INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONES: 224281/2/3/4/5/6
CABLE: CENTRATOM - TELEX 460392-I

SMR/113 - 16

AUTUMN COLLEGE

ON

THE TROPOSPHERE, STRATOSPHERE AND MESOSPHERE

10 September - 19 October 1984

ABSORPTION AND SCATTERING FROM HYDROMETEORS

ATTENUATION

F. FEDI

Fondazione Ugo Bordoni
Viale Trastevere 108
00153 Rome
Italy

Programme

1. Absorption and scattering from hydrometeors and their importance at frequencies above 10 GHz. Radio spectrum. Needs, advantages and problems of the use of frequencies above 10 GHz. Attenuation and Cross-polarisation.

2. Attenuation caused by a single spherical drop (Mie, 1908). Scattered wave: amplitude complex functions, associate Legendre functions and Mie coefficients. Absorbed, scattered and total power removed by a single spherical drop. Extinction, absorption and scattering cross-sections: Q_t, Q_a, Q_s. Behaviour of Q_s and Q_a and their dependence on wavelength. Calculation of Q_t. Index of refraction of water. Total power removed by a single spherical drop.

3. Attenuation caused by a distribution of spherical drops of different sizes (Ryde, 1945). Rain intensity. Drop-size distribution. Relationship between attenuation per unit length γ and rain intensity R. Microstructure of precipitation (temperature, drop-size distribution and terminal velocity). Specific attenuation versus frequency and rain intensity.

4. Influence of the shape of the raindrops. Extinction section for a single spheroidal raindrop (Oguchi, 1960). Specific attenuation for a distribution of spheroidal raindrops of different sizes. Experimental test of the validity of the γ-R relationship. Cumulative distribution of attenuation P(A). Validity of the γ-R relationship for estimating P(A). CCIR recommended values (Fedi, 1979).

5. Terrestrial links. Design criteria of links at frequencies above 10 GHz. Information necessary. Validity of P(A) in space and time. Direct methods. Indirect method: microstructure, time and space structure of precipitation.

5.1. Microstructure of rainfall. Relationship γ-R.

5.2. Time structure of rainfall. Cumulative distribution of R measured at a point. Concentration in short periods of time. Rapid-response and conventional raingauges. Influence of integration time. Best integration time and percent of time for reference. Space-time ergodicity. Characterization on a global basis.

5.3. Space structure of rainfall. Rain cells. Equivalent path length.

5.4 - Prediction method - Importance of rain intensity value exceeded for one hour per year. CCIR method of prediction (Fedi, 1981) - Accuracy - Applicability, Physical significance, accuracy limits.

6. <u>Earth-space links</u>. Information needed. Prediction procedures - Microstructure, horizontal and vertical structure of precipitation. CCIR prediction method (Fedi, 1981) - Accuracy, year-to-year variability. Future research work.

A CONTRIBUTION OF RADIOPROPAGATION RESEARCH TO RADIOCOMMUNICATIONS DEVELOPMENT: PREDICTION OF ATTENUATION DUE TO RAIN

Francesco FEDI
Fondazione Ugo Bordoni
Viale Trastevere 108, Roma, ITALY

As a result of the envisaged progressive use of frequencies above 10 GHz for radiocommunications, attenuation due to rain has been one of the most important topics of radiopropagation research in the past years. Activities in URSI Commission F and CCIR Study Group 5 have been particularly noteworthy. In this review attention is focused on the possibilities presently available of predicting rain attenuation statistics for the design of terrestrial and Earth-space links.

1. INTRODUCTION

The progressive saturation of the spectrum and the increasing demand for new services have resulted in pressures to utilize frequencies above 10 GHz both for terrestrial and Earth-space radiocommunications.

Attenuation due to rain plays an important role in limiting the availability of radiosystems at these frequencies and the possibility of predicting rain attenuation statistics has received considerable attention in the past years being a prerequisite for system design.

The subject was reviewed in late 1980 during a Symposium organized by URSI Commision F /1,2/. Since that date the situation has evolved and efforts have been made for providing prediction methods suitable for practical applications.

In this paper particular attention is given to the prediction method provisionally suggested in late 198[illegible] by Study Group 5 of the CCIR /3/. The method provides a simple way of evaluating rain attenuation cumulative distribution both on [illegible] and Earth-space links. The ap[illegible] [illegible]sical significance and accuracy [illegible] the method is examined and areas in which [illegible] is needed are indicated.

2. THE PREDICTION METHOD

<u>Input data</u> The input data required for predicting the rain attenuation cumulative distribution for an average year, at a given frequency, polarisation and elevation angle, is the value of point rainfall intensity $R_{0.01}$ (mm/h), measured at the ground with an integration time of about one minute, exceeded for 0.01% of an average year in the location of interest.

The method consists of the following successive steps.

a) <u>Calculation of specific attenuation</u>

The specific attenuation $\gamma_{0.01}$ (dB/km) is calculated as:

$$\gamma_{0.01} = k\, R_{0.01}^{\alpha} \qquad (1)$$

The procedure for the evaluation of the parameters k and α - once the frequency f (GHz), polarisation τ (deg) with respect to the horizontal (for circular polarisation $\tau = 45°$) and elevation angle θ (deg) are given - is:

$$k = [k_H + k_V + (k_H - k_V) \cos^2\theta \cos 2\tau]/2$$
$$\alpha = (k_H\alpha_H + k_V\alpha_V + (k_H\alpha_H - k_V\alpha_V)\cos^2\theta \cos 2\tau)/2k \qquad (2)$$

The k_H, k_V, α_H, α_V values in the range 10-30 GHz are:

f(GHz)	k_H	k_V	α_H	α_V
10	0.0101	0.00887	1.276	1.264
12	0.0188	0.0168	1.217	1.200
15	0.0367	0.0335	1.154	1.128
20	0.0751	0.0691	1.099	1.065
25	0.124	0.113	1.061	1.030
30	0.187	0.167	1.021	1.000

Values at intermediate frequencies can be obtained by interpolation using a logarithmic scale for f and k and a linear scale for α. Values at frequencies up to 400 GHz are given in /3/.

The procedure is based on a given model for the microstructure of rainfall (size distribution, temperature, terminal velocity and shape of the raindrops) which is supposed to be, on average, the same in every location.

b) <u>Calculation of the attenuation exceeded for 0.01% of time.</u>

The attenuation $A_{0.01}$ (dB) exceeded for 0.01% of time is given as:

$$A_{0.01} = \gamma_{0.01} \cdot L_e \qquad (3)$$

where L_e (km) is the "effective path length".

