RAIN ATTENUATION STATISTICS FOR FREQUENCIES ABOVE 10 GHz FOR TERRESTRIAL PATHS

by

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احصائيات التوهين الناتج عن المطر للذبذبات الكهرومغناطيسية مافوق (10) جيكاهيرتز بين محطات الاتصالات اللاسلكية

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خلاصة المقالة

ان النمو المستمر في شبكات الاتصالات اللاسلكية حول العالم اوجد الحاجة الى استعمال ذبذبات عالية جديدة مافوق (10) جيكاهيرتز . وبما ان العوامل الجوية وبالاخص المطر لها تأثير كبير على هذه الذبذبات فقد اصبح من الضروري الحصول على احصائيات للتوهين الناتج عن المطر لكل منطقة يصمم لها شبكات اتصالات لاسلكية تعمل ضمن هذه الذبذبات . في هذا البحث نستعرض الطرق المستعملة للحصول على مثل هذه الاحصائيات وتقدم طريقة جديدة تعتمد على مايعطيه الرادار من معلومات حول المطر للحصول على احصائيات التوهين بالنسبة الى محطتي اتصالات تكون المسافة بينهما غير محدودة .

Abstract

The continuous increase in communication links all over the world has made it necessary to look for new frequency bands. Frequencies above 10GHz were viewed favourably. However, atmospheric effects and especially rain is known to attenuate these waves. Thus rain attenuation statistics have to be established for locations where frequencies above 10GHz are to be used. This paper surveys the methods available for establishing attenuation statistics and introduces a new method for processing radar output data to give these statistics for an infinitely long link.

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1. Introduction

The recent overcrowding of frequency bands caused by the rapid growth of terrestrial and earth-space microwave links has made it necessary to look for new bands. Frequencies above 10 Ghz were, for obvious reasons, viewed very favourably. However, various atmospheric effects are known to have some influence on radio propagation at these frequencies. Thus, a thorough understanding of these effects is sought before a satisfactory system can be implemented.

Electromagnetic waves may suffer losses due to absorption by oxygen and water vapour present in the atmosphere. Also, fog, hail, snow and rain attenuate these waves (1). It is now well established that attenuation caused by rain is the most dominant of these effects and consequently the most extensively studied (2). However, recent evidence (4) indicates that although dry snow causes little attenuation at frequencies below 40 GHz, melting snow or sleet is highly attenuating.

Assuming that attenuation due to rain is the most predominant, a design engineer would require a knowledge of the absolute probability of attenuation-events for a particular link and frequency in order to match it with a system threshold appropriate for the preformance required of that link. The precipitation process varies with space and time and has a probability distribution which, for the same location, varies from year to year (5). Therefore, long-term attenuation statistics have to be established for locations where frequencies above 10 GHz for terrestrial and/or earth-space communications are to be used.

This report attempts to briefly survey the methods most suitable for terrestrial radio relay links, with emphasis on the weather radar method, owing to its importance. A few important applications of the weather radar will also be mentioned. Finally, a procedure for processing a certain form of the radar output data in order to extract rain attenuation statistics will be given.

2. Methods for Establishing Attenuation Statistics

By attenuation statistics is meant the probability distribution of the different fading levels. Also of interest is the distribution of fading durations. In recent review paper, Rogers (6) gave an account of the methods used for obtaining attenuation statistics for both terrestrial and earth-space radio paths. Of those, the following listed below are most suitable for terrestrial paths.

2.1. Direct Measurement

By setting up an actual link along a path of certain length and geographical location, it is possible to obtain rain attenuation statistics for that path and for a certain frequency provided that the link is operated for time periods long enough for statistical confidence.

Lin (7) summarized the results of 31 sets of such experiments on rain attenuation at frequencies above 10 GHz and time base of at least six months at locations in Europe, Japan and North America. He found that, for each location, the conditional probability of attenuation, provided that it is raining, is approximately lognormal. Thus the conditional probability that attenuation exceeds A (dB) is:

$$P(A) = \frac{1}{2}\,\mathrm{erfc}\left\{\frac{\log(A/Am)}{\sigma_a\sqrt{2}}\right\} \qquad (1)$$

Where Am is the median value of attenuation during the raining time, σ_a is the standard deviation of log attenuation and erfc is the complementary error function. For suitable values of Am and σ_a, the above distribution was found to fit the experimental results for terrestrial paths of 1 to 80 Km and for several earth-space links. Thus, given the probability for rain at a particular path and the parameters Am and σ_a it would be possible to obtain the attenuation distribution for that path. However, as Rogers (6) has observed, it is not clear how these parameters can be established for an arbitrary situation.

Lin (7) also analyzed the data on fade durations and found them to be approximately lognormal. Again, it is not clear how the parameters of the distribution may be found in advance for a particular link.

It seems that statistics based on actual propagation experiments are available for a limited number of frequencies, path configurations and for time periods too short for statistical confidence. Moreover, the cost of these experiments made it necessary to turn to indirect methods of measurements.

On the other hand, this is not to imply that direct attenuation measurements are dispensible. On the contrary, it has been found necessaty to establish a limited number of these experiments, usually in association with other methods, for calibration purposes.

2.2 Indirect Measurements

These include using raingauges, radars or radiometers to obtain rain attenuation statistics. For terrestrial paths the first two methods will be considered.

2.2.1. Statistics inferred from Raingauge Records

i) Theoretical considerations

The first theoretical approach to calculate the radio wave attenuation caused by rain was made by Ryde (9). Medhurst (10) has given a good account of the Ryde theory. Based on the attenuation suffered by a plane electromagnetic wave encountering a spherical water drop as derived by the Mie theory (11), Ryde evaluated the specific attenuation (dB/Km) due to uniform rainrate along the path at a certain temperature and for several frequencies. Necessary parameters are the drop-size distributions and the terminal velocities of drops in still air. The assumptions made are:

- drops are spherical in shape
- drops are randomly scattered, i.e. no clusters of raindrops are appreciably formed
- The electromagnetic wave front is indeed plane, i.e. in the far-field region of the antenna
- updrafts and winds have negligible effect on the terminal velocities of drops
- multiple scattering effects are negligible

Attenuation through a path of length L in uniform rain is:

$$A(\mathrm{dB}) = \int_0^L Y\, dx \qquad (2)$$

where Y (x) (dB/Km) is the specific attenuation characteristic of that rain and given by:

$$Y = 0.4343 \int_0^\infty n(r)\, Q_t(r)\, dr \qquad (3)$$

where n(r) dr (m^{-3}) the drop-size distribution. $Q_t(r)$ (cm^2) is the total attenuation cross-section of a drop of radius r. $Q_t(r)$ is determined theoretically by the Mie theory. Techniques for computing $Q_t(r)$ for water spheres to a high accuracy are available.

