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Annapolis, Maryland 21402

AN INITIAL CRITICAL SUMMARY OF MODELS FOR PREDICTING THE ATTENUATION OF RADIO WAVES BY TREES

PREPARED FOR

DEPARTMENT OF DEFENSE
ELECTROMAGNETIC COMPATIBILITY ANALYSIS CENTER
ANNAPOLIS, MARYLAND 21402

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This report is a review of models and data that can be used to predict the increase in attenuation due to trees and underbrush that are located between a radio transmitter and receiver. Applications in the 3 MHz to 95 GHz band are addressed with emphasis placed on the 200 to 9200 MHz range. It is shown that the conventional technique for predicting the loss caused by propagation through a small grove of trees is often substantially in error. An improved empirical model is developed to mitigate the problem; a physical justification for the model is presented.

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PREFACE

The Electromagnetic Compatibility Analysis Center (ECAC) is a Department of Defense facility, established to provide advice and assistance on electromagnetic compatibility matters to the Secretary of Defense, the Joint Chiefs of Staff, the military departments and other DoD components. The center, located at North Severn, Annapolis, Maryland 21402, is under the policy control of the Assistant Secretary of Defense for Communication, Command, Control and Intelligence and the Chairman, Joint Chiefs of Staff, or their designees, who jointly provide policy guidance, assign projects, and establish priorities. ECAC functions under the executive direction of the Secretary of the Air Force and the management and technical direction of the Center are provided by military and civil service personnel. The technical support function is provided through an Air Force-sponsored contract with the IIT Research Institute (IITRI).

To the extent possible, all abbreviations and symbols used in this report are taken from American National Standard ANSI Y10.19 (1969) "Letter Symbols for Units Used in Science and Technology" issued by the American National Standards Institute (ANSI), Inc.

Users of this report are invited to submit comments that would be useful in revising or adding to this material to the Director, ECAC, North Severn, Annapolis, MD, 21402, Attention: XM.

EXECUTIVE SUMMARY

The traditional model for predicting the increase in loss due to propagation through trees is this exponential decay (EXD) model:

$$L = 0.26\ F^{0.77}\ d_f$$

where L is the loss due to the trees in dB, F is the frequency in GHz, and d_f is the depth of the trees in meters. In this report, it is shown that for problems in the 230-MHz to 95-GHz band, a better prediction is obtained from this modified exponential decay (MED) model:

$$\begin{aligned} L &= 1.33\ F^{0.284}\ d_f^{0.588} && \text{for } 14 \le d_f \le 400 \\ &= 0.45\ F^{0.284}\ d_f && \text{for } 0 \le d_f < 14 \end{aligned}$$

The MED model is found to be applicable to cases in which the ray path is blocked by dense, dry, in-leaf trees found in temperate-latitude forests.

Comparisons between eight sets of measurements and predictions of the EXD and MED models are presented. It is seen that the rms prediction errors of the EXD model are 37, 27, 24, 15, 14, 13, 10, and 4 dB; the corresponding prediction errors of the MED model are 6, 9, 7, 8, 2, 7, 10, and 2 dB.

The problems for which other authors have found diffraction models to be applicable are discussed. These models can be used for geometries in which the majority of the signal propagates over, rather than through, the trees. The studies described pertain to the 25-MHz to 5-GHz band. Guidelines for choosing between the MED model and the diffraction models are presented. There is no documented criterion for choosing between the knife-edge and smooth-sphere diffraction models, however.

Kinase's empirical-theoretical model was found to be applicable to problems where one antenna is located well above the foliage. The model is based on the assumption that the second antenna is in an area η% of which is covered with trees. η is an input parameter which can be varied from 1 to 50. Kinase's model is based on data in the 80 - 700 MHz frequency range.

The Jansky and Bailey empirical model was found to be applicable to problems where both antennas are immersed in a tropical forest. Path lengths can vary from 8 to 1600 meters, frequencies from 25 to 400 MHz. Antenna heights should be less than 7 meters. A comparison between a limited set of measurements and predictions of the Jansky and Bailey empirical and a lateral-wave theoretical model is presented. In this comparison, the empirical model is seen to be more accurate. The theoretical model predictions were made using measured values of the electrical parameters of the forests in which the loss measurements were made. Use of effective values of these electrical parameters appears to increase the accuracy of the theoretical model, but no guidelines for determining such values have been reported.

A review of tropical and nontropical measurements showed that, very often, the field strength at an antenna that is moved through foliage will be Rayleigh distributed. Thus, circuit performance calculations should account for this multipath-fading behavior in addition to accounting for the median foliage loss. Equations for computing bit-error rates for signals subjected to frequency-flat Rayleigh fading are presented for FSK and PSK.

GLOSSARY

Symbol	Word	Definition
ℓ_{bo}	Basic transmission loss (ratio) in the absence of foliage	The ratio of the power input to a lossless isotropic transmitting antenna to the power available at the terminals of a remote lossless isotropic receiving antenna. ℓ_{bo} is a value that is computed or measured with no trees between the transmitter or receiver.
L_{bo}	Basic transmission loss, dB, in the absence of foliage	$10 \log \ell_{bo}$
d_f	Depth of foliage, meters	The depth of the trees between the transmitter and receiver, in meters.
α	Differential attenuation due to foliage, dB/meter	This quantity is determined by first subtracting the loss on a path without trees from the loss on a comparable path with trees. The result, in dB, is divided by the depth of the trees, in meters.

Symbol	Word	Definition
L_b	Basic transmission loss, dB, with foliage	$L_b = L_{bo} + \alpha d_f$
EXD Model	Exponential decay model	A model based on the assumption that α will not be a function of the depth of trees.
MED Model	Modified exponential decay model	A model in which α is assumed to be a function of the depth of trees.
F		Frequency in GHz.
f		Frequency in MHz.

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SECTION 1

INTRODUCTION

1.1 BACKGROUND

In October 1978, the Electromagnetic Compatibility Analysis Center (ECAC) Marine Corps Deputy Director requested that a study be made of the availability of models and data that could be used to estimate the impact of trees and underbrush on the propagation of radio waves. The information was desired to support the Marine Corps' requirement to determine the feasibility of using Joint Tactical Information Distribution System (JTIDS) terminals in support of land-based operations of the Fleet Marine Force (FMF). Material applicable to predicting the performance of other Marine radio systems in forest environments was to be collected also.

Persuant to this request, an effort was undertaken in FY79 during which 50 reports, journal articles, and texts were reviewed. Their contents fell into two broad categories -- available prediction models and available measurements.

Comparisons were made between predictions from the frequently cited exponential decay (EXD) propagation model and measurements. A large discrepancy was observed and reported to the ECAC Marine Office. It was agreed that a task could be carried out in FY80 to investigate solutions to this problem. As a result, an improved empirical algorithm, the modified exponential decay (MED) model, was developed.

The MED model was described in an abstract submitted to the United States National Committee of the International Union of Radio Science (URSI) in January 1980. The abstract was accepted and the paper presented at the North

American Radio Science Meeting.[1] A formal document was prepared for the Marine Corps Development and Education Command later in the year.[2]

Subject to the limitations documented in References 1 and 2, the MED model was accepted by the Study Group 5 of the International Radio Consultative Committee (CCIR).[3]

In FY81, the material in the Consulting Report (see Reference 2) was expanded and redocumented in the form of this Technical Report. The reasons for this action were as follows.

1. Readers of the Consulting Report had requested more evidence to support the conclusions in that document.
2. The acceptance of the MED model by the CCIR had led to a need for a report that described the basis and limitations of the model and that was accessible to the international radio-engineering community.

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[1] Weissberger, M. and Hauber, J., "Modeling the Increase in Loss Caused by Propagation Through a Grove of Trees," Program and Abstracts of the North American Radio Science Meeting, Quebec, Canada, 2-6 June 1980.

[2] Weissberger, M.A., An Initial Critical Summary of Models for Predicting the Attenuation of Radio Waves by Foliage, ECAC-CR-80-035, Electromagnetic Compatibility Analysis Center, Annapolis, MD, July 1980.

[3] International Radio Consultative Committee (CCIR), Influence of Terrain Irregularities and Vegetation on Tropospheric Propagation, Report 236-4 (MOD F), Doc. 5/5007-E, 7 September 1981.

1.2 OBJECTIVE

The objective of this effort was to present an integrated description of the FY79-FY81 ECAC study of the effects of trees and underbrush on radio-wave propagation.

1.3 APPROACH

The information gathered during the study was organized into the remaining eight sections of this report.

Section 2 is a review of the models and data that can be used to predict the attenuation caused by propagation through (rather than over) groves of trees that are as deep as 400 meters. It is shown that the exponential decay (EXD) model, though generally assumed applicable to such problems, is often inaccurate. The MED model is presented as a means to overcome some of the problems with the EXD algorithm. Comparisons between MED predictions, EXD predictions, and measured data in the 230-MHz to 95-GHz frequency range are documented. An approximate rule for determining which antenna-tree geometries will be conducive to propagation through the trees (and MED applicability) is developed.

Section 3 is a summary of data relating to paths in which the trees are far enough from both antennas so that the waves diffract over the forest. The examples reported are in the 25-MHz to 5-GHz frequency range.

Section 4 contains a description of Kinase's model[4] for predicting the loss that occurs when one antenna is elevated well above the forest and the

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[4] Kinase, A., Influences of Terrain Irregularities and Environmental Clutter Surroundings on the Propagation of Broadcasting Waves in the UHF and VHF Bands, NHK Technical Monograph No. 14, Japan Broadcasting Corporation, Tokyo, Japan, March 1969.

second antenna is located in a region, η% of which is covered with vegetation or man-made structures. The basis for the model is data in the 80-700 MHz band.

Section 5 is a description of the Jansky and Bailey[5] empirical model for computing the loss between two antennas immersed in a tropical jungle. Path lengths can vary from 0.08 to 1.6 km. The model applies to the 25-400 MHz band.

Section 6 contains a collection of plots of measured foliage attenuation versus frequency in the 2-MHz to 10-GHz range. Plots of attenuation versus distance and attenuation versus antenna height are shown for the 900-1200 MHz band.

Section 7 is a summary of information relating to the variation of signal strength with position that occurs when an antenna is moved through a forest. It is seen that, very often, a Rayleigh distribution can be used to categorize the variations.

Section 8 includes closed-form expressions for the bit-error rate that can be expected for FSK and PSK transmissions when the signal strength is Rayleigh distributed.

Section 9 is a summary of this report.

Differences between this report and the original Consulting Report include the following.

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[5] Jansky and Bailey Engineering Department, Tropical Propagation Research, Final Report, Volume 1, Atlantic Research Corporation, Alexandria, VA, 1966, AD660318.

a. Additional data is presented to demonstrate that the loss-versus-frequency trend is more accurately predicted by the MED model than by other models.

b. Quantitative evidence has been included to demonstrate that the Jansky and Bailey empirical model is a reasonably accurate means of predicting the attenuation of VHF signals coupled between low antennas separated by tropical foliage. Contrasts with another prediction procedure are also presented.

c. Summaries of three sets of measurements of the multipath-induced spatial variability of signal strength in nontropical forests are presented. These complement the tropical data in the original documentation.

d. A clearer presentation of the percentiles of the Nakagami-Rice distribution has been included. This is based on an earlier report by Norton.[6]

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[6] Rice, P., Longley, A., Norton, K., and Barsis, A., Transmission Loss Predictions for Tropospheric Communications Circuits, NBS TN 101, National Bureau of Standards, Boulder, CO, Revised January 1967.

SECTION 2

PREDICTING THE INCREASE IN LOSS CAUSED BY PROPAGATION THROUGH A GROVE OF TREES

2.1 THE EXPONENTIAL DECAY (EXD) MODEL: BACKGROUND

The traditional approach to modeling the additional loss caused by propagation through vegetation is to assume that this loss increases exponentially with the distance through the foliage.[7,8,9,10,11] Thus, received power is calculated using:

$$P_r = \frac{P_t \, g_t \, g_r}{\ell_{bo}} \, e^{-\alpha_1 d_f} \qquad (1)$$

where

P_t = transmitted power, in watts
P_r = received power, in watts
g_t = transmitter antenna gain (ratio)
g_r = receiver antenna gain (ratio)

---

[7] Saxton, J.A. and Lane, J.A., "VHF and UHF Reception, Effects of Trees and Other Obstacles," Wireless World, May 1955.

[8] LaGrone, A.H., "Forecasting Television Service Fields," Proceedings of the IRE, June 1960.

[9] Currie, N.C., Martin, E.E., and Dyer, F.B., Radar Foliage Penetration Measurements at Millimeter Wavelengths, ESS/GIT-A-1485-TR-4, Georgia Institute of Technology, Atlanta, GA, 31 December 1975, ADA023838.

[10] International Radio Consultative Committee (CCIR), "Influence of Terrain Irregularities and Vegetation on Tropospheric Propagation," Report 236-4, XIV Plenary Assembly, International Telecommunication Union, Geneva, Switzerland, 1978.

[11] Krevsky, S., "HF and VHF Radio Wave Attenuation Through Jungle and Woods," IEEE Transactions on Antennas and Propagation, July 1963.

ℓ_{bo} = basic transmission loss in the absence of foliage (ratio)

α_1 = differential attenuation due to foliage, in meter^{-1}

d_f = distance through the foliage, in meters.

Equation 1 describes the flow of electromagnetic radiation through an infinite medium composed of either a lossy dielectric continuum or a collection of randomly located discrete lossy scatterers.[12] A variation of the equation was used by Bouguer in 1729 to describe the propagation of light through liquids.

In logarithmic units, Equation 1 becomes:

$$\boxed{P_R = P_T + G_T + G_R - L_{bo} - \alpha d_f} \qquad (2)$$

where P_R and P_T are in dBW, G_T and G_R in dBi, L_{bo} in dB, d_f in meters, and α in dB/meter. α in Equation 2 is related to α_1 in Equation 1 by:

$$\alpha = \alpha_1 \times 10 \log e = 4.34\ \alpha_1 \qquad (3)$$

Values of α can be obtained from measurements using:

$$\alpha = (L_1 - L_2)/d_f \qquad (4)$$

where

L_1 = the measured loss, in dB

L_2 = the measured loss on a comparable path without trees, in dB.

Therefore, the additional dB of attenuation due to the trees on the path is αd_f.

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[12] Ishimaru, A., Wave Propagation and Scattering in Random Media, Academic Press, New York, NY, 1978.

Equations 1 and 2 describe a decay of the received signal (watts) due to trees (or an increase in the loss due to trees) that varies exponentially with d_f when α (and α_1) do not vary with d_f. Models composed of Equation 1 (or 2) and a formula for α_1 (or α) that does not contain d_f will be called exponential decay (EXD) models in this report. Subsection 2.2 contains examples of this type of model. In subsection 2.3, preliminary evidence is presented to show that for $d_f \gtrsim 15$ meters, α decreases with increasing d_f and, therefore, the EXD model is not valid here. An empirical "modified exponential decay" (MED) model, that accounts for this behavior of α, is described. In subsection 2.4, predictions from the MED and EXD models are shown in comparison with measured values. It is seen that the MED model is consistently more accurate.

2.2 EXAMPLES OF EXPONENTIAL DECAY MODELS REPORTED IN THE LITERATURE

Saxton and Lane (see Reference 7) summarized groups of measurements taken by Saxton, Trevor,[13] and McPetrie[14] in nontropical deciduous woods. In TABLE 1, the subset of this data that relates to propagation through dry (i.e., not rained upon), in-leaf trees, is provided. Saxton used Equation 4 to compute values of α and plotted them in a manner similar to that shown in Figure 1. LaGrone (see Reference 8) documented this analytical expression for Saxton's plot:

$$\alpha = 0.26\ F^{0.77} \qquad (5)$$

---

[13] Trevor, B., "Ultra-High-Frequency Propagation Through Woods and Underbrush," RCA Review, July 1940.

[14] McPetrie, J.S. and Ford, L.H., "Some Experiments on the Propagation of 9.2-cm Wavelength, Especially on the Effects of Obstacles," Journal of the IEE, Part IIIa, London, England, 1946, p. 531.

TABLE 1

MEASURED VALUES OF THE ADDITIONAL ATTENUATION DUE TO DRY TREES IN LEAP[a] -- THE SAXTON AND LANE DATA

F (MHz)	Depth of Trees (m)	Loss (dB)	α (= Loss/Depth) (dB/m)	Polarization	Description of Trees
100	>200	Not Reported	0.06	V	Deciduous with some pine, underbrush; in Europe
100	>200		0.03	H	
500	152	18.0	0.12	H ≅ V	Deciduous with underbrush; near Philadelphia
540	85	17.0	0.20	V	Mostly deciduous; in England
540	85	15.0	0.18	H	
540	24	6.0	0.25	V	Lime trees (deciduous); in England
540	24	3.6	0.15	H	
1200	24	8.4	0.35	H ≅ V	Lime trees (deciduous); in England
3260	24	9.8	0.41	H ≅ V	Lime trees (deciduous); in England

[a] See Reference 7.

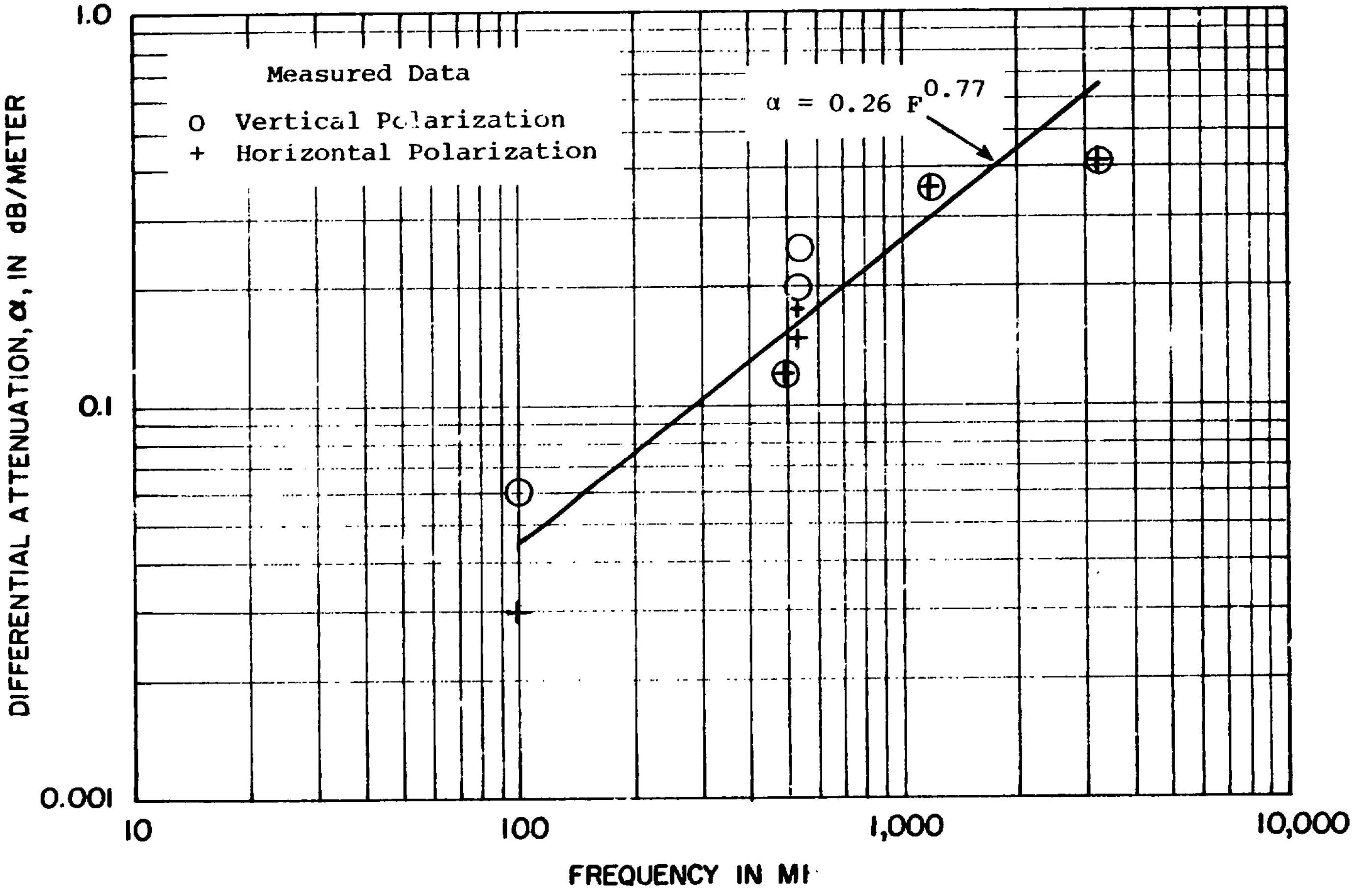

Figure 1. Saxton and Lane's portrayal of α as a function of frequency (see Reference 7). The straight line represents their description of the trend of α. The equation associated with this line was developed by LaGrone (see Reference 8). In subsection 2.3, it is shown that these representations of the data are misleading. A more realistic approach is presented.

where

α = the differential attenuation, in dB/m
F = the frequency, in GHz.

Alternative values for α were published in ensuing years -- one by Krevsky in 1963 (see Reference 11), one in NBS TN 101 (see Reference 6), another in a paper by Rice in 1971,[15] and a fourth in the CCIR Plenary-approved reports (see Reference 10). Each is a form of the EXD model -- that is, α is presented as being independent of the depth of trees, d_f. To allow a compact presentation, quantitative examples of EXD predictions presented in the main body of this report will be based on LaGrone's equation. Studies of the alternate formulations are included in APPENDIX A.

2.3 THE BASIS OF THE MED MODEL

The EXD model is based on the data in TABLE 1, which extends in frequency from 0.1 to 3.2 GHz and encompasses values of foliage depth (d_f) from 24 to 200 meters. As part of the ECAC study, predictions from the EXD model were compared with measurements (different from those within TABLE 1) that fell both within and beyond this range of frequency and d_f. One of the sets of measurements that fell within the parameter range was collected by Frankel[16] at several sites in west-central California. The data is listed in TABLE 2. Figure 2 is a comparison between EXD predictions (α from Equation 5 times d_f) and the measurements. It is seen that the agreement is poor with errors ranging as high as 43 dB. Comparisons with other sets of measurements, which will appear in later figures, showed similar problems.

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[15] Rice, P.L., "Some Effects of Buildings and Vegetation on HF/UHF Propagation," Conf. Proc. of the 1971 IEEE Mountain-West Conference on Electromagnetic Compatibility, Tucson, AZ, November 1971.

[16] Frankel, M.S., L-Band Forest Experiments, Packet Radio Temporary Note 254, SRI International, Menlo Park, CA, 19 May 1978.

TABLE 2

MEASURED VALUES OF THE ADDITIONAL ATTENUATION DUE TO DRY TREES IN LEAF[a] --

FRANKEL'S DATA

F (MHz)	Depth of Trees (m)	Loss (dB)	α (= Loss/Depth) (dB/m)	Polarization	Description of Trees
1850	50	12.2	0.24	V	Oak, madrone, pine, redwood. Dense underbrush. Dense tree tops. Average tree height = 10 m.
	60	12.5	0.21		
	90	15.0	0.17		
	100	16.7	0.17		
	150	20.0	0.13		
1850	50	9.4	0.18	V	This data was taken in the area described above but along a different path.
	60	9.5	0.16		
	90	12.0	0.13		
	100	13.6	0.14		
	150	-	-		
1850	50	9.0	0.18	V	Dense underbrush to 6 m. Tall redwood and fir trees penetrate this layer and extend to 26 m.
	60	10.7	0.18		
	90	16.3	0.18		
	100	18.9	0.19		
	150	28.9	0.19		
1850	50	12.1	0.24	V	Dense underbrush composed of young eucalyptus trees. Average height is 6 m.
	60	11.5	0.19		
	90	13.0	0.14		
	100	14.5	0.15		
	150	24.6	0.16		

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[a] See Reference 16. See subsection 2.4.3 for a note on a fifth set of data that is in Reference 16 but not summarized here.

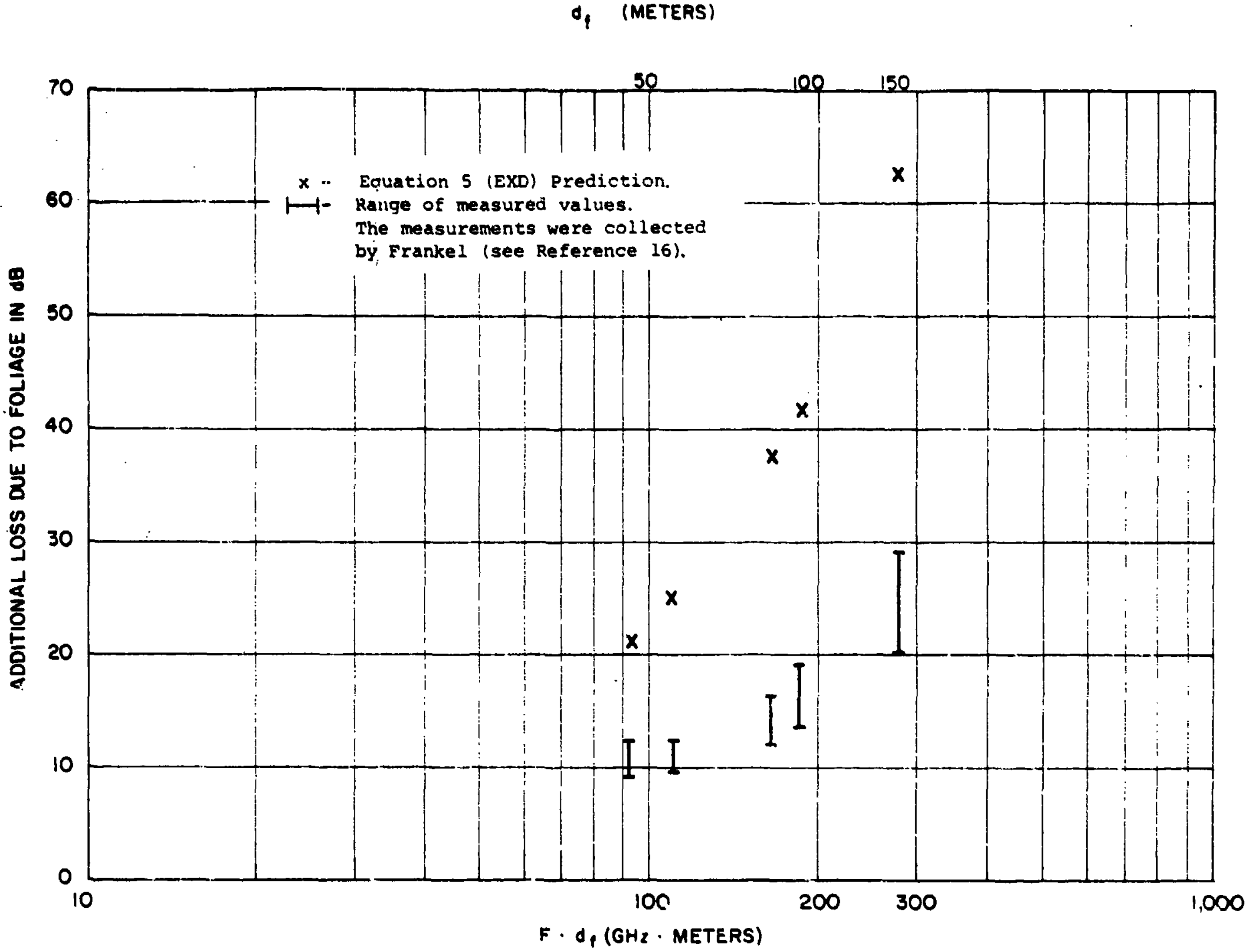

Figure 2. Graph illustrating the errors that may arise when the EXD model is used. The MED model, as will be shown, mitigates these problems. The frequency is 1850 MHz and the polarization is vertical. The x-axis of this graph is the product of frequency (F) in GHz and the depth of trees (d_f) in meters. This parameter was selected because the applicability of the EXD model can be more readily described in terms of ranges of F . d_f than it can be by individual ranges of F and d_f.

As early as 1958, Josephson[17] had observed that the EXD model was not applicable for prediction of loss through large depths of trees in temperate forests. However, he provided no substitute computational procedure. Reviews of the literature by this author and others[10,18] revealed that no one else had reported a successful alternative.[a] Therefore, the MED model was developed to mitigate the problems associated with the use of the EXD model. The MED model was first documented in an abstract submitted in January 1980 for a paper presented later in that year (see Reference 1). The development of this model will now be described.

Figure 2 demonstrates that use of the EXD model could result in substantial errors. Figure 3 shows one source of the problem -- namely that the measured differential attenuation, α, decreases as the depth of trees increases. The EXD model is based on the assumption that α is not a function of the depth of trees. Thus, if the attenuation rate measured at 50 meters, $\alpha = 0.21$ dB/m, were used in the EXD model to predict the loss at 150 meters, the predicted value would be 32 dB. In contrast, the average measured loss at 150 meters is only 24 dB, corresponding to $\alpha = 0.16$ dB/m.

A key step in developing the MED model was quantifying the decrease of α. The California data was not used to develop the actual MED equation, because it was limited to a single frequency. The Saxton and Lane data was unsuitable, because the measurements for each frequency were taken through a depth of trees different than the depth for any of the other frequencies.

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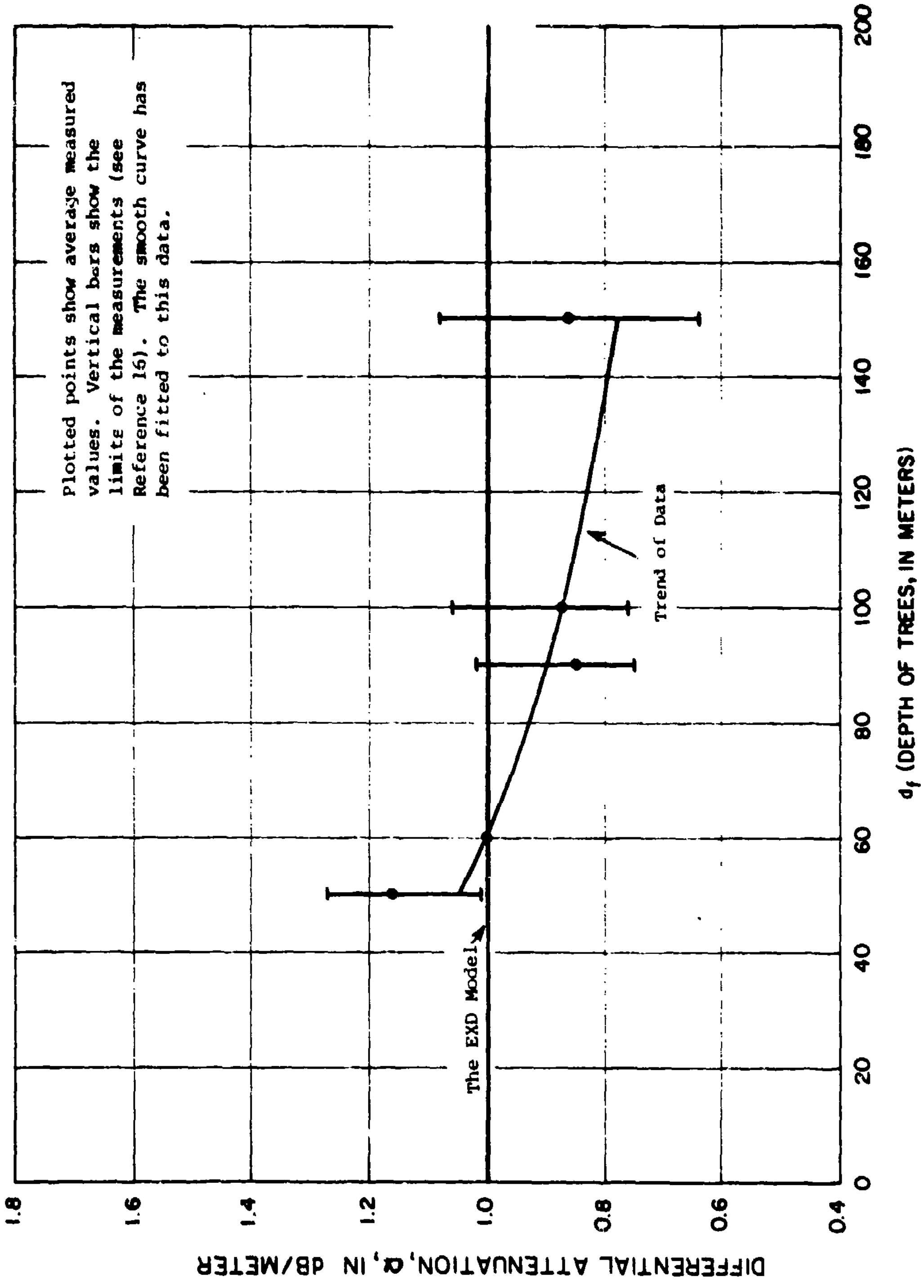
[a] Empirical and theoretical procedures were developed for the 1-400 MHz band for the problem of antennas separated by a tropical jungle. These procedures are discussed in Section 5 of this report.

[17] Josephson, B. and Blomquist, A., "The Influence of Moisture in the Ground, Temperature and Terrain on Ground Wave Propagation in the VHF-Band," IRE Transactions on Antennas and Propagation, April 1958.

[18] Nelson, R.A., UHF Propagation in Vegetative Media, Final Report for Project 8998, SRI International, Menlo Park, CA, April 1980.



Plotted points show average measured values. Vertical bars show the limits of the measurements (see Reference 16). The smooth curve has been fitted to this data.

Figure 3. Trend of α vs depth of trees for the California data.

Properly separating distance and frequency trends was, therefore, impractical. The data reported by McQuate in 1968[19] was chosen, because it covered a wide frequency range and allowed separation of frequency and distance trends. The data used is presented in TABLES 3 and 4.

Least-squares fitting of this data resulted in the following equation:[a]

$$\boxed{\begin{aligned} \alpha &= 1.33\, F^{0.284}\, d_f^{\,-0.412} && 14 \le d_f \le 400 \\ &= 0.45\, F^{0.284} && 0 \le d_f < 14 \end{aligned}} \qquad \begin{aligned} &(6a) \\ &(6b) \end{aligned}$$

where

α = the differential attenuation, in dB/m
F = the frequency, in GHz
d_f = the depth of the trees, in m.

Combining Equation 6a with Equations 3 and 1 results in a formula with this form:

$$P_r = \frac{p_t\, g_t\, g_r}{\ell_{bo}}\, e^{-\alpha_1 (F, d_f) d_f} = \frac{p_t g_t g_r}{\ell_{bo}}\, e^{-\alpha_1{}'(F) d_f^{\,1-k}} \qquad (7)$$

In contrast to EXD models (in which α_1 is not a function of d_f), Equation 7 predicts an additional loss due to foliage that does not increase exponentially with d_f raised to the first power. Instead, the increase is less rapid. Equation 7 is called the MED model. Equations 6 and 2 comprise a logarithmic form of this model and are used to compute loss values in the rest of the section.

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[a] The distance limits and the equation for $d_f < 14$ come from considerations explained later in the section.

[19] McQuate, P. L., et al., Tabulations of Propagation Data Over Irregular Terrain in the 230-9200 MHz Frequency Range, Part I; Gunbarrel Hill Receiver Site, ESSA TR ERL 65-ITS 58-1, Institute for Telecommunication Sciences (ITS), Boulder, CO, March 1968.

TABLE 3

McQUATE'S MEASURED VALUES OF THE ADDITIONAL ATTENUATION DUE TO DRY TREES IN LEAF[a]

Remote Antenna Height = 2 m
(Page 1 of 2)

F (MHz)	Depth of Trees (m)	Loss (dB)	α (= Loss/Depth) (dB/m)	Polarization	Description of Trees
230	14	6.0	0.43	H	Cottonwood trees, 9 m tall. There is a 12-m clearing between the trees and the closer antenna.
410		8.0	0.57		
751		8.3	0.59		
910		6.8	0.49		
1846		7.0	0.50		
4595		-	-		
9190		-	-		
230	15	5.5	0.37	H	Cottonwood trees, 15 m tall. There is a 9-m clearing between the trees and the closer antenna.
410		3.0	0.20		
751		-	-		
910		3.0	0.20		
1846		4.5	0.30		
4595		14.5	0.97		
9190		25.5	1.70		
230	45	9.5	0.21	H	Cottonwood trees, 12 m tall. There is a 6-m clearing between the trees and the closer antenna.
410		9.0	0.20		
751		10.7	0.24		
910		16.0	0.36		
1846		17.7	0.39		
4595		32.0	0.71		
9190		33.8	0.75		

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[a] See Reference 19.

