Radio Wave Propagation Through Rain Forests of India

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Abstract—**A radio wave attenuation measurement program was undertaken in tropical rain forests of India at frequencies from 50 to 800 MHz, antenna heights from 1.5 to 16.5 m above the ground with both horizontally and vertically polarized emissions, and at various separation distances varying from 40 to 4000 m. The results of these studies are presented, discussed, and an empirical model derived from these measurements is suggested.**

Introduction

THE PRESENCE OF forest foliage along a radio path causes attenuation of radio waves and results in reduction of communication range of the radio equipment. A quantitative knowledge of excess propagation loss suffered by the radio waves due to the presence of foliage is essential for planning a communication link in any forested terrain. Trevor [1], Herbstreit and Chrichlow [2], [3], Bateman *et al.* [4], Whale [5], McPetrie and Ford [6], Saxton and Lane [7], Head [8] and Lagrone and Chapman [9] conducted studies on radio wave attenuation characteristics of forests. The Jansky and Bailey Division of the Atlantic Research Corporation conducted extensive radio wave propagation measurements in tropical rain forests of Thailand [10]–[13]. Sachs and Wyatt [14], Tamir [15] and Dence and Tamir [16] suggested theoretical models to deal with the radio wave propagation in forests and explained the associated phenomenon with the help of lateral-wave mode of propagation. Because no such study had ever been carried out in Indian forests, extensive measurements were conducted in subtropical pine forests [17], tropical moist deciduous forests [18], and tropical wet evergreen forests [19] to determine the attenuation caused by forest foliage as a function of frequency, distance, polarization, antenna height and type of foliage. The measurements were carried out at four spot frequencies in the VHF/UHF range and for horizontal and vertical polarizations. Special cross-polarization measurements were also performed to study this phenomenon [20]. The composite picture of the propagation studies conducted by the authors in Indian forests is described in this paper.

Manuscript received June 24, 1987; revised November 10, 1988. This paper was presented at the 1986 International IEEE Antennas and Propagation Society Symposium and USNC/URSI Meeting, Philadelphia, PA, June 9–13, 1986.

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IEEE Log Number 9034319.

Description of the Forests

A variety of forests are found in northern India, but a tropical, moist deciduous forest and a tropical, wet evergreen forest were chosen for these measurements due to their high density. The reserve forest near Dehradun, which is a tropical, moist deciduous forest, was chosen for these measurements. It was a very dense forest over a flat terrain with tall trees and thick low level foliage located in an area with an average annual rainfall of 1830 mm. The main species of trees found in this forest were Shorea Rubusta, Moringa Oleifera, Ougeinia Cokeinensis and Syzygium Cumini. The average height of the trees was about 20 m and average tree trunk diameter was about 45 cm. The average canopy diameter was about 5 m. The density of the forest was about 150 trees per acre, and the height of the undergrowth was somewhere between 2 and 3 m. The trees in this forest were deciduous and hence shed their leaves during the spring season. Measurements were conducted during the season when the trees had shed their leaves and then the measurements were repeated immediately after the rainy season when the trees were in full leaf.

A tropical evergreen forest growth over fairly level terrain stretching to about 4 km was selected at the foothills of the Himalayas in Assam. This was a very dense forest with tall trees having thick underbrush and an annual rainfall of 3000 mm. The undergrowth was so heavy that it could be trodden only after a modest amount of path cutting. The two main species of trees found in this forest were Dipterocarpus and Shorea Assamica. The average height of the trees was about 25 m and their average diameter about 50 cm. The average canopy diameter was about 4.5 m. The height of the undergrowth was somewhere between 3 and 4 m. The density of the forest was 164 trees per acre.

Experimental Details

Experiments were performed in these forests to determine the absolute and relative magnitudes of the attenuation caused by the forest growth as a function of frequency, distance, polarization and antenna heights. The measurements were conducted in three phases, twice in the Dehradun forest and once in Assam forests. Airborne Instrument Laboratory (AIL) power signal source type 125 was used as the transmitting source for measurements at 200, 500, and 800 MHz whereas for 50 MHz transmission a continuous wave (CW) transmitter was designed and fabricated. Half-wave dipole antennas were used for transmission in horizontal and vertical modes of polarizations. The height of the transmitting antenna, mounted

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on a pneumatic mast, could be varied from 3.95 to 16.45 m. A Bird thruline power meter was used for measuring the incident as well as the reflected power for estimating the effective radiated power.

A Rhode and Schwarz field-strength meter (type ESU) with a wide-band log-periodic antenna was used for measuring the received signal at 200, 500, and 800 MHz. A wide-band dipole was used for the measurements at 50 MHz. The receiving antenna height could be varied from 1.5 to 3.5 m above the ground. Fifteen receiving points were chosen at varying distances (from 40 m to 4 km) from the fixed transmitting point in such a way that all the receiving and transmitting points were fully immersed in foliage. Measurements were confined to a maximum separation distance of 4 km and a maximum antenna height of 16.45 m to make the results of the observations applicable to short range, mobile, or manpack communication.

Under the experimental program, field strength was measured at four frequencies, two polarizations, four transmitting antenna heights and three receiving antenna heights, resulting in 96 combinations of system parameters for each selected distance between transmitting and receiving locations. There were 15 receiving points in each of the three phases of the experimentation resulting in 4320 measurements of received field strength which were the averaged values of six repetative measurements for the specific combination of system parameters. In addition to these co-polar measurements, cross-polar measurements were also accomplished to study this phenomenon in the presence of vegetation [20]. This yielded another 1000 measured values of signal strength.

The data were collected in the form of manually tabulated field notes and reduced to basic transmission loss (L_B) values for further analysis. No clear and consistent difference in the data for the three phases of measurements in different forests was noticeable and hence the data were combined and the "composite" data were obtained. To reduce the number of curves to a managable amount it was decided to normalize the transmission loss values for antenna height product $H_t \cdot H_r = 25$ (transmitting antenna height being H_t m and receiving antenna height H_r m) and to study the variation of L_B as a function of distance, frequency, and polarization. The effect of the antenna height on the transmission loss was studied separately [21].

Results and Discussions: Basic Transmission Loss and Distance Dependence of Basic Transmission Loss

The variation of basic transmission loss L_B with distance for horizontally and vertically polarized waves is shown in Figs. 1 and 2. These curves show two distinctly different trends of distance dependence of L_B over the entire distance range of measurements. In general, it was observed that up to a nominal distance, somewhere around 400 m from the transmitter, the loss increases exponentially, beyond which the variation in L_B was found to be logarithmic. It was inferred that for shorter distance, the energy reached the receiving antenna entirely by propagating through the forest resulting into an exponential increases in L_B. Beyond a nominal distance of 400 m, the signal at the receiving antenna reached partially by propagating through the forest and partially by lateral-wave mode.[1] As the distance increased, the contribution of the lateral wave was more predominant than that of the wave through the forest. The overall effect was that the loss varied with distance as 40 log d, as experimentally observed and shown in Figs. 1 and 2. These observations were in conformity with the lateral-wave model suggested by Tamir [15] and the experimental results of Jansky and Bailey [10]–[13] wherein the lateral-wave predominance was experimentally noticed at distance larger than about 320 m. However, at 50 MHz, the exponential decay of the field at short distances was not evident from these measurements.

It may be mentioned here that the changeover from exponential to logarithmic decay was not always at 400 m distance. In the large database containing various sets of measurements, the changeover was found to be between 350 to 450 m distance. With this in view, a fixed receiving location at 400 m from the transmitting antenna was chosen for repeating all the sets of measurements and this distance was normalized for smoothening the curves later.

The standard deviation of the measured data around their mean tendencies plotted in Figs. 1 and 2 are given in Table I. The deviation was found to vary from 2.32 dB to as high as 5.71 dB. It was also found to be higher for vertically polarized waves than horizontally polarized waves. This could be due to the greater interaction between vertically polarized waves and the vertical tree trunks resulting into greater scattering as well as higher depolarization of radio waves.

Basic Transmission Loss Model

To take into account both types of propagation modes, the following empirical model is suggested:

$$L_B = -27.57 + 20 \log f - 20 \log \left[\frac{Ae^{-\alpha d}}{d} + \frac{B}{d^2}\right] \quad (1)$$

where

L_B	predicted basic transmission loss (dB)
f	frequency (MHz)
d	separation distance (m)
A, B	constants evaluated from the measured data
α	constant describing the rate of attenuation (dB/m).

The last term in (1) denotes the distance dependence of L_B. The factor $Ae^{-\alpha d}/d$ indicates the superimposition of an exponential factor above the 20 log d increase for initial separation distances of about 400 m. The factor B/d^2 corresponds to the 40 log d increase in L_B for larger distances, which essentially is the characteristics of the lateral waves.

The constants α, A, and B were evaluated by forcing (1) to pass through the composite experimental data on L_B, and are listed in Table II.

At 50 MHz frequency for both the polarizations, the con-

[1] Note, however, that from the theoretical viewpoint the lateral-wave mode concept is difficult to justify at the higher test frequencies (500 and 800 MHz), even though the experimental results seem to conform with this model; see discussions at the end of the next section.