To relate Y to the rainrate R, the latter may be expressed in terms of the drop-size distribution by:

$$\dot{R} = 1.508 \times 10^{-2} \int_0^\infty n(r)\, u(r)\, r^3\, dr \qquad (4)$$

Where u(r) is the terminal velocity of a drop of radius r. The constant in (4) is such that u(r) is in m/s, R in mm/hr and n(r) dr in m^{-3} and r in mm.

Values of u(r) as a function of r are given by Gunn and Kinzer (12). Thus, for the same temperature and frequency, it is possible to actually measure drop-size distributions and, by using relations (3) and (4), calculate Y and R. If this is done for a large number of rains, regressions may be made of Y against R. Usually log Y is plotted versus log R on which a straight line usually fits the data implying a relation of the form.

$$Y = ar^b \tag{5}$$

Relation (5) is convenient and very widely used with a and b constants depending on frequency and temperature.

Crane (13) used the procedure outlined above and established values of a and b for frequencies ranging from 2.86 GHz to 69.7 GHz A comprehensive review of the approximate empirical Y-R relations and how they are affected by the various meteorological conditions is given by Bettencourt (14).

An alternative approach to determine the Y-R relation is to use a model drop-size distribution. Two very similar model distributions have been extensively quoted in the literature. One was obtained by laws and parsons (15) (quoted by Medhurst (10)) in Washington D.C. The other model is that of Marshal and Palmer (16) based on observations made in Ottawa. The Marshal-palmer distribution is expressed by:

$$n(r) = n_0 e^{-kr} \tag{6}$$

Where n_0 was found to be approximately constant at 8000$m^{-3}mm^{-1}$for all rain and the slope parameter depended only on the rainfall rate according to

$$k(R) = 8.2R^{0.21} \tag{7}$$

where k is in mm^{-1} and R in mm/hr.

Wexler and Atlas (17) found that using the Marshal-Palmer (and also two other model distributions) to calculate Y-R relations for frequencies ranging from 3 GHz to 48 GHz gave results very similer to those of Crane (13) obtained by making actual measurements of the drop-size distributions. However, it must be emphasized that drop-size distributions vary with space, time and type of rain. The influence of the change in drop-size distribution on the Y-R relationship is nearly negligible in the 20-30 GHz band. Outside this frequency band the Y-R relationship is more strongly dependent on the drop-size distribution (3).

Medhurst (10) compared actual experimental measurements with theoretical predictions based on the Mie-Ryde theory. He found the comparison not satisfactory. Besides questioning the accuracy of measuring some parameters used in the experimental procedure, he also questioned the validity of some of the assumptions the theory is based on. However, it is now well established (3), (4) and (6) that the Mie-Ryde theory is valid and that in general any error due to some simplifying assumptions in the theory is much less than the errors caused by experimental measurements and uncertainty in the meteorological parameters.

ii) Evaluation of Raingauge Records

The Mie-Ryde theory of rain attenuation predicts the attenuation per unit path length from the measurement of rainrate at a point near that path. This is clearly based on the assumption that the rainrate along the path is the same as that at the point of measurement. But it is a fact that rain is a process that varies with time and space. Thus, the important parameter to measure would be the average rainrate over the particular propagation path. In fact very few data are available on average path rainfall rate as opposed to an abundance of point rainfall data for many locations throughout the world. Point rainrate distributions can be used to evaluate attenuation statistics if they are supplemented by information about the spatial and temporal properties of the rain.

There have been several approaches to this problem, the most important of these are:

a. **The Bussey Hypothesis**

Bussey (19) first proposed a relationship between point and path average rainrate which has since been used in the design of radio systems. Dudzinsky (1) summarized Bussey's hypothesis and demonstrated its application with an example.

Briefly, Bussey found that the annual distribution of one-hour point rainfall rates is approximately the same as the annual distribution of instantaneous 50 Km path rates in Ohio, USA. He further suggested that two-hour point data correspond to a 100 Km path, half-hour data to 25 Km path, 10-minute data to an 8 Km path and so on.

Dudzinsky (1) concluded that although insufficient experimental data are available for confirming Bussey's hypothesis, the space-time ergodicity proposed by Bussey is valid provided that certain, not yet fully defined, restrictions are placed on the length of the path over which the average is taken.

Therefore, by using Bussey's arguments, the path average rainfall rate distributions for different path lengths may be obtained from the point rainrate distributions provided that point rainfall data are available for different intervals in the area concerned. In this way, and by converting rainrate to attenuation, it is possible to estimate the performance of microwave links in the presence of rain.

b. Bell Telephone Raingauge Network

A more direct approach to the problem of obtaining path average rainfall data to generate attenuation statistics was made by Bell Telephone laboratories in Alabama and New Jersey, USA (20). In the New Jersey experiment, 100 raingauges forming a 130 Km^2 grid were installed. Clearly, many paths of various lengths exist in such a network and a relatively large amount of data were obtained for such paths. Also operating within the same network were two propagation experiments of 1.9 and 6.4 Km path length at frequencies of 30.9 and 18.5 GHz respectively. From this experiment path average rain rates were readily obtainable to generate attenuation statistics. However, in practice, it is not economically feasible to measure rain attenuation in this manner wherever a microwave link is to be installed.

c. Drufuca's Method

To generate attenuation statistics from raingauge records, Drufuca (21) used the concept of 'synthetic storm' which Hamilton and Marshal used for the first time in 1961. As a storm or rainfall pattern moves over a raingauge, the measured point rainrate varies with time. This variation is due to two factors: the spatial displacement of the rain pattern relative to the raingauge, and the changes that occur in that rain pattern during the time required to pass over the raingauge. Both of these effects are present in the raingauge records and in order to separate them, more information regarding the structure and motion of the storm will be needed. The 'synthetic storm' describes the rain pattern as the variation of rainfall rate with distance along a line in the direction of storm motion. In other words, this method ignores the changes occuring in a rain pattern with time and thus the variation of rainrate with time registered by a raingauge is wholly attributed to the spatial movement of the storm. As may be expected, this will not describe the distribution of rain with distance exactly. However, Drufuca (21) quotes Taylor's hypothesis-which finds support in other literature-in proposing that although a one to one correspondence does not exist, the statistical properties of a large number of synthetic storms are nearly the same as the corresponding statistical properties of real storms.

To apply this method, rainfall rate is first converted to specific attenuation by using relation (5). Next, the time scale is converted to distance by using the translational velocity of the storm. The attenuation A(dB) as a function of time is plotted by calculating for each value of time (time is zero at the beginning of the storm) the integral:

$$A(x_0, L) = \int_{x_0}^{x_0 + L} Y(x)dx \tag{8}$$

Where L is the length of the path (constant) and x_0 the starting point which is changed at the same rate as the storm translational velocity. Thus, by changing L, attenuation statistics for different hop lengths may be obtained.

iii) Concluding Comments

Bussey's hypothesis is not yet fully confirmed by experimental results and needs rainrates for several intergration times (of raingauge) that might not be available. That they can be derived on the basis of some assumptions introduce yet more approximations.

