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PROPAGATION OF MILLIMETER WAVES IN RAIN

by

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I. INTRODUCTION

In recent years, there has been increasing interest in the utilization of millimeter waves for communications and remote sensing [1,2]. This frequency spectrum is attractive because it offers the promise of large bandwidth, relief to the already crowded radio frequency spectrum and high gain, high resolution antennas of reduced size and weight. However, atmospheric losses impose some limitations on the application of millimeter waves. Millimeter waves are attenuated by atmospheric absorption and scattering. Except for the 1.35 cm water vapor absorption line and the 5 mm oxygen absorption line [3 and Fig. 1], the most pronounced effect is due to rainfall.

Attenuation of cm and mm waves by atmospheric precipitations was first predicted by Stratton [4], in a theoretical paper published in 1930. In it he extended an earlier investigation of Mie [5], and concluded that rainfall might attenuate waves of 5 cm or less appreciably. Since then, there has been numerous work done both experimentally and theoretically. However, Medhurst [6] was the first to make a systematic comparison between the then available experimental data in the literature and the theoretically predicted attenuation versus rain rate. In the paper, Medhurst extended the work of Ryde and Ryde, which was based on the Mie theory. It was observed that in many cases, there is fairly good agreement between theory and experiment, but in some cases there is a tendancy for the measured attenuation to fall well above the maximum theoretical level. In the years that have elapsed since Medhurst's paper, several experiments have been reported. Again they exhibit the same characteristics as Medhurst observed.

It is well known that for a rain of given rate the measured attenuation is widely scattered. It generally varies with temperature, humidity, wind velocity and even the drop size distribution. In almost all of the reported measurements, there is a conspicuous lack of records of the local weather conditions. Because of this inadequacy in meteorological information, it is difficult to draw any definite conclusion as to the applicability of Mie theory to rainfall. However, since the approach, based on Mie theory, merely considers the interaction of a plane wave with a single isolated scatterer, and the total attenuation is simply to be the additive sum of absorption and scattering from each individual scatterer, it is possible that this single scattering theory is not sufficient to describe mm wave propagation in rain. In fact, Crane [7] has recently shown that it is important to consider the multiple scattering effects of rain for frequencies above 20 GHz.

The formulation of multiple scattering effects of a general electromagnetic wave propagation in an isotropically scattering random medium was given by the authors [8]. These results give explicit expressions for the beam, spherical and plane sources as function of density, cross sections and source parameters. It is shown that the beam wave average intensity is essentially coherent for most practical applications, whereas the plane wave case has significant contribution from both coherent and incoherent propagation. In general, the effect of multiple scattering is to increase the received power, therefore the predicted attenuation is less than that of the single scattering theory.

The purpose of this paper is to apply these results to mm wave propagation in rain. It is our intention to compare with the existing theory and reported measurements. The good agreement with published experimental measurements indicates the applicability of the theory to rainfall attenuation predictions. The results are of interest to the electrical engineers concerned with the utilization of millimeter wave bands for radio relay, terrestrial and satellite communication systems. To the meteorologist, the results are useful for estimating area rain intensity from attenuation measurements.

II. THEORY OF SCATTERING PROPAGATION

In this section, we summarize some results obtained previously [8]. These results will be used to predict rainfall attenuation of mm wave propagation.

A. SINGLE DROP

We consider a plane wave (say component x, of the electric field)

$$u_i = e^{ikz} \tag{1}$$

incident on a rain drop at $r = 0$, where $k = 2\pi/\lambda$ is the free space wave number and $e^{-i\omega t}$ time dependence is assumed. The scattered wave in the far field is

$$u = \frac{e^{ikr}}{r} f(\hat{r},\hat{z}) \tag{2}$$

where f is the scattering amplitude, and $\hat{z}$ and $\hat{r}$ are directions of incidence and observation respectively. From the optical theorem we have

$$\sigma = \frac{4\pi}{k} \operatorname{Im} f(\hat{z},\hat{z}) \tag{3}$$

also

$$\sigma_s = \int_{4\pi} |f(\hat{r},\hat{z})|^2 d\Omega \tag{4}$$

where σ and σ_s are total and scattering cross sections respectively.

B. MIE THEORY

A complete theory of scattering of a plane wave by a sphere of any composition in an external medium was obtained by Mie [5] in 1908. This has become the basis for most subsequent discussions in the subject. Mie separated the field equations in spherical coordinates into two groups - one transverse magnetic and the other transverse electric. Matching the boundary conditions at the surface of the sphere, he obtained the cross sections of a spherical particle.

$$\begin{aligned} \sigma &= \frac{\lambda^2}{2\pi} (-\operatorname{Re}) \sum_{n=1}^{\infty} (2n+1)(a_n + b_n) \\ \sigma_s &= \frac{\lambda^2}{2\pi} \sum_{n=1}^{\infty} (2n+1)(|a_n|^2 + |b_n|^2) \end{aligned} \tag{5}$$

where a_n and b_n are spherical Bessel functions of order n, and they are given in terms of the complex index of refraction, the radius of the sphere a, and wavelength of the medium λ.

The total cross section σ and scattering cross section σ_s given by

Eq. (5) have been computed by Lowan [9] for water spheres at 18°C for various wavelengths 3 mm and 10 cm. These values are used for the numerical computations in this paper. More recently, Herman, Browning and Battan [10] tabulated values of σ and σ_s for wavelengths between 0.62 and 10 cm at 0°C.

C. MULTIPLE SCATTERING BY MANY DROPS

We consider a volume V of scatterers specified by the density d. The scatterers may be either identical or given by some averaging process. Taking into account the multiple scattering effects, for an incident electric field E_i, the average (coherent) field $\langle E \rangle$ is given by the integral equation

$$\langle E \rangle = E_i + i \int \frac{e^{ik|\bar{r}-\bar{r}'|}}{|\bar{r}-\bar{r}'|} f(\hat{z}',\hat{z}')\langle E(\bar{r}')\rangle \, dV(\bar{r}') \tag{6}$$

For mm wave propagation in rain, the drop size is small compared to wavelength, and we may make an isotropic assumption for the scattering amplitude. When the incident radiation is plane wave, we get for the coherent field

$$\langle E \rangle = e^{iKz} \tag{7}$$

where

$$K = k\left(1 + \frac{2\pi d}{k^2} f(\hat{z},\hat{z})\right) \tag{8}$$

is the modified wave number and the coherent intensity is given by

$$|\langle E \rangle|^2 = C = e^{-d\sigma z}$$

Similarly we obtain for the average intensity

$$\langle I \rangle = C + \frac{\sigma}{\sigma_s} \frac{\alpha_o}{(1-\alpha_o)\left(\frac{1}{1-\alpha_o^2} - \frac{\sigma}{\sigma_s}\right)} \left(e^{-d\sigma\alpha_c z} - e^{-d\sigma z}\right)$$

$$+ \frac{1}{2}\frac{\sigma_s}{\sigma} \int_0^1 \frac{g(u, \sigma_s/\sigma)}{(1-u)} \left(e^{-d\sigma z} - e^{-\frac{d\sigma z}{u}}\right) du \tag{9}$$

where α_o is the positive root of

$$\frac{\sigma}{\sigma_s} = \frac{\tanh^{-1}\alpha_o}{\alpha_o} \tag{10}$$

and

$$g(u, \sigma_s/\sigma) = \frac{1}{(1 - \frac{\sigma_s}{\sigma} u \tanh^{-1}u)^2 + (\frac{\pi\sigma_s u}{2\sigma})^2} \tag{11}$$

Eq. (9) is obtained through a Fourier transform technique applied to the integral equation.

