton and Lane (A-23) report a lower loss rate for horizontally larized waves at the low end of the band while Sturgill et al. (A-25) port no difference between horizontal and vertical polarization loss ates at frequencies above 400 MHz. Sturgill et al. also report no sig-icant statistical difference between data collected in the wet and seasons in tropical vegetations. The rate of attenuation is greater trees in full leaf than for bare (leafless) trees.

Although there is a large amount of spread in the loss-rate values, here is rough agreement in most respects. The differences can arise

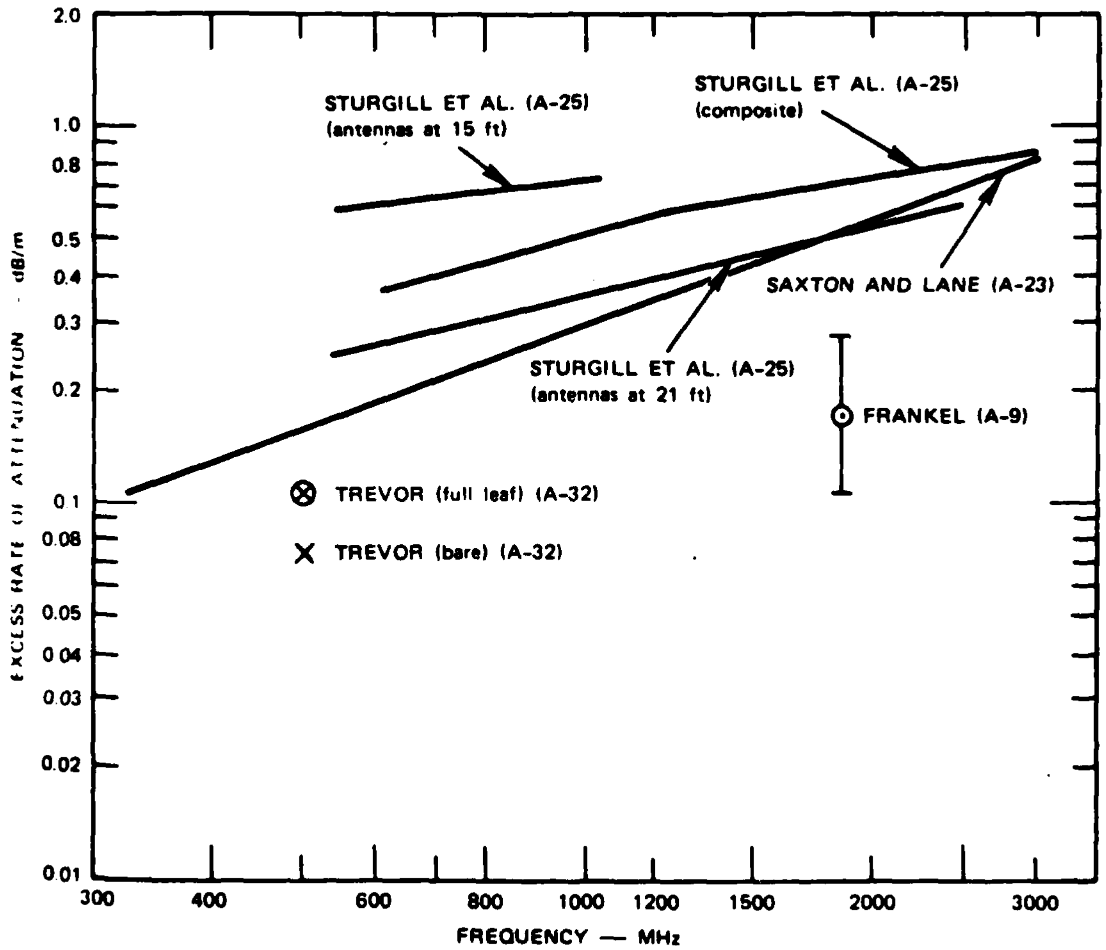

FIGURE 7 EXCESS RATE OF ATTENUATION vs. FREQUENCY

as a result of inhomogeneities (randomness) within a given forest and from the differences between forests. The problem of how to charac-
and from the differences between forests. The problem of how to characterize a vegetative medium so that quantitative predictions of UHF propagation properties within the medium can be made is in a very rudimentary stage of development. Some measures that have been used include (1) weight of vegetation per acre and (2) cross sectional area of tree trunks (at a fixed height) per acre. There is certainly correlation between loss rates and these measures, but other factors such as type of tree, amount of undergrowth, state of leaf growth, rain or wet foliage, and the like all need to be included. Because UHF propagation effects depend on the electrical properties of the medium, it may turn out that the foliage must be characterized in terms of some electrical measurements. (It is to be hoped that it will be something much less complicated than a series of propagation measurements.)

C. Scattering and Absorption Properties of an Isolated Tree

There have been a few UHF measurements of the scattering and absorption properties of a single tree. Information from the experiments can help to characterize UHF propagation through forests. McPetrie and Ford (A-18) measured the diffraction of 9.2 cm ($f \approx 3260$ MHz) waves behind the trunk of a tree. Signal-strength measurements were made at a height of 5 ft above ground at a distance of 100 ft behind the tree. Figure 8 shows their measured results (small circles) in comparison with computed Fresnel diffraction curves for a very long, opaque strip of the same width as the trunk diameter of the tree (5 ft, 7 in.). (The propagation paths did not pass through the branches of the tree.) The solid curve was calculated on a point basis, while the dashed curve is a running average over a 4-ft width to correspond to the diameter of the receiving antenna. There is reasonable agreement with the theoretical curves. The integrating effect of a large (compared to wavelength) antenna is to smooth out the diffraction curve. It is of interest to note that a signal enhancement can occur at particular angles because of the diffraction around an obstacle. This may be why some particular propagation paths through a forest have a lower loss than most multiple-scatter paths.

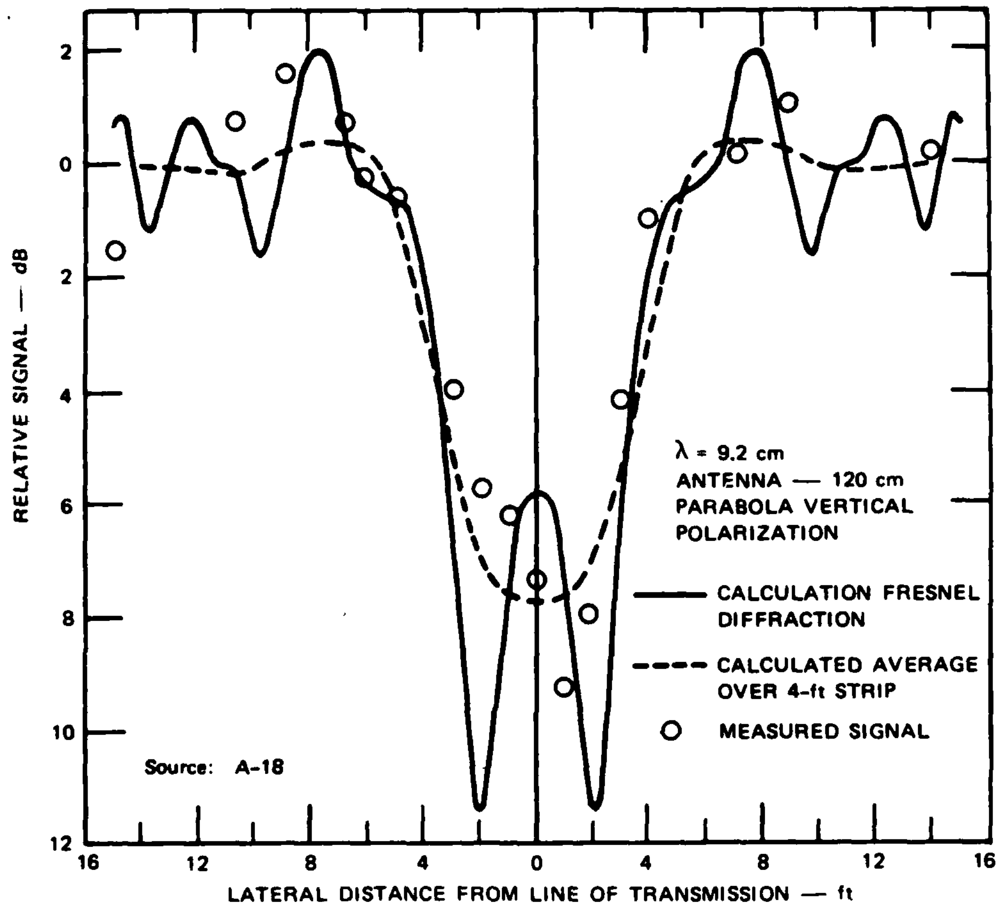

FIGURE 8 DIFFRACTION STUDY OF A NARROW OPAQUE OBSTACLE

Measurements of the diffraction and absorption characteristics of a UHF signal passing through the foliage of an isolated live oak tree have been made by LaGrone and Chapman (A-15). The tree was approximately 30 ft tall and had a foliage spread of about 50 ft. Three lateral runs were made behind the tree at distances of 300 ft, 600 ft, and 900 ft. All of the transmission paths were through the foliage of the tree as indicated in the figure. A wavelength of 10.4 cm (f = 2880 MHz) was used. Figure 9 shows the measured results. Losses in excess of 25 dB were obtained when the receiving antenna was almost directly behind the center of the

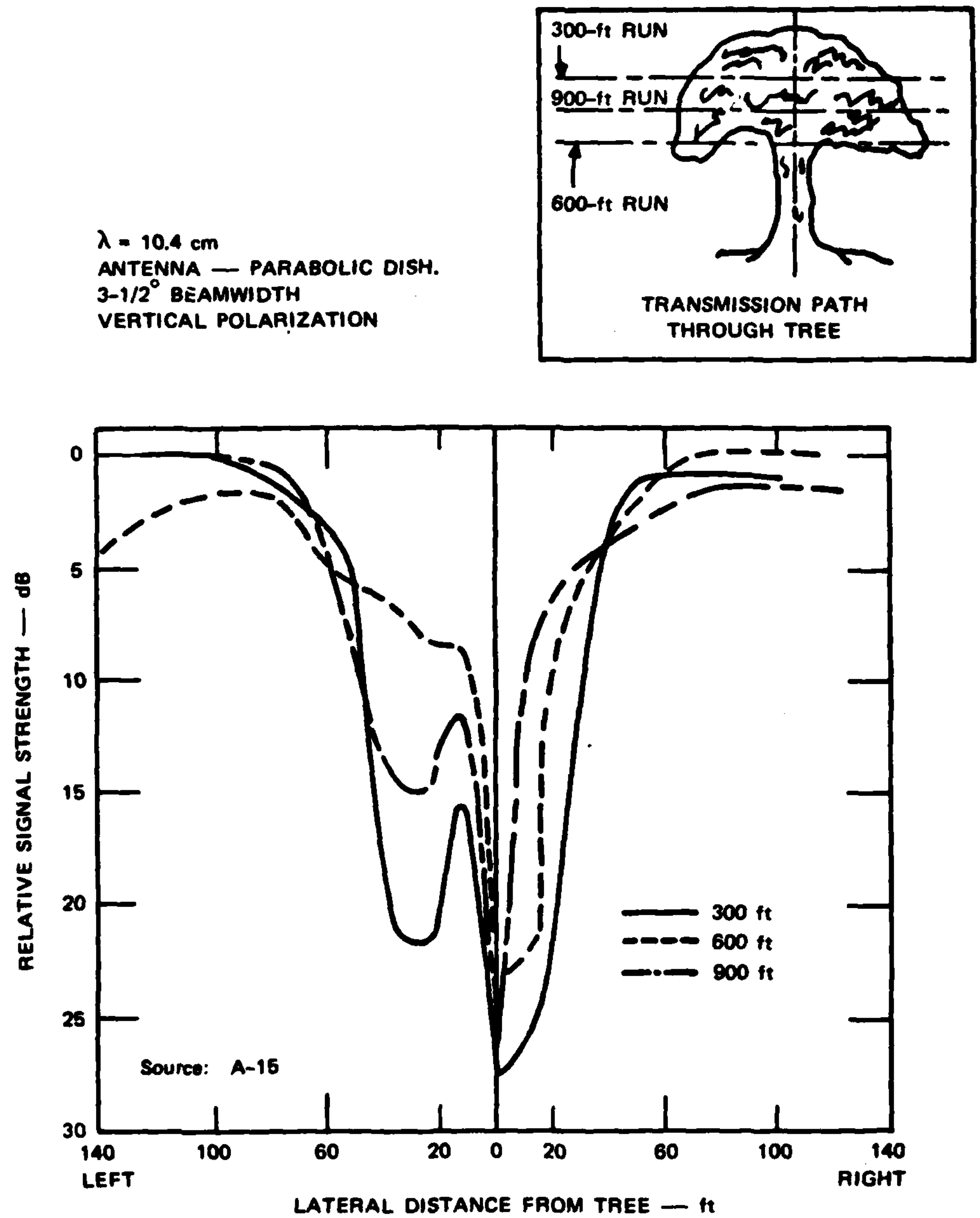

FIGURE 9 DIFFRACTION AND ABSORPTION STUDY AT VARIOUS DISTANCES BEHIND A LIVE OAK TREE

tree foliage. These results indicate, as expected, that a single large tree located in what would otherwise be a line-of-sight path can prevent this propagation path from being the lowest-loss path.

D. Pulse Measurements

One area in which measurements seem to be lacking is the area of pulse-type (wide-bandwidth) measurements in vegetative media. Such measurements are needed to give information on multipath propagation and pulse broadening or coherence bandwidth* to assess the effects of propagation on spread-spectrum or other wideband communications systems. Schmid (B-43) discusses an empirical model that permits calculation of the probability of occurrence of multipath propagation of VHF and UHF signals over irregular terrain. The intended application is for propagation over terrain (not through foliage) that is characterized by a random distribution of obstacles. The model predicts that for constant transmitter-receiver separation, the expected amplitude of the received echoes decreases with increasing echo delay; and for constant echo delay, the occurrence of echo pulses is expected to increase as the transmitter receiver distance increases.

Pulse-type measurements have been carried out by Turin et al., (B-69) in an urban environment. Their multipath propagation experiment involved 100-ms pulses at 488 MHz, 1280 MHz, and 2920 MHz. Although their results are not directly applicable to propagation in vegetative media, there may be some common characteristics. A mobile receiving van

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*Coherence bandwidth is the inverse of pulse broadening (spreading). A narrow transmitted pulse is spread as it propagates through a vegetative medium as a consequence of differing path length for the individual components of a multiply-scattered wave (see Section IV-B). Different communication MODEMs have differing susceptibilities to pulse spreading. Coherence bandwidth can be measured by transmitting two identical signals on two separate frequencies and measuring the correlation (at the same time) of the two received signals. The separation frequency at which the correlation decreases to a specific level is the coherence bandwidth of the propagation channel.

was used to obtain multipath time delay (i.e., excess range) for four areas within the San Francisco Bay area.* Figure 10 shows an example of the deduced probability of a multipath signal (within a range interval of 100 ft) with a given excess range (i.e., time delay). A line-of-sight path existed for areas B, C, and D as indicated by the peak at zero excess range. Area A was within the high-rise financial district of San Francisco, so there was no line-of-sight path from the transmitter (located on the Hall of Justice building, about 1 mi away, for this test). The curves in Figure 10 seem to contradict the prediction of Schmid's (B-43) model, namely that the width of the curves should increase with increasing propagation range. Turin's results seem to show that the multipath spread depends almost totally on the local environment of the receiver.

Turin et al. (B-69), and later Suzuki (C-42), under Turin's direction, considered a statistical model describing multipath propagation in urban areas. If the transmitted signal is given by $\mathrm{Re}\{s(t) \exp(i\omega_o t)\}$, $t \epsilon (-\infty, \infty)$ and the received signal is expressed by $\mathrm{Re}\{\rho(t) \exp(i\, \omega_o t)\}$, $t \epsilon (-\infty, \infty)$, then $\rho(t)$ can be written

$$\rho(t) = \sum_{k=o}^{\infty} a_k \, s(t - t_k) \exp(i\theta_k) + n(t)$$

where $s(t)$ is a complex-valued, low-pass waveform and ω_o is the angular frequency of the carrier. With this model, the propagation medium is characterized by random variables,

$$\left\{a_k\right\}_o^\infty , \quad \left\{t_k\right\}_o^\infty , \text{ and } \left\{\theta_k\right\}_o^\infty .$$

The additive noise, $n(t)$, is modeled to be Gaussian. A log-normal distribution of path strengths $\{a_k\}$ is found except for short path delays. The path arrival time, $\{t_k\}$, basically has a Poisson distribution.

*The four areas were the financial district of San Francisco (Area A), Downtown Oakland (Area B), Downtown Berkeley (Area C), and the residential area of Berkeley (Area D). The transmitter-to-receiver distances for the four areas were about 1 mi, 5.5 mi, 1.5 mi, and 1.5 mi respectively.

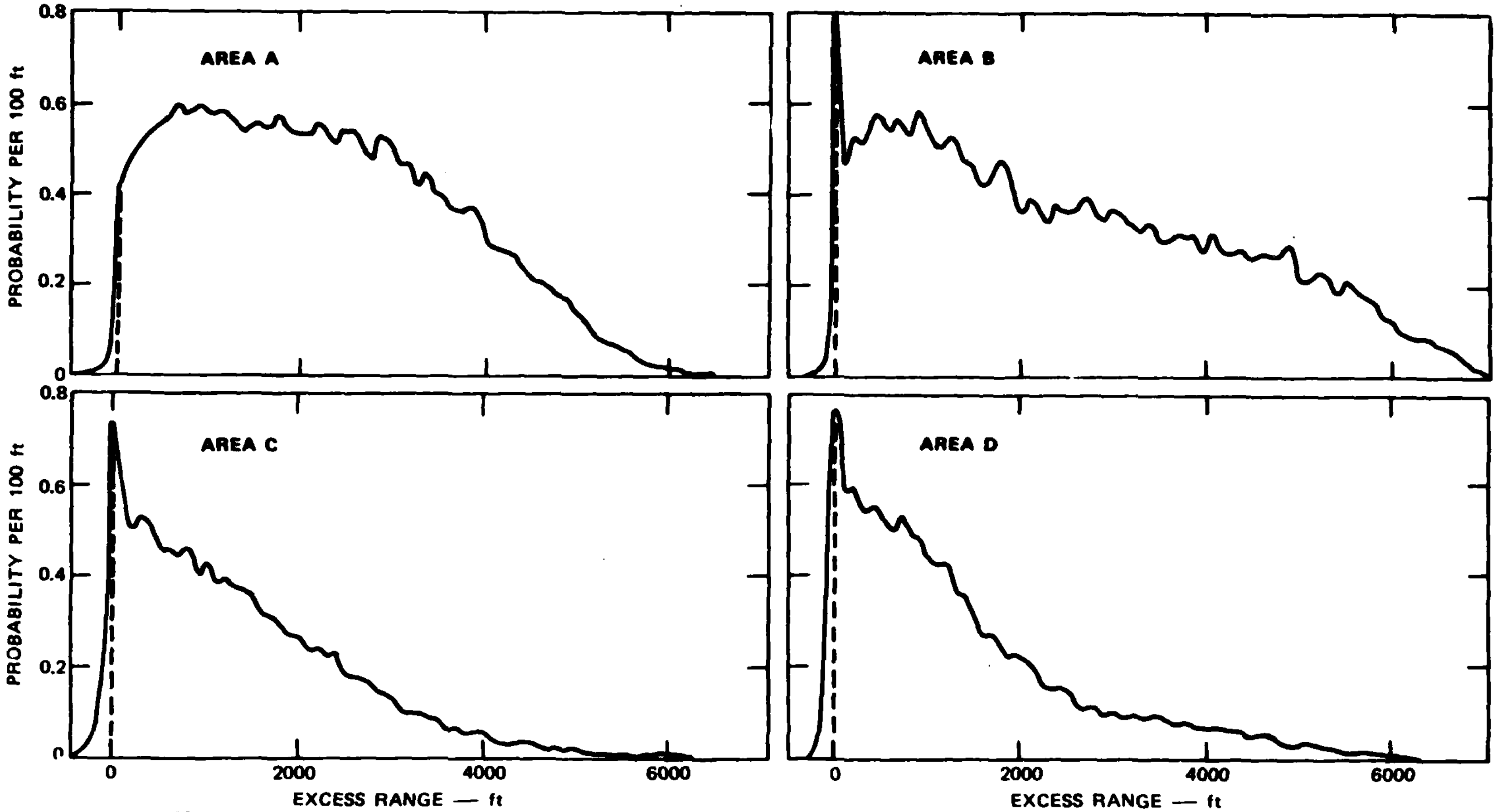

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FIGURE 10 PROBABILITY OF OCCUPANCY CURVES AT 1280 MHz

This same approach may be useful for describing multipath propagation in vegetative media.

Pulse-type measurements in an urban environment have been carried out by Nielson (B-33) at a frequency of 1370 MHz. Similar measurements were subsequently performed by Hubbard et al. (B-24) in urban and suburban areas of Boulder, Colorado at a frequency of 8.6 GHz. Similar, preliminary measurements have been made with the same system at frequencies of 600 MHz, 1200 MHz, and 1800 MHz in forests--under a joint program by NTIA/ITS* and CORADCOM. This program appears to be an important step toward obtaining the necessary experimental data for characterizing UHF propagation in vegetative media.

*N tional Telecommunications and Information Administration/Institute for Telecommunication Sciences, U.S. Dept. of Commerce.

IV PROPAGATION MECHANISM

A. Basic Considerations

We are considering electromagnetic-wave propagation as a means for achieving point-to-point communication in a vegetative environment. The properties of the wave propagation are controlled by a number of parameters such as:

(1) Distance and topography between transmitting and receiving antennas.

(2) Antenna heights.

(3) Properties of the propagating medium.

(4) Antenna polarization.

Items (1) and (2) determine whether the wave propagation is line of sight, diffracted over (or around) obstacles, or through the vegetative medium. Item (3) influences path loss, pulse spreading, and wave depolarization. All four items, together with the choice of communication modem, determine the potential performance of a communication link.

The mechanism of propagation of UHF waves through vegetation will depend on:

(1) The relative sizes of the scattering elements with respect to the wavelength. It is yet to be determined whether a tree is to be considered as the basic scattering element or if the various parts of a tree should be considered as the scattering elements.

(2) The electrical scattering and absorbing properties of the scattering elements.

(3) The relative number density and distribution of scattering elements.

At VHF (particularly below 100 MHz where $\lambda > 3m$) and lower frequencies, a vegetative medium can be considered as a homogeneous slab* because wavelengths are large compared with the scattering elements and the effects of the scatterers are averaged or smoothed to approximate a homogeneous medium. This is not true for UHF waves in the frequency range of interest where $(15\ cm) < \lambda < (75\ cm)$. Thus it appears that any agreement that is obtained between experimental results and predictions of a theory that a forest as a homogeneous medium at frequencies above 400 MHz is fortuitous.

A realistic model for the propagation of UHF waves in a vegetative environment must consider that there is a more-of-less random distribution in location, size, and possibly orientation of scattering elements. In addition, the electrical scattering properties and wind-induced motion of the foliage need to be included in the model.

In order to explore possible propagation mechanisms, let us consider a conceptual experiment.

B. Conceptual Experiment

Assume a flat topography with transmitting and receiving antennas at a fixed height and with a fixed polarization (e.g., horizontal). An impulse is to be transmitted so the received signal will be the impulse response of the propagation medium from the transmitting antenna to the receiving antenna. (An essentially infinite bandwidth is assumed for both the transmitter and the receiver.)

Start with a zero number density of ideal† scatterers and then increase the density to see what types of propagation behavior may be expected. The intent here is to lead to recommendations for experiments,

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*The well-known lateral-wave theory (Tamir B-60) that has been used successfully at VHF considers the vegetative medium to be a homogeneous slab. It is generally considered to be valid below 100 MHz.

†The scatterers are assumed to reradiate an exact replica of the incident signal; i.e., the transfer function of each scatterer is constant in amplitude and linear in phase. Only the relative amplitude and time delay varies from one scatterer to another.