TABLE 3

(Page 2 of 2)

F (MHz)	Depth of Trees (m)	Loss (dB)	α (= Loss/Depth) (dB/m)	Polarization	Description of Trees
230	60	9.0	0.15	H	Dense cottonwood trees. There is a 3-m clearing between the trees and the closer antenna. The tree height was not reported by McQuate; it is probably in the 9-15 m range.
410		13.3	0.22		
751		11.0	0.18		
910		11.0	0.18		
1846		30.8	0.51		
4595		14.0	0.23		
9190		18.0	0.30		
230	60	10.0	0.17	H	Cottonwood trees, 12 m tall. The clearing size was not reported by McQuate but appears to be less than 6 m.
410		21.5	0.36		
751		24.5	0.41		
910		7.2	0.12		
1846		20.0	0.33		
4595		13.2	0.22		
9190		20.8	0.35		
230	91	11.5	0.13	H	Dense cottonwood trees, 14 m tall. There is a 3-m clearing between the trees and the closer antenna.
410		15.0	0.16		
751		10.5	0.12		
910		13.0	0.14		
1846		18.8	0.21		
4595		31.5	0.35		
9190		46.0	0.51		

TABLE 4

McQUATE'S MEASURED VALUES OF THE ADDITIONAL ATTENUATION DUE TO DRY TREES IN LEAF[a]

Remote Antenna Height = 13 m
(Page 1 of 2)

F (MHz)	Depth of Trees (m)	Loss (dB)	α (= Loss/Depth) (dB/m)	Polarization	Description of Trees
230	14	4.3	0.31	H	Cottonwood trees, 9 m tall. There is a 12-m clearing between the trees and the closer antenna.
410		8.7	0.62		
751		7.7	0.55		
910		7.0	0.50		
1846		3.0	0.21		
4595		-	-		
9190		-	-		
230	15	6.0	0.40	H	Cottonwood trees, 15 m tall. There is a 9-m clearing between the trees and the closer antenna.
410		2.3	0.15		
751		-	-		
910		2.0	0.13		
1846		3.8	0.25		
4595		13.5	0.90		
9190		15.7	1.05		
230	45	10.3	0.23	H	Cottonwood trees, 12 m tall. There is a 6-m clearing between the trees and the closer antenna.
410		8.0	0.18		
751		7.7	0.17		
910		13.0	0.29		
1846		17.0	0.38		
4595		38.0	0.84		
9190		28.0	0.62		

[a] See Reference 19.

TABLE 4

(Page 2 of 2)

F (MHz)	Depth of Trees (m)	Loss (dB)	α (= Loss/Depth) (dB/m)	Polarization	Description of Trees
230	60	8.7	0.15	H	Dense cottonwood trees. There is a 3-m clearing between the trees and the closer antenna. The tree height was not reported by McQuate; it is probably in the 9-15 m range.
410		11.2	0.19		
751		16.5	0.28		
910		14.0	0.23		
1846		28.0	0.47		
4595		31.0	0.52		
9190		23.5	0.39		
230	60	9.2	0.15	H	Cottonwood trees, 12 m tall. The clearing size was not reported by McQuate but appears to be less than 6 m.
410		26.8	0.45		
751		17.0	0.28		
910		24.0	0.40		
1846		21.0	0.35		
4595		10.8	0.18		
9190		22.0	0.37		
230	91	13.5	0.15	H	Dense cottonwood trees, 14 m tall. There is a 3-m clearing between the trees and the closer antenna.
410		12.7	0.14		
751		13.5	0.15		
910		10.0	0.11		
1846		18.7	0.21		
4595		34.5	0.38		
9190		45.5	0.50		

Figures 4 through 7 illustrate how the trend of α versus distance predicted by Equation 6 compares with four sets of measurements. Figure 4 shows the trend of the means of the Colorado data. Good agreement is expected here because the model is based fully on this data. The EXD trend is shown for contrast. Figure 5 shows the comparison with the California data. The agreement is reasonably good, even though this data was not used in the development of the model. Figure 6 shows the comparison with measurements taken by the Hughes Aircraft Company in Florida at 400 MHz.[20] Again, the MED model predicts the general decrease of α with distance, as was measured. The EXD model does not.

Figure 7 shows the trend of α versus depth of trees measured by Currie[9,21] in Georgia at 9 and 16 GHz. It is seen that, at the short tree-depths ($0 \leq d_f \leq 14$) reported, the measured values of α actually increase slightly with increasing d_f. Possible reasons for this are discussed in subsection 2.5.2. Because of this observation and the lack of sufficient information to allow development of a general model for loss-versus-distance behavior at these short distances, the decreasing α-versus-distance trend of the MED model was modified for $d_f < 14$ to predict a constant α-versus-distance trend (like the EXD model). This is reflected in Equation 6c.

2.4 VALIDATION OF THE MED MODEL

At end of the previous subsection it was demonstrated that the MED model predicted the trend of differential attenuation, α, versus distance more

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[20] Kivett, J.A. and Diederichs, P.J., PLRS Ground-to-Ground Propagation Test Technical Report (Draft), FR 80-14-6, Hughes Aircraft Company, Fullerton, CA, January 1980.

[21] Currie, N.C., Dyer, F.B., and Martin, E.E., "Millimeter Foliage Penetration Experiments," 1976 IEEE Antennas and Propagation Symposium Record, Amherst, MA, 1976.

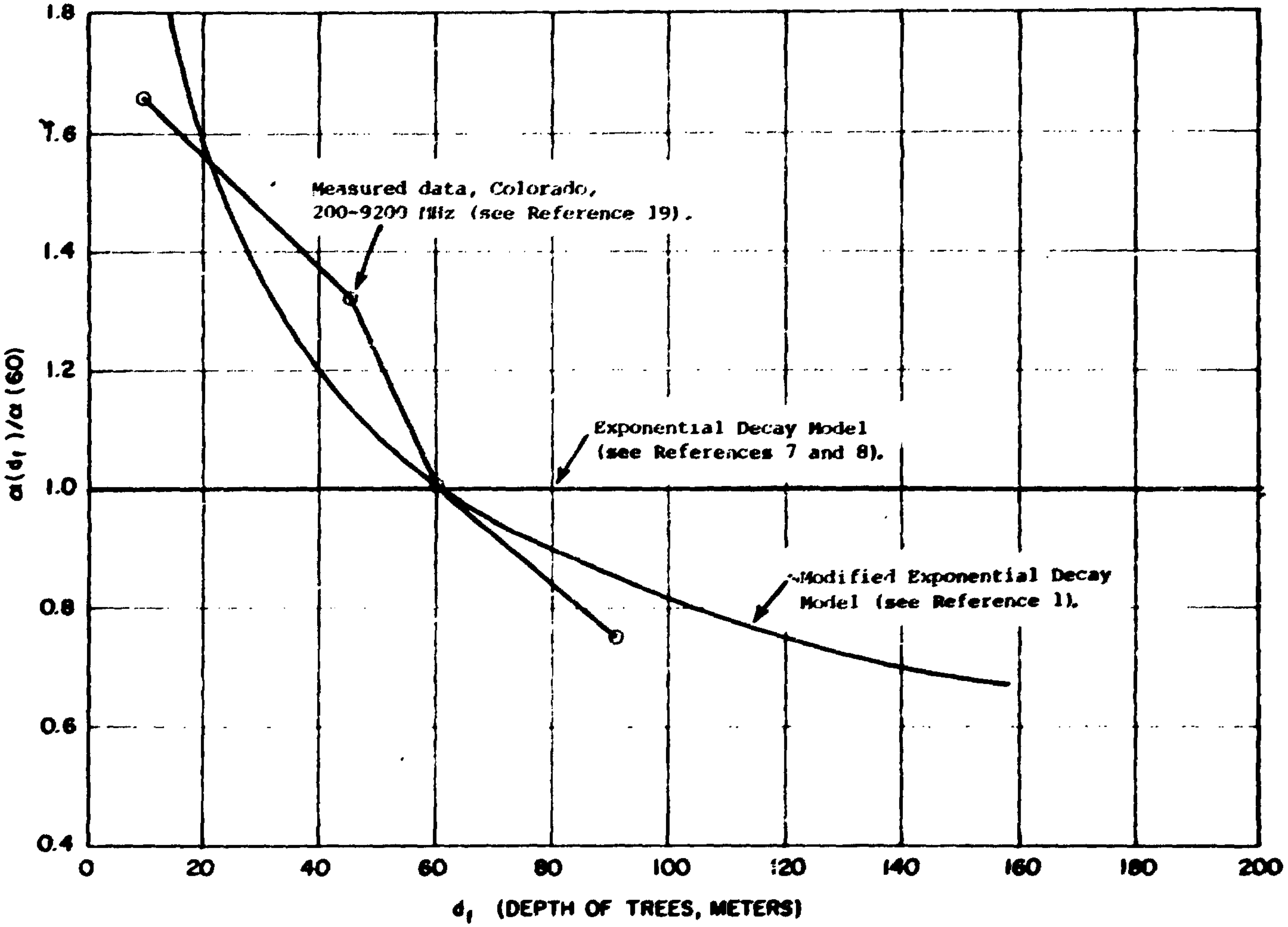

Figure 4. Trend of α vs depth of trees - Colorado measurements compared with the MED and EXD models. The MED equation is based on this set of data.

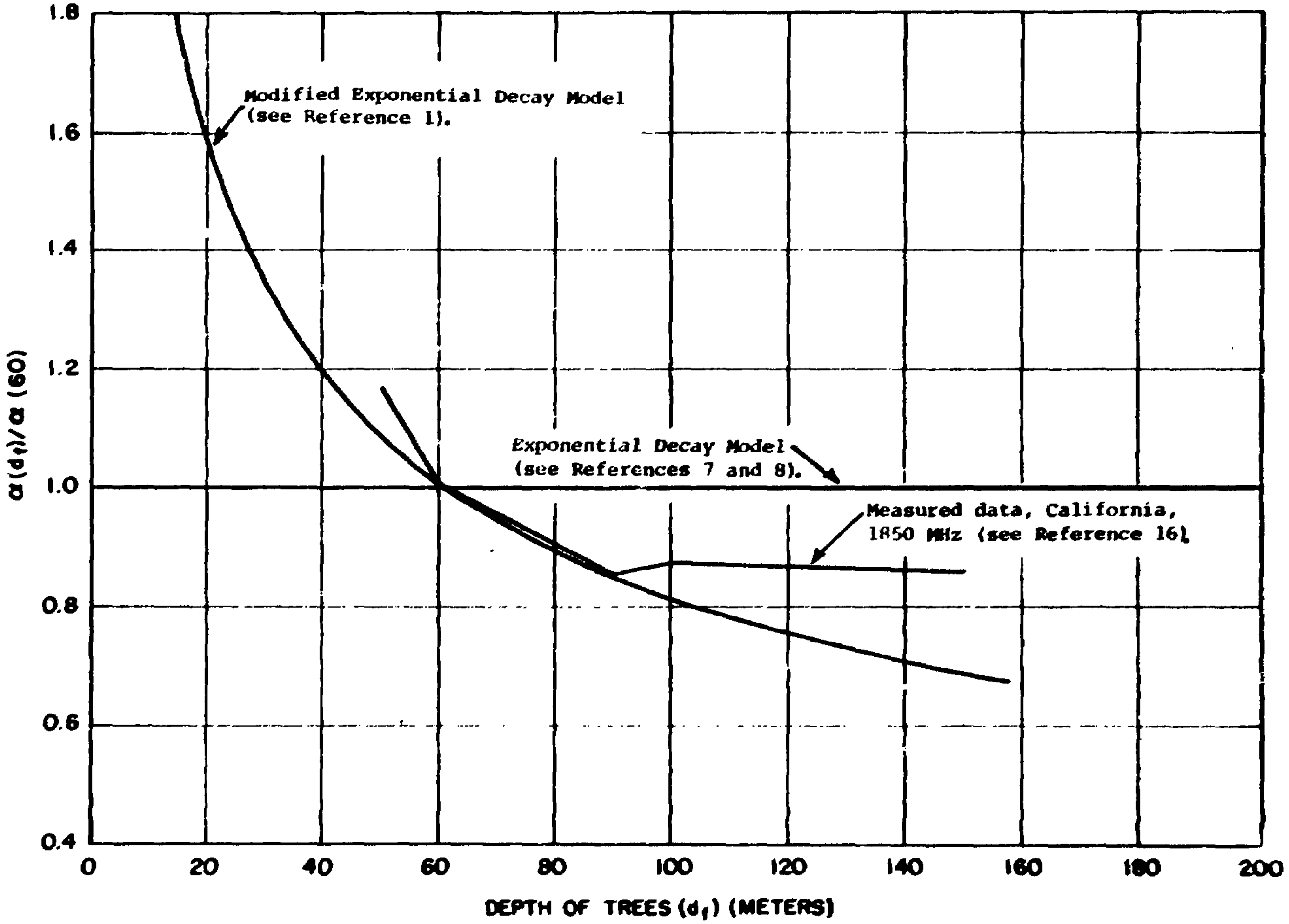

Figure 5. Trend of α vs depth of trees - California measurements compared with the MED and EXD models.

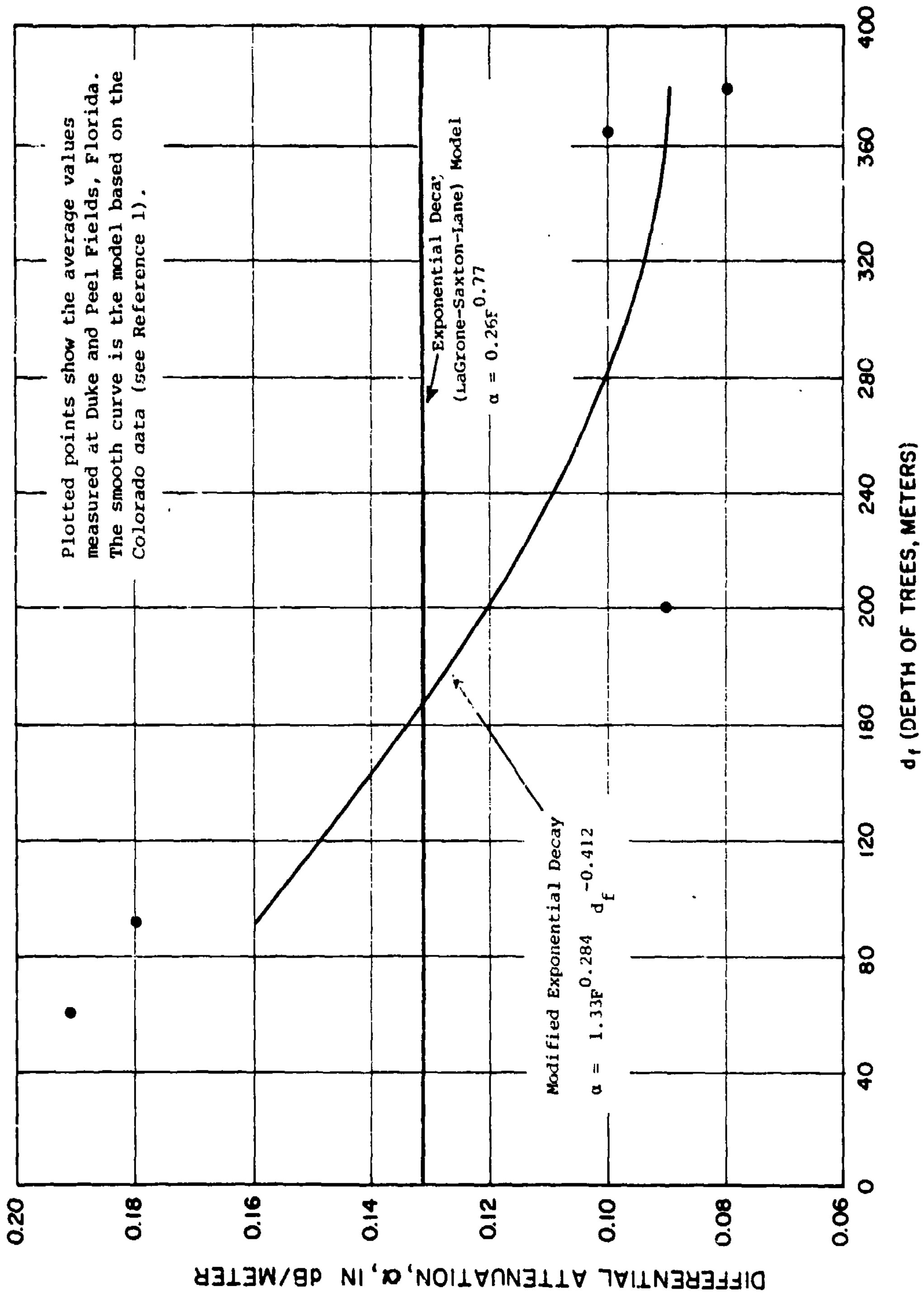

Figure 6. Trend of α vs depth of trees for the Florida data and the EXD and MED equations.

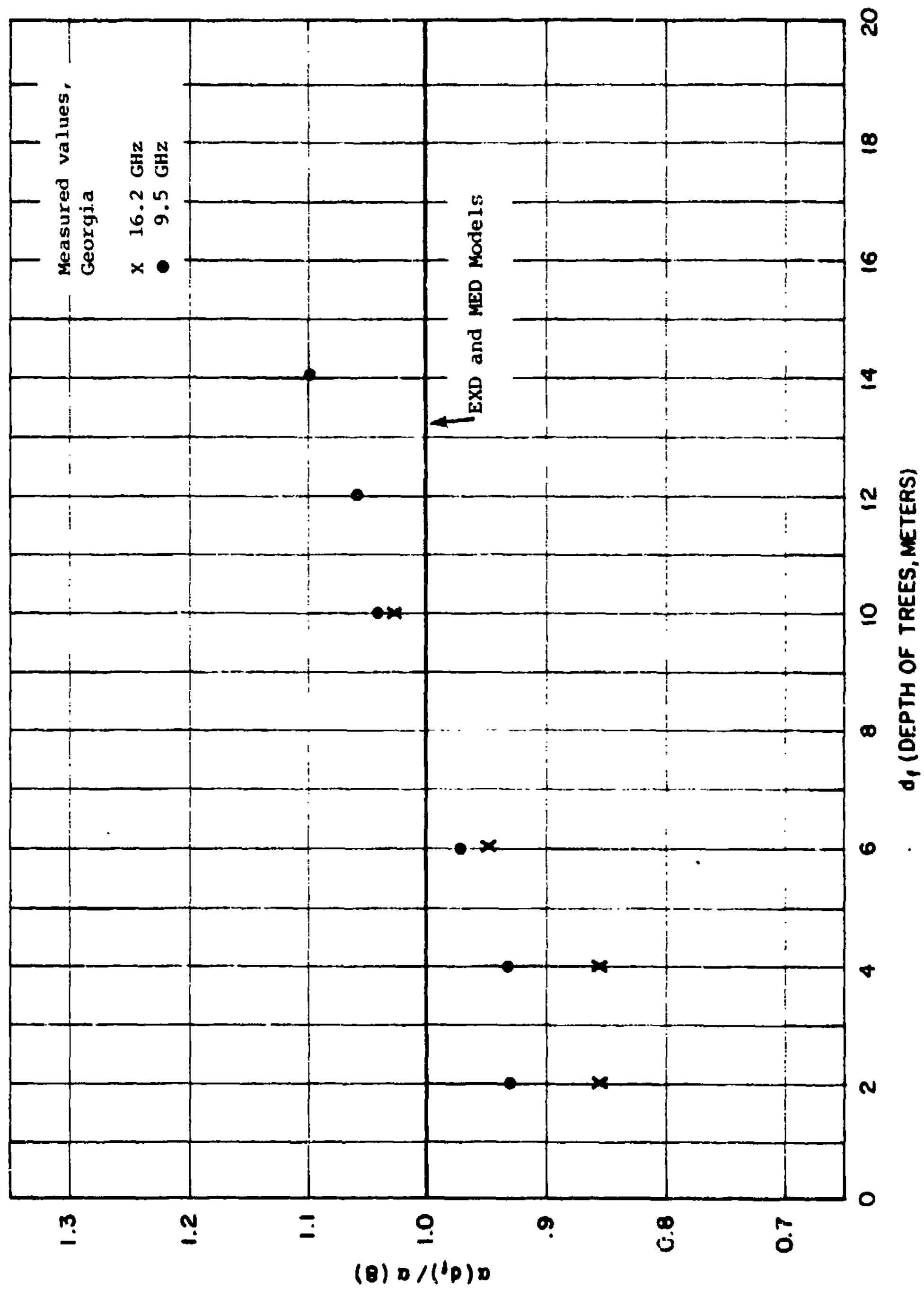

Figure 7. Trend of α vs depth of trees, Georgia data and models. At very small values of d_f like this, there is no evidence that α decreases with distance. Therefore, the slope of the MED model is set equal to the slope of the EXD model at this range.

accurately than the EXD model. In this subsection, comparisons between predicted and measured values of the actual loss will be presented. Loss values for the MED model were computed by multiplying α from Equation 6 by d_f; EXD values were computed by multiplying the α from Equation 5 by d_f. Whereas in the previous comparisons normalization had been done to emphasize the relationship between predicted and measured trend, no such normalization was done in the comparisons shown in this section.

For each data set and each model, a root mean square (rms) error, in dB, is presented. These were computed using Equation 8:

$$\text{rms error} = \sqrt{\frac{\sum_{i=1}^{N} (E_i)^2}{N}} \tag{8}$$

where

N = the number of measurements

E_i = the error in predicting the i^{th} measurement, in dB

= loss prediction $_i$ (dB) - loss measurement $_i$ (dB). (9)

2.4.1 The Saxton and Lane Data - Europe and Pennsylvania, 500-3200 MHz

Figure 8 illustrates the comparison between predictions of the two models and the Saxton and Lane measurements (see TABLE 1) made at frequencies higher than 500 MHz. The rms error of the EXD model is 4 dB. The rms error of the MED model is 2 dB. The fact that the MED model is even slightly more accurate than the EXD model when compared with these measurements is noteworthy, since the EXD model was actually based on this data, whereas the MED model was based on a completely independent set of data.

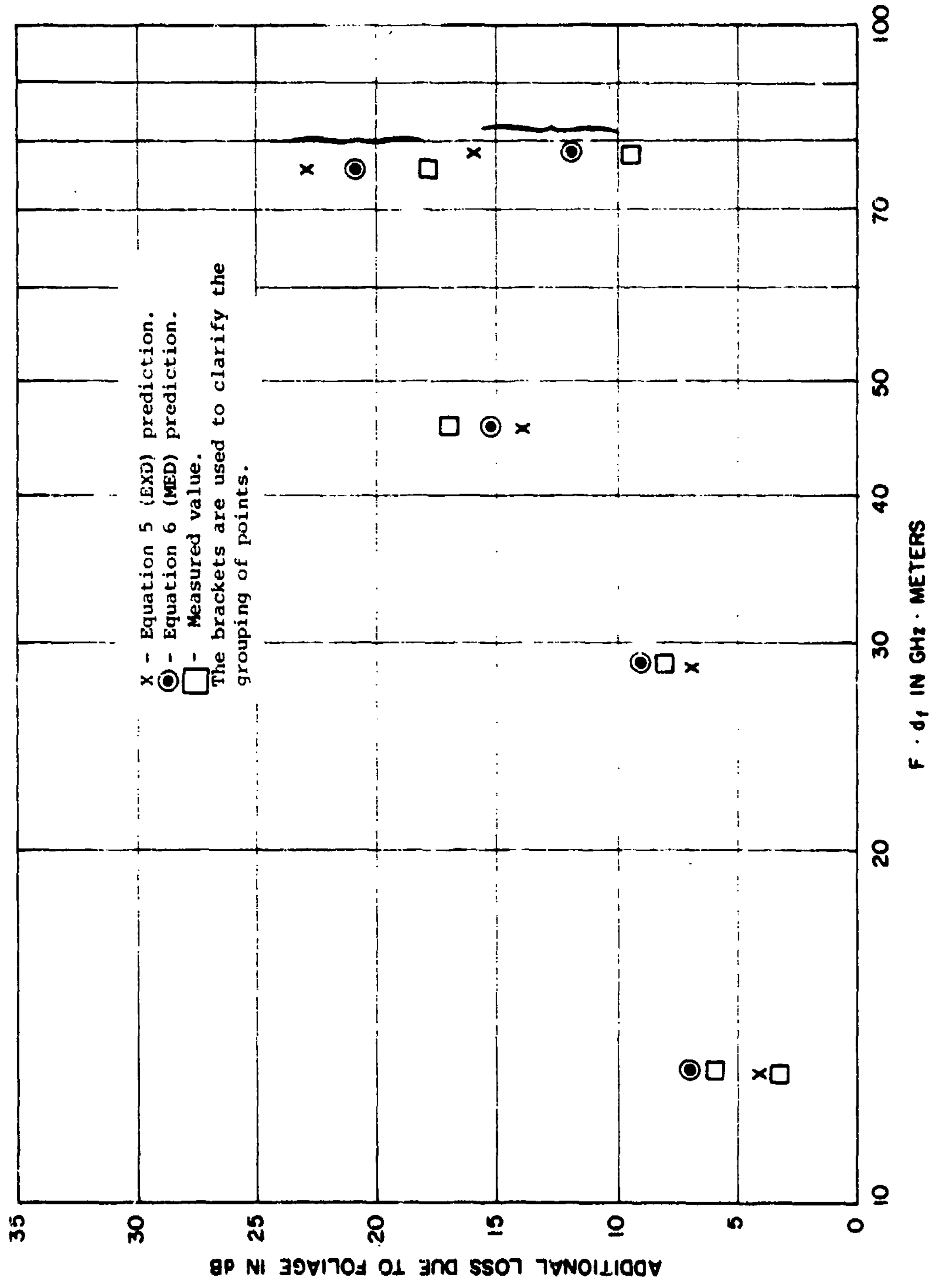

Figure 8. Predicted and measured losses for the Saxton and Lane data.

2.4.2 McQuate's Data - Colorado, 200 - 9200 MHz

Figures 9 through 12 show comparisons between model predictions and McQuate's Colorado measurements. The MED model was based on these measurements. TABLE 5 below summarizes the rms errors.

TABLE 5

RMS ERRORS OBSERVED WHEN THE EXD AND MED MODEL PREDICTIONS WERE COMPARED WITH McQUATE'S COLORADO DATA (230-9200 MHz)

Depth of Trees (m)	RMS Error (dB)	
	MED	EXD
14-15	10	10
45	7	13
60	9	27
91	6	37

It may be noted that while the data used to develop the EXD model varied in frequency from 0.1 to 3.2 GHz and in d_f from 24 to 200, the product $F \cdot d_f$ was always less than 100. In general, the prediction errors of the EXD model occur when $F \cdot d_f$ is much greater than 100. These errors are a consistent prediction of more loss than was measured.

2.4.3 Frankel's Data - California, 1850 MHz

Comparisons between the predictions of the two models and Frankel's California measurements are shown in Figure 13. The rms error for the EXD model is 24 dB and for the MED model it is 7 dB.

Frankel reported measurements at a fifth site. This data is not shown in TABLE 2, nor is it reflected in Figure 2 or 13. The measurement site, Coyote Point Area 2, was covered only sparsely with trees that were separated somewhere between 3 and 5 meters with no intervening underbrush. The

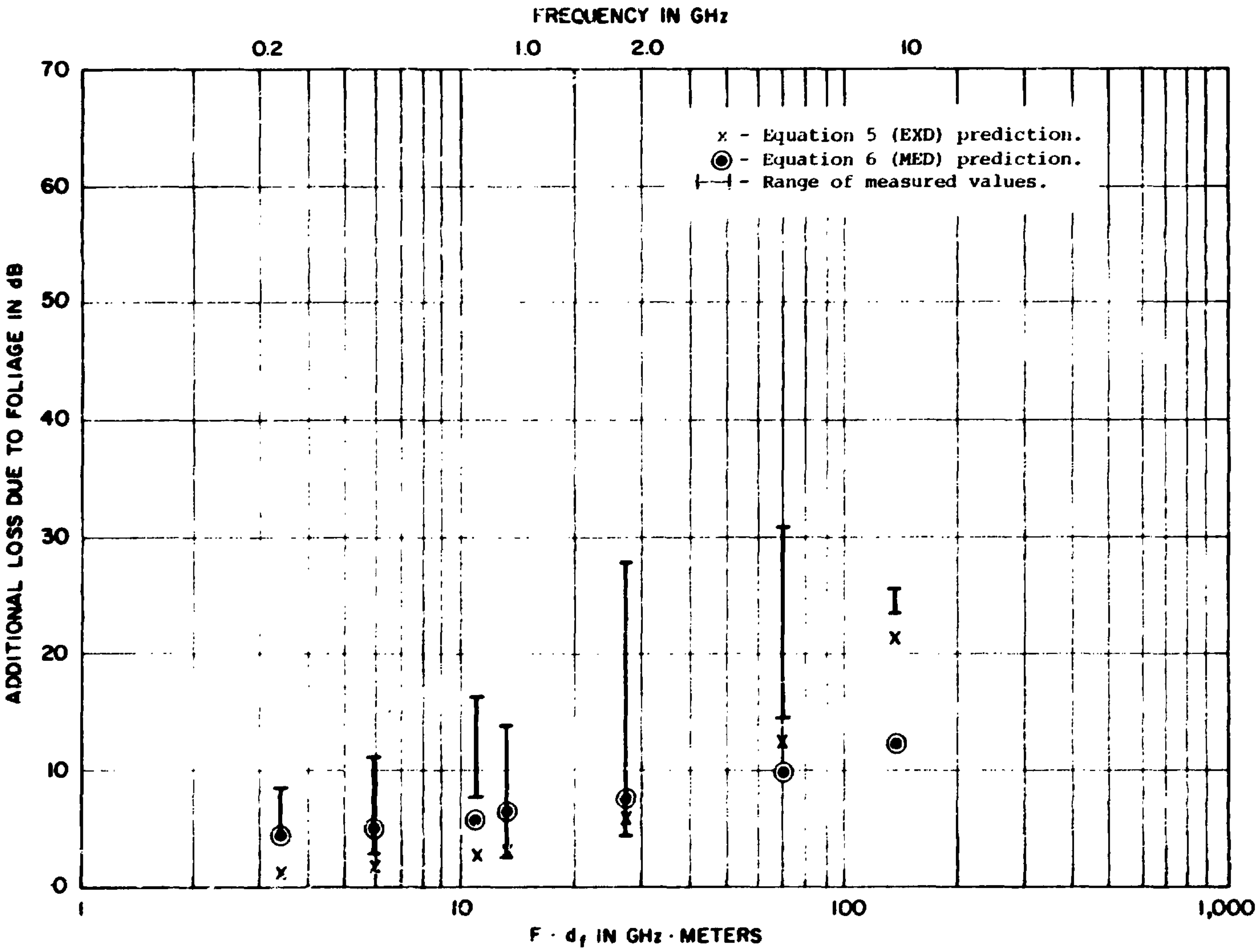

Figure 9. Predicted and measured losses for the 14- and 15-meter Colorado paths. The rms error for both models is 10 dB. The MED model is based on the data shown here and on the next 3 graphs.

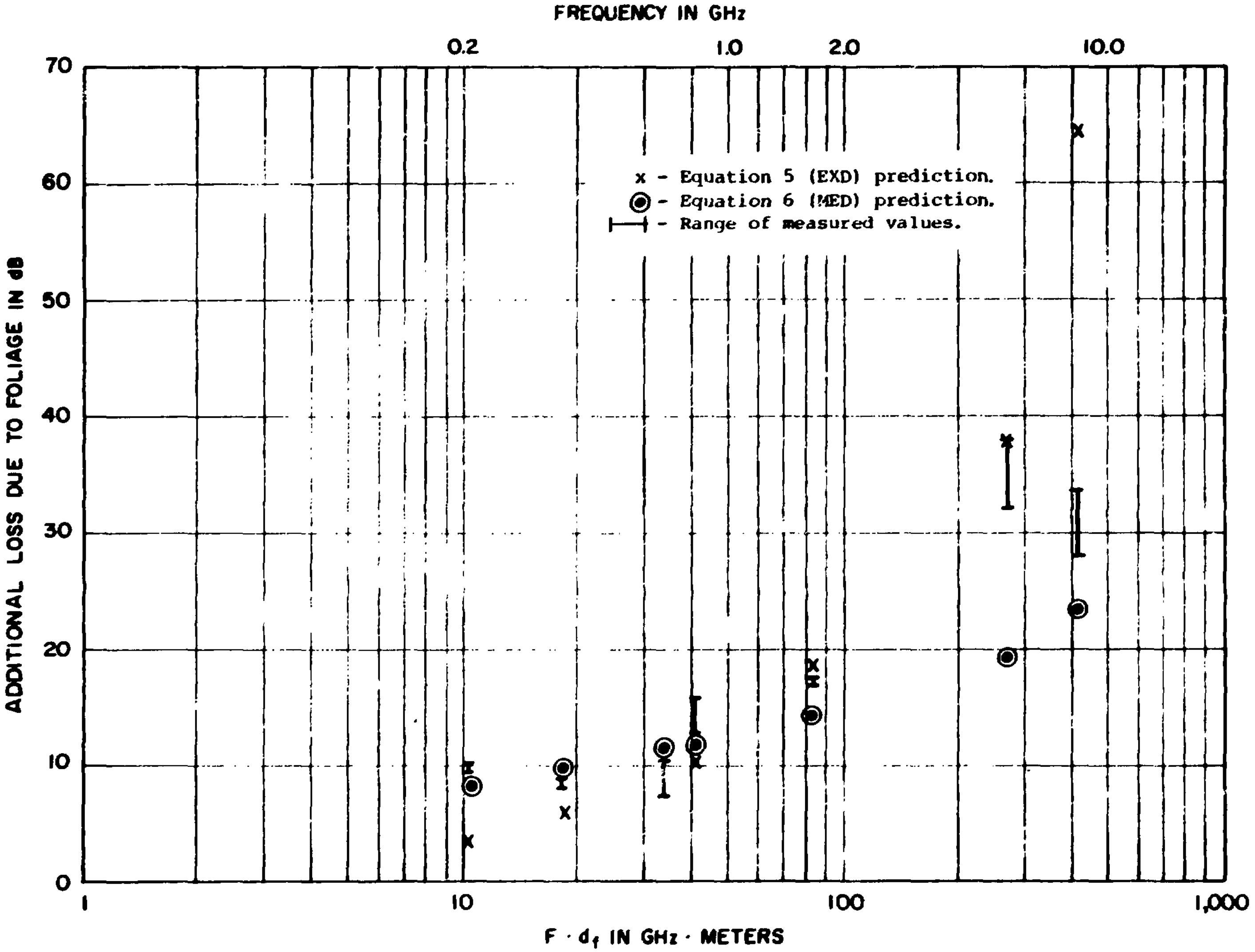

Figure 10. Predicted and measured losses for the 45-meter Colorado data. The rms error of the MED model is 7 dB. It is 13 dB for the EXD model. Note the 35-dB error of the EXD model at 9.2 GHz.

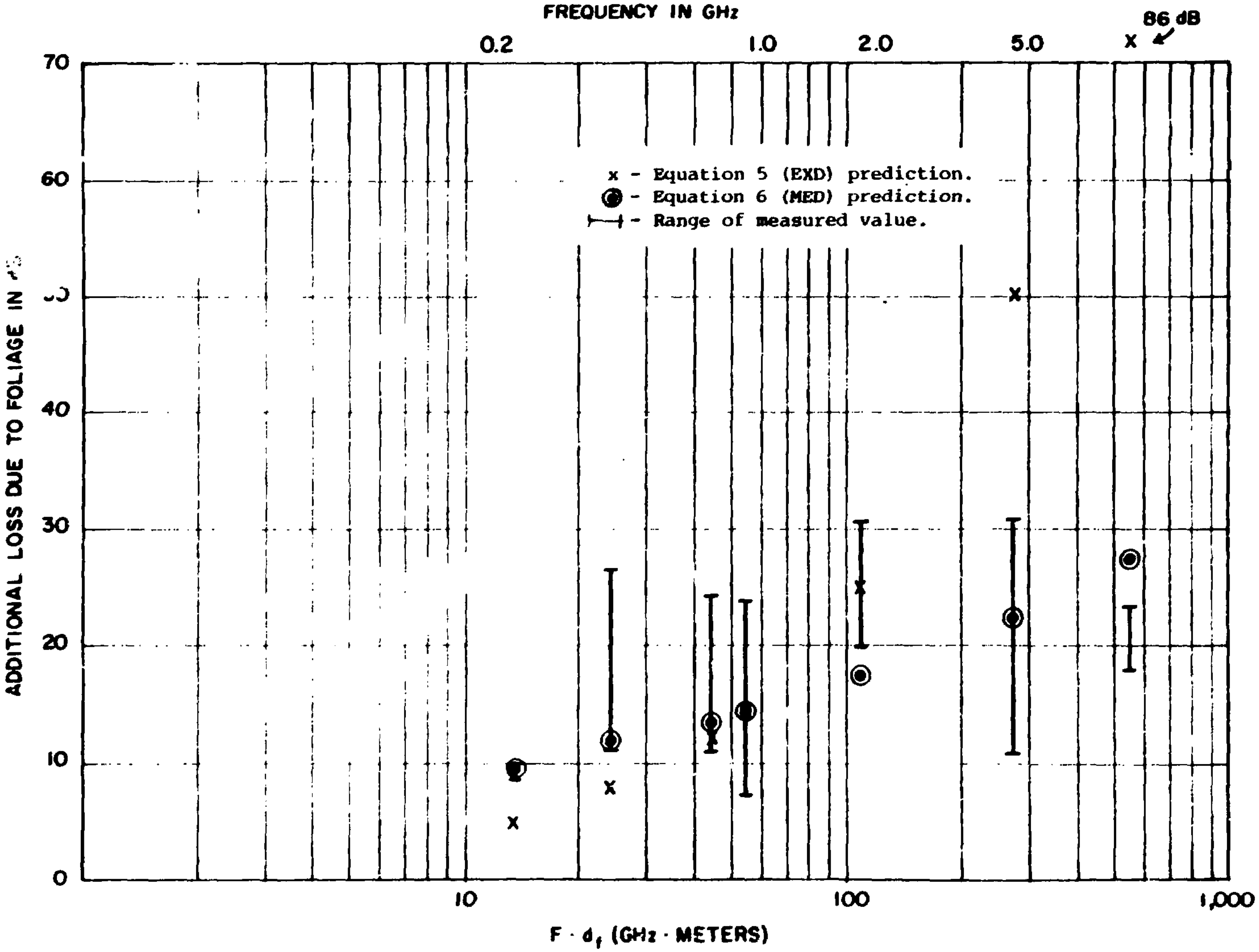

Figure 11. Predicted and measured losses for the 60-meter Colorado data. The rms error of the MED model is 9 dB; for the EXD model it is 27 dB. Note the 30 and 60-dB errors of the EXD model at 4.6 and 9.2 GHz.