The effective path length, according to (3), can be defined as the length of a fictitious path along which a constant specific attenuation would cause the same attenuation as that exceeded for 0.01% of time on the actual path. It depends on the model assumed for the spatial structure of rainfall and the procedure for its evaluation is different for terrestrial and Earth-space paths.

INTERNATIONAL CONFERENCE ON COMMUNICATIONS (ICC 84)
Amsterdam, May 1984

For terrestrial paths L_e depends on the horizontal structure of rainfall and is written as:

$$L_e = L\ r \quad (4)$$

where L (km) is the actual path length and r is a reduction factor which is assumed to depend only on L:

$$r = \frac{1}{1+0.044\ L} \qquad (5)$$

For Earth-space paths L_e depends both on the horizontal and vertical structure of rainfall. The latter can be characterized by a "rain height" H_R (km) below which the specific attenuation (1) is assumed constant and which allows the effective path length to be written as follows:

$$L_e = \frac{H_R - H_o}{\sin\theta}\ r \qquad (6)$$

In (6) H_o (km) is the altitude of the earth station, θ is the elevation angle (θ>10 deg) of the radiolink and r is the reduction factor (5) applied to the horizontal projection of the portion of the actual path subject to rain:

$$L = \frac{H_R - H_o}{\mathrm{tg}\,\theta} \qquad (7)$$

The rain height at the latitude ϕ (deg) of the earth station is approximated, for $\phi \geq 40$ deg, with the average height of the 0°C isotherm, for which the following behaviour versus latitude is assumed:

$$H_R = 5.1 - 2.15 \log\left(1 + 10^{(\phi-27)/25}\right) \qquad (8)$$

For ϕ<40 deg H_R is multipled by a reduction coefficient to take into account the fact that in tropical regions the top of the rain is often below the freezing level /3/.

c) Calculation of cumulative distribution of attenuation

The attenuation Ap exceeded for other percentages P of an average year is evaluated as:

$$A_P = A_{0.01} \cdot b\ P^{-a} \qquad (9)$$

where b and a are given by:

b=0.22; a=0.33	for	$0.001 \leq P \leq 0.01$
b=0.15; a=0.41	for	$0.01 < P \leq 0.1$
b=0.12; a=0.50	for	$0.1 < P \leq 1.0$

3. APPLICABILITY, PHYSYCAL SIGNIFICANCE AND ACCURACY

3.1 Applicability

The method is extremely simple to apply. The only meteorological parameter required is the value of the one-minute point rainfall intensity exceeded for 0.01% of an average year, in the location of interest. This parameter allows a very easy identification of the various climatic regions through rain intensity contours and can replace, for attenuation predictions, the depth of rainfall (mm) with which these regions have been normally characterized for many years. The value of 0.01% has been proposed /4, 5/ i) since it is intermediate in the range presently of interest (0.001% - 0.1%) ii) since the corresponding rainfall intensity values are statistically more stable and can be measured more accurately than those exceeded for 10^{-3} % and iii) since they allow a more precise distinction among the various locations than the generally low values exceeded for 0.1%.

Reference to rainfall intensity makes it possible an attempt to utilize the considerable data base available for many decades and several locations in the archives of the Meteorological Offices. The unification of the procedures for terrestrial and earth-space links is another advantage for practical applications.

3.2. Physical significance

Microstructure of precipitation The first part of the method (step (a)), regarding the relationship between specific attenuation and rainfall intensity, is based on a physical model for the microstructure of rainfall at the ground level (oblate spheroidal raindrops, randomly distributed in space, aligned with a vertical rotational axis and dimensions related to the equivolumic spherical drops) built on purely meteorological data (distribution, terminal velocity and temperature of the drops). The applicability of this relationship to real rainfall situations, the influence of the hypotheses and parameters adopted in the calculations and limitations of the experimental techniques used to ascertain its validity have been the subjects of considerable research work in the past years /1/.

The use of the established relationship for the design of terrestrial links seems not to be a controversial point at the moment, although some doubts still exist on the validity of the assumed average microstructure of rainfall in equatorial and tropical regions.

For earth-space links applications the assumption of a constant specific attenuation up to the top of rain drastically oversimplifies the complexity of the real phenomena. Although supported by radar observations showing a nearly constant value of reflectivity from the ground to the base of the bright band, this hypothesis is still a controversial point. A distinction among the various types of rain storms (stratiform, convective, etc.), which may have different microstructures, is not made and the presence of other types of hydrometeors aloft (e.g. in the melting layer), which may be important at high frequencies, is ignored. The effect of these phenomena on attenuation is presently the subject of considerable experimental activity especially in conjunction with the use of dual-polarisation radars. The importance of these systems for precipitation studies has been underlined in a Symposium organized by URSI Commission F in 1982 /6/ and preliminary results have been presented in a subsequent Symposium held in 1983 /7/.

Horizontal and vertical structure of precipitation The second and third part (steps (b) and (c)) of the method have been derived empirically from radio data.

Expression (5) of the reduction coefficient versus path lenght has been derived from data obtained on a considerable number of terrestrial links /5/ located in Europe, Japan and North America. The procedure of estimating A_p from $A_{0.01}$ has been found /4,5/: i) approximating a log-normal distribution by a piece-wise power law; ii) noting that the standard deviations of the log-normal approximations of a considerable sample of experimental rain attenuation distributions - obtained in different locations and for different frequencies, polarisation and path lengths - resulted to be approximately constant; iii) considering that this assumption could simplify the prediction procedure considerably (allowing to refer to a single value of the cumulative distribution of rain intensity) and could cause an inaccuracy of the same order of that deriving from the estimate of the specific attenuation or from the characterization of a given location with a certain rainfall intensity distribution. Finally, the reduction coefficient for the rain height in tropical regions has also been obtained empirically /3/ from attenuation data obtained on Earth-space links.

Finding empirical parameters which can describe a common behaviour of radio data is already a considerable achievement, especially if the data, as in this case, were obtained in different climatic regions. Under the pressure of the urgent need of system planning this approach provided a first simple answer for practical applications. However, a model developed on the basis of independently measured meteorological parameters and the use of radio data only to validate the model would certainly be more physically meaningful and render the extrapolation to other locations less questionable.

3.3. Accuracy

The marked site-to-site and year-to-year variability of experimental rain attenuation cumulative distributions has confirmed the need of a prediction method with which the use of long-term rain intensity data available for a considerable number of locations is possible. Consequently, radio data have been mainly utilized to refine and validate the prediction procedure.