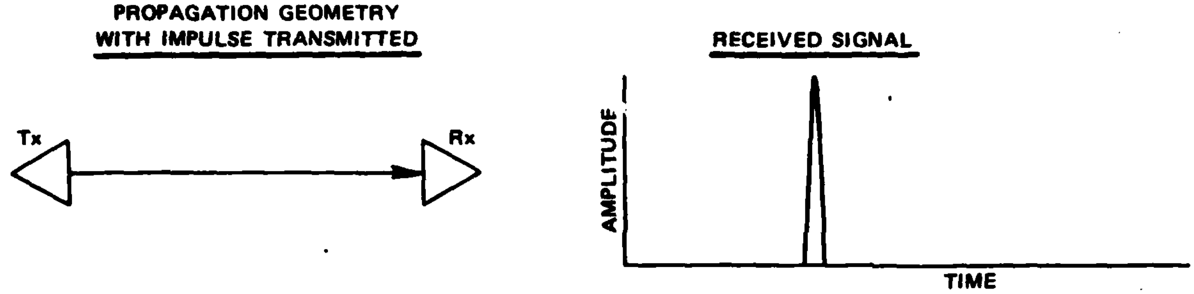
first, to characterize the medium and, second, to indicate its controlling physical parameters. The medium will be considered as a random distribution of scatterers.

Figure 11(a) indicates that with no scatterers the received signal is simply a replica of the transmitted signal delayed by the line-of-sight propagation time. When a few scatterers are introduced [Figure 11(b)] the received signal consists of a series of replicas of the transmitted signal--the direct signal plus delayed replicas for each scatterer. The amplitudes of the delayed replicas are proportional to the scattering amplitude in the appropriate direction; the extra delays result from greater distances of propagation by way of scatterers. This situation can also be referred to as multipath propagation. It can cause difficulties if the amplitude of the delayed pulses are comparable to the direct-pulse amplitude and the spread in delay time is comparable with the reciprocal of the chip rate for a direct-sequency spread-spectrum signal. Both of these first two cases are deterministic and can be treated by analytic methods.

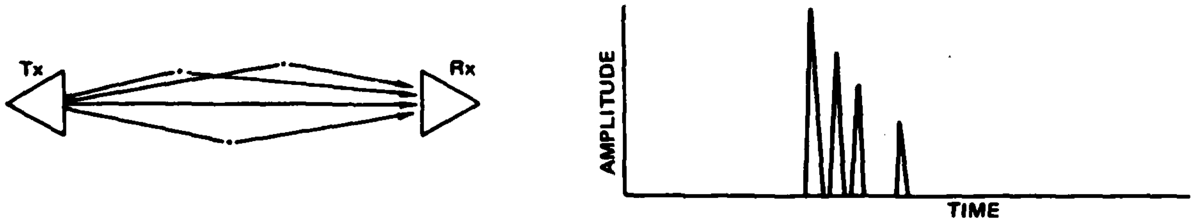
A variation on the behavior depicted in Figure 11(b) can take place if a tree (or other obstacle) is directly in the line of sight between the transmitting and receiving antennas. This situation can result in a smaller (or no) signal from the direct path than for scattered paths.

In the next case [Figure 11(c)], the number of scatterers is increased to the point where the direct wave is weakened by scattering and absorption and there are a multiplicity of scattered waves. It appears that this case could be approximated theoretically by first-order multiple-scattering theory. The received signal is the sum of the direct field and the scattered field.

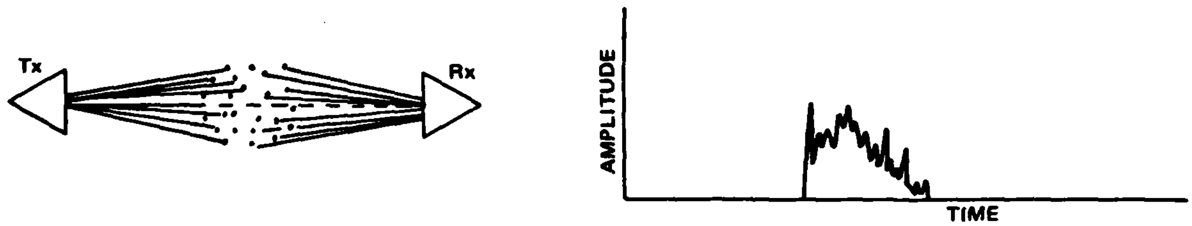
Finally Figure 11(d) illustrates the situation if the density of scatterers is sufficiently great and the path length sufficiently long so that no direct signal is received--only the multiple-scattered signals. A variation of this behavior occurs if there are particular low-loss propagation paths that would appear as prominent peaks in the impulse response, in addition to the more-or-less smooth envelope of all the



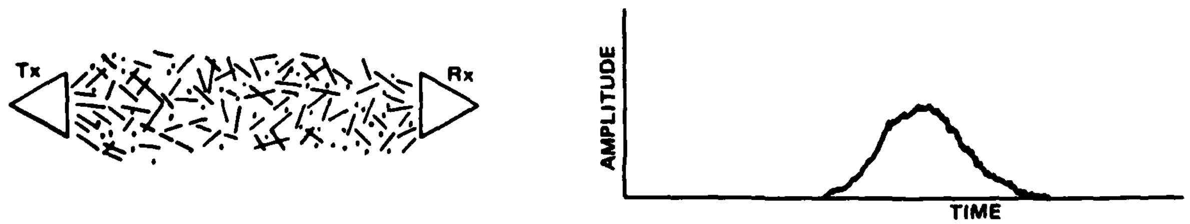
(a) DIRECT LINE-OF-SIGHT PROPAGATION WITH NO SCATTERERS



(b) DIRECT- AND SINGLE-SCATTER PATHS



(c) WEAKENED DIRECT PATH AND A MULTIPLICITY OF SINGLE-SCATTER PATHS



(d) NO DIRECT PATH BUT A MULTIPLICITY OF MULTIPLE-SCATTER PATHS

FIGURE 11 IMPULSE RESPONSE AS A FUNCTION OF THE NUMBER DENSITY OF SCATTERERS other multiple-scattered paths. Single-tree diffraction patterns (LaGrone and Chapman, A-15; McPetrie and Ford, A-18) suggest that diffraction from taller-than-average trees could provide preferred propagation paths.

In both of these last two cases [Figure 11(c) and 11(d)] the smearing of the received pulse by the propagation medium will act as a limit to maximum usable bandwidth or chip rate of a spread-spectrum signal.

Measurements along the lines suggested by this conceptual experiment may lead to better understanding of the propagation mechanism for UHF waves through vegetation.

It appears that a workable theoretical model of UHF propagation in vegetative media does not presently exist. We will next consider some theoretical approaches and outline one promising approach.

C. Theoretical Approaches

A realistic theoretical model of UHF radio-wave propagation in a vegetative medium must include the following consideration. Wavelengths in the band of interest are not long compared with the scale sizes of the principal scattering elements (namely, entire trees) in a forest. Hence, the medium cannot be considered as a homogeneous medium.* Here, instead, it is appropriate to be dealing with the theory of wave propagation and scattering in a random medium--more specifically, the interaction of waves with a random distribution of discrete scatterers. There are two theoretical approaches to this problem (Ishimaru, C-24). One is called transport theory or radiative-transfer theory. It is a phenomenological heuristic approach that deals exclusively with energy and transport of wave intensities. Transfer equations are developed that are equivalent to the Boltzmann equation in the kinetic theory of gases. This approach is not suited to the treatment of interference phenomena such as diffraction.

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*At frequencies below 100 MHz, a forest can be treated as a uniform slab because wavelengths (> 3 m) are larger than the scattering elements (e.g., trees) so the effects are averaged over a wavelength.

The other theoretical approach is called multiple-scattering theory. It is the more fundamental of the two approaches and is a wave theory that deals with differential and integral equations governing field quantities (including amplitude and phase, rather than intensities as in the transport theory approach). Interference effects are obtained as a normal result of this approach. Because experimental measurements on individual trees have shown the importance of diffraction effects, multiple-scattering wave theory is the appropriate approach for analysis of UHF propagation in a vegetative medium.

Information on the scattering and absorption properties of individual scatterers is a necessary input for multiple-scattering theory. This information can be obtained empirically from measurements or from theoretical modeling. In certain circumstances, the individual tree can be used as the principal scattering element (e.g., in the absence of underbrush or for elevated antennas). A first approximate is to consider all trees in particular forest to have identical scattering properties. Further approximations deal with more than one type of scatterer.

D. Outline of Multiple-Scattering Formalism

The following outline, as developed by Twersky (C-47), indicates how multiple-scattering theory can be approached. For simplicity of presentation, a scalar field, Ψ, will be assumed. Consider a configuration (1,2,..., N) of N scatterers, where the configuration stands for all the significant properties (as yet undefined) of the scatterers, including their locations ($\vec{r}_1$, $\vec{r}_2$, ..., $\vec{r}_N$). The scattered-wave solution for a given configuration is denoted by $\Psi(1, 2, \ldots, N)$.

In order to calculate expectation (or average) values of various quantities, an ensemble of configurations with an appropriate probability distribution function W(1, 2, ..., N) is introduced. Then the expectation value of Ψ is defined by its ensemble average.

$$\langle \Psi \rangle = \int \ldots \int \Psi(1, 2, \ldots N)\, W(1, 2, \ldots, N)\, d1\, d2 \ldots dN$$

where the integration is over all values of the parameters that define a configuration. This expectation value is referred to as the coherent field. Similarly the expectation value of the total intensity (energy density) is given by the ensemble average of $|\Psi|^2$. This average total intensity consists of two parts, namely the coherent intensity, $|\langle\Psi\rangle|^2$, plus the average absolute squared deviation, V, of Ψ from its mean value, which is called the incoherent intensity.

$$\langle|\Psi|^2\rangle = |\langle\Psi\rangle|^2 + V$$

The normalized expectation value of the flux $\vec{J}$ (e.g., Poynting vector) is given by

$$\langle \vec{J} \rangle = \mathrm{Re}\,(\Psi^* \nabla \Psi /ik)$$

where $k = 2\pi/\lambda$ is the wave number and the asterisk indicates complex conjugate.

In order to obtain useful results for average values that are defined above, an appropriate probability distribution function, W, must be constructed and a solution for ψ obtained in terms of an arbitrary configuration. Expressions for W will involve the average number of scatterers (e.g., trees) per unit volume in the medium (e.g., forest) and include the distribution of possible scattering properties.* There appear to be analogies with the theory of liquids, in that short-range order can be expected in the locations of trees.

To seek a solution of the scattering problem, consider first the scattering from a single object. An incident plane wave (at $\vec{r}_a$) with wave vector $\vec{k}$ can be expressed by

$$\varphi^a = e^{i\,\vec{k}\cdot\vec{r}_a} \quad .$$

The far-field scattered wave at $\vec{r}_a$ from a scattering object at $\vec{r}_s$ is given by

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*Consideration of identical scatterers could be a first approximate.

$$u_s^a = f(\hat{o}, \hat{\imath}) \frac{e^{i k|\vec{r}_a - \vec{r}_s|}}{|\vec{r}_a - \vec{r}_s|}$$

where $f(\hat{o}, \hat{\imath})$ is the scattering amplitude in the direction $\hat{o}$ resulting from an incident wave in the direction $\hat{\imath}$. The scattering amplitude can be obtained either empirically or from theory (preferably both). A first step here could be to use the scattering amplitude from a single tree for $f(\hat{o}, \hat{\imath})$. Data similar to that of Figures 8 and 9 could be used.

For a configuration of N, not necessarily identical scatterers, located at $\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_N$, the solution at $\vec{r} = \vec{r}_a$ (outside the surfaces of the scatterers) can be represented by

$$\Psi(\vec{r}_a; 1, 2, \ldots, N) = \varphi(\vec{r}_a) + \sum_{s=1}^{N} U(\vec{r}_a - \vec{r}_s)$$

or, in abbreviated notation

$$\Psi^a = \varphi^a + \sum_{s=1}^{N} U_s^a \quad .$$

This equation expresses the total scattered wave, Ψ^a, at $\vec{r}_a$ in terms of the incident wave, φ^a, plus a summation of scattered waves. The scattered wave, U_s^a, at $\vec{r}_a$ resulting from scatterers at $\vec{r}_s$ can be further expressed in terms of the total wave, Φ^s, which is incident upon the scatterer at $\vec{r}_s$ and the scattering characteristic, u_s^a, of the object located at $\vec{r}_s$ as observed at $\vec{r}_a$. Thus

$$U_s^a = u_s^a \Phi^s$$

The total wave, Φ^s, incident upon the scatterer at $\vec{r}_s$ is referred to as the effective field. This field consists of the incident wave, φ^s, at $\vec{r}_s$ and all the waves scattered by other scatterers (i.e., excluding the wave from the object at $\vec{r}_s$) and is written as

$$\Phi^s = \varphi^s + \sum_{\substack{t=1 \\ t \neq s}}^{N} U_t^s \quad .$$

The last three equations for Ψ^a, U_s^a and Φ^s can be combined to give the following fundamental pair of equations:

$$\Psi^a = \varphi^a + \sum_{s=1}^{N} u_s^a \; \Phi^s$$

$$\Phi^s = \varphi^s + \sum_{\substack{t=1 \\ t \neq s}}^{N} u_t^s \; \Phi^t$$

This pair of equations can lead to integral equations for the expectation values for Ψ, $|\Psi|^2$ and $\vec{J}$ (as well as various other moments of the field Ψ). The formalism outlined here provides a possible starting point for a theoretical description of UHF propagation in vegetative media.

Clearly, the determination of the distribution of scattering properties of individual scatterers in the medium is an essential input for this work. The distribution of scatterer locations is another required input (which could be obtained by a statistical investigation of representative forests).

Theoretical prediction obtained from this approach are necessarily statistical in nature. One must keep in mind that any particular experimental measurement does not involve an ensemble of scatterer configuration; only one specific (i.e., actual) configuration is involved. The results obtained should, on the average, conform to the expectation values from an ensemble. However, the number of configurations of a macroscopic ensemble of trees is very much smaller than the corresponding numbers for ensembles on a molecular level (e.g., Avogadro's number $\approx 6 \times 10^{23}$ molecules/gram mole); thus the fluctuations around the predicted values for a macroscopic ensemble can be expected to be relatively larger than those obtained in statistical thermodynamics. These statistical considerations, together with the fact that diffraction of UHF waves by a tree can produce enhanced field strength in certain directions, provide a possible explanation why low-loss propagation paths through a forest can occur sometimes in addition to average expected values.

V CHARACTERIZATION OF THE MEDIUM

Characterization of the medium by a nonelectromagnetic description is not readily amenable to a generalized quantitative evaluation. That is to say, it is not easy to make an accurate estimation of the expected effects under one set of conditions on the basis of experimental observations carried out under different conditions (Saxton and Lane, A-23). Quantitative measures of weight of foliage per acre, or tree-trunk area at a fixed height per acre (Doeppner et al., B-12) are correlated with some UHF propagation properties. But these measures do not provide a complete picture. Full-leaf versus leafless condition (Trevor, A-32) is another parameter that has been shown to be significant. Wet versus dry leaves also has an effect. It also seems likely that the type of leaf (e.g., evergreen vs deciduous) or age of leaf (young/green vs dying/brown) would have an effect on UHF propagation.

At present, there are insufficient quantitative experimental data reported in the literature to make a realistic characterization of the medium that would allow quantitative predictions to be made. Furthermore, it is unlikely that a tractable theoretical model can be developed for predicting the scattering properties of a realistic distribution of imperfectly conducting bodies with irregular shapes. (Most theoretical treatments of scattering are confined to perfectly conducting objects with simple geometric shapes.)

Perhaps it is too much to expect that any nonelectromagnetic-wave measurements or even non-UHF electromagnetic-wave measurements can be used to characterize a vegetative medium. When one also considers possible nonuniformities in the distribution of foliage and the irregularities in topography, it would seem that some guide as to the order of magnitude of effects is the most that can be expected.

On a more positive note, it should be possible to make diagnostic measurements using UHF waves to characterize the properties of forests of potential interest. To do this, consider the medium to be time-variant but linear with respect to interactions with UHF waves (i.e., a linear superposition of effects is valid). All motions of the scatterers are much smaller than the speed of propagation of electromagnetic waves. The electric signal $E_o(t)$ at the receiving antenna resulting from an input signal $E_i(t)$ at the transmitting antenna can be expressed as

$$E_o(t) = \int_{-\infty}^{t} E_i(t') \, h(t, t') \, dt'$$

where $h(t, t')$ is the impulse response of the propagation medium, including the transmitting and receiving antennas. If the propagation medium is time-invariant, then h is simply a function of the time difference $t - t'$.

Simplistically speaking, one needs only to measure the impulse response of the medium between a particular transmitting antenna location (and polarization) and a particular receiving antenna location (and polarization) to completely characterize the medium on the specific path between the two antennas. This is true whether one considers the medium to be homogeneous or random. Thus one could sidestep the question of homogeneous versus random and characterize the propagation over one specific path in terms of the impulse response. Continued monitoring of the same path for different conditions of humidity, rain, snow, full leaf, or bare trees can be used to determine the effect of these parameters. Using this empirical approach a complete characterization of the medium (rather than a specific path) will require measurements on a very large number of paths to obtain an ensemble of impulse responses and the accompanying probability assignments.

A more realistic approach is: (1) to measure a representative set of impulse responses, (2) to measure a representative set of single-tree scattering and absorption characteristics, and (3) to use these data in conjunction with multiple-scattering theory to characterize the medium and propagation through it.

VI CONCLUSIONS AND RECOMMENDATIONS

A literature search has revealed that there have been a number of experimental investigations of UHF propagation in vegetative media but very little theoretical work has been reported in this field. There is a vast literature on the theory of wave propagation in random media in general, but specific application to UHF electromagnetic wave propagation in forests appears to be lacking. Even with respect to experimental work, there is a lack of wideband pulse information that can provide a detailed picture (in terms of the impulse response) of UHF propagation in vegetative media.

The experiments tend to fall into a few broad groups. In the first group, there is usually one prominent foliage-covered obstacle that prevents line-of-sight propagation from the transmitting antenna to the receiving antenna. The measured results in this group of experiments are usually explained satisfactorily by Fresnel diffraction theory. Thus the radio-wave propagation is interpreted as being primarily diffraction over (or around) the foliage-covered obstacle. Propagation through the foliage plays a lesser role than the diffraction effects.

In a second group of experiments, the radio waves apparently pass through the foliage for substantially the entire propagation path. Path loss in the UHF band is observed to increase with frequency. There is a large spread in the reported path-loss rates (dB/m) that appears, in part, to be caused not only by the randomness in a given medium, but also by the lack of any standard or definitive means for characterizing the important physical parameters of different media and for predicting the effect on UHF propagation. A greater path-loss rate is observed when trees are in full leaf and when the foliage is wet.

There have been a few investigations of the scattering and absorbing properties of a single tree at UHF. These experiments confirm the results of the first group of experiments in that a satisfactory explanation of the observed results is obtained from application of Fresnel diffraction theory.

Recently some preliminary wideband, high-time-resolution, pulse experiments have been undertaken as a joint NTIS/ITS, CORADCOM project. This type of experiment can provide the specific information that is needed to reveal the details of UHF propagation in vegetative media.

It is recommended that this type of pulse experiment be continued and expanded because it is well suited to exploring the specific details of UHF propagation in vegetative media and satisfying the needs of potential spread-spectrum communications systems (users) in this frequency range. Such experiments should be performed on several frequencies spread across the 400-MHz-to-2000-MHz band of interest in order to determine the frequency dependence of the observed phenomena. In addition to varying parameters such as distance, foliage type, and density of scatterers, it is recommended that selected paths be monitored under varying conditions of humidity, rain, snow, ice, and temperature in order to assess the role of these parameters. Empirical data from such experiments can have direct application for assessing propagation effects on spread-spectrum systems. The data can also be used to indicate the dominant propagation modes (e.g., single-scatter versus multiple-scatter) as a function of physical parameters as well as an aid to theoretical interpretation and understanding of propagation phenomena and characterization of vegetative media. It is recommended that these experiments be carried out in forests of actual operational interest (or as nearly so as possible) because the differences between forests are difficult to characterize and quantify.

It is recommended that additional scattering and absorption measurements be made on single trees. This type of experiment should also be done on several frequencies spread across the band of interest. Information on individual scatterers is needed both as an aid to the interpretation of other experiments and as an input for theoretical studies.

It is recommended that a theoretical effort be initiated to investigate the specific application of the theory of wave propagation and scattering in random media to the propagation of UHF radio waves in vegetative media. This effort should also be directed to interpret new wideband pulse data. The goal of this effort is to obtain a better understanding of the propagation phenomena and to provide a basis for assessing the effects of propagation on spread-spectrum system performance.

Appendix A

LITERATURE DIRECTLY RELATED TO UHF PROPAGATION IN A VEGETATIVE MEDIUM

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(1) Barsis, A. P., "Radio Wave Propagation Over Irregular Terrain in the 76- to 9200-MHz Frequency Range," IEEE Trans. Veh. Technol. (USA), Vol. VT-20, No. 3 pp. 41-62 (August 1971)

This paper presents descriptive and statistical analyses of radio propagation data over irregular terrain--with special emphasis on communications between low antennas in the VHF and UHF bands. Measured data are evaluated for medians and ranges of basic transmission loss and height gain. The results are compared with estimates for a propagation model developed by the Institute for Telecommunication Sciences. Effects of vegetation near the path terminals are demonstrated. Analysis results provide first estimates of propagation parameters in many terrain types and information regarding applicability of the propagation model.

Descriptors: Electromagnetic wave propagation, atmosphere; radio-wave propagation.

Identifiers: Radio wave propagation over irregular terrain; VHF; UHF; basic transmission loss; height gain; propagation model; vegetation.

(2) Chao-Han, Lin and Kung Chie Yeh, "Pulse Propagation in Random Media," IEEE Trans. Antenn., Vol. AP-26, No. 4, pp. 561-56 (July 1978).

In this article a new approach is developed to investigate pulse propagation in random media, taking into account the effects of multiple scattering. The technique is based on the idea of temporal moments of the signal. It is shown that these temporal moments are related to the coefficients of expansion for the two-frequency mutual coherence function gamma in terms of the frequency separation. These coefficients, and therefore the moments, can be solved analytically in sequence without making assumptions about the strength of the turbulence. Using these moments, a least-square orthogonal polynomial expansion procedure is developed to obtain the average intensity of the pulse as it propagates through the turbulence. It is also shown that the technique can be used for propagation through random media with discrete scatterers. An example is given to demonstrate the procedure.

Descriptors: Electromagnetic wave propagation.

Identifiers: Pulse propagation; random media; multiple scattering; temporal moments; coefficients of expansion; mutual coherence function; least-square orthogonal polynomial expansion; turbulence.

(3) Checcacci, P. F., and A. M. Scheggi, "Space-Varient Transfer Functions for the Characterization of Inhomogeneous Scattering Media," Radio Science, Vol. 13, No. 3, pp. 431-433 (May-June 1978)

This report outlines a set of transfer functions that turns out to be suitable for characterizing space-variant propagation media. The purpose of the paper is to show the possibility of using such functions for predicting the performance of a given antenna looking through an inhomogeneous medium as well as for indicating the type of measurements necessary to characterize the medium.

Descriptors: Antenna theory; radio-wave propagation; electromagnetic wave scattering; transfer functions; atmospheric electromagnetic wave propagation.

Identifiers: Transfer functions; inhomogeneous scattering media; space variant propagation media; antenna performance.

(4) D'Accardi, R. J., D. Dence, R. Kulinyi, and C. P. Tsokos, "Statistical Analysis and Modeling of Path Loss Distance Dependency," Final Report, July 1973-June 1974, Report No. ECOM-4231, 33 p, Project DA-1-S-762701-AH-92, Task 1-S-762701-AH-92-N-127, Army Electronics Command, Fort Monmouth, N.J. (July 1974).

In recent years extensive investigations have been made in Southeast Asia and the United States to improve communications-electronics performance in heavily forested environments. A careful inspection of the data from the investigations, the physical aspects of the design of the experiments, and the topological characteristics of the environment reveal that one should not view path loss from a deterministic point of view, but rather as a stochastic realization. Four stochastic models are proposed for analysis of such data, and selected analysis is shown for the two most logical models.

Descriptors: Radio transmission; losses; propagation; models; mathematical models; stochastic processes; statistical analysis; forests; environments.

(5) Conductron Corporation, Ann Arbor, MI, "Foliage Propagation Measurements, Vol. I: One-Way Path Measurements, 1963-1964," AD-359 560, Technical Report, 123 pp., AF33 657 10348, Project 4108, ARPA Order 377, Task 410804 (April 1965).