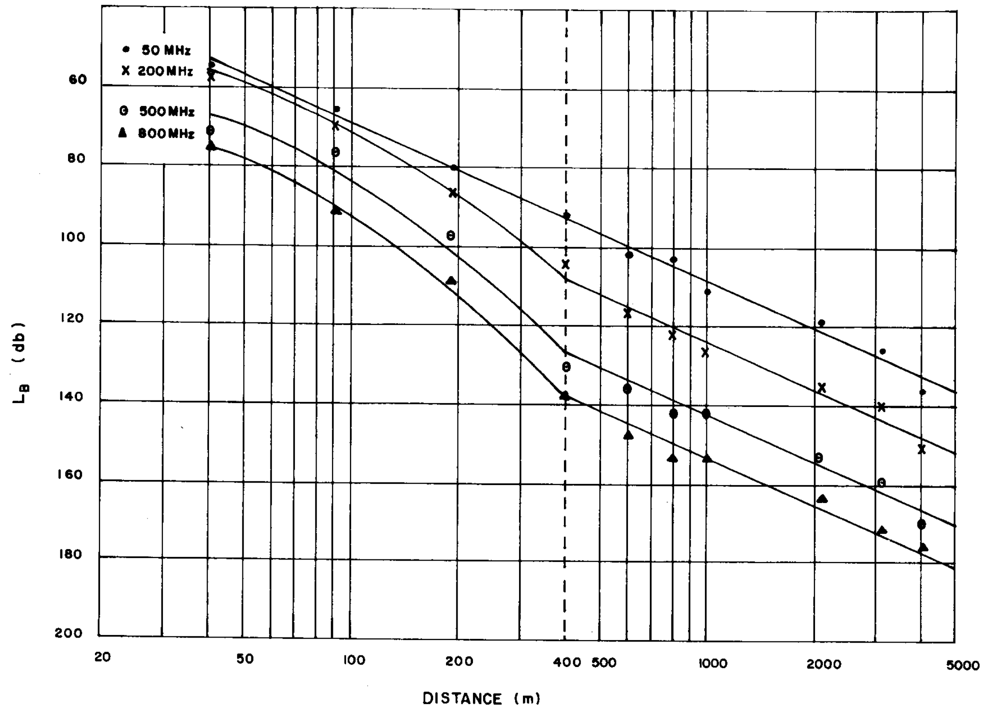

Fig. 1. Distance dependence of basic transmission loss (horizontal polarization).

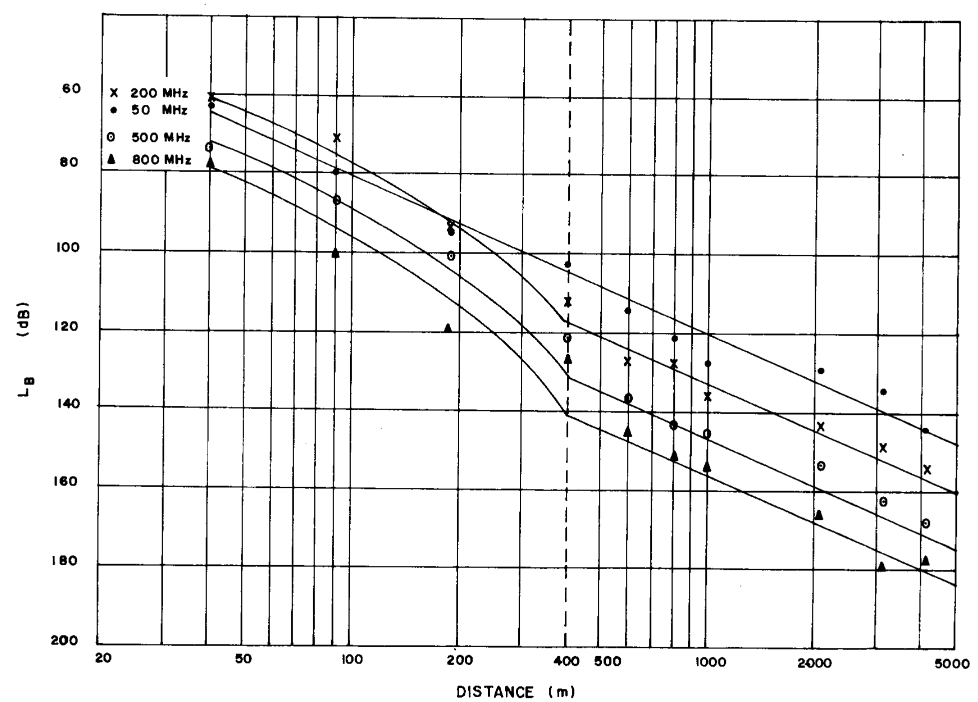

Fig. 2. Distance dependence of basic transmission loss (vertical polarization).

TABLE I
STANDARD DEVIATION OF THE MEASURED L_B DATA (dB)

	Frequency (MHz)			
Polarization	50	200	500	800
Horizontal	5.51	3.63	2.32	2.93
Vertical	5.71	3.83	2.48	2.57

TABLE II

Frequency (MHz)	Polarization	α (dB/m)	A	B
50	H	—	0	7.3670
200	H	0.0110	0.8201	5.0450
500	H	0.0138	0.6571	1.4304
800	H	0.0152	0.4491	0.6291
50	V	—	0	1.9170
200	V	0.0125	0.4989	1.8358
500	V	0.0135	0.3658	0.9040
800	V	0.0140	0.2661	0.5331

stant A in (1) is set equal to zero since the exponential decay at 50 MHz is not so apparent. Instead, L_B at this frequency is found to closely follow a consistent 40 log d increase over the entire distance range of 40–4000 m.

The graphical representation of the suggested empirical model for basic transmission loss as a function of distance for various frequencies and polarizations are shown as dashed curves in Figs. 3–10. The two irregular curves, shown by bold lines in these figures, are the envelopes of maximum and minimum L_B values experimentally determined for the three types of forests. A good agreement between the suggested model and the mean tendencies of the experimental data has been noticed.

The suggested empirical model is essentially based upon the lateral wave theory suggested by Tamir [15], which should be appropriate at the 50 and 200 MHz frequencies. But at higher frequencies (500 and 800 MHz) the approximations involved in this theory no longer seem to be justified. The interface between the canopy and the air-region above it is very rough at these frequencies, and should not support the lateral wave as assumed in the theory. However, the present measurements, even at higher frequencies, indicate that the attenuation rate is significantly reduced at large distances and that the excess vegetation loss becomes practically constant. It was not possible to identify from the available data the exact propagation mechanism which produced such results. Even the results of Jansky and Bailey [10]–[13] show such behavior up to 400 MHz frequency.

Based upon the results of Jansky and Bailey [10]–[13], Tamir [15] concluded that lateral wave seems to be tied to the tree-top line and is therefore capable of following its contour even if the vegetation extends over a terrain with certain amount of curvature due to hills or other obstructions. These conclusions were drawn from the measurements at sites which contained peaks of the order of 300 m, which created conditions adverse to the lateral wave mechanism. The results still pointed toward the existence of lateral wave theory.

SCATTER OF THE DATA

Large scatter in the experimentally obtained data from their mean tendencies was observed from the estimation of the standard deviation as well as the curves plotted in Figs. 3–10. Such large fluctuations in the case of radio wave propagation through forest are not unexpected due to the reasons described below.

LACK OF HOMOGENEITY OF FOLIAGE

The forest foliage is randomly distributed and shows asymmetry in azimuth as well as in elevation which results into the variation of the path loss suffered by radiowaves at different separation distance. Since all the receiving points chosen for the present measurements were not on a straight line from the transmitting terminal, the measurements taken at different azimuthal ranges varied because the amount of foliage (in the form of wood, bark and leaves) encountered on the ray path got altered. When the radio waves of higher frequencies (lower wavelength) probed the forest medium, the inhomogeneity looked larger.

VARIATION IN FOLIAGE PROXIMITY OF ANTENNA

The change in the foliage environment at close proximity of the antenna causes change in the radiation pattern of the antenna. During the course of measurements the receiving antenna was always in a different environment, when it was moved from one point to another. This caused deviations in the measured values of received field strength. This proximity in terms of wavelength was also different for antennas at different frequencies.

SCATTERING OF RADIO WAVES

The lateral waves are essentially a scattered field and hence the scattering of radio waves also resulted in wide fluctuations in the measured data. The presence of scattered field was confirmed by the authors during these measurements. When the receiving antenna was displaced within a small sector of few wavelengths, a significant variation of field strength (5–10 dB) was recorded. This variation in the field strength was attributed to the ever changing resultant field vector at the receiving antenna and the change in the direction of arrival of maximum signal. This aspect was taken care of by first aligning both the transmitting as well as the receiving antennas for maximum power transfer, before manually recording the received field strength data in every situation. This maximum power transfer alignment, in many cases, was not the optical line-of-sight alignment of the direction of the maximum antenna gains.