Experimental attenuation data obtained in the 10-40 GHz band on some 40 terrestrial radiolinks with path legths between 2 and 60 km located in Europe, Japan and North America have been compared with predicted results obtained from concurrently measured rainfall intensity data /5/. For selected values of percent of time in the range 0.001 - 0.1, the relative error between predicted and measured attenuation has been calculated for each link. The r.m.s. values of this error, calculated for each selected percent of time over the whole sample of the radiolinks, never exceeded about 15%, thus indicating that the method can provide the same order of accuracy achievable in characterizing a given location with a certain value of point rainfall intensity. Work is still in progress in the CCIR to extend the data base and to validate the prediction procedure in different climatic regions.

For Earth-space paths a similar consolidated data base of rain attenuation directly measured with satellite beacons is not yet available. Preliminary comparisons between experimental and predicted results seem to indicate that the accuracy achievable should be comparable with that obtained for terrestrial links. A considerable amount of research work is presently underway both in Europe, within the framework of the COST 205 Project, and in the CCIR to validate these findings and possibly refine the prediction method.

4. FUTURE WORK

A general consideration is perhaps appropriate before examining possible improvements and the associated future research work needed.

The simplicity of the prediction method presently available is obtained assuming in every location the same microstructure and horizontal structure of rainfall, the same behaviour of the rain attenuation cumulative distribution and the same dependence of the vertical structure of rainfall on latitude. These assumptions which oversimplify such complex phenomena as the rain structure and its effect on radiopropagation can certainly be refined, in many instances at the expense of simplicity, in order to achieve a better accuracy in estimating rain attenuation statistics. The ultimate limit, however, for this accuracy will always depend on the accuracy with which a given location can be characterized with a precise and stable cumulative distribution of point rainfall intensity.

Consequently, the refinement of rainfall intensity maps which are presently available /3/ should be one of the first objectives, especially for regions where the variability is higher or orographic and microclimatic effects are present. Research activities on the fine-scale variations of rainfall intensity have been considerable in the past /1/ and should continue in the future. The number of years which need to be examined to obtain an accuracy compatible with the availability objectives of the systems and methods generally valid to utilize rain data collected over periods up to one hour are examples of subjects which deserve particular attention.

For terrestrial links the situation in which the accuracy obtainable may be considered satisfactory for practical system design does not seem too far. Slight refinements of the expression for the reduction coefficient of the actual path lenght and examination of the advantage in accuracy obtainable utilizing the whole cumulative distribution of point rainfall intensity are two subjects which still deserve some attention. Validation of the concept of equivalent path lenght on the basis of a sound meteorological model for rain cells would also be desirable from a physical point of view and would increase the confidence in the predictions for regions where radio data are not available.

For earth-space links much work is still needed. Experimental validation, on the basis of radiometeorological data, of the average behaviour of the 0° C isotherm height versus latitude on a global basis and of the rain height, especially in tropical climates, is urgently needed.

Study of the effects of hydrometeors other than rain present in the melting layer and of the microstructure associated with the various types of rain storms are also important. The inclusion in the method of other parameters-such as

proportion of occurrence of storm types - should be considered as a way of improving prediction accuracy, provided that these parameters could be easily obtained in the locations of interest. The results of these studies seem to be of particular importance passing from systems in the 11-14 GHz band -whose availability seems to be dominated in most regions by intense convective rain storms - to systems at higher frequencies - whose availability might be dominated by other types of rain storms. In this context consideration, and perhaps priority, should be given to the evaluation of the improvement obtainable with site - diversity. Knowledge on this topic is still scarce: directly measured data and models are needed for the design of future systems.

Finally, it has to be noted that up to now attention has been concentrated on the possibility of predicting the average yearly distribution of rain attenuation. The considerable year-to-year variability should be taken into account in system design. Moreover no reference has been made to similar information for the "worst-month". Should this information be needed for system planning the evaluation of worst - month statistics from yearly statistics might become the weakest step of the whole procedure and the source of highest inaccuracy. Although the definition of the worst-month seems now consolidated /3/, the relationship between worst-month and yearly statistics still relies on empirical data and its accuracy has not yet been fully ascertained.

5. CONCLUSIONS

As a result of an extensive series of radiopropagation studies, a simple method for the prediction of rain attenuation statistics has been recently suggested.

For terrestrial links the method seems to need only a few refinements. For Earth-space links, even if substantial improvements might be introduced, the method can be provisionally utilized for system design.

This result already represents a considerable achievement of the efforts made in various parts of the world. Research work is still needed and the cooperation between URSI and the CCIR will continue to be extremely important.

6. REFERENCES

/1/ Fedi, F. (1981) Prediction of attenuation due to rainfall on terrestrial links, Radio Science, Vol. 16,5.

/2/ Brussaard, G. (1981) Prediction of attenuation due to rainfall on Earth-space links, Radio Science, Vol. 16,5.

/3/ CCIR (1983) Conclusions of the interim meeting of Study Group 5.

/4/ Fedi, F. (1981) Normalization procedures and prediction techniques for rain attenuation on terrestrial and earth-space radiolinks, IEE Conf. Publ. n. 195, 173-179.

/5/ Fedi, F. (1981) A simple method for predicting rain attenuation statistics on terrestrial and earth-space paths, Fondazione Ugo Bordoni Report n. 1B1081.

/6/ URSI Commission F Open Symposium on Multiple-Parameter Measurements of precipitation, Bournemouth, U.K., 1982, 1-200.

/7/ URSI Commission F Symposium on Wave Propagation and Remote Sensing, Louvain-la-Neuve, Belgium, 1983, ESA SP-194, 1-493.

Radio spectrum

$$\varepsilon_0 = \frac{1}{36\pi} 10^{-9}\ F/m \qquad \mu_0 = 4\pi\, 10^{-7}\ H/m \qquad \sigma_0 = 0\ S/m$$

$$\lambda_0 = \frac{3\,10^8}{f}$$

Denomination	f (Hz)	λ (m)	CCIR	Δf (kHz)	
VLF	10^3–10^4 (3 kHz – 30 kHz)	10^5 (100 km – 10 km)	4	27	
LF	10^4–10^5 (30 kHz – 300 kHz)	10 km – 1 km	5	×10	
MF	10^5–10^6 (300 kHz – 3 MHz)	1 km – 100 m	6	$\times 10^2$	Sound broad.; Mob. mar.
HF	10^6–10^7 (3 MHz – 30 MHz)	100 m – 10 m	7	$\times 10^3$	Fixed; Mobile; great dist.
VHF	10^7–10^8 (30 MHz – 300 MHz)	10 m – 1 m	8	$\times 10^4$	TV broad.; Mobile
UHF	10^8–10^9 (300 MHz – 3 GHz)	1 m – 10 cm	9	$\times 10^5$	TV broad.; Mobile; Radar; Radio relay
SHF	10^9–10^{10} (3 GHz – 30 GHz)	10 cm – 1 cm	10 (centimetric)	$\times 10^6$	Radio terrest. satell.; DBS
EHF	10^{10}–10^{11} (30 GHz – 300 GHz)	1 cm – 1 mm	11 (millim.)	$\times 10^7$	
	10^{11}–10^{12} (300 GHz – 3 THz)	1 mm – 0.1 mm (10^{-4})	12	$\times 10^8$	