$$\langle T(\bar{r})\rangle = C(\bar{r}) + d \int \frac{e^{-d\sigma|\bar{r}-\bar{r}'|}}{|\bar{r}-\bar{r}'|^2} |f(\hat{r}',\hat{z}')|^2 \langle T(\bar{r}')\rangle \, dV(\bar{r}') \tag{12}$$

It is noted that as the wave propagates in the medium, the coherent intensity decreases while the incoherent intensity increases in relative magnitude. In addition, as described elsewhere [8], the average intensity of a beam wave propagating in a discrete random medium is essentially coherent, and it is approximately given by

$$\langle T_{Be}\rangle \approx \frac{1}{1 + \frac{d\sigma z}{|K|^2 W_o^2} + \frac{z^2}{|K|^2 W_o^4}} \exp\left[-d\sigma z - \frac{\rho^2}{2W_o^2} \frac{2 + \frac{d\sigma z}{|K|^2 W_o^2}}{1 + \frac{d\sigma z}{|K|^2 W_o^2} + \frac{z^2}{|K|^2 W_o^4}}\right] \tag{13}$$

Therefore, beam wave experiences heavier attenuation as it propagates through rain than plane wave. However, the high gain associated with a narrow beam in practice will more than compensate for this additional loss.

III. APPLICATIONS TO RAINFALL ATTENUATION

A. INDEX OF REFRACTION

The refractive index $m = n + ix$ of water is generally complex at mm wavelengths and it is a function of frequency and temperature.

Saxton [11] has calculated curves showing the variation of the refractive index of water over the wavelength range 2 mm to 10 cm, which covers practically the whole dispersion region. He also described the effect of temperature. In addition, the calculated values were compared with experimental data obtained by other independent investigators. They were found to agree very well. In Table I, we give the refractive index of water for the wavelengths under investigation. Values at 20°C are taken from Saxton, and those at 18°C are from Lowan [9]. The values at 10°C and 0°C are those given by Herman, Browning and Battan [10].

B. DROP SIZE DISTRIBUTION AND TERMINAL VELOCITY

In order to relate accurately the attenuation to an actual rain of given intensity, it is necessary to know the drop size distribution. However, natural rainfall varies with prevailing wind, temperature, and other conditions. Furthermore, for a given propagation path, the rainfall is seldom uniform. It would seem practical then to compute the rainfall attenuation for rain with uniform average drop size. For our computations we choose the median drop size from the Laws and Parsons distribution [12]. The median drop divides the larger and smaller drops of a given rain intensity into two groups of equal volume. This median drop radius is shown in Fig. 2, for rainfall intensities ranging from 0 to 100 mm/hr.

The terminal velocities of water drops in still air are given by Gunn and Kinzer at a pressure of 760 mm and temperature of 20°C, and are readily available [13]. This is shown in Fig. 3.

It should be mentioned that in actual rainfall there is usually a vertical component of wind associated with it. Even though it may be small, the vertical component is very important. It is the up-and-down motion of air particles that is principally responsible for much of the atmospheric activities.

C. THEORETICAL ATTENUATION

For comparison with some of the readily available measurements in the literature, using Eqs. (9) and (13), numerical computations have been made for attenuation at wavelengths 3, 5, 9, 12.5, 17, 20 and 30 mm for rainfall intensities ranging from 0 to 100 mm/hr, using a CDC-6400 computer. According to Humphrey's classification of rain [14], the inten-

TABLE I

Variation of Refractive Index of Water   m = n + ix

with Wavelength and Temperature

T(°C)		λ(mm)						
		3	5	9	12.5	17	20	30
0		2.759	3.192		4.681		5.837	6.929
10		3.106	3.767		5.740		6.943	7.851
18	n	3.410	4.210	5.550	6.410	7.200	7.560	8.180
20		3.509	4.370	5.780	6.530	7.230	7.643	8.251
0		1.241	1.766		2.732		3.005	2.929
10		1.663	2.219		2.920		2.808	2.397
18	x	1.940	2.510	2.850	2.860	2.650	2.550	1.960
20		2.010	2.524	2.850	2.770	2.570	2.395	1.827

sities covered encompass rates of precipitation up to the grades of excessive rain and cloudburst encountered in nature.

The total and scattering cross sections are the accurate values computed by Lowan using Mie theory. Cross sections at $\lambda = 12.5$ and 20 mm are interpolated values from Lowan's data. Curves for these cross sections versus water drop radius at the wavelengths we mentioned are shown in Figs. (4a) and (4b).

In practice, it has been customary and convenient to express rain attenuation as a function of rainfall rate, p in mm/hour. This factor is proportional to the terminal velocity, which in turn depends on the size of drops. In order to get a quantitative measure of the attenuation as a function of rainfall rate, we must have a relationship between p and the average number of drops per cubic meter d (density of distribution). This is given by

$$p = 15.1\ vda^3$$

where v is the terminal velocity in meters per second and a is the raindrop radius in centimeters.

Using the values of a, v, σ and σ_s shown in Figs. 2-4, theoretical attenuation curves are calculated and plotted in Figs. 5-11. In addition, in each figure is shown the Mie theory curve based on Laws and Parsons drop size distribution, along with the Mie theory curve of a hypothetical rain of uniform drop size specified by the median of Laws and Parsons distribution. The Mie theory cases are taken from Medhurst.

D. MEASURED ATTENUATION

The attenuation of electromagnetic radiation by rainfall may be measured in two ways. In the first method, transmitting and receiving antennas are set up at the opposite ends of a line-of-sight path. In the second, reflecting targets are placed on the line of radar sight. Echo returned from the reflector is used to measure the attenuation. In both cases the rain intensities are estimated from rain gauges located along the path. There is however no uniformity of rain gauges used for the rain intensities. Although a great majority of the experiments referred to in this paper used funnel and gradual type rain gauges, they are not all of equal quality. Some are quite advanced devices, others are rather primitive. Hence, it is difficult to compare measurements by different workers. Furthermore, the degrees of reliability vary according to the number of rain gauges and path lengths.

An apparent and serious failure of almost all previously published experiments is the neglect of local climate conditions. Seldom is the ambient temperature, prevailing wind and humidity recorded. Considerations of these meteorological parameters are important, because raindrop absorption and scattering depend on the complex refractive indices, which are functions of temperature. Since a vertical component of wind may increase or decrease the terminal velocity of raindrops, a condition can be set up where the density of raindrops in the propagation path may be different from what is indicated by the rain gauges. Furthermore, the presence of wind may complicate the situation by giving a spatial distribution of drops such that smaller drops are carried further downwind than large drops. Lastly, the presence of atmospheric gasses and water vapor may modify the attenuation rate in some instances. Table II shows a summary of the parameters of rainfall attenuation measurements in the literature considered in this paper. [15]-[19], [21]-[24], [27]

For comparison with the theoretically predicted attenuations, the experimentally measured values are shown in Figs. 5-11, along with the theoretical curves.