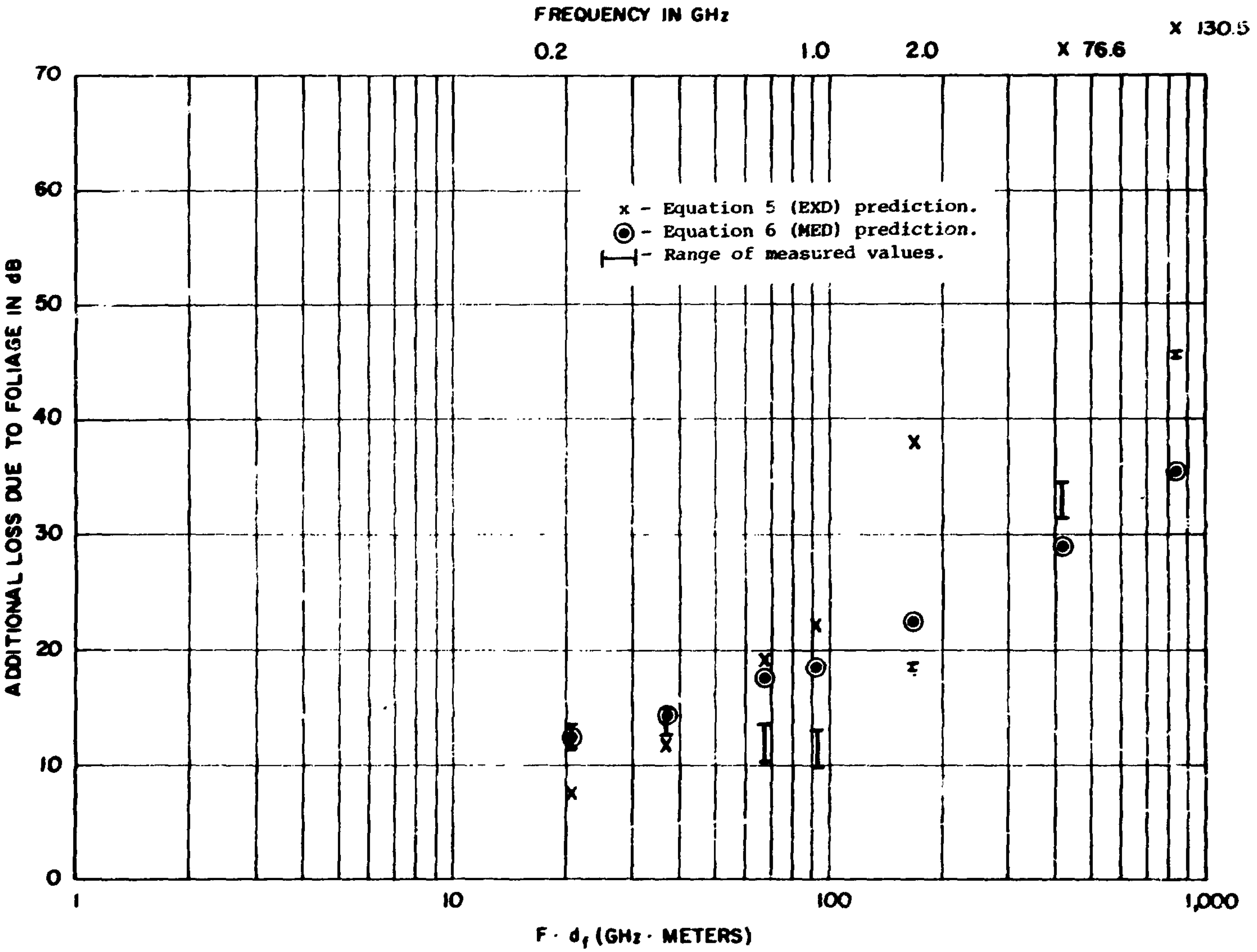

Figure 12. Predicted and measured losses for the 91-meter Colorado data. The rms error of the MED model is 6 dB; for the EXD model it is 38 dB. Note the 35 and 85-dB errors of the EXD model at 4.6 and 9.2 GHz.

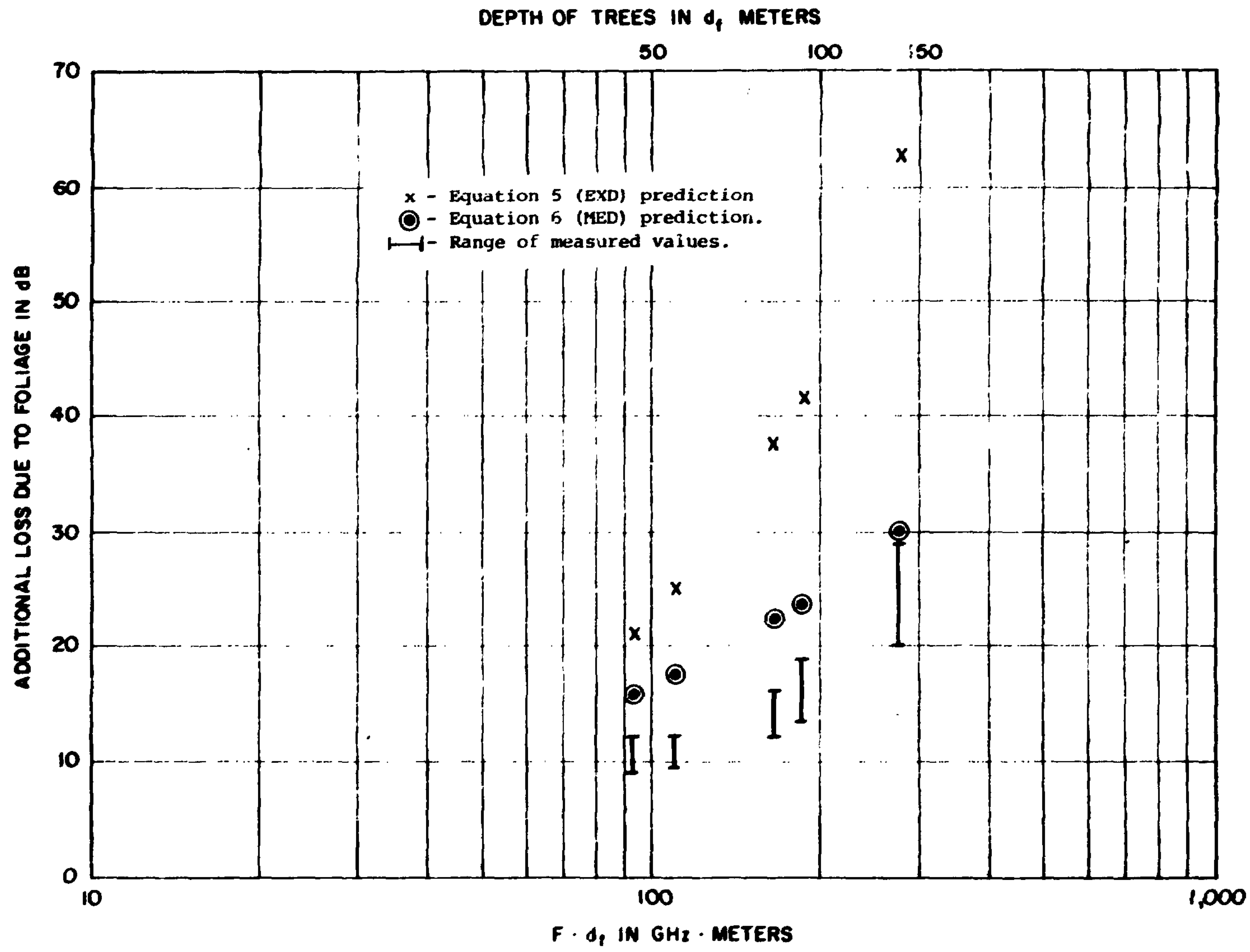

Figure 13. Predicted and measured losses for the California data. The rms error of the MED model is 7 dB; for the EXD model it is 24 dB.

attenuation measured through 150 meters of this sparse vegetation was only 12.8 dB. In contrast, the average attenuation due to 150 meters of foliage at Frankel's other four sites was 24.5 dB. The MED model prediction is 29.3 dB and the EXD model prediction is 62.6 dB. In summary, the MED model should not be used to estimate the loss caused by sparse vegetation, because it will overpredict. (The overprediction of the EXD model would be greater.)

2.4.4 The Hughes Aircraft Data - Florida, 400 MHz

TABLE 6 is a summary of the measurements taken by the Hughes Aircraft Company at two sites in Florida. The model predictions are shown in the same table. The data shown is an average of the data taken at these antenna height combinations: 6.4 - 6.7, 3.7 - 3.7, 1.8 - 1.8, 1.8 - 10.7, 1.8 - 6.7, 0.3 - 6.7, and 0.3 - 6.7 meters. For this data, the rms prediction error of the EXD model is 15 dB. For the MED model it is 8 dB.

Comparisons with measurements at tree depths larger than 400 meters showed that the MED model consistently overpredicted loss. Since the equation was based on data taken for tree depths less than 100 meters, inaccurate behavior at much longer distances is not unexpected. The EXD model was less accurate than the MED model at the large distances.

Comparisons were made with measurements taken at a third Florida site, Basin Bayou, where the tree density was much less than at the other two sites -- 5.1 m^2 of trunk area per acre[a] versus 7.4 and 10.2. Both the EXD and MED equations overpredicted the loss at this site.

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[a] Some physical insight into the meaning of these values may be gained by noting that in another Hughes report, the Basin Bayou area is described as one in which the vegetation was sparse enough so that you could walk through it easily and ride through it, with care, on a two-wheeled vehicle. In the area with the 10.2-m^2 trunk area density, walking would be difficult and riding not possible.

TABLE 6

COMPARISON BETWEEN THE HUGHES AIRCRAFT FLORIDA MEASUREMENTS AND PREDICTIONS[a]

F (MHz)	Depth of Trees (m)	Loss (dB)			Site Description
		Mean Measured[b]	MED Prediction	EXD Prediction[d]	
400	91-99	16.4 (8-23)[c]	14.5	4.7	Peel Airfield, Florida. Slash pine of medium density with light underbrush. Tree trunk density = 7.4 m^2/acre. Tree height = 9.8-12.2 m
	364-371	35.9 (19-41)[c]	32.9	46.7	
400	200-203	18.0 (17-20)[c]	23.1	25.6	Duke Airfield, Florida. Choctawhatchee sand pine, some oak. Tree trunk density = 10.2 m^2/acre (very dense). Tree height = 9.1-10.7 m.
	380-386	31.1 (29-39)[c]	33.1	48.8	

[a] See Reference 20.

[b] Vertical polarization.

[c] Values in parentheses are extremes of measured values.

[d] The rms prediction error of the EXD model is 15 dB. It is 8 dB for the MED model.

Restrictions on the use of the MED model that have been derived from these and other observations are summarized in subsection 2.6.

2.4.5 The Georgia Institute of Technology Data - Georgia, 9.4-95.0 GHz

Currie (see References 9 and 21) reported measurements of the attenuation caused by propagation through deciduous (oak, dogwood, hickory, sweetgum, maple) in-leaf trees, and coniferous (young pine) trees in northern Georgia. TABLE 7 summarizes his results. Currie's data was taken with a radar and reflector. His values of the measured loss have been revised here to account for the assumption that the attenuation for a normal communications link would be one-half of the value measured with a radar. Furthermore, the depth-of-tree values have been revised under the assumption that a straight line between the two antennas would intercept branches along 50% of its length. In his reports, Currie endorses these approximations.

The predictions of the two models are shown in TABLE 7. The rms error of the EXD model is 14 dB while the error of the MED model is 2 dB. It may be noted that Saxton and Lane never recommended use of their empirical model at frequencies greater than 3.2 GHz. However, it was used as a basis for comparison in this 9.4 - 95.0 GHz study, because other authors (see References 9 and 21) have recommended it for use in this range.

2.4.6 Summary of Subsection 2.4

Comparisons of measurements and predictions from the MED and EXD models have shown that the MED model is consistently more accurate than the EXD model. Rms errors of the MED model were (from highest to lowest) 10, 9, 8, 7, 7, 6, 2, and 2 dB. For the EXD model the rms errors were 10, 27, 15, 24, 13, 37, 14, and 4 dB. The measurements all involved blockage of at least one antenna by dry (i.e., not rained upon), dense groves of trees that were either in-leaf deciduous or evergreen. The depth of the groves ranged from 2 to 400 meters. The vegetation was the type found in mid-latitude wooded areas.

TABLE 7

COMPARING MILLIMETER WAVE MEASUREMENTS WITH PREDICTED LOSS VALUES

Frequency (GHz)	Depth of Trees (m)			Type of Loss (dB)
	5	10	14	
9.4	4.5	9.8	14.5	Measured
	4.2	8.5	11.9	MED Prediction
	7.4	14.7	20.6	EXD Prediction
16.2	6.3	13.5	NA[a]	Measured
	4.9	9.9	NA	MED Prediction
	11.1	22.2	NA	EXD Prediction
35.0	8.8	NA	NA	Measured
	6.2	NA	NA	MED Prediction
	20.0	NA	NA	EXD Prediction
95.0	10.3	NA	NA	Measured
	8.2	NA	NA	MED Prediction
	43.3	NA	NA	EXD Prediction

[a] Not available.

The rms error of the MED model for this set of data is 2 dB and of the EXD model it is 14 dB.

Source of measurements: References 9 and 21.

Polarization: Vertical and horizontal were approximately equal.

Description of trees: Deciduous (oak, dogwood, hickory, sweetgum, maple) and coniferous (young pine), North Georgia.

There were three paths for which the MED model, while more accurate than the EXD model, could not be described as being applicable. One involved tree depths greater than 400 meters, and the other two involved sparse vegetation. Further, no attempt was made to compare the model with measurements taken at frequencies lower than 200 MHz.

2.5 FURTHER DISCUSSION OF THE MED MODEL

It has been demonstrated that the MED model is a worthwhile problem-solving tool. Further discussion on the basis of the MED model follows. The topics addressed are:

a. The mode of propagation that is described by the MED model (subsection 2.5.1)

b. The reasons for the loss-versus-distance dependence of the MED model (subsection 2.5.2)

c. The justification of the frequency-dependence of the MED predictions (subsection 2.5.3)

d. The justification of the lack of polarization dependence of the MED model (subsection 2.5.4).

2.5.1 The Mode of Propagation Described by the MED Model

In subsection 2.4, it is demonstrated that the modified exponential decay (MED) model provides a reasonably accurate description of five sets of measurements. In this subsection, supplementary information concerning three of these sets will be presented to demonstrate that the measurements represent instances of propagation (at least initially) through the forest rather than over the forest. This conclusion is used in subsection 2.6 to help define antenna-forest geometries to which the MED model is applicable.

In the Hughes Aircraft Florida (see Reference 20) measurement program, antennas were placed initially (see Figure 14) at opposite ends of a 400-meter grove of trees. Then both antennas were moved away from the trees until

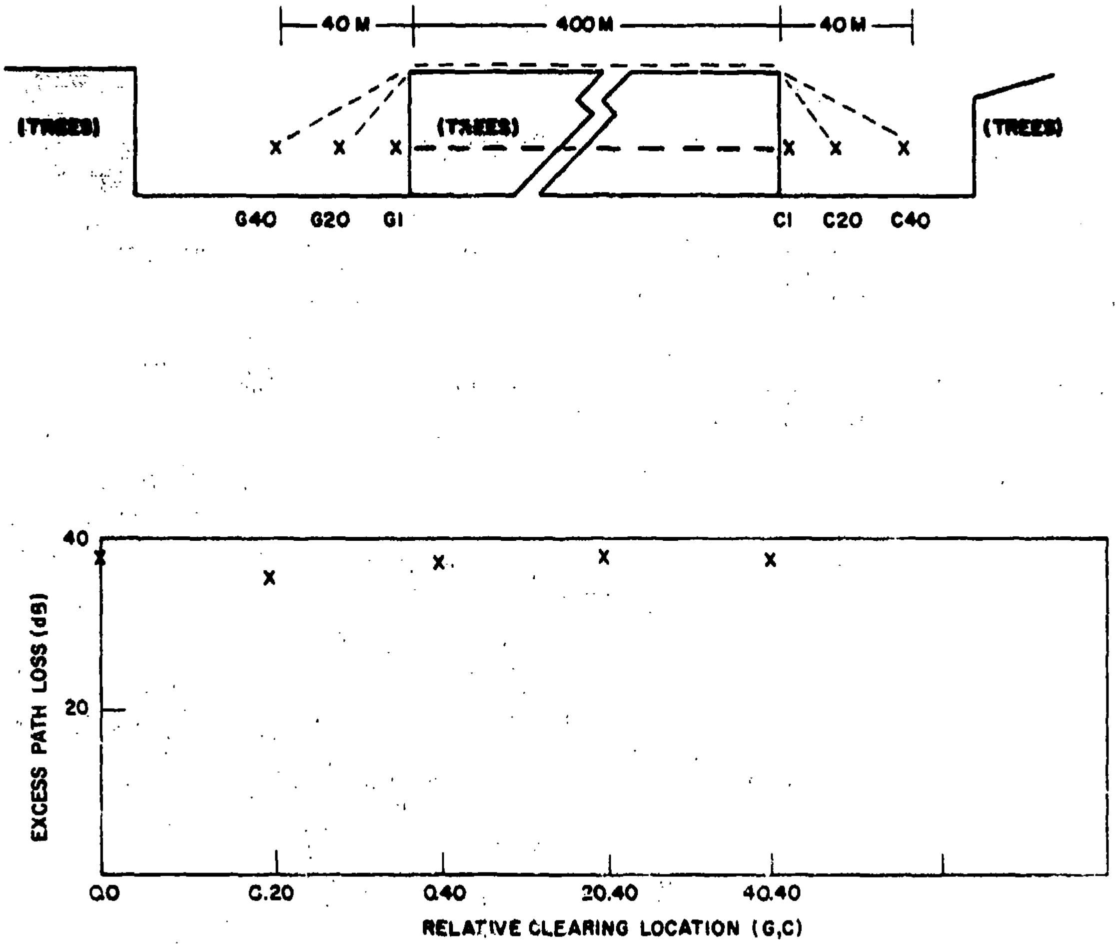


Figure 14. An experiment at 400 MHz (see Reference 20) demonstrating that a particular propagation path starts through the trees rather than over them. If the path started over the trees, increasing the clearing size would have decreased the loss. This does not occur. Since the MED model does predict the measured loss (± 4 dB), this constitutes evidence that the MED model applies to geometries in which the energy flow is, for the part of the ray path nearest to an antenna, through the trees.

40-meter clearings existed at each end of the grove. The loss did not change as the antennas were moved. Had the majority of the energy been propagating over the trees, then the loss would have been reduced by at least 6 dB when the antennas were moved away. This is because the angle over the tree tops through which the rays would have had to diffract would have been significantly reduced as the clearings were enlarged. Since no reduction in loss was observed, this constitutes evidence that the energy propagated primarily through the trees. Signal transit-time measurements taken by Hughes Aircraft confirm this conclusion.

In the California study, Frankel (see Reference 16) changed the mainbeam orientation of the 15-dBi antennas used in the measurements. The greatest received power was achieved when the horns were aimed at each other. Tilting the antennas towards the top of the trees caused a decrease in the received power. Again, this is evidence that the majority of the energy propagated through the vegetation.

The third set of measurements germane to this discussion is the one reported by Saxton and Lane (see Reference 7). Saxton and Lane compared the measured attenuations with the attenuations predicted by diffraction theory. They concluded that the measurements were of propagation through the trees.

Because the MED model provided fairly accurate predictions (rms errors of 8, 7, and 2 dB) of these three sets of measurements, it is reasonable to assume that the MED model describes propagation in which the antenna-forest geometry is such that the power flow is, for the part of the ray path nearest to the an antenna, through the forest.

2.5.2 Notes on the Loss-Versus-Distance Trend

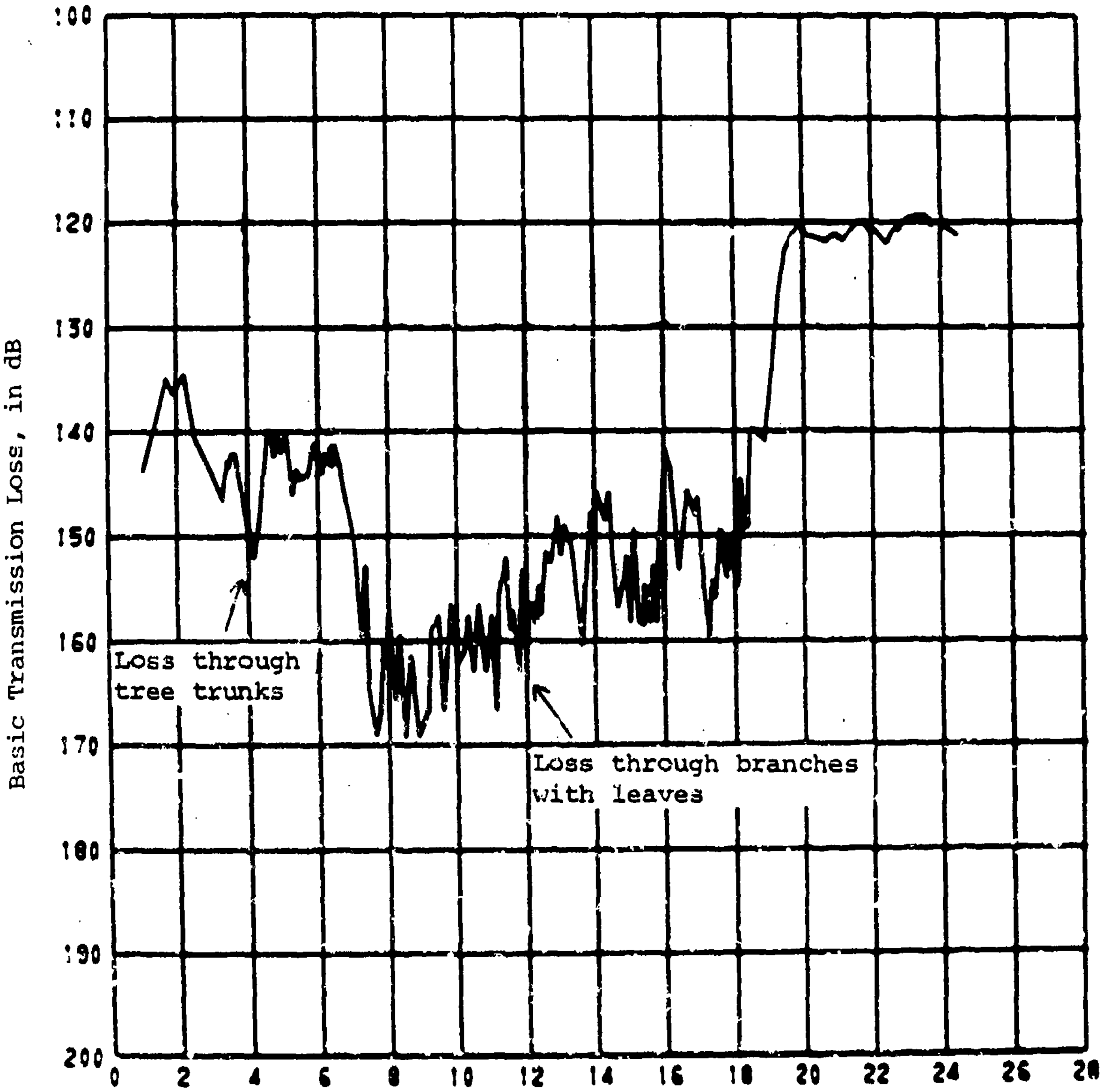
Figures 3 through 6 illustrate that for depths of trees (d_f) greater than about 15 meters, the differential attenuation, α, in dB/meter, decreases as d_f increases. A review of theory (see Reference 12) indicates that this type of behavior does not generally describe propagation through an infinite medium -- whether it is filled with discrete scatterers or a lossy-dielectric continuum. Therefore, it is likely that the decreasing α is due to the finite size of the region that offers the largest attenuation per meter.

It appears that this region of large attenuation per meter is the volume filled densely with in-leaf (or in-needle) branches. Three cases can be cited here to support this statement. One is Frankel's (see Reference 16) vertical polarization data at 1850 MHz. He measured attenuation at a site where there were only bare trunks between the two antennas. Loss values for 60-90 meter tree depths averaged 8 dB for this area in contrast to the 13-dB average for the areas with foliage. Figure 15 illustrates the second case. Here it is seen that as the height of a tree-obstructed antenna is lowered from the branchy region (~ 8 meters) to the bare-trunks region below the branches, the attenuation decreases by 20 dB. In subsection 2.7, data is summarized indicating that the attenuation decreases when leaves fall from the branches. This data constitutes the third case.

Therefore, there are regions of lower loss on top of (i.e., free space) and beneath (i.e., the bare trunk region) the high loss region. It is possible that while the ray path starts in the lossy region of the trees nearest to the antenna, a fraction of the path is in the lower loss regions. As d_f increases, the fraction grows larger and, therefore, the average value of α for the path decreases. The MED model is an empirical description of this decrease.

Kivett's (see Reference 20) 400-MHz measurements involved transit time as well as attenuation. He noted that when the antenna height was lowered from above to below the tree tops, the transit time of the dominant signal increased. This suggests that, for his data, the low-loss route was across the top of the trees.

A formal theoretical explanation of this behavior is not presently available for frequencies greater than 200 MHz. (The lateral-wave model provides one possible explanation for frequencies below 200 MHz and for very dense tropical forests. See Section 5 of this report.)



Antenna Height Above Ground, in m.

Figure 15. An example of the loss caused by propagation through bare trunks being lower than the loss through the branchy region: 9190 MHz, horizontal polarization.[22]

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[22] McQuate, P.L., Harman, J.M., and McClanahan, M.E., Tabulations of Propagation Data Over Irregular Terrain in the 230-9200 MHz Frequency Range, Part IV: Receiver Site in Grove of Trees, OT/TRER 19, Institute for Telecommunication Sciences (ITS), Boulder, CO, October 1971.

Figure 7 (in subsection 2.3) shows that at very short depths of trees (d_f < 14 meters), α increases with d_f. There are two questions to be answered here. First, why does α not decrease with distance? Second, why does α increase with distance? A reasonable answer to the first question is that at the short distances represented in this data, the geometry was not conducive to energy propagating over the top of or underneath the branchy region. This is because these "external" ray paths would have been appreciably longer than the direct ray path. Also, the scattering angle would have been steeper. A possible answer to the second question is that the propagation of energy was taking place through diffusion -- a type of multiple scattering. This phenomenon, according to Ishimaru (see Reference 12), takes place when waves propagate through random scatters that occupy more than about 1% of the total volume. This volume guideline will be met often in forest environments. The effective value of α will increase to an asymptotic value if diffusion is the type of propagation. Diffusion effects may not have been noticed in the Colorado, California, Florida, and Saxton and Lane data sets, because at the larger distances involved in these measurements, two things occur.

1. The difference between the value of α at a specific distance and the asymptotic value of α becomes theoretically smaller as distance increases.
2. The leakage of energy around the densely foliated area could have been enough at the larger distances to dominate the trend of α versus distance.

Another answer to the second question is that for small groves of trees, there were openings in the foliage through which the small wavelength signals could propagate with almost no attenuation.

To reduce errors caused by extrapolation of the decreasing-α-with-distance trend in Equation 6a, the MED model was modified so that α is computed as being independent of d_f for d_f < 14 meters. This behavior is represented in Equation 6b.

2.5.3 Justification of the Loss-Versus-Frequency Trend of the MED Model

The MED model was developed as an empirical means of accounting for the observed dependence of differential attenuation on distance. Comparison of MED Equation 6 with EXD Equation 5 shows that the former predicts that loss will increase with frequency according to $F^{0.284}$, whereas the latter indicates an increase proportional to $F^{0.770}$. Figure 16 illustrates the trends. The magnitude of the difference between these relations can be better appreciated by noting that the MED equation predicts that the loss due to foliage at 4000 MHz will be 130% larger than the loss at 200 MHz. The EXD equation predicts that the increase will be 900%. The question then arises as to why there is such a difference and which is the more realistic model. A hypothesis supporting the MED model is presented. Empirical verification for the hypothesis follows.

It appears that the loss-versus-frequency trend predicted by the EXD model is inaccurate because of the nature of the data on which it was based. This data is the Saxton and Lane measurement set which appears in TABLE 1 of this report. An examination shows that the higher frequency data was measured through smaller tree depths, in general, than was lower frequency data. The effective α's computed from this data were larger at the high frequencies for two reasons. First, the loss due to a fixed amount of foliage becomes greater, in general, as frequency increases. Second, at a fixed frequency, the dB/meter due to a small grove of trees is more than the dB/meter due to a large grove. This is because, as has just been suggested, when the tree depth increases, a higher percentage of energy propagates outside the highly attenuating branchy region. Thus, since tree depth was not considered in the development of EXD Equation 5, the empirically determined exponent of F carried the weight of two different phenomena. It appears that the developers of Equation 5 would have arrived at a smaller (and more generally applicable) value of the exponent of F if they had had access to measurements of signals at many frequencies propagating through a single depth of trees.

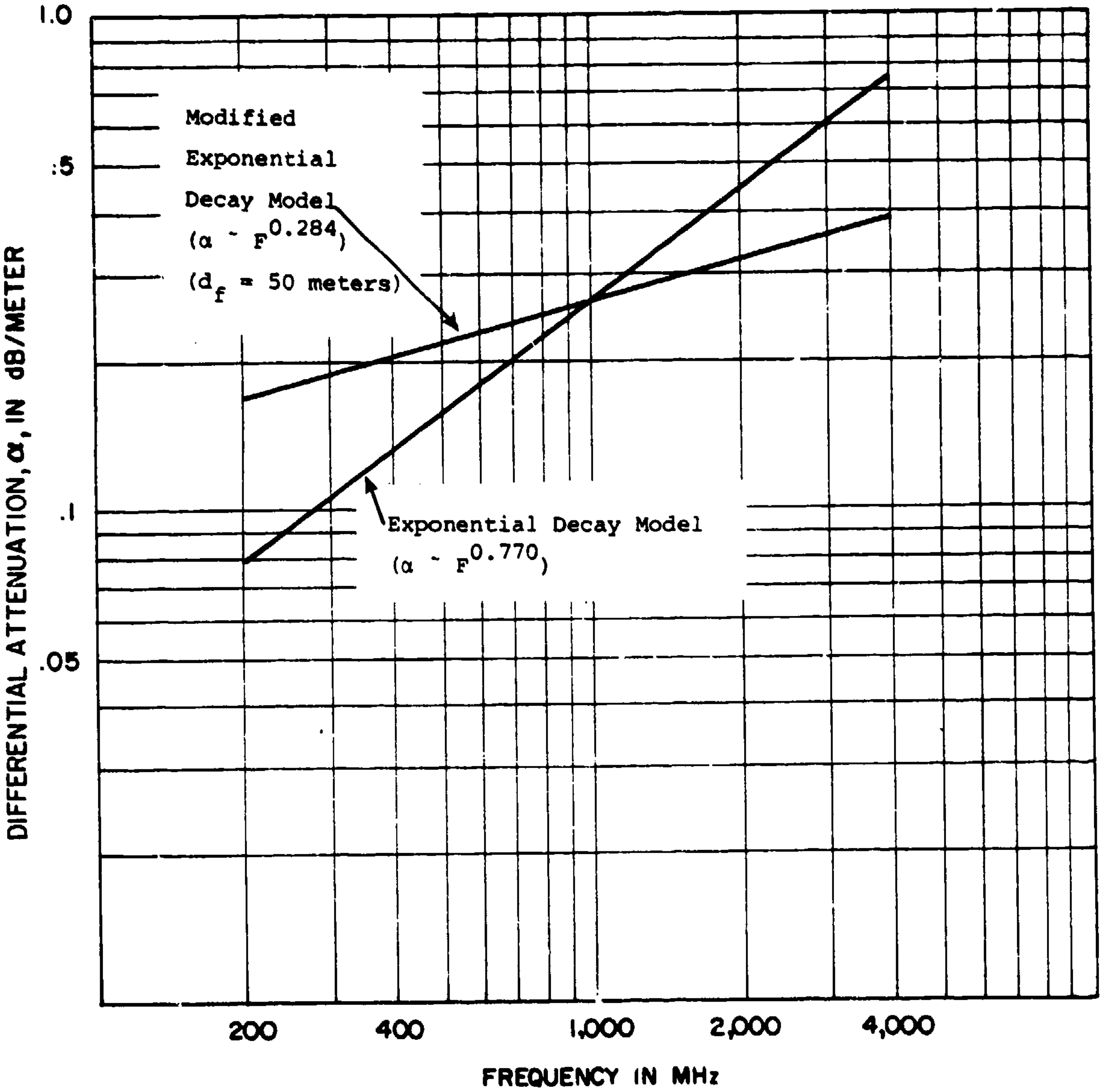

Figure 16. The trends of α vs frequency for the Saxton-Lane-LaGrone EXD model and the MED model. The expression of the EXD model predicts that loss will increase 900% between 200 and 4000 MHz. The MED model predicts a 130% rise over this range. Data studied indicate that the MED model is more accurate.

(Another contributing factor to the discrepancy between the two relationships is the fact that they were developed from data in different frequency ranges. The EXD relations were developed from data at frequencies as low as 100 MHz. The MED relation is based on data at 230 MHz and above. There is some evidence that $F^{0.77}$ is an appropriate relationship at frequencies of 100 MHz and below.[23,24])

Figures 17 through 20 represent empirical support for the hypothesis that, at frequencies from 150 MHz to 95 GHz, the trend of loss versus frequency is better described by $F^{0.284}$ than $F^{0.770}$. A quantitative summary of these figures is provided in TABLE 8. These rms errors were computed using Equation 8. However, each error, E_i, is defined as a percentage using Equation 10 below:

$$E_i(\%) = \frac{\text{Predicted loss (dB)} - \text{Measured loss (dB)}}{\text{Measured loss (dB)}} \times 100\% \qquad (10)$$

Use of percentages prevented the high-frequency (and high attenuation) part of the data from playing an unduely large role in determining the overall error statistics.

A comparison between the $F^{0.284}$ trend of the MED model and frequency trends recommended by other authors (see References 6, 10, 11, and 15) is provided in APPENDIX A.

2.5.4 Justification of the Lack of Polarization-Dependence of the MED Model

The measurements taken by McQuate that form the basis of the MED model were of horizontally polarized signals. It also appears that the model provides a reasonable estimate of the attenuation of vertically polarized signals in mid-latitude woods within the 200 MHz to 95 GHz band. This subsection contains a summary of the observations supporting this statement.

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[23] Hagn, G.H., SRI Special Technical Report 19, SRI, Menlo Park, CA, January 1966, AD484239.

[24] Hagn, G.H., Research Engineering and Support for Tropical Communications, SRI, Menlo Park, CA, 1 September 1962, AD889169.

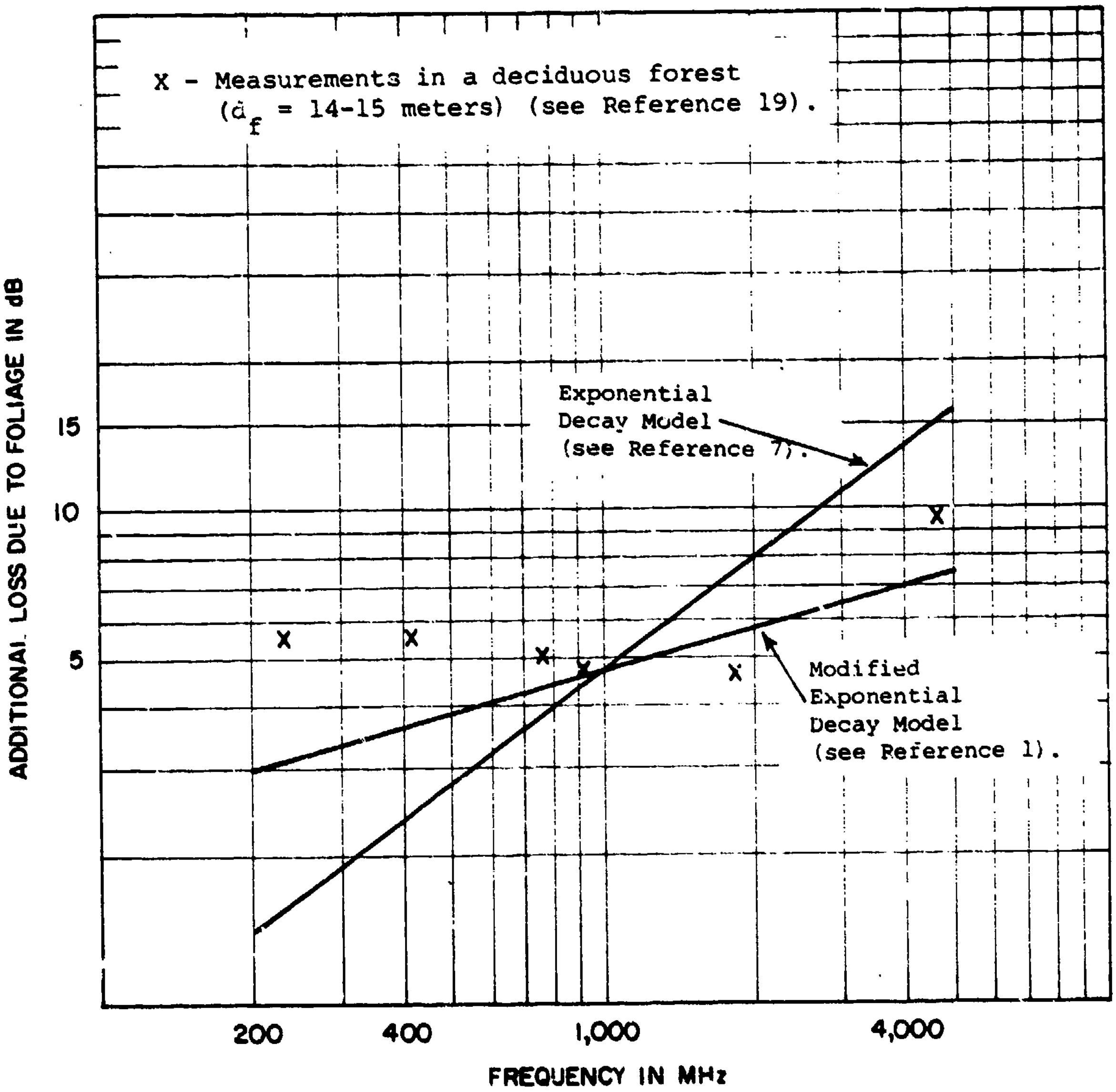

Figure 17. Illustration comparing the trends of loss vs frequency predicted by two models with the measured values of the trend. The rms error of the MED model is 26%. The error of the Saxton-Lane-LaGrone model is 54%.