The more direct approach applied by Bell laboratories in evaluating the path average rainrate by using a dense network of raingauges over short paths, although more reliable, is not economically feasible for use on any large scale.

Drufuca's approach which is in good agreement with experimental results as tested in Canada and Italy (22) seems to afford the most suitable method of converting point rainfall statistics to attenuation statistics using raingauge records and rain storm translational speeds as measured by the nearest radiosonde station. The speeds that correlate best with the rain storm movements were found to be those at the 700 mb (or r $\approx$ 3 Km above sea-level).

Finally, obtaining rain statistics from raingauge records is extremely valuable since these records are available almost all over the world and over long periods of time. Especially when direct propagation measurements are not available, this method provides a reference against which other indirect techniques (such as radar) may be calibrated.

2.2.2 Statistics Inferred from Radar Measurements

i) Introduction

Ever since the development of radar during World War II, it was realized that radar can also be used to observe precipitation.

The weather radar is a technological spin-off of radar technology especially designed to cope with meteorological targets. These (e.g. rain drops) usually move at much lower speeds than the usual conventional targets such as jet airplanes and are distributed in space. A comprehensive review of the theory and applications of weather radars was made by Battan (23). Also, a review paper on the applications of radar to meteorological operations and research was made by Smith et al. (24).

Generally speaking, a weather radar should be of high power, narrow beam width, short pulse duration, high sensitivity and large dynamic range. Also of great importance is the radar operational wavelength. Using a small wavelength (e.g. 3 cm) will lead to a two-way attenuation of the pulse as it traverses precipitation, while using larger wavelengths require bigger antennas to keep the beam-width narrow. Table (1) below, gives possible performance characteristics of weather radars (24).

Table 1
Possible Performance Characteristics of Weather Radars

Wave Lenth (cm)	Beam Width (deg)	Antenna Diameter (m)	Peak power (MW)	Pulse Duration (μs)	Minimum average Receiver Power (Watts)	Range (Km)	Minimum Reflectivity Factor Zmin $mm^6 m^{-3}$	Minimum Detectable Rainrate mm hr^{-1}	
3.2	1	2.3	0.2	1	10^{-13}	100	2	0.06	at 100 Km
5.4	1	3.9	0.2	1	3.2×10^{-14}	100	2	0.06	
10	1	7.1	0.5	1	3.2×10^{-14}	100	2	0.06	

Although the 3.2-cm radar sets are more easily available, it may suffer up to 40 dB attenuation in a record storm making it entirely unsuitable for quantitative measurement in medium and heavy precipitation. However, the 5.4-cm radar set has a more tolerable 6 dB attenuation while the 10-cm radar would have a negligible 0.6 dB under the same conditions (24). Clearly, the 10-cm radar is the most suitable for measurements in the presence of heavy precipitation.

Radars, however, are inherently limited by uncertainty in the calibration and choice of empirical reflectivity factor-rainrate (Z-R) relationship where the latter is dependent on the type of rain and drop-size distribution. More accurate calibration of the radar (i.e. relating received echo power to reflectivity) may be achieved by installing a target of known cross section (such as a metallic sphere (23)) in the field of the radar.

On the other hand, radars possess extremely valuable features giving data which often are not possible to obtain by other means such as the temporal and spatial structure of precipitation. However, in order to exploit fully the potentials of weather radars, more work is needed to solve problems related to obtaining faster rate of data acquisition and handling, storing and processing large amounts of data (24).

Some basic theoretical consideration will be dealt with before describing some of the weather radar applications, especially that of acquiring rain attenuation statistics.

ii) Radar Equation For Distributed Targets

The radar equation makes it possible to evaluate the scattering characteristics of the target from the echo power received and radar parameters. One form of this equation, as given in (24), is:

$$\overline{P_r} = (4.28 \times 10^4 \, m/s) \, P_t \, \tau \, \lambda^2 G^2 \, \theta \frac{\Phi \, \eta \, k}{r^2} \qquad (9)$$

Where $\overline{p_r}$ is the average received power in Watts, p_t is the peak transmitted power in Watts, λ is the radar wavelength in metres, τ is the pulse duration in seconds, G is the antenna gain, θ and Φ are the 3 dB beamwidths of the antenna in the horizontal and vertical directions in radians, η is the radar reflectivity (back-scattering cross section per unit volume) in m^{-1}, r is the range to the target in metres, and k is the attenuation factor.

For target particles smaller than the radar wavelength (e.g. $D/\lambda \approx 0.3$ where D is the particle diameter) the Rayleigh approximation applies and thus:

$$\eta = \frac{\pi^5}{\lambda^4} |K|^2 \Sigma D^6 / V_c \qquad (10)$$

Where V_c is the effective volume of the contributing region summing over that region. i.e. V_c is the inverse of the integral of drop-size distribution. K is a function of the complex index of refraction of the precipitation particles.

Since the quantity $\Sigma D^6 / V_c$ above is independent of the wavelength and characteristic of the atmosphere only, it is customary to write:

$$Z = \Sigma D^6 / V_c \qquad (11)$$

Where Z is called the reflectivity factor. Thus, for Rayleigh scattering:

$$\eta \propto Z \qquad (12)$$

The constant of proportionality being a function of frequency and temperature.

If D/λ] 0.3 rendering the Rayleigh approximation no longer applicable, it is still useful to retain the concept of the reflectivity factor by expressing η as:

$$\eta = \frac{\pi^5}{\lambda^4} |K|^2 Z_e \qquad (13)$$

here Z_e is called the equivalent reflectivity factor, obviously $Z_e = Z$ in the Rayleigh region. $|K|^2$ is taken as 0.93 for wavelengths in the 3-10 cm region. Thus, equation (9) may be written:

$$\overline{P_r} = \left[(1.22 \times 10^{7}\ \mathrm{m/s}) \frac{P_t \tau G^2 \theta \Phi}{\lambda^2} \right] \frac{Z_e}{r^2} k \qquad (14)$$

For radars using 10-cm wavelengths or longer, the Rayleigh scattering usually applies and Z may be determined by two independent methods:

a. By employing relation (10) Z is determined from radar measurements of reflectivity as λ and |K| are known.

b. By employing relation (11) Z may be obtained by measuring the drop-size distribution.

A very useful relationship is that relating the reflectivity factor to the rainrate. Problems related to obtaining Z-R relationship have occupied meteorologists very long indeed. Such a relation would inevitably depend on the drop-size distribution which has been proved to vary with time, space, and type of rain (18). Therefore, no universal Z-R relationship exists. However, a widely used relationship is that obtained by assuming a Marshal-Palmer distribution for moderate, widespread rain:

$$Z = 200 R^{1.6} \qquad (15)$$

R in mm/hr and Z in $\mathrm{mm^6 m^{-3}}$. The coefficient in relation (15) tends to be somewhat less than 200 for drizzle and somewhat more for thunderstorms. The exponent is usually near 1.5 for most of the reported data(6).