E. DISCUSSION

From the graphical presentation, it is seen that the multiple scattering prediction of attenuation of mm wave propagation in rain of uniform drop size specified by the median is in good agreement with experimental measurements and Mie theory, when the latter assumes a drop size distribution given by Laws and Parsons, down to 5 mm range. For the cases of 3 and 5 mm shown in Fig. 5 and 6, the theoretical values deviate considerably from both experimental and Mie for higher rainfall rates. This is more pronounced in the 3 mm case. However, at low intensities the attenuations are the same for theory and experiment. These are not inconsistent with the present theory. For, at these wavelengths, the drop sizes are increasingly comparable to wavelength as the rain intensities

TABLE II

Summary of Parameters of the Rainfall Attenuation Measurements

Wavelength λ(mm)	3	3.32	6.2	8.6	8.6	12.5	16.4	20	28	32
Method	radar	radio	radio	radar	radar	radio	radio	radio	radio	radio
Transmitter Diameter	15cm	2ft	18in	4.9m	2.44m	2ft	72cm	8ft	2.1m	15in
Receiver Diameter	15cm	2ft	18in	4.9m	2.44m	2ft	72cm	12ft	2.1m	-
Pathlength	150m *	1.97Km	1200ft	26.5Km *	400m *	6400ft	6.4Km	15.78Km	24.5Km	900ft
Rain Gauge Type	funnel gradual	-	f&g	record-ing type	f&g	f&g tipping bucket	capac-itor	tipping bucket	record-ing	f&g
Rain Gauge Numbers	1	2	1	8	1	9	4	6	11	1
Author	Lane, Gordon-Smith, Zavody	Weibel & Dressel	Mueller	Harrold	Okamura, etc.	Anderson, etc.	Semplak & Turrin	Blevis, Dohoo, McCormick	Easter-brook, Turner	Robertson, King
Year	1967	1967	1946	1967	1959	1947	1969	1967	1967	1946
Polarization	-	-	**	-	**	-	***	***	-	**

* reflector
** horizontal
*** vertical

get higher, the isotropic scattering approximation is no longer justified and the theory does not apply, whereas for lower rain intensities drop sizes are still small compared to wavelengths.

The situation at 12.5 mm displayed in Fig. 8 is of a different character. The only available experimental data (the reason may be 12.5 mm is generally considered to be an atmospheric stop-band for mm wave) fall above the theoretically predicted attenuation by a considerable amount. The discrepancy, however, may not be due to the inapplicability of the theory but rather due to the inadequacy in the handling of meteorological information. Aside from the fact that additional attenuation is experienced from the proximity of 12.5 mm wavelength to the 1.35 mm water vapor absorption line (see Fig. 1), there are evidences [25] that Hawaiian orographical rains generally have different structures, therefore the raindrop size distribution is not the same as that measured by Laws and Parsons which was used for the theoretical computation. Furthermore, as Anderson, Day, Freres and Stokes [20] have observed, there was a light wind associated with the orographic precipitation. However, this was not taken care of in their interpretation of the experiment.

It is apparent from this study that attenuation does not increase linearly with rainfall rate. The only possible exception of this is around 9 mm.

In light of the high degree of collimation obtainable from mm wave beam using moderate size antennas, it is of interest to investigate the effects of wave types. In particular, we have studied plane and beam waves. As shown by Eqs. (9), (13) and elsewhere [8], the beam wave average intensity is essentially coherent. Furthermore, the coherent intensity normalized to free space is the same as plane wave. This has been computed and shown in Figs. 5-11. On the other hand, plane wave has significant contribution from both coherent and incoherent intensities as shown in Figs. 5-11. Within the range of applicability of the present multiple scattering theory, the maximum difference between the two wave types is about 3 db/Km.

Physically this corresponds to the fact, because of the finite beam size, waves scattered out of the beam which would normally be multiply scattered and eventually reach the receiving antenna, as in the plane wave, will not do so for beam wave until further away. By then, the coherent intensity is attenuated so much that they both appear as noise to the receiver.

The effects of non-sphericity to raindrops have not been considered in this paper. It has been shown that large falling raindrops tend to be flattened at the bottom. Therefore, it is plausible that rainfall attenuations are polarization dependent. Semplak [26] has recently shown that there is a significant difference in mm wave attenuations for horizontal and vertical polarizations for the same rainfall. It is also clear from the measurements cited above that there are many ambiguities concerning rain attenuation experiments. It would seem desirable and important to carry out a series of experiments with due care exercised in the measuring and recording of all the pertinent meteorological parameters. The additional experiments will go a long way to elucidate the present uncertainties.

IV. CONCLUSIONS

This work shows the effect of multiple scattering on mm wave propagation in rain. It has been shown that using the median drop size given by Laws and Parsons distribution, computed theoretical attenuation agree well with measurements at wavelengths range from 5 mm and up for all grades of rainfall intensities. Furthermore, the multiple scattering theory is in agreement with the Mie theory, when the latter assumes a full spectrum of drop sizes. In addition, the effect of wave type have been investigated to show a maximum difference of 3 db/Km for plane and beam waves. The limits of applicability of the theory have also been indicated.

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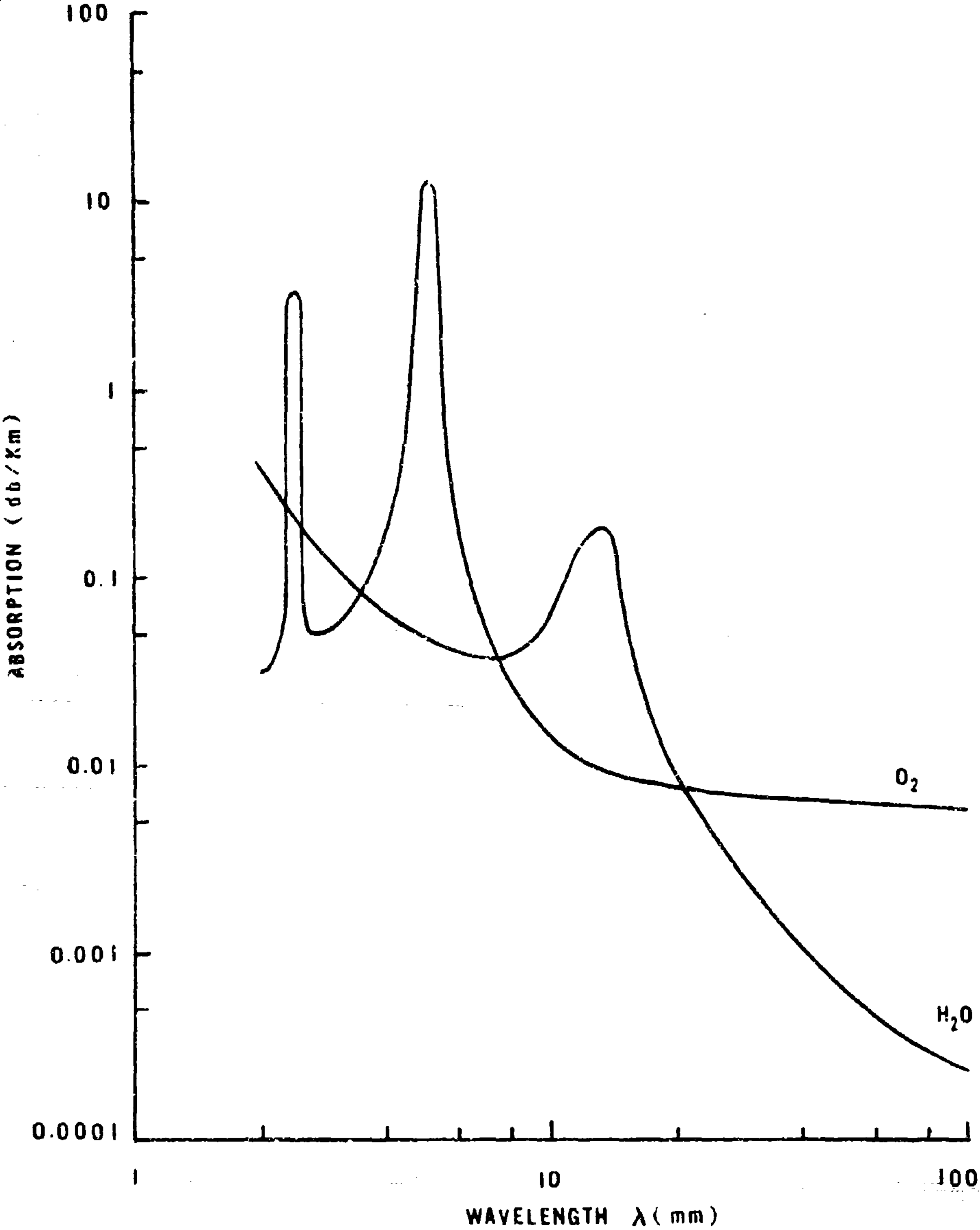