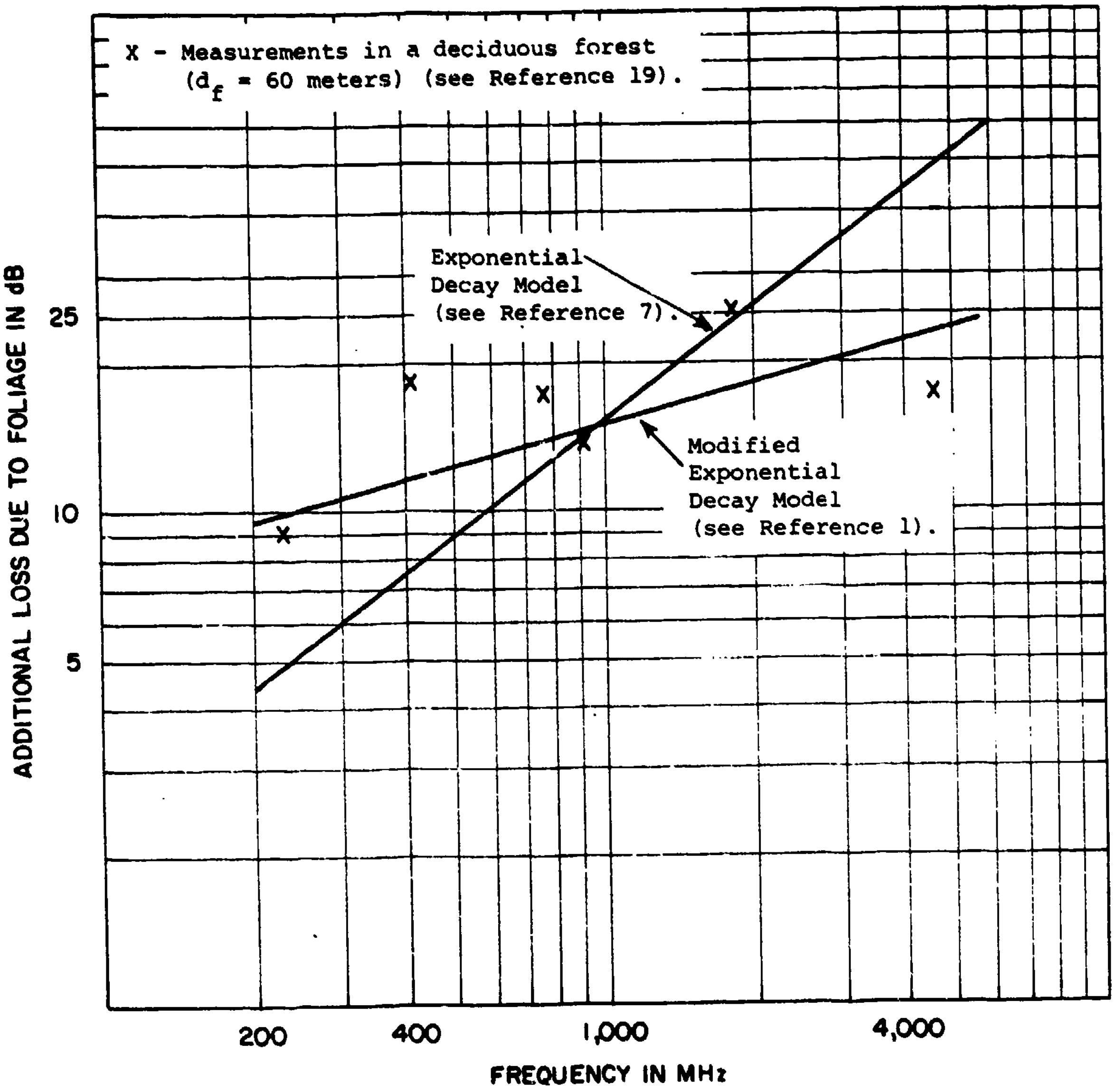

Figure 18. Illustration comparing the trends of loss vs frequency predicted by two models with the measured value of the trend. The rms error of the MED model is 24%. The error of the Saxton-Lane-LaGrone model is 76%.

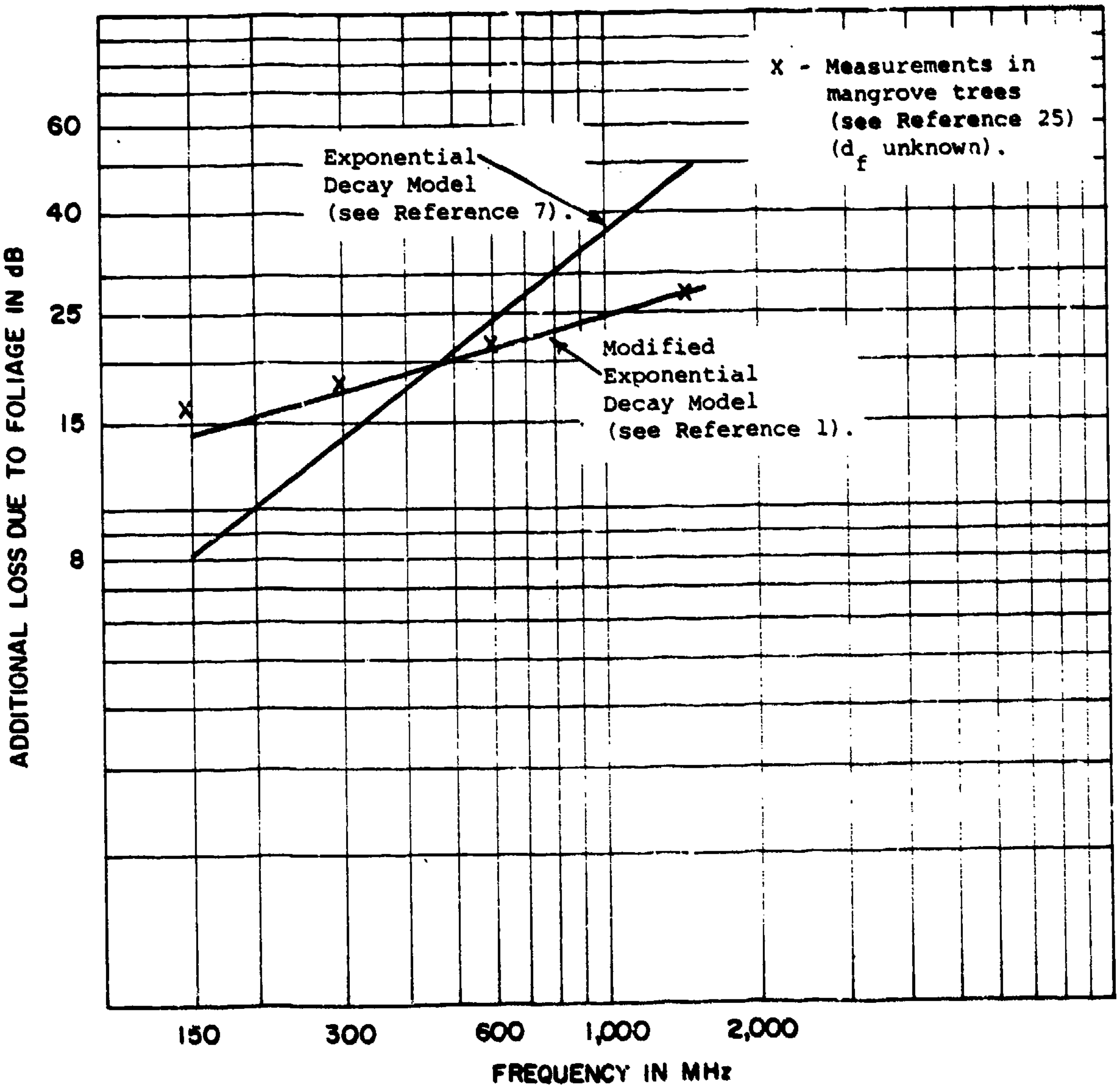

Figure 19. Illustration comparing the trends of loss vs frequency predicted by two models with the measured value of the trend. The rms error of the MED model is 7%. The error of the Saxton-Lane-LaGrone model is 51%. Each plotted measurement was computed from Horwitz's (Reference 25) curves as follows: Additional loss due to foliage = 1/2 (loss inside mangroves + loss behind mangroves - 2 x loss in front of mangroves).

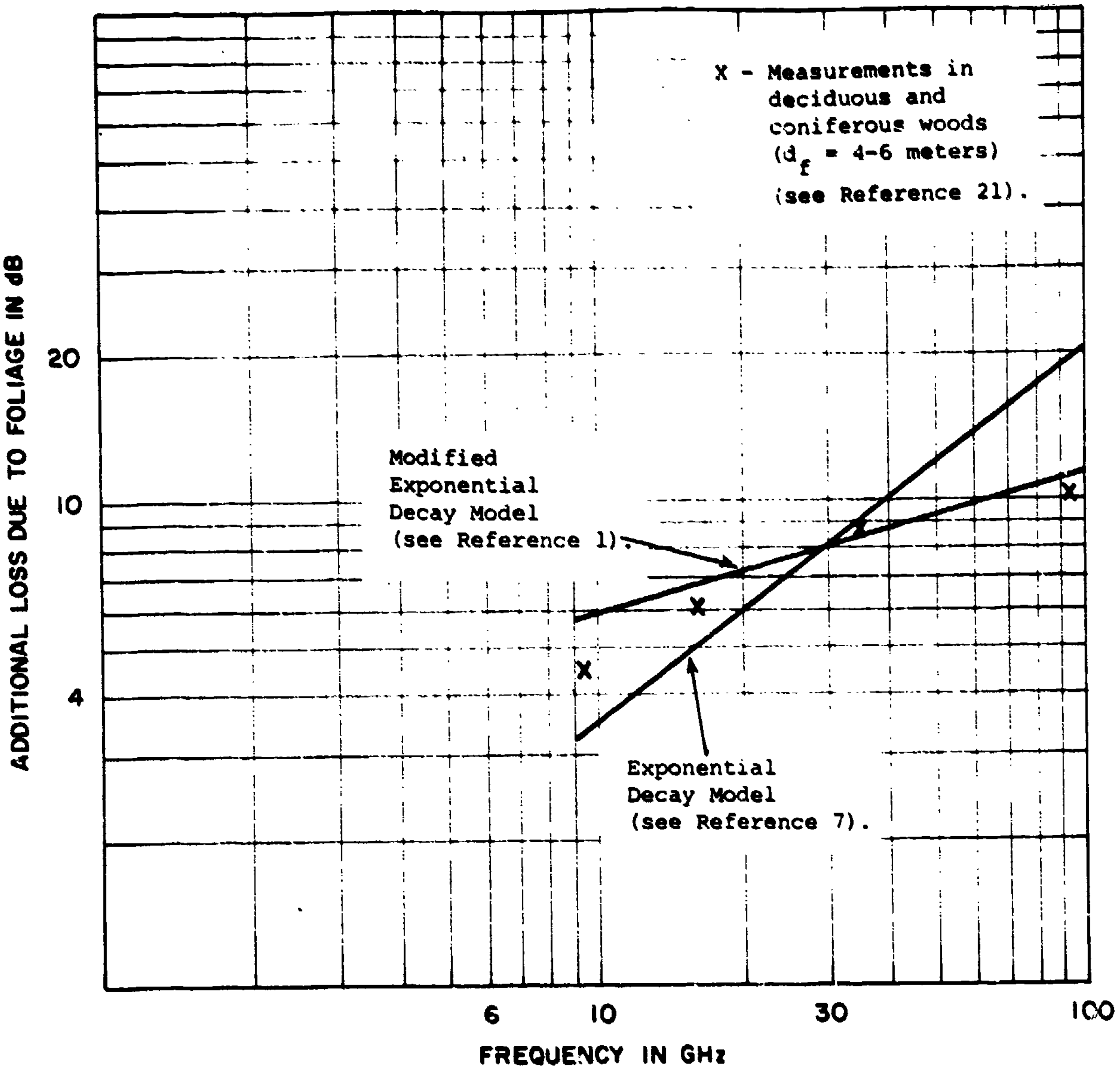

Figure 20. Illustration comparing the trends of loss vs frequency predicted by two models with the measured value of the trend. The rms error of the MED model is 16%. The error of the Saxton-Lane-LaGrone model is 39%.

TABLE 8

A COMPARISON OF THE RMS ERRORS OF THE MED AND SAXTON-LANE-LaGRONE EXD MODELS WHEN THEY ARE USED TO PREDICT LOSS-VERSUS-FREQUENCY TRENDS

Data Description	Models Used	
	MED	Saxton-Lane-LaGrone (EXD)
Deciduous forest, Colorado, 200-4500 MHz, horizontal polarization, d_f = 14-15 m	26%	54%
As above, d_f = 60 m	24%	76%
Mangroves, Australia,[25] 150-1500 MHz, vertical polarization, d_f unknown	7%	51%
Deciduous and coniferous woods, Georgia, 9-95 GHz both polarizations, d_f = 4-6 m	16%	39%
	Rms Error of Predicted Trend	

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[25] Horwitz, C.M., "Optimization of Radio Tracking Frequencies," *IEEE Transactions on Antennas and Propagation*, May 1979.

These include:

1. The model predicts the measurements of vertically polarized signals made by Hughes at 400 MHz (see TABLE 6) and by SRI at 1850 MHz (see Figure 13).

2. The Georgia Institute of Technology researchers observed no difference between the attenuation of the two polarizations in the 9.5-95 GHz band (see References 9 and 21).

3. Saxton and Lane's data summary (see TABLE 1) shows only a 2-dB difference between the polarizations at 540 MHz. The 500 and 1200 MHz data showed no differences.

4. Hughes' measurements[26] at 1 GHz showed that the average difference between vertical and horizontal polarization was 1.5 dB.

As frequency decreases, the difference between the attenuation of the two polarizations increases (see, for example, the 100-MHz data in TABLE 1). This is one reason that it is not recommended that the MED model be used at frequencies less than 200 MHz.

2.6 SUMMARY OF NOTES ON THE APPLICABILITY OF THE MED MODEL

2.6.1 Frequency and Depth-of-Trees Criteria

Figure 21 shows the frequency and depth-of-trees combinations for which Equation 6 (the MED model) has been shown to give reasonably accurate results (rms error 10 dB or less). The model will predict too much loss if the depth of trees is greater than 400 meters or if the frequency is below 200 MHz.

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[26] Hughes Aircraft Company, Final Report - JTIDS Ground Foliage Propagation Tests, Technical Report FR-80-16-503, Fullerton, CA, April 1980.

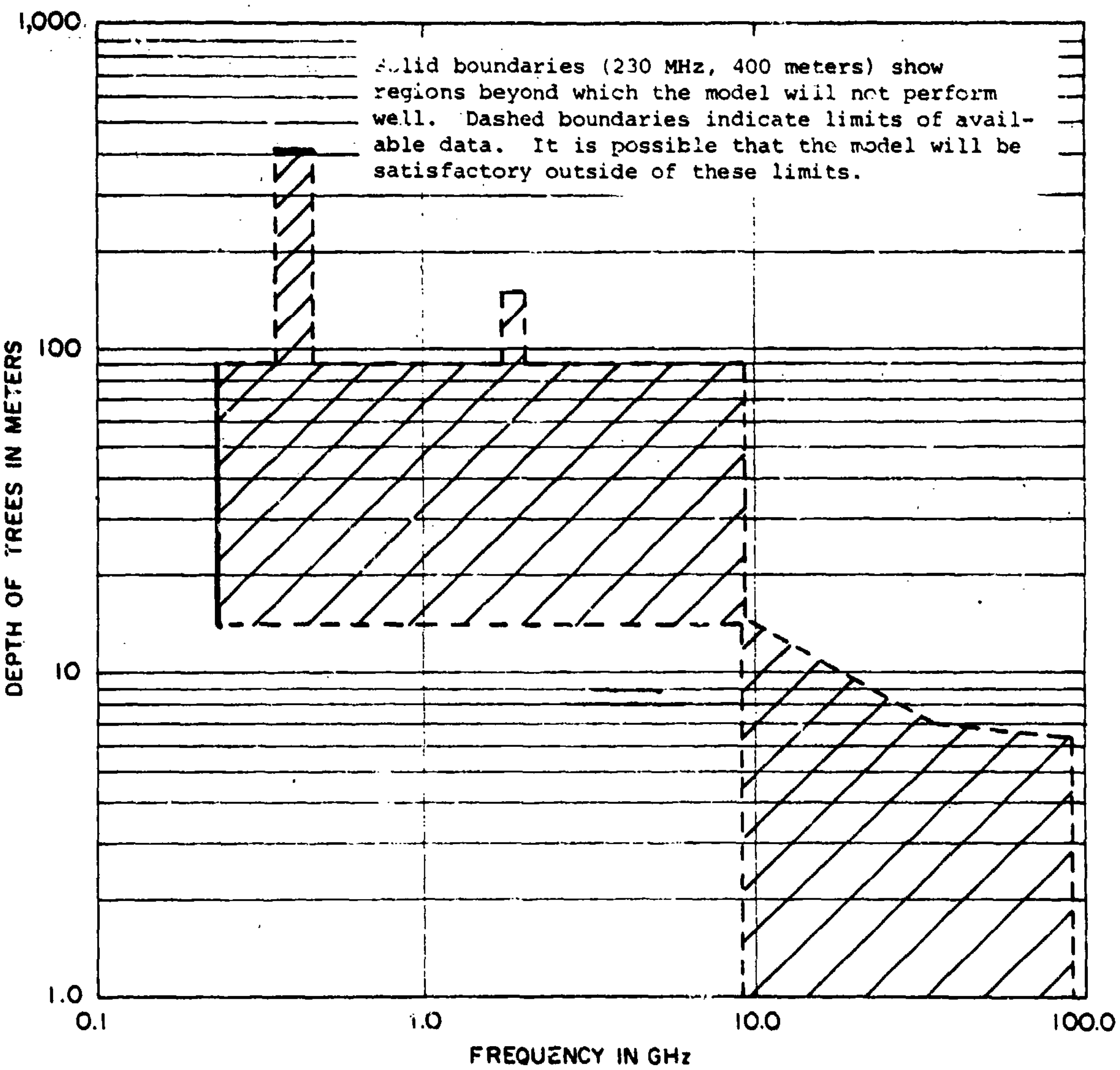

Figure 21. Observed range of applicability of the MED model for temperate forests.

2.6.2 Clearing-Size Criteria

In subsection 2.5.1, it was demonstrated that the MED model applied to problems in which the flow of power was primarily through the forest rather than over the forest. Section 3 of this report will present diffraction models[27,28,29] that apply to the problem of propagation over the forest. This subsection is a discussion of guidelines for determining which type of algorithm is applicable.

The general guidance for predicting which algorithm should be used is this: the MED model will be applicable to problems in which one or both antennas are very near to groves of trees that are less than 400 meters deep. The diffraction model will be applicable to problems in which both antennas are separated by a large clearing from a large grove of trees.

The most accurate approach to determine applicability is to compute the loss using both methods. The more appropriate method is that which results in the lower estimated loss for the particular problem.

A preliminary estimate of the result may be obtained by considering the types of problems for which the MED model has been found to be accurate in the past and the types of problems for which diffraction models have been shown to be accurate. The clearing size is a parameter which can be used to describe the different problems. The measure of clearing size that will be used in this discussion is the take-off angle from the antenna that is nearest the

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[27] Head, H.R., "The Influence of Trees on Television Field Strengths at Ultra-High Frequencies," Proceedings of the IRE, June 1960.

[28] LaGrone, A.H., "Propagation of VHF and UHF Electromagnetic Waves Over a Grove of Trees in Full Leaf," IEEE Transactions on Antennas and Propagation, November 1977.

[29] Meeks, M.L., "A Low-Angle Propagation Experiment Combining Reflection and Diffraction," 1979 International Antennas and Propagation Symposium Digest, 18-22 June 1979.

trees to the tops of the trees. When one of the antennas is immersed in the foliage, for example, this angle will be 90°. As both antennas are moved farther away from the forest, this angle will approach 0°.

TABLE 9 is a list of problems that have been accurately described by either the MED model or by a diffraction model. This table may be summarized as follows -- between 230 and 9190 MHz, MED was the only model to satisfactorily describe loss behavior when at least one of the antennas was close enough to the trees so that the take-off angle from it to the top of the trees was in the 26°-90° range. Each of these two types of models was found to have some application for problems in the 8°-26° range. Only the diffraction models were applicable in the 0°-8° range.

For completeness, it can be noted that there are cases where combinations of propagation through, and diffraction over the trees both take place. In fact, the diffraction model procedures described in Section 3 are actually combination models. They use effective antenna heights which are less than the physical tree heights to account for the fact that there is some propagation through the upper parts of the trees at the edge of the

TABLE 9

MEASUREMENTS THAT HAVE BEEN ACCURATELY DESCRIBED BY EITHER THE MED MODEL OR A DIFFRACTION MODEL

Author	Reference No.	Frequency (MHz)	Clearing size (Take-off Angle, deg)	Better Model[a]
McQuate	19	230 - 9190	9° - 66°	MED
Kivett	21	400	8° - 90°	MED
Frankel	16	1850	90°	MED
Head	27	485	0 - 26°	D
LaGrone	28	82 - 2950	0 - 12°	D
Meeks	29	1090	3°	D

[a]MED = Modified exponential decay; propagation through the trees.
D = Diffraction (knife-edge or spherical); propagation over the trees.

clearing. Longley[30] and the Hughes[26] researchers proposed their own techniques for combining "propagation over" and "propagation through" models. Studies have not been conducted yet to determine which of the two models is more accurate.

2.6.3 Trunk-Density Criteria

The MED model applies to problems in which the ray path is blocked by a dense grove of trees. It was observed (subsection 2.4) that the model was applicable to the Florida data when the trunk density was 7.4 to 10.2 m^2/acre but not for cases in which the density was 5.1 m^2/acre. This was investigated as the basis for developing a quantitative definition of "dense." Using data reported by Doeppner,[31] calculations were done of the approximate trunk density in a wet-dry tropical forest. A value of 3.3 m^2/acre was obtained. Since, as will be shown in subsection 2.7.1 of this report, the attenuation in this type of tropical forest is much larger than in the temperate forests discussed previously, it does not appear that trunk-area density by itself is a useful indicator of the regions where MED Equation 6 will apply. The amount of underbrush, actual number of trunks per unit area, orientation of branches, moisture content of the wood, and type of leaves are all factors of potential significance in determining the general applicability of an MED equation.

Further data related to the correlation between trunk density and loss is provided by Presnell.[32,33]

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[30] Longley, A.G. and Hufford, G.A., Sensor Path Loss Measurements - Analysis and Comparison with Propagation Models, OTR-75-74, Institute for Telecommunication Sciences (ITS), Boulder, CO, October 1975.

[31] Doeppner, T.W., Hagn, G.H., and Sturgill, L.G., "Electromagnetic Propagation in a Tropical Environment," Journal of Defense Research, Winter 1972.

[32] Presnell, R.I., PLRS Ground-to-Ground Propagation Measurements, SRI Project 8171, SRI, Menlo Park, CA, June 1980.

[33] Presnell, R.I., JTIDS Ground-to-Ground Propagation Measurements, SRI Project 8171, SRI, Menlo Park, CA, June 1980.

2.6.4 Antenna-Height Criteria

Since leakage over and under the branchy region of the trees plays a role in determining loss, factors such as antenna height, tree height, and structure of the trees will also affect the loss. At present, there is not enough data to allow development of a general model to account for these factors.

Further data related to the correlation between antenna height and loss in a temperate forest is presented in the Hughes studies (see References 20 and 26).

2.6.5 Polarization Criteria

In light of the discussion in subsection 2.5.4, it is reasonable to recommend the use of the MED model for both horizontal and vertical polarization predictions.

2.7 SUPPLEMENTARY MEASUREMENTS OF THE LOSS CAUSED BY PROPAGATION THROUGH A GROVE OF TREES

In the preceding parts of Section 2, data has been presented which pertains to the attenuation caused by propagation through groves of dry, in-leaf trees in temperate mid-latitude forests. In this subsection, measurements of the loss caused by propagation through groves of trees under other circumstances are cited.

2.7.1 Tropical-Forest Data

Jansky and Bailey researchers (see Reference 5) determined that propagation through short (< 80 meters) distances in a Pak-Chong, Thailand, jungle could be described by the EXD model, Equation 2. At these distances in the 50-400 MHz band, it was found that L_{bo} was L_{bfs}, the free-space transmission loss. Measured values of α are listed in TABLE 10. The vertical polarization data from TABLE 10 is plotted in Figure 22; the horizontal data is plotted in Figure 23. For comparison, Equation 6 is plotted as a dashed line. It is seen that the jungle attenuation is 2 to 5 times larger than the temperate-forest data represented by the equation.

(It is possible that an analysis of the raw Jansky and Bailey data would show that a form of the MED model would be more accurate than the EXD model. Such a study was beyond the scope of this effort. However, it can be noted that the Jansky and Bailey researchers only recommended use of the EXD relation for distances small enough so the $F \cdot d_f$ was less than 32. Figures 8 through 13 indicate that for this range, the MED model is not significantly better than the EXD model -- at least in temperate forests.)

TABLE 10

EXPERIMENTAL VALUES OF α FOR A TROPICAL FOREST

F (MHz)	Depth of Trees (m)	α (= Loss/Depth) (dB/m)	Polarization	Description of Trees[34]
50	$10 < d_f < 80$	0.0	$V \cong H$	Leafy jungle with heavy undergrowth. Median tree diameter is 10 cm. Mean separation between trees is 1.3 m. Total number of trees is 362 per acre. This is a semi-dry tropical forest. Annual average temperature is 80.7° F. Average annual rainfall is 63 inches.
100	$10 < d_f < 80$	0.39 0.17	V H	
250	$10 < d_f < 80$	0.43 0.22	V H	
400	$10 < d_f < 80$	0.48 0.30	V H	

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[34] Hicks, J.J., et al., Tropical Propagation Research, Final Report, Vol. II, Atlantic Research Corporation, Alexandria, VA, November 1969, p. 10. (See also Reference 31, p. 370, and Reference 5, p. 29.)

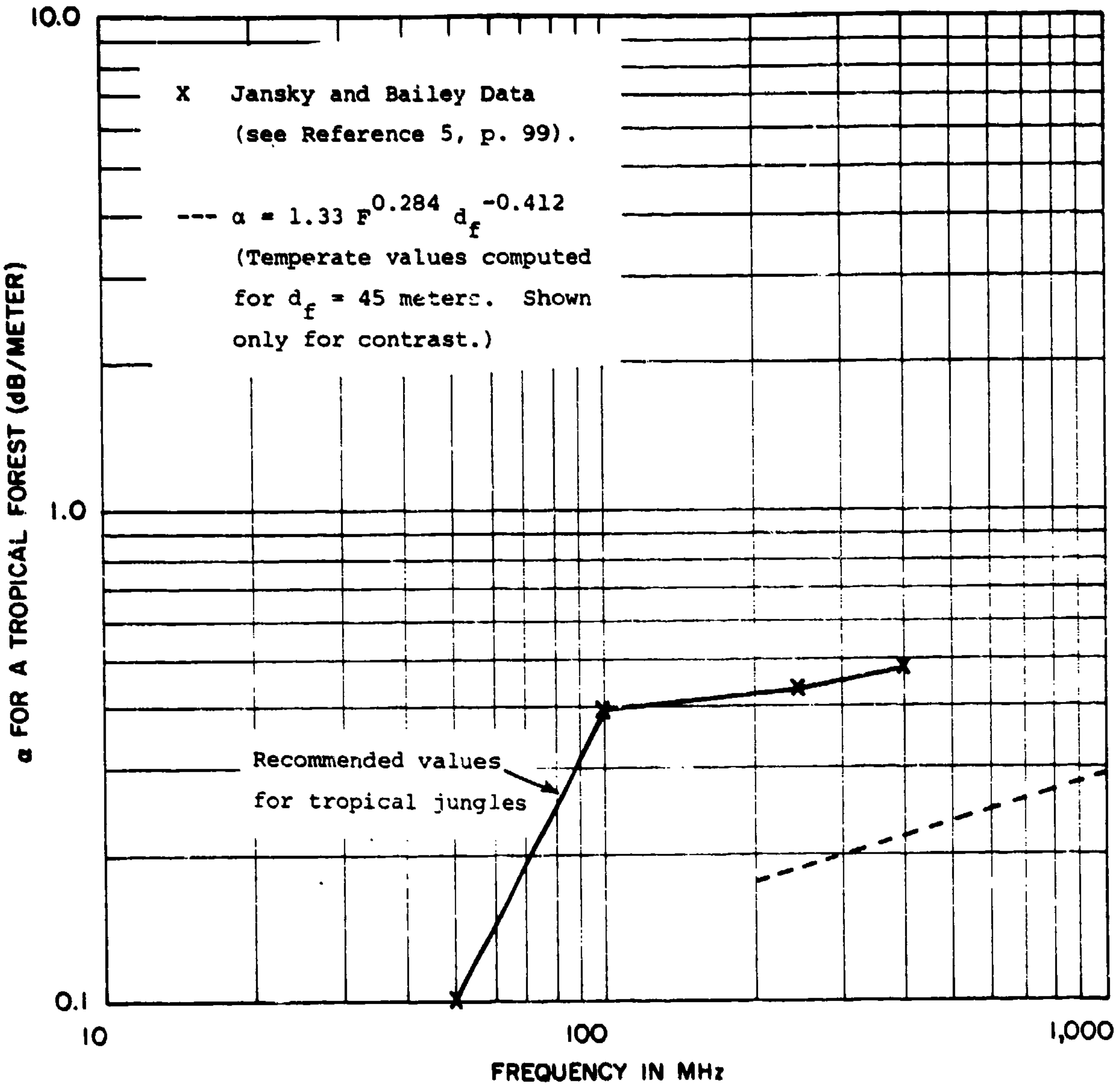

Figure 22. Differential attenuation due to foliage -- tropical jungle and vertical polarization.

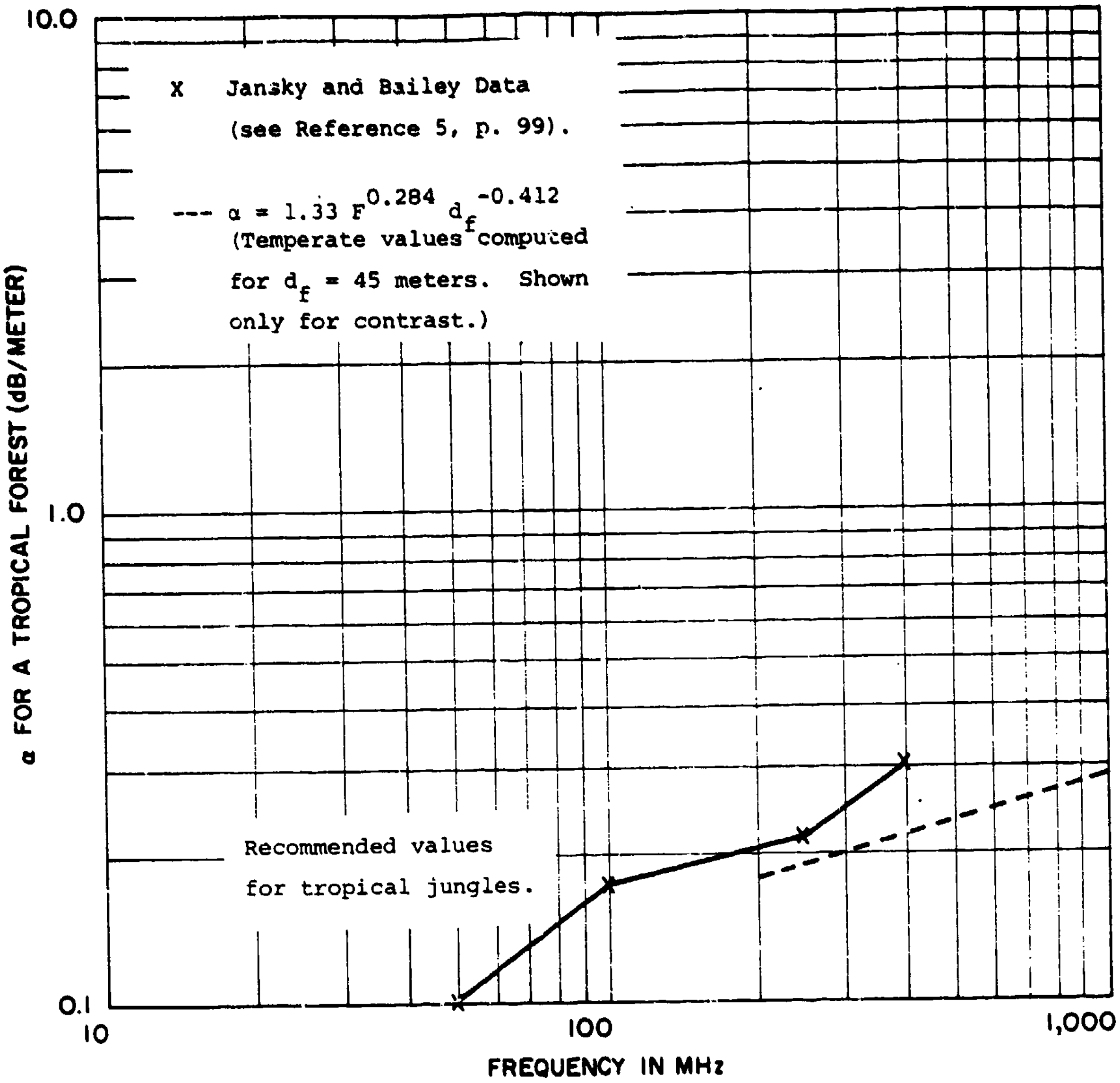

Figure 23. Differential attenuation due to foliage -- tropical jungle and horizontal polarization.

The Jansky and Bailey researchers reported that losses at tree depths greater than 80 meters were less than the EXD model predicted. Section 5 of this report summarizes behavior at these larger distances in the tropical forest.

Section 5 of this report also includes a validation of the Jansky and Bailey empirical model. Although no comparisons were made with data taken at distances less than 80 meters, there were comparisons made with data in the 100-160 meter range. The values of α from TABLE 10 still play a significant role in determining the predicted loss at these distances. A total of eight, 100-160 meter tropical-forest measurements taken at three sites (none of them Pak Chong) were compared with the Jansky and Bailey empirical model predictions. The mean error was -1.3 dB; the rms error was 8 dB. Thus, the values of α shown in TABLE 10 appear to provide reasonable accuracy for predicting attenuation at short distances in tropical forests at Pak Chong and at other sites.

2.7.2 Leafless-Tree Data

Trevor (see Reference 8) found that the attenuation caused by 152 meters of leafless deciduous trees with underbrush at 500 MHz was 15 dB for vertical polarization and 12 dB for horizontal polarization. In contrast, the attenuation for this same grove with leaves was 18 dB for both polarizations. The corresponding effective α's were 0.10 and 0.08 dB/meter without leaves and 0.12 dB/meter with leaves.

At 250 MHz, Trevor found that the attenuation through the same grove of leafless trees was 14 dB for the vertical polarization and 10 dB for horizontal polarization. No data at this frequency was taken for the trees in leaf. However, for comparison, it may be noted that the MED equation indicates a loss of 17 dB due to in-leaf trees at this value of frequency and depth of trees. Sofaer and Bell[35] reported the data listed in TABLE 11.

TABLE 11

LOSS DUE TO IN-LEAF TREES VERSUS LEAFLESS TREES

Description Of Trees	Freq. (MHz)	Pol.	Additional Loss (dB)	
			In Leaf	Few Leaves
Large Grove	50	V	~0	~0
	200	V	9	5
	750	H	19	15
Single Row	50	V	~0	~0
	200	V	3	~0
	750	H	5.5	3

The Federal Communications Commission (FCC) reported[36] that the additional loss caused by leaves was 4.5 dB at 450 and 950 MHz. Values of the depth of trees and of the comparable loss without any trees were not reported. More data with these limitations appears in Reference 22.

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[35] Sofaer, E. and Bell, C.P., "Factors Affecting the Propagation and Reception of Broadcasting Signals in the UHF Bands," Proceedings of the IEE, London, England, July 1966.

[36] International Radio Consultative Committee (CCIR), Methods and Statistics for Estimating Field-strength Values in the Land Mobile Services Using the Frequency Range 30 MHz to 1 GHz, Doc. USSG 5/D-11, 1981 (Submitted by the FCC).