For agiven rainfall type, the Y-R and the Z-R empirical relations may be combined to give a relation of the form:

$$Y = \alpha Z^{\beta} \tag{16}$$

Where α and β for a given frequency depend largely on the model drop-size distribution.
A more direct method of relating Y to Z is to calculate Z and Y for a given model drop spectrum. or for many measured spectra so that a best fit Y-Z relation may be obtained. In this way the rain rate is bypassed altogether. Crane (13) used this approach on a large rainfall sample in North Carolina. USA. and determined Y-Z relations of a form like relation (16) for frequencies of 7.5. 9.4. 16.0 and 34.9 GHz. The rms deviation of the data points was about 40% or less for each frequency.

iii) Weather Radar Applications

1. Establishing rain attenuation statistics

By using the appropriate Y-Z relation at the chosen frequency it is possible to evaluate the attenuation over a propagation path through rain by the radar-measured reflectivity factor along the path. If raindrops in the Rayleigh region are the only scatterers present in the radar beam. then usually good agreement exists between attenuation by radar and that measured directly.

McCormick (as in Rogers(6)) demonstrated this by comparing attenuation measured directly through rain at frequencies of 4. 8 and 15 GHz with radar measurements from an airplane to the ground. Joss et al. in a widely quoted contribution (18) confirmed the accuracy of the radar-estimated rain attenuation. Five disdrometers. three raingauges and three vertically pointing radars operating at 5. 10 and 35 GHz were used in the experiment. Using the disdrometers data Y was calculated at 35 GHz and Z_e at 5 GHz. Then a regression was used to find the best fit. This best fit Y-Z_e relationship was compared with another. found independently of the disdrometers data by comparing the reflectivity profiles at 5 and 35 GHz. The idea being that if nearly the same volume of rain was illuminated by the two wavelengths. one attenuating and the order non-attenuating. the difference between the reflectivities gives a measure of the two way attenuation. The results (18) gave good agreement for $Z_e > 10^3$ mm^{6}m^{-3}. At lower values of Z_e. the attenuation measured aloft exceeded that at the ground. The explanation offered is that the radar beam aloft may illuminate could droplets which are 'not seen' by the groundbased disdrometers. Fortunately this effect is only significant in light rain which is less interesting any way.

One of the distinguishing features of radar is its ability to collect attenuation statistics rapidly due to the large sample size of rain the radar penetrates as it probes the atmosphere deeply in all directions.

Radar has been used to obtain attenuation and diversity-gain statistics for earth-space paths (6). For terrestrial paths Drufuca (5). along with his analysis of raingauge records. analysed the summer 1971 data from McGill University weather radar. the main characteristics of which are listed in Table 2.

TABLE 2

The McGill Weather Radar Main Features In 1971

Frequency: 2,880 MHz
Antenna diameter: 30-ft paraboloid (θ. Φ = 0.8°)
Peak power: 2 MW
Pulse Repetition Frequency: 60 Hz
Pulse length 0.3 μsec (pulse compression a 4 μsec pulse with a factor 13)
Sensitivity: -104 dBm (equivalent to a rainfall rate of 0.2 mm/hr at 200 Km)

Dynamic range: 80 dB

It is interesting to note that out of the whole summer, Drufuca used the radar data of six days totalling 22 hours and 20 minutes only to produce attenuation statistics to a lower level of probability than 10-years of raingauge data. Although raingauge data will distinguish itself by showing the year to year variability, this clearly demonstrates the immense speed of the radar for providing attenuation statistics.

Gain diversity statistics for parallel paths ofdifferent lengths and separations were also obtained by radar (5). An important result was that path diversity separations beyond about 10 miles gave relatively little reduction in joint probability especially for the weaker attenuation levels. Fedi (3) gave a comprehensive evaluation of the radar method for measuring attenuation. The errors, limitations and advantages of the radar-measured attenuation were outlined.

He concluded that a properly calibrated single-wavelength radar or, better still, a dual-wavelength radar provided a very useful tool for evaluating rain attenuation on terrestrial and earth-space paths. It must be pointed out that, for terrestrial links, the radar beam must be kept below the melting layer. This layer contains mixed-state scatterers which have large radar cross sections giving high reflectivity (Bright Band) but lower attenuating effect than raindrops of the same reflectivity.

2. Other Applications

Owing to the importance of the weather radar, few other applications will be briefly mentioned. As stated earlier, a full account may be found (23) , (24).

The estimation of areal rain plays an important role for example, to the hydrologist in the forecasting of floods; to farmers for avoiding soil erosion; sewerage engineers for designing the correct sizes of drainage pipes etc. This has been done, up to now , by widely-spaced raingauges in the area of interest. These may give reasonably accurate prediction of area rain when the latter is caused by stable systems of clouds causing widespread, uniform rain. In the presence of convective activity it is usually found that high rainfall rate is concentrated within a small area only. Harrold et al. (8) have shown that radar provides an easier and better estimate of areal rain than a few scattered raingauges. Essentially, an echo intergration technique in time and space is required to estimate the total rain over an area. As early as in 1948, attempts to measure rain by radar were made, and fairly reliable techniques now exist (See Battan (23) pp. 104-113). In fact, some hydrological studies indicated that the amount of precipitation estimated by radar over an area, was in excellent agreement with results obtained by using a dense raingauge network (24). Smith et al. (24) have indicated that radar can also locate potentially dangerous local storms or, on a larger scale, can locate and track hurricanes. By following identifiable echo structures it is possible to estimate the velocity of the wind associated with some parts of the hurricane and thus a 0.5-1 hour surveillance provides information regarding the stage of development of the hurricane and the course of the storm. Radar ia also a very useful tool in studying the structure and dynamics of storms. High power systems have been used to investigate the clear atmosphere (24).

Finally, radar measurements, being in real time may be used for short-term weather forecasts which, in severe weather, may be utilized for several purposes as, for example, temporary adjustments on the microwave communication equipments for accomodating the anticipated weather conditions.

3. A Method for Establishing Rain Attenuation Statistics for Terrestrial Paths from Radar Output.

The statistical storm models, reviewed by Rogers (6), have been used to generate rain attenuation statistics on slant paths. Goldhirsh et al. (26) used radar reflectivity data directly to produce conditional rain attenuation and diversity statistics for earth-space paths. For terrestrial paths, Drufuca (21) obtained rain attenuation statistics and diversity gain statistics by simulating a large number of paths of various lengths over the radar map of precipitation using the McGill weather radar mentioned earlier.