A series of one-way measurements have been performed to determine the propagation characteristics of meter-wavelength electromagnetic radiation through various types of foliage cover under varying seasonal conditions. The resulting data has been analyzed to determine the degree of success that can be expected when using a coherent, focused, synthetic-antenna, fine-resolution radar to observe targets that lie under the cover of natural foliage. In performing the one-way propagation measurements, an airborne CW transmitter and a multiple-channel receiving station located on the ground have been employed. Measurements, initiated in June 1963 and terminated in July 1964, were made at six sites representative of the temperate and semitropical forestations typical of the continental United States and Puerto Rico. At each site, measurements were made at four radiation wavelengths corresponding to frequencies of 140 Hz, 280 MHz, 560 MHz, and 1120 MHz, at elevation angles of 30°, 45°, and 60°.

Descriptors: Radar signals, target recognition; target recognition, radar signals; electromagnetic radiation; radar interference; attenuation; penetration; measurement; trees; photographs; Puerto Rico; Florida; Mississippi; Michigan; radar antennas; coherent radar; resolution; CW radar; antennas; propagation; VHF; UHF; phase shift circuits; phase modulation; amplitude modulation.

Identifiers: Foliage; seasons.

(6) Conductron Corporation, Ann Arbor, MI, "Foliage Propagation Measurements, Vol. III: Two-Way Path Measurements, 1963-1964," AD-363 896, Technical Report, 228 pp, Contract AF33 657 10348, Project 4108, ARPA Order 377, Task 410804 (July 1965).

A series of two-way propagation measurements were performed to determine the resolution that can be expected when a coherent, focused, synthetic-antenna, fine-resolution radar operating at meter wavelength is used to observe targets that lie under the cover of natural foliage. To perform these tests a low-power, long-wavelength, synthetic-aperture radar known as "pipsqueak" was employed. Radar data were obtained at radiation frequencies of 280 MHz and 1120 MHz. This unit was designed to operate at short range so that aircraft motion compensation would not be necessary when flying in moderately smooth air. Measurements of corner reflectors in the open and under cover of foliage were made to determine the resolution capabilities of the radar in a foliage environment. For convenience, the same size corner reflectors were employed for measurements at both radiation frequencies. As a result, the corner reflector cross section at 1120 MHz is approximately 16 times the cross-section at 280 MHz and therefore must be taken into account in the data analysis.

Descriptors: Radar cross-sections, trees; radar cross-sections, grasses; radar signals, propagation; penetration; radar images; data processing; aerial photographs; azimuth; photographic film; radar antennas; radar targets; detection; surface targets; radar corner reflectors; optical equipment; Michigan; Mississippi; Florida; Puerto Rico; Doppler radar; lenses; coherent radar; UHF.

Identifiers: Foliage; pipsqueak radar.

(7) Evans, H. L., and J. A. Green, "Foliage Propagation Measurements, Vol. IV: Final Report, June 1964-November 1965 on Phase 3," 358 pp., Contract AF 33(657)-10348, ARPA Order 377-4, Project AF-4108, AF-5955, Task 410804, A0377-4, Conductron Corporation, Ann Arbor, MI (May 1966).

This paper reports radar measurements to determine the propagation characteristics of electromagnetic radiation through various types of foliage cover under different seasonal conditions. Measurement sites in the continental United States and Puerto Rico typified temperate and semitropical forestations; each site was visited at least twice. One-way propagation measurements at 10 discrete frequencies between 4.375 MHz and 10.8 GHz employed an airborne CW transmitter and multichannel ground receiving station; incidence angles were 10°, 20°, 40°, and 60° with horizontal and vertical polarizations. Reduction of data permitted analysis of significant parameters characterizing the received signal; for example, the attenuation of both like- and cross-polarized signals just beneath the canopy and again at the forest floor; comparisons of direct and ground-reflected signal attenuations; and the one-way phase defect standard deviation of like-polarized signals at the forest floor.

Descriptors: Plants (botany), electromagnetic properties; propagation; reflectivity surface targets; penetration; target acquisition; search radar; VHF; UHF; super high frequency; polarization; attenuation; ships; trees; terrain; radar images; resolution; radar antennas; antenna arrays; phase-locked systems; data processing; aerial reconnaissance; radar signals; test equipment; computer logic; radar interference.

Identifiers: Foliage; pipsqueak radar.

(8) Evans, H. L., and J. A. Green, "Foliage Propagation Measurements, Vol. V: Statistical Forest Model and Measurements Summary," AD 381 820, Final Report, 129 pp., Contract AF 33 (657)-10348, ARPA Order 377, Project AF-4108, AF-5955, Task 410804, A0377-4, Conductron Corporation, Ann Arbor, MI (January 1967).

A wide-ranging program of measurements and analysis in the air/ground propagation of electromagnetic energy through deciduous and coniferous types of forest foliage is reviewed and salient findings are presented in this report. Data were obtained via field trips to selected forest sites in temperate, semitropical, and tropical regions of the western hemisphere. In one-way propagation experiments, an airborne transmitter was operated in conjunction with a ground receiving and recording station. Antennas mounted above and beneath the forest canopy intercepted free-space and foliage-penetrating energies. Comparative analyses of signals yielded measured of foliage-induced phase and amplitude perturbations. Foliage effects in two-way operation were examined by flying a synthetic-aperture radar of experimental design over the same forest sites. An aspect sensitivity study and an exercise in statistical forest analysis are also reported.

Descriptors: Trees, electromagnetic properties; radio transmitters; air-to-surface; terrain; penetration; measurement; mapping; absorption; statistical analysis; mathematical models; camouflage; radar transmission; radar reflections; surface targets; target acquisition; radar images; VHF; UHF; detection; angle of arrival; aerial reconnaissance; electrooptical photography.

Identifiers: Foliage; forests; radar transmission; synthetic-aperture radar.

(9) Frankel, M. S., "L-Band Forest Experiments," Packet Radio Temporary Note 254, SRI International, Menlo Park, CA (19 May 1978).

Measurements of excess path loss were made through foliage in forests in the San Francisco Bay Area at a frequency of 1850 MHz during the month of February. An excess-loss value of 0.17 dB/m with a standard deviation of 0.08 dB/m was obtained.

(10) Fung, A. K., and F. T. Ulaby, "A Scatter Model for Leafy Vegetation," Agard Conf. Proceed. No. 244, Aspects of Electromagnetic Wave Scattering in Radio Communications, 16/1-10, A. N. Ince, Ed., Cambridge, MA (1978).

A model for vegetation scatter is developed using the first-order renormalization method. The vegetable medium is taken to be an inhomogeneous medium characterized by a random permittivity function with a cylindrically symmetric, fast-decaying correlation function. The backscattering coefficient from such a model is computed as a function of the incidence angle, frequency, and the moisture content of the vegetation. Comparisons are made with measured data from soya beans, alfalfa, and corn.

Descriptors: Electromagnetic wave scattering; backscatter; modelling.

Identifiers: Scatter model; vegetation scatter; renormalization method; permittivity function; correlation function; backscattering coefficient; electromagnetic wave scattering.

(11) Golden, A., "A Foliage Penetration Summary," Report No. RADC TR-78-34, Project 4600, Task 15, Rome Air Development Center, Griffiss AFB, NY (February 1978).

This report presents a brief survey of existing data on foliage attenuation of RF energy. It is shown that most researchers have concluded from this data that RF energy is attenuated more rapidly in foliage at higher frequencies. Also, signal reflections from the foliage/air interface are shown to be a significant loss mechanism that is relatively frequency-independent. Finally, curves for predicting RF signal reflection from and attenuation within foliage are presented.

Descriptors: Radar signals; attenuation; foliage; penetration; transmission loss; radar reflections; frequency; radar targets; forests.

(12) Huerta, M. A., J. C. Nearing, W. B. Pardo, and M. Reusch, "Some Physics of a Florida Forest," Report No. MIAPH-70-11, University of Miami, Coral Gables, FL (November 1969).

The University of Miami has studied the interaction of forest surroundings with electromagnetic radiation. Both theoretical and experimental approaches have been adopted; the results are put forward in this paper.

Descriptors: Electromagnetic wave propagation; biological effects of radiations; biophysics; radiation effects; radar measurement.

Identifiers: Trees; physical effects; forest surroundings; electromagnetic radiation.

(13) Kritikos, H., K. C. Lang, W. Boerner, G. N. Tsandoulas, and L. B. Spence, "Investigation of Rough Earth Propagation Models," Technical Report No. 68-05, Contract AF 30(602)-3290, Project AF-4540, Task 454002, Monitor RADC-TR-67-531, University of Pennsylvania, Moore School of Electrical Engineering (October 1967).

The purpose of this report is to discuss the most important propagation models, assess their usefulness, point out the most reliable models, and suggest new areas of research. The report also reviews research undertaken in the Moore School on antenna placement considerations, diffraction of a caustic by an impedance plane, illumination of a rough surface by a beam of radiation, and diffraction radiation by multiple wedges.

Descriptors: Radio waves, propagation; electromagnetic radiation, propagation; radio transmission, terrain; atmospheric motion; reflection; diffraction; attenuation; absorption; jungles; trees; troposphere; radio frequency; range (distance); meteorological phenomena, communication and radio systems; effectiveness; reliability; antennas; antenna lobes; antenna radiation patterns; scattering; models (simulations); earth models; microwave; surface roughness.

(14) Lagrone, A. H., "Propagation of VHF and UHF Electromagnetic Waves Over a Grove of Trees in Full Leaf," IEEE Trans. Antenn., Vol. AP 25, No. 6, pp. 866-869 (November 1977).

Results are reported of horizontally polarized signal strength measurements at frequencies of 82 MHz, 210 MHz, 633 MHz, 1280 MHz, and 2950 MHz. Measurements of signal strength versus height were made at various distances behind a grove of live oak and hackberry trees in full leaf. Propagation took place over approximately the same path near the receiver terminal at all frequencies. Ideal knife-edge diffraction curves provided exceptionally good agreement with the measured curves.

Descriptors: Radio wave propagation.

Identifiers: Horizontally polarized signal strength measurements; knife-edge diffraction curves; UHF propagation; VHF propagation; groves of trees; full lead.

(15) Lagrone, A. H., and C. W. Chapman, "Some Propagation Characteristics of High UHF Signals in the Immediate Vicinity of Trees," IRE Trans. Antenn., Vol. AP-9, pp. 487-491 (September 1961).

Results are reported of measurements made at very low angles of 2880-MHz vertically-polarized signals over wooded areas, with the elevation angle to the transmitter the principal variable. The effects of one tree and of many trees on the apparent location of a signal source, as determined with a narrow-beam antenna, are reported. A hypothetical direction-finding system is assumed and its pointing characteristics determined.

(16) Lagrone, A. H., P. E. Martin, and C. W. Chapman, "Frequency Characteristics of Radio Propagation Over a Grove of Trees in Full Leaf," Report No. 644, AD 272 045, Contract AF19 604 8038, Monitor AFCRL 62 23, Electrical Engineering Research Lab, University of Texas (Austin) (January 1962).

Results are reported of horizontally polarized signal-strength measurements made at frequencies of 82 MHz, 210 MHz, 633 MHz, 1280 MHz, and 2950 MHz. Height-gain runs were made at all frequencies behing two groves of live oak and hackberry trees in full leaf. The sites were selected so that propagation took place over approximately the same path near the receiver terminal at all frequencies. Measurements were repeated at several distances behind the two groves of trees. Theoretical analyses are reported for several cases for comparison with field-measured data.

Descriptors: Radio signals; radio waves; terrain; trees; dipole antennas; measurement; polarization; propagation; radio transmission; theory; UHF; VHF; wave propagation.

(17) Longley, Anita G., and G. A. Hufford, "Sensor Path Loss Measurements: Analysis and Comparison with Propagation Models," Report No. OTR-75-74, 186 pp., Office of Telecommunications, Washington. D.C; Army Electronic Proving Ground, Fort Huachuca, Arizona (October 1975).

The data from a large measurement program at VHF and UHF are carefully evaluated, summarized, and compared with values predicted from models of radio propagation over irregular terrain. Particular problems of low antennas and the effects of vegetation are considered. Modifications in prediction models are suggested for particular application to sensor systems.

Descriptors: Radio transmission; VHF; UHF; terrain, abnormalities; attenuation; fading; vegetation; detectors; predictions.

(18) McPetrie, J. S., L. H. Ford, "Some Experiments on the Propagation Over Land of Radiation of 9.2-cm Wavelengths, Especially on the Effect of Obstacles," J. Inst. Elec. Engrs., Vol. 93, Pt. IIIA, No. 2, pp. 531-538 (March-May 1946).

The salient results are brought together of a number of experiments on the propagation of radiation of a wavelength of 9.2 cm, carried out during the 1943-to-1944 period. All the measurements described were made over land, some over open country, and some over transmission paths which were obstructed by various obstacles. The obstacles included trees, both leafless and in full leaf, brick walls, windows, and other parts of buildings.

Many of the obstacles caused such large attenuations that they should generally be regarded as opaque objects round which diffraction takes place. Stone buildings, groups of trees so dense that the sky cannot be seen through them, and the trunks of trees come into this category. Semi-transparent obstacles (causing a loss of signal of 10 dB or less), include windows, tile or slate roofs, the sides of a light wooden hut, and thin screens of trees when the transmittion path lies through the branches.

(19) McQuate, P. L., J. M. Harman, and M. E. McClanahan, "Tabulations of Propagation Data Over Irregular Terrain in the 230- to 9200-MHz Frequency Range, Part IV, Receiver Site in Grove of Trees," Report No. OT/TRER-19, Institute for Telecommunication Sciences, Boulder, CO (October 1971).

This report contains tabulations and graphs of transmission loss data resulting from propagation experiments in the 230-MHz to 9200-MHz frequency range conducted over irregular terrain in Colorado. This part presents data obtained at a common receiver site, located in a small grove of cottonwood trees, over propagation of paths varying in length from 0.5 km to 50 km.

Descriptors: Radio transmission; UHF; microwave frequencies; transmission loss; terrain; abnormalities; trees (plants); data; Colorado.

(20) Murray, O. M., "Attenuation Due to Trees in the VHF/UHF Bands," Marconi Review, Vol. 37, No. 192, pp. 41-50 (1974).

This article describes a program set up to measure the attenuation due to trees in the VHF/UHF broadcasting bands. The results obtained are presented, and suggestions are made for an extension program that could resolve some of the apparent anomalies found. (3 refs.)

Descriptors: Radio transmission, absorption; radio broadcasting.

(21) Reudink, D. O., and M. F. Wazowicz, "Some Propagation Experiments Relating Foliage Loss and Diffraction Loss at X-band and UHF Frequencies," Vol. COM-21, No. 11, pp. 1198-1206 (November 1973) and IEEE Trans. Commun., Vol. VT-22, No. 4, pp. 114-122 (November 1973).

Measurements of signal attenuation were made from a suburban hilltop base station to a mobile vehicle on several streets in the surrounding countryside. Measurements of signal strength were simultaneously made in the winter of 1971 at frequencies of 836 MHz and 11.2 GHz and then repeated in the summer to determine the effects of foliage. The presence of foliage reduced the received signal strength; the effect was more pronounced at X-band than at UHF. In cases where the shadowing obstacle was tree-covered, signal levels at UHF were typically 10 dB lower when the trees were in full leaf, whereas at X-band this additional loss could be as high as 20 dB. The experimental data were compared to values predicted by knife-edge diffraction and reasonable agreement was found (11 refs.)

Descriptors: Radio-wave propagation; fading; electromagnetic wave diffraction; electromagnetic wave absorption.

Identifiers: Foliage loss; diffraction loss; signal attenuation; UHF; EM wave diffraction; EM wave attenuation; X-band; radio wave propagation effects; 836 MHz, 11.2 GHz.

(22) Rice, P. L., et al., "IEEE/Mountain-West Electromagnetic Compatibility," Conference Record, IEEE/Mountain-West Electromagnetic Compatibility Conference Record, Tucson/Sierra Vista, Arizona. November 11-12, 1971, Available from IEEE (71C60-MC) (1971).

This conference record includes 23 papers dealing with various aspects of electromagnetic compatibility, such as propagation modeling, noise, measurements and side effects, analysis of interference in large-scale ensembles, shielding and standards, closed circuits and nearfield analysis. Following is a list of titles and authors: "Some Effects of Buildings and Vegetation on VHF/UHF Propagation," P. L. Rice; "Model for Calculating Transmission Loss Over Irregular Terrain," by A. G. Longley; "Ionospheric Interference Propagation," by G. C. Josephson; "Transients in an Electronics Manufacturing Facility," W. Ellison; "RFI/EMC Measurements at UHF for Satellite Earth Terminals," A. F. Barghausen and L. D. Schultz; "Lunar Roving Vehicle/Apollo 15 Electromagnetic Compatibility," W. S. Kastorff; "Prediction of Mitigation Requirements for Interference Voltages on Telephone Lines Exposed to ELF Electromagnetic Fields," W. M. Moran; "Evaluation Model for Interference Prediction," A. J. Hoehn; "Simulation: Convolution Versus Numerical Integration," J. R. Thompson; "Architectural RF Shielding," F. J. Nichols; "Applications of a Current Probe-Coupled Impedance Measurement System," Roger A. Southwick; "National EMC Standards for Non-Message EM Energy-Transfer Systems," C. L. Frederick, Sr.; "Shooting Holes in Shielding Theory," R. B. Cowdell.

Descriptors: Electromagnetic compatibility; electromagnetic waves; electric measurements; space vehicles; telephone lines; electric shielding.

(23) Saxton, J. A. and J. A. Lane, "VHF and UHF Reception: Effects of Trees and Other Obstacles," Wireless World, pp. 229-232 (May 1955).

Some experiments to determine the attenuation caused by screens of trees and thick woods at frequencies of 100 MHz, 540 MHz, and 1,200 MHz are described, and these and other data are used to estimate the attenuation over the frequency range 30 MHz to 3,000 MHz. The nature of the diffraction loss and variation of field strength behind opaque obstacles of various kinds for the same frequency band is examined on the basis of the Fresnel theory of diffraction.

(24) Schouten, A., "Attenuation Effect of Foliage Upon Radar-Frequency Propagation--Results of a Trial at Pershore (U.K.)," AD888-431, Technical Memo, 128 pp., Report No. STC-TM-310, Shape Technical Center, The Hague (Netherlands) (September 1971).

This is an account of the part that STC played in a trial at Pershore (UK), the object of which was to measure the attenuation effect of propagating microwave power through different kinds of foliage. To do this, transmitters were positioned in front of the foliage; receivers located behind the foliage were moved about both horizontally and vertically and measurements were taken of the received power. The measurements showed that the resultant field patterns created above the optical line of sight can be described by free-space propagation with ground-reflection effects. Below the line of sight, the field patterns conformed with knife-edge diffraction theory. The foliage acted as an attenuating screen, the attenuation being 0.6-0.8 dB per meter of foliage thickness for the L-band frequency and 1.0-1.2 for the S-band frequency.

Descriptors: Radar signals, propagation; attenuation; plants (botany); microwave frequency; trees; radar transmitters; diffraction; polarization; climate; wind; interference; site selection; Great Britain; terrain; measurement; data; analysis of variance; radio transmission; L-band; S-band; X-band.

Identifiers: NATO; terrain masking; vegetation.

(25) Sturgill, L. G., "Tropical Propagation Research," 1 Jan-30 June 1966, Vol. 1, Final Report, Contract DA-36-039-sc-90889, U.S. Army Electronics Command, ARPA Order 371, Jansky and Bailey Engineering Department, Atlantic Research Corporation, Alexandria, VA (1967).

This report presents the results obtained from the first phase of an extensive experimental and theoretical research program on radio-wave propagation in the environment of a tropical, thickly vegetated jungle. The experimental work during this first phase was carried out in Thailand in a geographical area classified as a wet-dry, or monsoon, tropical region. The vegetation in the main test area has a density of about 130 tons per acre and is considered to be typical of many jungle regions throughout Southeast Asia. The propagation tests and analyses contained in this report cover the frequency range of 100 KHz to 10 GHz for propagation distances extending from 25 ft to 30 mi and antenna heights from about 7 ft to 80 ft above ground. Except at the lowest frequencies, all tests were conducted at both horizontal and vertical polarizations. Most of the data are presented in graphs of basic transmission loss plotted against horizontal distance, terrain characteristic, antenna height, and transmission polarization or frequency. Also covered are the results of special measurements in the 1-GHz to 10-GHz frequency range, the data from which is applicable to problems with line-of-sight systems propagating horizontally through vegetation. The large quantity of measured data demonstrates the complex effects upon path loss of irregular topography combined with dense tropical vegetation.

Descriptors: Radio transmission, tropical regions; Thailand; propagation; climatology; Southeast Asia; ranges (distance); refraction; experimental data; jungles; tropical tests; radio frequency; terrain, antennas; altitude; polarization; attenuation.

(26) Hicks, J. J., A. P. Murphy, et al., "Tropical Propagation Research," Final Report, Vol. 2, Contract DA-36-039-sc-90889, U.S. Army Electronics Command, ARPA Order 371, Jansky and Bailey Engineering Department, Atlantic Research Corporation, Alexandria, VA (November 1969).

This report, Volume 2, is sequential to Volume 1, which covered an extensive series of radio propagation measurements in a wet-dry (monsoon) tropical jungle in Central Thailand. In contrast, Volume 2 presents results of measurements in a tropical rain forest area in Southern Thailand. Radio-path loss measurements have been conducted in the rain forest area at frequencies from 2 MHz to 400 MHz, for antenna heights above ground from 7 ft to 120 ft, with both vertically and horizontally polarized transmitting antennas, and at a large variety of path ranges and configurations in the jungle vegetation. This report also includes results from jungle-to-air measurements at frequencies of 25 MHz, 50 MHz, 100 MHz, 250 MHz, and 400 MHz, generally with aircraft altitudes of about 500 ft. The results from a series of ground-to-ground measurements for paths of mixed proportions of forest and clearing are presented, along with a theoretical model of this type of propagation path. Finally, an attempt is made to summarize the general conclusions that can be drawn from the work thus far and that may be useful to a wide variety of communications problems in tropical jungle environments.

Descriptors: Radio transmission, tropical regions; climatology; ranges (distance); jungles; tropical tests; attenuation; radio frequency; terrain, antennas; trees; rainfall; Thailand; Southeast Asia.

(27) Robertson, R. G., J. Hicks, et al., "Tropical Propagation Research," Final Report, Vol. 3, Contract DA-36-039-sc-90889, U.S. Army Electronics Command, ARPA Order 371, Jansky and Bailey Engineering Department, Atlantic Research Corporation, Alexandria, VA (1970).

The overall objective of this program was to collect and analyze radio propagation data from actual representative environments needed to advance the state of the art in the design and development of improved radio communications systems in these environments. The report summarizes the results of a series of specialized measurements, using pulse and swept-frequency transmitted signals. Various types of amplitude, frequency, and phase displays were recorded at the test receiver locations. The objective of these measurements was to obtain data that exhibit the multipath characteristics of the jungle path. The report discusses the methods of making these measurements and the results of a limited analysis of the data. The probability distributions of signal amplitude at VHF in the tropical rain forest test area in Thailand are presented. These distributions are generally a prerequisite to the practical estimation of error-rate performance of digital, or wideband, systems in this type of environment. An example is given in which the experimental probability distributions are used to obtain the error rate in an FSK modulation system in this type of environment.

Descriptors: Radio transmission, tropical regions; radio frequency; attenuation; ranges (distance); antennas; tropical tests; jungles; terrain; climatology; Thailand; Southeast Asia.

(28) Hicks, J. J., et al., "Tropical Propagation Research," Final Report, Vol. 4, U.S. Army Electronics Command, Report No. TR-PL-10126-00-0, Contract DA-36-039-sc-90889, ARPA Order 371, Jansky and Bailey Engineering Department, Atlantic Research Corporation, Alexandria, VA (December 1972).

This report presents results from a special series of measurements designed to characterize the influence of a jungle environment on the transmission of digital signals. Measurements were conducted by transmitting a swept-frequency signal, 4-MHz wide about center frequencies of 50 MHz, 100 MHz, and 150 MHz, and photographically recording the received envelope and phase, compared to a fixed reference antenna at the receiving terminal. The test antenna was incrementally moved along both a radial and transverse direction with respect to the line of transmission from the transmitter.

Descriptors: Radio transmission, tropical regions; VHF; jungles; attenuation; statistical data; polarization; Southeast Asia; Thailand.

(29) Swarup, S., and R. K. Tewari, "Radio Wave Propagation Through Subtropical Pine Forest," Indian J. Radio and Space Phys., Vol. 3, No. 2, pp. 181-185, Symposium on Aeronomy and Radio Wave Propagation, February 1974, New Delhi, India (June 1974).