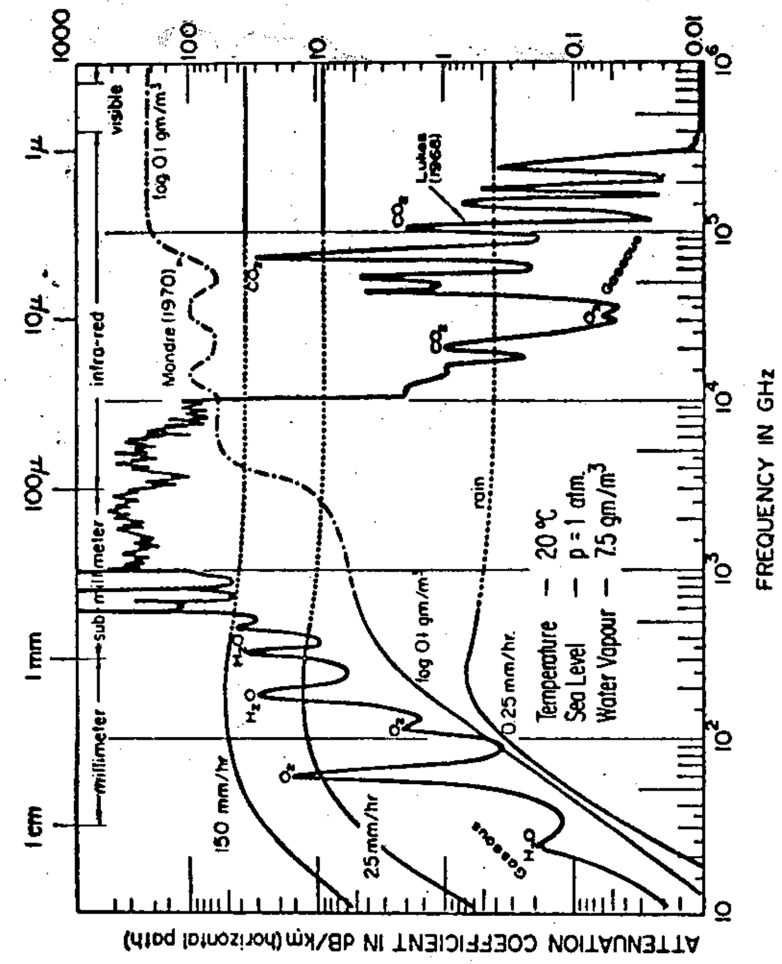
Use of frequencies above 10GHz

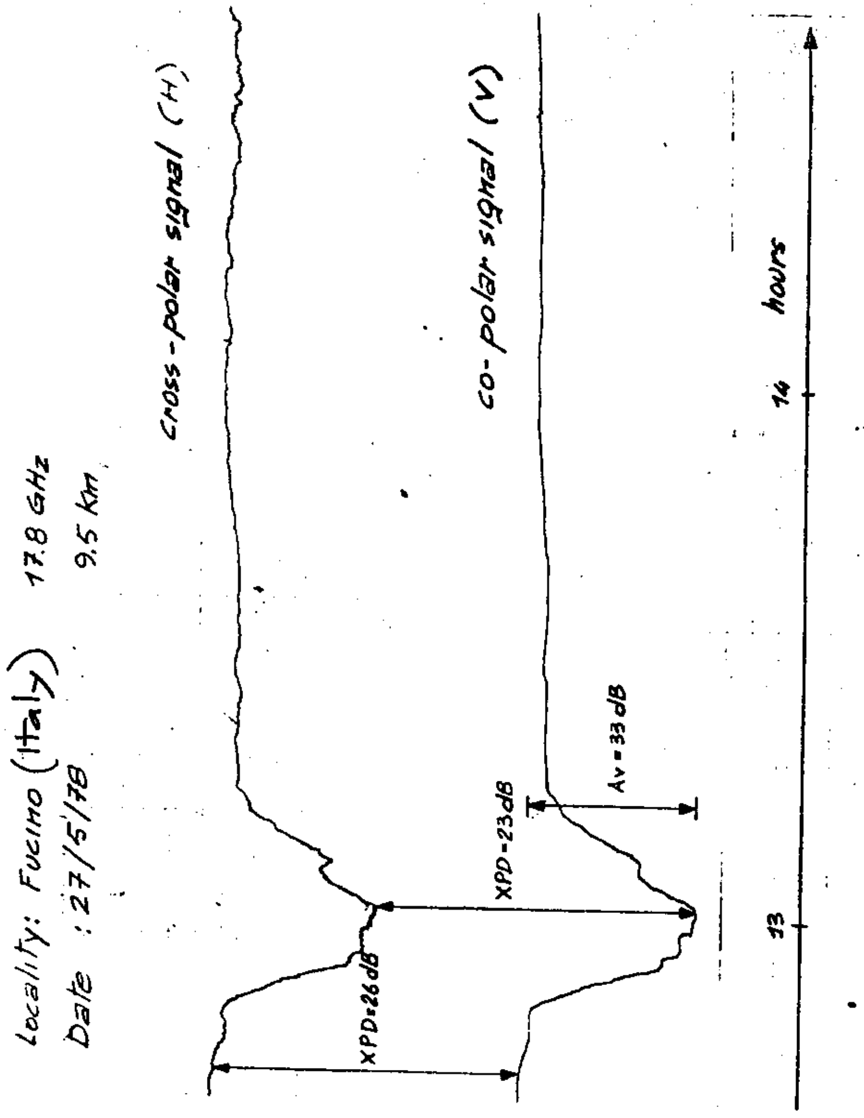
Needs
- progressive saturation $f < 10GHz$
- increasing demand for conventional and new services

Advantages
- enormous increase capacity
- introduction digital modulation
- directive antennas

Problems : Influence of absorption and scattering from hydrometeors

- Attenuation
- Cross-polarisation





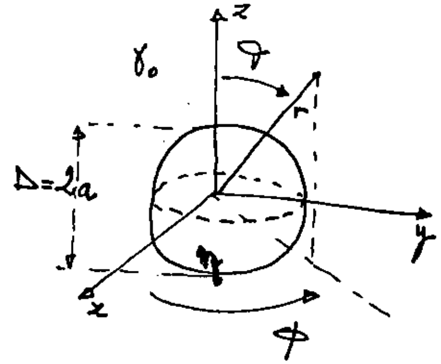
Single spherical drop

(Mie 1908)