The idea behind the method used in this study is the same as that of Drufuca. It amounts to establishing the rain pattern in the horizontal plane as seen by the radar in the form of constant-rain contours. These contours are digitized and total attenuation is computed for a variety of paths sweeping across the rain pattern.

As to the rainfall pattern, Rogers (27) stated: (Rain is known to be cellular in character, with more or less well defined individual cells of heavy rain often organized into a large mesoscale pattern. Local climatological, or topographic effects may be of great importance in determining the form of this mesoscale pattern). Conforming to this description of rainfall pattern on a large scale, Zawadski (28), (29) obtained normalized space autocorrelation functions of the radar PPI patterns of storms occurring in Montreal. The constant-rain contours, assumed to be those shown in figures

2 and 3 will be analyzed in this study. To illustrate how rain attenuation is calculated from these rain patterns for an infinite link situated across the pattern, consider figure 1 which is a simplified model of a real situation depicted to demonstrate the method. C1 and C2 are constant-rain contours (cells) corresponding to rainrates, R1 and R2 respectively (R1 $<$ R2). Rain cells C1 and C2 may be of any shape whatso ever. These cells are made into a computable form by approximating each cell to a many-sided polygon whose sides may be increased until it nearly coincides with the cell it is simulating. Such polygons are P1 and P2, simulating cells C1 and C2 respectively. Each polygon is defined by the X-Y coordinates of its nodal points (e.g. for P1 nodal points are 1.1, 1.2, 1.3, etc.). Now, a microwave link over a path such as AB will make intersections with P1 at $P_{1.1}$ and $P_{1.2}$ and with P2 at $P_{2.1}$ and $P_{2.2}$. By finding the coordinates of these intersection points, the distances between them may be calculated. Thus, at the time the storm and the link have the configuration shown in figure 1, the following may be calculated for link AB.

$$\text{Average rainrate on path AB} = \frac{(p_{1.1}p_{2.1} + p_{2.2}p_{1.2})R1 + p_{2.1}p_{2.2}R2}{p_{1.1}p_{1.2}} \text{(mm/hr)(per Km).}$$

$$\text{Total attenuation on path AB} = (p_{1.1}p_{2.1} + p_{2.2}p_{1.2})aR_1^b + p_{2.1}p_{2.2}aR_2^b \text{(dB)}$$

The total attenuation is calculated using relation (5) for the specific attenuation and multiplying by the length of link situated inside the particular rain contour and summing for all contours.

Also, for simulation purposes, it is easier to have the link sweeping across a stationary storm rather than the opposite. Thus, the line AB (the link) is made to move across the system of concentric polygons (cellular rain pattern) at the speed of that particular storm. At successive time intervals (which may be made as short as the need arises), the path average rainfall rate and the total attenuation may be computed. This procedure may be repeated for different inclinations of the link relative to the storm system (taking account of all possible configurations) and for sufficiently long time to yield attenuation statistics for that storm and link at any required frequency.

A computer program has been constructed which does what is described above.

This program was used to analyze the rain patterns of figures 2 and 3.

Radar- estimated attenuation statistics are always conditional (unless they are operated without stop throughout the whole time) and may be calibrated against raingauge-estimated or direct measurement statistics (21) in order to be converted to absolute statistics.

In the foregoing description, it is observed that the length of the link has not been specified. In fact, it was assumed infinite in the sense that it will always contain the storm regardless of its size.

Therefore, this procedure has to be completed by taking account of the link length and thus obtaining attenuation statistics for different path lengths. It is the intention of the author to develop the computer program to achieve this end.

It may be of interest to observe that by obtaining path average rainrates at very close time intervals, and all over the storm pattern, an estimate of the area rain for the storm, can be found.

3.1. Example

The normalized space aurocorrelation functions of the PPI's of storms in Montreal, Canada, were obtained by Zawadski (28), (29). Those shown in figures 2 and 3 were chosen to be analyzed in order to yield attenuation statistics. The frequency chosen was 16 GHz. Clearly, one may choose any frequency for which an empirical Y-R relationship exists.

The steps taken to analyze each rain pattern were as follows:

1. Assume maximum rainfall rate for each storm to be 100 mm/hr. In actual situations this may be measured.
2. The rain pattern was superimposed on ordinary graph paper.
3. Polygons were drawn to correspond as closely as possible to the constant rain contours. Then the X and Y coordinates of the nodal points of each polygon were read. These were used as data to the computer program (shown in the Appendix). Other data regarding the rain rate for each contour and the link configuration and speed were also provided.

   Given this data, the program gives total attenuation suffered by the link as it crosses the storm for successive intervals in time until the link clears the storm.
3. The computer program calculates the specific attenuation from the rain rate by using relation(5).

   $Y = aR^{b}$ dB/Km

   Where the a and b values used are those darived by Crane (13) at a frequency of 16 GHz.
4. For each rain pattern 10 different link configurations were analyzed. Total time durations of attenuation levels at 5-dB intervals were calculated.
5. figure 4 shows the percentage probability that a certain attenuation level is exceeded for both rain patterns considered.

From figure 4 the following points emerge:

a. The percentage probability that certain attenuation levels are exceeded is lognormally distributed. This is in agreement with the findings of Lin (7) discussed earlier in this report.

b. At high and low percentage probability, the distribution departs from lognormal. This is believed to be due to insufficient observation time for statistical validity at the high and low attenuation levels. This is shown in figure 4 as distribution derived from 26 hours observation time in rain pattern 1337 figure 2 continue to be lognormal at attenuation levels where the distribution derived from 13 hours' observation time in rain pattern 1326 figure 3 departs from the lognormal distribution.

c. High attenuation levels are due to taking the link to be infinite. In fact, the largest dimension of the rain patterns 1337 and 1326 are 185 and 265 Km. respectively.

As previously stated, a follow-up work will take account of the finite leogwo'th of the link and give a procedure for extracting rain-attenuation statistics from rain patterns obtained by radar for different link lengths.