This report presents results of measurements made in a subtropical pine forest to study its effect on radio-wave propagation in the frequency range of 50 MHz to 800 MHz. The basic transmission loss in the presence of vegetation has been found to increase with frequency and the distance between transmitter and receiver; it is also higher for vertical polarization. The rate of attenuation has been found to decrease sharply with the increase in the transmitter-receiver distance.

(32) Trevor, B., "Ultra-High-Frequency Propagation Through Woods and Underbrush," RCA Review, Vol. 5, No. 1, pp. 97-100 (July 1940).

Measurements of the attenuation of field strength through 500 ft of woods and underbrush on a frequency of 500 MHz showed a loss of approximately 17 dB to 19 dB in summer and 12 dB to 15 dB in winter as compared with propagation over level ground. No great difference was found between horizontal and vertical polarization.

At 250 MHz the attenuation through the same section of woods in winter showed a 10-dB loss with horizontal and a 14-dB loss with vertical polarization.

Transmission of 500-MHz signals over low scrub pines compared with that over sand ground showed a reduction of signal due to vegetation which can be interpreted as showing reflection rather than absorption of the indirect ray from a level considerably above ground or near the top of the vegetation.

(33) Wait, J. R., et al., "Workshop on Radio Systems in Forested and/or Vegetated Environments," Technical Report C3104K2, Fld: 20N, 17B, 46, 45C GRA17417, 313 pp., Report No. ACC-ACO-1-74. Summaries of 20 Technical Papers and 4 Working Group Reports presented at subject workshop held at Fort Huachuca, Arizona, on 6-9 November 1973. Advanced Concepts Office, Army Communications Command, Fort Huachuca, AZ (February 1974).

The purpose of the workshop was to review the state of the art in the theory of operation and design of radio systems for which the air/earth interface becomes a controlling factor. Each of the 20 technical papers are presented in summary, with the author's name, affiliation, and address. The papers are principally devoted to radio and radar propagation in jungles and forests, path loss predictions, electrical characteristics of the forest and earth media, and lateral-wave applications. The working group reports cover: (1) application of antenna and propagation theory, (2) spectrum usage below 300 MHz (including UHF radio 225 MHz to 400 MHz, but exclusive of radar), (3) spectrum usage above 300 MHz (including radar above 30 MHz, but exclusive of UHF radio 225-400 MHz), and (4) environmental descriptions (in relation to propagation and system performance modeling). Appendices provide names and addresses of all attendees plus a bibliographic summary of reports and articles from project SEACORE, which was sponsored by the Advanced Research Projects Agency and the U.S. Army Electronics Command.

Descriptors: Electromagnetic wave propagation; radio transmission; meetings; reviews; state of the art; jungles; forests; environments; radar; losses; propagation; spectra; utilization; electrical properties; vegetation; Southeast Asia; computerized simulation.

Identifiers: SEACORE project.

Descriptors: Radio-wave propagation; tropospheric electromagnetic wave propagation.

Identifiers: Subtropical pine forest; 50 to 800 MHz; VHF; UHF; transmitter-receiver distance; radio-wave propagation; transmission loss; vegetation; vertical polarization; rate of attenuation.

(30) Swarup, S., and R. K. Tewari, "Propagation Characteristics of VHF/UHF Signals in Tropical Mois_ Deciduous Forest," J. Inst. Elect. and Telecommun. Eng. (India), Vol. 21, No. 3, pp. 123-125 (March 1975).

This report describes the propagation studies conducted by HRPU in a tropical moist deciduous forest. The attenuation measurements were made in the frequency range of 50 MHz to 800 MHz and distances from 40 m to 4 km. Both horizontal and vertical polarizations were used. The results of the nature and magnitude of the attenuation caused by the presence of vegetation are presented. They support the theory of the lateral-wave mode of propagation of radio waves in jungle environments. These results have been compared with those of measurements made in a subtropical pine forest.

Descriptors: Radio wave propagation; tropospheric electromagnetic wave propagation.

Identifiers: VHF/UHF signals; tropical moist deciduous forest; propagation characteristics.

(31) Swarup, S., and R. K. Tewari, "Depolarization of Radio Waves in Jungle Environment," Vol. AP-27, No. 1, pp. 113-116 (January 1979).

Radio waves become substantially depolarized while propagating through a jungle environment, because their scattering by the vegetation. The foliage supports induced currents that tend to be randomly oriented and therefore produces a depolarization of the overall field. This study reports results of cross-polarization measurements in the VHF/UHF band in tropical moist deciduous and tropical wet evergreen forests. It was found that vertically polarized waves suffer 5 dB to 15 dB higher depolarization than horizontally polarized waves. The cross-polarization discrimination is also found to be dependent on frequency as well as the separation distance between the transmitter and the receiver.

Descriptors: Radio-wave propagation; electromagnetic wave scattering.

Identifiers: Radio waves; jungle environment; scattering; VHF/UHF band; radio-wave depolarization.

Appendix B

LITERATURE ON EXPERIMENTS RELATED TO RADIO-WAVE PROPAGATION IN A VEGETATIVE MEDIUM

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LITERATURE ON EXPERIMENTS RELATED TO RADIO-WAVE PROPAGATION IN A VEGETATIVE MEDIUM

(1) Acquista, C., "Wave Propagation Through a Random Medium--The Random Slab Problem," Radio Science, Vol. 13, No. 6, pp. 963-968 (November-December 1978).

The first-order smoothing approximation yields integral equations for the mean and the two-point correlation function of a wave in a random medium. A method is presented for the approximate solution of these equations that combines features of the eiconal approximation and of the born expansion. It is applied to the problem of reflection and transmission of a plane wave by a slab of a random medium. Both the mean wave and the covariance are calculated to determine the reflected and transmitted amplitudes and intensities.

Descriptors: Electromagnetic wave propagation.

Identifiers: Random medium; random slab problem; reflection; transmission; plane wave; wave propagation.

(2) Adams, B.W.P., "Empirical Routine for Estimating Reflection Loss in Military Radio Paths in the VHF and UHF Bands," IEEE Conference Publication, No. 169, Part 2, pp. 26-31. International Conference on Antennas and Propagation, London, 28-30 November 1978, CODEN: IECPB4 (1978).

This paper describes a technique for calculating reflection loss in tactical military paths. The method was tested against a large set of path profiles and associated measurements. The result is a method that is considerably more accurate than previous ones, but no more difficult to use in the field. There are important tactical implications, particularly in the assessment of obstacle gain paths not previously predicted.

Descriptors: Radio transmission; military communications.

(3) Andrianov, V. A., N. A. Armand, and I. N. Kibardina, "Scattering of Radio Waves by an Underlying Surface Covered with Vegetation," Radiotekh i Elektron (USSR), Vol. 21, No. 9, pp. 1816-22; [Trans. Radio Eng. Electron Phys., Vo. 21, No. 9, pp. 12-16 (September 1976)].

This paper reports experimental measurements of the spectral-power density of a signal scattered by a surface covered with trees. The experiment was conducted for three sections of forest containing different types of trees, i.e., birch, alder, and pine. The spectral density of the scattered signal was found to be an exponential function of frequency in the region of small deviations from the carrier and a power function of frequency in the region of large deviations. The spectral width of the scattered signal depends on both the wind velocity and the type of vegetation.

Descriptors: Radio-wave propagation; electromagnetic wave scattering; wind.

Identifiers: Radio waves; surface; trees; spectral density; scattered signal; wind velocity; vegetation.

(4) Armstrong, B., and H. D. Ziesing, "A Study of Electromagnetic Wave Propagation at 112-118 MHz," Proc. Inst. Radio Electron. Eng. Aust., Vol. 30, No. 4, pp. 105-110 (April 1969).

A series of in-flight recordings of signal strength were obtained from horizontally polarized VHF omnidirectional ranges operating in the frequency band 112 MHz to 118 MHz. These measurements were made over irregular terrain, forests, and mixed land/sea paths in Australia. The recorded signal strengths were compared with predictions based on spherical earth theory. Particular attention is given to the relationship between field strength and terrain roughness. It is shown that use of a relative roughness parameter can improve field-strength predictions. In addition, the scattering of electromagnetic waves by trees located in the near vicinity of the transmitting source is investigated.

Descriptors: Electromagnetic wave propagation; atmosphere; radio-wave propagation; radio-wave propagation effects; electromagnetic wave scattering.

(5) Babaev, A. B., et al., "Experimental Investigation of the Characteristics of Reflection from Uneven Ground Surfaces," Trans. of Energeticheskii Institute (USSR), Vol. 110, pp. 87-89 (14 June 1974); Trans: Army Foreign Science and Technology Center, Charlottesville, VA, Report No. FSTC-HT-23-0224-74.

This article reports investigations of reflection characteristics from uneven ground surfaces. Flights were made over forests and other uneven surfaces and reflection characteristics were measured with a receiver having a linear amplitude characteristic. The results of measurements and observations are shown in table form.

(6) Blomquist, A., and L. Ladell, "Prediction and Calculation of Transmission Loss in Different Types of Terrain," Agard Conf. No. 144, Electromagnetic Wave Propagation Involving Irregular Surfaces and Inhomogeneous Media, 32/1-17 (1975).

A model for the calculation of transmission loss in the VHF and UHF regions has been developed. It has been used in service-area predictions in different types of irregular terrain in Sweden with much better results than the existing models. The method is easy to apply and requires no complicated computer technique. It takes proper account of the ground dielectric constant and the terrain profile and the effect of vegetation. It is thus a deterministic model giving the long-term median basic transmission loss. Measurements are presented of the variability of the additional loss in terms of percentages of time and locations. The effect of depolarization is given for various percentages of locations.

Descriptors: Radio-wave propagation; modeling.

Identifiers: VHF bands; UHF band; loss calculation; long-term median; depolarization; radio-wave propagation; transmission loss; service area predictions; irregular terrain; Sweden; ground dielectric constant; terrain profile; vegetation; deterministic model; variability; ground-wave propagation.

(7) Bogusch, A. J., Jr., and D. F. Sedivec, "A Note on L-Band Observations with High Range Resolution," AD-365-268, Report No. TN-1965-34, Contract AF19-628-5167, Project ARPA Order 498, Monitor ESD TDR-64-419, Lincoln Labs, Livingston, MA (August 1965).

This report describes some experiments involving the detection of personnel hidden in underbrush. These experiments were conducted with an elementary low-power L-band radar having a range resolution of about one foot. Comparative measurements of foliage penetration at L and X bands are reported.

Descriptors: Enemy personnel, detection; search radar, L-band; trees; grasses; terrain resolution; attenuation bandpass filters; pulse generators; parabolic antennas; radar reflections; traveling wave tubes; microwave amplifiers; radar signals; radar pulses.

Identifiers: Foliage; underbrush.

(8) Cartledge, L., and R. D. Yates, "An Experimental UHF Ground Surveillance Radar," Vol. 2, AD-757 565, Technical Report, Report No. TR-497-Vol-2, Contract F19628-73-C-0002, ARPA Order 1559, Monitor ESD TR-72-242, Lincoln Laboratory, Lexington, MA (October 1972).

This volume describes the use of the radar as a measurements system for studying targets and the clutter environment, in addition to its use for demonstrating the feasibility of detecting men walking in foliage by radar. Investigations of target-return spectra, clutter-return spectra, and clutter-return amplitude statistics are reported. Theoretical models relating clutter return spectra, and clutter return amplitude statistics are reported. Theoretical models relating clutter spectra to wind turbulence and tree resonances are presented and compared with experimental results. Similarly, a previous theoretical prediction of target return spectra is compared with experimental results. Clutter return amplitude statistics are measured and found to be Gaussian under certain conditions. Finally, the volume contains some comments on the relationships between the subclutter visibility and various parameters of digital MTI systems.

Descriptors: Coherent radar, UHF; search radar; phased arrays; moving target indicators, UHF; radar clutter; plants (botany); penetration; digital systems; radar reflections; power spectra.

Identifiers: Signal processing.

(9) Deloor, G. P., "Radar Ground Returns--Part 3, Further Measurements on the Radar Backscatter of Vegetation and Soils," Report No. PHL-1974-05-PT-3, TDCK-64135-PT-3, Physica Lab RVO-TNO, The Hague, Netherlands (March 1974).

Measurements of the radar backscatter coefficient gamma of single vegetation species, woods, and bare soils are reported. It is shown that in the measuring setup used, all samples investigated contained sufficient scatterers to give a Rayleigh distribution at the output and that the decorrelation time is sufficiently short to obtain an adequate number of uncorrelated samples in one measurement. In SLAR observations the radar backscatter coefficient gamma as a function of frequency and polarization is the only possible classifier for vegetation species. Its total variation, however, is small approximately and requires as a consequence a fairly high accuracy in the measurements when variations in radar backscatter coefficient gamma are also to be used as an indicator for variations in biomass, plant vigor, and moisture content.

Descriptors: Backscattering; radar scattering; soils; vegetation; forests; Rayleigh distribution; side-looking radar.

(10) Dence, D. F., and T. Tamir, "Transmission Losses in a Forest for Antennas Close to the Ground," Report No. ECOM-2940, USGRDR No. AD-669608, Contract No. DA-31-124-ARO(D), Army Electronics Lab, Fort Monmouth, NJ (February 1968).

During the last few years, measurements have been made to determine the electrical characteristics and the predominant mode of propagation in a forest environment. This work was essential because of the severe attenuation of radio communication signals that occur when operating in a forest medium. Theoretical investigations have shown that for distances greater than 1 km and for frequencies between 2 MHz and 200 MHz the forest can be represented to a first approximation as a conductive slab bounded on one side by air and on the other side by the earth. Using this conductive slab as a model, the transmission losses between two elementary dipoles located close to the ground in a forest were calculated for both horizontal and vertical polarization. Those parameters that would affect the transmission losses are examined and the sensitivity of the respective parameters is evaluated in detail.

Descriptors: Radio-wave propagation effects; antenna theory.

(11) Dence, D., and T. Tamir, "Radio Loss of Lateral Waves in Forest Environments," Communications/Adp Lab, Army Electronics Command, Fort Monmouth, NJ (13 January 1969); Revision of report (7 November 1968).

The radio loss between two small dipoles located in a forest is examined in the frequency range of 2 MHz to 200 MHz by characterizing the forest in terms of a dissipative slab backed by an imperfectly conducting round. A careful derivation of the total radio loss L shows that it consists of four distinct constituents; (1) a basic loss L_o associated with the forest-air interface; (2) a separation loss L, resulting from the vegetation; (3) a wave-interference loss L_i; and (4) an antenna input resistance loss L produced by the ground proximity. By choosing parameters describing typical forests, we show that the variation of the four constituents leads to a total loss whose behavior agrees with available experimental data and with previous theoretical considerations pertinent to high antennas. In contrast to these, the present investigation predicts, for low antennas, that vertical polarization is preferable to horizontal and that communication conditions may be further improved if the operating frequency is increased rather than decreased. The antenna height-gain effect is also examined in detail, and it is shown to be strongly affected by the ground proximity in a manner that had not been hitherto recognized.

Descriptors: Radio transmission; trees; radio signals; attenuation; high frequency; VHF; polarization.

(12) Doeppner, T. W., G. H. Hagn, and L. G. Sturgill, "Electromagnetic Propagation in a Tropical Environment," J. Defense Research 4B, pp. 353-404 (Winter 1972).

This paper summarizes an 8-year program conducted by the U.S. Army Electronics Command and the Advanced Research Projects Agency on electromagnetic propagation in tropical environments. Both the analytical and experimental tasks of the program are discussed in the context of a system equation. Various analytical representations of the jungle are given, and special emphasis is placed on that of a homogeneous, isotropic, dielectric slab. The lateral-wave solution of the slab model realistically explains many of the propagation phenomena observed in the jungle environment. Descriptive environmental parameters for forest areas that may be electrically meaningful are identified, and special techniques required to measure these parameters are discussed. An extensive Experimental program in two tropical forests of Thailand is discussed in the context of basic transmission loss, and detailed comparisons between experimental results and analytical predictions are presented. Pulse measurements of a tropical rain forest designed to measure the coherent bandwidth of the forest are described. Special investigations of radio noise in the tropics are outlined. Results of selected radio-system performance tests in Thailand are given. Major results of the program are summarized.

(13) Downey, M. J., "Effects of Trees and Foliage on the Propagation of UHF Satellite Signals," Report No. RSRE-77017, Royal Signals and Radar Restablishment, Christchurch (England) (May 1977).

The report describes measurements of the extra attenuation of UHF satellite signals resulting from locating the receiver equipment within woods in southern England. The results are summarized as probability distributions. At 254 MHz the average loss was 8 dB. The effects due to undergrowth and soil surface were minimal.

Descriptors: Radio transmission; communication satellites; tree canopy; foliage; UHF; Great Britain; radio signals; attenuation.

(14) Du, Li-Jen, "Rayleigh Scattering From Leaves," Report No. 2467-1, Contract F446200-67-C-0095, Project AF-5635, Task 563502, Monitor AFCRL 68-0454, Columbus Electroscience Lab, Columbus, OH (21 January 1969).

A Rayleigh region leaf model, consisting of a layer of uniformly distributed and randomly oriented leaves, is developed as a first approximation of a jungle environment. Such a model is appropriate for clutter calculations and for estimating the constitutive parameters of the medium. In this report, emphasis is focused on the latter application. Explicit expressions for the scattered field and the absorption and scattering cross-sections of a single leaf are developed. From these results, the effective dielectric constant and conductivity of a layer of uniformly distributed and randomly oriented leaves are derived. Numerical calculations are made of these parameters for a frequency range from 30 to 300 MHz, leaf water contents from 10 to 50 percent, and leaf volume concentrations from 0.03 percent to 0.1 percent.

Descriptors: Rayleigh scattering; jungles; radio transmission, jungles; electromagnetic wave reflections; radio interference; absorption; dielectric properties; conductivity; propagation; trees; mathematical models.

(15) Evans, J. E., et al., "Mathematical Models and Validation," MLS Multipath Studies, Vol. I, Project Report, March 1974-30 September 1975, Report No. ATC-63, Contract F19628-76-C-0002, DOT-FA74WA1-461, Monitor FAA-RD-76-3-1, Lincoln Laboratory, Lexington, MA (25 February 1976).

This report summarizes MLS multipath work carried out at Lincoln Laboratory from March 1974 to 30 September 1975. The focus of the program was to develop realistic models for (1) the multipath in representative real-world environments and (2) the multipath characteristics of candidate MLS techniques. These multipath and system models were used in a comprehensive computer simulation to predict the strengths and weaknesses of major MLS systems when subjected to representative real-world environments. The report is organized into two volumes. Volume I describes the algorithms and validation of various portions of the program. In Volume II, the simulation (or selected portions thereof) is applied to key multipath-related MLS issues. Mathematical models are given for the major MLS multipath sources (ground reflections, building and aircraft reflections, and shadowing by objects and humped runways), and it is shown that they agree well with field data (including the Lincoln measurements at Logan Airport). Models for the techniques (Doppler and scanning beam) considered in phase II of the U.S. MLS program are presented with validation by comparison with theory and bench tests. Also presented are the results of a general study in motion averaging. The validated computer simulation (and portions thereof) is then applied to studying (1) the critical areas required by the TRSB system to avoid excessive reflection effects, (2) the expected TRSB performance with vertical polarization and benefits that might be derived with an alternative polarization, and (3) siting of a specific TRSB system at Friendship International Airport (MD).

Descriptors: Instrument landings; microwave landing systems; multipath transmission; algorithms; mathematical models; scattering; L band; C band; polarization; reflection; ground effect; buildings.

(16) Evans, J. E., et al., "Application of Multipath Model to Key MLS Performance Issues," MLS Multipath Studies, Vol. II, Report No. ATC-63-Vol-2, 171 pp., Contract F19628-76-C-0002, DOT-FA74WAI-461, Monitor FAA-RD-76-3-2, Lincoln Laboratory, Lexington, MA (25 February 1976).

This report summarizes MLS multipath work carried out at Lincoln Laboratory from March 1974 to September 30, 1975. The focus of the program is the development of realistic models for (1) the multipath in representative real-world environments and (2) the multipath characteristics of candidate MLS techniques. These multipath and system models are used in a comprehensive computer simulation to predict the strengths and weaknesses of major MLS systems when subjected to representative real-world environments. The report is organized into two volumes. Volume 1 describes the algorithms and validation of various portions of the program. In Volume II, the simulation (or selected portions thereof) is applied to key multipath-related MLS issues.

Descriptors: Microwave landing systems; instrument landings; multipath transmission; aircraft; L band; C band; computerized simulation; algorithms; scattering; reflection; runways; electromagnetic wave reflections; buildings.

(17) Gitterman, H. N. and S. N. Watkins, "Line-of-Sight-Propagation Experimentation and Modeling for Partially Illuminated Terrain," Technical Memo AD-643 318, Report No. EDL-M878, Contract DA-28-043-AMC-00379(E), Monitor ECOM 00379-M878, Electronic Defense Labs, Sylvania Electronic Systems, West, Mountain View, CA (November 1965).

A series of experiments was conducted to evaluate a model that predicts line-of-sight (LOS) propagation loss over partially illuminated terrain. Height-gain measurements were made at the receiver for a number of paths of varying irregularity, roughness, and vegetation cover. The measurements indicate that two regions must be recognized: the first, below 500 MHz where specular effects are predominant and the specular reflection coefficient varies from approximately 0.20 to unity; and the second, above 500 MHz where both the specular and the diffuse reflection coefficients generally range from 0.20 to 0.40. Appropriate changes have been made in the original LOS model to reflect more accurately the propagation effects in these two regions over the frequency range of interest, 40 MHz to 20 GHz.

Descriptors: radio transmission, terrain; VHF; UHF; super-high frequency; reflection; diffusion; attenuation; roughness; plants (botany); scattering; mathematical models.

(18) Hagn, G. H. and K. A. Posey, "Survey of Literature Pertaining to the Equatorial Ionosphere and Tropical Communication," Special Technical Report No. TR-12, SRI 4240-24, Contract DA-36-039-AMC-00040(E), Grant ARPA Order 371, Project SRI-424-, SRI International, Menlo Park, CA (February 1966).

A survey of the literature pertaining to the equatorial ionosphere, tropical radio communications, and related subjects is presented in bibliographical form. Authors' abstracts have been included whenever possible. The survey is intended to cover the period from the late 1920s and early 1930s through the early 1960s.

Descriptors: Ionosphere, tropical regions; communication and radio systems, ionosphere; bibliographies, ionosphere; abstracts; reviews; electromagnetic radiation; radio waves; ionospheric propagation; state-of-the-art reviews; geomagnetism; jungles; atmosphere models.

(19) Hagn, G. H., N. K. Shrauger, and R. A. Sheperd, "VHF Propagation Results Using Low Antenna Heights in Tropical Forests," Special Technical Report No. 46, Contract DAAB07-70-C-0220, ARPA Order 371, Project SRI 8663, Monitor ECOM-0220-46-70, SRI International, Menlo Park, CA (March 1973).

Characteristics of VHF propagation in tropical terrain were studied using various simple, low receiving antennas and a manpack radio transmitter termed Xeledop (transmitting (X) elementary dipole with optional polarization). Measurements of received voltage were made at 50 MHz, 75 MHz, and 100 MHz, using both horizontal and vertical polarization while the Xeledop was carried down trails in clearings and tropical forests. Data are also given for cases of cross-polarization. The measurements of received signal covered in this report (and other manpack Xeledop measurements previously reported) are converted to radio system loss. Conversion from received voltage to system loss for a system using half-wave dipoles is also possible through relationships derived here, and an approximate formula is given for conversion to basic transmission loss. The use of horizontal polarization produces a much lower system loss than does the use of vertical polarization in the forest for the cases studied, with the exception of very low antenna heights. Tests made with a balloon-borne Xeledop elevated several hundred feet indicated the operational superiority of vertical dipoles over horizontal dipoles for balloon-elevated relays used in jungle terrain. The system loss for vertical polarization exceeded that obtained with horizontal polarization and optimum geometry, but optimum geometry for horizontal polarization was difficult to maintain.

Descriptors: Radio transmission, tropical tests; VHF; polarization; portable; jungles; radio equipment; antennas; terrain; Southeast Asia.

Identifiers: SEACORE project.

(20) Hagn, G. H., E. L. Younker, and H. W. Parker, "Research-Engineering and Support for Tropical Communications," Semiannual Report No. 6, 1 October 1965-31 March 1966, Contract DA-36-039-AMC-00040(E), ARPA Order 371, Project SRI 4240, SRI International, Menlo Park, CA (June 1966).