100
10
1
0.1
0.01
0.001
0.0001
ABSORPTION (db/Km)
1
10
100
WAVELENGTH λ(mm)
O2
H2O

Figure 1

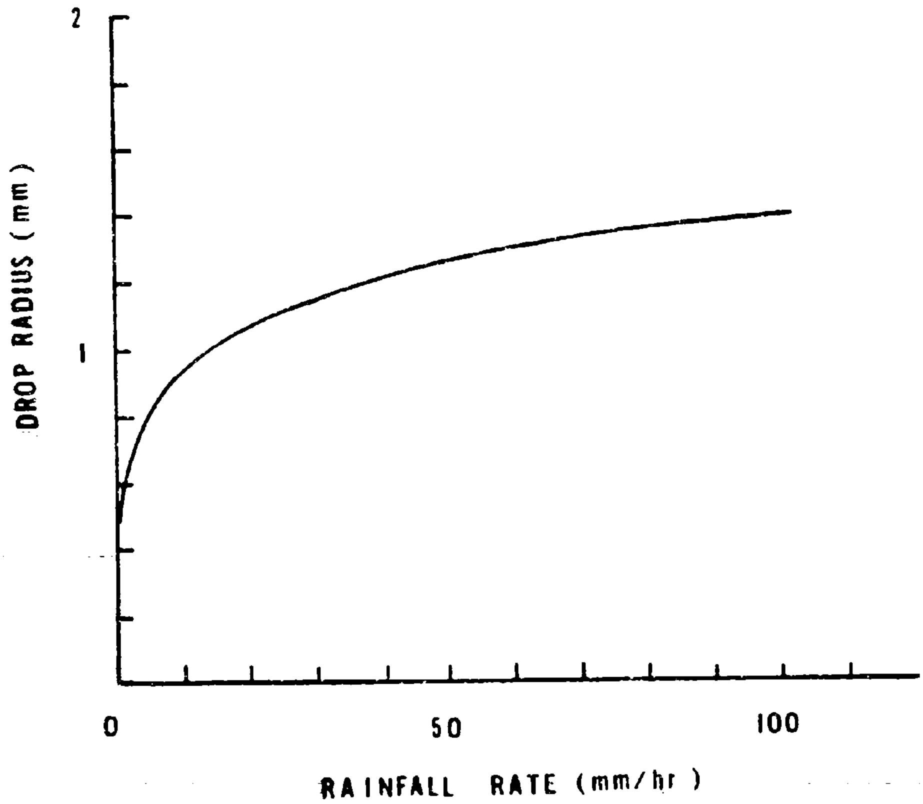


Figure 2

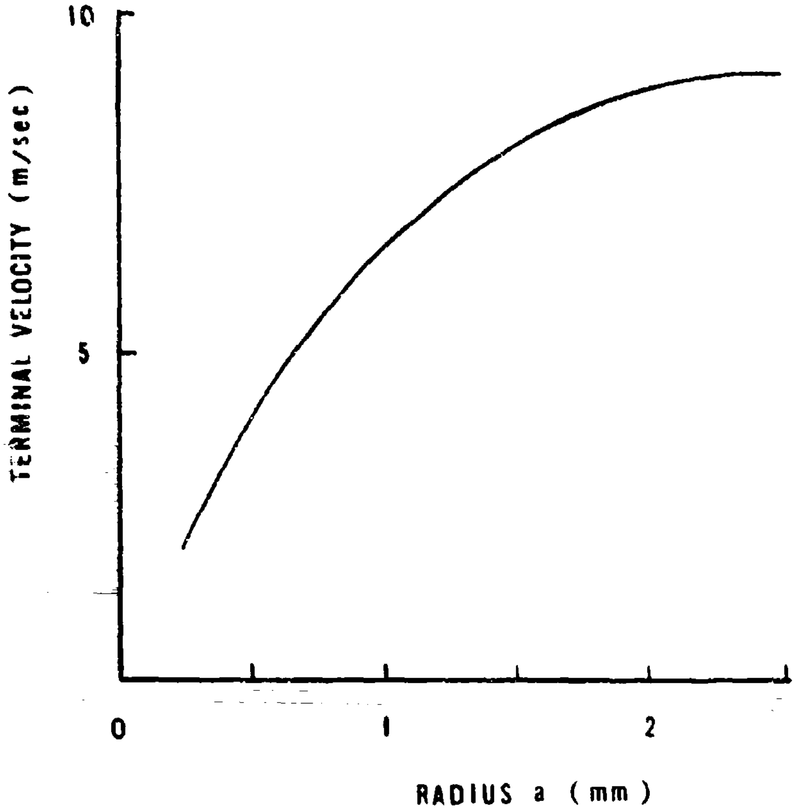
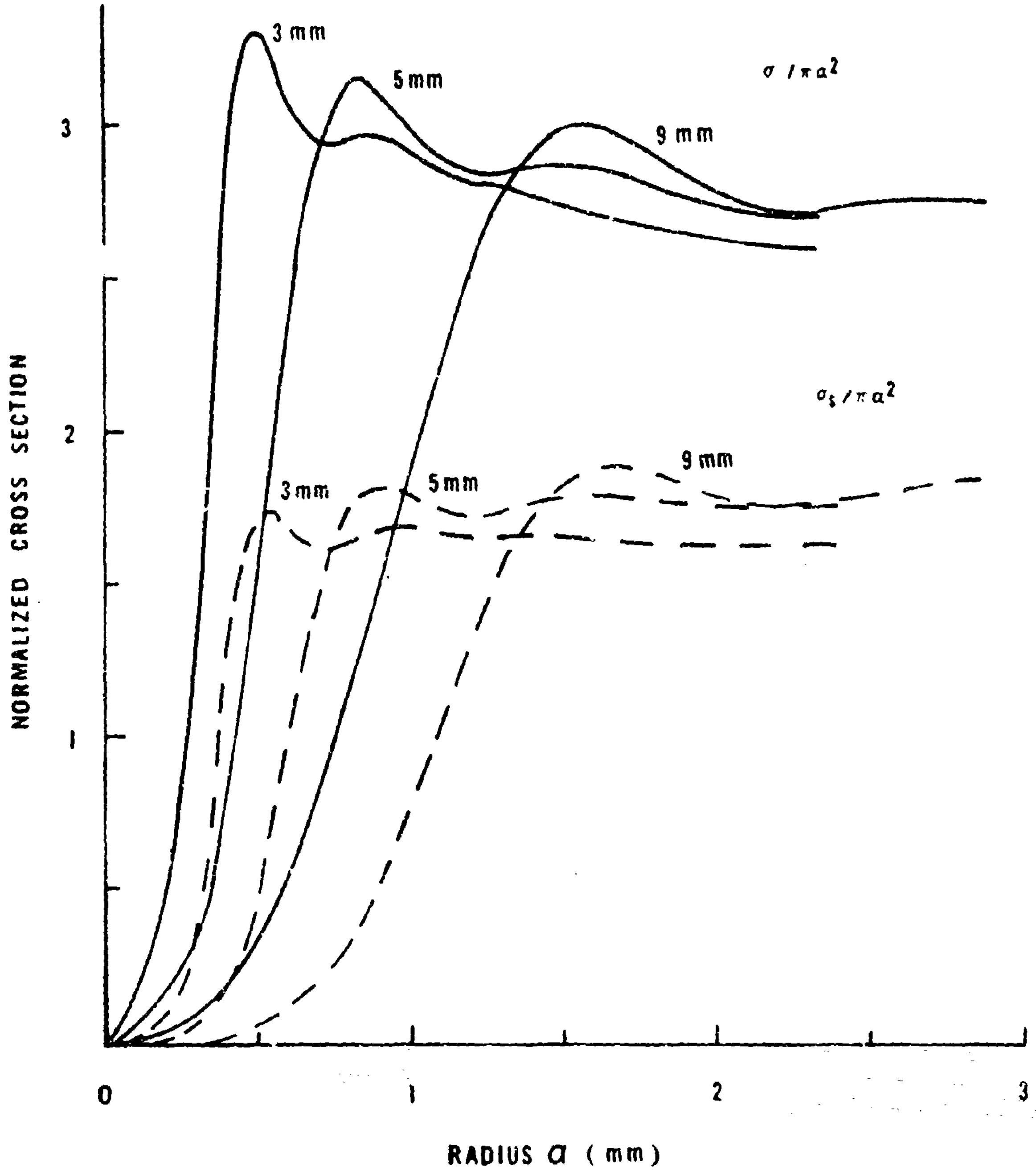