- Free space $\gamma_0 = j\frac{2\pi}{\lambda}$
- Spherical drop

$$\eta = \eta_1 - j\,\eta_2$$

η_1 → scattering; η_2 → absorption



- $\alpha = \frac{2\pi a}{\lambda}$

- Incident

$$\begin{cases} \underline{E}^i = \underline{i}_x E_0 \, e^{j\omega t - \gamma_0 z} \\ \underline{H}^i = \underline{i}_y \frac{E_0}{\eta} \, e^{j\omega t - \gamma_0 z} \end{cases}$$

$f = \omega/2\pi \qquad \eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi\ \Omega$

$$\Downarrow$$

$\underline{E}^t, \underline{H}^t$ (transmitted) ; $\underline{E}^s, \underline{H}^s$ (scattered)

solution of $\boxed{\nabla^2 \underline{C} - \gamma_0^2 \underline{C} = 0}$

boundary conditions : for $r = a$

field <u>inside</u> $\underline{E}^t, \underline{H}^t$

field <u>outside</u> $\underline{E}^i + \underline{E}^s$; $\underline{H}^i + \underline{H}^s$

$$\begin{cases} \underline{i}_r \times (\underline{E}^i + \underline{E}^s) = \underline{i}_r \times \underline{E}^t \\ \underline{i}_r \times (\underline{H}^i + \underline{H}^s) = \underline{i}_r \times \underline{H}^t \end{cases}$$

<u>Scattered wave</u>

For $r \gg a$

$$\begin{cases} E_r^s, H_r^s \propto \lambda/r^2 \\ E_\theta^s = \eta H_\phi^s \propto \{1/r \; S_2(\theta) \cos\phi\} \\ E_\phi^s = -\eta H_\theta^s \propto \{1/r \; S_1(\theta) \sin\phi\} \end{cases}$$

$S_1, S_2 \rightarrow$ complex amplitude functions

$$\begin{cases} S_1 = \sum_1^\infty n \dfrac{2n+1}{n(n+1)} \left[a_n \pi_n(\cos\theta) + b_n \tau_n(\cos\theta)\right] \\ S_2 = \sum_1^\infty n \dfrac{2n+1}{n(n+1)} \left[a_n \tau_n(\cos\theta) + b_n \pi_n(\cos\theta)\right] \end{cases}$$

$\pi_n, \tau_n \rightarrow$ associated Legendre functions : spherical armonis with parameter θ

$a_n, b_n \rightarrow$ Mie coefficients (α, m)

→ For $r \gg a$, <u>scattered field</u>:

- E_θ, H_θ ; E_ϕ, H_ϕ
- $\underline{E}^s, \underline{H}^s$ $\perp$ and $\perp$ to z
- in general elliptically polarized
  exeptions $\phi = 0$, $\phi = \pi/2$, $\theta = 0$
- components of $\underline{E}^s, \underline{H}^s$

⇒ Integrate Poynting vector over the surface of a sphere

$$S_r = \frac{1}{2} \mathrm{Re}\left(\underline{E} \times \underline{H}^*\right) \quad \begin{cases} \underline{E} = \underline{E}^i + \underline{E}^s \\ \underline{H} = \underline{H}^i + \underline{H}^s \end{cases}$$

$$S_r = \frac{1}{2}\mathrm{Re}\left[E_\theta^i H_\phi^{i*} - E_\phi^i H_\theta^{i*}\right] + \frac{1}{2}\mathrm{Re}\left[E_\theta^s H_\phi^{s*} - E_\phi^s H_\theta^{s*}\right] + \frac{1}{2}\mathrm{Re}\left[E_\theta^i H_\phi^{s*} - E_\phi^i H_\theta^{s*} + E_\theta^s H_\phi^{i*} - E_\phi^s H_\theta^{i*}\right]$$

$\int_{surface}$: $S_r \rightarrow -P_a$; first term $\rightarrow 0$; second term $\rightarrow P_s$; third term $\rightarrow -P_t$

$$\boxed{P_t = P_a + P_s}$$

Divide by the amplitude of incident S^i

$$\boxed{Q_t = Q_a + Q_s}$$

extinction — absorption — scattering

cross sections (m^2)

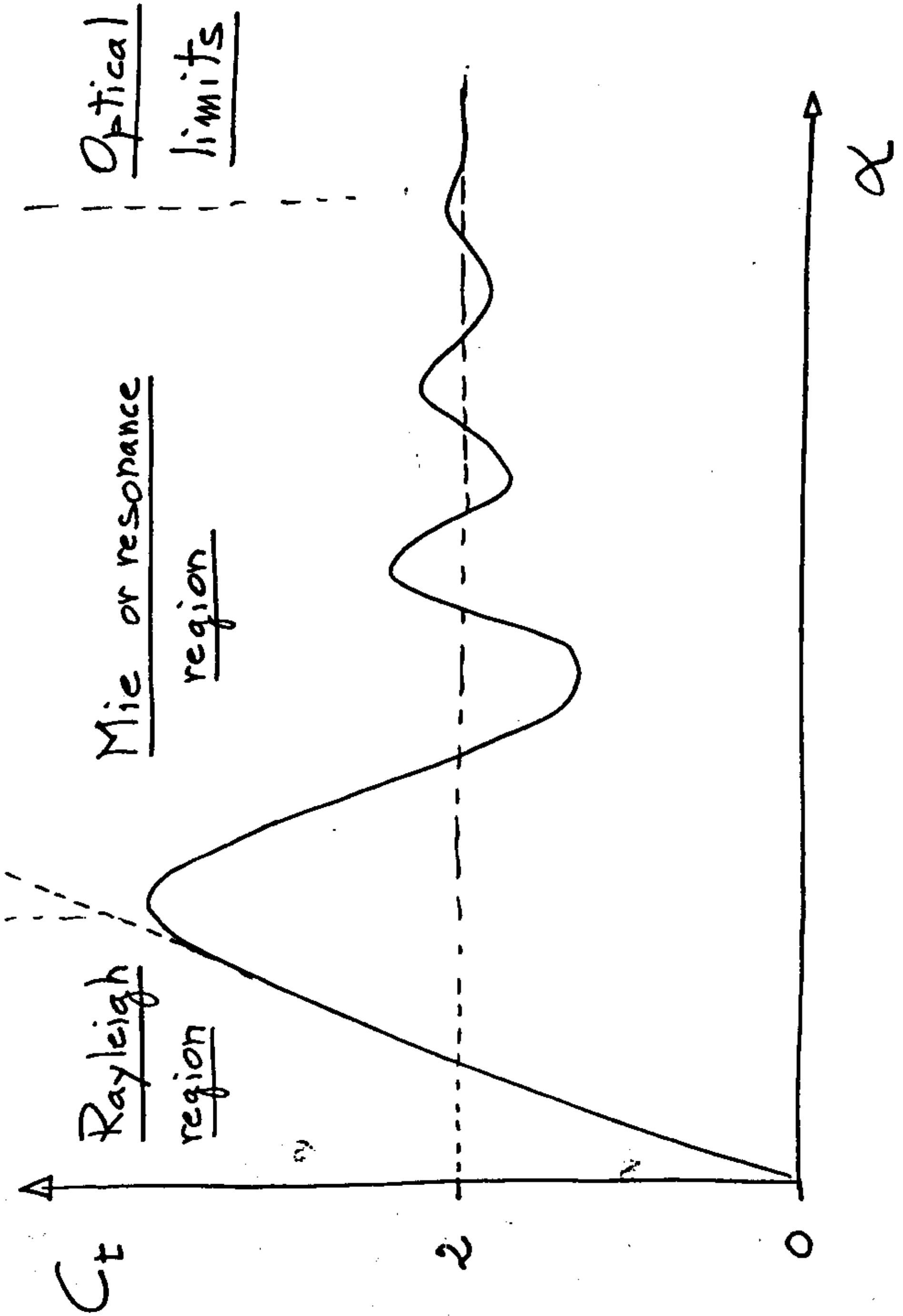
$$\begin{cases} Q_t = \dfrac{\lambda^2}{2\pi} \, \mathrm{Re} \displaystyle\sum_{1}^{\infty} n \, (2n+1)\,(a_n + b_n) \\ Q_s = \dfrac{\lambda^2}{2\pi} \displaystyle\sum_{1}^{\infty} n \, (2n+1) \left\{ |a_n|^2 + |b_n|^2 \right\} \\ Q_a = Q_t - Q_s \end{cases}$$