EFFECT OF ANTENNA BEAMWIDTH

The received field strength is constituted of the energy reaching the receiving antenna by way of direct ray, reflected ray, diffracted ray and scattered ray. These different components may arrive off axis at the receiving antenna and their magnitude, phase, and polarization randomly distributed. The

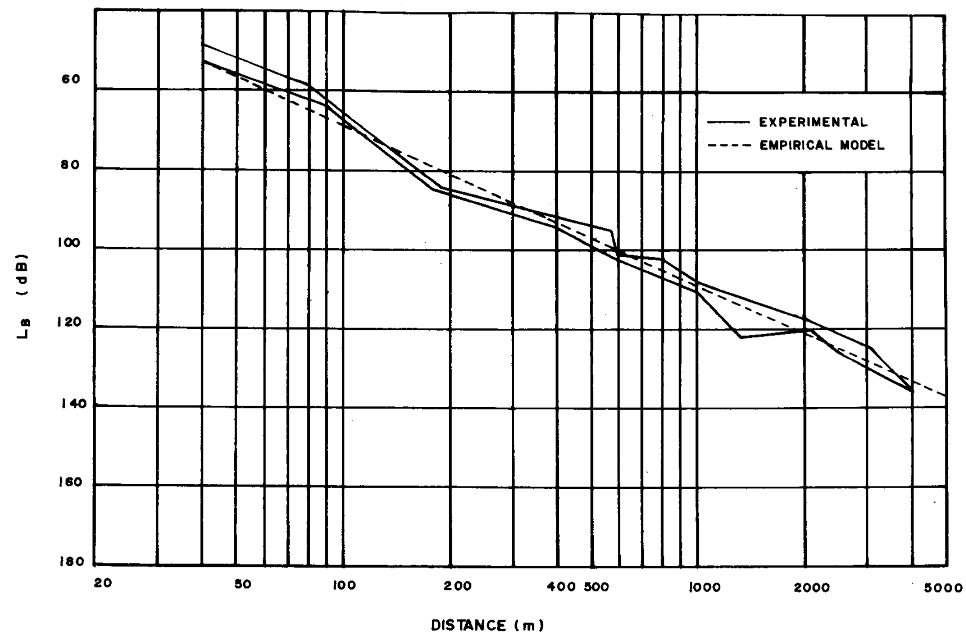

Fig. 3. Comparison of empirical model with experimental data (50 MHz, horizontal polarization).

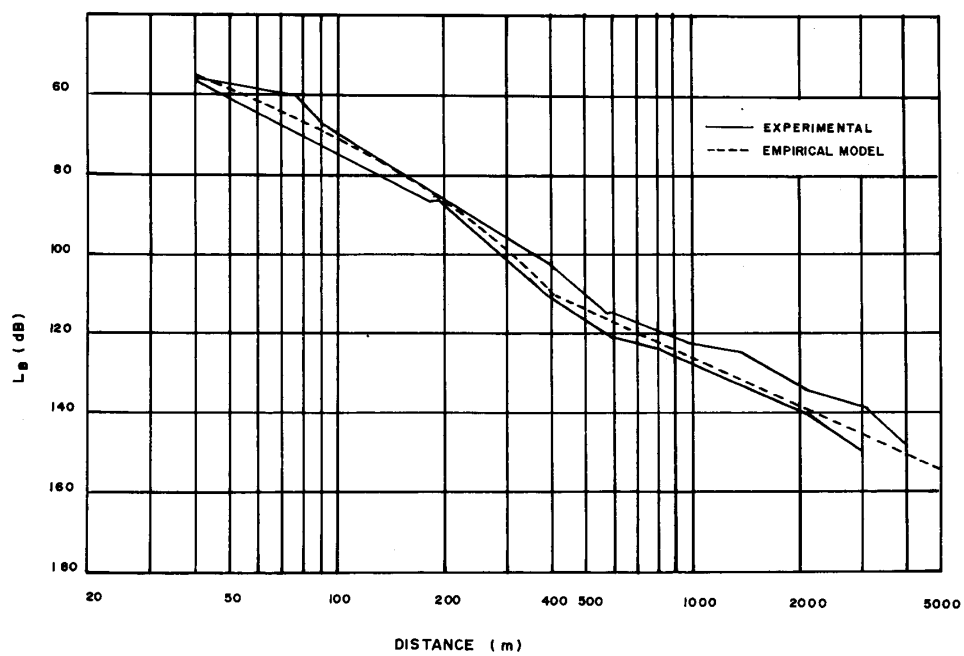

Fig. 4. Comparison of empirical model with experimental data (200 MHz, horizontal polarization).

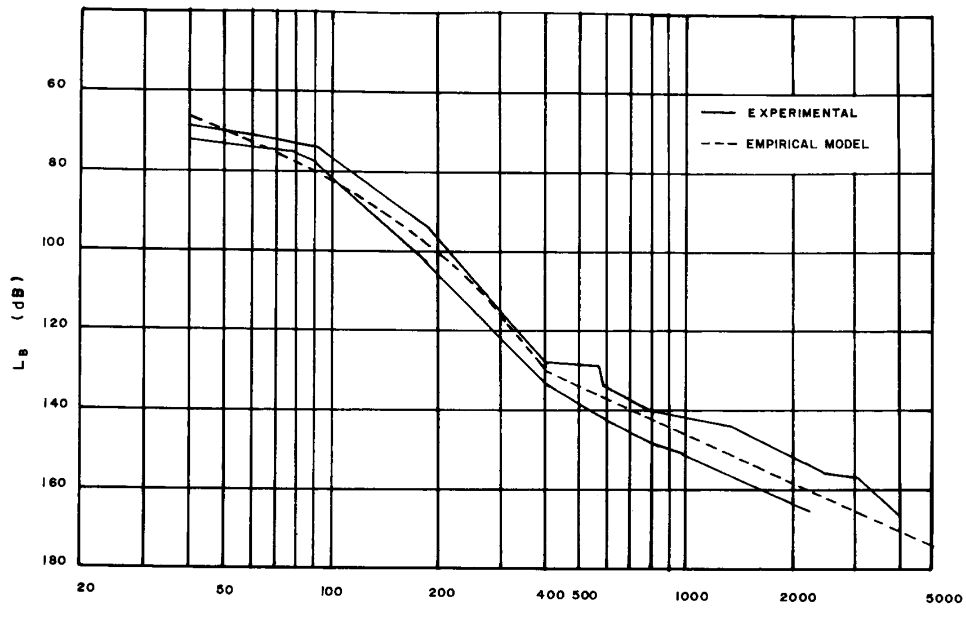

Fig. 5. Comparison of empirical model with experimental data (500 MHz, horizontal polarization).

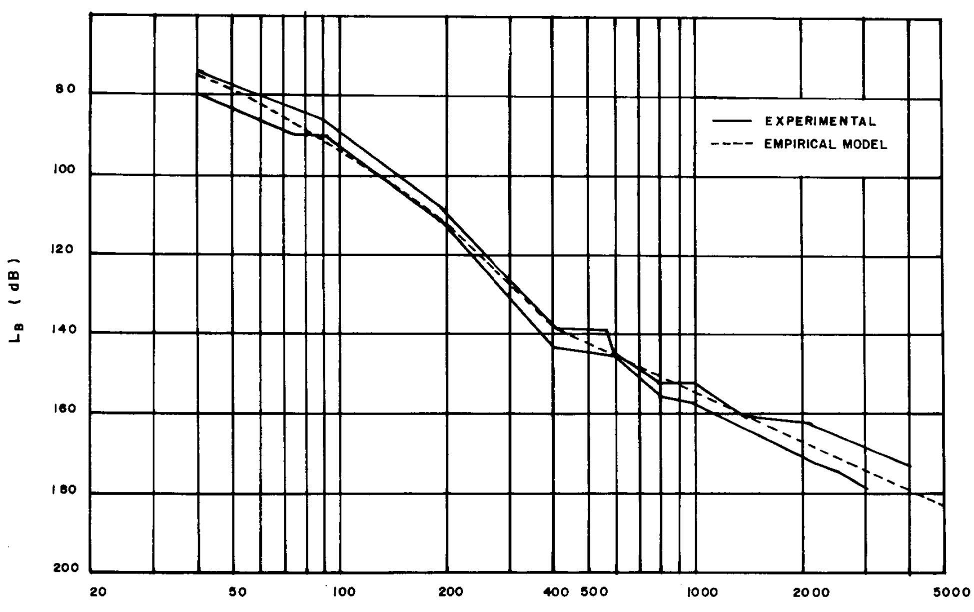

Fig. 6. Comparison of empirical model with experimental data (800 MHz, horizontal polarization).