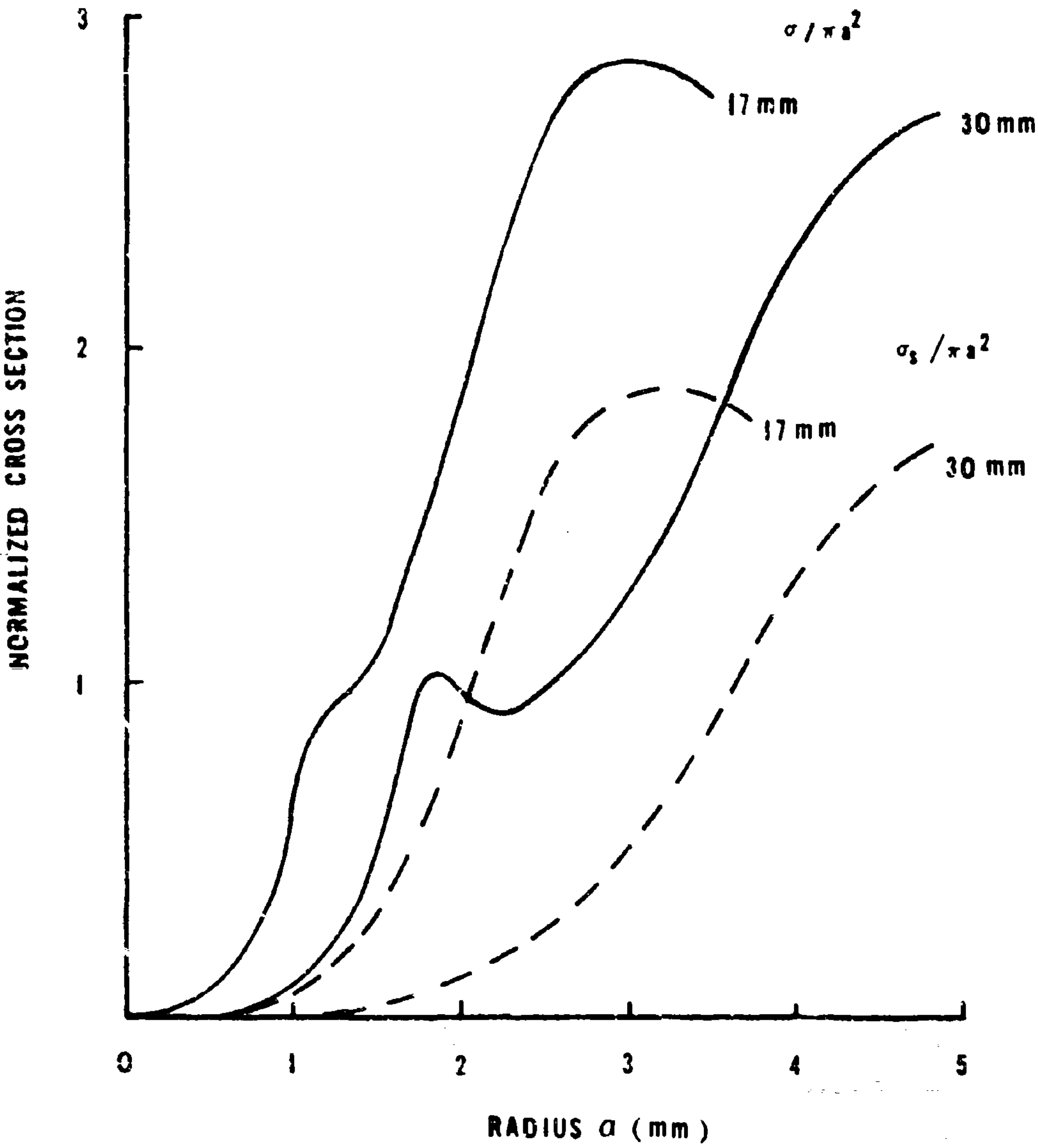


Figure 3



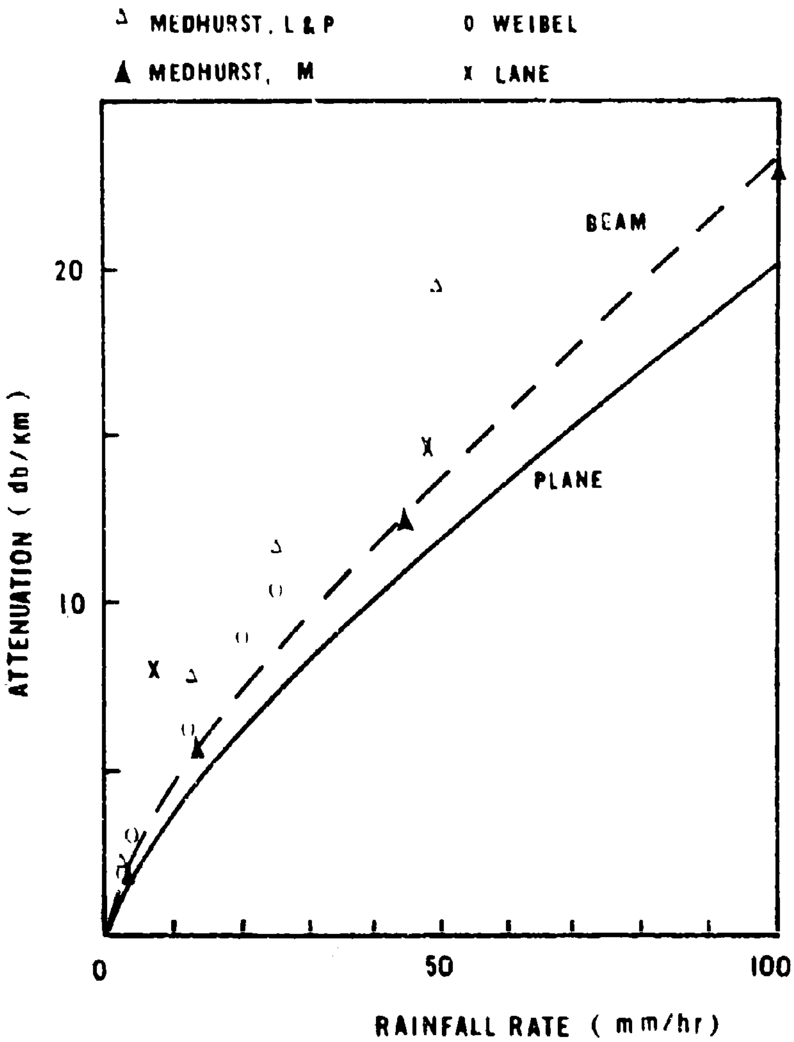
3 mm
5 mm
9 mm
σ / πa²
σs / πa²
3 mm
5 mm
9 mm
NORMALIZED CROSS SECTION
3
2
1
0
1
2
3
RADIUS a (mm)