The work described in this report was performed with the support, and using the facilities, of the Military Research and Development Center at Bangkok, Thailand, a joint Thailand/United States organization. This report summarizes the technical effort conducted under Contract DA 36-039-AMC-00040(E) for the period covering 1 October 1965 through 31 March 1966. In several cases, work described has been conducted by Thai personnel assigned to the Military Research and Development Center. For additional technical details, consult the published reports listed in Section III. The operations analysis work conducted under the contract is reported separately.

Descriptors: Radio communication systems, Armed forces research; radio equipment, tropical regions; environmental tests; lightning; noise (radio); Thailand; performance (engineering); radio signals; antenna radiation patterns; ionosphere; jungles.

(21) Heiser, W. and R. Reffelt, "Propagation Models for Short-Term Variations in Land Mobile Channels," Volume II--Bibliography, Report No. CSC-71-587, 94 pp., Contract DAA005-69-C-0236, Project RDT/E-1-S-765801-M-613, Task 1-S-765801-M-61302, Computer Sciences Corporation, Paramus, NJ (September 1970).

Descriptors: Communication and radio systems, propagation; radio transmission, multipath transmission; bibliographies; abstracts; reports; computer programs; mathematical models; attenuation; terrain; mobile; VHF, UHF; tropical regions, jungles; trees; site selection.

(22) Herbstreit, J. W. and W. Q. Crichlow, "Measurement of the Attenuation of Radio Signals by Jungles," Radio Science, Vol. 68D, No. 8 (August 1964).

Quantitative field strength measurements on frequencies between 2 MHz and 100 MHz were obtained through jungles in Panama and New Guinea during World War II. They conclude that the jungle attenuation of radio signals is so great that for satisfactory communications over distance greater than one mile, skywave propagation or elevated antennas should be employed.

(23) Huerta, M. A., et al., "Some Physics of a Florida Forest," Report No. MIAPH-70-11, University of Miami, Coral Gables, FL (November 1969).

The University of Miami has studied the interaction of forest surroundings with electromagnetic radiation. Both theoretical and experimental approaches have been adopted and the results are put forward in this paper.

Descriptors: Electromagnetic wave propagation; biological effects of radiations; biophysics; radiation effects; radar measurement.

Identifiers; Trees; physical effects; forest surroundings; electromagnetic radiation.

(24) Hubbard, R. W., R. F. Linfield, and W. J. Hartman, "Measuring Characteristics of Microwave Mobile Channels," U.S. Department of Commerce, NTIA-Report 78-5 (June 1978).

This report describes the application of a high resolution (6 ns) pseudo-random noise (PN) channel probe for evaluating the transmission character of a land-mobile communication channel. Preliminary measurements were performed at a microwave frequency in a number of locations in Boulder, Colorado. Examples of data are presented which characterize the frequency correlation of the channel transfer function, and provide additional information on the spectral distortions caused by multipath.

The data processing and analysis techniques are emphasized in the report, as they are ideally suited to developing a useful statistical summary of channel parameters. The methods are rapid, and are made from data recorded in standard analog magnetic tape in the field locations. It is recommended that a wideband channel characterization program be undertaken in the near future before spectrum congestion precludes obtaining useful data.

Descriptors: Channel characterization; frequency correlation function; impulse response; land-mobile radio; microwaves; multipath.

(25) Ikrath, K., et al., "Exploitation and Performance of Forest Trees as Antennas for Radio Communications in Dense Forest-Covered Terrains," Research and Development Technical Report No. ECOM-3508, 30 pp., Project DA-1-H-662701-A-44B, Task 1-H-662701-A-44806, Army Electronics Command, Fort Monmouth, NJ (November 1971).

A new approach for the solution of the problem associated with the transmission of electromagnetic energy in dense forests was conceived and successfully demonstrated in field experiments at Lebanon State

Forest, NJ. In actual testing in dense vegetation, forest trees coupled with a toroidal hybrid electromagnetic antenna coupler (HEMAC) showed themselves to be superior in performance to a vertical whip antenna. The analysis of the data complied indicate that the signal emitted through the use of a HEMAC in a forest duct decays as 1/r and $1/\sqrt{}$, which indicates the existence of both space and surface wave modes.

Descriptors: Omnidirectional antennas, trees; jungles, radio communication systems; radio transmission; antenna components; coupling circuits; coils.

Identifiers: Hybrid electromagnetic antenna couplers.

(26) Ince, A. N., "Aspects of Electromagnetic Wave Scattering in Radio Communications," Conference Proceedings of Advisory Group for Aerospace Research and Development Neuilly-Sur-Seine (France), Report No. AGARD-CP-244. Small portion of text in French. Presented at the Electromagnetic Wave Propagation Panel Symposium, 3-7 October 1977, Cambridge, MA (September 1978).

The scattering of electromagnetic waves is of importance in many communication systems and has been intensively studied in the last quarter of a century. Scattering phenomena can be used to advantage to communicate over the horizon, or they may act adversely as in the case of transmission to a terminal in a jungle or heavily urbanized environment. Examples of the former are the VHF (ionoscatter and meteor-burst) and UHF (troposcatter) links that make use of the scatter from inhomogeneities and discontinuities in the ionosphere and troposphere respectively. Examples of adverse effects occur in relatively short-range UHF communications to mobile units surrounded by trees or buildings. The symposium was therefore concerned with the theory of scattering and reflection in the troposphere, the ionosphere, from meteor trails, and also scattering from ground environmental hazards such as hills, trees, and buildings. Included in the propagation aspect is the prediction of long- and short-term signal characteristics and modeling of radio channels using the scatter mode of propagation. Consideration is also given to transmission and signal-processing techniques for effective communications over such channels. The symposium was thus designed for geophysicists, communication system planners and designers, and for the users of such systems.

Descriptors: Radio transmission; electromagnetic scattering; ionospheric propagation; tropospheric scatter communications; meteors; vegetation; laser communications; over-the-horizon detection; radiation attenuation; multipath transmission; channels.

(27) Kessler, W. J. and M. J. Wiggins, "A Simplified Method for Calculating UHF Base-to-Mobile Statistical Coverage Contours Over Irregular Terrain," IEEE Veh. Techol. Group, 27th Annual Conference, Orlando, FL, March 16-18, 1977. Published by IEEE (77CH1k76-7VT), New York, NY, pp. 227-236 (1977).

The paper describes a simplified procedure based on the use of the FCC F(50,50) signal-strength charts to provide an approximate determination of the statistical coverage contours for a UHF base-to-mobile radio system operating over irregular terrain. This chart, which is statistical in nature, represents a composite of a vast amount of empirical data and theoretical considerations in that it provides signal strengths 50 percent of the time at 50 percent of the locations in dBμ (decibels above one microvolt per meter) at an elevation of 30 ft above ground level. Hence the use of the descriptive term F(50,50). Appropriate adjustments are included in the procedure to account for mobile antenna height-gain variations, signal-strength reduction due to shrubbery, trees, and the like in the immediate vicinity of the mobile units, signal-strength reduction due to terrain variations differing from a Δh of 50 m, and signal-probability requirements different from 50 percent. Procedures are also discussed for estimating the net signal-strength probability characteristics due to two or more contours of known probability.

Descriptors: Radio systems, mobile; field plotting; applications; statistical methods, applications.

Identifiers: Ultra high frequencies; statistical service contours.

(28) Kinase, A., "Influences of Terrain Irregularities and Environmental Clutter Surroundings on Propagation of Broadcasting Waves in UHF and VHF Bands," Nippon Hoso Kyokai-Tech Monograph, No. 14 (March 1969).

This paper gives results of analysis of effects of irregular terrain and environmental clutter on ground-wave propagation at frequencies in UHF and VHF bands, at such distances that variations in atmospheric refractive index are usually of little significance. The report is particularly concerned with urban propagation characteristics of broadcasting waves at the 700-MHz band. Methods of predicting urban clutter effects with introduction of new parameters and screening effects of buildings are discussed.

Descriptors: Radio waves; propagation.

(29) Krause, G. E., "FOREST--A Computer Program to Compute Radio Loss Between Two Antennas Embedded in a Forest Environment," Research and Development Technical Report No. ECOM-4212, Project DA-1-S-762701-AH-92, Task 1-S-762701-AH-92-N-127, Army Electronics Command, Fort Monmouth, NJ (April 1974).

FOREST is the computer adaption of a mathematical model to compute radio loss between two dipole antennas embedded in a forest environment for the 2 to 200 MHz frequency range. The model was reported in an article titled "Radio Loss of Lateral Waves in Forest Environments" by Dence and Tamir, which appeared in Radio Science (April 1969). The model assumes the transmission mode is a wave traveling laterally at the forest-air interface from the transmitting to the receiving site. The computer program is written in FORTRAN for use in the time-share mode on the Burroughs B5700 computer. A single frequency and single distance may be specified, or up to ten frequencies at from one to ten distances may be called for. The program contains parameters to typify thin, average, and dense forests, or the user can enter specific parameters when they are known.

Descriptors: Radio transmission; computer programs; radio waves; forests; environments; losses; dipole antennas; VHF; attenuation; FORTRAN.

Identifiers: FOREST computer program.

(30) LaGrove, A. H. and C. W. Chapman, "Some Propagation Characteristics of High UHF Signals in the Immediate Vicinity of Trees," IRE Trans. Antenn., Vol. AP-9, pp. 487-491 (September 1961).

Results are reported of measurements made at very low angles of 2880-MHz vertically polarized signals over wooded areas, with the elevation angle to the transmitter the principal variable. The effects of one tree and of many trees on the apparent location of a signal source, as determined with a narrow-beam antenna, are reported.

(31) Lippman, B. A., "The Jungle as a Communication Network," Report No. DRC-IMR-168/1, rev. ed., Defense Research Corporation, Santa Barbara, CA (September 1965).

Elementary arguments and a simple model are used to clarify the dominant features of radio transmission through jungles. Part I represents the jungle as a plane uniform slab of constant conductivity and permittivity. A critical frequency is defined; below it, the slab behaves like a conductor; above it, like a dielectric. From these two limiting cases an upper limit on attenuation, which holds independently of the operating frequency, is derived. The model is applied to Herbstreit's experiments in the Panama jungle. Reasonable assumptions regarding the dielectric constant and density of the jungle lead to values between 0.02 and 0.04 mhos/m for the conductivity of the vegetation, which corresponds quite well with that of moist earth.

Part II discusses the applicability of the uniform dielectric model used in Part I. Equivalent circuit concepts are used to analyze the jungle as a four-terminal network. The model of Part I is shown to be strictly applicable only to a uniform--or at least a symmetrical--jungle. The determination of the network parameters for the equivalent circuit representing the jungle is discussed. The relation between the complex propagation constant and the amplitude of the forward scattered field is given. Also stated are the results of using the Born approximation (and a rough first correction to it) to solve the field problem.

Descriptors: Jungles, radio transmission; networks; attenuation; mathematical models.

(32) Lorchirachoonkul, V., "A Study of Electromagnetic Properties of an Isolated Tree," Special Technical Report No. 41, 96 pp., Contract DA-36-039-AMC-00040(E), ARPA Order 371, Project SRI-4240, SRI International, Menlo Park, CA (February 1968).

The objective of this report is to establish an electrical model representing an isolated tree. Such representation is feasible by using a perfectly conducting cylinder of smaller radius. This leads to the concept of using an equivalent radius of the tree to link the unknown electromagnetic theories of the tree to the well-developed theories of the perfectly conducting cylinder. Data from three kinds of experiments are analyzed to validate the electrical model: (1) patterns of radio waves scattered from an isolated tree and from an aluminum mast, (2) input impedance of a half-wavelength vertical antenna in the vicinity of an isolated tree, and (3) patterns of an isolated tree as a shunt-fed grounded radiator. The frequencies used in the experiments were 50 MHz, 75.1 MHz, and 100 MHz; the polarization was vertical. The variation of the input impedance of a half-wavelength vertical antenna as it is moved close to a tree trunk that is similar to that of a half-wavelength horizontal antenna as it approaches a lossy ground. The directivity of a tree as a shunt-fed grounded radiator is demonstrated experimentally, and the front-to-back ratio is about 16 dB.

Descriptors: Radio transmission, jungles; radio waves, attenuation; trees, electrical properties; models (simulations); scattering; electrical impedance; antennas; VHF; Thailand; antenna radiation patterns; propagation.

Identifiers: Agile project; SEACORE program.

(33) Nielson, D. L., "Microwave Propagation and Noise Measurements for Mobile Digital Radio Application," Packet Radio Note 4, Contract DAHC15-73-C-0187, SRI Project 2325, SRI International, Menlo Park, CA (January 1975).

This report describes the radio environment at 1370 MHz for urban, suburban, and rural areas on the basis of data derived largely from a measurement program constructed for that purpose in support of packet radio system design. The measurements consisted of propagation data at two post-detection bandwidths, 9 MHz and 100 Hz, and noise data at an impulse bandwidth of approximately 16 MHz.

(34) Nguyen, D. T., "Field Near the Interface of a Jungle Dielectric Slab, Electron Letter, Vol. 12, No. 3, pp. 62-63 (5 February 1976).

The transmitted far field of a short vertical dipole located in a jungle dielectric medium is evaluated by the steepest-descent technique. At near-grazing angles of transmission, the technique is modified to account for the influence of the branch point. The influence is found significant only in the field amplitude and is confined within a short distance from the jungle-air interface, within which the difference between the path of the geometric-optical wave and that of the lateral wave is less than a wavelength.

Descriptors: Antennas; dipole; radiation.

(35) Ooi, T., T. Kikuchi, and K. Tsujimura, "UHF Radiowave Propagation Characteristics for Cordless Telephone," IEEE Conference Publication. IEEE 1978 National Telecommunications Conference, 25.5/103 (3-6 December 1978).

The authors have recently made measurements of radio-wave propagation characteristics in the 800-MHz and 2000-MHz bands by placing an antenna at a height as low as 1.5 m and at a distance within several kilometers of the transmitter. The measurements were conducted in three environments: (1) a suburban residential area in Tokyo, (2) an urban area in Tokyo with dense office buildings, and (3) in both occupied and vacant conditions within reinforced concrete buildings. Results are given and discussed.

Descriptors: Radio-wave propagation; mobile radio systems; radiotelephony.

Identifiers: UHF radio-wave propagation characteristics; cordless telephone; measurements; 800 MHz, 2 GHz.

(36) Paolini, E., "Propagation of Industrial Interference over Actual Ground at 400 to 1000 MHz," IEEE International Electromagnetic Compatible Symposium Record, pp. 118-121 (July 1971).

Data attained on a specified test range can be used to predict interference fields. Interferences generated by industrial sources and received by an antenna (both placed near the ground) propagate entirely along an earth path, whereas useful radio transmissions propagate largely along a free-space path. The value of the received interference field is a result of multiple random reflections and diffractions caused by all obstacles existing over a real earth, making it possible to statistically establish an average attenuation law with values having a large standard deviation. The loss of polarization, the lack of cancellation effects, and the independence of path attenuation versus the height of the receiving antenna are evaluated.

Descriptors: Radio interference (electric lines, inductive interference); industrial electronics.

Identifiers: Electromagnetic interference control.

(37) Parker, H. W., and G. H. Hagn, "A Feasibility Study on the Use of Open-Wire Transmission Lines, Capacitors, and Cavities to Measure the Electrical Properties of Vegetation," Special Technical Report No. TR-13, Contract DA-36-039-AMC-00040(E), Grant ARPA Order 371, Project SRI 4240, SRI International, Menlo Park, CA (August 1966).

This report describes the theory, design, and usefulness of experiments to measure effective complex dielectric constants in foliage and vegetation by means of rigid open-wire transmission lines. The frequency ranges of 30 MHz to 75 MHz (VHF) and 4 MHz to 30 MHz (HF) are covered by using a 5/8-inch diameter, 3-inch spacing line and a 4-inch diameter, 40-inch spacing line, respectively. Use of these instruments allows one to place bounds on the macroscopic electrical parameters of foliage. Results are presented of measurements with this equipment in October 1965 in the Hoh Rain Forest, Olympic National Park, Washington. There, in the most dense growth available, representative values of effective relative permittivity and effective conductivity were estimated to average about 1.2 and 8×10^{-5} mhos/m, respectively. An experiment relating the density of freshly cut willow boughs to the properties of the sample measured by the VHF transmission line is described in detail. From this it is estimated that vegetation intrinsic conductivities are of the order of 0.03 mhos/meter or greater in living willows during mid-October. The relative permittivity is linearly related to "biodensity" as indicated by the theory of the complex dielectric constant of mixtures. Other methods of measurement, such as the use of large capacitors or resonant cavities, are discussed.

Descriptors: Transmission lines; plants (botany); dielectric properties; radio waves, propagation; trees; VHF; cavity resonators; capacitors; humidity; attenuation; high frequency; frequency.

(38) Parker, H. W. and W. Makarabhiromya, "Electric Constants Measured in Vegetation and in Earth at Five Sites in Thailand," Special Technical Report No. 43, Contract DA-36-039-AMC-00040(E), ARPA Order 371, Project SRI 4240, SRI International, Menlo Park, CA (December 1967).

Balanced two-conductor open-transmission-line probes were used to measure effective electric constants in vegetation and in the earth. Effective relative permittivity and permeability in undergrowth at five dispersed sites were practically unity. Median effective conductivity of the undergrowth varied insignificantly between sites but showed distinctive variation with frequency, from about 20 ± 30% at 6 MHz to 300 ± 30% (μ-mho/m) at 100 MHz. In the few instances where measurements were made among mature trees the results were similar to those obtained for undergrowth. The most important parameters influencing vegetation constants were stem spacing (related to stem number density) and intrinsic stem conductivity (estimated to be between 0.05 mho/m and 0.5 mho/m). Ground-constant values varied greatly between sites in a manner consistent with the variation of soil moisture content. Environmental forestry and soil surveys, summarized in the appendices to this report, are useful in explaining or applying the electric-constant results.

Descriptors: Radio transmission, jungles; radio signals; attenuation; mathematical models; electrical conductance; dielectric properties; permeability (magnetic); trees; soils; programming (computers); Thailand.

Identifiers: SEACORE program.

(39) Rosenbaum, S. and L. W. Bowles, "Clutter Return from Vegetated Areas," Report No. TN-1971-34, Contract F19628-70-C-0230, ARPA Order 1559, Project AF-649L, Monitor ESD-TR-71-138 (10 September 1971).

The objective of this report is to present an analytical-stochastic model capable of predicting relevant statistical scattering features of electromagnetic waves propagating within vegetated environments. The propagation phenomena are described by formulating the scattering associated with random permittivity fluctuations superimposed on a lossy deterministic background slab. The mean backscattered power, its variance and one-point distribution are calculated. The spectral characteristics of clutter from windblown foliage are investigated using two models: one presuming the velocity field to constitute a multivariate normal process and another presuming the scatterer's motion to be quasi-harmonic over limited time segments.

Descriptors: Radar clutter, plants (botany); terrain; mathematical models; electromagnetic waves; scattering; predictions; propagation.

(40) Rosenbaum, S. and L. W. Bowles, "Clutter Return from Vegetated Areas," IEEE Trans., Antenn, VAP-22 n2, pp. 227-236 (March 1974).

This article presents an analytical stochastic model to predict relevant statistical scattering features of electromagnetic waves propagating within vegetated environments. The propagation phenomena are described by formulating the scattering associated with random permittivity fluctuations superimposed on a lossy deterministic background slab. The distorted-wave Born approximation is used to determine the backscattered power and its temporal spectrum.

Descriptors: Electromagnetic scattering; radar clutter; vegetation, propagation; electromagnetic radiation; stochastic processes; statistical analysis.

(41) Sachs, D. L., "A Conducting-Slab Model for Electromagnetic Propagation Within a Jungle Medium, II," Report No. DRC-IMR-471, Contract DA-31-124-ARO(D)-312, ARPA Order-632, Defense Research Corporation, Santa Barbara, CA (May 1966).

A theoretical determination of the path loss in radio propagation through jungle is obtained by considering the jungle as a homogeneous conducting dielectric slab on a flat earth. An exact integral is obtained for the component of the electric field parallel to an electric dipole for vertical and horizontal polarization and for antennas within or above the jungle. An analytic evaluation of the integral leads to an approximate expression for the field and an estimate of the error. Where this accuracy is insufficient, a numerical evaluation of the integral is performed. Experimental measurements of path loss in a Thailand jungle are compared with the calculation. The results agree within a standard deviation of 6 dB for transmission frequencies between 6 MHz and 100 MHz.

Descriptors: Radio transmission, jungles; models (simulations); numerical analysis; polarization; predictions; propagation.

(42) Sachs, D. L. and P. J. Wyatt, "A Conducting-Slab Model for Electromagnetic Propagation Within a Jungle Medium," Report No. GRC-TM-376, Contract DA-31-124-ARO(D)-312, Grant ARPA Order-632, General Research Corporation, Santa Barbara, CA (May 1966).

A theoretical determination of the path loss in radio propagation through jungle is obtained by considering the jungle as a homogeneous conducting dielectric slab on a flat earth. An exact integral is obtained for the vertical component of the electric field within the jungle due to a vertical electric dipole within the jungle. An analytic evaluation of the integral leads to an approximate expression for the field and an estimate of the error. When this accuracy is insufficient, a numerical evaluation of the integral is performed. The combination of analytic and numerical techniques leads to the evaluation of the electric field and thereby path loss to any accuracy desired. Experimental measurements of path loss in a Thailand jungle are compared with the calculations. The results agree within a standard deviation of 6 dB when the jungle conductivity is taken as 0.15 mho/m.

Descriptors: Radio transmission, jungles; models (simulations), numerical analysis; mathematical prediction; propagation.

(43) Schmid, H. F., "Prediction Model for Multipath Propagation of Pulse Signals at VHF and UHF Over Irregular Terrain," IEEE Trans. Antenn., Vol. AP-18, No. 2, pp. 253-258 (March 1970).

A prediction model is presented that permits the probability of occurrence of distinct multipath propagation of VHF and UHF pulse signals over irregular terrain to be calculated. The model applies to terrain characterized by an irregular distribution of obstacles (such as hills, buildings, trees, etc.) that makes it impractical to calculate the effect of multipath propagation by diffraction or bistatic-reflection theory. Statistical data on wave propagation over irregular terrain form the basis for the empirical model developed. Generally, the model predicts that for constant transmitter-receiver separation, the amplitude of the received echoes decreases with increasing echo delay, and for constant echo delay, the occurrence of echo pulses increases as the transmitter-receiver distance increases. The results obtained from the model for rural, hilly terrain and for a built-up metropolitan area are compared with available measured data.

Descriptors: Radio waves; propagation.

Identifiers: Multipath propagation; prediction models.

(44) Smith, G. W., "A General Computer Model of Radio Communication Link Performance," Report No. GRC-TM-1013, Contract DA-31-124-ARO(D)-312, ARPA Order 632, Monitor AROD 5656-16-RT, General Research Corporation, Santa Barbara, CA (January 1969).

This report describes a general-purpose computerized model of radio communication performance. This link-status model determines to what degree any given communication link is operable as a function of terminal equipment and what propagation path conditions exist between units at each end of the link. Propagation via ground wave or via near-vertical skywave paths is considered. The ground-wave portions of the model include methods for determining the nature and structure of vegetation and of altitude variations along the propagation path; in addition, the model calculates path loss using the most appropriate of nine methods, eight of which are based upon the characterization of vegetation as a lossy dielectric slab. The model explicitly treats ground-wave propagation for frequencies from 10 kHz to well into the UHF region over smooth or rough terrain, all with an arbitrary mix of vegetation and clear areas. All antenna heights (including satellites) and ranges may be accommodated, with due consideration for earth curvature and atmospheric refraction.

Descriptors: Communication and radio systems; models (simulations); data transmission systems, models (simulations); radio transmission; radio waves; propagation; radio interference; terrain; plants (botany); ionospheric propagation; attenuation; signal-to-noise ratio; HF; VHF; UHF; computer programs.

(45) Sturgill, L. G., "Tropical Propagation Research," Semiannual Report No. 1, July-December 1962, 1442J2, USGDR, Contract DA36 039-SC-90889, Jansky and Bailey Research and Engineering Department, Atlantic Research Corporation, Alexandria, VA (January 1963).

This report reviews the basic concepts of the theoretical and experimental studies of radio propagation in jungle environments. Results of a survey of literature pertaining to radio propagation in tropical areas and propagation over rough terrain are included. The details of a site survey are presented and describe, to a certain extent, the environment in which the proposed tests will be conducted. A discussion of the tests planned includes a description of the measurements, test equipment, and measurement techniques. The theoretical studies required to fulfill the requirements of the contract are summarized and presented along with the results accomplished to date. A theoretical analysis of the quadrant dipole antenna is included in the appendix.