2.7.3 Data for Trees After a Rainstorm

The attenuation caused by propagation through a grove of trees that is wet from rain is an important factor in determining system performance. Only a small amount of data has been reported. This includes the following.

a. At 400 MHz, rain on 1000 meters of trees increased the attenuation by 4 dB (see Reference 20).

b. At 1000 MHz, rain on 200 meters of trees increased the loss by 20 dB at low antenna heights. When the antennas were raised so that the energy propagated across the top of the forest, the loss did not change when it rained (see Reference 26).

c. The increase in loss in the 9.4-95 GHz band varied from 14 to 50 dB. TABLE 12 is a summary of this data (see Reference 9).

TABLE 12

THE ATTENUATION DUE TO WET TREES IN LEAF[a]

F (GHz)	Loss Due to Foliage (dB)		Polarization	Description	Depth of Trees (m) (Approximate)
	Wet	Dry			
9.4	19.0	4.5	V ≅ H	Deciduous trees (oak, dogwood, hickory, sweet-gum, maple); North Georgia.	5
16.2	25.5	6.3	V ≅ H		5
35.0	30.9	8.8	V ≅ H		5
95.0	60.6	10.3	V ≅ H		5

[a] See Reference 9, Figures 21 and 22.

2.8 SUMMARY OF SECTION 2

If a transmitted signal propagates through a grove of trees d_f meters deep, the mean received power can be estimated with this equation:

$$\boxed{P_R = P_T + G_T + G_R - L_{bo} - \alpha d_f} \qquad (2)$$

It has been shown, that for propagation through the branchy region of dry temperate forests with trees in leaf, the attenuation coefficient, α, can be computed by this MED equation:

$$\boxed{\begin{aligned} \alpha &= 1.33\ F^{0.284}\ d_f^{-0.412} & 14 \le d_f \le 400 \\ &= 0.45\ F^{0.284} & 0 \le d_f < 14 \end{aligned}} \qquad \begin{aligned} (6a) \\ (6b) \end{aligned}$$

Equation 6 was developed from measurements of the attenuation caused by propagation through deciduous trees in Colorado. Comparisons with measurements demonstrated that this equation is more accurate than the commonly reported EXD equation:

$$\alpha = 0.26\ F^{0.77} \qquad (5)$$

The data examined in the comparison was taken in England, Pennsylvania, California, Georgia, Florida, and Colorado.

The MED equation was shown to be applicable in the 230 MHz to 95 GHz[a] frequency range and for groves of trees as deep as 400 meters. Figure 21 shows the frequency-depth combinations that were examined.

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[a] As final typing of this report was being completed, a study prepared by E. J. Violette of the Institute for Telecommunication Sciences was received. TABLE 4.3 of the document, CECOM-81-CS020-F, June 1981, contains measurements of α at 9.6 - 57.6 GHz. The trends of these values as a function of F and d_f are quite close to those predicted by MED Equation 6. However, the actual values are notably larger than the predictions. They are also larger than Currie's and McQuate's measured values in this frequency range. A study to resolve these differences is desirable.

The equation is applicable to dense, temperate, mid-latitude forests. There is presently, however, no dependable means of quantifying density.

The equation is applicable when at least one of the antennas is within or near the grove of trees. An approximate criterion for being near the trees is that the take-off angle from the antenna nearest the trees to the tree tops is greater than 16°. In some instances, however, the model was found to be applicable for angles as low as 8°. It is desirable to compute the MED loss and the diffraction loss (described in Section 3) for each specific problem. The appropriate model will be the one with the lower predicted loss.

If the foliage is wet from a rainstorm or if it is characteristic of tropical areas (very lush and with heavy underbrush), then α will be larger than is predicted by Equation 6. If there are no leaves on the trees, α will be smaller. Available data for these circumstances is presented in subsection 2.7.

SECTION 3

DIFFRACTION OVER TREES

3.1 INTRODUCTION

This section summarizes reports of cases in which it was found that the characteristics of loss were predicted by the assumption that the majority of the energy propagated was caused by diffraction over the trees.

Figure 24 illustrates the basic parameters for a diffraction calculation. While the figure shows that the calculations can be done for a continuum of geometries, reports on the model have only dealt with two extremes: the infinitely narrow obstacle -- knife-edge diffraction (KED) -- and the smooth-spherical obstacle with a radius equal to 4/3 times the true radius of the earth.

With the limited amount of information available, it has not been possible to develop a precise criterion for determining when the KED model should be used and when the smooth-spherical diffraction (SSD) model is applicable.

3.2 HEAD -- THE SSD MODEL

Head's study (see Reference 27) discusses two models. One, the SSD that requires knowledge of the specific antenna-forest geometry, and the other, a type of "area" model in which the details of the location of the trees in relation to the antennas are not required. In this subsection, Head's findings on the SSD model are summarized. His area model is discussed in Section 4 of this report.

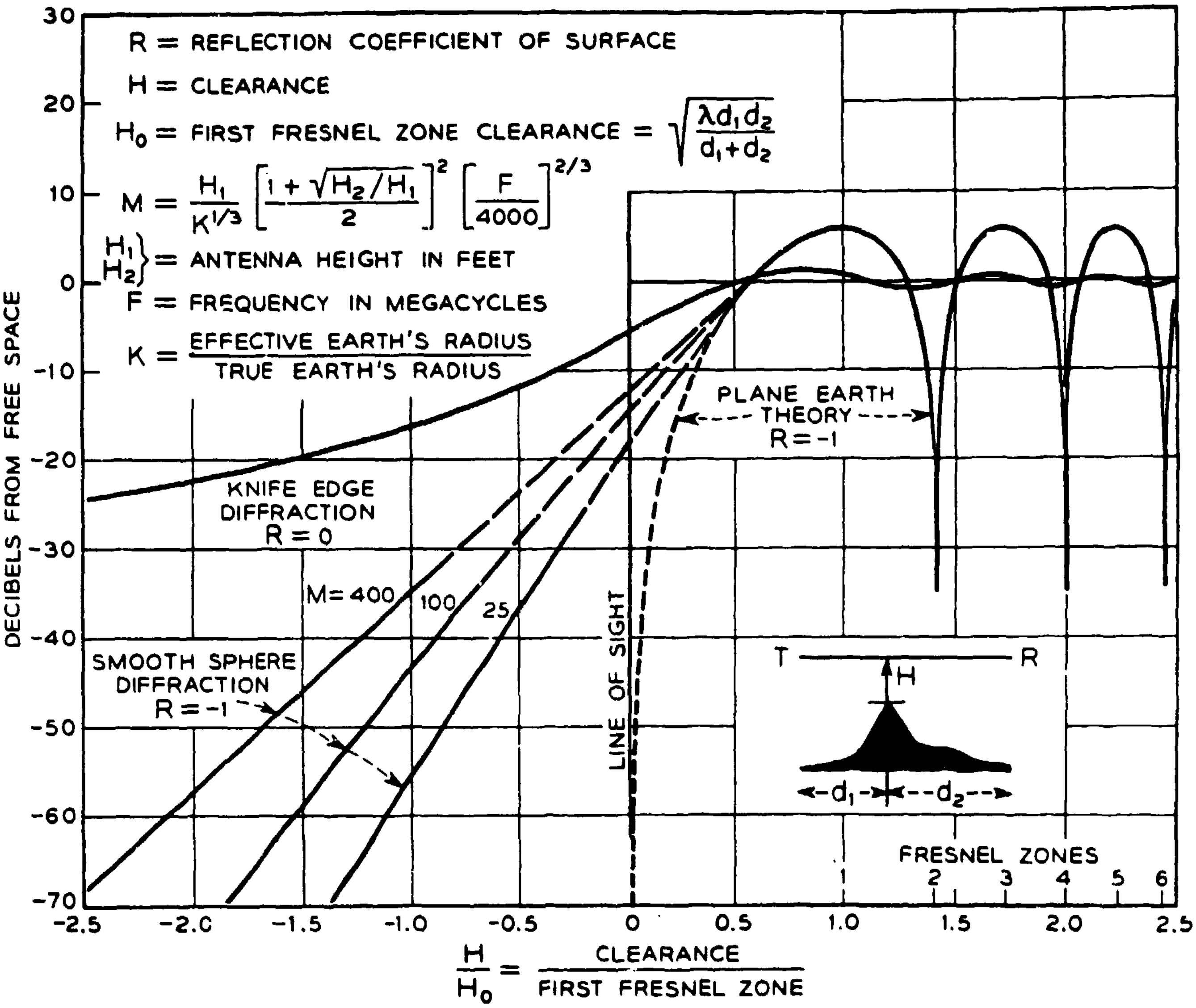

Figure 24. The additional loss due to diffraction over knife-edges (KED) or smooth-spheres (SSD).[37]

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[37] Bullington, K., "Radio Propagation Fundamentals," Bell System Technical Journal, May 1957.

The salient features of Head's study were:

1. The terrain (Eastern Shore, Maryland) was very smooth. Thus, the tops of the trees could be reasonably described as a portion of a smooth spherical shell.
2. The measurements were made at 485 MHz using horizontal polarization.
3. The trees were approximately divided evenly between deciduous and coniferous types. The data was taken in December and January; thus, the deciduous trees were leafless.
4. The model only provided a good match to the data for clearing depths of at least 0.01 miles (= 53' = 16 m). When the antenna was closer to the trees, the diffraction loss was so large that the signal through the trees (such as the one described by the MED model) became more significant than the diffracted signal.
5. The model provided a good match to the data only for cases in which the ratio of ray-path clearance to Fresnel-zone radius (H/H_0 in Figure 24) was greater than -0.6. The reason for this presumably is the same as the reason for the antenna-forest separation criterion cited in number 4 above.
6. The height of the antenna nearest to the trees was 9.1 meters. The height of the trees was 16.8 m. When combined with the 0.01 mile (16 m) antenna-tree separation, this corresponds to take-off angles between the antenna and the tree tops of less than 26°.
7. Head found that the comparison between calculations and measurements was best when the height of the trees was assumed to be 3.0 meters less than their physical height. It seems possible that the difference between the true and effective heights would have been less if all of the trees were in leaf.
8. The "M" parameter for the diffraction analysis was calculated using antenna heights above local terrain; the height of the trees did not enter into this calculation.

3.3 MEEKS -- THE KED MODEL

Meek's study (see Reference 29) involves propagation of vertically-polarized signals over an isolated pine-tree covered hill at 1090 MHz. Both antennas were in clearings and were more than 0.9 km from the hill. Meeks used KED calculations in which the height of the obstacle was assumed to be the height of the hill plus the height of the trees. He accounted for terrain reflections when the reflection points fell on unvegetated terrain. He assumed that they were negligible in other cases. Generally, his predictions compared well with the measurements.

3.4 LaGRONE -- THE KED MODEL

LaGrone (see Reference 28) showed that KED provided a good description of measured data in an experiment involving these circumstances:

1. Frequencies ranged from 82 to 2950 MHz.
2. Horizontal polarization was used.
3. The trees were live oak and hackberry, in full leaf. The grove was 800-1600 meters thick. There was some underbrush.
4. The receiver was moved from 4.5 to 111.3 meters from the trees. The transmitter was (apparently) at least 2 km from the trees.
5. The knife-edge was assumed to be at the edge of the grove of trees that was closest to the receiver.
6. The optimum height of the knife-edge was found to be 4.5 meters less than the true tree height (9 meters) at 82 MHz. The difference was 1.3 meters at 210 and 633 MHz and 0.6 meters at 1280 and 2950 MHz, respectively.
7. The reflected ray between the trees and the receiver was taken into account in the modeling.
8. In LaGrone's article, comparisons with KED predictions are only shown for clearing depths of 35 meters or greater. The implication is that the model was less satisfactory for smaller clearings.

9. The height of the antenna nearest to the trees was varied from 1.5 to 10 meters. Thus, the take-off angle to the tree tops was less than 12°.

10. While LaGrone shows "spherical earth" propagation curves for comparison with the data, these curves do not include either the effects of the trees or the terrain. Thus, while he shows that KED does provide a good model for the additional loss due to trees, he does not demonstrate that a rounded obstacle (such as was used by Head) would not be a better model.

3.5 OTHER EXAMPLES OF KED BEHAVIOR

Figure 25 is an example of the relationship between knife-edge diffraction calculations and measurements at 25 MHz. It is seen that the model predictions are resonably accurate.

The review of the accuracy of ECAC's propagation predictions for the Gallant Eagle exercise[38] suggests that the KED model is useful in predicting foliage effects at 5 GHz.

Longley and Hufford's study (see Reference 30) of data at 170 and 410 MHz suggests that models like KED are valid when the take-off angle to the tree tops is less than 6°. For cases when the clearing size is small enough that the take-off angle is greater than 6°, they use a combination of the EXD model and diffraction models. Direct empirical support of the 6° threshold is not provided.

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[38] Shiers, A., Tactical Performance Assessment Program Report, Gallant Eagle 79, Patrick AFB, FL, December 1978.

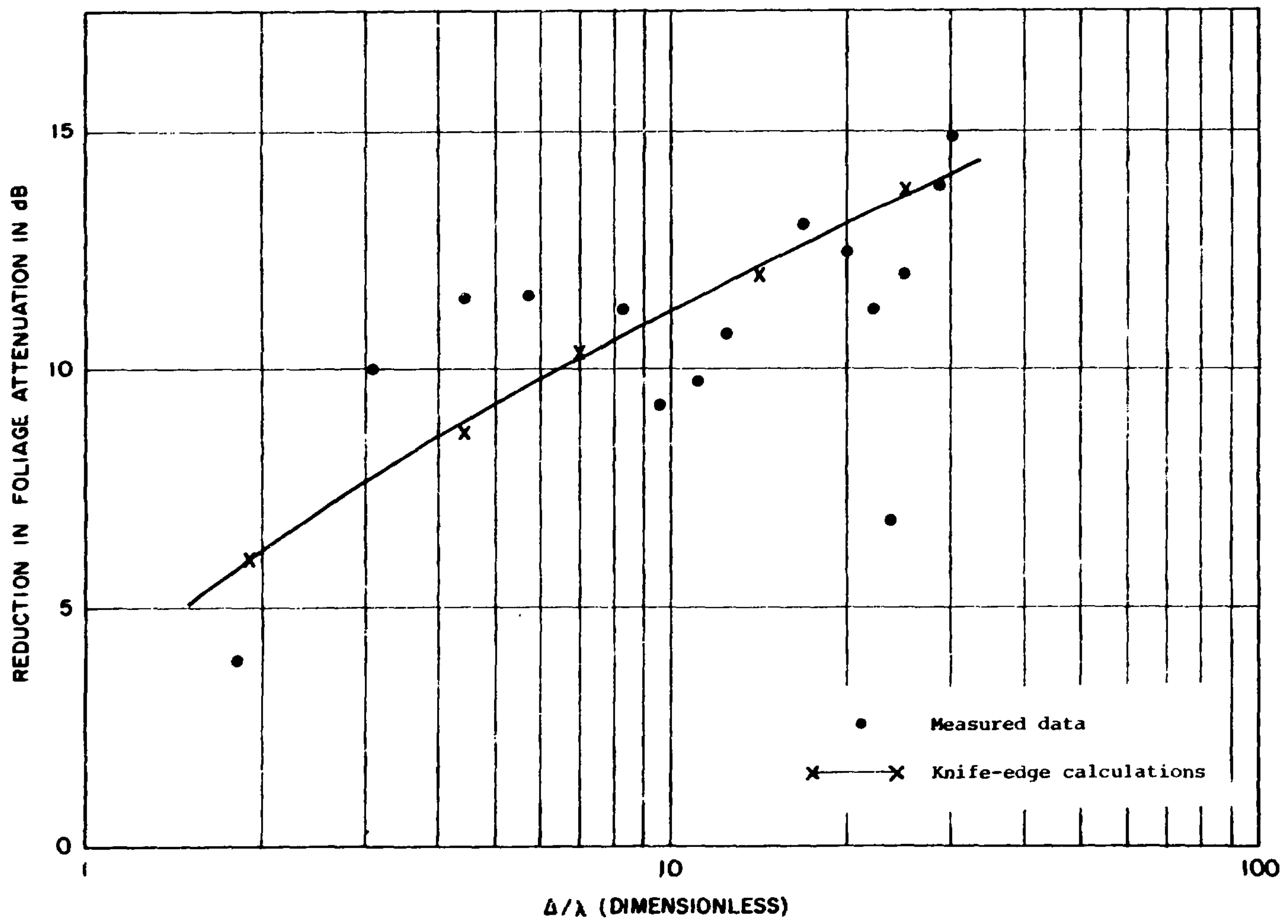

Figure 25. Reduction in foliage attenuation vs. clearing size (Δ) in wavelengths, 25 MHz, tropical vegetation. The measurements were reported by Hicks (see Reference 34, p. 109).

3.6 SUMMARY OF THE DIFFRACTION MODEL STUDIES

Diffraction modeling has been shown to be useful from 25 to 5000 MHz. It can be used as the sole measure of foliage effects if it results in a lower loss than the loss through the trees as calculated by the MED model. This will occur when the antennas are in clearings. The clearing size required will depend on the frequency, tree height, antenna height, and depth of trees. Reported nominal required clearing sizes range from 16 to 35 meters for the VHF and UHF bands for temperate forests. When antenna heights and tree heights are included in the list of characteristics, it appears that a rough guideline for determining when diffraction is a factor is that the antenna nearest to the trees must be in a clearing large enough so that the take-off angle to the tree tops is smaller than about 8° to 26°. (Other information regarding this criterion is provided in subsection 2.6.2.)

The effective height of the diffracting obstacle is smaller than the height of the tree tops. Reported differences are plotted in Figure 26.

In the KED model, a reasonable approximation can be made by assuming that the obstacle is located at the edge of the grove that is closest to the antenna. Ground reflections between this location and the antenna should be taken into account.

Presently, there is some ambiguity as to when a tree grove should be modeled as a knife edge and when it should be modeled as a spherical obstruction. A further analysis of Head and LaGrone's data might help clarify this matter. Kinase's formula (see Reference 4) for propagation over an extended-slab obstacle may also be applicable to this problem.

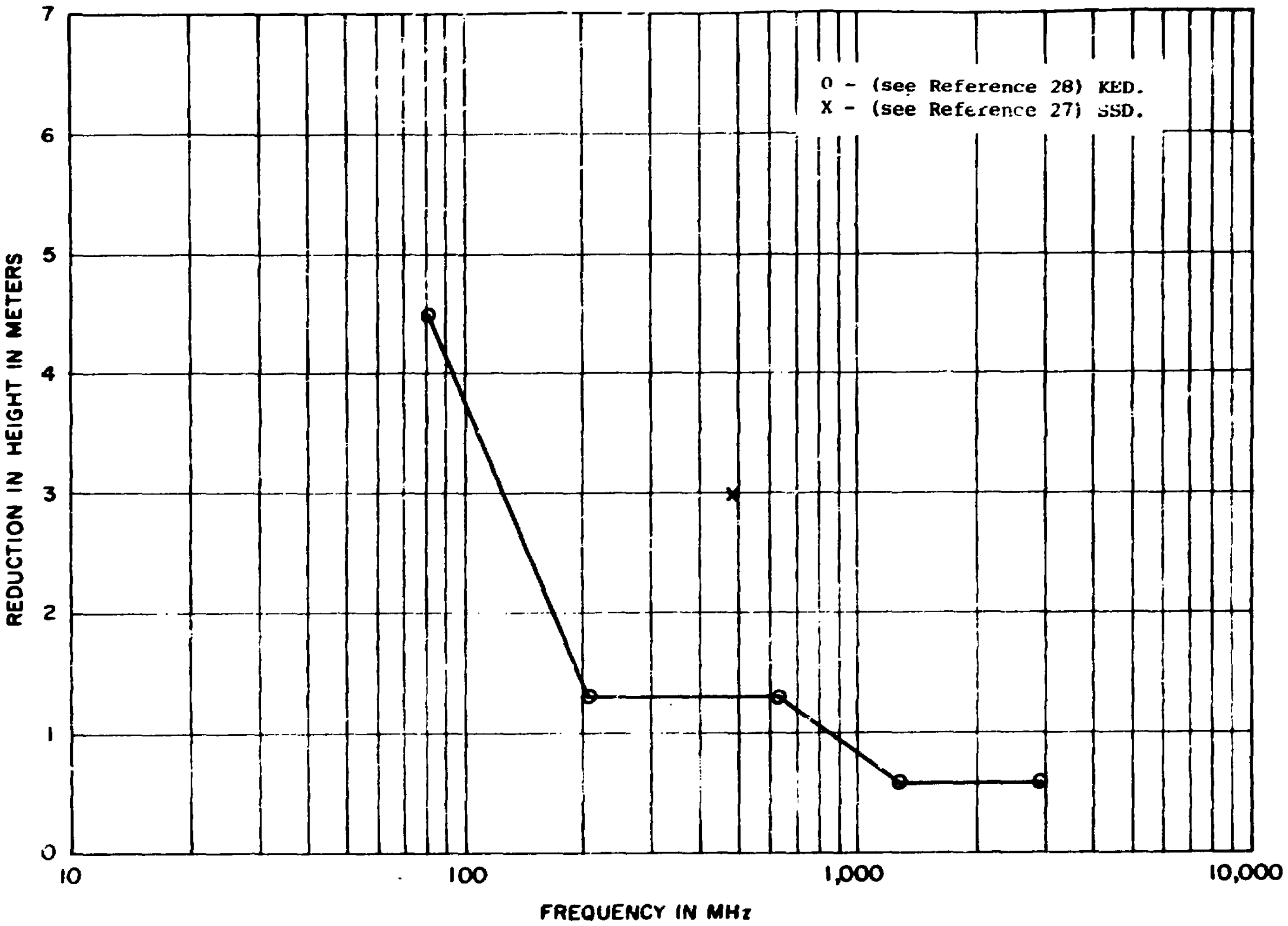

Figure 26. True tree height minus effective obstacle height required to obtain accurate diffraction loss calculation.

SECTION 4

KINASE'S AREA MODEL FOR TRANSMISSION FROM AN ELEVATED ANTENNA

By combining theoretical analysis with observed loss behavior at 80, 150, and 700 MHz, Kinase (see Reference 4) developed a model for computing the loss due to obstructions in the foreground of one antenna. The model assumes that the second antenna is elevated well above the clutter. The obstructions that were involved in the measurements were both foliage and man-made structures.

A key input to Kinase's model is, η, which is defined as the percent of the land in a 2-km square around the "randomly sited" terminal that is covered by vegetation. It is reasonable to assume that better results could be achieved by considering only the 1 x 2 km rectangle in front of this terminal.

Figures 27 and 28 show the loss predicted by Kinase's model.

Head (see Reference 27) also developed an area model that solved the same type of problem as the Kinase model, i.e., one antenna elevated above the clutter and the other in a region where only the percentage of forest cover was defined. However, the Head model is probably less precise than the Kinase model because it does not use the take-off angle from the randomly sited terminal to the base station as a parameter. For cases in which diffraction is the dominant mechanism, this is a shortcoming because the angle through which the rays must diffract will be lower (and the loss lower) for higher take-off angles. For cases in which most of the energy propagates through the trees, this is again a shortcoming because higher take-off angles will mean shorter path lengths through the foliage and lower losses. Thus, excluding take-off angle as a parameter represents, in theory, a weakness of the Head "percent cover" model.

Further evaluation of these procedures is desirable. An interim recommendation is that the Kinase model be used for this type of problem.

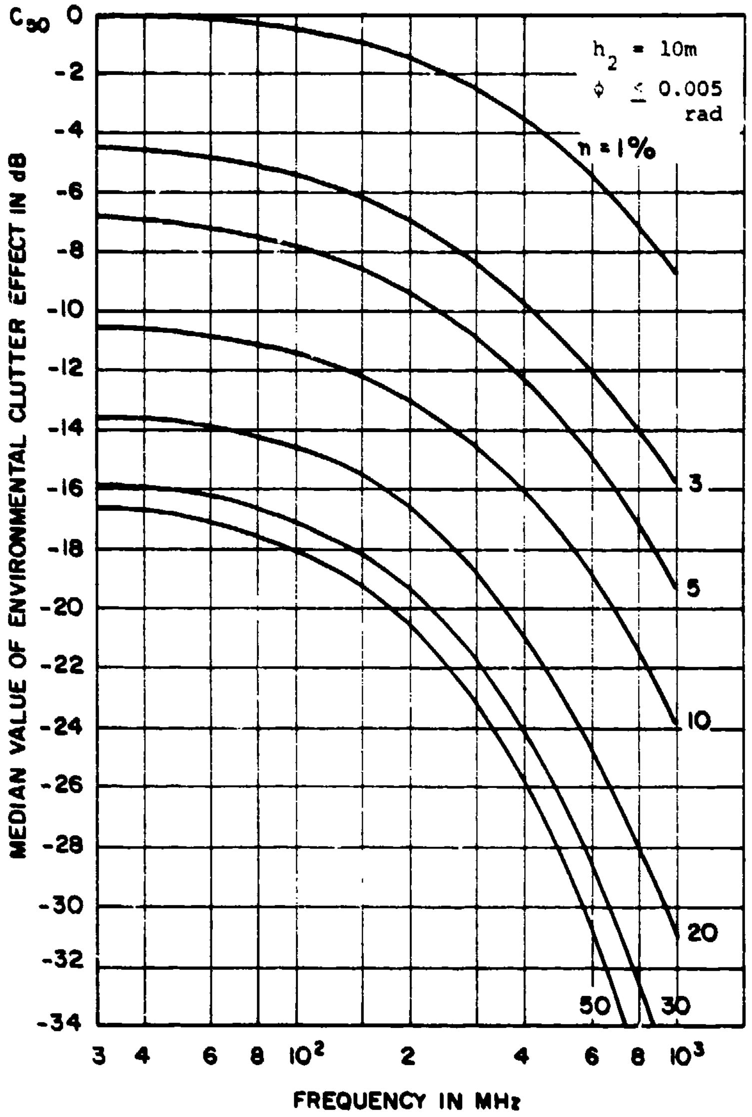

Figure 27. Kinase's estimate of the additional loss due to foliage and man-made structures that cover η% of the surface area.[4,39] φ is the takeoff angle from the randomly sited terminal to the base-station antenna.

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[39] Longley, A.G., Radio Propagation in Urban Areas, OT Report 78-144, Institute for Telecommunication Sciences (ITS), Boulder, CO, April 1978. The curves originally appeared in Reference 4.

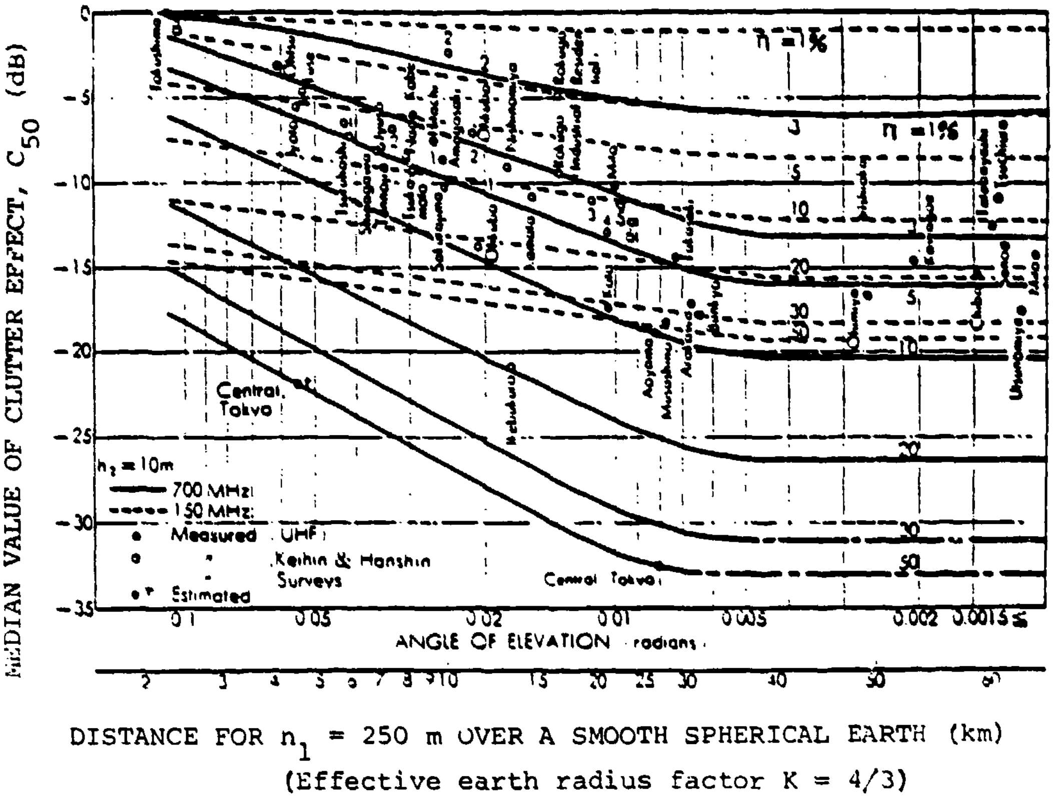

Figure 28. Kinase's model for clutter due to man-made obstructions and vegetation (see Reference 4 or 39).

SECTION 5

THE JANSKY AND BAILEY EMPIRICAL MODEL FOR LOSS IN A TROPICAL FOREST

5.1 THE BASIC EQUATION

This model applies to cases in which both antennas are immersed in foliage and separated by distances from 8 to 1600 meters (0.005 - 1.0 miles). Frequencies can range from 25 to 400 MHz. Antenna heights can be from 2 to 7 meters. The model can be adapted to either polarization. The model was developed by Jansky and Bailey researchers from the measurements that they took in a Pak Chong, Thailand, tropical forest (see Reference 5, p. 93). A description of that environment is presented in TABLE 10 of this report (see Subsection 2.7.1).

The equation for calculating loss is:

$$L_b = 36.57 + 20 \log f - 20 \log \left[\frac{Ae^{-1609\alpha d}}{d} + \frac{B}{d^2} \right] \qquad (11)$$

where

L_b = basic transmission loss, in dB
f = frequency, in MHz
α, A, B = empirical constants listed in TABLE 13
d = path length, in mi (statute).

For distances less than 80 meters, the loss trend follows that of the EXD model. For distances greater than about 160 meters, the loss increases as 40 log d.

This model predicts the mean of the attenuations expected for a set of paths of length d. There is, however, substantial variability of loss as an antenna moves a distance of about half a wavelength. In order to predict actual system performance, this local variability of the signal should be taken into account. Sections 7 and 8 describe techniques for accomplishing this.

TABLE 13

CONSTANTS FOR THE JANSKY AND BAILEY EMPIRICAL MODEL

Frequency (MHz)	Polarization	α	A	B
25	V	0.0	0.0	0.00212
50	V	0.0	0.0	0.00106
100	V	0.045	0.615	0.000529
250	V	0.050	0.759	0.000443
400	V	0.055	1.02	0.000523
25	H	0.0	0.0	0.00424
50	H	0.0	0.0	0.00424
100	H	0.020	0.472	0.00551
250	H	0.025	0.774	0.000588
400	H	0.035	1.11	0.000598

5.2 VALIDATION OF THE JANSKY AND BAILEY EMPIRICAL MODEL

5.2.1 Low Antenna Height Data - the Accuracy of the Jansky and Bailey Empirical Model

As part of this ECAC study, predictions of the Jansky and Bailey empirical model were generated for comparison with published measurements that had been taken at five sites. The sites, each containing a different type of tropical foliage, were:

a. Pak Chong, Thailand (see Reference 5, Figures 5.13, 5.14, 5,21, and 5.22) - A wet-dry semi-evergreen forest. Median tree height is 9.1 meters, median trunk diameter is 0.1 meters. The Jansky and Bailey empirical model is based on this data.

b. Songkhala, Thailand (see Reference 34) - A tropical rain forest. Median tree height is 18.3 meters, median trunk diameter is 0.3 meters. (The measured values in TABLE 14 are the average of the x- and y- radial values for a transmitter height of 4 meters and receiver heights of 2.4 and 4.5 meters. This data was reported in Semiannual Report 10 of the Tropical Propagation Research series).

c) Panama[40] - Median tree height is estimated (see Reference 31) to be 11.6 meters. Trunk diameter is 0.2 meters.

d) Chumphon, Thailand[41] - A fresh-water swamp forest. Median tree height is 11.9 meters. Median trunk diameter is 0.1 meters.

e) Ban Mun Chit (see Reference 41) - A dry evergreen forest. Median tree height is 6.1 meters. Median trunk diameter is 0.1 meters.

All measurements were made on circuits with antennas that were less than 6.1 meters above the ground.

The predictions and measurements are listed in TABLE 14. It is seen that the rms errors of the Jansky and Bailey empirical model lie between 5 and 14 dB, depending on frequency and polarization. The column labeled "Theoretical Model" will be described in the next subsection.

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[40] Herbstreit, J.W. and Crichlow, W.Q., "Measurement of the Attenuation of Radio Signals by Jungles," Radio Science, August 1964.

[41] Hagn, G.H., Shrauger, N.K., and Shepherd, R.A., VHF Propagation Results Using Low Antenna Heights in Tropical Forests, Special Technical Report 46, Stanford Research Institute, Menlo Park, CA, March 1973.

TABLE 14

COMPARISON BETWEEN PREDICTED AND MEASURED VALUES OF THE TOTAL BASIC TRANSMISSION LOSS BETWEEN ANTENNAS SEPARATED BY TROPICAL FOLIAGE

(Page 1 of 4)

$90 \leq$ FREQUENCY (MHz) ≤ 100

HORIZONTAL POLARIZATION

Distance (km)	Basic Transmission Loss (dB)			Locations
	Measured	Jansky and Bailey Empirical Model	Theoretical Model	
1.60	118	122	NA[a]	Pak Chong
1.60	122	122	NA	Songkhala
1.60	139	122	NA	Panama
0.80	119	110	NA	Panama
0.70	114	107	NA	Chumphon
0.40	98	98	143	Ban Mun Chit
0.40	100	98	151	Chumphon
0.20	78	84	133	Ban Mun Chit
0.20	72	84	140	Chumphon
0.16	79	79	NA	Panama
0.10	74	69	130	Chumphon
0.10	64	69	122	Ban Mun Chit
Rms error (dB)		7.5	55.9	

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[a] Not available.

TABLE 14 (Continued)

(Page 2 of 4)

$90 \leq$ FREQUENCY (MHz) ≤ 100

VERTICAL POLARIZATION

Distance (km)	Basic Transmission Loss (dB)			Location
	Measured	Jansky and Bailey Empirical Model	Theoretical Model	
1.6	132	142	NA[a]	Pak Chong
1.6	139	142	NA	Songkhala
1.6	142	142	NA	Panama
0.8	129	130	NA	Panama
0.4	125	118	147	Chumphon
0.2	112	106	137	Chumphon
0.2	88	101	NA	Panama
0.1	86	89	126	Chumphon
	Rms Error (dB)	6.8	30.0	

[a] Not available.

TABLE 14 (Continued)

(Page 3 of 4)

$40 \leq$ FREQUENCY (MHz) ≤ 50

HORIZONTAL POLARIZATION

Distance (km)	Basic Transmission Loss (dB)			Location
	Measured	Jansky and Bailey Empirical Model	Theoretical Model	
1.6	106	118	NA[a]	Pak Chong
1.6	121	118	NA	Songkhala
0.4	94	94	NA	Chumphon
0.4	96	94	118	Ban Mun Chit
0.2	78	82	96	Chumphon
0.2	78	82	107	Ban Mun Chit
0.1	68	70	84	Chumphon
0.1	64	70	95	Ban Mun Chit
	Rms error (dB)	5.4	23.9	

[a] Not available.

TABLE 14 (Continued)

(Page 4 of 4)

40 ≤ FREQUENCY (MHZ) ≤ 50

VERTICAL POLARIZATION

Distance (km)	Basic Transmission Loss (dB)			Location
	Measured	Jansky and Bailey Empirical Model	Theoretical Model	
1.60	118	130	NA[a]	Pak Chong
1.60	141	130	NA	Songkhala
1.60	149	130	NA	Panama
0.80	125	118	NA	Panama
0.16	92	90	NA	Panama
0.10	101	82	72	Chumphon
	Rms errors (dB)	13.2	29.0	

[a] Not available.

5.2.2 Low Antenna Height Data - Comparisons with the Theoretical Lateral-Wave Model

A lateral-wave mechanism has been proposed by several authors[42,43,44,45,46] as a means of explaining the observed loss in tropical forests. The lateral-wave behaves in such a way that loss increases with distance as 40 log d. Thus, trends predicted by theoretical lateral-wave models are consistent with the trends observed in tropical forests in Thailand (25 to 400 MHz, see Reference 5) and in India, (50 to 800 MHz, see Reference 10). Further lateral-wave models predict loss-versus-frequency (see Reference 46) and loss-versus-antenna height (see Reference 43) trends that have been observed in measurement programs. With regard to predicting the actual basic transmission loss for a particular set of parameters, the theoretical lateral-wave models do not appear to be as accurate as the Jansky and Bailey empirical model. Evidence supporting this remark will follow.

Comparisons between the theoretical model predictions and measurements are also listed in TABLE 14. The predicted values were computed by Hagn (see Reference 41) using the equations of Dence and Tamir (see Reference 45).

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[42] Sachs, D.L. and Wyatt, P.J., "A Conducting Slab Model Electromagnetic Propagation Within a Jungle Medium," Radio Science, February 1968.

[43] Tamir, T., "Radio Wave Propagation in Forest Environments," IEEE Transactions on Antennas and Propagation, November 1967.

[44] Tamir, T., "Radio Wave Propagation Along Mixed Paths in Forest Environments," IEEE Transactions on Antennas and Propagation, July 1977.

[45] Dence, D. and Tamir, T., "Radio Loss of Lateral Waves in Forest Environments," Radio Science, April 1969.

[46] Ott, R.H. and Wait, J.R., Excitation Mechanisms for Forest-Covered and Vegetated Media, Tech. Report ACC-ACO-8-73, Institute for Telecommunication Sciences (ITS), Boulder, CO, November 1973.