Figure 4a



NORMALIZED CROSS SECTION
RADIUS a (mm)
σ / πa²
17 mm
30 mm
σs / πa²
17 mm
30 mm
0
1
2
3
4
5
1
2
3

Figure 4b



Δ MEDHURST, L & P
O WEIBEL
▲ MEDHURST, M
X LANE
BEAM
PLANE
ATTENUATION (db/km)
20
10
0
50
100
RAINFALL RATE (mm/hr)

Figure 6

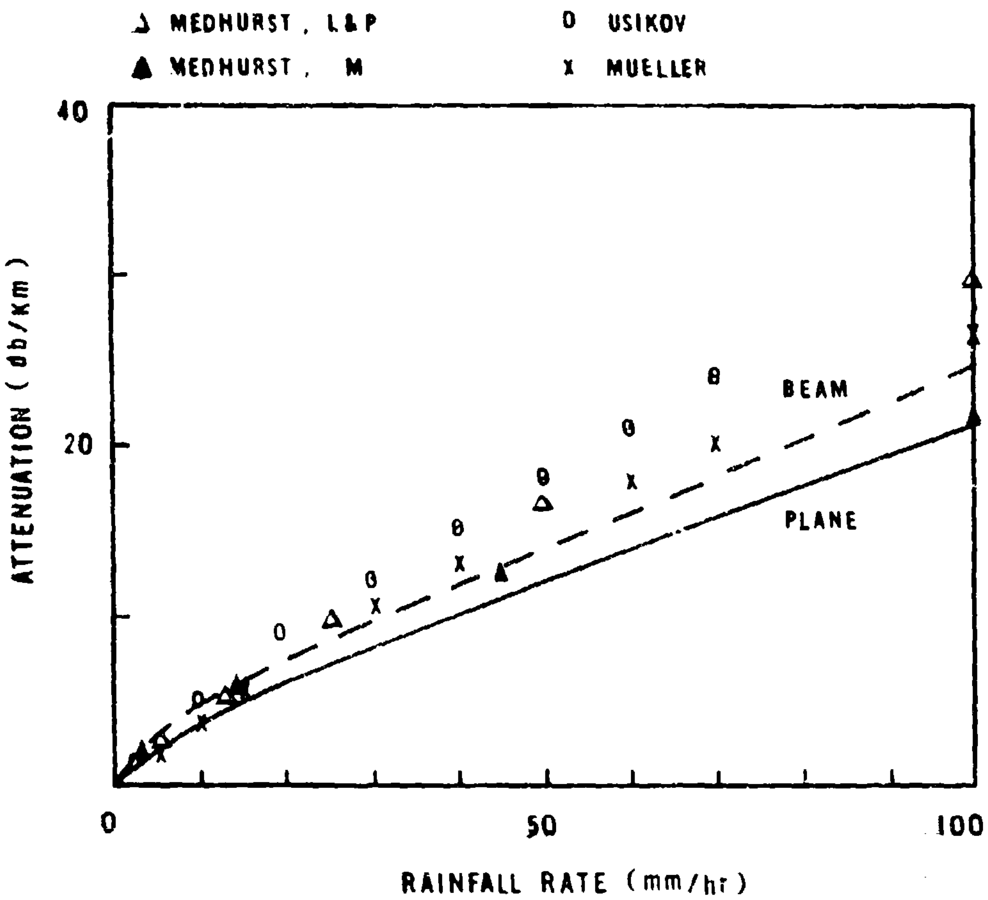
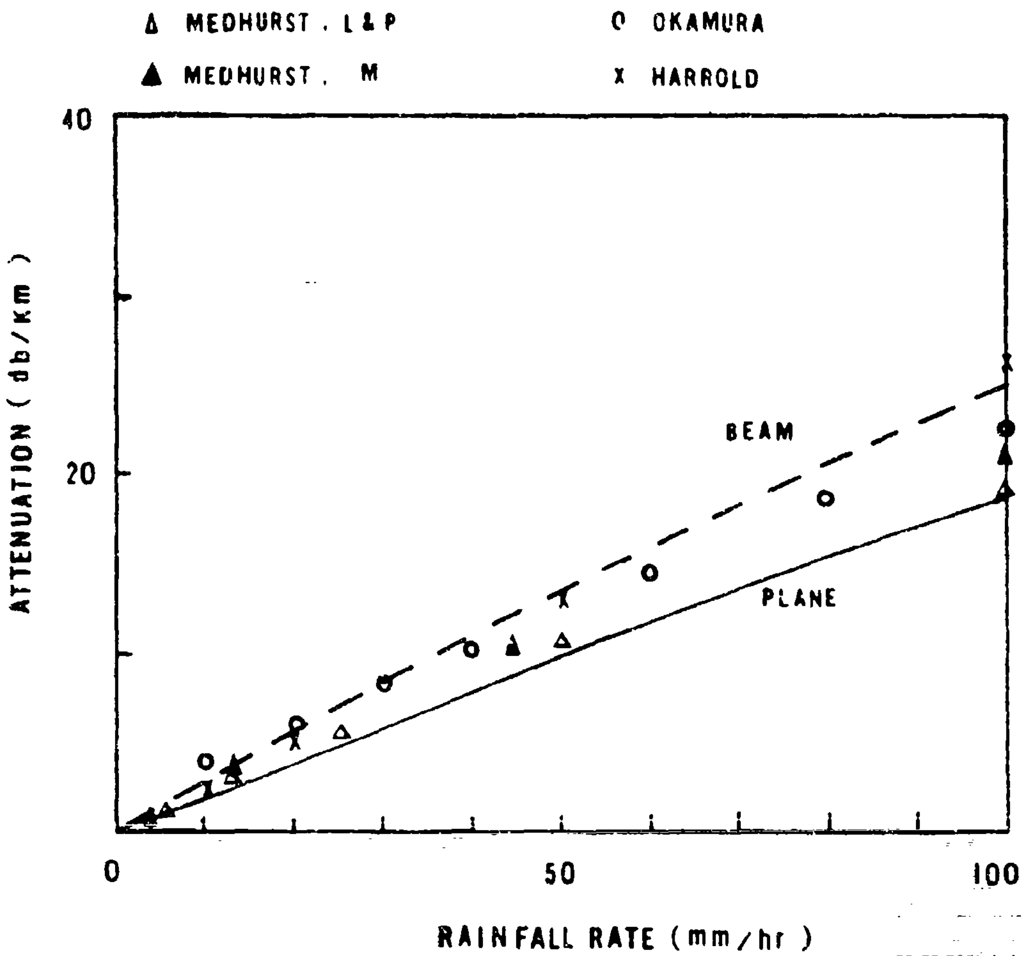