Descriptors: Radio waves, tropical regions; tropical regions, radio waves; propagation, radio waves; theory; test equipment; transmitter-receivers; antennas; measuring devices (electrical and electronic); power supplies; environmental tests; jungles; communication equipment.

(46) "Tropical Propagation Research," Semiannual Report No. 2, January-June 1963, 1442J1, USGRDR, Contract DA36-039-SC-90889, Jansky and Bailey Research and Engineering Department, Atlantic Research Corporation, Alexandria, VA (June 1963).

During the period of this report, considerable effort was devoted to preparing the equipment to be used to conduct the field measurements, detailed planning necessary to initiate site construction, and preparing a mathematical model for calculating rough-terrain path loss in the absence of foliage for each of the possible propagation modes. This report presents a summary of the work completed to date. The problem of classifying the tropical environment is reviewed, and an initial classification containing five divisions is presented. Undoubtedly when the six study areas established for this phase of the program are completed the original classification system will be modified. The results of a study intended to determine accurate propagation-prediction methods for the several possible propagation modes are presented with a discussion of each method. The conclusions reached are applicable to a major portion of the frequency range of interest.

Descriptors: Radio waves, tropical regions; tropical regions, radio waves; propagation, radio waves; terrain; mathematical models; Thailand; jungles; transmissions; attenuation; test equipment; antennas; measuring devices (electrical and electronic); powers supplies; environmental tests; communication equipment.

(47) "Tropical Propagation Research," Semiannual Report No. 3, July-December 1963, Contract DA36-039-SC-90889, Jansky and Bailey, Research and Engineering Department, Atlantic Research Corporation, Alexandria, VA (December 1963).

A method has been developed for classifying tropical vegetation into five visually recognizable divisions in accordance with the shape characteristics of each division. The real purpose of such a classification system is to allow the observer to measure roughly the variety of growths that may be encountered in tropical regions in relation to communication problems. It remains in the next step to develop units of numerical measure for each of these classifications so that the effects of vegetation can be numerically related to propagation-prediction techniques. In the course of developing instrumentation suitable for the performance of the field measurements under extreme environmental conditions, it was necessary to develop and fabricate several special-purpose items, some of the details of which are presented.

Descriptors: Radio waves, tropical regions; tropical regions, radio waves; propagation, radio waves; transmission; attenuation; terrain; mathematical models; Thailand; jungles; antennas; powers supplies; environmental tests; communication equipment; test equipment; tests.

Identifiers: Vegetation.

(48) "Tropical Propagation Research," Semiannual Report No. 4, January-June 1964, Contract DA36-039-SC-90889, Project 371, Jansky and Bailey Research and Engineering Department, Atlantic Research Corporation, Alexandria, VA (June 1964).

Previous reports dealt with the experimental and theoretical aspects of the program leading up to the beginning of field measurements for radio-wave propagation in a vegetated area in Thailand. This area is about 30 m square and has been selected to provide terrain of various degrees of roughness largely covered by dense tropical vegetation. This report presents results from the field measurements made through May 1964. The field data has been reduced to graphic form, generally in terms of basic transmission loss as a function of distance and antenna index data, are also reported. The field data obtained from the measurements at 100 megacycles have been analyzed extensively by comparing the measured data with the theoretical data calculated from areas without vegetation but with the same terrain profiles, using the same distances and antenna heights. The results of this analysis, although limited to one example, begin to indicate that the rate of attenuation due to tropical vegetation alone decreases as the path length is increased.

Descriptors: Radio waves, propagation; radio transmission, jungles; communication and radio.

(49) "Tropical Propagation Research," Semiannual Report No. 5, 1 July-31 December 1964, Contract DA36-039-SC-90889, Project 371, Jansky and Bailey Research and Engineering Department, Atlantic Research Corporation, Alexandria, VA (May 1964).

Basic information about RF propagation phenomena in tropical environments is needed to develop improved equipment and techniques for military use in Southeast Asia and other areas of similar environment. RF propagation measurements were made at test frequencies between 100 kHz and 10 GHz to accomplish this mission. The results of such measurements made in Thailand during May 1964 through November 1964 are graphically represented in this report. Transmission path loss as a function of both distance and receiving antenna height, as well as monthly variations of surface refractivity, temperature, barometric pressure, and rainfall are illustrated.

Descriptors: Radio waves, propagation; radio transmission, jungles; jungles, communication and radio systems; Thailand; Southeast Asia; tropical regions; tropical tests; correlation techniques; antennas; attenuation; instrumentation; rainfall; temperature; barometric pressure; terrain; programming (computers).

(50) "Tropical Propagation Research," Semiannual Report No. 7, 1 July-31 December 1965, Contract DA-36-039-SC-90889, Grant ARPA Order 371, Jansky and Bailey Research and Engineering Department, Atlantic Research Corporation, Alexandria, VA (January 1966).

The overall purpose of this program was to provide basic information about radio propagation phenomena that can be used to improve communications equipment and techniques for military forces in Southeast Asia and other areas with similar environments. The first comprehensive series of measurements of propagation and environmental data was obtained in a wet-dry tropically vegetated area in Thailand in the vicinity of the town of Pak Chong. Propagation measurements were made at discrete test frequencies in the 100-kc to 10-gc range. A major portion of this program is concerned with the collection and analysis of basic data on radio propagation in relation to the physical characteristics of the natural environment that influence propagation losses, such as terrain features, climate, vegetation, and radio noise. The quantitative effects of the environment on radio propagation losses are being studied through correlation analysis. The information thus obtained will be used to develop a comprehensive model that will permit practical predictions of range performance of tactical mobile communications equipment in a tropical environment. The field measurements originally planned in the 100 kc to 425 mc frequency range at Pak Chong were essentially completed during this reporting period. This report summarizes the results of these measurements and presents certain tentative conclusions that can be drawn from the work thus far.

Descriptors: Radio transmission, Thailand; radio waves; Southeast Asia; propagation; measurement, climate; rainfall; barometric pressure; temperature; collecting methods; tropical regions; radio frequency; terrain; radio ranges; diurnal variations; noise (radio); communication and radio systems; trees; jungles.

(51) "Tropical Propagation Research," Semiannual Report No. 8, 1 July-31 December 1966, Contract ARPA Order 371, Project DA-36-039-SC-90889, Jansky and Bailey Engineering Department, Atlantic Research Corporation, Alexandria, VA (January 1967).

This is a report on a research program involving studies of the propagation of radio waves in a tropically vegetated environment. It represents the first report of activities in an area located about 40 miles from the coastal town of Songkhla in Southern Thailand. A primary objective of this work was to supplement and also provide a comparison with the results, described in previous reports, of the extensive experimental and theoretical program near Pak Chong, Thailand. Songkhla is classified as a rainy tropical region and is characterized as having a 50% heavier rainfall and much denser and taller vegetation than Pak Chong, which is classified as a wet-dry tropical region. Contained in the report are descriptions of the environment in the test area and of the test facilities that have been established. The experimental goals and test procedures are set forth, covering such topics as the effects upon transmission loss of frequency, antenna heights, polarization, and transmission range. Some preliminary results of measurements, based on all the data obtained from Songkhla as of 31 December 1966, are given in the form of 15 plots of basic transmission loss as a function of distance for various frequencies, transmitting antenna heights, and paths. The receiving antennas are fixed at a height of 6 feet, and the polarization is horizontal. Much of the instrumentation used at Songkhla is the same as that used at Pak Chong. Several changes, however, were necessary and are described in the report.

Descriptors: Radio waves, tropical regions; propagation, radio waves; jungles; Thailand; antennas, environmental tests; radio transmission; test equipment; communication equipment; attenuation; terrain.

(52) Sturgill, L. G., "Tropical Propagation Research," Semiannual Report No. 9, 1 January-30 June 1967, Contract DA-36-039-SC-90889, ARPA Order 371, Project DA-1P520501A448, Task 1P620501A448-01, Jansky and Bailey Engineering Department, Atlantic Research Corporation, Alexandria, VA (July 1967).

This is the ninth semiannual report of a research project to study radio propagation in tropical areas with heavy vegetation. The experimental results reported here are from the first series of Thailand (Area 2). The test area, which receives about 90 inches of rainfall annually, is covered with extremely thick jungle. Graphs are presented of basic transmission loss as a function of distance out to 1.4 m for frequencies of 25 MHz, 50 MHz, 100 MHz, and 250 MHz using different transmitting antenna heights, polarizations, and transmission paths. The receiving antenna height is fixed at 6 ft. Certain of these tests are compared with identical ones made previously in the jungles near Pak Chong, Thailand (Area 1), where the vegetation is significantly lower and less dense. The climate of the test area is also described and compared with that of Area 1.

Descriptors: Radio waves, ionospheric propagation; tropical regions; climatology; Thailand; antenna configurations; wave transmission; attrition; ranges (distance); direction finding; predictions.

(53) "Tropical Propagation Research," Semiannual Report No. 10, 1 July-31 December 1967, Contract DA-36-039-SC-90889, ARPA Order 371, Jansky and Bailey Engineering Department, Atlantic Research Corporation, Alexandria, VA (1967).

The purpose of the Tropical Propagation Research Project is to investigate radio wave propagation in tropical environments. Its research is conducted through field-measurement programs in Thailand that are followed up by mathematical analyses in the United States. This semiannual report describes recent experimental results from the project's second phase of tests. A section of heavy rain forest, identified as Area 2, is the setting for the tests discussed in this report.

(54) Hicks, John J. and R. G. Robertson, "Tropical Propagation Research: Pulse Transmission at VHF in a Tropical Rain Forest," Semiannual Report No. 11, 1 July-31 December 1968, Contract DA-36-039-SC-90889, ARPA Order 371, Jansky and Bailey, Research and Engineering Department, Atlantic Research Corporation, Alexandria, VA (December 1968).

This report presents results from experimental and analytical investigation of the propagation of radio waves in tropical jungle environments. The experimental work was done in a tropical rain forest test area in Southern Thailand. The objective of this program is to obtain and analyze information that is generally applicable to improving the development, design, and operation of short-range communications systems for tropical jungle environments.

Descriptors: Radio transmission, tropical regions; propagation; Thailand; jungles; pulse systems; digital systems; attenuation; VHF.

(55) Robertson, R. G., "Tropical Propagation Research," Semiannual Report No. 12, 1 January-30 June 1969, Contract DA-36-039-SC-90889, ARPA Order 371, Jansky and Bailey Engineering Department, Atlantic Research Corporation, Alexandria, VA (June 1969).

The report is the twelfth in a series presenting results from an experimental and analytical investigation of the propagation of radio waves in tropical jungle environments. The program's objective is to obtain and analyze information that is generally applicable to improving the development, design, and operation of short-range communications systems for tropical jungle environments. The experimental work has been done in a tropical rain forest test area in Southern Thailand. The work covered by this report is especially concerned with the conduct of a special forest survey of the tropical rain forest in the test area. The objective of this forest survey was to obtain more detailed data on the statistical parameters associated with the vegetation. Statistical data is presented on the distribution of tree heights, diameters at breast height, biomass, basal area, etc.

Descriptors: Radio transmission, tropical regions; jungles, radio waves; propagation; attenuation; trees; shrubs; rainfall; VHF.

Identifiers: Tropical rain forests.

(56) Stutzman, W. L., F. W. Colliver, and H. S. Crawford, "Electromagnetic Propagation Measurements for Estimating the Weight of Standing Forest Vegetation," IEEE URSI, AP-S International Symposium 1977, pp. 128-131 (June 1977).

This report presents results of an experimental investigation of weight estimation using electromagnetic transmission measurements through forest stands. The technique is non-destructive and relatively fast, and yields statistically meaningful results. It employs a light-weight portable microwave transmit-receiver link for measuring the attenuation and depolarization introduced by the vegetation (3 refs.)

Descriptors: Microwave measurement; weighing; attenuation measurement; natural resources.

Identifiers: Standing forest vegetation; weight estimation; electromagnetic transmission measurements; microwave; attenuation; depolarization.

(57) Stutzman, W. L., et al., "Instrumentation for Microwave Attenuation Measurements of Standing Vegetation," Proceedings of 1975 IEEE Southeastcon Region 3 Conference on Electricity and Expanding Technology, 5C-3/1-4 (April 1975).

Microwave signals that pass through standing vegetation are attenuated. Experiments performed on stands of pine trees show that the weight of the trees is correlated with the measured attenuation. This paper discusses the instrumentation used and makes suggestions for refining the technique. Future applications for the technique are also discussed.

Descriptors: Microwave measurement; attenuation measurement; instrumentation.

Identifiers: Microwave attenuation measurements; standing vegetation; pine trees; attenuation; instrumentation.

(58) Surgent, L. V., Jr., "Evaluation of the Multipurpose Foliage Penetration Radar (M-Fopen) in Hawaii," Report No. LWL-TR-74-73, Project LWL-05-P-70, Monitor 18, Army Land Warfare Lab (Aberdeen Proving Ground, MD), (May 1974).

This report describes the implementation, procedure, and results of the Multipurpose Foliage Penetration Radar (M-Fopen) conducted by the 25th Infantry Division. Maximum ranges of detection were determined for the M-Fopen operating in various types of terrain and foliage, and the probability of detection was calculated for each range, target, and foliage combination. These tests demonstrated the capability of the M-Fopen to penetrate up to 700 meters of foliage and detect moving targets, with a negligible false-alarm rate. A tactical exercise was conducted during which the M-Fopen and the standard AN/PPS-5 Ground Surveillance Radars were deployed and the detection performance and false-alarm rates of each compared. Detection experiments were performed with the M-Fopen using a helicopter (AH-1G) as the target to determine the Doppler signature of the aircraft. These demonstrated both that a unique Doppler signature does exist for helicopters and that helicopters are detectable using the M-Fopen even though the path between the radar and the aircraft is blocked by foliage.

Descriptors: Radar; foliage; penetration; multipurpose; Doppler radar; moving target indicators; manportable equipment; VHF; helicopters; Hawaii.

Identifiers: M-Fopen radar; AN/PPS-5; AH-1G aircraft; H-1 aircraft; NTISDODA.

(59) Surgent, L. V., Jr., "Foliage Penetration Radar: History and Developed Technology," Report No. LWL-TR-74-74, Project LWL-05-P-70, Monitor 18, Army Land Warfare Lab Aberdeen Proving Ground, ML (May 1974).

This report documents the Army Land Warfare Laboratory's Foliage Penetration Radar program, including its historical aspects, the technology developed, and four resulting systems that saw combat in Southeast Asia. Applications are presented of the Fopen technology to intrusion-detection systems, airborne Fopen radars, swimmer-detection systems, and a radar capable of detecting low-flying aircraft concealed by foliage. A review of signal-processing techniques and tradeoffs for ground-surveillance radars and a summary of propagation research concludes the report.

Descriptors: Radar; foliage; penetration; signal processing; radar signals; propagation; reviews; combat surveillance; intrusion detection.

(60) Tamir, T., "The Role of the Sky and Lateral Waves on Propagation in Forest Environments," Final Report, Contract DA-31-124-ARO(D)-399, ARPA Order 371, Duke University, Durham, NC (March 1967).

Propagation of electromagnetic waves in forest environments at medium and high radio frequencies is examined for the case where both the transmitting and receiving points are situated within the vegetation. A conductive slab in the presence of a reflecting ionosphere is used to describe the forest configuration. This model is further simplified by disregarding the ground-forest interface. The radiated field of an arbitrarily-oriented small dipole is found to consist primarily of two separate waves: a lateral wave that skims along the treetops and a sky wave that is produced by a single-hop reflection at the ionospheric layer. These two field constituents are compared and their domains of preponderance calculated for a wide range of the pertinent parameters: it is then found that the lateral wave plays the major role since the sky wave is restricted to a narrow frequency band and its amplitude is appreciable only at large distances. The lateral wave field is examined in detail and is shown to yield a simple physical picture for the propagation mechanism in forests. Its features are found to be qualitatively consistent with the field behavior reported in the literature, and the quantitative aspects agree well with the available experimental data. The observed variation of the field with distance, the height-gain effect, the vegetation factor, the basic path loss, and depolarization effects are separately examined and are all shown to express merely one or another of the intrinsic properties of a lateral wave. The ground-proximity effect produced by the presence of a planar-conducting ground is also estimated and shown to be of minor importance in most cases.

Descriptors: Radio transmission, terrain; trees; propagation; plants (botany); radio waves; ionospheric propagation; medium frequency; high frequency; antennas; altitude; attenuation; polarization.

(61) Tamir, T., "An Experimental Study of Radio-Wave Propagation in Dissipative Environments," Report No. PIBEP-70-055, Contract DAAB07-68-C-0222, Monitor ECOM-0222-1-Jan-70, Department of Electrophysics, Polytechnic Institute of Brooklyn, NY (January 1970).

This paper describes preliminary work on the design and operation of an X-band measurement setup for simulating radio-wave propagation in dissipative environments. Research activities within the past period include basic design considerations and in particular the tentative utilization and measurement of an aluminum-coated mylar film to be used as a major component in the projected measuring instrumentation.

Descriptors: Radio transmission, trees; X-band; simulation; test equipment.

(62) Tamir, T., "Experimental Verification of a Lateral Wave Above a Lossy Interface," Electron Letter, Vol. 6, No. 12, pp. 357-358, (11 June 1970).

Lateral waves have been recognized and theoretically investigated, but their existence has not been verified experimentally under controlled laboratory conditions. The present work describes an experiment consisting of microwave-field measurements above a lossy dielectric interface with conditions such that a strongly dominant lateral wave is theoretically predicted. The results agree well with the expected field, and therefore confirm the existence of lateral waves.

Descriptors: Electromagnetic waves.

Identifiers: Lateral waves.

(63) Tamir, T., "On the Electromagnetic Field Radiated Above the Tree Tops by an Antenna Located in a Forest," Research and Development Technical Report, Contract DA-31-124-ARO(D)-399, Project DA-1-H-662701-A-350, Task 1-H-662701-A-35001, Monitor ECOM-3443, Prepared in cooperation with Polytechnic Institute of Brooklyn, NY, Duke University, Durham, NC (June 1971).

Theoretical investigations of the electromagnetic field in forest environments have usually considered the case in which both the transmitting antenna and the receiving terminal were located within or very close to the vegetation. The present work examines the case in which one of the two antennas is located inside the forest while the other is situated above the treetops. The mechanism of wave propagation and its effect on the field variation are discussed for heights that start at the forest-air interface and extend vertically to large elevations. It is shown that the field just above that interface and up to a critical height H is dominated by a lateral wave. Above the height H_c, the field is given by a refracted line-of-sight wave whose amplitude is subject to a strong height-gain effect. This gain continues up to a height H_m, above which the field starts decreasing monotonically. Both vertical and horizontal polarizations are examined; typical results are given for several representative forest varieties. While the present results extend certain conclusions obtained from previous work, they also represent an important first step in solving communication problems involving mixed paths that cross partly through vegetation and partly through air or clearings.

Descriptors: Radio transmission, trees; radio fields; HF; VHF; attenuation.

(64) Tamir, T., "Effect of a Forest Environment on the Performance of Doppler Radar Systems," Technical Memo, Contract DA-31-124-ARO(D)-120, Project LWL-05-P-70, Monitor LWL-CR-05P70, Tamir (T), Teaneck, NJ (December 1971).

The aim of the report is to examine the effect of a forest environment on the performance of a remote-sensing system that detects the Doppler-shifted signal scattered by moving objects. For this purpose, the influence of the terrain on the radar equation is determined by estimating the additional path loss due to the presence of dissipative media between the transmitter antenna and the moving scatterer. For most situations of practical importance, it is shown that the additional path loss can be expressed in terms of a terrain factor, which accounts for the presence of both the foliage and the ground. This terrain loss is evaluated for the case of a moving target located in the vegetation and for a transmitter antenna that may be placed either inside the vegetation or above the treetops. The calculated results are given for a wide range of distances between the antenna and the target, for various antenna heights and for different types of wooded areas.

Descriptors: Doppler radar, attenuation; radar signals, trees; terrain; performance (engineering).

Identifiers: Remote sensing.

(65) Tamir, T., "Frequency Dependence of Radio Losses for Radar Systems in Forest Environments," Technical Memo, Contract DA-31-124-ARO(D)-120, Project LWL-05-P-70, Monitor LWL-CR-05P70, Tamir (T), Teaneck, NJ (July 1972).

The effects of changing the frequency of Doppler radar systems operating over bare ground or in a forest environment are explored for targets that are close to the ground. For this purpose, a criterion is formulated that enables a judicious comparison to be made between a system that operates at a reference frequency f_0 and another that operates at a frequency f. Results are presented here for horizontally polarized fields over bare ground or in the presence of a forest.

Descriptors: Doppler radar, attenuation; radar signals; trees; plants (botany); penetration; very high frequency.

(66) Tamir, T., "Mixed-Path Considerations for Radio-Wave Propagation in Forest Environments," Agard Conference Proceedings No. 144, Electromagnetic Wave Propagation Involving Irregular Surfaces and Inhomogeneous Media, 33/1-11 (March 1974).

The propagation of radio waves is examined for communication paths that may lie partly within a forest and partly in the air region outside the vegetation. For this purpose, the geometry of a mixed path involving a forest layer adjacent to a bare-ground area is shown to exhibit four characteristic regimes. If the transmitting antenna is inside the forest, these regimes correspond to the receiving antenna being located (1) inside the forest, (2) above the treetops, (3) at a relatively high altitude above the bare-ground region, or (4) at a relatively low height above the bare-ground region. Depending on frequency, distances, and which of the four regimes is involved, the predominant field along the mixed path may be a refracted wave or a lateral wave. It is possible to establish path losses in practically any regions involving reasonably flat ground contours. The frequency range of applications for these considerations extends well into the VHF region. All four cases are treated separately and analytic expressions for the electric field are presented for large distances away from a dipole radiator.

Descriptors: Radio-wave propagation.

Identifiers: Radio-wave propagation; mixed-path propagation; treetop propagation regimes; bare-ground area; antenna inside forest; antenna above treetops; forest environments; forest layer; high altitude; refracted wave; lateral wave; path losses; VHF region; analytic expressions; electric field; losses; VHF region; analytic expressions; electric field; dipole radiation.

(67) Tamir, T., "Radio-Wave Propagation Along Mixed Paths in Forest Environments," IEEE Trans. Antenn., Vol. AP-25, No. 4, pp. 471-477 (July 1977).

The propagation of radio waves is examined for communication paths that may be partly within a forest and partly in regions outside the vegetation. Analytic results are found for simple canonic geometries in which the fields can be described in terms of ray trajectories. By viewing a realistic forest environment as a combination of such canonic cases, it is possible to evaluate radio losses in complex situations by using a ray-tracking approach. The pertinent fields can then be expressed in terms of relatively simple analytical expressions, which hold well for frequencies between 2 MHz and 200 MHz.

Descriptors: Radio transmission; propagation.

(68) Taylor, J., et al., "Open-Wire Transmission Lines Applied to the Measurement of the Macroscopic Electrical Properties of a Forest Region," Special Technical Report, Contract DAA807-70-C-0220, DA-36-039-AMC-00040(E), Project ARPA Order 371, SRI 8663, Monitor ECOM-0220-42, SRI International, Menlo Park, CA (October 1971).

The theoretical capabilities of two-conductor, open-wire transmission lines (OWLs) as probes to measure the macroscopic electrical properties of a forest are examined under the premise that a forest can be represented as a lossy dielectric slab. A laboratory experiment with a line inserted in a relatively homogeneous, isotropic slab of Styrofoam was performed to verify certain approximations in the analysis of such a line when a void (hole) exists in the slab near the line. The effective sensing radius for a 300-ohm line is shown to be about one and one-half line spacings. The limitations of a transmission-line probe for inhomogeneous and anisotropic dielectrics are discussed. The forest also is considered as a synthetic dielectric composed of lossy scatterers. The equivalent circuit of a short scatterer (length short relative to the RF wavelength) as a load on the transmission line is shown to be a lossy capacitor.

Descriptors: Radio transmission, trees; trees, electrical properties; measurement; transmission lines; scattering.

(69) Turin, G. L., F. D. Clapp, T. L. Johnston, S. B. Fine, and D. Lavry, "A Statistical Model of Urban Multipath Propagation," IEEE Trans. Veh. Technol., Vol. VT-21, No. 1, pp. 1-9 (February 1972).

An urban multipath propagation experiment, involving the simultaneous transmission from a fixed site of 100-ns pulses at 488, 1280, and 2920 MHz and their reception at a mobile van, is described. A statistical analysis of the data in the resulting multipath responses is given and used as a basis for a statistical model of urban multipath propagation.