The physical parameters of the forest -- conductivity, dielectric constant, and height -- that were used as model inputs were values measured by Hagn. The computed rms errors of the model with these inputs range from 24 to 56 dB, depending on the frequency and polarization.

In another comparison between theoretical model predictions and measurements, Ott (see Reference 46) reported that his version of the lateral-wave model over-predicted the loss measured in the 50 - 300 MHz range by 18 dB.

The Jansky and Bailey research team also investigated a version of the lateral-wave model (see Reference 34). They demonstrated that the model would yield quite accurate results if carefully selected "effective" values of the forest's physical parameters were used as model inputs. They obtained their effective values through an iterative process in which comparisons were continuously made between model predictions and the loss values measured at a particular site. The effective values were different for each site investigated. No clear-cut procedure was defined to determine the effective values for a site at which loss measurements had not yet been made. Four years later, researchers from Jansky and Bailey and SRI observed that this problem remained.[47] To this author's knowledge, no further progress had been made on this aspect of the use of the lateral-wave model prior to the preparation of this report.

As another example of errors that may occur when one tries to use the theoretical lateral-wave model, consider the comparison between predictions and Pak-Chong measurements that appeared in a paper by Dence and Tamir (see Reference 45) documenting a "second generation" lateral-wave model. The results are listed in TABLE 15.

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[47] Wait, J., Ott, R., and Telfer, T., editors, Workshop on Radio Systems in Forested and/or Vegetated Environments, AD 780-712, Institute for Telecommunication Sciences (ITS), Boulder, CO, February 1974, pp. I-E-2, I-E-4, and I-C-10.

TABLE 15

PREDICTED AND MEASURED BASIC-TRANSMISSION LOSSES (50 MHz, 1 km, Pak Chong, 3-m ant. hts.)

Polarization	Measured Loss (dB)[a]	Theoretical Model Values Cited by Model Developers[a]	Theoretical Model Values Made by Using Measured σ and ε[b]	Jansky and Bailey Empirical Model
Vertical	117	111	94	122
Horizontal	104	107	92	110

[a] Reference 45, Figure 7.
[b] Reference 45, Figure 9.

The predictions reported by the model developers are based on the electrical parameters of an "average" forest. These are defined as $\varepsilon = 1.1$ and $\sigma = 1 \times 10^{-4}$ mho/m. Measured values of σ and ε at 50 MHz near Pak Chong, however, were $\varepsilon = 1.02$ and $\sigma = 4 \times 10^{-5}$ (see Reference 47, p I-C-11). The predictions resulting from use of those measured values are listed in the third column of numbers in TABLE 15. The magnitudes of the errors are 23 and 12 dB. The errors of the Jansky and Bailey empirical model would be 5 and 6 dB for this problem.

(The subset of basic-transmission-loss values in TABLES 14 and 15 that are attributed to References 41 and 45 were derived from the "radio-loss" and "system-loss" values in those reports by adding 4 dB to these other losses. This is the procedure recommended on p. 105 of Reference 41. It is also consistent with Equations 1 and 13 and Figure 6 of Reference 45.)

A "lateral wave" model was recently endorsed by the Hughes research team (see Reference 26). They reported correlation between model predictions and measurements taken at 1000 MHz in Florida. However, their model, while indeed using a lateral-wave geometry, is really an empirical model. Their empirical estimate of the trend of the tree-top mode loss is:

$$L \sim 20 \log d + (.01) \times d \qquad (12)$$

where d = the distance across the top of the trees, in meters. In contrast, the theoretical lateral-wave model predicts a 40 log d dependence. (It should be remembered that the developers of this theoretical model did not claim that it would be accurate at frequencies higher than about 200 MHz.)

In summary, at frequencies greater than 50 MHz, selected empirical models have been observed to be more practical for generating accurate predictions of L_b in forest environments than selected theoretical lateral-wave models. In particular, when predicting L_b between two low (2-7 m) antennas in a tropical jungle at 50 and 100 MHz, the Jansky and Bailey empirical model is more accurate than one particular theoretical lateral-wave model, if measured values of the jungle's electrical parameters are used as inputs to the theoretical model. Pending further research, it appears reasonable to recommend use of this empirical model over the frequency range for which it was designed, i.e., 25 - 400 MHz.

5.2.3 Further Discussion on the Accuracy of the Jansky and Bailey Empirical Model

Preliminary studies were done in which the predictions from Equation 11 were modified, in accordance with guidelines in Reference 5, to account for antenna heights greater than 7 meters. When comparisons between these predictions and high-antenna height measurements were made, the resulting errors were larger than those shown in TABLES 14 and 15.

Theoretical considerations reported in Reference 45 indicate that when antenna heights are lower than the 2-meter minimum considered in TABLES 14 and 15, the actual received power may be lower than that predicted through use of Equation 11.

Studies of data reported by Dence (see Reference 47) indicate that areas exist for improvement in the empirical modeling of loss in a tropical jungle. For example, a study of some of the Jansky and Bailey data reveals that L_b is proportional to 13 log d in one parameter range and 53 log d in another. These are situations for which Equation 11 would predict 40 log d. Dence cites the development of an improved empirical model as a desirable future task.

5.3 SUMMARY OF SECTION 5

The Jansky and Bailey empirical model (Equation 11) offers reasonably accurate (rms errors from 5 to 14 dB) predictions of basic transmission loss for the problem of two low (2 - 7 m) antennas, separated by distances from 8 to 1600 meters in tropical forests. The model is applicable in the 25 - 400 MHz band. Comparisons with a limited set of 50 - 100 MHz measurements indicate that the theoretical lateral-wave model is not as accurate if measured values of the forest's electrical parameters are used as inputs to the model. Use of effective values of the forest's parameters will increase the accuracy of the theoretical model, but no guidelines for choosing these values have been reported.

The empirical model predicts the mean of the attenuations expected for a set of paths of length d. There is, however, substantial variability of loss as an antenna is moved a distance of about half a wavelength. In order to predict actual system performance, this local variability of the signal should be taken into account. Sections 7 and 8 describe techniques for accomplishing this.

SECTION 6

MEASURED VALUES OF THE ADDITIONAL LOSS CAUSED BY TREES

This section contains a set of plots of the additional loss that is caused by the intervention of trees between the transmitting and receiving antennas. The values plotted represent the loss on a path with trees minus the loss on a nearby path without trees.

Figures 29 through 36 are plots of measured loss versus frequency. These graphs should be especially useful to analysts who have the task of recommending the optimum band for a new equipment. Figures 37 and 38 supplement the preceding plots by showing further details of the data from the 900 to 1300 MHz band.

The figures are intended to supplement the preceding sections by providing data that is not necessarily described by any of the previously described models.

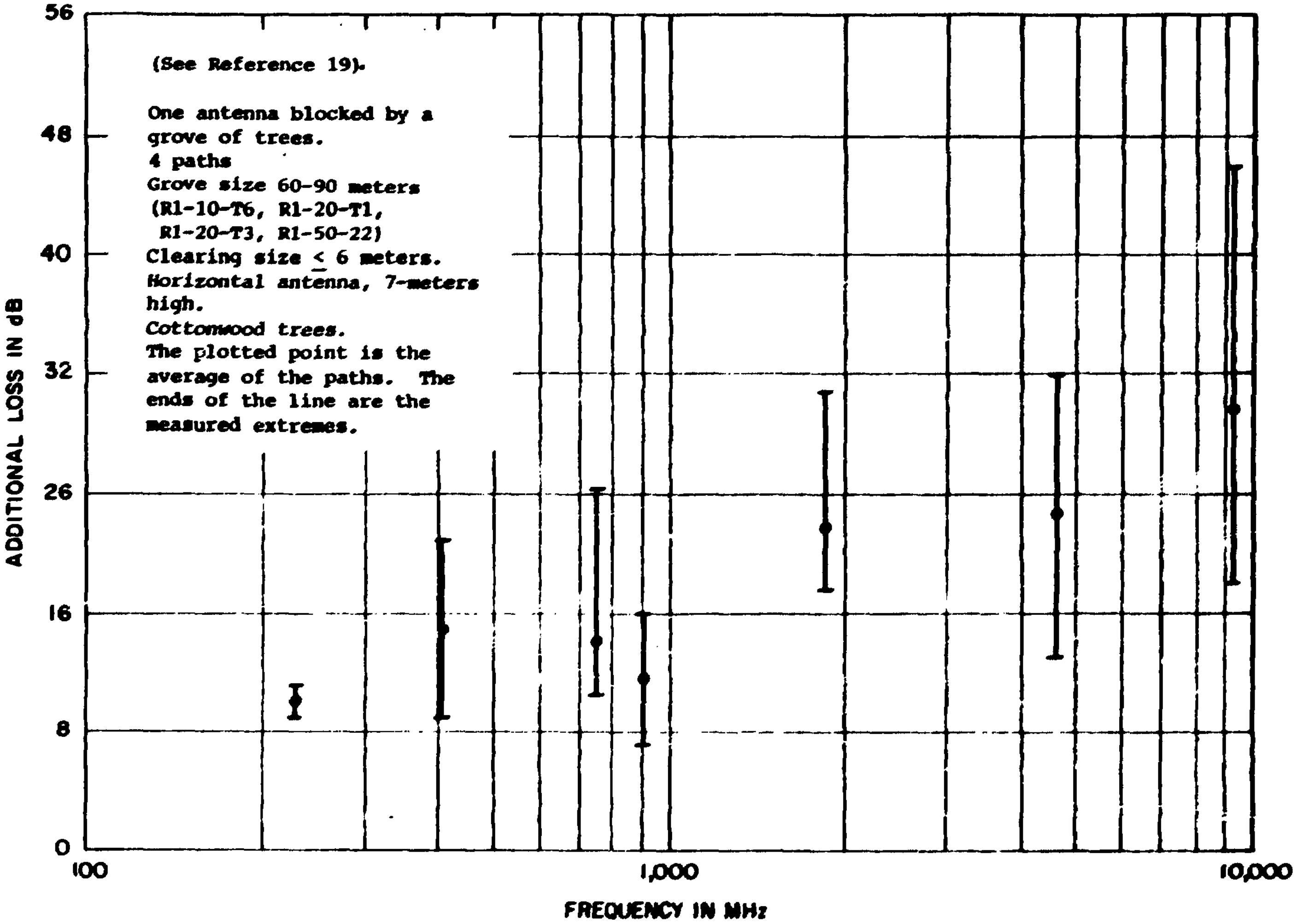

Figure 29. Additional loss due to foliage vs frequency -- one antenna blocked by a 60-90 meter grove.

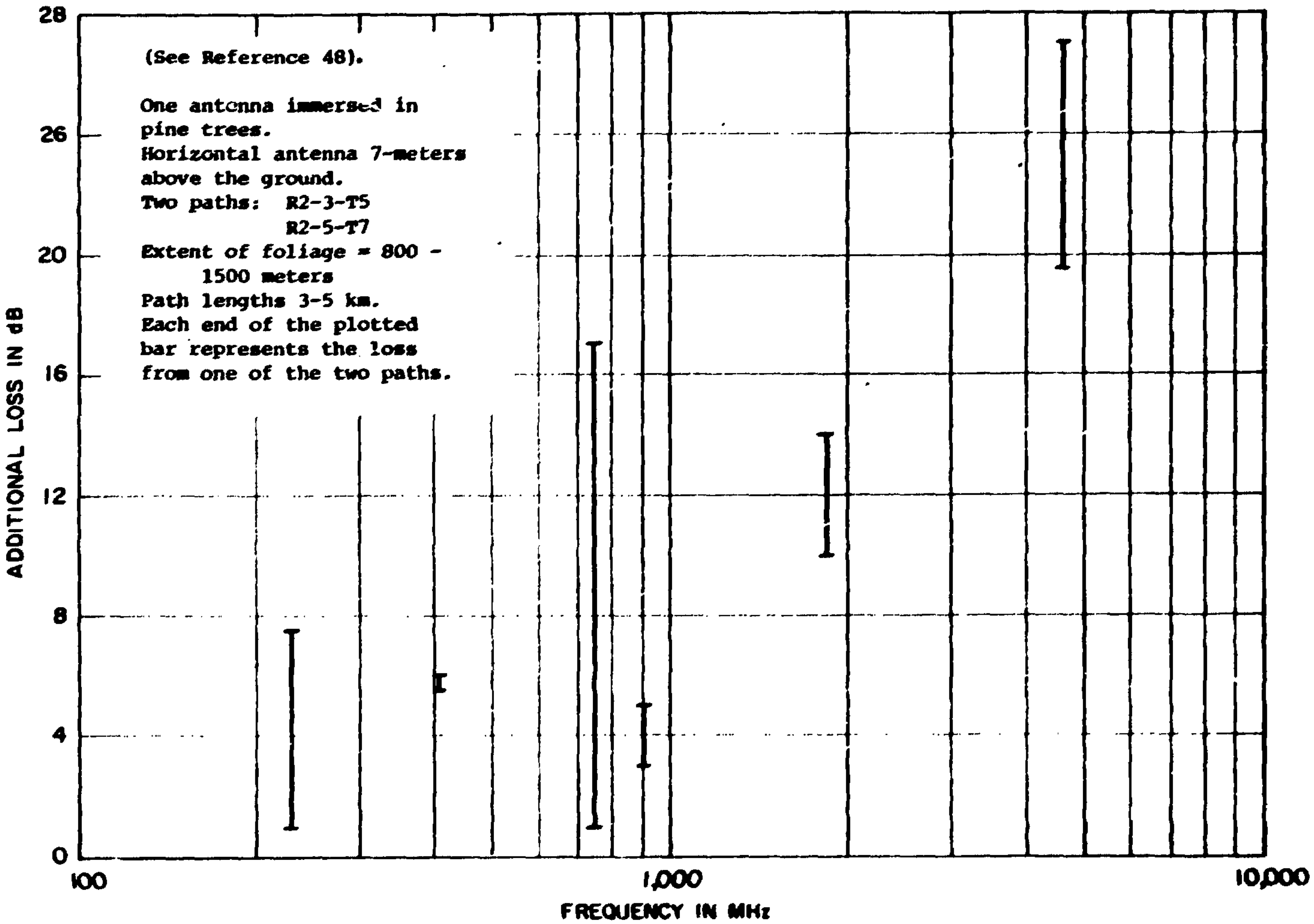

Figure 30. Additional loss due to foliage vs frequency -- extensive grove of trees, no clearing.

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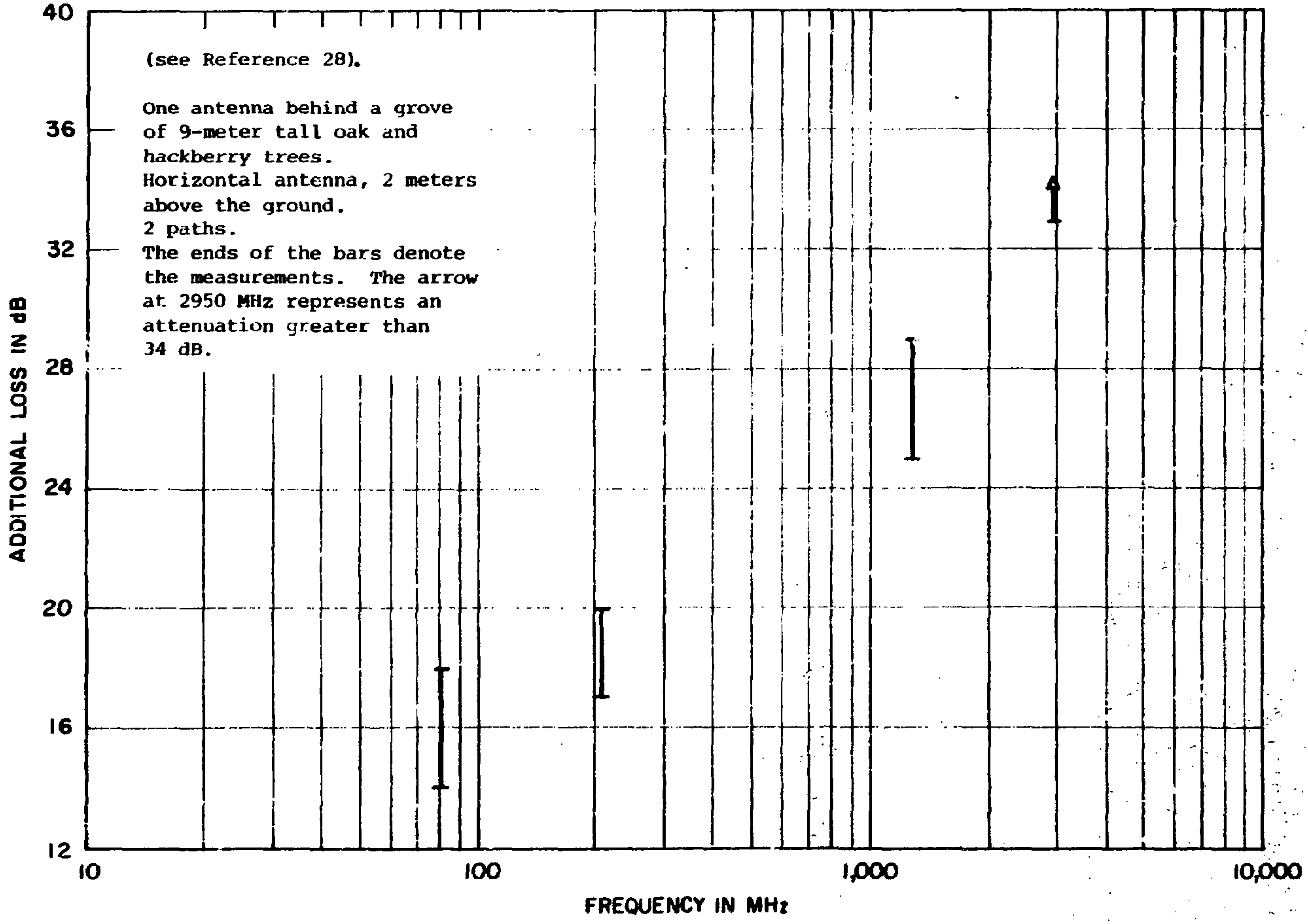
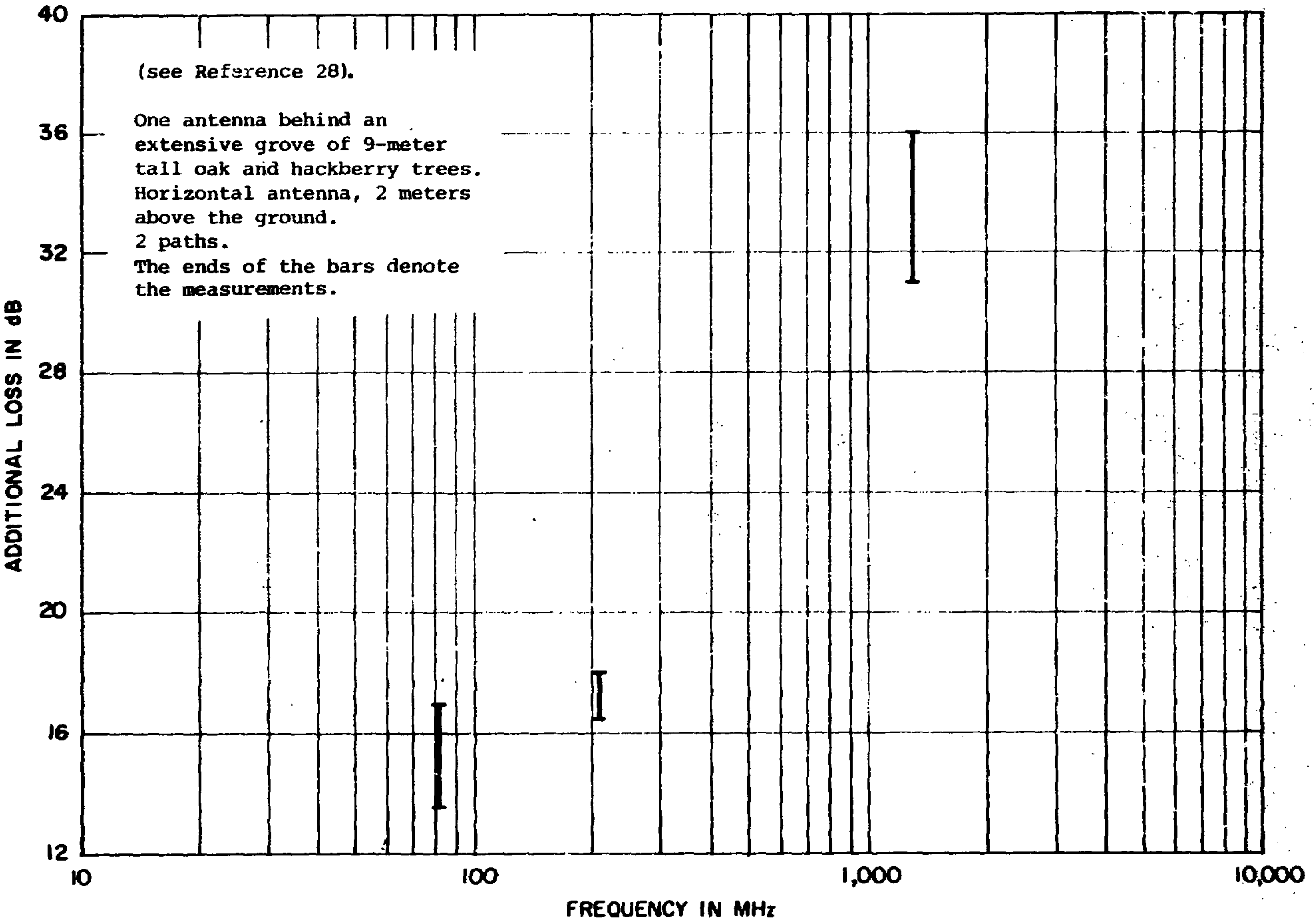
[48] McQuate, P.L., et al., Tabulations of Propagation Data Over Irregular Terrain in the 230-9200 MHz Frequency Range, Part II: Fritz Peak Receiver Site, ESSA TR ERL 65-ITS, Institute for Telecommunication Sciences (ITS), Boulder, CO.



(see Reference 28).

One antenna behind a grove of 9-meter tall oak and hackberry trees.
Horizontal antenna, 2 meters above the ground.
2 paths.
The ends of the bars denote the measurements. The arrow at 2950 MHz represents an attenuation greater than 34 dB.

Figure 31. Additional loss due to foliage vs frequency -- extensive grove of trees, 5-20 meter clearing.



(see Reference 28).

One antenna behind an extensive grove of 9-meter tall oak and hackberry trees.
Horizontal antenna, 2 meters above the ground.
2 paths.
The ends of the bars denote the measurements.

Figure 32. Additional loss due to foliage vs frequency -- extensive grove of trees, 35-65 meter clearing.

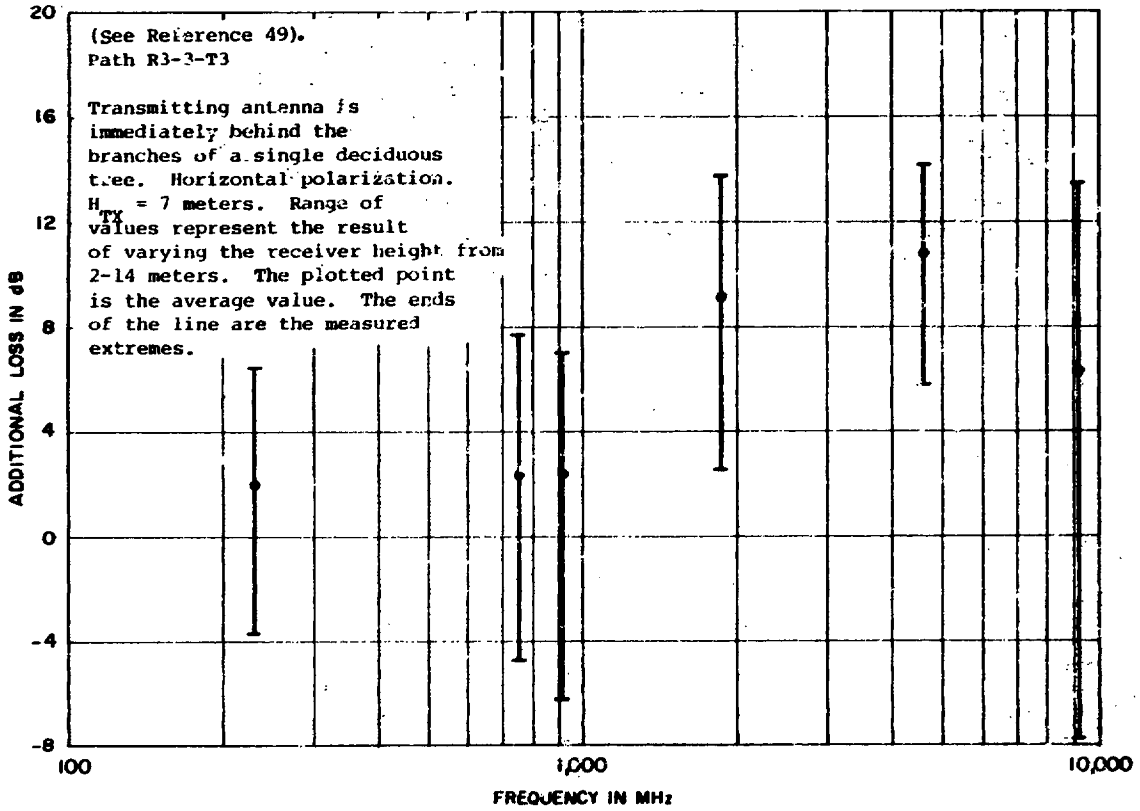


Figure 33. Additional loss due to foliage vs frequency -- one antenna immediately behind a single tree.

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[49] McQuate, P.L., et al., Tabulations of Propagation Data Over Irregular Terrain in the 230-9200 MHz Frequency Range, Part III: North Table Mountain-Golden, ESSA TR ERL 65-ITS 58-3, Institute for Telecommunications Sciences (ITS), Boulder, CO, October 1970.

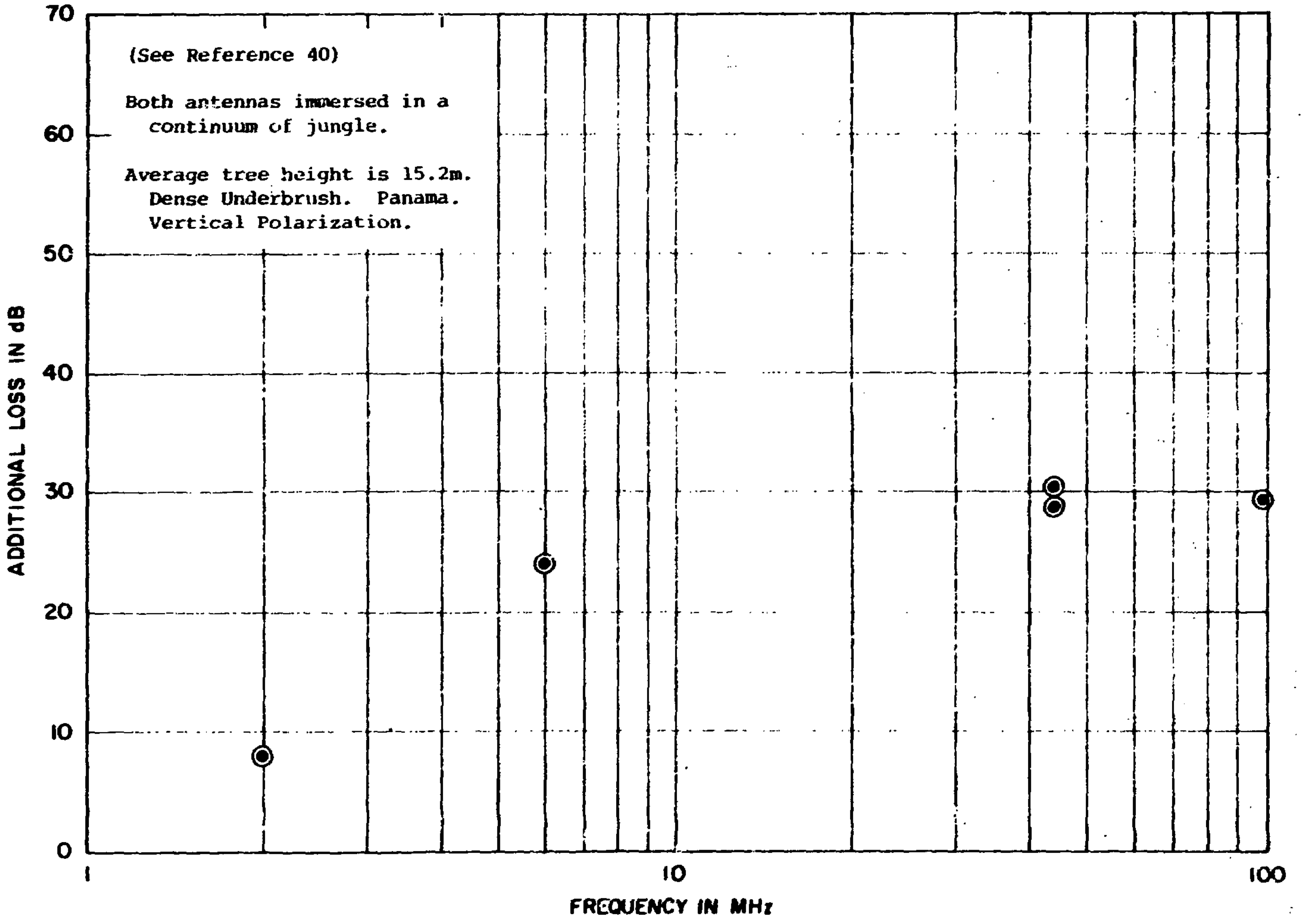


Figure 34. Additional loss due to foliage vs frequency -- both antennas immersed in a tropical jungle, antenna separation = 0.3 km.

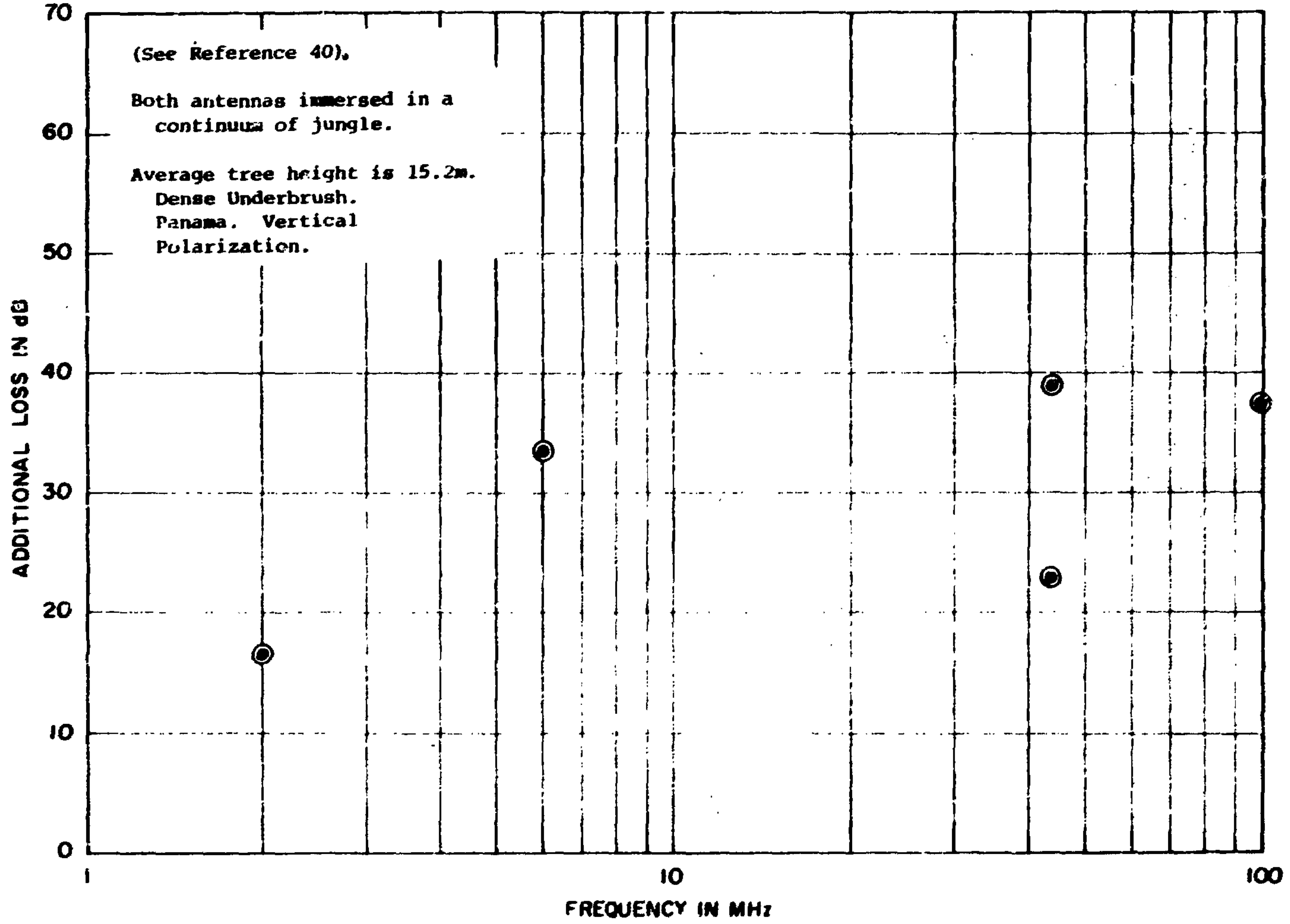
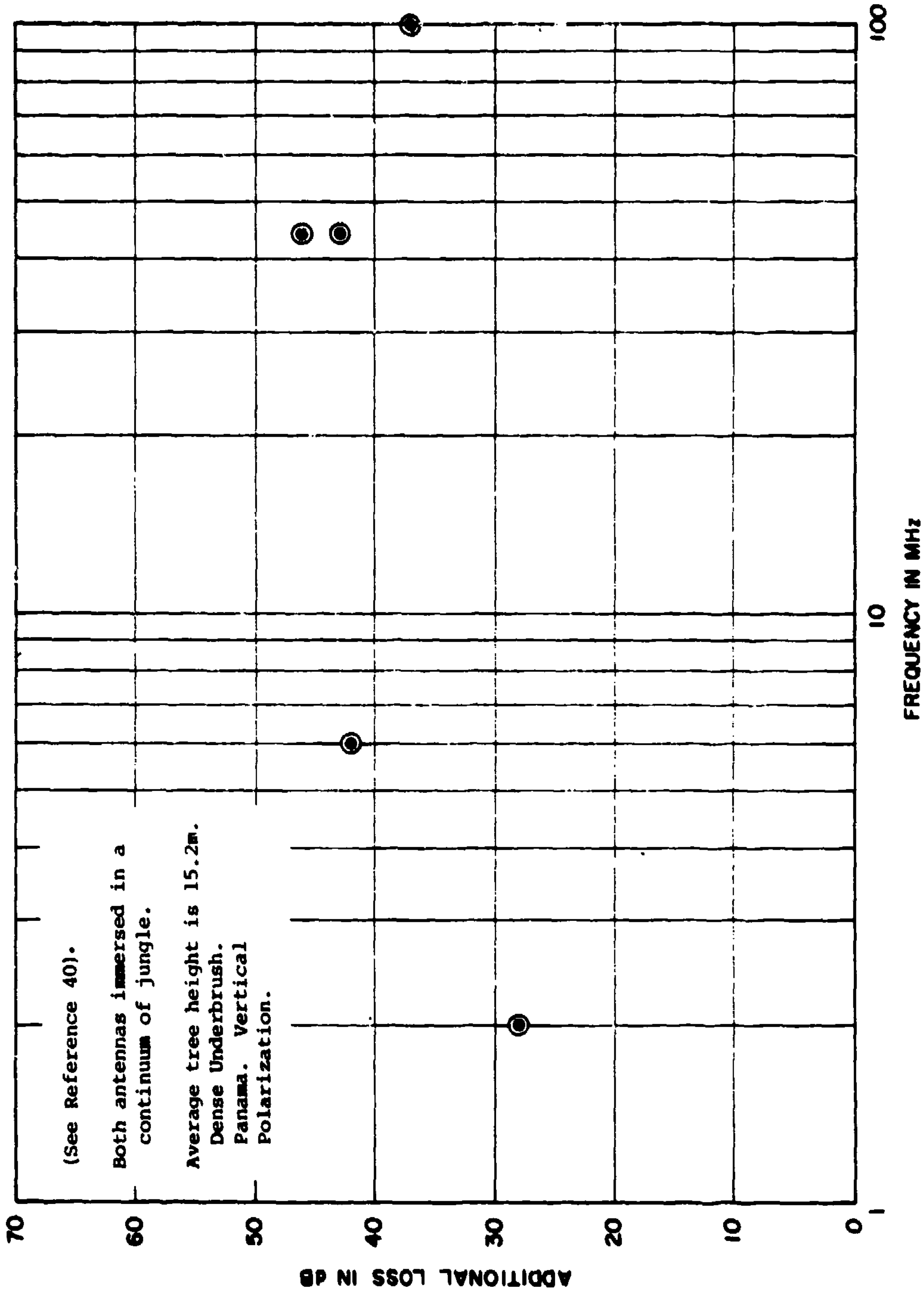


Figure 35. Additional loss due to foliage vs frequency -- both antennas immersed in a tropical jungle, antenna separation = 0.8 km.



(See Reference 40).

Both antennas immersed in a continuum of jungle.

Average tree height is 15.2m. Dense Underbrush. Panama. Vertical Polarization.

Figure 36. Additional loss due to foliage vs frequency -- both antennas immersed in a tropical jungle, antenna separation = 1.6 km.