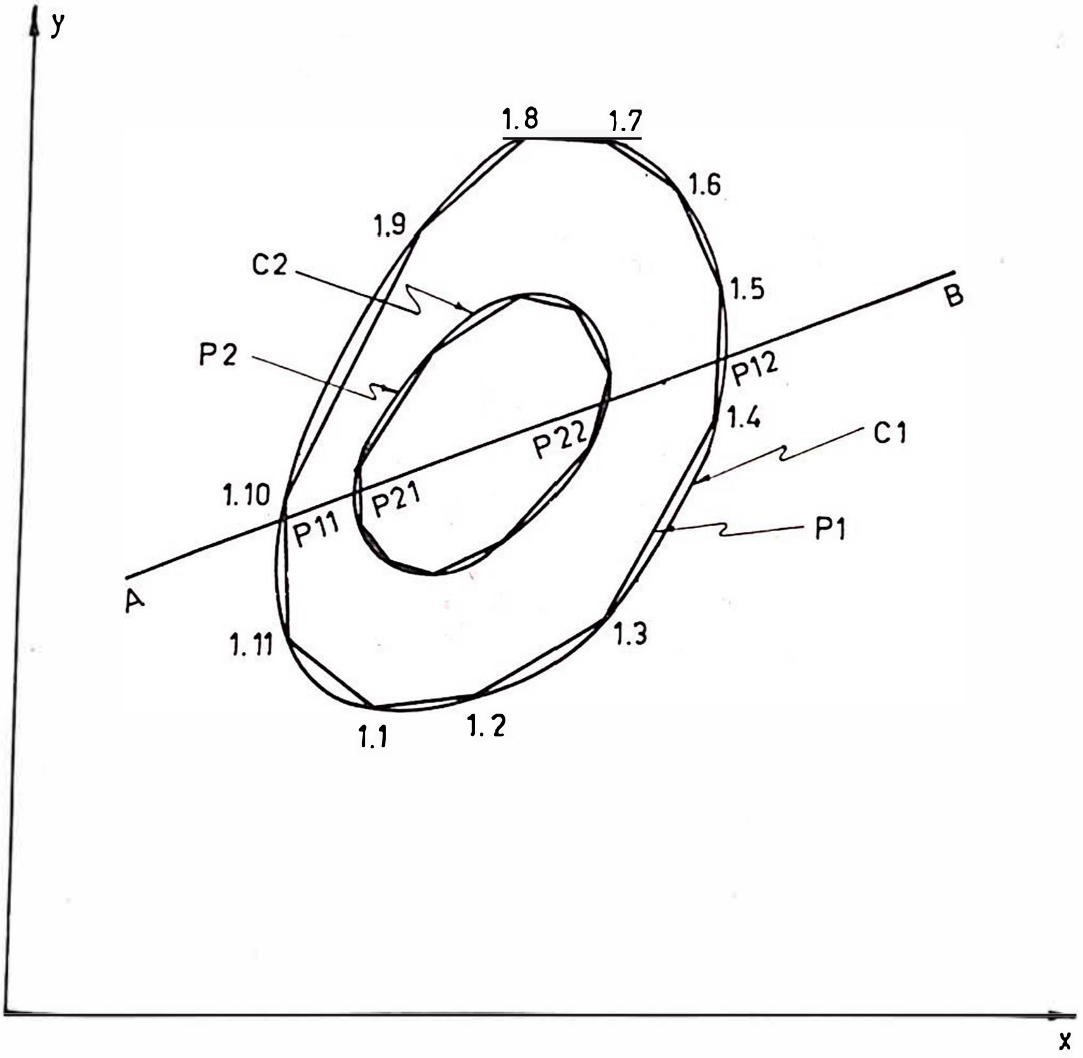

Fig. (1): A model of a link AB sweeping across two rain-cells Cl and C2.

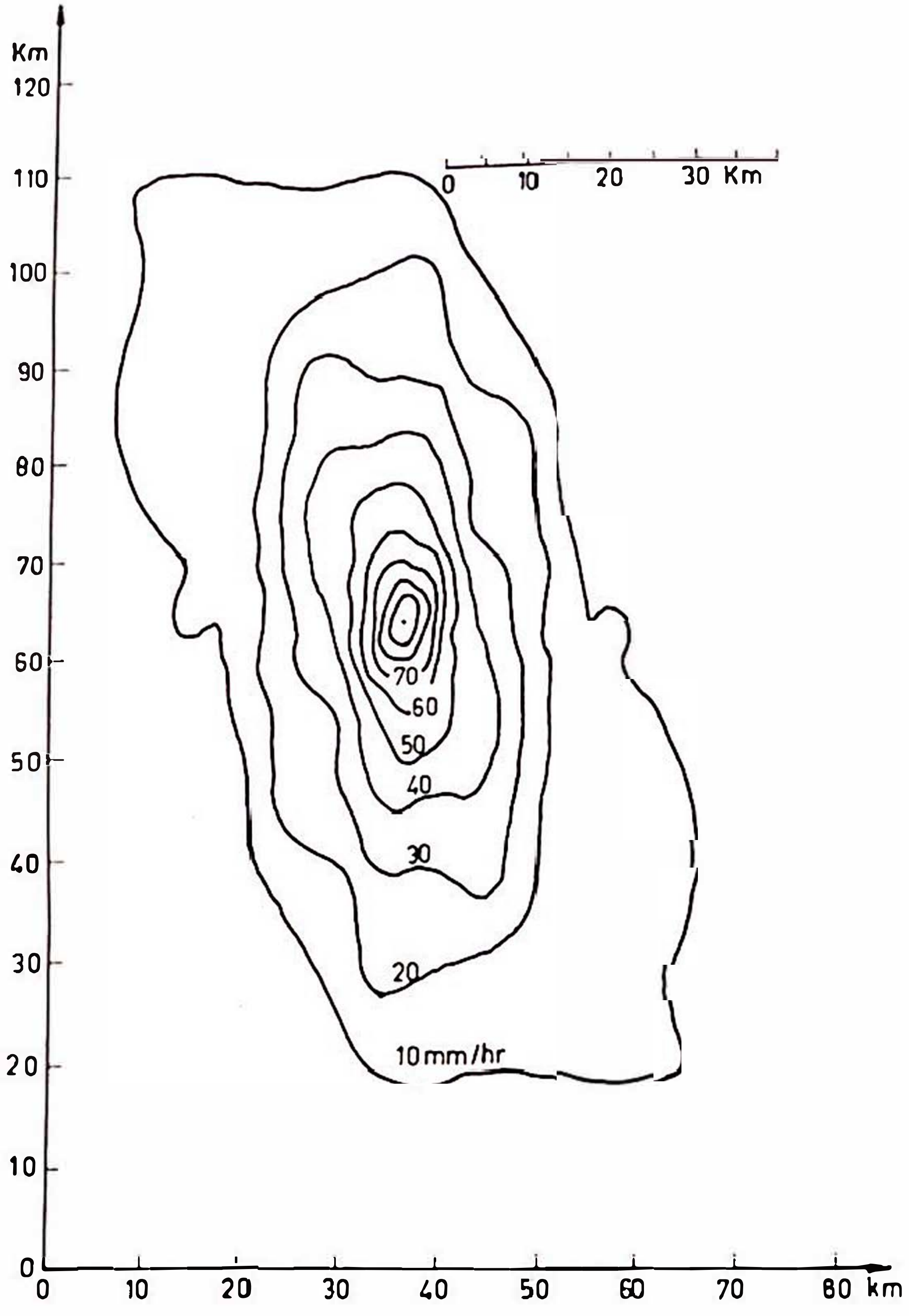

Fig. (2): Space normalized ACF corresponding to the precipitation of the 20th July1970 taken at 13.37 [29].