(70) Wagner, R. D., Jr., "Tropical Propagation Research Ground/Air Evaluation," Technical Report No. RADC-TR-70-42, Project AF-6523, Task 652307, Rome Air Development Center, Griffiss AFB, NY (April 1970).

Descriptors: Radio transmission, jungles; tropical regions; surface to air; HF; VHF; UHF; propagation; attenuation; polarization range (distance); Thailand.

(71) Wells, P. I., "The Attenuation of UHF Radio Signals by Houses," IEEE Trans. Veh. Technol., Vol. VT-26, No. 4, pp. 358-362 (November 1977).

This paper reports the results of a measurement program that was conducted to determine the attenuation of UHF radio signals penetrating the inside of a typical house. The measurements were made so as to

determine the building attenuation as a function of frequency, construction type, climate, and the elevation angle to the signal source. At three frequencies, 860 MHz, 1550 MHz, and 2569 MHz, using the ATS-6 geosynchronous satellite as a signal source, most measurements were made on two principal house types, wood frame with a wood outside surface, and wood-frame with a brick-veneer outside surface. The average measured building attenuation for all houses and all frequencies was 6.3 dB.

Descriptors: Radio-wave propagation; electromagnetic wave absorption.

Identifiers: Attenuation; UHF radio signals; building; 860 MHz, 1550 MHz; 2569 MHz.

(72) Younker, E. L., G. H. Hagn, and H. W. Parker, "Research Engineering and Support for Tropical Communications," Semiannual Report No. 7, 1 April-30 September 1966, Contract DA-36-039-AMC-00040(E), ARPA Order 371, Project SRI 4240, SRI International, Menlo Park, CA (September 1966).

Communications research in a tropical environment is needed to develop improved equipment and techniques for use by military forces in Southeast Asia and other areas of similar environment. This report covers the following research effort in Thailand during 1 April through 30 September 1966: (1) radio noise study and measurement, (2) ionospheric electron content studies using Faraday rotation techniques on signals from beacon satellite S66 (studies on ionospheric stability through Doppler technique applied to signal frequency dispersion and a study of disturbances in the earth's field using magnetometers), (3) investigation of ionospheric factors related to local frequency prediction using oblique-incidence sounders, (4) investigation of the effects of the tropical environment on antenna performance using airborne and man-carried antenna-pattern measuring systems (Xeledops): measurement of earth and vegetation electrical constants; theoretical model studies related to them.

Descriptors: Radio communication systems, Armed forces research; radio equipment, tropical regions; environmental tests; noise (radio); radio signals; Thailand; performance (engineering); ionospheric propagation; antenna radiation patterns; jungles.

(73) Zapp, R., "Effect of Vegetation Upon Antenna Pattern with Scatter Propagation on UHF," AGARD Conference Proceedings No. 70, AGARD Avionics Panel Technical Symposium, Duesseldorf, West Germany, 31 August-4 September 1970, 7 pp., Paper 34, 10 refs. (1970).

Descriptors: Radio waves, propagation.

Appendix C

LITERATURE RELATED TO THEORIES OF WAVE PROPAGATION IN RANDOM MEDIA

Appendix C

LITERATURE RELATED TO THEORIES OF WAVE PROPAGATION IN RANDOM MEDIA

(1) Bahar, E. and B. S. Agrawal, "Transmission of Horizontally Polarized Waves and Trapped Waveguide Modes in Inhomogeneous Media," IEEE Trans. Antenn., Vol. AP25, No. 6, pp. 807-813 (November 1977).

A generalized Wentzel-Kramer-Brillouin (WKB) approach is used to obtain full-wave solutions for horizontally polarized waves in inhomogeneous media when no closed form analytic solutions are known. This approach is suitable for complex permittivity profiles with critical coupling regions even when the permittivity gradient approaches zero. The transmission and reflection coefficients and the characteristic surface impedance for inhomogeneous layers of finite thickness are computed for several permittivity profiles. Excitation of propagating and evanescent waves is considered, and the results are shown to satisfy the realizability and reciprocity relationships in electromagnetic theory. Sinusoidal permittivity profiles for which closed-form analytical solutions are known are also considered to provide an additional check on the generalized WKB solutions.

Descriptors: Electromagnetic wave propagation; guided electromagnetic wave propagation; radio-wave propagation.

Identifiers: Horizontally polarized waves; trapped waveguide modes; inhomogeneous media; full-wave solutions; complex permittivity profiles; reflection coefficients; characteristic surface impedance; WKB approach; transmission coefficients.

(2) Barabanenkov, Yu. N., Yu. N. Kravtrov, S. M. Rytov, and V. I. Tamarstii, "Status of the Theory of Propagation of Waves in a Randomly Inhomogeneous Medium," Soviet. Phys. Uspetihi, Vol. 13, No. 5, pp. 551-680 (March-April 1971).

This review is an attempt to outline the existing theoretical methods and the limits of their applicability, as well as the role of the new methods for treating multiple scattering of waves. Consideration is limited to volume scattering in continuous media during free propagation.

(3) Bourret, R., "The Depolarization of Electromagnetic Radiation in a Random-Medium Evolution of the Stokes Parameters," Rev. Cethedec (France), Vol. 11, No. 40, pp. 65-86 (1974).

By applying random perturbation theory to the propagation of electromagnetic radiation in a medium with a stochastic index, the author obtains explicit results for the coherency matrix and for the Stokes parameters as a function of the propagation distance and a physical parameter characterizing the medium. These results are valid in the parabolic approximation for plane-wave propagation, wherein the essential restriction is only that backscattering be negligible. The final results obtained are not altered by the presence of a longitudinal electric component generated by the inhomogeneities.

Descriptors: Electromagnetic wave propagation; coherence; random processes; perturbation theory; polarization.

Identifiers: EM wave propagation; depolarization; negligible backscattering; medium's parameters; physical parameters characterization; random medium; Stokes parameters; random perturbation theory; stochastic refractive index; explicit results; coherency matrix; propagation distance; parabolic approximation; plane-wave propagation; longitudinal electric component.

(4) Bremmer, H., "General Remarks Concerning Theories Dealing with Scattering and Diffraction in Random Media," Radio Science, Vol. 8, No. 6, pp. 511-534 (June 1973).

The theories considered deal mostly with the effect of random media on the propagation of electromagnetic or other waves traversing them. The purpose aimed at thus consists of finding connections between the statistical properties of these waves and the given statistical properties of the medium itself. The characteristics of this medium are to be fixed by one or more wave equations or by equivalent dispersion relations. The waves may be investigated as such. Considering the wave function, PSI (R,T) of one or more associated scalar or vector components, or, more generally, the theory may refer to related quantities, e.g., the squared modulus #PSI#/sup 2/, which fixes an energy density or, as in quantum mechanics, a probability density.

Descriptors: Scattering; diffraction; wave equations; wave propagation; wave functions.

Identifiers: Scattering; diffraction; random media; statistical properties; wave equations; dispersion relations; wave function; energy density; probability density.

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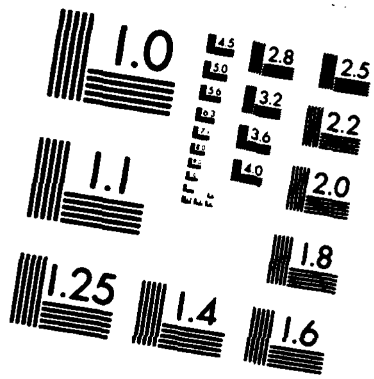

MICROCOPY RESOLUTION TEST CHART

(5) Broer, L.J.F., "Some Properties of Wave Equations in Inhomogeneous Media," Radio Science, Vol. 14, No. 2, pp. 245-251 (March-April 1979).

The paper attempts to put together some of the basic notions and results in the field of wave equations in a slightly more general and systematic way than is usually employed.

Descriptors: Wave equations.

Identifiers: Wave equations; inhomogeneous media.

(6) Brown, W. P., Jr., "Moment Equations for Waves Propagated in Random Media," J. Opt. Soc. Am., Vol. 62, No. 1, pp. 45-54 (January 1972).

This article shows that the partial differential equations obtained by Tatarski, Beran, and Ho for the first, second, and fourth statistical moments of a wave propagating in a random medium are special cases of a general partial differential equation satisfied by the MTH moment when the refractive-index inhomogeneities are sufficiently weak. In addition, the moment equations are derived that apply regardless of the strength of the inhomogeneities. The results obtained in this case are in the form of difference relations satisfied for the moments.

Descriptors: Light, refractive index light.

Identifiers: Moment equations; random media; wave propagation; refractive index inhomogeneities.

(7) Chow, P. L., "On Some Methods for Waves in Random Media," IEEE, 1978 International Symposium Digest Antennas and Propagation, p. 161 (May 1978).

This report discusses the problem of a time-harmonic wave propagation in an unbounded random medium governed by the reduced wave equation with a random refractive index. By employing the Feynmankac formula and the method of characteristic functional, the exact moments of the wave field can be constructed for the free-space as well as for the half-space problems. The author is mainly concerned with deriving several analytical results, obtainable by other perturbation methods, from the funcional integral approach. Also reviewed are some related works in random media by using the functional calculus approach.

Descriptors: Electromagnetic wave propagation.

Identifiers: Random media; reduced wave equation; random refractive index; time-harmonic wave propagation.

(8) Dashen, R., "Path Integrals for Waves in Random Media," J. Math. Phys., Vol. 20, No. 5, pp. 894-920 (May 1979).

The problem of wave propagation in a random medium is formulated in terms of Feynman's path integral. It turns out to be a powerful calculational tool. The emphasis is on propagation conditions where the rms (multiple) scattering angle is small but the log-intensity fluctuations are of the order unti-the so-called saturated regime. It is shown that the intensity distribution is then approximately Rayleigh with calculable corrections. In an isotropic medium, the local or Markov approximation, which is commonly used to compute first and second (at arbitrary space-time separation) moments of the wave field, is explicitly shown to be valid whenever the rms multiple scattering angle is small. It is then shown that in the saturated regime the third and higher moments can be obtained from the first two by the rules of Gaussian statistics. There are small calculable corrections in the Gaussian law leading to coherence tails. Correlations between waves of different frequencies and the physics of pulse propagation are studied in detail. Finally it is shown that the phenomena of saturation is physically due to the appearance of many Fermi paths satisfying a perturbed ray equation.

For clarity of presentation, much of the paper deals with an idealized medium that is statistically homogeneous and isotropic and is characterized by fluctuations of a single typical scale size. However, the extension to inhomogeneous, anisotropic, and multiple-scale media is given. The main results are summarized at the beginning of the paper.

Descriptors: Wave propagation; quantum theory; random processes.

Identifiers: Waves; random media; Feynman's path integral; rms multiple scattering angle; Gaussian statistics; pulse propagation; Fermi paths; perturbed ray equation.

(9) Ferencz, C. S., "Electromagnetic Wave Propagation in Inhomogeneous Media--Strong and Weak Inhomogeneities," Acta Tech. Acad. Sci. Hung. (Hungary), Vol. 85, No. 3-4, pp. 433-444 (1977).

This paper deals with a classification of the inhomogeneities in a way that seems to be more objective than earlier methods. It gives a simple form for Maxwell's equations, which means general usability in examination of propagation, and also gives variations for the dispersion equations, investigating several questions of the commonly used method of 6-dimensional designation.

Descriptors: Electromagnetic wave propagation; dispersion (wave).

Identifiers: Inhomogeneous media; weak inhomogeneities; Maxwell's equations; dispersion equations; 6-dimensional designation; EM wave propagation; strong inhomogeneities; inhomogeneities classification.

(10) Fisher, A. D., "A Model for Microwave Intensity Propagation in an Inhomogeneous Medium" IEEE Trans. Antenn., Vol. AP25, No. 6, pp. 876-882 (November 1977).

A combined analytic and phenomenological approach, utilizing Maxwell's equations in the born approximation with radiative transfer theory is used to describe the propagation of microwave intensity in a scattering medium characterized by three-dimensional random fluctuations in refractive index, as well as nonrandom variations in permittivity, temperature, and loss. This approach yields microwave intensities as a function of polarization, direction, and position. Numerical techniques are presented to solve the transport equations, which included cases of spatially varying coefficients and highly peaked phase functions. Some computed results illustrating the behavior of microwave intensity in various media are presented. The effects of scatterer geometry and scale sizes, correlation functions, and gradients in temperature, loss, and scattering parameters are also demonstrated. This model should be particularly useful in interpreting active and passive remote-sensing data.

Descriptors: Microwaves; electromagnetic wave scattering; radiowave propagation; modeling.

Identifiers: Microwave intensity propagation; inhomogeneous medium; Maxwell's equations; Born approximation; transport equations; computed results; scattering parameters; remote-sensing data; model.

(11) Foldy, L. L., "The Multiple Scattering of Waves," Phys. Rev., Vol. 7, pp. 107-119 (1945).

While the problem of the multiple scattering of particles by a random distribution of scatterers has been treated classically through the use of the Boltzmann integro-differential equation, the corresponding problem of the multiple scattering of waves seems to have received scant attention. All previous treatments have considered the problem in the "geometrical optics" limit, where the rays are regarded as trajectories of particles and the treatment for particles is then applied, so that the interference phenomena in wave scattering are neglected. In this paper the problem of the multiple scattering of scalar waves by a random distribution of isotropic scatterers is considered in detail on the basis of a consistent wave treatment. The introduction of the concept of "randomness" requires averages to be taken over a statistical ensemble of scatterer configurations. Equations are derived for the average value of the wave function, the average value of the square of its absolute value, and the average flux carried by the wave. The second of these quantities satisfied an integral equation that has some similarities to the corresponding equation for particle scattering. The physical interpretation of the results is discussed in some detail and possible generalizations of the theory are outlined.

(12) Fung, H. S. and A. K. Fung, "An Application of Scalar Renormalization to the Scattering of Electromagnetic Waves from a Three-Dimensionally Inhomogeneous Medium with Strong Dielectric Fluctuations," Final Report, February 1974-August 1975, No. RSL-TR-234-11, Contract DAAK02-73-C-0106, Kansas Univ./Center for Research, Inc., Lawrence Remote Sensing Lab-Army Engineer Topographic Labs, Fort Belvoir, VA (August 1975).

A theory of polarized radar scattering from a three-dimensionally randomly inhomogeneous lossy medium with strong dielectric fluctuations has been developed using the scalar renormalization method. Satisfactory agreements were obtained when theoretically computed backscattering coefficients were compared with scattering data taken from soybeans and alfalfa over incident angles from 10 degrees to 70 degrees. In view of the assumed inhomogeneous medium and the comparisons made with data, it appears that the theory is applicable to those vegetations that can be modeled as a volume of air with randomly embedded leaves. Extension of the present theory to include depolarization effects is possible. However, the complete treatment of such a problem is very complicated.

Descriptors: Radar signals; electromagnetic scattering; dielectrics; vegetation; approximation; Fourier transformation; wave equations; plane waves; backscattering.

(13) Furutsu, K., "Multiple Scattering of Waves in a Medium of Randomly Distributed Particles and Derivation of the Transport Equation," Radio Science, Vol. 10, No. 1, pp. 29-44 (January 1975).

In a previous paper, the characteristic functional of the wave function has been found to be the solution of a basic equation which has the same form as the original wave equation and is given in terms of the characteristic functional of the refractive index. In this paper, the theory is applied to the case of scalar wave propagation in a medium of randomly distributed particles, and the transport equation is derived by use of an analytical procedure. The renormalization of the medium and of the one-particle scattering matrix is explicitly introduced, and is bound to play an essential role for energy conservation. The Fourier transform of the resulting single Green's function (in the infinite medium) has a set of poles of infinite number. The transport equation is expressed by a series of residue values at the poles of the original and complex conjugate Green's functions, and has a wider range of applicability than that of the conventional transport equation. As a method of solving the transport equation, a set of eigenfunctions is introduced, and the solution is obtained in terms of the eigenfunction series. The diffusion function associated with each eigenfunction is also obtained.

(14) Gardner, C. S. and P. C. Lam, "Plane Wave Scattering in Inhomogeneous Turbulence," Radio Science, Vol. 13, No. 6, pp. 923-931 (November-December 1978).

The parabolic equation method is used to study wave propagation in inhomogeneous random media. Differential equations for the average field and second-order mutual coherence function are derived. The equations are similar in form to those obtained for homogeneous media but are considerably more difficult to solve. Approximate solutions for plane-wave propagation are obtained and their region of validity determined. Numerical examples of a localized turbulent ball are presented to illustrate some of the features of the average field and mutual coherence function. The results show a high dependence on the transverse extent of the medium and are significantly different from the corresponding results for homogeneous media.

Descriptors: Electromagnetic wave scattering; atmospheric turbulence.

Identifiers: Inhomogeneous turbulence; parabolic equation method; wave propagation; inhomogeneous random media; localized turbulent ball; plane-wave scattering; atmosphere.

(15) Hevenor, R. A., "Backscattering of Radar Waves by Vegetated Terrain," Technical Report No. ETL-0105, May 1974-October 1975, Army Engineer Topographic Labs, Fort Belvoir, VA (June 1977).

This report presents a vector theory for the backscattering of electromagnetic radar waves from vegetation. The basic technique employed in the solution required simulating the vegetation with a random medium. This medium possesses an electrical permittivity that is generated by a continuous random process and is characterized by a particular probability density function. A solution for the radar backscatter coefficient is obtained in terms of the statistical characteristics of the random medium, and the theory is compared with experimental data. Insight is given into the nature of depolarization, but explicit results for the depolarized terms are not obtained at this time because of the complexity and difficulty of the solution. Some of the conclusions of this work are: a theory has been developed for computing the like polarized (HH and VV) radar backscatter coefficients from certain types of vegetation by using a vector renormalization approach; no rigorous quantitative comparison of theory with the experiment was possible; however, qualitative comparisons indicate reasonable agreement; and although no explicit solution was obtained for the depolarization components, it was learned that one cause of depolarization is the anisotropy associated with the correlation function of the dielectric fluctuations.

Descriptors: Radar signals, electromagnetic scattering; backscattering; terrain intelligence; vegetation; simulation; random variables; probability density functions; dielectric properties; anisotropy; depolarization; coefficients; computations; computer programs.

(16) Holway, L. H., Jr., "Multiple Scattering from Random Plasma Inhomogeneities," Radio Science, Vol. 8, No. 7, pp. 681-697 (July 1973).

Small-angle multiple scattering is considered from randomly spaced cylindrical plasma striations. It is shown that multiple scattering from several underdense plasma clouds can cause considerable backscatter even though a single underdense cloud is capable only of deflecting the ray through fairly small angles. In a case in which the deflection angles are small and many deflections occur before a ray passes through the scattering region, the ray density can be shown to satisfy a Fokker-Planck transport equation. The transport equation is solved by a finite-difference method to obtain scattering patterns and waveform distortion. The methods of solving the transport equation can be applied to the scattering of radio waves, laser pulses, and other radiation propagating in random media.

Descriptors: Radio transmission; scattering; radar; reflection; plasmas.

Identifiers: Multiple scattering.

(17) Hong, Shin Tsy, I. Sreenivasiah, and A. Ishimaru, "Plane Wave Pulse Propagation Through Random Media," IEEE Trans. Antenn., Vol. AP-25, No. 6, pp. 822-828 (November 1977).

This paper presents the theory of plane-wave pulse propagation through a random medium under the forward-scattering assumption. Since pulse propagation characteristics are determined by the two-frequency mutual coherence function, a set of normalized curves is given for different propagation parameters (operating frequency, propagation distance, turbulence strength or density of scatterers, etc.). From the curves one can obtain the coherence bandwidth of a wave for a variety of situations. A received pulse form due to an input delta function is given in a normalized form that is applicable to the whole range of strong fluctuation . The results are applied to optical pulse propagation in dense clouds. It is shown that the high data-rate optical-pulse communication through clouds may be limited due to a narrow coherence bandwidth on the order of megahertz. A good agreement between the theoretical prediction and the available experimental data has been demonstrated for both the received pulse shapes and the pulse durations of an optical pulse in clouds.

Descriptors: Electromagnetic waves; propagation.

Identifiers: Plane waves.

(18) Howe, M. S., "On the Kinetic Theory of Wave Propagation in Random Media," Philos. Trans. A (GB), Vol. 274, No. 1242, pp. 523-549 (1973).

The classical theory of wave propagation in random media is discussed with reference to its practical limitations, and in particular to the inability of the lowest-order approximation to the Bethe-Salpeter equation (1951), which describes the propagation of correlations, to account for conservation of energy. An alternative kinetic theory is formulated, based on the theory of energy-transfer processes in random media. The proposed theory satisfies conservation of energy and the second law of thermodynamics. It is illustrated by a consideration of three problems, each of which is difficult or impossible to treat by classical scattering theory. These involve the transmission of energy through a slab of random medium; the scattering theory of geometrical optics; and scattering by a randomly inhomogeneous half space.

Descriptors: Electromagnetic wave propagation; geometrical optics; kinetic theory; acoustic wave propagation; wave propagation.

Identifiers: Multiple scattering; Bethe-Salpeter equation; randomly inhomogeneous half space; kinetic theory; wave propagation; random media; energy transfer processes; slab; geometrical optics.

(19) Howe, M. S., "A Kinetic Equation for Wave Propagation in Random Media," Q. J. Mech. and Appl. Math. (GB), Vol. 27, Pt. 2, pp. 237-253 (May 1974).

The multiple scattering of waves in randomly inhomogeneous media is discussed. An asymptotic multiple-scales analysis is presented that leads to a kinetic equation describing the evolution in space and time of wave energy in wave-number space. A wide class of scalar wave propagation problems is considered by means of an approach based on the use of a Lagrangian density. The example of nondispersive waves propagating in a medium in which the refractive index is a random function of position is used to demonstrate that the theory recovers well-known results of single-scattering theory and geometrical optics (ray theory) in the respective opposite asymptotic extremes of wavelength long and short compared to the correlation scale of the inhomogeneities. This, it is argued, gives confidence in the theory's ability to make predictions at intermediate wavelengths that cannot be treated by classical methods.

Descriptors: Wave propagation; wave equations.

Identifiers: Kinetic equation; wave propagation; random media; multiple scattering of waves; wave energy; Lagrangian density; nondispersive waves; single-scattering theory; geometrical optics; intermediate wavelengths; asymptotic multiple-scales analysis.

(20) Ippolito, L. J., Jr., "Scattering in Discrete Random Media with Implications to Propagation Through Rain," Ph.D. Thesis, George Washington Univ., Washington, D.C. Report No. NASA-TM-X-71352; X-953-77-131 (May 1977).

This paper investigates the multiple-scattering effects on wave propagation through a volume of discrete scatterers. The mean field and intensity for a distribution of scatterers was developed using a discrete random media formulation, and second-order series expansions for the mean field and total intensity were derived for one-dimensional and three-dimensional configurations. The volume distribution results were shown to proceed directly from the one-dimensional results. The multiple-scattering intensity and the classical result was found to represent only the first three terms in the total intensity expansion. The Foldy approximation to the mean field was applied to develop the coherent intensity and was found to exactly represent all coherent terms of the total intensity.

Descriptors: Rain; scatter propagation; wave scattering; approximation; attenuation coefficients; statistical analysis; atmospheric attenuation; discrete functions; electromagnetic wave transmission; Fourier transformation.

Identifiers: Atmospheric scattering.

(21) Ishimaru, A., "Pulse Propagation in the Time-Varying Random Media," 1974 URSI Symposium on Electromagnetic Wave Theory, IEEE, London (July 1974).

Presents a study on the time variation of the strong fluctuations in the time-varying random continuum and in moving discrete scatterers. The transmitted wave may be a pulse of any arbitrary shape and duration, and thus in general it may be broadband.

Descriptors: Electromagnetic wave propagation; fluctuations.

Identifiers: Time-varying random media; pulse propagation; strong fluctuations; moving discrete scatterers.

(22) Ishimaru, A., "Theory and Application of Wave Propagation and Scattering in Random Media," Proc. IEEE, Vol. 65, No. 7, pp. 1030-1061 (July 1976).

This article presents a review of basic theories and recent advances in the studies of wave propagation and scattering in random media. Examples of the random media include the atmosphere, the ocean, and biological media whose characteristics are randomly varying in time and space. The study of electromagnetic, optical, and acoustic waves in such media has become increasingly important in recent years, primarily in the areas of communication, detection, and remote sensing. Topics covered in this paper are divided into waves in randomly distributed scatterers, waves in random continua, and remote sensing of random media. Transport theory with various approximate solutions and multiple-scattering theories are discussed and their relationships are clarified. Included in the analyses are propagation characteristics of intensities, wave fluctuations, pulse propagation and scattering, coherence bandwidth, and coherence time of communication channels through random media. Remote-sensing techniques include recent advances in the use of inversion techniques to deal with ill-posed problems.