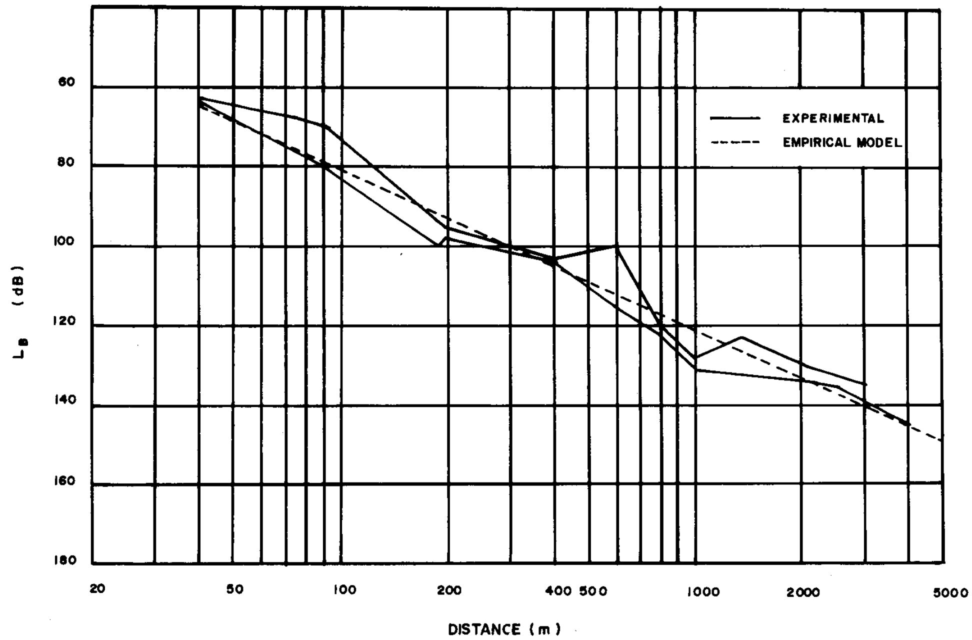

Fig. 7. Comparison of empirical model with experimental data (50 MHz, vertical polarization).

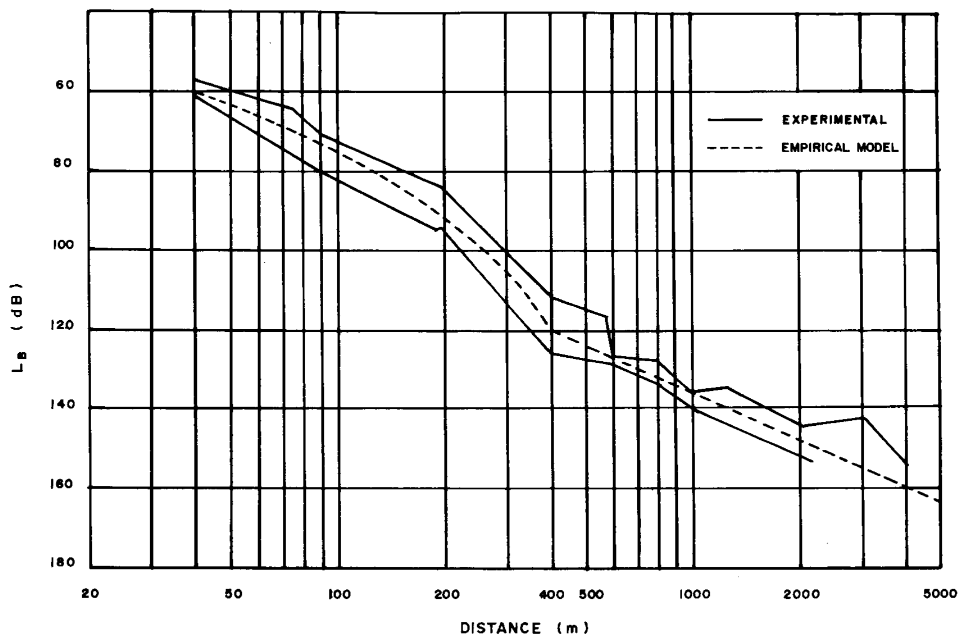

Fig. 8. Comparison of empirical model with experimental data (200 MHz, vertical polarization).

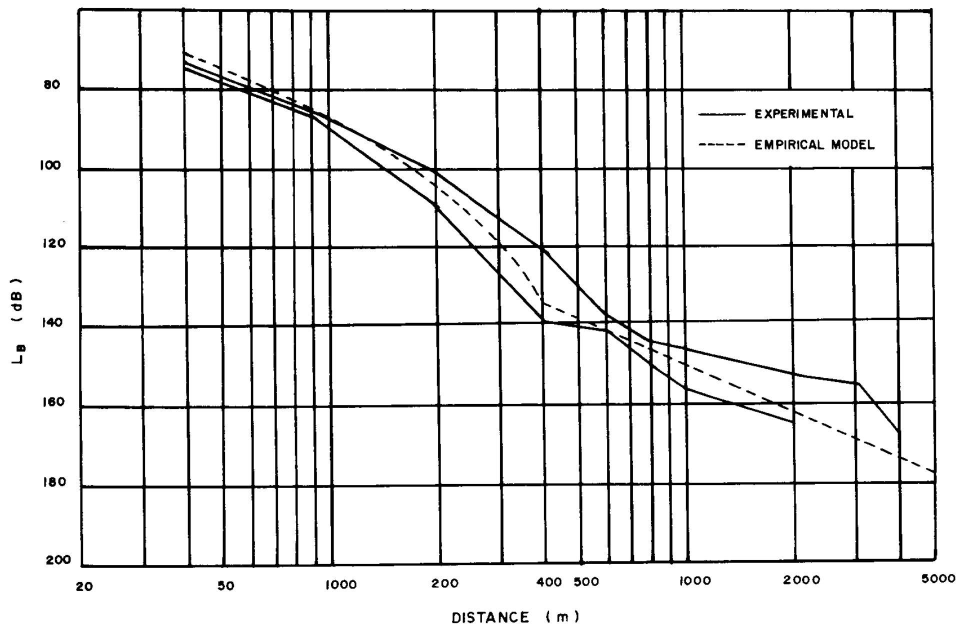

Fig. 9. Comparison of empirical model with experimental data (500 MHz, vertical polarization).

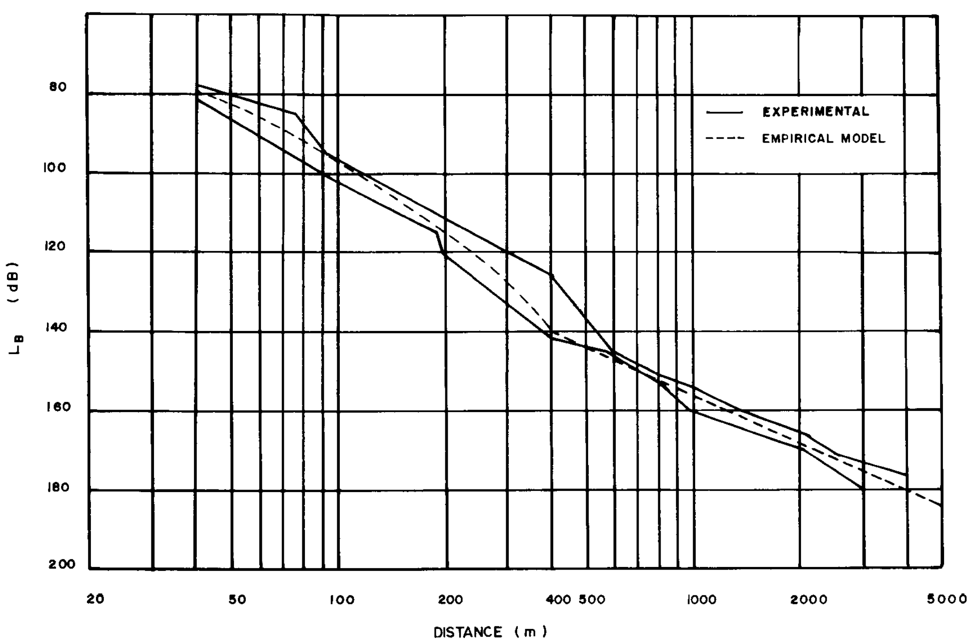

Fig. 10. Comparison of empirical model with experimental data (800 MHz, vertical polarization).