a_n, b_n "Mie coefficients" $\to \eta, \alpha$

$$Q = Q(\lambda, \alpha, \eta)$$

$$\boxed{C_t = Q_t / \pi a^2}$$ extinction factor

$$C_t = \frac{2}{\alpha^2} \, \mathrm{Re} \sum_{1}^{\infty} n \, (2n+1)(a_n + b_n) \longrightarrow \begin{cases} \alpha \\ \eta \end{cases}$$



- For $\underline{\alpha \ll 1}$ $(a \ll \lambda)$

$$\begin{cases} Q_s \propto \lambda^2 \left(\frac{2\pi a}{\lambda}\right)^6 = \lambda^2 \alpha^6 \\ Q_a \propto \lambda^2 \left(\frac{2\pi a}{\lambda}\right)^3 = \lambda^2 \alpha^3 \end{cases}$$

- absorption >> scattering
- attenuation $\propto a^3$

- For $\underline{\alpha << 1}$

$$Q_s \propto 1/\lambda^4 \implies \text{Lord Rayleigh}$$

particles << λ visible $\Rightarrow \alpha << 1 \Rightarrow$ scattering $\propto 1/\lambda^4$

$\lambda_{blu} < \lambda_{red} \Rightarrow$ blu more scattered than red

- Q_t, Q_s, Q_a <u>do not depend on the polarisation state of the incident wave</u> (drops spherical)

$$Q_t = Q_t(\lambda, D, \eta)$$

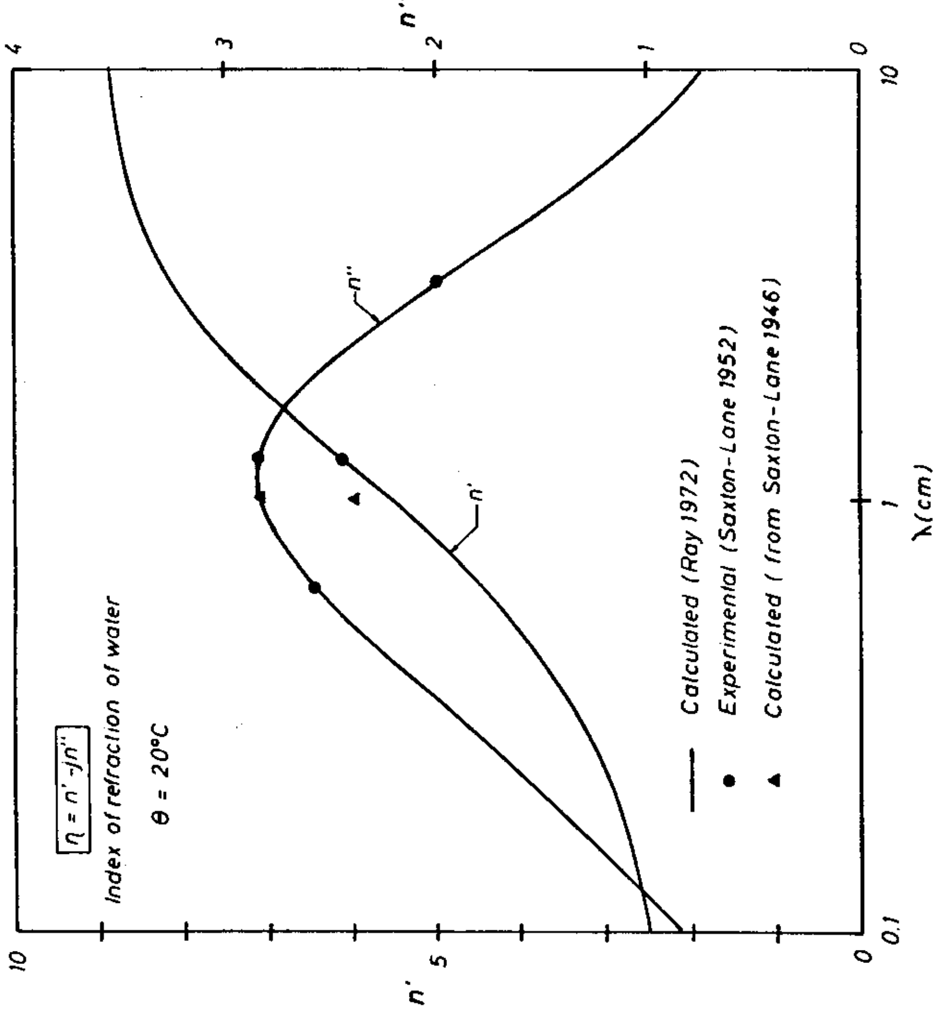
λ

$D \rightarrow \eta$ (index of refraction of water)