MEDHURST, L&P
MEDHURST, M
USIKOV
MUELLER
40
20
ATTENUATION (db/km)
BEAM
PLANE
0
50
100
RAINFALL RATE (mm/hr)

Figure 6



Δ MEDHURST . L & P
▲ MEDHURST . M
O OKAMURA
X HARROLD
40
20
0
50
100
ATTENUATION (db/km)
RAINFALL RATE (mm/hr)
BEAM
PLANE

Figure 7

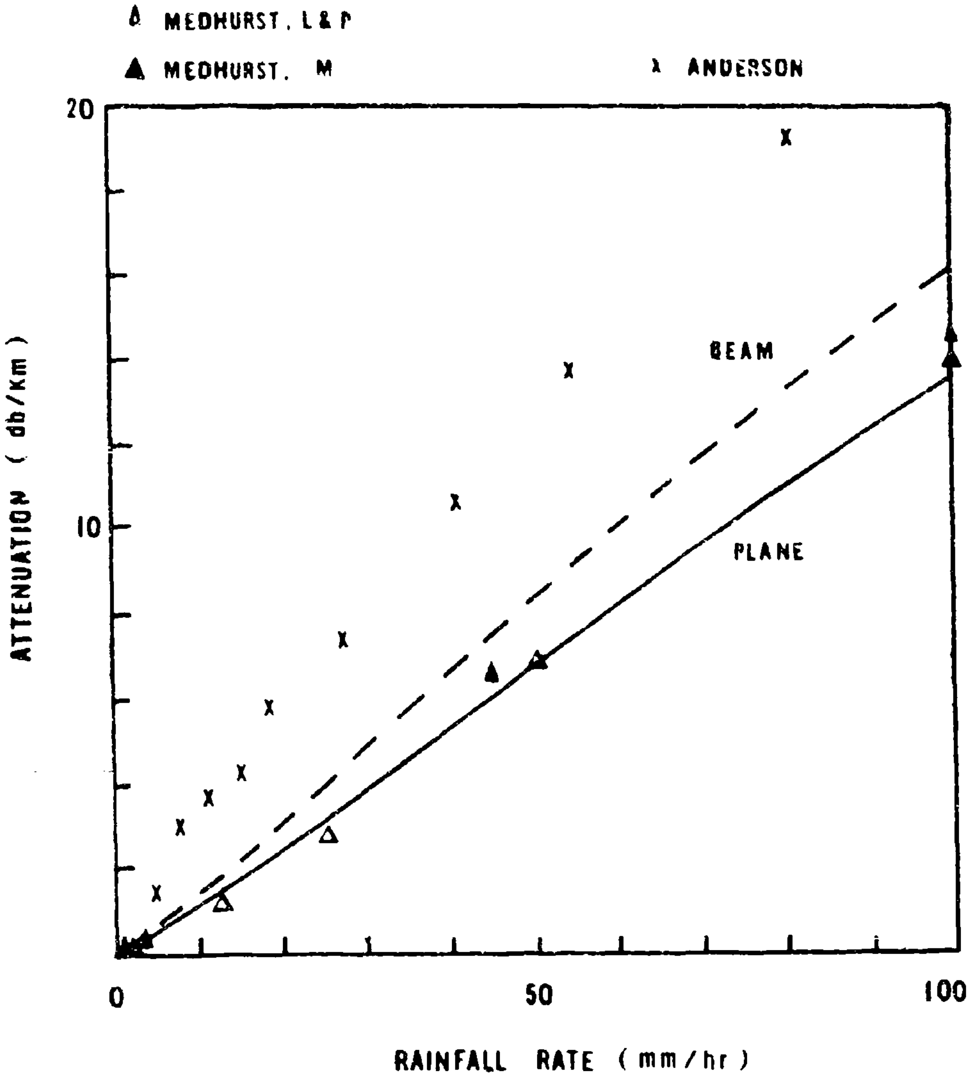
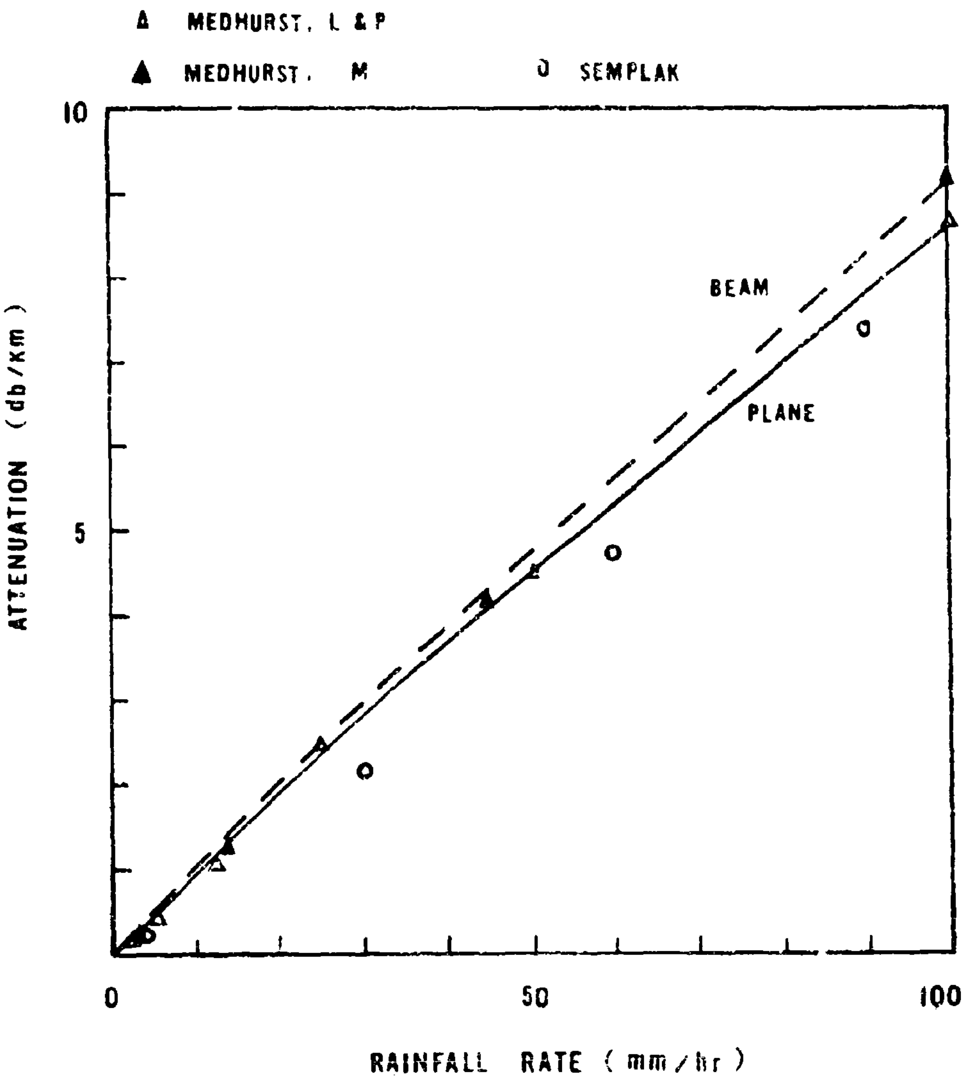