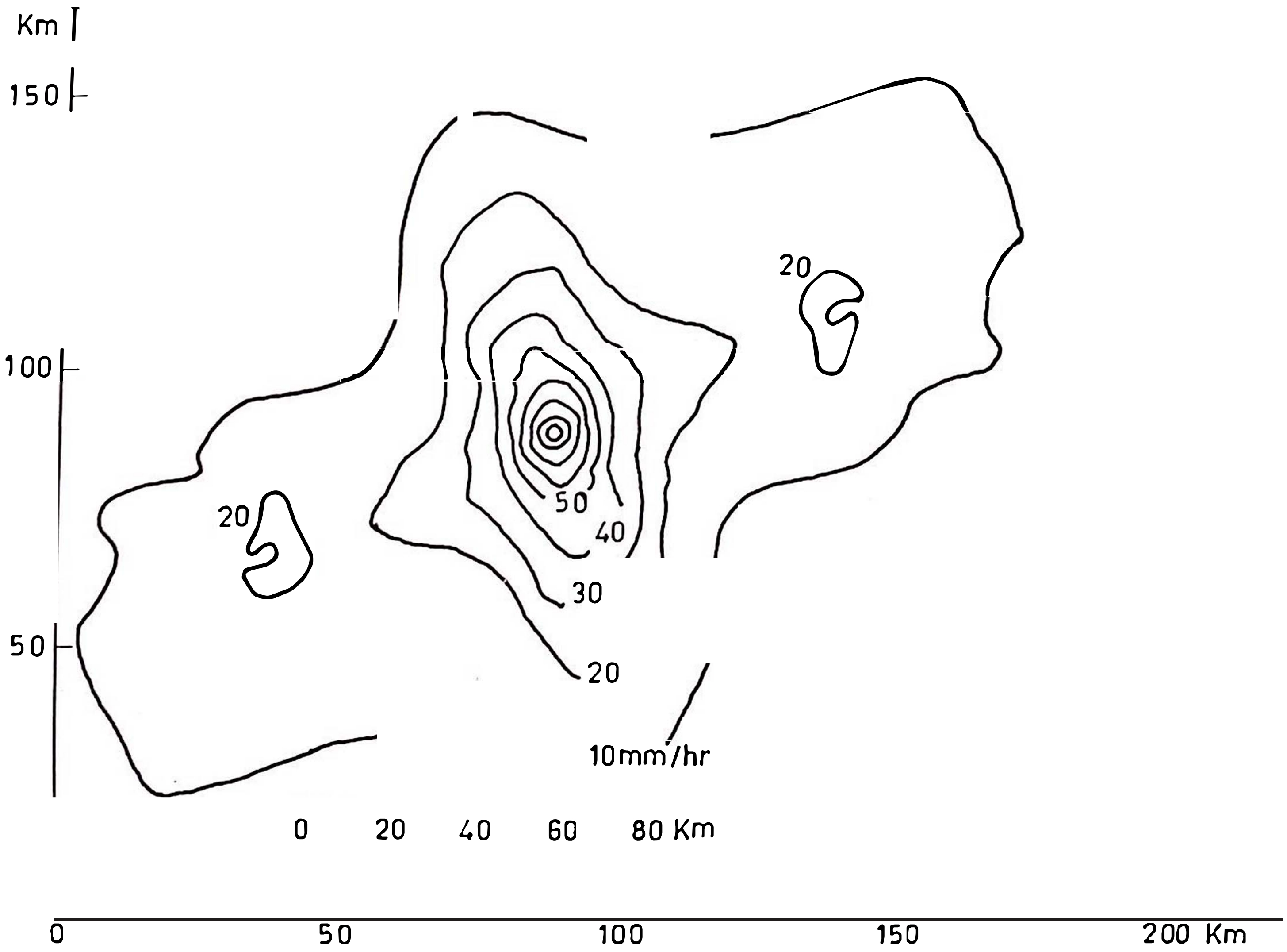

Fig. (3): Space normalized ACF corresponding to the precipitation pattern of the 16th September 1969 taken at 13.26 [28].