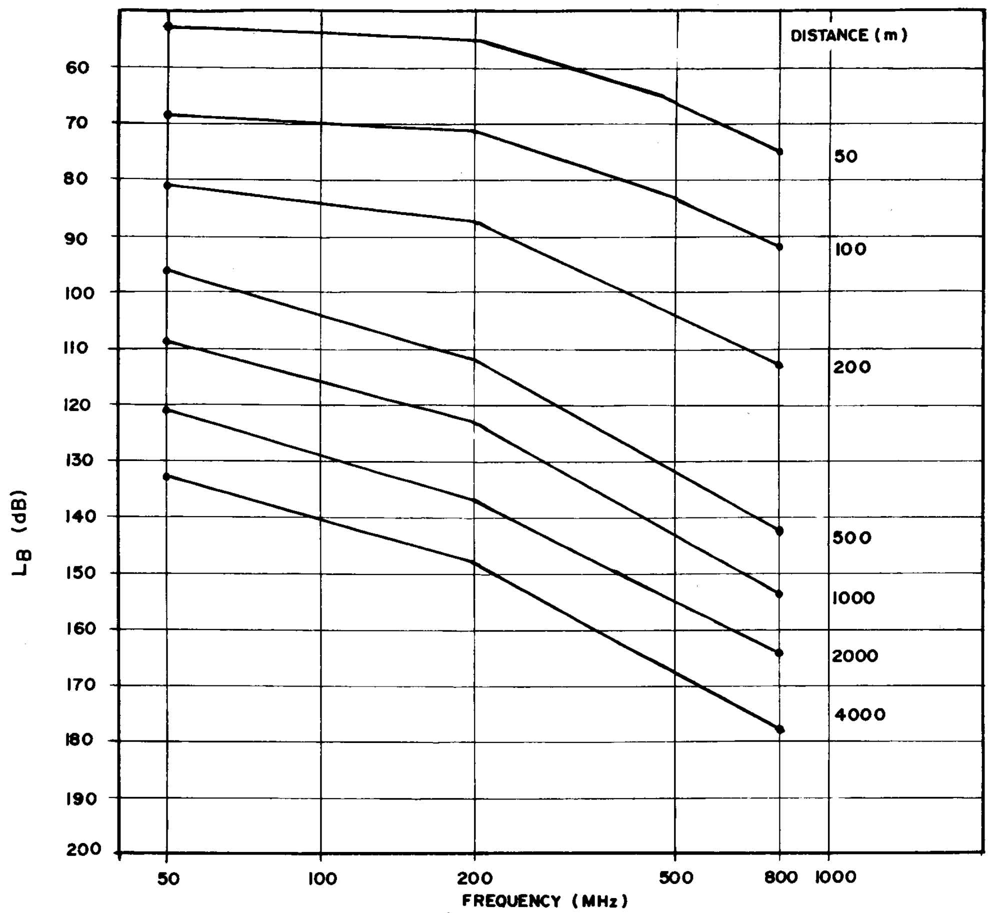

Fig. 11. Frequency dependence of basic transmission loss (horizontal polarization).

quantity of the power extracted from the resulting field would depend upon the beamwidth of the antenna. With the reduction of the beamwidth the foliage inhomogeneity also becomes more noticeable.

Effect of the Change in Wind Velocity

Wide variations in the received field strength have also been recorded during the periods of strong winds in the forest. This change in the received field is believed to be caused by the change in orientation of various scatterers (like tree, leaves and branches) due to varying wind velocity. Care was taken during these measurements that the field-strength meter should be first stabilized for two minutes before recording the median values. Inspite of this, in some cases, the recorded field strength might not have been the true representative value of the otherwise expected field strength for that set of the fixed experimental parameters. Such variations were also reported during measurements in Thailand Forest [10] where the time variability of basic transmission loss was correlated with wind velocity [27].

Frequency Dependence of Basic Transmission Loss

Frequency dependence of L_B is graphically shown in Figs. 11 and 12 for different separation distances between the transmitter and receiver. The data used in these curves have been derived from the smoothened curves given in Figs. 1 and 2. In all the cases L_B was found to increase with increase in the frequency of transmission for horizontal as well as vertical polarizations except for the lowest frequency of measurements.

The possible reasons for higher losses observed at 50 MHz were: higher depolarization of radio wave at lower frequencies [20], especially at vertical polarization; wider beamwidth of dipole antenna (used as receiving antenna at 50 MHz) than the log-periodic antenna (used for 200, 500, and 800 MHz reception), which might have resulted in reception of more out-of-phase scattered signal; and the effect of foliage proximity in terms of wavelength, since the induction field for 50 MHz antenna would have been larger than that for other antennas used at higher frequencies. The same antenna foliage proximity at a given receiving terminal would have had larger effect on the 50 MHz received field strength. The combined effect of these factors resulted in high losses exhibited at 50 MHz. It was interesting to note that this behavior was consistent in all sets of measurements.

Polarization Dependence of L_B

Fig. 13 is the plot of the difference between L_B values for vertical and horizontal polarizations at various frequen-

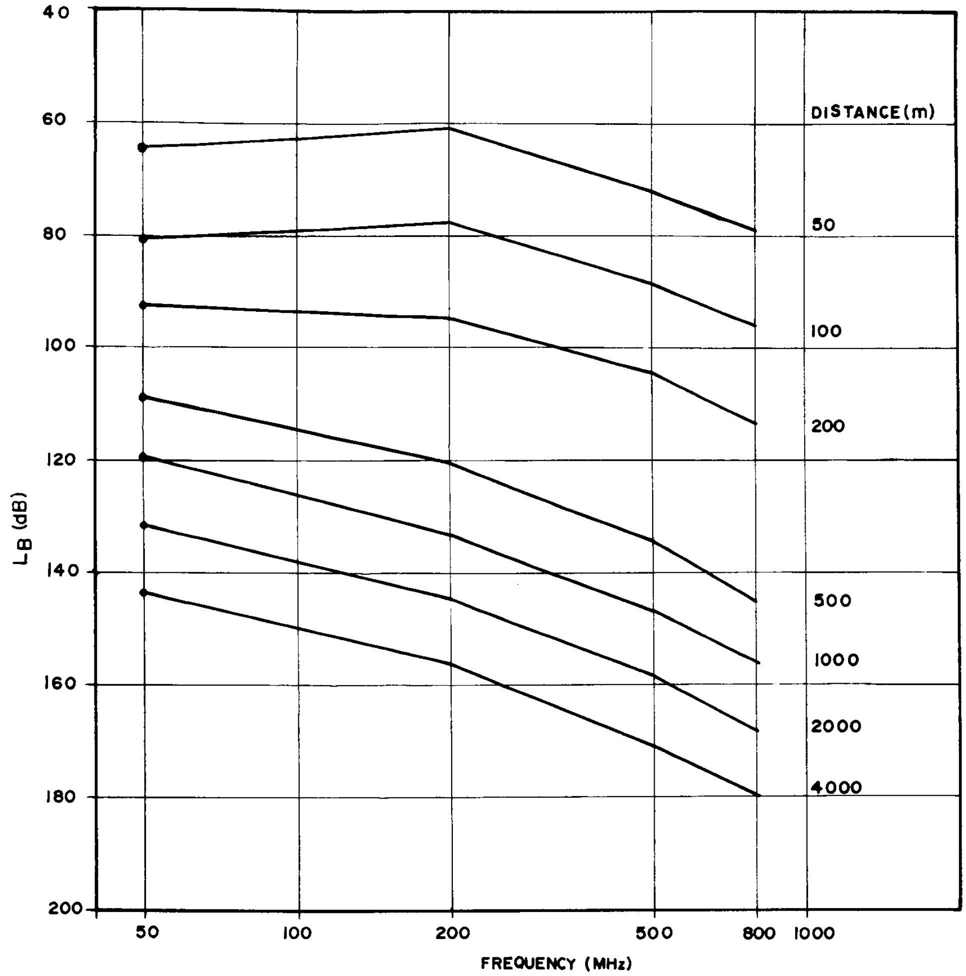

Fig. 12. Frequency dependence of basic transmission loss (vertical polarization).

cies at the antenna heights mentioned therein. Distance has not been kept as one of the variables since no dependence on distance has been observed over the entire range of measurement. Two transmitting antenna heights (lowest and highest) have arbitrarily been chosen. The values plotted in the curves are simply the number of decibels by which L_B values for vertical polarization exceeded horizontal polarization for the same terminal points. Thus, a positive "difference-loss" on Fig. 13 indicates that the horizontal polarization is favored whereas a negative value would correspond to an advantage with the vertical polarization. The sample L_B values chosen for this analysis were extracted from the unsmoothened raw data since smoothened data may not give a realistic estimate of the polarization dependence of L_B. It has been observed that for low frequencies the horizontal polarization is heavily favored (almost consistently by about 18 dB at 50 MHz) but the margin tends to decrease with frequency, becoming independent of polarization somewhere around 500 MHz. The predominence of positive values of "difference loss" in Fig. 13 indicates that the horizontal polarization may usually result in reduction of loss experienced by radio waves while propagating through a foliated environment.

These plots of "difference loss" are representative of the entire cross section of the data collected for various antenna height combinations and distance ranges. It was further found that the scattering effect of the foliage gives rise to a significant cross-polarized component of the received signal. Detailed copolar and cross-polar measurements were conducted to study the phenomenon; the results have been reported by authors in an earlier paper [20].