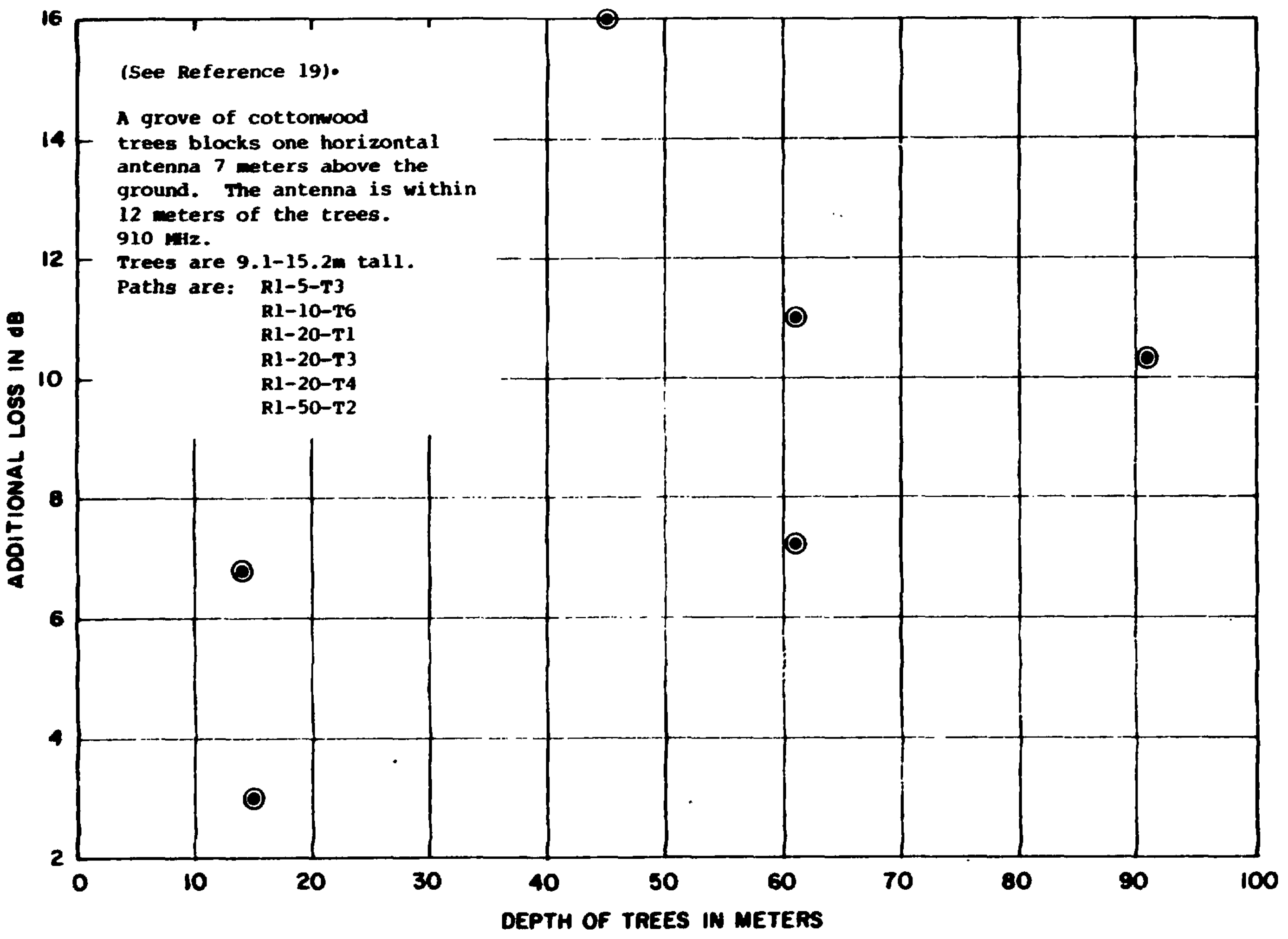
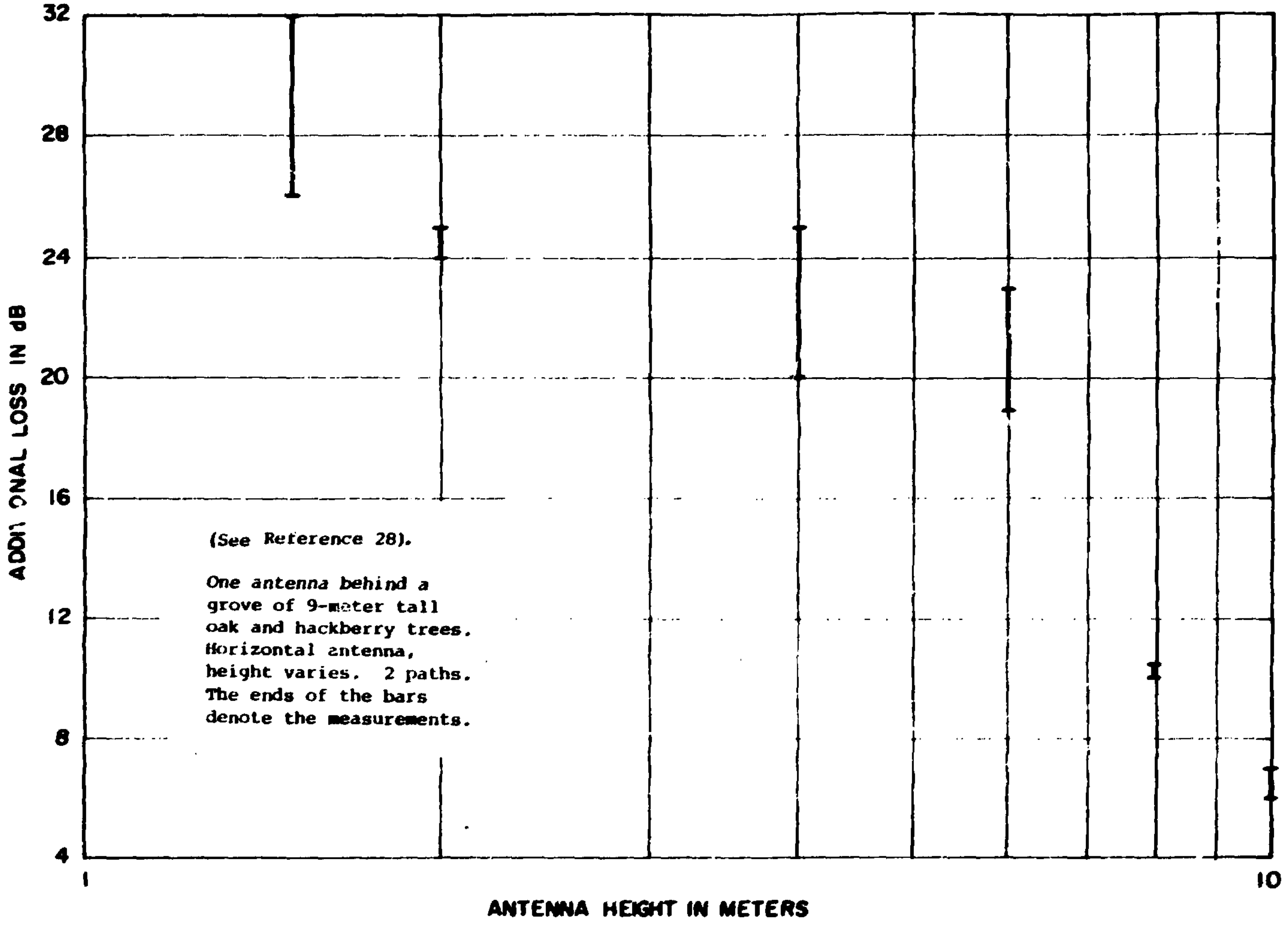


Figure 37. Additional loss due to foliage vs depth of trees, 910 MHz, clearing size less than 12 meters.



(See Reference 28).

One antenna behind a grove of 9-meter tall oak and hackberry trees. Horizontal antenna, height varies. 2 paths. The ends of the bars denote the measurements.

Figure 38. Additional loss due to foliage vs antenna height -- extensive grove of trees, 1290 MHz, clearing size less than 20 meters.

SECTION 7

THE VARIATION OF SIGNAL STRENGTH WITH POSITION IN A FOREST

7.1 INTRODUCTION

In a forest environment, transmitted waves may reach the receiver via a number of paths, e.g., direct, ground-reflected, lateral-wave, air-tree-interface reflected, single-tree scattered, and multiple-tree scattered. Because each path will generally have a length that is different from that of the other paths, the phase of a signal received from one path will be different than the phase of a signal received from another path. Signals from several paths will usually be received at any specified point. The combination of signals with differing phases results in phenomena that appear in the space, frequency, and time domains. The phenomena in the space (position) domain will be discussed in this section.

The models presented in Sections 2 and 5 of this report can be used to predict the mean of the powers that is expected at the set of all points that are at a constant distance from the transmitter. Figure 39 illustrates that there is, however, considerable variation of the signal about the mean level due to multipath phenomena. Subsections 7.2 and 7.3 describe two theoretical models that can be used to describe the statistical behavior of these variations. Observed statistics are discussed in subsection 7.4. Two methods for expressing the performance of communications systems in an environment with spatial multipath patterns are presented in Section 8.

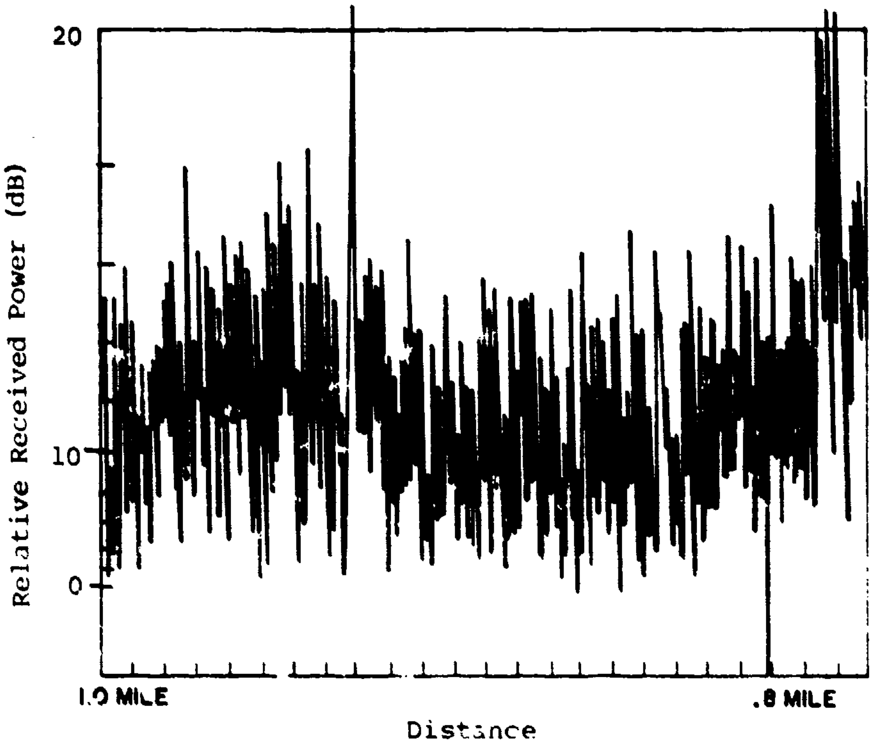


Figure 39. An illustration of the spatial variation in signal strength due to multipath in the forest environment. The frequency is 250 MHz, polarization is vertical, and the receiver is located in a tropical forest in central Thailand (see Reference 5, p. 104).

7.2 A MODEL UTILIZING THE RAYLEIGH DISTRIBUTION[50]

If the signal strength at a point can be modeled with these assumptions:

1. The total field is due to contributions from many paths; the magnitudes of the component vectors are random, but the total power of the sum of the vectors is constant[a]
2. The contribution of any one vector to the total received power is small
3. The phase of each vector is a random variable that is uniformly distributed over the range 0-2π

then the probability that the amplitude of the resultant vector is greater than A, P(A), is given by the Rayleigh distribution:

$$P(A) = \exp(-A^2/A_R^2) \qquad (13)$$

where

A_R = the RMS value of the resultant vector.

When Equation 13 is solved for P(A) = 0.5, the median amplitude, $A_{0.5}$, is found to be equal to $A_R\sqrt{\ln 2}$. Thus, Equation 13 is equivalent to:

$$P(A) = \exp\left(\frac{-A^2 \ln 2}{A_{0.5}^2}\right) \qquad (14)$$

Values from Equation 14 are shown on the bottom line of TABLE 16. (The remainder of the Table is explained in subsection 7.3.)

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[a] Rayleigh stipulated that the amplitudes were equal; Norton showed that this condition was not necessary.

[50] Norton, K.A., et al., "The Probability Distribution of the Amplitude of a Constant Vector Plus a Rayleigh-Distributed Vector," Proceedings of the IRE, October 1955.

TABLE 16

CHARACTERISTICS OF THE RAYLEIGH AND NAKAGAMI-RICE DISTRIBUTIONS[a]

10 log Γ_F (dB)	$S_{.01}-S_{.5}$ (dB)	$S_{.1}-S_{.5}$ (dB)	$\bar{S}-S_{.5}$ (dB)	$S_{.9}-S_{.5}$ (dB)	$S_{.99}-S_{.5}$ (dB)	σ (dB)
$+\infty$[b]	0.00	0.00	0.00	0.00	0.00	0.00
10	3.54	2.12	-0.21	2.80	-5.98	2.00
0	7.02	4.48	-0.94	-7.53	-17.55	5.09
-10	8.19	5.20	-0.92	-8.18	-18.38	5.56
$-\infty$[c]	8.22	5.21	-0.92	-8.18	-18.39	5.57

NOTE: $S_{.XX}$ = signal power exceeded at XX% of the locations = 20 log $A_{.XX}$.

[a] See Reference 6.

[b] Constant signal.

[c] Rayleigh signal.

If the field at any point in the midst of or "near" a forest is due to a multitude of components that satisfy the three criteria listed above, then Equation 13 or 14 can be used to estimate the probability that the field strength will have a particular amplitude. (The problem with quantifying the word "near" is discussed in subsection 7.4.) At another point in the forest that is "far" from the first point, the phases and amplitudes of the components that contribute to the resultant field strength vector will be uncorrelated with the phases and amplitudes of the components of the field at the first point considered. The field strength at this second point can be considered another random variable with an amplitude probability determined by Equations 13 and 14. (The term "far" will be given a quantitative definition in subsection 7.4.) Thus, the voltage at the input terminals to a receiver that is moving in this forest environment will be characterized by a Rayleigh distribution.

7.3 A MODEL UTILIZING THE NAKAGAMI-RICE DISTRIBUTION[51,a]

This distribution describes the field that is obtained when a constant vector is added to a Rayleigh-distributed vector with random relative phase uniformly distributed between 0 and 2π. It will apply to situations in which one component of the field at a receiver remains relatively constant for small changes in position, but a multitude of scattered components, also contributing to the field, do change randomly as the receiver is moved. The probability of the normalized resultant amplitude being larger than A, P(A) is:

$$P(A) = \int_{a=A}^{\infty} 2a\,\Gamma_F\, I_o\,[2a\,\Gamma_F]\ \exp[-\Gamma_F(a^2 + 1)]\, da \qquad (15)$$

where

A = normalized resultant amplitude = resultant amplitude/A_s
Γ_F = $A_s{}^2/2\sigma^2$
$A_s{}^2/2$ = the power in the constant vector
σ^2 = the power in the Rayleigh-distributed vector
I_o = the modified Bessel function of the first kind, zeroth order.

This distribution was derived independently by Nakagami in 1940 and S.O. Rice in 1944. TABLE 16 contains values of the distribution with 10 log Γ_F as a parameter. When this parameter is $-\infty$, there is no constant component and a Rayleigh distribution results.

When the criteria for this model are met, movement of an antenna from place to place produces a voltage at the receiver input terminals that has a Nakagami-Rice distribution. The movements have to be in an area small enough so that Γ_F remains relatively constant.

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[a] Also, see Reference 50 and Reference 6, p. V-5.

[51] Robertson, R.G., et al., Tropical Propagation Research, Final Report, Vol. III, Atlantic Research Corporation, Alexandria, VA, 1969, p. 31.

7.4 MEASURED VALUES OF THE DISTRIBUTION OF FIELD STRENGTHS THAT RESULT FROM MOVEMENT OF A TERMINAL

7.4.1 Tropical Forests

Robertson (see Reference 51) measured the distribution of received signals that occurred when a receiver was moved about in a dense tropical rain forest in southern Thailand. His study covered the 50 - 150 MHz band.

Robertson's experiments involved path lengths in the 0.3 - 2.4 km range. Transmitter heights varied from 4 to 61 meters, receiver heights from 1.8 to 6.1 meters. The tree canopy height varied from 19.8 to 36.6 meters. The number of trunks per acre was 590 (see Reference 31, p. 370).

Robertson observed that:

1. For receivers within the forest, the field strength can be characterized by a Nakagami-Rice distribution ($\Gamma_F > 0$) for horizontal polarization and by a Rayleigh distribution ($\Gamma_F = 0$) for vertical polarization.
2. Γ_F is larger in clearings than it is in the forest. That is, the steady component of the signal is more significant in relation to the randomly varying component when the receiver is in a clearing.
3. Γ_F becomes smaller as frequency increases. That is, the randomly varying component of the signal increases significantly as the frequency increases.
4. In some cases, raising the antenna height increases Γ_F. In other cases, there is no change.
5. Γ_F becomes smaller as the height or density of the forest increases.

For horizontal polarization, 10 log Γ_F was always less than 11 dB for receivers in the forest. In 22 percent of the cases, the Rayleigh distribution (10 log $\Gamma_F = -\infty$) provided a suitable model. For receivers in clearings, 10 log Γ_F was as high as 18 dB; the Rayleigh distribution applied to 7 percent of the cases.

For vertical polarization with the receiving antenna in the forest, 10 log Γ_F was always less than 4 dB. The Rayleigh distribution applied to 69 percent of the cases. With the receiver in a clearing, 10 log Γ_F was as high as 10 dB, and the Rayleigh distribution was suitable for modeling 11 percent of the cases.

In subsections 7.2 and 7.3, it was mentioned that the Rayleigh and Nakagami-Rice distributions applied to receivers in the midst of or "near" a forest. There is not enough data to support an empirical definition of "near." It is noted, however, that Robertson did observe a Rayleigh distribution with the receiver 61 meters from the trees. This observation was made for both polarizations. Antenna heights were less than 6.1 meters.

The separation between the terminal and the trees that is required to preclude multipath effects is a function of the many parameters that influence propagation in a forest environment: antenna heights, path length, terrain features, height and density of the trees, seasonal variations of foliage, polarization, and frequency. Generalization from a small number of observations is not recommended.

In the Rayleigh model description, it was mentioned that two points would have to be separated "far enough" from each other in order for the field strength at one point to be uncorrelated with the field strength at another point. Robertson observed that 0.5 λ was a sufficient separation for reception points located along the same great circle path to the receiver. 1.0 λ separation was needed if the two reception points were on a line transverse to the great circle path.

In another area of Thailand, Jansky and Bailey crews found 0.37 λ was sufficient for uncorrelated amplitudes. This was based on measurements taken along a single great circle path from the transmitter. This result was found to be independent of frequency in the 25 - 400 MHz band (see Reference 5, p. 107).

These measurements confirm a theoretical prediction by Gans.[52] He determined that 0.5 λ would be appropriate for the separation between receiving antennas along the same great circle path. He showed that the distance will increase if the receiver is moved away from the scatterers.

At frequencies where small correlation distances are expected, it is reasonable to consider space diversity as a technique for reducing loss of signal due to multipath fades.[53]

7.4.2 Nontropical Forests

Measured values of the distribution of field strengths resulting from the movement of a terminal in temperate forests have been reported by Josephson,[17] Okumura,[54] and Englund.[55]

Josephson published a graph, reproduced here as Figure 40, that shows the range of small scale variability of VHF signals in a pine forest. The

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[52] Gans, M.J., "A Power Spectral Theory of Propagation in the Mobile Radio Environment," IEEE Transactions on Vehicular Technology, February 1972.

[53] Vincent, W.R. and Hagn, G.H., "Comments on the Performance of VHF Vehicular Radio Sets in Tropical Forests," IEEE Transactions on Vehicular Technology, August 1969.

[54] Okumura, Y., et al., "Field Strength and Its Variability in VHF and UHF Land-Mobile Radio Service Station," Review of the Tokyo Electrical Communication Laboratory, September 1968.

[55] Englund, C.R., et al., "Some Results of a Study of Ultra-Short-Wave Transmission Phenomena," Proceedings of the IRE, March 1933.

variability is described as the difference between the levels not exceeded at 10% and at 90% of the locations. From TABLE 16 one can see that this difference is 13.5 dB for a Rayleigh-distributed signal. This difference is reached at 80 MHz.

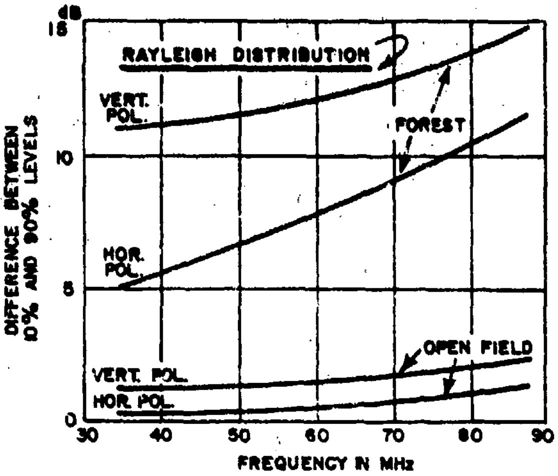

Figure 40. The observed variability of the signal received in a nontropical forest (see Reference 17).

Okumura showed that measurements taken at 450, 900, and 1900 MHz "in or behind" a forest were Rayleigh-distributed. The antennas were vertically polarized.

Englund reported a fluctuation of about 10 dB, peak-to-peak in the 60 - 80 MHz band in woods and at the edge of the woods in New Jersey. This is less severe than the fluctuation of a Rayleigh-distributed signal. Vertical polarization was used in this test.

7.5 SUMMARY OF SECTION 7

The field at any point in a forest generally consists of components that have traveled along different paths. As one or both antennas is moved through the trees, the phase relationship between the components changes. Therefore, the magnitude of the composite field changes. Furthermore, the shadowing effect of individual near-by trees changes as the antennas are moved. These changes caused substantial fluctuations of the received power. The distribution of the received power has been found experimentally to be described by a Nakagami-Rice distribution. In many cases, the best description is a special case of this distribution -- the Rayleigh distribution -- which tends to occur when the antennas are in dense forests and when the frequency is above 100 MHz. For vertically polarized antennas, it has also been observed at frequencies as low as 50 MHz.

Measurements have been made in tropical forests of the minimum separation between two points such that the field strengths at these points are not correlated. These separations were less than 1 λ in the 25 - 400 MHz band.

SECTION 8

THE IMPACT OF FREQUENCY-FLAT FADING ON SYSTEM PERFORMANCE

8.1 THE EFFECTS OF THE VARIATION OF SIGNAL STRENGTH WITH POSITION ON SYSTEM PERFORMANCE

In the previous section it was shown that a terminal carried through a forest will be subjected to multipath effects. Two methods for describing the resulting degradation to system performance will now be discussed. The first results in the prediction of the overall bit-error rate that can be expected. The second leads to a prediction of the fraction of time that the bit-error rate will not fall below a specified level. The latter technique can be applied to analog systems also. In that case, the method will result in a prediction of the percentage of time that a specified articulation index or articulation score will not fall below a particular value.

Both prediction methods are based on these two assumptions:

1. The transmitted signal bandwidth is narrow enough so that frequency-selective fading does not distort the signal.
2. The spacing between the transmitted bits is large enough so that multipath delays do not result in intersymbol interference.

With these assumptions, the key multipath effect is the random increase and decrease of the signal level as one or both terminals move about.

It should be noted that the formulas in this section represent theoretical predictions of system performance given a frequency flat channel. In many instances, the forest will produce a channel that has a significant variation in gain within the bandwidth of a signal. In these cases, the degradation to the quality of the received signal will be even more severe than is indicated by the formulas in this section (see, e.g., Jakes[56]).

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[56] Jakes, W.C., "An Approximate Method to Estimate an Upper Bound on the Effect of Multipath Delay Distortion on Digital Transmission," IEEE Transactions on Communications Systems, January 1979.

8.2 PREDICTING AN OVERALL BIT-ERROR RATE

This method is described by Robertson,[51] Nesenbergs,[57] and Sunde.[58] Bit-error rates are calculated using a form of the theorem of total probability:

$$BER = \int_0^\infty (BER|S/N)\ p(S/N)\ d(S/N) \tag{16}$$

where

BER = the actual bit-error rate in the presence of fading
BER|S/N = the bit-error rate for a fixed signal-to-noise ratio
p(S/N) = the probability density for S/N.

Robertson calculated the bit-error rate for a noncoherent FSK system using Equation 16. The bit-error rate in the absence of fading (but with Gaussian noise) was assumed to be:

$$BER|S/N = \frac{1}{2} e^{-(S/N)/2} \tag{17}$$

Combining Equations 17, 16, and 13 results in a BER in the presence of Rayleigh fading of:

$$BER = \frac{1}{S/N + 2} \tag{18}$$

Here the signal-to-noise ratio is the mean value. The values are plotted in Figure 41. It is observed that for 10 log S/N = 11 dB, the BER for a Rayleigh faded signal is almost two orders of magnitude larger than the BER for an unfaded channel with the same average signal strength.

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[57] Nesenbergs, M., "Binary Error Probability Due to an Adaptable Fading Model," IEEE Transactions on Communications Systems, March 1964.

[58] Sunde, E.D., Communication Systems Engineering Theory, John Wiley and Sons, New York, NY, 1969.

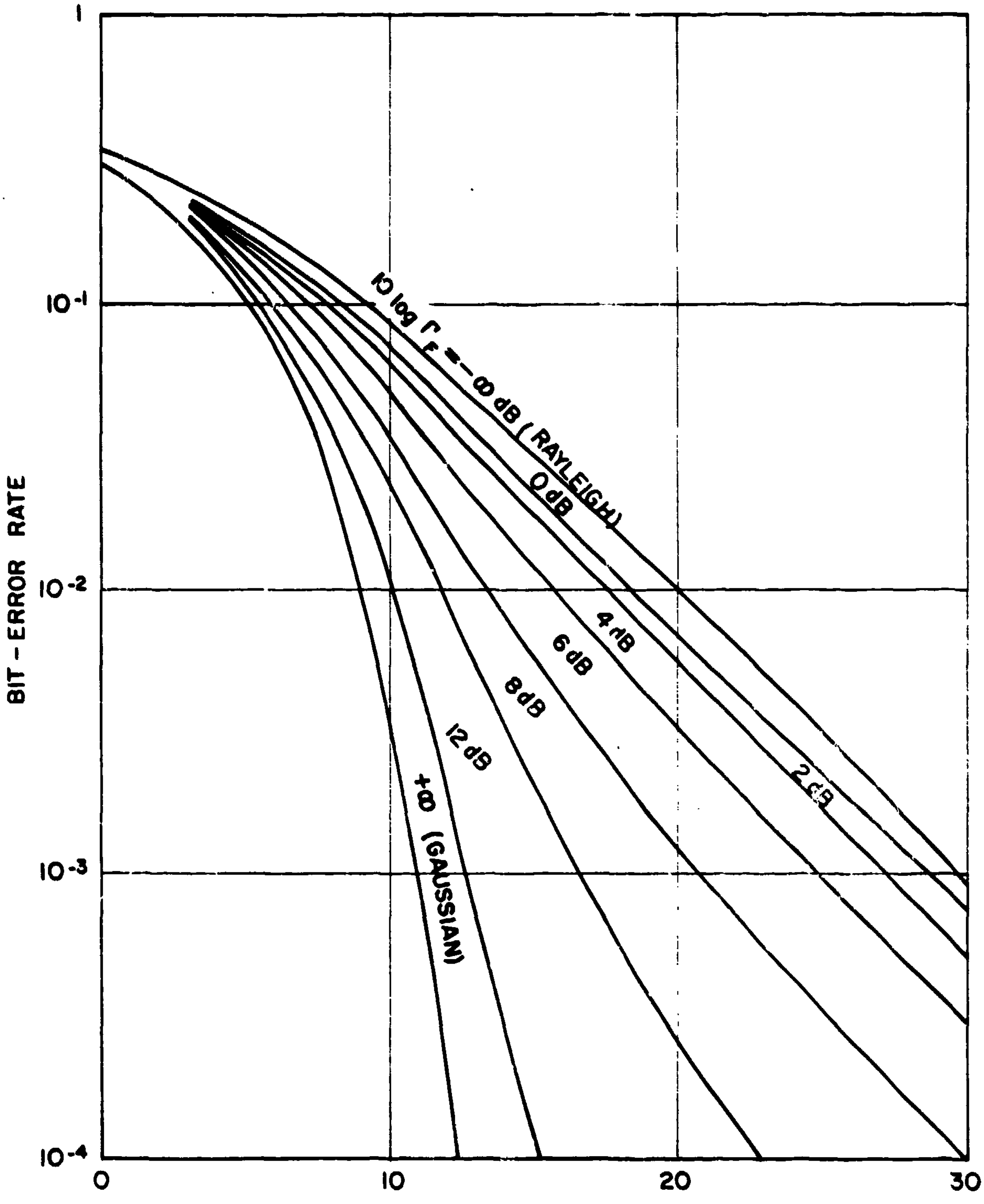

Figure 41. BER for noncoherent FSK system subjected to Rayleigh or Nakagami-Rice fades. The curve labeled Gaussian represents the error rate for a constant signal power and Gaussian noise (see Reference 51, p. 74).

Using Equation 16, Sunde shows that for coherently detected binary PM, the unfaded BER, expressed by:

$$\mathrm{BER}\,|\,S/N = 1/2 \ \mathrm{erfc}\sqrt{S/N} \tag{19}$$

becomes:

$$\mathrm{BER} = 1/2\left(1 - \left(\frac{S/N}{S/N + 1}\right)^{1/2}\right) \tag{20}$$

$$\approx \frac{1}{4\ S/N} \tag{20a}$$

in the presence of Rayleigh fading.

For binary PM with differential phase detection, the unfaded BER is:

$$\mathrm{BER} = \frac{1}{2}\, e^{-S/N} \tag{21}$$

With Rayleigh fading it becomes:

$$\mathrm{BER} = \frac{1}{2\ (S/N + 1)} \tag{22}$$

$$\approx \frac{1}{2\ S/N} \tag{22a}$$

For binary FM (i.e., FSK) with dual filter synchronous detection:

$$\mathrm{BER} = 1/2 \ \mathrm{erfc}\left(\frac{S/N}{2}\right)^{1/2} \tag{23}$$

which becomes:

$$\mathrm{BER} = 1/2\left(1 - \left(\frac{S/N/2}{1 + S/N/2}\right)^{1/2}\right) \tag{24}$$

$$\approx 1/2\left(\frac{1}{S/N + 2}\right) \tag{24a}$$

in the presence of Rayleigh fading.

For binary FM with frequency discriminator detection, the error rate is approximately:

$$BER \approx \frac{1}{2\ S/N} \tag{25}$$

in the presence of Rayleigh fading.

In a forest environment, these effects can be reduced, in theory, by employing space diversity with two antennas separated by distances on the order of 0.37 to 1.0 λ (see subsection 7.4.)

8.3 PREDICTING THE FRACTION OF TIME THAT A SPECIFIED BIT-ERROR RATE WILL NOT BE EXCEEDED

This technique is described in the Lenkurt Handbook.[59] It is used in the Institute for Telecommunication Sciences codes such as the Automated Digital Systems Engineering Model (ADSEM)[60] and in ECAC codes such as the Exercise Support Program.[a] The method can be applied to cases of both Rayleigh and Nakagami-Rice signal strength distributions. The Rayleigh case can be treated with a closed-form equation. The development of this equation will now be shown.

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[a] These documents and models do not address foliage effects specifically. They do, however, describe a technique for predicting the effect of a Rayleigh-faded signal on system performance.

[59] GTE Lenkurt, Inc., Engineering Considerations for Microwave Communications Systems, San Carlos, CA, 1975.

[60] Hause, L.G. and Hildebrandt, T.H., Programmer's Guide for the Automated L.O.S. Microwave Engineering Program, Institute for Telecommunication Sciences (ITS), Boulder, CO, November 1978.

If the signal power needed for a specified bit-error rate is S_{BER}, then the fade margin relative to the mean signal power, $\overline{S}$ ($\sim A_R^2$), is:

$$f_m = \overline{S}/S_{BER} \tag{26}$$

and

$$F_m = 10 \log(\overline{S}/S_{BER}) \tag{27}$$

The probability of having a signal power greater than S_{BER} is, from Equation 13:

$$P(S_{BER}) = \exp(-S_{BER}/\overline{S}) = \exp\left(-\frac{1}{f_m}\right) \tag{28}$$

$$= \exp\left(-10^{-F_m/10}\right) \tag{29}$$

Thus, given a fade margin referenced to a mean signal level, Equation 28 or 29 can be used to predict the probability (which is equivalent to the fraction of time) that the circuit will achieve the specified bit-error rate if the spatial variation of signal strength due to multipath in the forest environment is Rayleigh-distributed and the transmitter or receiver moves about in this environment.

If the fade margins calculated relative to the median signal levels are designated as $f_{0.5}$ and $F_{0.5}$ ($= 10 \log f_{0.5}$), then:

$$\begin{aligned} f_{0.5} &= S_{0.5}/S_{BER} = A_{0.5}{}^2/A_{BER}{}^2 = A_R{}^2 \ln 2/A_{BER}{}^2 \\ &= \overline{S} \cdot \ln 2/S_{BER} = f_m \cdot \ln 2 = f_m \cdot 0.693 \end{aligned} \tag{30}$$

Solving Equation 30 for f_m and inserting this into Equation 28 yields:

$$P(S_{BER}) = \exp\left(-\ln 2/f_{0.5}\right) \quad (31)$$

$$= \exp\left(-\ln 2 \cdot 10^{-F_{0.5}/10}\right) \quad (32)$$

For completeness, it can be noted that Equations 29 and 32 are a more generalized form of equation than sometimes appear in handbooks (e.g., see Reference 59). These latter equations are obtained by assuming that the fade margin is larger than 10 dB. Then, using the first two terms of the series expansion for e^{-x}, the following relations are obtained:

$$P(S_{BER}) = 1 - 10^{-F_m/10} \quad (33)$$

and

$$P(S_{BER}) = 1 - \ln 2 \cdot 10^{-F_{0.5}/10} \quad (34)$$

8.4 SUMMARY OF SECTION 8

Two methods for describing the degradation to system performance that occurs when a terminal moves through a forest are described. One is a prediction of the overall bit-error rate that can be expected. Calculations are presented for binary phase and frequency-modulated systems. The second method yields a prediction of the fraction of time that the received-signal level would be above a user-specified signal-to-noise ratio. This can be applied to both analog and digital systems. Neither technique accounts for degradation which can occur if the transmission bandwidth is larger than the bandwidth over which the fades are flat. Thus, it can be stated that the degradation will be at least as great as is predicted by these methods.

SECTION 9

SUMMARY

The traditional model for predicting the increase in loss due to propagation through trees is this exponential decay (EXD) model:

$$L = 0.26\ F^{0.77}\ d_f \qquad (35)$$

where L is the loss due to the trees in dB, F is the frequency in GHz, and d_f is the depth of the trees in meters. In this report, it is shown that for problems in the 230-MHz to 95-GHz band, a better prediction is obtained from this modified exponential decay (MED) model:

$$L = 1.33\ F^{0.284}\ d_f^{0.588} \quad \text{for } 14 \leq d_f \leq 400 \qquad (36a)$$

$$= 0.45\ F^{0.284}\ d_f \quad \text{for } 0 \leq d_f < 14 \qquad (36b)$$

Equation 6 was found to be applicable to cases in which the ray path is blocked by dense, dry, in-leaf trees found in temperate-latitude forests. It is useful for values of d_f (the depth of trees) as large as 400 meters.

Comparisons between eight sets of measurements and predictions of the EXD and MED models are presented. It is seen that the rms prediction errors of the EXD model are 37, 27, 24, 15, 14, 13, 10, and 4 dB; the corresponding prediction errors of the MED model are 6, 9, 7, 8, 2, 7, 10, and 2 dB.

The problems for which other authors have found diffraction models to be applicable are discussed. These models can be used for geometries in which the majority of the signal propagates over, rather than through, the trees. The studies described pertain to the 25 MHz to 5 GHz band. Guidelines for choosing between the MED model and the diffraction model are presented. There is no documented criterion for choosing between the knife-edge and smooth-sphere diffraction models, however.

Kinase's empirical-theoretical model was found to be applicable to problems in which one antenna is located well above the foliage. The model is based on the assumption that the second antenna is in an area η% of which is covered with trees. η is an input parameter which can be varied from 1 to 50. Kinase's model is based on data in the 80-700 MHz frequency range.

The Jansky and Bailey empirical model was found to be applicable to problems in which both antennas are immersed in a tropical forest. Path lengths can vary from 8 to 1600 meters, frequencies from 25 to 400 MHz. Antenna heights should be less than 7 meters. A comparison between a limited set of measurements and predictions of the Jansky and Bailey empirical and a lateral-wave theoretical model is presented. In this comparison, the empirical model is seen to be more accurate. The theoretical model predictions were made using measured values of the electrical parameters of the forests in which the loss measurements were made. Use of effective values of the forest electrical parameters will increase the accuracy of the theoretical model, but no guidelines for choosing such parameters have been reported.