Descriptors: Electromagnetic wave propagation; light propagation; electromagnetic wave scattering; light scattering; acoustic wave propagation; acoustic wave scattering; reviews.

Identifiers: Wave propagation; scattering; random media; review; wave fluctuations; pulse propagation; coherence bandwidth; electromagnetic waves; optical waves; acoustic waves; remote-sensing techniques.

(23) Ishimaru, A. and S. T. Hong, "Propagation Characteristics of a Pulse Wave in a Discrete Time-Varying Random Medium," Technical Report No. Scientific-1; TR-176, Contract F19628-74-C-0005, University of Washington, Seattle, Dept. of Electrical Engineering (March 1974).

The propagation characteristics, coherence time, coherence bandwidth, and pulse waveform of a wave passing through a discrete time-varying random medium are considered in this report. They are formulated based on Foldy-Twersky theory. Using its first-order solution, explicit expressions are given for plane spherical, and beam waves. These expressions apply to the cases of small transmitting bandwidths and/or short propagation distances. Numerical calculations are made for mm plane and spherical waves propagated through rain.

Descriptors: Microwaves, millimeter waves; wave propagation; radiofrequency pulses; radiative transfer; integral equations; Maxwell's equations; refractive index; coherent electromagnetic radiation; attenuation; rain.

(24) Ishimaru, A., "Wave Propagation and Scattering in Random Media" (Academic Press, New York, 1978).

This two-volume book is based on a set of lecture notes for a first-year graduate course on waves in random media, given in the Department of Electrical Engineering at the University of Washington. Volume 1 deals with single scattering theory and transport theory. This single scattering theory is applicable to waves in a tenuous distribution of scatterers. Transport theory, which is also called radiative transfer theory, deals with the transport of intensities through a random distribution of scatterers. Volume 2 is devoted to the theory of multiple scattering of waves by randomly distributed scatterers, theories of weak and strong fluctuations of waves in random continuous and turbulence, and fundamentals of rough surface scattering, and remote sensing of the characteristics of random media.

(25) Keller, J. B., "Diffraction of Waves in Random Media," Contract No. N00014-67-A-0467-0015, NTIS, Springfield, VA (January 1975).

The subjects of this investigation can be classified under two headings: In diffraction, various asymptotic methods were devised and applied to numerous wave propagation problems. In waves in random media, new limit theorems and perturbation methods were used to get exact results.

Descriptors: Light diffraction; geometrical optics; light transmission.

Identifiers: Asymptotic methods; wave propagation; waves in random media; limit theorems; perturbation methods; light diffraction.

(26) Keller, J. B., "Progress and Prospects in the Theory of Linear Wave Propagation," SIAM Rev., Vol. 21, No. 2, pp. 229-245 (April 1979).

The development of the theory of linear wave propagation is described after a brief sketch of what wave propagation is. First, the classical techniques of images and separation of variables are considered, followed by Sommerfeld's extension of the image method to multi-sheeted spaces and Watson's transformation of series solutions to more rapidly converging forms. Then the Wiener-Hopf method of solving certain integral equations and Schwinger's variational method of calculating scattering parameters are introduced. Next the normal mode theory of propagation and its development by Pekeris, Fock, Brekhovskikh and others is described. Then the WKB method and its extensions are presented. This is followed by discussions of ray theory, of the parabolic equation method, and of waves in heterogeneous and random media. Finally, prospects for the future are considered, with emphasis on the use of computers and methods of calculation.

Descriptors: Integral equations.

Identifiers: Linear wave propagation; scattering parameters; ray theory; computers; parabolic equation method.

(27) Kresa, K., "Proceedings of the Technical Workshop on Radar Scattering from Random Media," ARPA-T10-69-1, 107 pp.. Advanced Projects Agency, Washington, D.C., Strategic Technology Office, (1968).

The volume is a summary of presentations and discussions of a technical workshop on radar scattering from random media held at the Institute for Pure and Applied Sciences, University of California (San Diego), La Jolla, California, on 5-16 August 1968, and sponsored by the Advanced Research Projects Agency. The workshop was divided into theoretical and experimental panels. Summaries of the reports of these panels are the result of collaboration among several workshop participants.

Descriptors: Atmosphere entry, ionization trails; radar signals, scattering; symposia; theory; plasma medium; turbulence; wake; perturbation theory; microwaves; guided missile tracking systems; reentry vehicles.

Identifiers: Scattering cross-sections.

(28) Krevsky, S., "HF and VHF Radio-Wave Attenuation Through Jungle and Woods," Contract DA36 039AMC00011E, Radio Corp. of America, New York Defense Electronic Products (February 1963).

In this communication, a simple extension of the theory developed by Stratton and Wheeler was applied to HF and VHF radio-wave attenuation in the dense jungles. The theory for the loss in the foliage is essentially the same as that for loss in any medium (such as sea water) where the field is attenuated exponentially with distance. Experimental information is derived on the attenuation of ground-wave field strength vs. distance at various frequencies for vertically polarized waves through the dense jungles of New Guinea.

Descriptors: Radio waves, jungles; HF; VHF; propagation; attenuation; communication theory; radio transmission; ranges (distance); New Guinea.

(29) Kung, C. Y. and C. C. Yang, "Mean Arrival Time and Mean Pulse Width of Signals Propagating Through a Dispersive and Random Medium," IEEE Trans. Antenn., Vol. AP-25, No. 5, pp. 710-713 (September 1977).

An electromagnetic pulse propagating through the ionosphere can be modified owing to dispersion as well as random scattering from electron density irregularities. As a result, the pulse arrival time and the pulse width are altered. In this paper it is shown how such quantities can be computed and related to the medium parameters. In this connection the two-frequency mutual intensity function enters in the formulation naturally. The results show that the mean arrival time is dominated by a term which indicates that the pulse is traveling at the group velocity corresponding to the carrier frequency. But there are also small but important corrections resulting from random scattering and higher-order dispersion. Our results also show the importance of scattering and dispersion in lengthening the pulse. These results have important implications in satellite-based navigational and communication systems. (10 refs.)

Descriptors: Ionospheric electromagnetic wave propagation.

Identifiers: Mean pulse width; dispersive; random medium; electromagnetic pulse propagating; ionosphere; random scattering; electron density irregularities; pulse arrival time.

(30) Kupiec, I., L. B. Felsen, et al., "Reflection and Transmission by a Random Medium," Radio Science, Vol. 4, No. 11, pp. 1067-1077 (November 1969).

The mean field is considered for a bounded medium with a refractive index having a real random part. It has been shown previously that for suitable ranges of the amplitude and correlation length of the refractive index fluctuations this field satisfies a certain integrodifferential equation. This equation is solved for a plane wave incident from either side on the plane boundary of a semi-infinite random medium, for the Green's function of a semi-infinite random medium, and for a plane wave incident on a slab of random medium, provided that the background refractive index is homogeneous throughout. The cases of both one- and three-dimensional fluctuations are considered, and explicit expressions are given for the reflection, transmission, and coupling coefficients for a medium with an exponential correlation function. A Wiener-Hopf factorization required for other correlation functions is described, as are methods for treating reflection and transmission at a curved boundary of a random medium. A principal finding is the inadequacy of treating the mean wave in a bounded random medium by using just the refractive index for an unbounded random medium, for in addition we must include a transition layer near the boundary.

Descriptors: Wave transmission, stochastic processes; reflection; refractive index.

(31) Lang, R. H., "Path Integral Approach to Forward Scattering in Random Media," IEEE 1978 International Symposium Digest: Antennas and Propagation, pp. 159-160 (May 1978).

A review is given of the use of path integrals in the analysis of wave propagation in a forward-scattering random medium. The application of this method to forward-scattering problems stems from the fact that solutions to the parabolic equation can be represented exactly in terms of path integrals. This method has proven useful for obtaining the standard results of geometric optics as well as for determining the behavior of the higher-order moments of the field in the saturation regime. The above results have been obtained by asymptotically evaluating the path integral expressions for the moments in the appropriate parameter regime.

Descriptors: Electromagnetic wave scattering.

Identifiers: Random media; path integrals; forward-scattering problems; higher-order moments; EM wave scattering.

(32) Lax, M., "Multiple Scattering of Waves," Rev. Mod. Phys., Vol. 23, pp. 287-310 (1951).

(33) Lax, M., "Multiple Scattering of Waves, 2. The Effective Field in Dense Systems," Physical Review, Vol. 85, pp. 621-629 (1952).

The multiple scattering of waves interacting with a system of particles is treated by a self-consistent approach. Scattering processes are described by operators that permit anisotropy, absorption, and creation. The scattering system may be randomly, partially, or completely ordered.

The propagation constant, k', of the coherent wave in the scatterer medium differs from the vacuum constant, k, by $(k')^2 = k^2 + 4\pi ncf(k',k')$, where n is the scatterer density and f is an operator whose matrix elements, f(b,a), represent the scattering amplitude in direction, b, for a wave incident in direction a on a single scatterer bound by the forces of its neighbors. The parameter c, defined by

$$cf(k',k') = \int \exp(-ik' \times r) f \times \Psi_e(r) dr \quad ,$$

is a measure of the ratio of the effective field $\Psi_e(r)$ to the average field.

An integral equation is found for $\Psi_e(r)$ with the help of a "quasi-crystalline" approximation. A variational expression is then found for c that becomes exact for point scatterers.

A comparison is made of finite and infinite scattering systems. The extinction theorem is proven. The macroscopic viewpoint is found to be applicable to small systems whose size is large compared to the scatterer potential range, and the range of scattered position correlations.

(34) Lee, R. W. and J. C. Harp, "Wave Propagation in a Random Medium," Report No. Scientific-1; SU-SEL-68-066, Contract F19628-68-C-0055, AFCRL-68-0343, Stanford Electronics Labs., Stanford Univ. (June 1968).

A simple technique has been used to derive statistical characterizations of the perturbations imposed upon a wave (plane, spherical, or beamed) propagating through a random medium. The method is essentially physical rather than mathematical, and is probably equivalent to the Rytov method. The limitations of the method are discussed in some detail; in general they are restrictive only for optical paths longer than a few hundred meters, and for paths at the lower microwave frequencies. Situations treated include arbitrary path geometries, finite transmitting and receiving apertures, and anisotropic media. Results include, in addition to the usual statistical quantities, time-lagged functions, mixed functions involving amplitude and phase fluctuations, angle-of-arrival covariances, frequency covariances, and other higher-order quantities.

Descriptors: Wave transmission, atmosphere; electromagnetic waves; propagation; polarization; isotropism; attenuation; atmosphere models; atmospheric sounding; stochastic processes.

Identifiers: Rytov method.

(35) Mano, K., "Multiple Scattering in the Wave Propagation Through Random Media," Inst. Electronics and Communication Engrs. (Japan), 1971 International Symposium on Antennas and Propagation, Summaries of Papers 207-208 (September 1971).

A theoretical analysis is presented.

Descriptors: Scattering, electromagnetic waves; electromagnetic wave propagation; electromagnetic wave scattering.

Identifiers: Electromagnetic wave scattering; multiple scattering; wave propagation through random media.

(36) Mihara, Y. T., et al., 1971 International Symposium on Antennas and Propagation, Summaries of Papers (Inst. of Electron and Commun. Eng. of Japan, Tokyo, 1971).

This is a summary of 133 papers presented; following are some titles and authors: "Diffraction by a Moving Semi-Infinite Screen in an Anisotropic Plasma," Y. Mihara and T. Wakabayashi; "Multiple Scattering in Wave Propagation through Random Media," K. Mano; "Temporal Frequency Spectra of Multifrequency Waves in a Turbulent Atmosphere," A. Ishimaru;

"On Diffraction of Radio Waves in Stratified Atmosphere," N. A. Armand; "Mode Conversion of a Gaussian Light Beam Propagating through the Atmosphere," M. Imai; "Focusing of Highly Fluctuating Waves," P. V. Bliokn and V. G. Sinitsin; "Refraction Effect in the Earth-Ionosphere Waveguide for VLF Radio Waves," K. Sao and S. Shimakura; "Simple Condition on the Validity of the Rayleigh-Gans-Born Approximation in the Ionosphere," J. C. Hassab; "Doppler Effect in an Anisotropic Medium," K. A. Barsukov; "On the Propagation of Beam Waves in an Inhomogeneous Medium," S. Kozaki, "Power Spectrum of Waves Scattered by an Ionospheric Layer," D. J. Fang; Synthesis of Ionospheric Valley in the Computation of N(h)-Profiles," Chun-ming Huang.

Descriptors: Antennas; electromagnetic waves; plasmas; light, propagation; waveguides; ionosphere.

Identifiers: Radio waves.

(37) Miller, P. F., "The Probability Distribution of a Wave at a Very Large Depth within an Extended Random Medium," J. Phys. A (GB), Vol. 11, No. 2, pp. 403-422 (February 1978).

A plane wave is incident normally onto the boundary of a semi-infinite stationary random medium. The statistical moments of the field variable, both at one and at several points, are calculated when the refractive index of the medium at different points has a joint Gaussian probability distribution and Gaussian power spectrum, and the observer is at a very great depth within the medium. From these moments the probability distributions are calculated. The method uses a perturbation expansion. The limit of infinite distance and the limit of infinite depth are considered.

Descriptors: Electromagnetic wave propagation; random processes.

Identifiers: Probability distribution; very large depth; extended random medium; boundary; statistical moments; field variable; refractive index; Gaussian probability distribution; Gaussian power spectrum; perturbation expansion; limit of infinite distance; limit of infinite depth.

(38) Molodtsov, S. N. and A. I. Saichev, "On the Frequency Correlation of Waves in a Medium with Large-Scale Random Inhomogeneities," IZV. Vuz Radiofiz (USSR), Vol. 20, No. 8, pp. 1244-1246 (1977); Trans. Radiophys and Quantum Electron.

The frequency correlation of the complex amplitudes of waves propagating in a randomly inhomogeneous medium is found to geometric-optic approximation.

Descriptors: Electromagnetic wave propagation; geometrical optics.

Identifiers: Frequency correlation; complex amplitudes; randomly inhomogeneous medium; geometrical optics; wave propagation.

(39) Okafuji, S., "Second Moment of a Wave Propagating in a Random Medium," Electron and Commun. Jap. (USA), Vol. 57, No. 7, pp. 77-84 (July 1974).

The second moment of a wave in a random medium is obtained herein from statistical properties of the incident wave on the interface of the medium by means of the ladder-type approximation of Feynmann diagrams. From the second moment, under the assumption of a Gaussian medium and Gaussian spatial correlation, an expression for the correlation length along the direction of propagation (normal to the interface) is found in a simple form. Without the above assumptions, a simple expression for this that agrees with Beran's result is derived. The discussion is extended to the case where the intensity of the incident wave is Gaussian (spatially nonuniform) and the relations between the spot size and correlation length of the incident wave before and after propagation are studied.

Descriptors: Electromagnetic wave propagation.

Identifiers: Random medium, electromagnetic wave propagation, second moment.

(40) Papanicolau, G. C., "Transport Equations for Waves in Random Media," IEEE 1978 International Symposium Digest. Antennas and Propagation 165-167 (1978).

This paper discusses the conditions under which transport theory can provide a good approximation to the average wave intensity and to higher-order moments.

Descriptors: Electromagnetic wave propagation.

Identifiers: Random media; transport theory; approximation; higher-order moments; residual effects; EM wave propagation.

(41) Rino, C. L., "Iterative Methods for Treating the Multiple Scattering of Radio Waves," J. Atmos. and Terr. Phys. (GB), Vol. 40, No. 9, pp. 1011-1018 (September 1978).

An iterative method is developed for treating multiple scattering in an extended random medium. The basis of the method is to use the single-scatter theory to derive a recurrence relation for the complex field. Since no restriction is placed on the incremental layer thickness, the single-scatter theory can always be applied in this manner, subject only to the narrow-angle scatter restriction. Indeed, in the differential thickness, the recurrence relation, which is a difference equation, converges to the parabolic wave equation. The recurrence relation for the complex field is then used in conjunction with the Markov assumption to derive recurrence relations for the complex field moments of all orders.

Descriptors: Radio wave propagation; electromagnetic wave scattering; atmospheric techniques; iterative methods; ionospheric electromagnetic wave propagation.

Identifiers: Multiple scattering; radio waves; iterative method; extended random medium; complex field; single-scatter theory.

(42) Suzuki, H., "A Statistical Model for Urban Radio Propagation," IEEE Trans. Comm., Vol. COM-25, No. 7, pp. 673-679 (July 1977).

A statistical model, based on extensive experimental data, was established to characterize the urban radio propagation medium in various urban environments. Describing the medium by a linear filter, the peaks of the multipath response were analyzed statistically concerning the distribution of the path strength and the path arrival time. The statistical properties of these quantities depend on the modulation delay time. The resulting model can be used for simulation experiments in order to avoid costly hardware tests of ad hoc systems.

(43) Takeno, S., "A theory of Multiple Scattering of Waves in a Random Medium," (Probr. Theor, Phys. (Japan), Vol. 42, No. 6, pp. 1221-1237 (December 1969).

A theory of the multiple scattering of waves or particles interacting with a system of many scatterers in a medium is developed. A relationship between the total field and the effective field or the field seen by a given scatterer is obtained in a self-consistent manner using the Feenberg-Feshbach perturbation method. A configurational averaging procedure is applied to a wave equation to derive an equation obeyed by the coherent total field, which is in turn expressed by partial or conditional averages of the total field with one or more scatterer positions held fixed. A formal solution for such a set of hierarchy equations is obtained by introducing the mass operator, which is expressed in the form of continued fractions involving an effective transition operator and many scatterer-correlation functions. An equation for the effective transition operator is obtained in a self-consistent manner. It is shown that results thus obtained can be applied to the case of strong or dense scatterers as well as that of weak or dilute scatterers. Various approximate expressions are obtained for the mass operator and the effective transition operator, which, when using approximation procedures of lower orders, reduce to the results obtained previously. As an application, a brief discussion of the index of refraction of the medium is given.

(44) Tateiba, M., "Successively Forward-Scattered Waves Propagating Through a Random Medium," Electron. and Commun. Jap. (USA), Vol. 56, No. 1, pp. 34-41 (January 1973).

Presents an approximate method for forward scattering in a random medium, developing approximate expressions for the average value and correlation function of a wave scattered in the forward direction only. With the technique developed here, it is now possible, under certain conditions, to give a reasonable treatment of the forward-scattering effect, which has hitherto been considered in a rather uncertain fashion. The results obtained should be useful in considering field coherence, and they should also be effective for short-wavelength radiation such as light beams.

Descriptors: Electromagnetic wave scattering; correlation theory.

Identifiers: Random medium; approximate method; forward scattering; correlation function; EM wave scattering; forward-scattering effect.

(45) Tateiba, M., "Moment Equation of a Wave Propagating Through Random Media," Mem. Fac. Eng. Kyushu Univ., Fukuoka, Japan, Vol. 33, No. 4, pp. 129-137 (March 1974).

A new derivation of the moment equation is presented for a wave scattered successively in the forward direction by random inhomogeneities. The wave is expressed formally in a compact form by means of an ordered exponential function. Unlike the conventional process of the derivation, a moment equation for an arbitrary incident wave is systematically derived under definite conditions. The equation has a reasonable form in the sense of forward scattering and reduces to the equations obtained by several authors, to a good approximation. The solution of the moment equation is given in the particular case that the correlation function of the medium may be approximated by the first term of its Taylor's series.

Descriptors: Electromagnetic wave propagation.

Identifiers: Moment equation; wave propagating, random media; random inhomogeneities; ordered exponential function; correlation function; forward scattering.

(46) Tchen, C. M., "Stochastic Theory of the Scattering of Electromagnetic Waves from a Random Medium," Waves, Pt. 2 (August 1968).

Descriptors: Electromagnetic scattering; random processes; wave equations; wave propagation; conferences; differential equations; electron density (concentration); hydrodynamic equations; Maxwell's equations; plasma dynamics; power spectra.

(47) Twersky, V., "On Propagation in Random Media of Discrete Scatterers," Proc. of Symposium in Applied Math., Vol. 16, pp. 84-116 (Amer. Math. Soc., Providence, RI (1964).

(48) Twersky, V., "Scattering by Discrete Random Media," Proc. Symp. on Turbulence of Fluids and Plasmas, April 16-18, 1968, Microwave Res. Inst. Symp. Ser., Vol. 18, pp. 143-161 (1969).

Descriptors: Electromagnetic waves; scattering; waves.

(49) Uscinski, B. J., "Use of Physical Concepts in Dealing with Problems of Multiple Scatter," J. Atmos. and Terr. Phys. (GB), Vol. 40, No. 12, pp. 1257-1266 (December 1978).

A physical picture is presented of the processes that produce intensity fluctuations in a wave propagating in a random medium in the case of multiple scatter. Two different mechanisms that can lead to intensity fluctuations are identified, and it is shown why a scintillation index greater than unity can arise when a parameter gamma that characterizes different media is very large. The position of this focal region is shown to behave like gamma/sup -1/3/, in agreement with other theories. It is shown that when gamma is large, the field in the medium is similar to that produced by a deeply modulated phase-screen and that the results of deep phase-screen theory can be usefully applied to the extended medium. The framework of physical concepts allows the probability distributions of amplitude and phase of the field in a multiple-scattering random medium to be discussed.

Descriptors: Scattering; wave propagation; random processes; fluctuations; modulation.

Identifiers: Physical concepts; random medium; intensity fluctuations; scintillation index; waves multiple scattering; focal region position; deeply modulated phase screen; wave intensity fluctuations; amplitude fluctuations; phase probability distributions.

(50) Varadan, V. K., V. N. Bringi et al., "Coherent Electromagnetic Wave Propagation Through Randomly Distributed Dielectric Scatterers," Phys. Rev. D, Vol. 19, No. 8, pp. 2480-2489 (15 April 1979).

The authors present a vector multiple-scattering analysis of the coherent wave propagation through an inhomogeneous media consisting of a random distribution of identical oriented, nonspherical dielectric scatterers. The single-scattering aspect of the problem is dealt with through application of the transmission or T matrix. Configurational averaging techniques are employed to determine the 'Hole' correction integrals, which are subsequently solved to yield the dispersion relations characterizing the bulk or effective properties of the medium. Closed-form solutions in the Rayleigh limit are derived for both spherical and spheroidal scatterer geometries. These solutions, together with the T matrix, form the basis of the authors' computational method for determining the coherent wave phase velocity and attenuation as a function of frequency (ka) and scatterer concentration. Numerical results are presented for spherical and oblate spheroidal geometries over a range of ka values (0.05-2.0) and scatterer concentrations (0.05-0.20). (16 refs.)

Descriptors: Electromagnetic wave propagation; dispersion relations.

Identifiers: Randomly distributed dielectric scatterers; 'hole' correction integrals; dispersion relations; spheroidal scatterer geometries; coherent-wave phase velocity; attenuation; vector multiple-scattering analysis; T-matrix; coherent electromagnetic wave propagation; spherical scatter geometries.

(51) Zavortnyi, V. U., "Strong Fluctuations of Electromagnetic Waves in a Random Medium with a Finite Inhomogeneity Correlation Range," Zh. Eksp. and Teor. Fiz. (USSR), Vol. 75, No. 1, pp. 56-65. [Translated in Sov. Phys. Jetp. (USA)].

The propagation of electromagnetic waves in a medium with random inhomogeneities of the refractive index is considered in the approximation of the parabolic equation. The statistical moments of the intensity for waves of arbitrary order (I/SUP N/) are written down as Feynman continual integrals (in operator form). Expressions for the higher-intensity moments are obtained by taking into account the finiteness of the longitudinal fluctuation correlation range of the refractive index in the region of both weak and strong intensity fluctuations. The limits of applicability of the Markov approximation in which the range is assumed to vanish on calculating the intensity moments (I/SUP N/) are found.

Descriptors: Electromagnetic wave propagation; fluctuations; Markov processes.

Identifiers: Electromagnetic waves; random medium; finite inhomogeneity correlation range; parabolic equation; statistical moments; Feynman continual integrals; intensity fluctuations; Markov approximation.

Appendix D

AUTHOR INDEX

Appendix D

AUTHOR INDEX*

*This index lists the authors by reference number in Appendices A, C, and C.

Appendix E

SUBJECT INDEX

Appendix E

SUBJECT INDEX

This index catalogues the references of Appendices A, B, and C, related by the four principal topics of Section III of this report. The topics listed in this appendix have been generalized to include other related references.

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