MEDHURST, L & P
MEDHURST, M
ANDERSON
20
10
0
50
100
ATTENUATION (db/km)
RAINFALL RATE (mm/hr)
BEAM
PLANE

Figure 9



Δ MEDHURST, L & P
▲ MEDHURST, M
O SEMPLAK
10
5
0
50
100
ATTENUATION (db/km)
RAINFALL RATE (mm/hr)
BEAM
PLANE

Figure 9

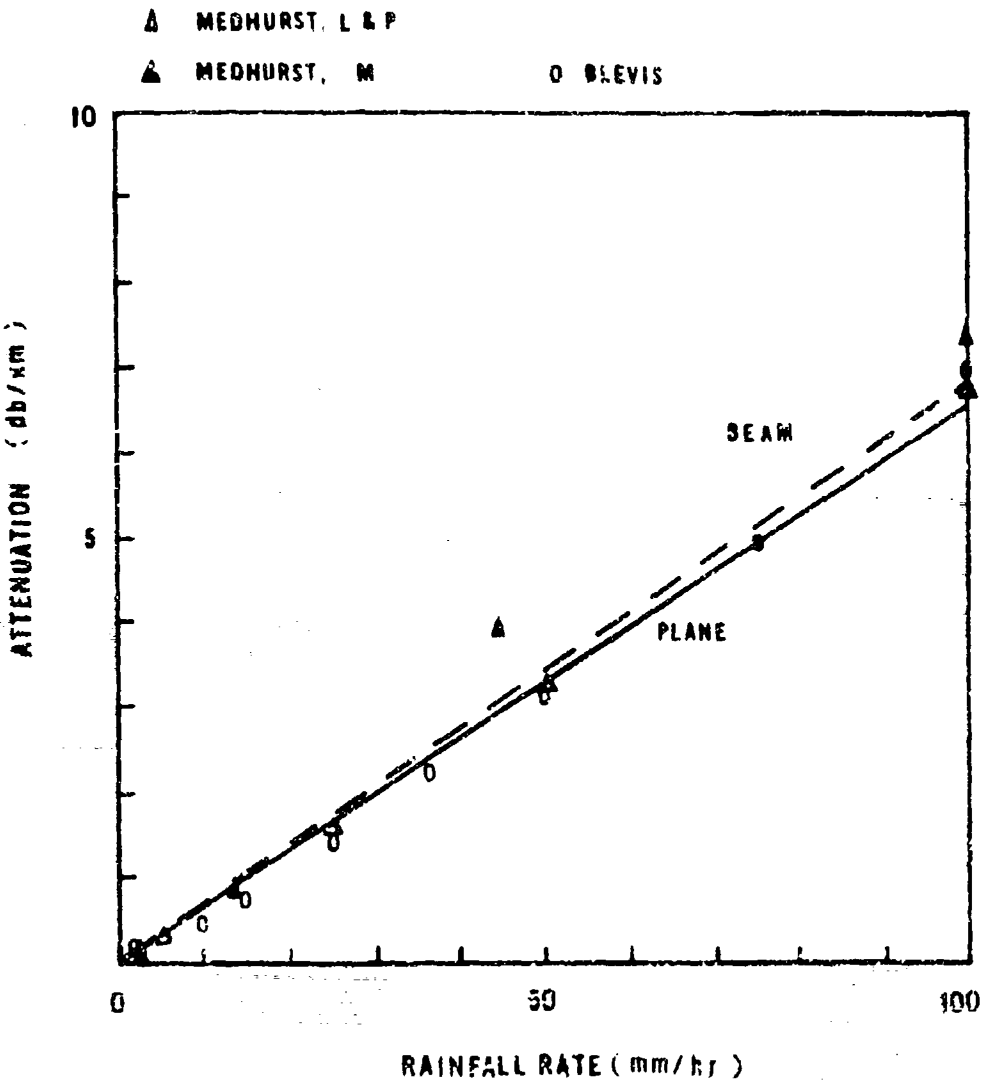
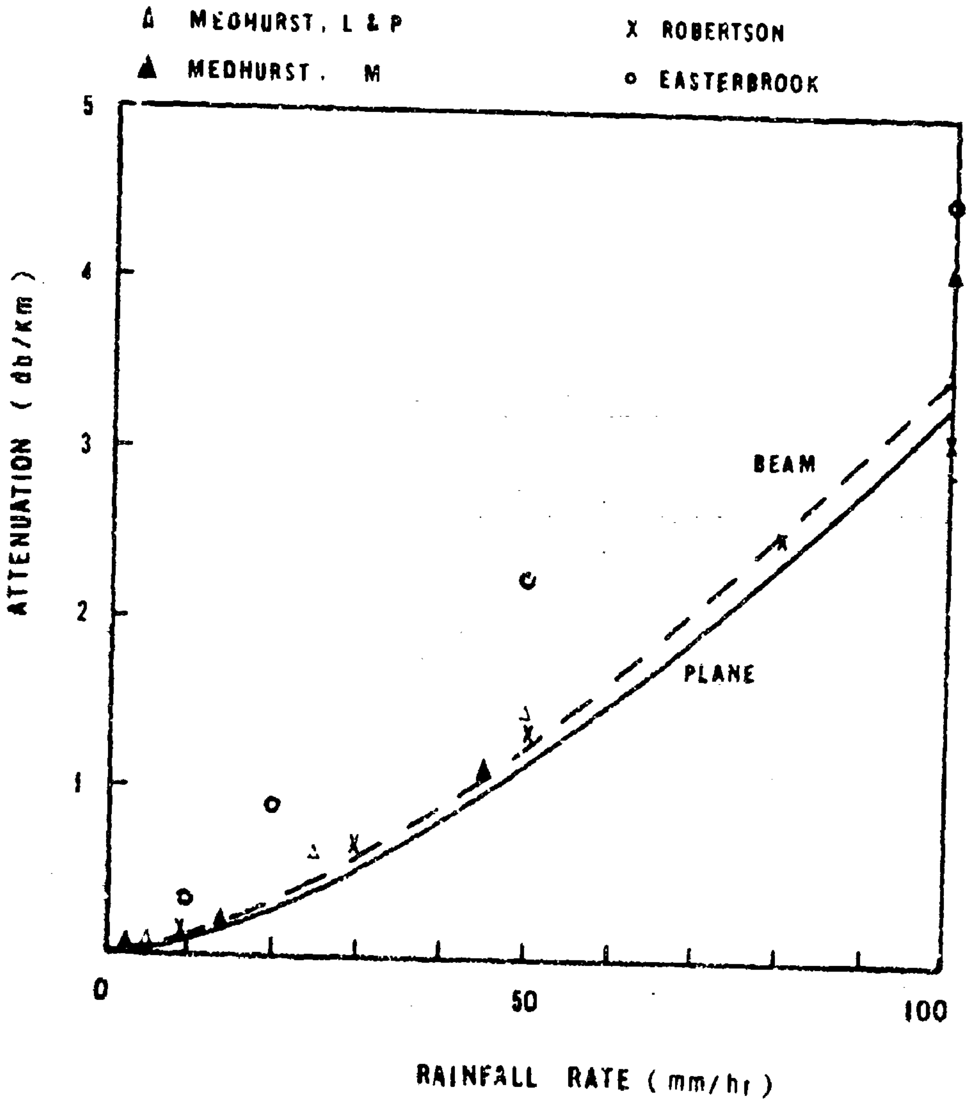

MEDHURST, L & P
MEDHURST, M
O BLEVIS
10
5
0
50
100
ATTENUATION (db/km)
BEAM
PLANE
RAINFALL RATE (mm/hr)

Figure 13

26



MEDHURST, L & P
MEDHURST, M
X ROBERTSON
o EASTERBROOK
5
4
3
2
1
0
ATTENUATION (db/km)
BEAM
PLANE
50
100
RAINFALL RATE (mm/hr)

Figure 11