Seasonal Variation of L_B

During the monsoon season the foliage grows considerably and the ground is always wet, whereas during other seasons the foliage growth is reduced. To study the seasonal variations of propagation loss in forested environments, experiments were carried out in the tropical moist deciduous forest of Dehradun. The trees of this forest were deciduous and shed leaves during the spring season. Since density of the foliage and moisture content of the soil was considered to have an

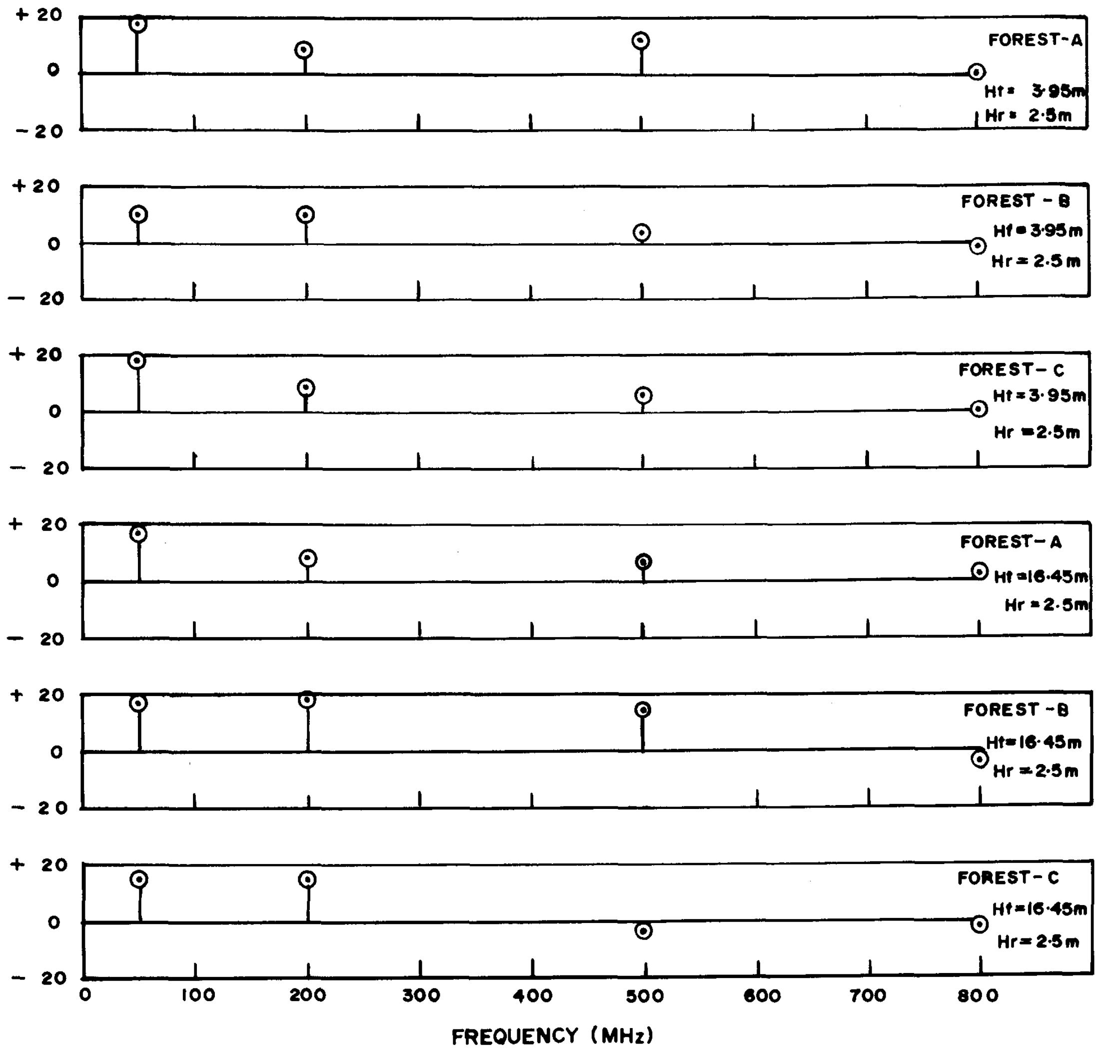

Fig. 13. Polarization dependence of basic transmission loss.

effect on the attenuation characteristics of the forest, measurements were conducted during the season when the trees had shed their leaves and then the measurements were repeated immediately after the rainy season when the ground remains wet and the trees were in full leaf.

These measurements have shown that, in general, the L_B was found to be more in wet season than in dry season, irrespective of the frequency. This effect was not noticeable at lower frequencies but at higher frequencies the difference in loss was found to be higher by about 11 dB for horizontal polarization and 9 dB for vertical polarization. The difference in loss is due to the change in the electrical constants (conductivity and permittivity) of vegetation slab as well as of earth.

Effect of Climate and Type of Vegetation

Climate is the most basic element of the environment. Landforms, soils, hydrology and vegetation feel the impact of climate. In turn, climate, soil, and surface features play important roles in influencing the abundance and variety of vegetation. There is especially close correlation between zones of climates and zones of vegetation. The climate, landforms, soil, hydrology, and type of vegetation are considered as a set of components whose magnitude are different from one area to another, and upon which the attenuation characteristics of forests greatly depends. The predictions based on studies in certain types of forests lack the knowledge of how these predictions would vary for various geographical locations, within acceptable confidence limits.

The attenuating properties of forest depend not only on density and other physical characteristics, but also on type of trees present in the forest. These vary in type of their wood, bark, leaves and certain other physical characteristics.

To study the variability of attenuation characteristics for different types of forests the results of Dehradun and Assam forests were compared. Considering both the polarizations together, the basic transmission loss values were found to be higher for Assam forests than Dehradun forests and the difference ranged from 1 to 5 dB.

The higher basic transmission loss for Assam forests was neither substantial nor did it follow any consistent trend with frequency, distance, and polarization. Accordingly such a minor difference may not be considered as a definite conclusion, particularly because of the wide scattering in the experimental data and their smoothening thereafter. In addition, some experimental error would be associated with each set of measurement. However, there was a very small change in the density of the two forests associated with these measurements. In view of this it would not be unreasonable to draw the inference that the little changes in the density of the forests do not have any noticeable effect on the attenuation of radio waves caused by the vegetation growth.

Foliage Loss (L_f)

The quantitative effect of vegetation on the radio wave attenuation is considered as the difference between the measured path loss over a vegetated path and the expected path loss in absence of vegetation for the same set of systems and path parameters. This additional loss due to the presence of foliage is termed as "foliage loss" (L_f) and is expressed in decibels. The L_f values have been obtained through the Egli model [22] from the measured smoothened data on basic transmission loss and its variation was studied as a function of distance, frequency, and polarization.

The pattern of distance dependence of L_f was found to be the same as L_B and likewise indicated two characteristically different trends for through-the-foliage as well as lateral-wave modes of propagation. The L_f was found to increase in distance for distances up to 400 m irrespective of frequency and polarization. This was due to the fact that the dominant role is played by direct and reflected wave contributions (through-the-foliage mode), the path of which is entirely through the lossy forest medium. These fields contain exponential term and suffer attenuation throughout the path of travel.

The experimental data on foliage loss for distance beyond 400 m suggested that the effect of vegetation upon the foliage loss is independent of the horizontal distance ranges. This is due to the fact that the lateral-waves encounter foliage only while traveling between the two antennas and the tree-tops whereas rest of the radio path is through the air region. Increase in the separation distance between the transmitter and receiver, hence, does not affect the foliage loss.

The L_f for through-the-foliage as well as lateral-wave mode were found to increase with increase in frequency. The frequency dependence of foliage loss for both the polarizations is shown in Fig. 14. These curves were drawn by averaging the L_f values for distances beyond 400 m for all the three forests. The bold vertical lines represent the spread of the L_f values for the three sets of measurements. It was found that the foliage loss increases with increase in frequency for both the polarizations, the rate of increase being higher for horizontally polarized waves. The L_f values were found to be higher for vertically polarized waves but this difference was found to reduce from about 13 dB at 50 MHz to a negligible amount of about 2 dB at 800 MHz. The dotted curves on the Fig. 14 show the results reported for Thailand forests [10]–[13] for comparison.

These curves are of practical importance as they can be used within reasonable accuracy for predicting basic transmission loss for any forest in India having characteristics similar to those where these measurements were made, by using the following expression:

$$L_B = 88 + 20 \log f(\text{MHz}) + 40 \log d(\text{km}) - 20 \log [Ht(m) \cdot Hr(m)] + L_f\,(\text{dB}). \quad (2)$$

The first four terms on the right-hand side of the expression account for the basic transmission loss expected in a terrain not covered with vegetation and are based on the Egli model [22]. The inclusion of L_f, readily available from the curves in Fig. 14, makes the expression suitable for its applicability in forested terrain.

Specific Attenuation (α)

The specific attenuation is obtained by dividing the foliage loss (L_f) by the thickness of the forest slab through which the propagation takes place, and is expressed in dB/m. The specific attenuation also exhibited two distinct characteristics for through-the-foliage and lateral-wave mode of propagation. In the case of through-the-foliage mode the specific attenuation values evaluated from the measured data were found to be independent of the distance since in this mode the foliage loss increased with increase in distance and hence specific attenuation remained constant. However, relatively large variations in the α values were noticed due to azimuthal inhomogenity in the forest media.