A review of tropical and nontropical measurements shows that, very often, the field strength at an antenna that is moved through foliage will be Rayleigh-distributed. Thus, circuit performance calculations should account for this multipath-fading behavior in addition to accounting for the median foliage loss. Equations for computing bit-error rates for signals subjected to frequency-flat Rayleigh fading are presented for FSK and PSK.

APPENDIX A

ALTERNATE FORMULATIONS FOR α FOR THE EXD MODEL

Section 2 of this report presents LaGrone's formula for α and shows how it compares with the modified exponential decay (MED) model and with measured values of loss. This appendix shows three alternate formulations of α. Each is based (for frequencies above 100 MHz) on Saxton and Lane's data (see Reference 7). Each represents a form of the exponential decay (EXD) model, i.e., α is described as being independent of distance. This appendix includes a comparison between the parameter sensitivities of these expressions, the MED model, and measurements.

In NBS TN 101 (see Reference 6), Rice presented this equation for α:

$$\alpha = 0.244 \log F + 0.290 \qquad \text{(A-1)}$$

where α is in dB/meter and F is the frequency in GHz.

In 1971, Rice presented (see Reference 15) a more elaborate graphic description. This is illustrated in Figure A-1.

The CCIR Plenary Assembly of 1976 (see Reference 10) approved the graph reproduced here as Figure A-2.[a]

Figures A-3 through A-5 show how these values of α compare with those predicted by the MED model (Equation 6). The MED values have been computed for $d_f = 50$ meters.

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[a] Krevsky developed a formula for α (see Reference 11) which was, for mid-latitude woods, $\alpha = .09\ F^{0.48}$. This was based on the assumption that the forest was a lossy dielectric. He suggested that the formula only be applied to signals at frequencies below 100 MHz. It is not considered in future discussions since they are concerned with frequencies higher than this.

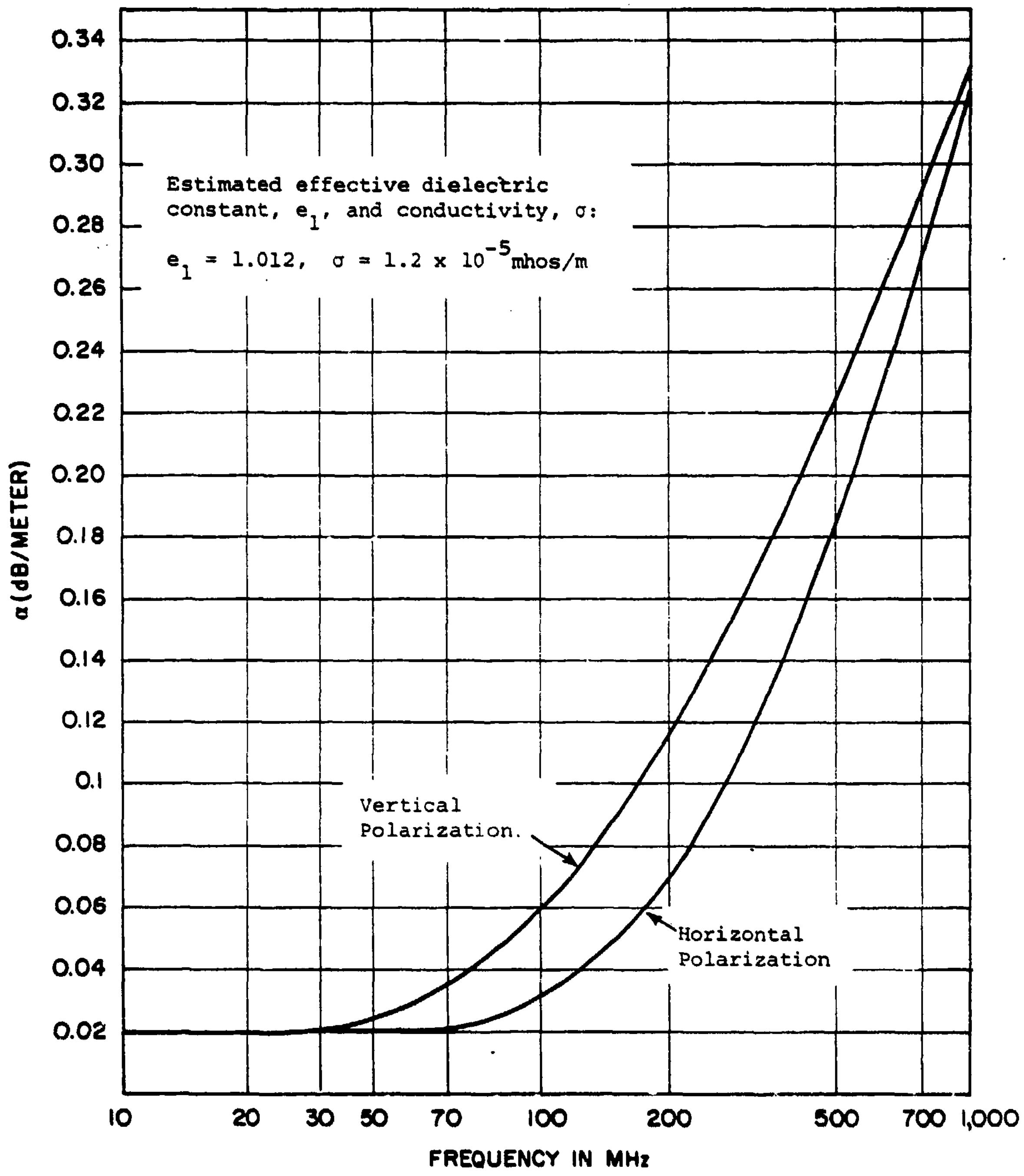
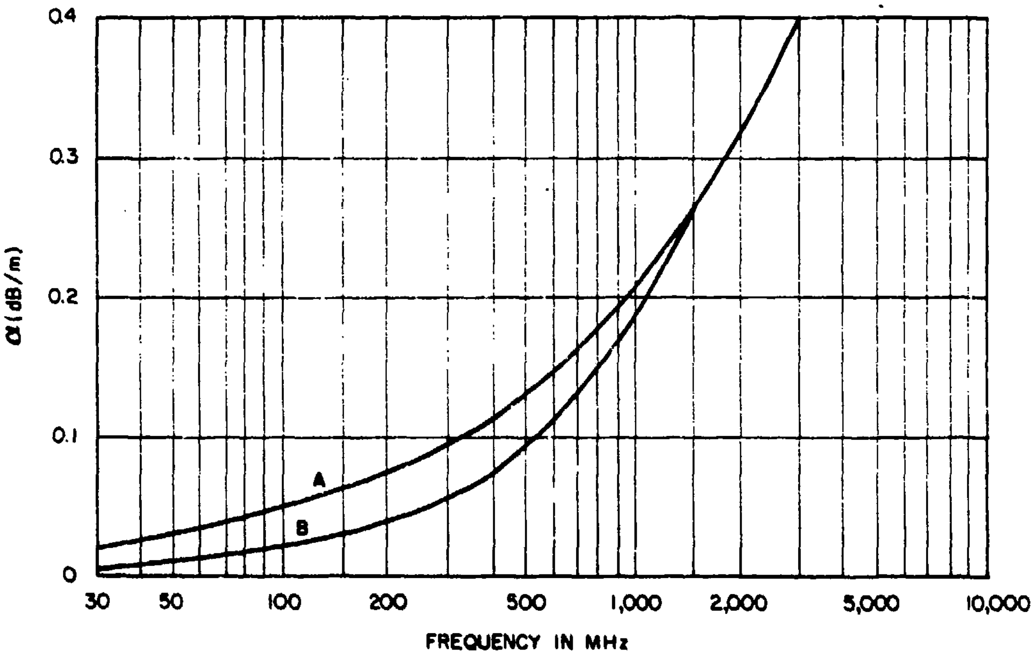


Figure A-1. Rice's 1971 representation of α (see Reference 15).



A: Vertical polarization.
B: Horizontal polarization.

Figure A-2. The representation of α accepted by the CCIR 1978 Plenary Assembly (see Reference 10).

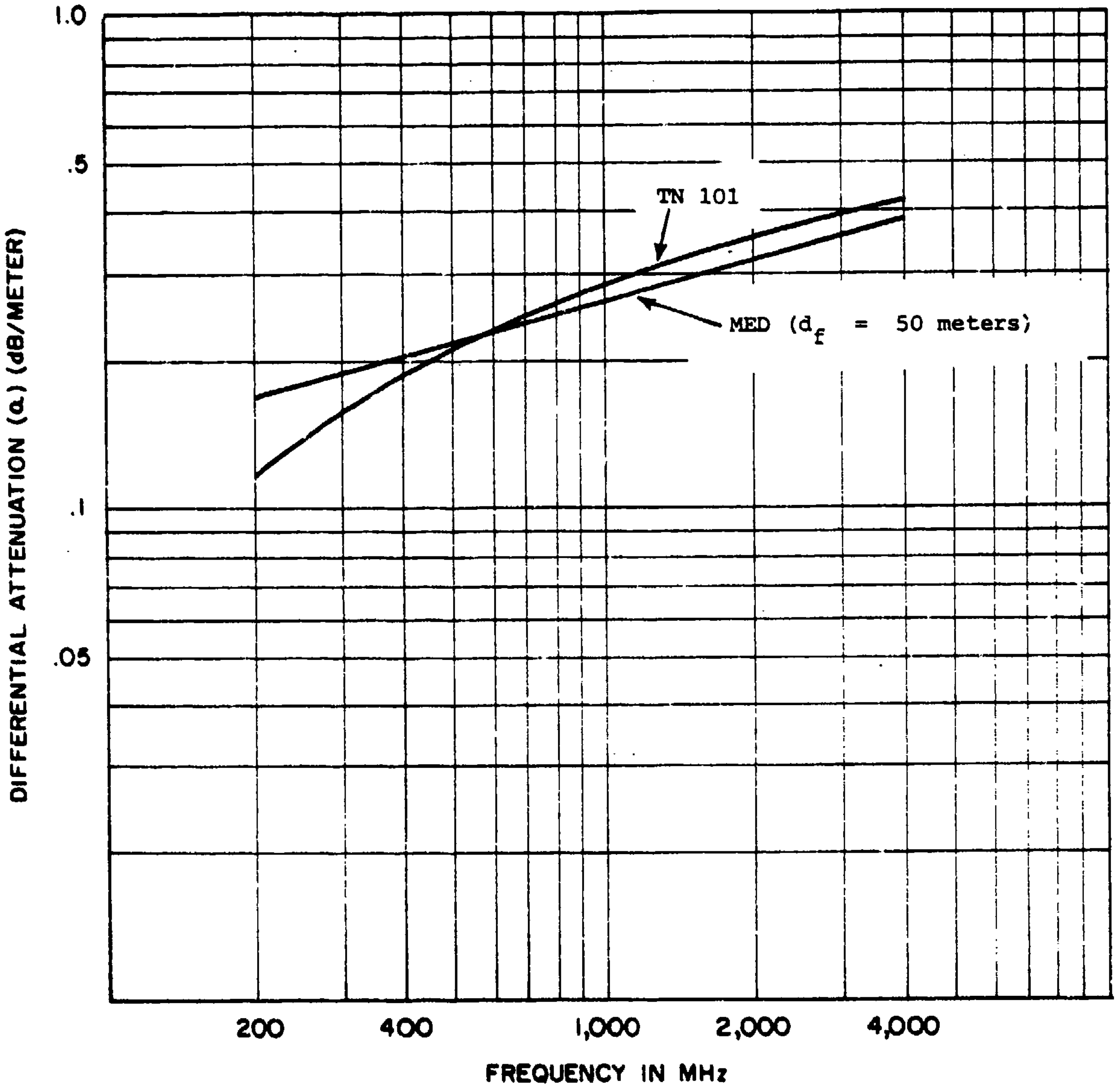


Figure A-3. The trend of α vs frequency for the TN 101 (see Reference 6) and MED (see Reference 1) models.

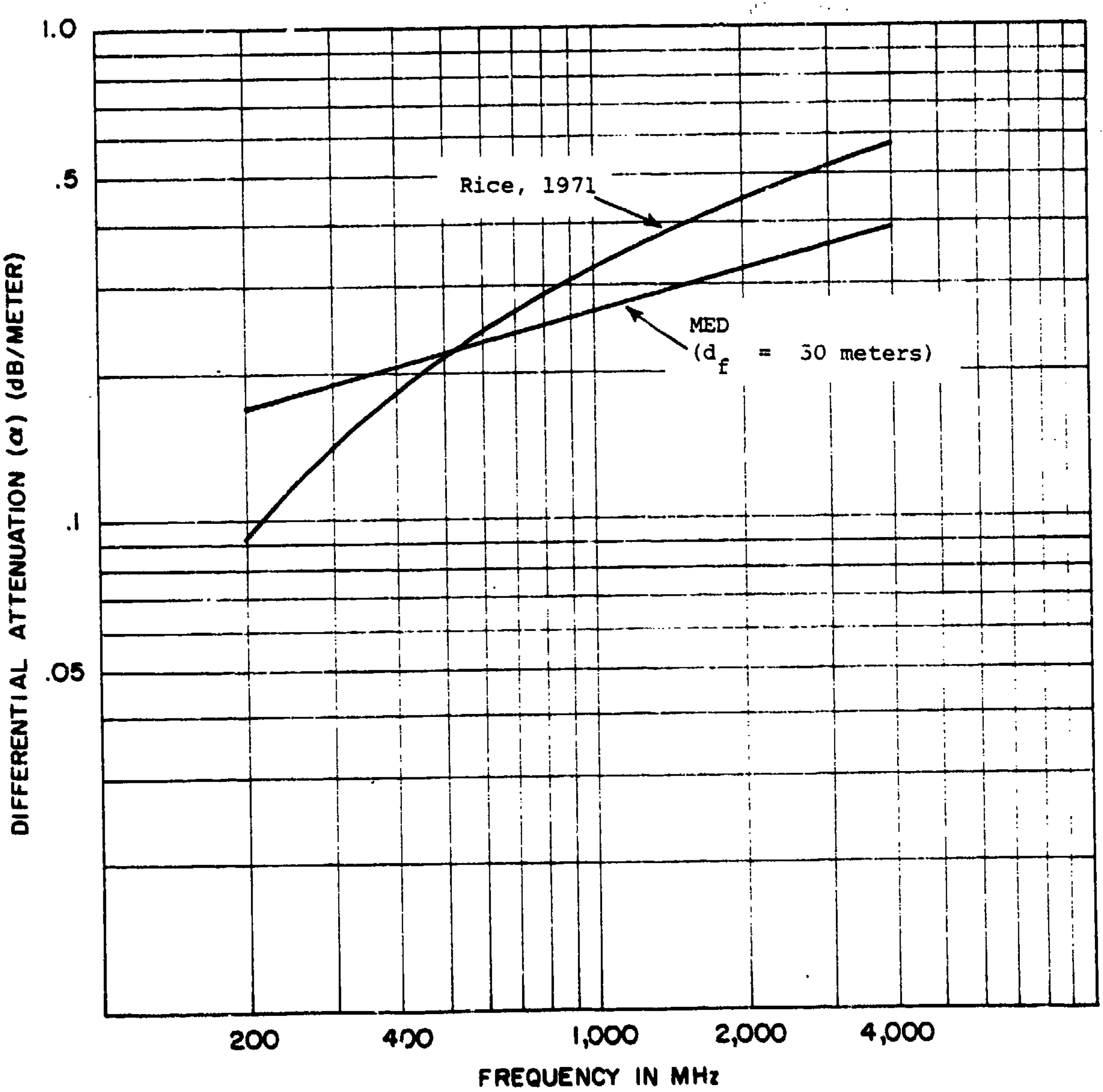


Figure A-4. The trends of α vs frequency for the 1971 Rice (see Reference 15) and MED (see Reference 1) models.

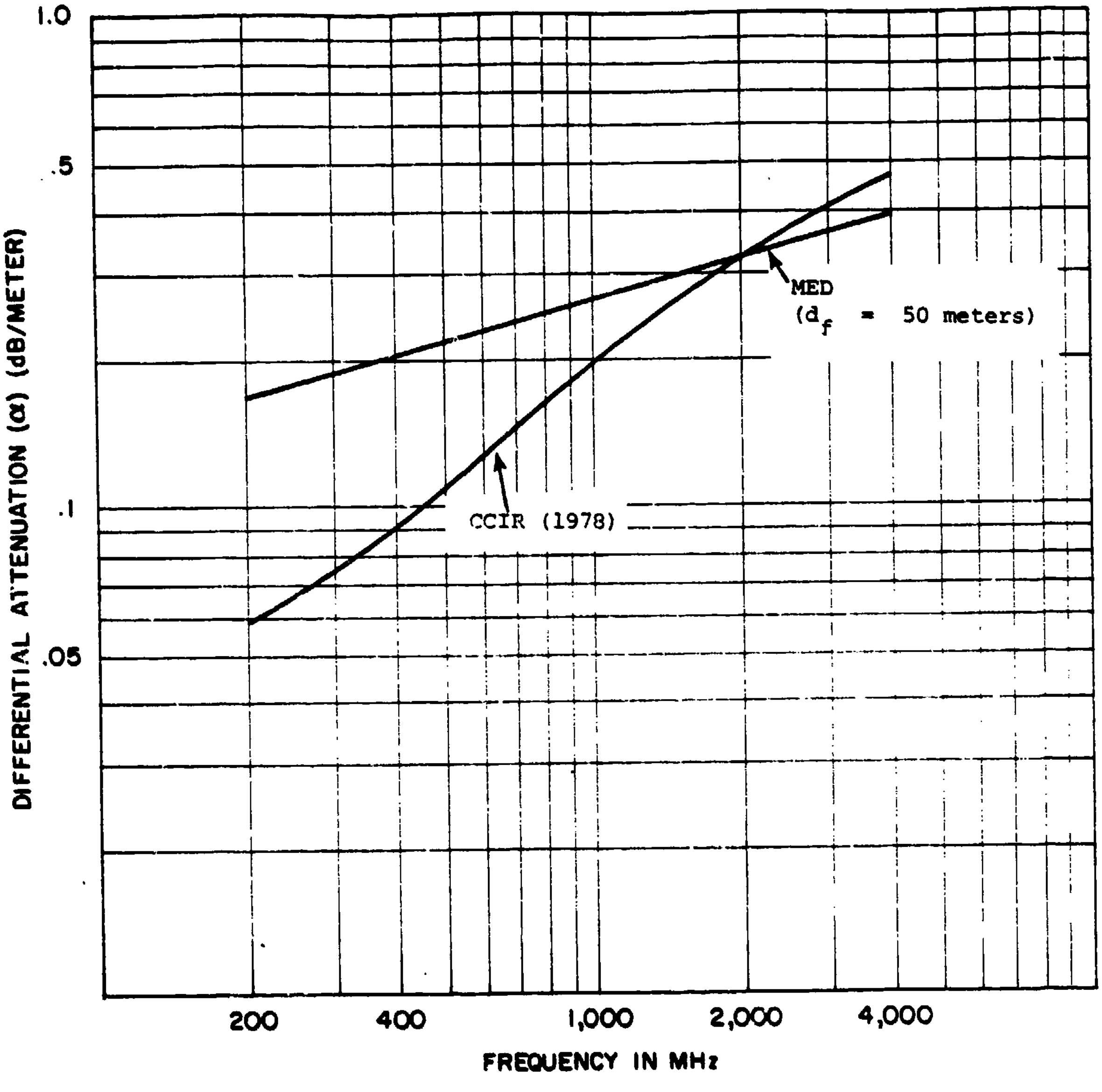


Figure A-5. The trends of α vs frequency for the CCIR 1978 Plenary Assembly (see Reference 10) and MED (see Reference 1) models.

The variation of α with the depth-of-trees is the same for these EXD formulations as it is for Equation 5, LaGrone's EXD model. Therefore, the comparisons shown previously in Figures 3 through 7 in Section 2 apply to these formulations. Again the MED model provides a more realistic representation of the measured trends for tree depths greater than about 14 meters. The models are equivalent in accuracy for tree depths less than 14 meters.

Figures A-3 through A-5 and Figure 13 allow a graphic comparison between the loss versus frequency trends of each of the EXD formulations and the MED model. TABLE A-1 provides a quantitative description of the differences.

TABLE A-1

PERCENT INCREASE IN LOSS DUE TO PROPAGATION THROUGH FOLIAGE THAT OCCURS WHEN THE FREQUENCY IS INCREASED FROM 200 TO 4000 MHz

Model	MED	TN 101	Rice-71	CCIR-78	Saxton-Lane-LaGrone
Percent Increase	130	270	520	700	900

In Section 2, it is demonstrated that the loss-versus-frequency trend predicted by the MED model ($F^{0.284}$) was more accurate than that predicted by the Saxton-Lane-LaGrone EXD model ($F^{0.770}$). TABLE A-1 indicates that this version of the EXD model represents somewhat of an extreme in comparison with the TN 101, Rice-71, and CCIR-78 formulations. The question of the relative accuracies of the MED and the other EXD formulations (with regard to frequency trend) arises. Time constraints precluded comparisons with all three alternatives, but a comparison with the TN 101 (0.244 log F) procedures was carried out. The results are shown graphically in Figure A-6 through A-9. A quantitative summary of these results, and those provided earlier in Section 2.5.3, appears below in TABLE A-2. It is seen that the MED procedure predicts all of the measured loss trends more accurately than either of the two EXD formulations. Section 2 contains a possible explanation of why this is so.

TABLE A-2

A COMPARISON OF THE RMS ERRORS OF THREE MODELS
WHEN THEY ARE USED TO PREDICT LOSS-VS-FREQUENCY TRENDS

Data Description	Model Type		
	MED	TN 101	Saxton-Lane-LaGrone
Deciduous forest, Colorado, 200 - 4500 MHz horizontal polarization, d_f = 14 - 15 meters	26%	34%	54%
As above, d_f = 60 meters	24%	28%	76%
Mangroves, Australia, 150 - 1500 MHz, vertical polarization, d_f unknown	7%	25%	51%
Deciduous and coniferous woods, Georgia, 9 - 95 GHz, both polarizations, d_f = 4 - 6 meters	16%	25%	39%
	Rms Error of Predicted Trend (Computed with Equations 8 and 10)		

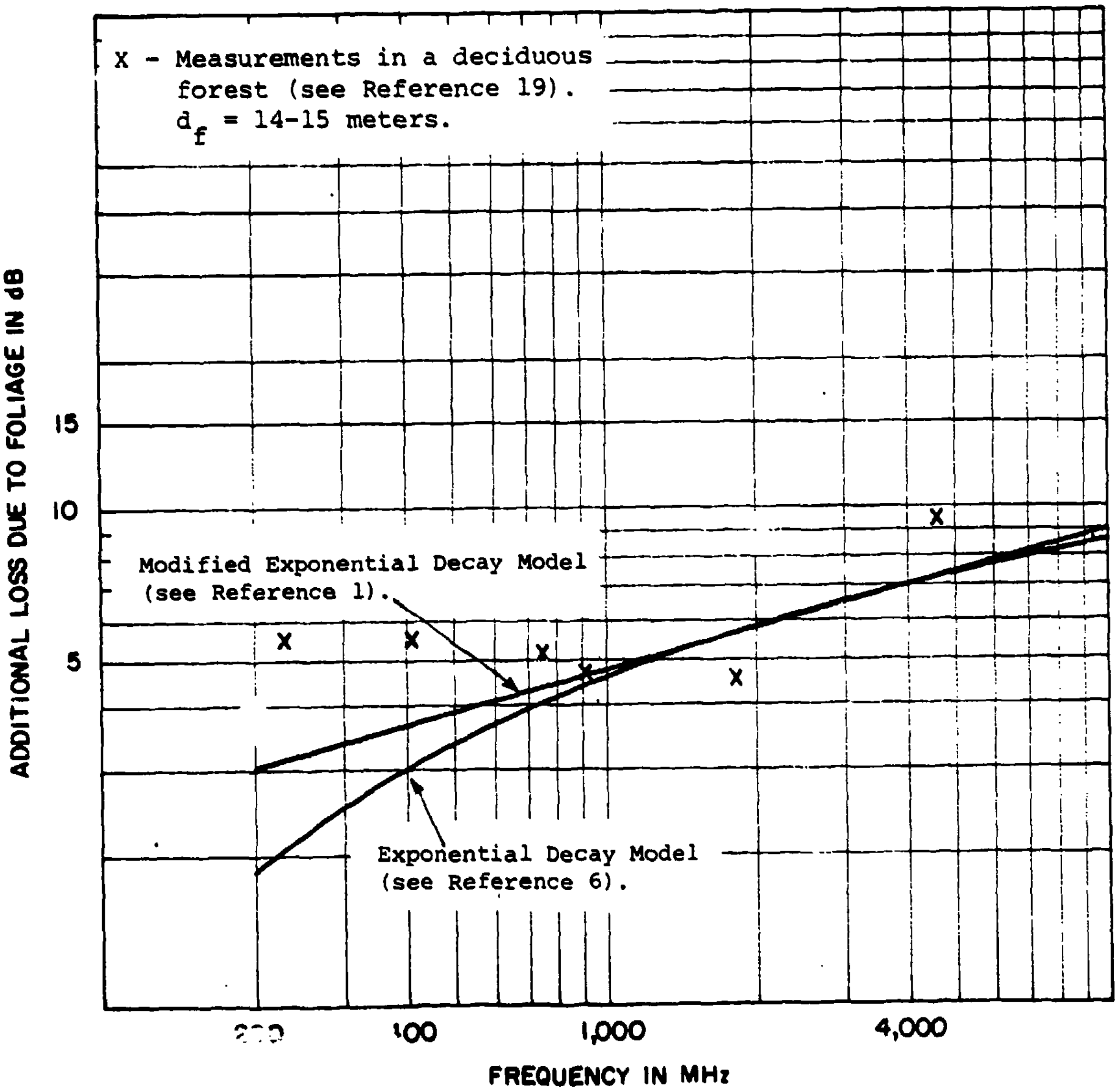


Figure A-6. Illustration comparing the trends of loss vs frequency predicted by two models with the measured values of trend. The rms error of of MED model is 26%. The error of the TN 101 model is 34%.

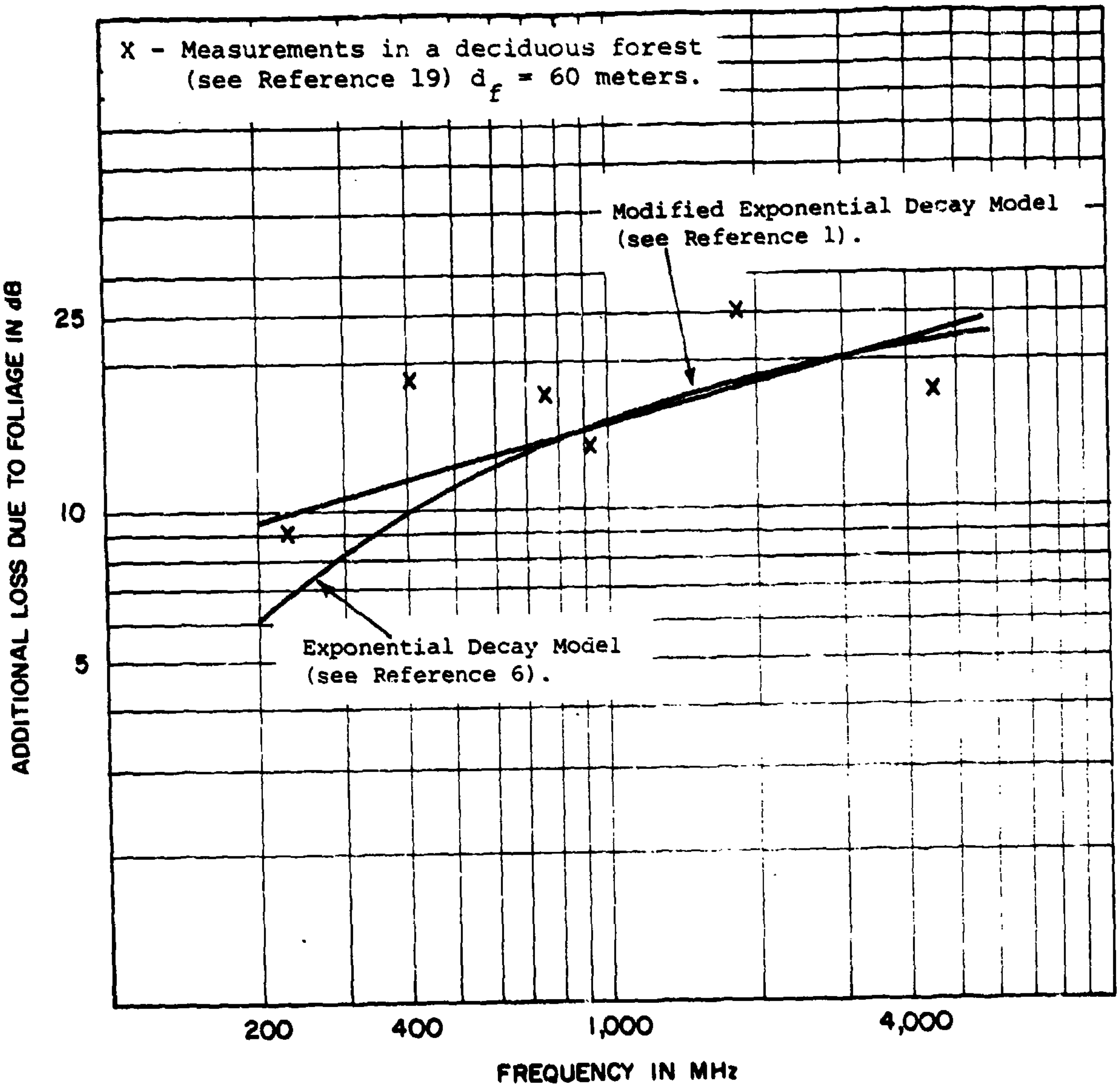


Figure A-7. Illustration comparing the trends of loss-vs-frequency predicted by two models with the measured values of the trend. The rms error of the MED model is 24%. The error of the TN 101 model is 28%.

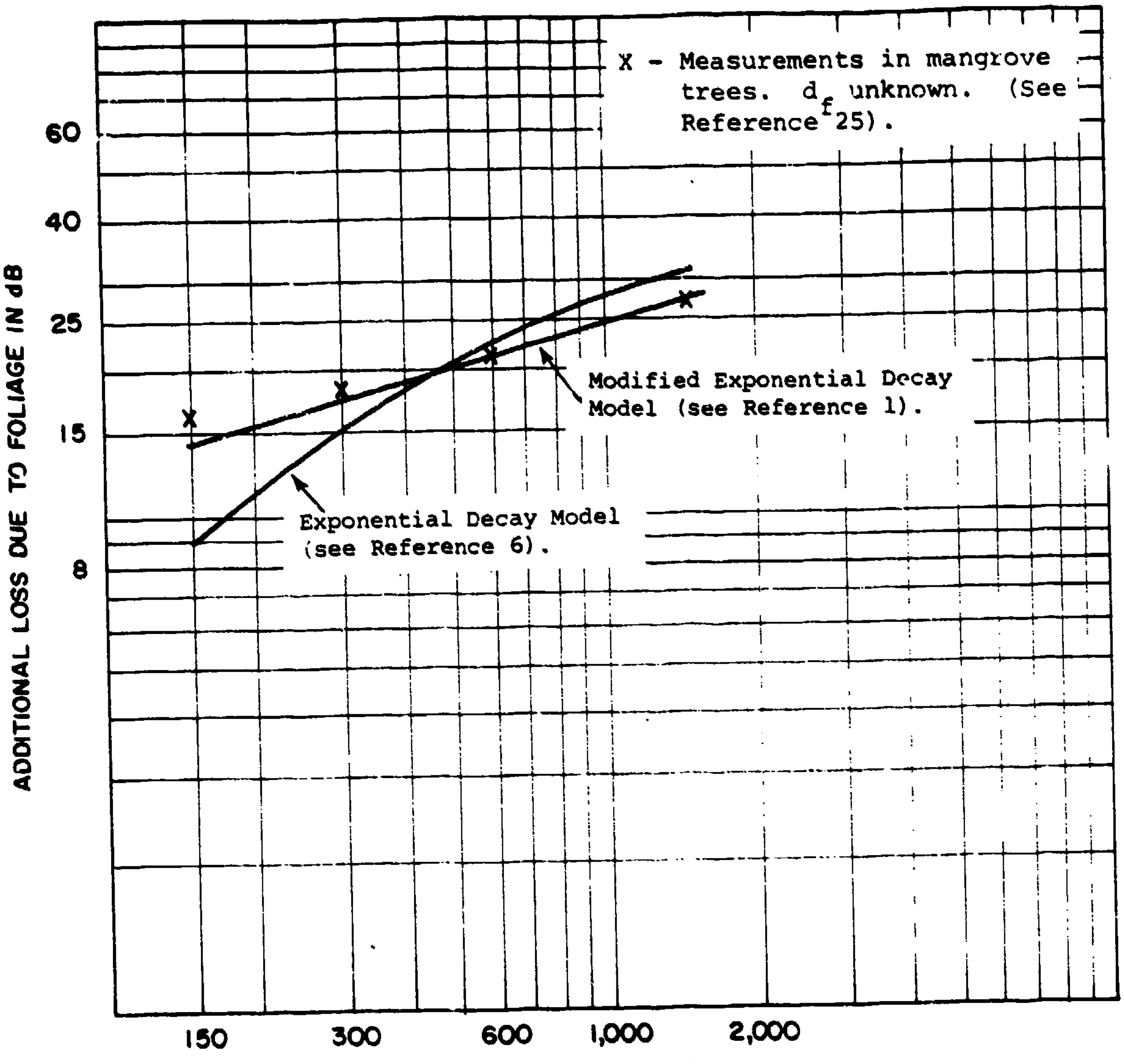


Figure A-8. Illustration comparing the trends of loss vs frequency predicted by two models with the measured values of the trend. The rms error of the MED model is 7%. The error of the TN 101 model is 25%.

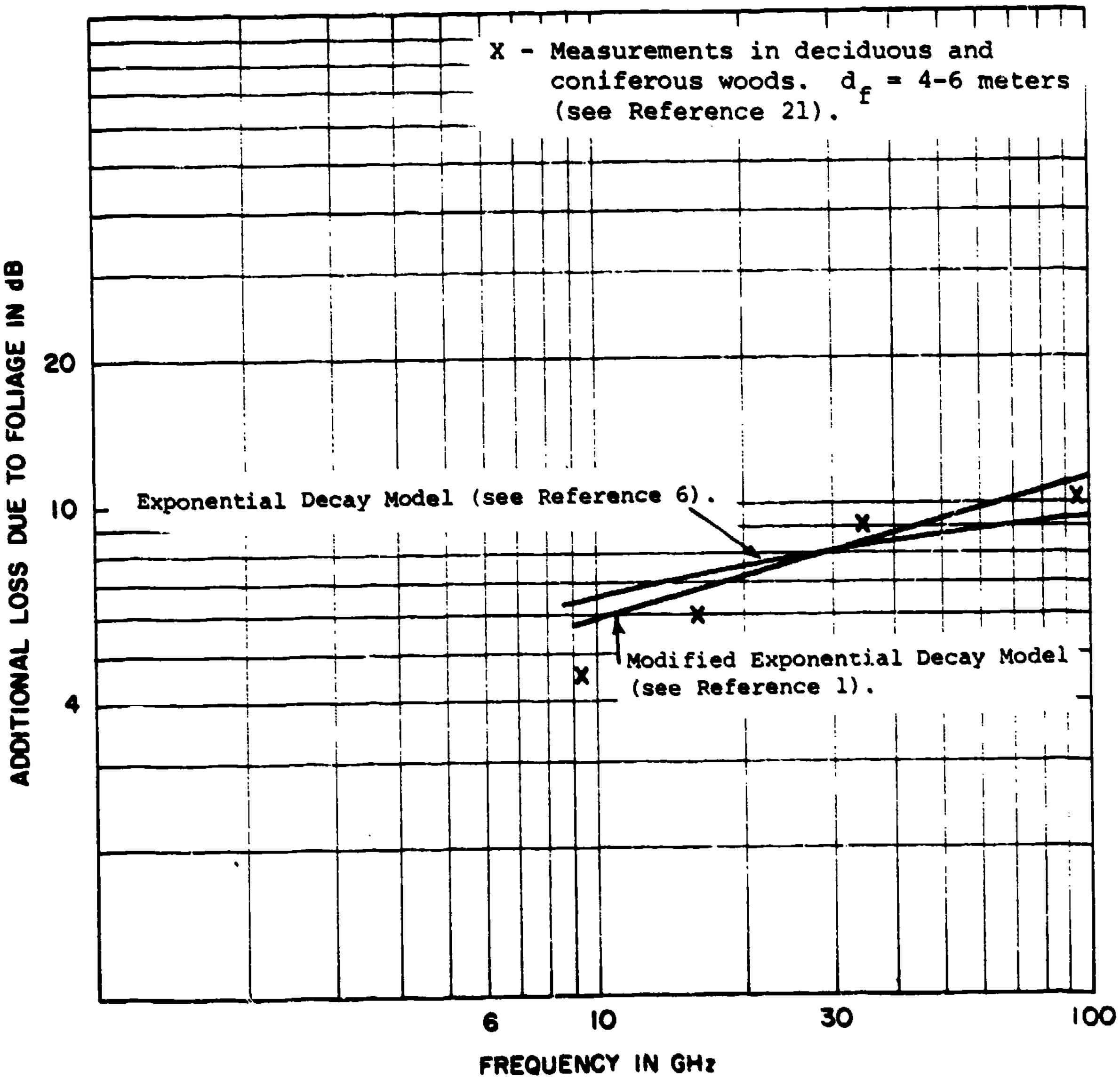


Figure A-9. Illustration comparing the trends of loss vs frequency predicted by two models with the measured values of the trend. The rms error of the MED model is 16%. The error of the TN 101 model is 25%.

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