Total energy removed per unit time by a single spherical drop:

$$P_t = S\, Q_t \left[D, \lambda, \eta\right]$$

$$\eta = \eta(\lambda, \vartheta)$$



Ryde Theory (1945)

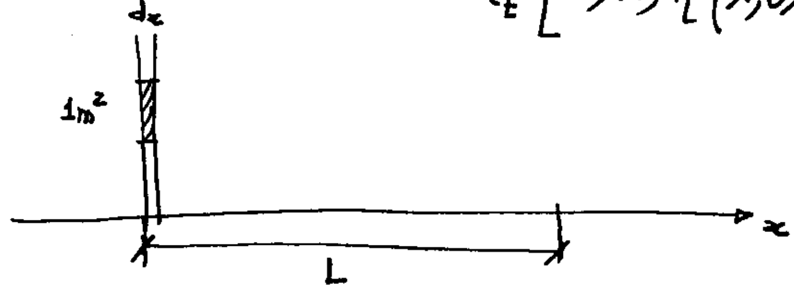
✱ Single spherical drop

$$P_t = S \cdot Q_t \left[D, \lambda, \eta(\lambda, \theta) \right]$$

✱ N identical spherical drops

Hyp. single scattering

$$P_N = N \cdot S \cdot Q_t \left[D, \lambda, \eta(\lambda, \theta) \right]$$



✱ N = number of identical drops per unit volume

for each m²

$$-dP_t = -dS \cdot 1 = S \, dx \cdot 1 \cdot N \cdot Q_t$$

→ total number of drops in the volume $dx \cdot 1$

$$-dS = S \, dx \, N \, Q_t$$

$$-dS = S N_\Delta Q_\Delta \, dx$$

Drops do not have the same Δ

* $n_\Delta \, d\Delta$ = number of drops per unit volume with $\Delta \div \Delta + d\Delta$

$$N = \int_0^\infty n_\Delta \, d\Delta$$ = total number of drops per unit volume

$$-dS = S \, dx \int_0^\infty n_\Delta Q_\Delta \, d\Delta$$

Integrating over L :

$$\log_e \frac{S_0}{S_L} = L \int_0^\infty n_\Delta Q_\Delta \, d\Delta$$

Specific attenuation γ (dB/unit length)

$$\gamma = \frac{1}{L} \, 10 \log_{10} \frac{S_0}{S_L} = \frac{1}{L} \left(10 \log_{10} e\right)\left(\log_e \frac{S_0}{S_L}\right)$$

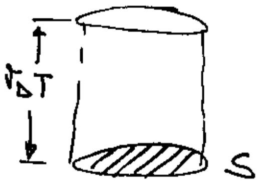
$$\boxed{\gamma = 4.34 \int_0^\infty n_\Delta Q_\Delta \left[\Delta, \lambda, \eta(\lambda, \theta)\right] d\Delta}$$

Rain intensity

$$R = \frac{V_{H_2O}}{ST} = \frac{1}{ST} \frac{\pi}{6} \int_0^\infty \Delta^3 N_S \, d\Delta$$

$N_S \, d\Delta$ = number of drops ($\Delta \div \Delta + d\Delta$) passing through S in T

$N_S \, d\Delta$ = number of drops contained in volume : $(v_\Delta T) \cdot S = V$



v_Δ = terminal velocity of drop Δ

In the unit volume :

$$n_\Delta \, d\Delta = \frac{N_S \, d\Delta}{V} = \frac{N_S \, d\Delta}{v_\Delta S T}$$

$$R = \frac{\pi}{6} \int_0^\infty n_\Delta v_\Delta \Delta^3 \, d\Delta$$

$\frac{\pi}{6} n_\Delta v_\Delta \Delta^3 d\Delta$ = volume of water collected per unit time and surface due to drops of diameter $\Delta \div \Delta + d\Delta$

Drop-size distribution

Experimentally

$$m_\Delta \, d\Delta = \frac{V_{H_2O}\ (\text{due to } \Delta \div \Delta + d\Delta)}{V_{H_2O}\ (\text{total})}$$

$$m_\Delta \, d\Delta = \frac{\frac{\pi}{6}\, n_\Delta \rho_\Delta \Delta^3 d\Delta}{\frac{\pi}{6}\int_0^\infty n_\Delta \rho_\Delta \Delta^3 d\Delta} = \frac{\frac{\pi}{6}\, n_\Delta \rho_\Delta \Delta^3 d\Delta}{R}$$

$$\int_0^\infty m_\Delta \, d\Delta = 1$$

$$n_\Delta \, d\Delta = \frac{R \; m_\Delta d\Delta}{\pi/6 \; \rho_\Delta \Delta^3}$$

$$\gamma = 4.34 \int_0^\infty n_\Delta Q_\Delta \left[\Delta, \lambda, \eta(\lambda, \vartheta)\right] d\Delta$$

$$n_\Delta d\Delta = \frac{R \; m_\Delta d\Delta}{\pi/6 \; \rho_\Delta \Delta^3}$$

$$\boxed{\gamma = \frac{4.34}{\pi/6} R \int_0^\infty \frac{Q\left[\Delta, \lambda, \eta(\lambda, \vartheta)\right]}{\rho_\Delta \Delta^3} m_\Delta \, d\Delta}$$

* λ, R fixed $\rightarrow \gamma \Rightarrow$ microstructure $\begin{cases} \vartheta \rightarrow \eta(\vartheta, \lambda) \\ m_\Delta d\Delta \\ \rho_\Delta \end{cases}$

* γ is not simply proportional to R
  ($m_\Delta d\Delta$ depends on R)