In addition to the attenuation caused due to foliage, the α contained a constant loss factor which was the result of change in antenna pattern due to the cluster of foliage in the immediate vicinity of both the antennas. This additional loss was more or less constant for one set of transmitter-receiver and was independent of distance between them. This resulted in a higher rate of attenuation at short distances and slow decreases of α with increase in distance.

To study the frequency dependence of through-the-foliage specific attenuation, the composite data for short distance ranges (40–400 m) was considered and the gross average of the values over this distance range were plotted as a function of frequency in Fig. 15 for horizontal as well as vertical polarizations. The through-the-foliage specific attenuation was found to increase with increase in frequency. The values were found to be higher for vertically polarized waves but the difference for the two polarizations was found to reduce with increase in frequency which is in close agreement with various results reported earlier. Muehe and Cartledge [23] obtained the through-the-foliage α at 400 MHz in the range of 0.1 to 0.3 dB/m (depending upon the forest density) which agreed well with our experimentally observed α values as 0.12 and 0.18 dB/m at 500 MHz for horizontally and vertically polarized waves, respectively. For comparison the curves given by CCIR [24], the experimental curves of Saxton and Lane [7] and the theoretical curve given by La Grone [26] have also been plotted in Fig. 15. The experimentally obtained α values

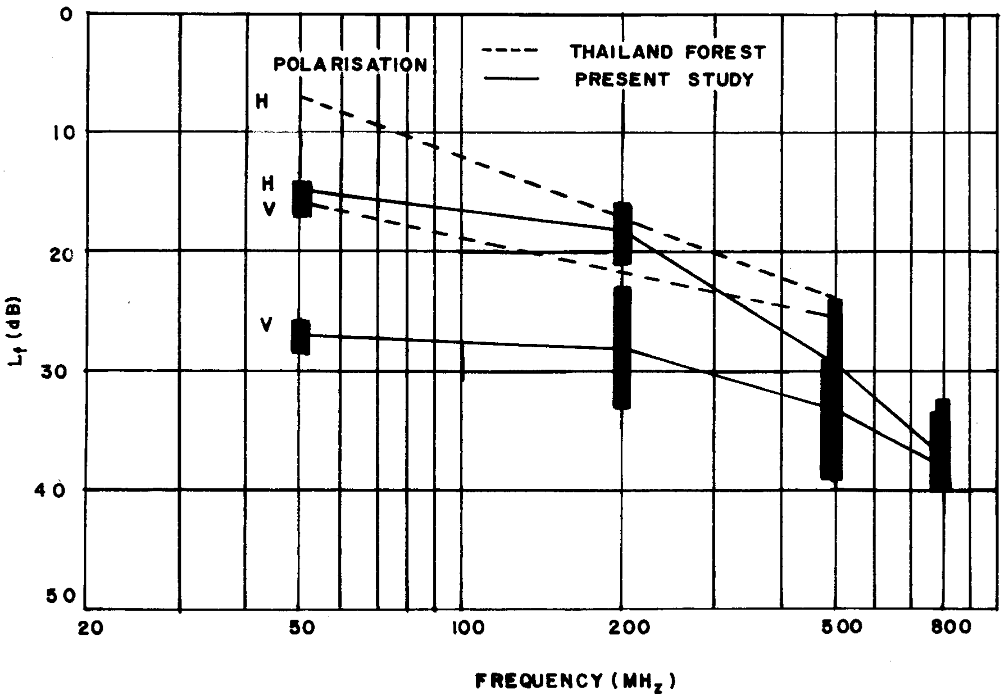

Fig. 14. Frequency dependence of foliage loss.

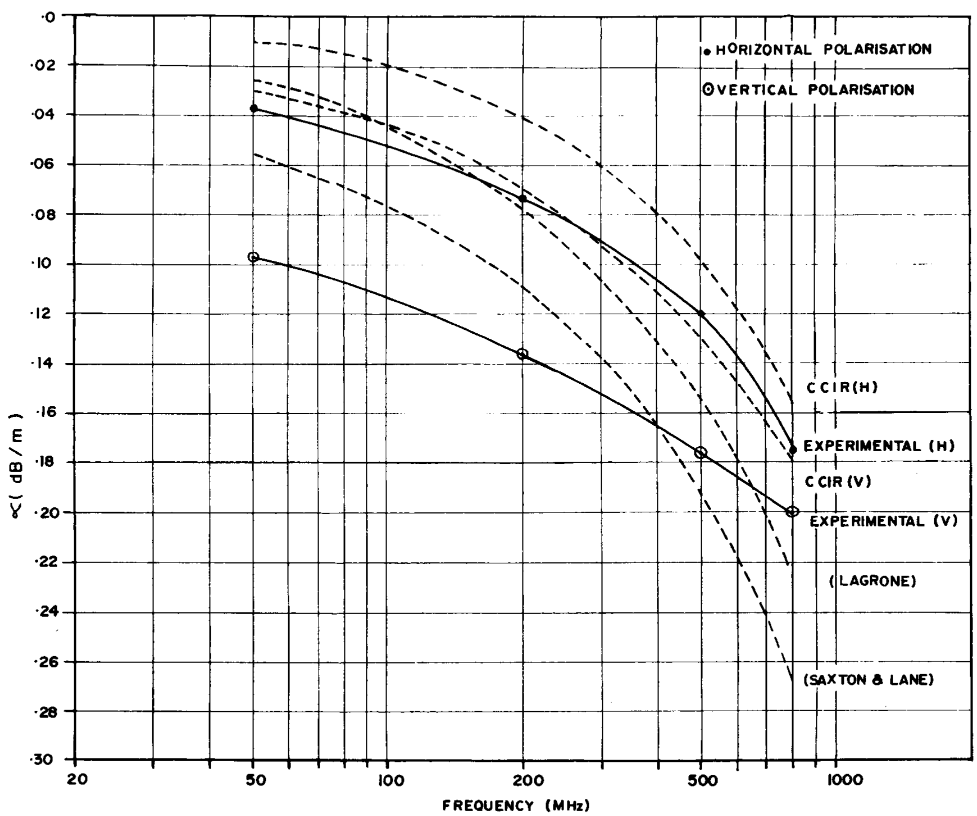

Fig. 15. Frequency dependence of specific attenuation for through-the-foliage mode.

for horizontal polarization were found to be nearer to those of CCIR [24] but for vertical polarization experimental values were found to be consistently higher. The experimentally observed values were also found to increase at a slower rate than those reported by others. The experimental data, if averaged for both polarizations, showed an excellent agreement with the Saxton and Lane curves [7] for lower frequencies. The experimental α values for vertical polarization exceeded by 0.064 dB/m, 0.058 dB/m and 0.022 dB/m for 200, 500, and 800 MHz, respectively. CCIR curves [24], based on numerous data collected during various measurements, show about 0.03 dB/m higher rate of attenuation for vertically polarized waves which is about the same as noted from the measured data. McPetrie and Ford [6] found this difference as 0.01 dB/m at 540 MHz whereas Saxton and Lane [7], from the measurements at 100 MHz in dense pine forest with no undergrowth, reported the attenuation rates as 0.06 and 0.03 dB/m, respectively, for vertically and horizontally polarized waves.

For certain situations, however, horizontally and vertically polarized waves were reported to undergo essentially the same amount of attenuation. Trevor's [1] measurements at 250 MHz showed higher attenuation for vertically polarized waves but during the measurements conducted at 500 MHz in trees with or without leaves it was found to be independent of polarization. The measurements by Saxton and Lane [7] in deciduous forests also did not indicate any marked polarization dependence at 540 and 1240 MHz frequencies.

The present study partially supports and partially opposes these observations. For long distance ranges (400–4000 m) the difference between the values for the two polarizations was found to decrease with frequency, becoming frequency independent around 500 MHz. But at short distances the α values were found to be consistently higher for vertical polarization.

In the case of separation distances where the lateral-wave component of the field predominates (> 400 m) the foliage loss becomes approximately constant or increases at an extremely slow rate. The curves in Figs. 16 and 17 exhibit that with increase in distance the specific attenuation decreases asymptotically to a constant value determined only by the density of the vegetation in the immediate vicinity of the antenna and the vertical dimensions of the vegetation in relation to the antennas height. This behavior of α characteristically supports the predominance of lateral-wave component of the field at higher distances. The total variation in α over the total distance was found to decrease from 0.1 dB/m to 0.004 dB/m. The values of α were found to increase with increase in frequency for both the polarizations and for all separation distances. The frequency dependence of α was more noticeable at shorter distances and was found to decrease with increase in distance, becoming more or less frequency independent around 3 km.

Antenna Height Gain in Forest

The data collected during this measurement program contained a large number of vertical path loss profiles. These profiles were based on the field strength measurements at twelve different combinations of transmitting and receiving antenna heights. In almost all the cases these vertical profiles exhibited increase in field strength with increase in antenna heights. The increase in either or both the antenna heights reduces the path lengths in the lossy forest medium resulting into corresponding exponential reduction in the total attenuation suffered by radio waves. The relative difference in the resulting L_B values is termed as height gain (G_h) and is expressed in dB. Based on the three sets of measurements the following empirical mathematical model [21] was suggested.

$$G_h = -12 - 4 \log f \text{ (MHz)} + 20 \log(Ht \cdot Hr). \quad (3)$$

The model is valid for all the frequencies in the frequency range of 50–800 MHz. No comments can be made for its suitability beyond 800 MHz since its validity is yet to be ensured.