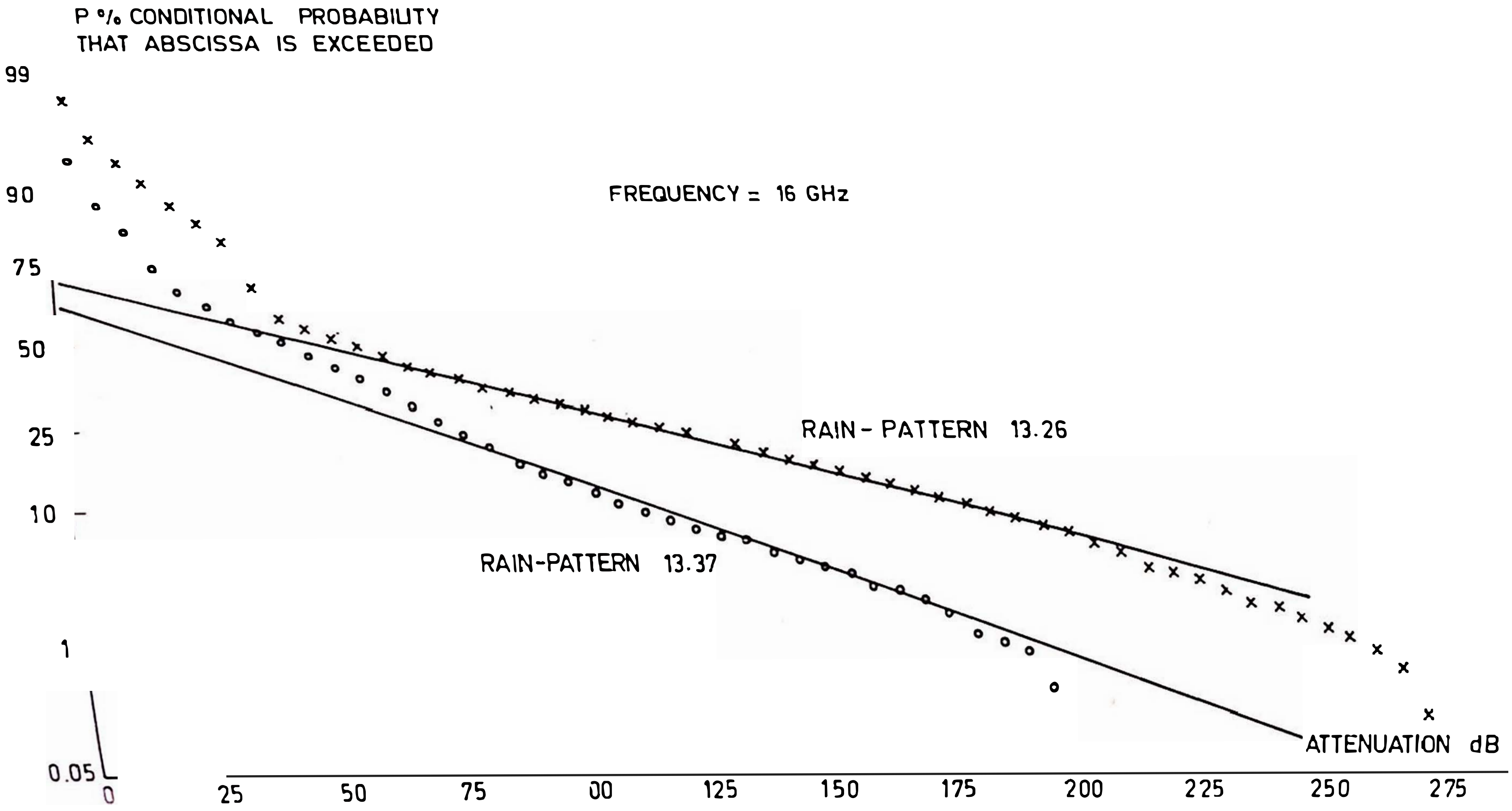

Fig. (4): Conditional probability for the attenuation exceeded for the rain-patterns 13.37 and 13.26 on links of 185 and 265 Km respectively.

References

(1) Dudzinky. S.J.. 1975: Atmospheric Effects on Terrestrial mm-Wave Communications. Microwave Journal. Dec.. pp. 39.

(2) Inter-Union Commision on Radio Meteorology. Colloquium on the Fine Structure of Precipitation and Electromagnetic Propagation. Papers are collected in a special issue of journal de Recherches Atmospheriques. Jan-Juni 1974.

(3) Fedi. F.. 1974: Attenuation: Theory and Measurements. Working Group Report I. J. Rech. Atmos.. 8. pp. 465-472.

(4) Watson. P.A.. 1975: Results of Measurements of Attenuation by Rain and other Hydrometeors.. URSI General Assembly Meeting. Lima. Peru.

(5) Drufuca. G.. 1974: The Statistics of Rainfall Rate and the Design of Communication Systems. Working Group Report. J. Rech. Atmos.. 8. pp. 473-476.

(6) Rogers. R.R.. 1975: Models - Their Theoretical and Physical Foundations. URSI General Assembly. Lima. Peru.

(7) Lin. S.H.. 1973: Statistical Behaviour of Rain Attenuation. BSTJ. 52. pp. 557-581.

(8) Harrold. T.W. and C.A. Nicholass. 1972: The Accuracy of some Recent Radar Estimates of Surface Precipitation. Meteor. Mag.. Vol. 101. 1200. pp. 193-205.

(9) Ryde. J.W.. 1941: Echo Intensity and Attenuation due to Clouds. Rain. Hail. Sand. and Duststorms at Centimetre Wavelengths. Report 7831. General Electric Co. Research Labs.. Wembley. England.

Ryde. J.W.. and D. Ryde. 1944: Attenuation of Centimetre Waves by Rain. Hail and Clouds. Report 8516. GEC Research Labs.. Wenbley. England.

Ryde. J.W.. 1945: Attenuation of Centimetre and Millimetre Wave by Rain. Hail. Fogs and Clouds. Report 8670. GEC Research Labs.. Wembley. England.

(10) Medhurst. R.G.. 1965: Rainfall Attenuation of Centimeter Waves. Comparison of Theory and Measurement. Trans. IEEE. AP-13. pp. 550-564.

(11) Mie. G.. 1908: Beitrüge zur Optik Trüber Medien. Speziell Kolloidaler Metallosungen. Ann. der Phys.. Vol. 25. pp. 377-445.

(12) Gunn. R.. and G.D. Zinzer. 1949: The Terminal Velocity of Fall of Water Drops in Stagnant Air. J. Meteor. 6. pp. 243-248.

(13) Crane. R.K.. 1971: Propagation Phenomena Affecting Satellite Communication Systems Operating in the Centimetre and Millimetre Wavelength Bands. Proc. IEEE. 59. pp. 173-188.

(14) De Bettencourt. J.T.. 1974: Statistics of Millimetre Rainfall Attenuation. J. Rech. Atmos.. 8. pp. 89-119.

(15) Laws. J.O.. and D.A. Parsons. 1943: The Relation of Raindropsize to Intensity. Trans. Am. Geophys. Union. 24. pp. 432-460.

(16) Marshall. J.S.. and W. Mck. Palmer. 1948: The Distribution of Raindrops with Size. J. Meteor. 5. pp. 165-166.

(17) Wexler. R.. and D. Atlas. 1963: Radar Reflectivity and Attenuation of Rain. J. Appl. Meteor. 2. pp. 276-280.

(18) Joss. J.. Cavalli. R.. and R.K. Crane. 1974: Good Agreement between Theory and Experiment for Attenuation Data. J. Rech.. Atmos.. 8. pp. 299-318.

(19) Bussey. H.E.. 1950: Microwave Attenuation Statistics Estimated from Rainfall and Water Vapour Statistics . Proc. IRE 38. pp. 781-785.

(20) Hogg. D.C.. 1969: Statistics on Attenuation of Microwaves by Intense Rain. BSTJ. Vol. 48. 9.

pp. 2949-2962.

(21) Drufuca, G., 1973: Rain Attenuation Studies, Stormy Weather Group Scientific Report MW-77, McGill University.

(22) Drufuca, G., 1975: Practical Models for Engineering Applications, URSI General Assembly, Lima, Peru.

(23) Battan, L.J., 1973: Radar Observations of the Atmosphere, Univ. of Chicago Press, 324pp.

(24) Smith, P.L., Hardy, K.R., and K.M. Glover, 1974: Applications of Radar to Meteorological Operations and Research, Proc. IEEE, Vol. 62, pp. 724-745.

(25) Zawadski, I.I., and R.R. Rogers, 1972: ADA: An Instrument for Measuring Attenuation Due to Rain over Slant Paths, Radio Sci., 7, pp. 619-624.

(26) Goldhirsh, J. and F.L. Robinson, 1975: Attenuation and Diversity Statistics Calculated from Radar Reflectivity Data of Rain, Trans. IEEE, AP-23, 2, pp. 221-227.

(27) Rogers, R.R., 1974: The Mesoscale Structure of Precipitation and Space Diversity, Working Group Report IV, J. Rech., Atmos., 8, pp. 485-490.

(28) Zawadski, I.I., 1973: Statistical Properties of Precipitation Patterns, J.Appl. Meteor., 12, pp. 459-472.

(29) Zawadski, I.I., 1974: Statistics of Radar Patterns and EM Propagation, J. Rech. Atmos., 8, pp. 391-397.