Conclusion

Some of the results of the data analysis obtained from the radiowave propagation measurements conducted in tropical moist deciduous forest (Dehradun) and tropical evergreen forest (Assam) discussed here are strongly supported by the existing theories whereas others have not been conclusively supported as would be desired. Hence, in some cases, the results should be viewed as a conclusion applicable to a specific situation only. These results probably have a general applicability in the rain forests of India but they should not be hastily accepted without appreciation of the forest details. The results of these measurements are summarized as follows.

Distance Dependence of Radio Wave Attenuation

1) The basic transmission loss (L_B) of radio waves, in presence of foliage, increases with increase in the separation distance between transmitter and receiver. This increase in L_B has been found to be exponential upto a nominal distance of about 0.4 km, beyond which it showed a 40 dB per decade increase for all the frequencies in UHF range. However, at 50 MHz (VHF) the L_B values approximately increased by 40 dB per decade over the entire distance. Regardless of polarization the measured L_B values showed the presence of through-the-foliage and tree-top modes. It is inferred that at distances less than 0.4 km the through-the-foliage mode dominates whereas beyond a distance of 0.4 km the tree-top mode dominates.

2) If the quantitative effect of foliage is regarded as the difference between the measured L_B values in forest and the computed transmission loss in absence of foliage, termed as foliage loss, measurements showed that the effect of the foliage on the attenuation is independent of the separation distance, beyond a nominal distance of 0.4 km. This suggested that the principal mode of propagation beyond 0.4 km is along the forest-air boundary (lateral-wave mode) whereas the distances less than 0.4 km it is through-the foliage mode.

3) The foliage loss was found to be lower for horizontally polarized emission than for vertically polarized emission. This difference was found to diminish around 500 MHz.

4) Although the tendency of L_B to increase with distance (> 0.4 km) is 40 log d, the diffracted field showed large deviation from the mean value.

5) Strong noticeable fluctuations in the receiving field was observed due to change in wind velocity prevailing at the time of measurements.

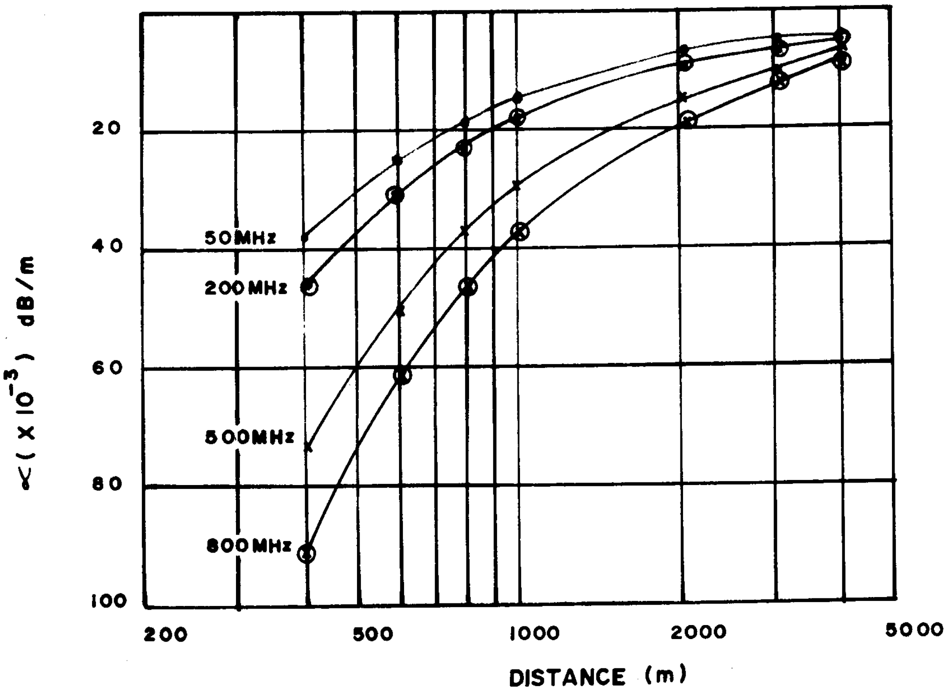

Fig. 16. Distance dependence of specific attenuation for lateral-wave mode (horizontal polarization).

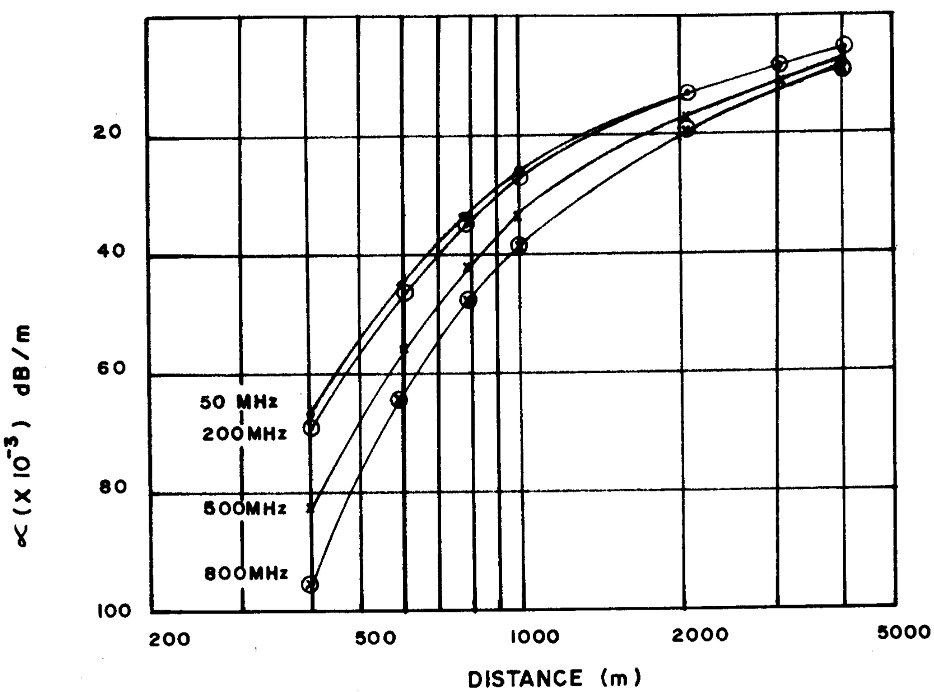

Fig. 17. Distance dependence of specific attenuation for lateral-wave mode (vertical polarization).

6) Large variations in the received field was noticed by moving the receiving antenna by few wavelengths. This characteristic is due to the scattering of radio waves while propagating through the forested media.

6) The specific attenuation (dB/m) was found to decrease asymptotically with increase in distance to a constant value. This is due to the fact that the foliage loss is independent of distance beyond 0.4 km.

Frequency Dependence of Radio Wave Attenuation

1) The L_B values were found to increase with an increase in frequency irrespective of polarization.

2) The foliage loss as well as the specific attenuation were also found to increase with an increase in frequency irrespective of polarization.

Polarization Dependence of Radio Wave Attenuation

1) The transmission loss was found to be higher for vertically polarized waves than for horizontally polarized waves but this difference was found to reduce from 20 dB to a negligible value with the increase in frequency from 50 to 800 MHz.

2) The radio waves while propagating through forested terrain get substantially depolarized due to their scattering by the foliage. The vertically polarized waves were found to suffer higher depolarization than horizontally polarized waves.

Antenna Height Gain in the Presence of Foliage

1) The transmission loss in presence of foliage decreases with increase in either of the antenna heights irrespective of distance, frequency, and polarization.

2) No distance dependence of height gain was noticed.

3) The antenna height gain was found to increase as $20 \log (\mathrm{Ht} \cdot \mathrm{Hr})$.

4) The antenna height gain was found to reduce with an increase in frequency as $4 \log f$ but was found to be independent of polarization.

Effect of Climate and Forest Density on Radio Wave Attenuation in the Presence of Foliage

1) There is no significant statistical difference between the data collected in the two types of tropical forests where the measurements were conducted. However, the density of the two forests also did not show any significant variation.

2) The losses in wet season were found to be higher than dry season. The difference was due to change in the ground constants as well as excess of green leaves in wet season.

Acknowledgment

The authors wish to convey their thanks to Mr. V. P. Sandlas, Director DEAL, Dehradun, for his continuous encouragement and permission to publish this paper. The authors are also grateful to Messrs. N. S. Chhabra, M. L. Agarwal, Hazara Singh, M. Sajid and G. C. Pandey for helping with the field measurements.

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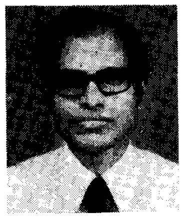

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