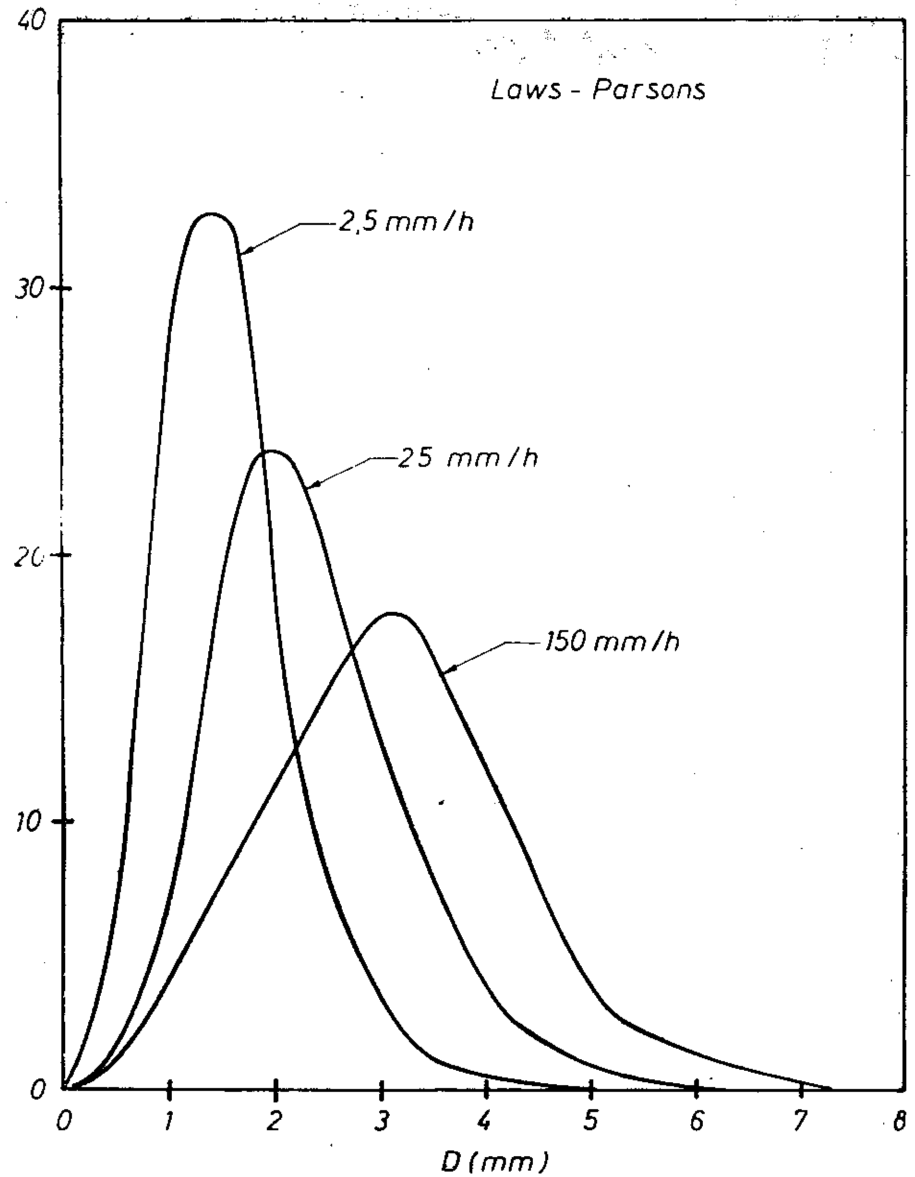
* for the λ considered
  the more $\frac{Q}{\rho_\Delta \Delta^3}$ constant with Δ
  - the more linear $\gamma - R \rightarrow \gamma = \kappa R$
  - the more independent $\gamma - R$ from changes in m_Δ for a certain R.

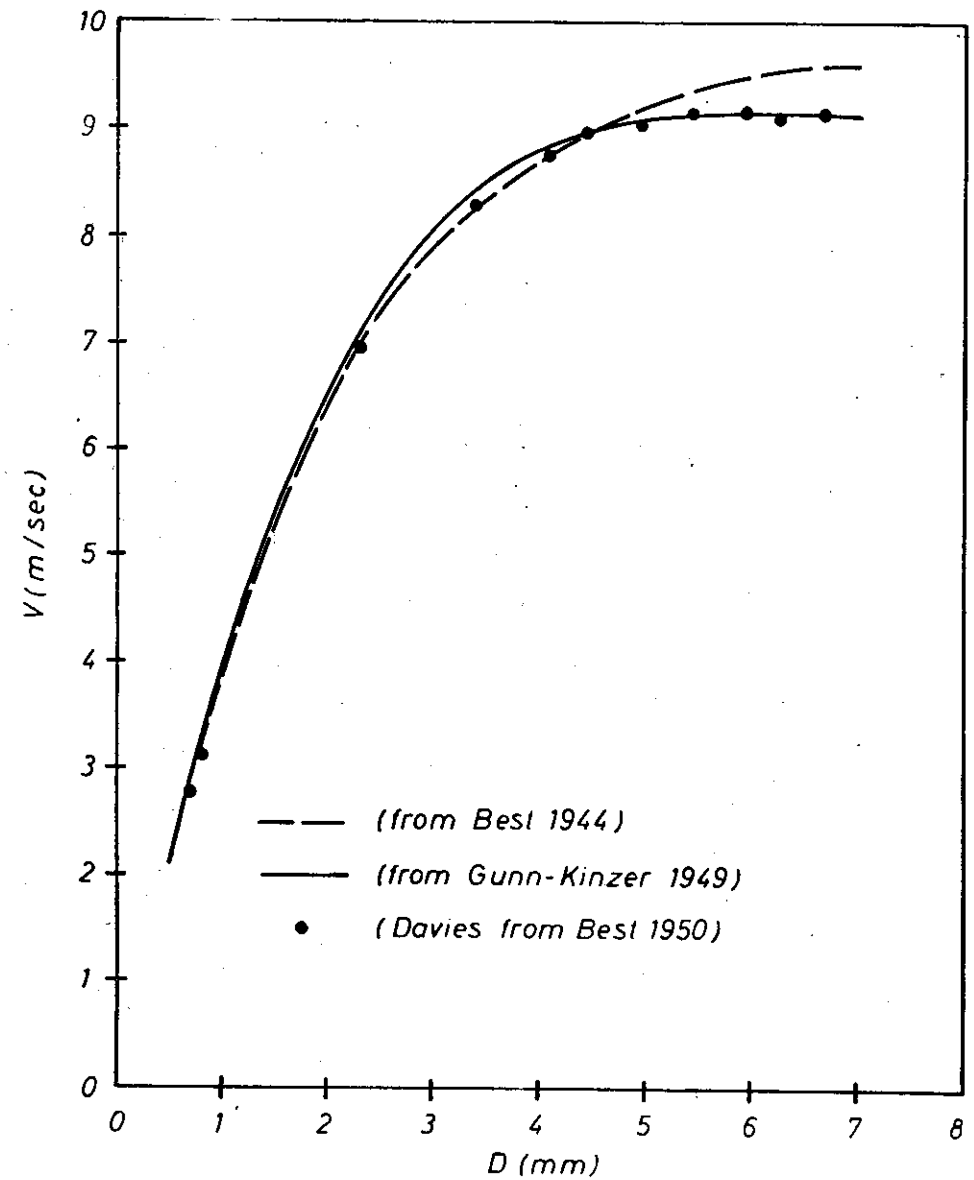
Microstructure

Temperature - Significant number of larger liquid water drops which contribute to attenuation occur between the height of the 0°C isotherm and the surface ($\vartheta \simeq 18°-20°C$). For ice (imaginary part of η is very small) absorbtion is low (low attenuation) scattering is considerable (high reflectivity)

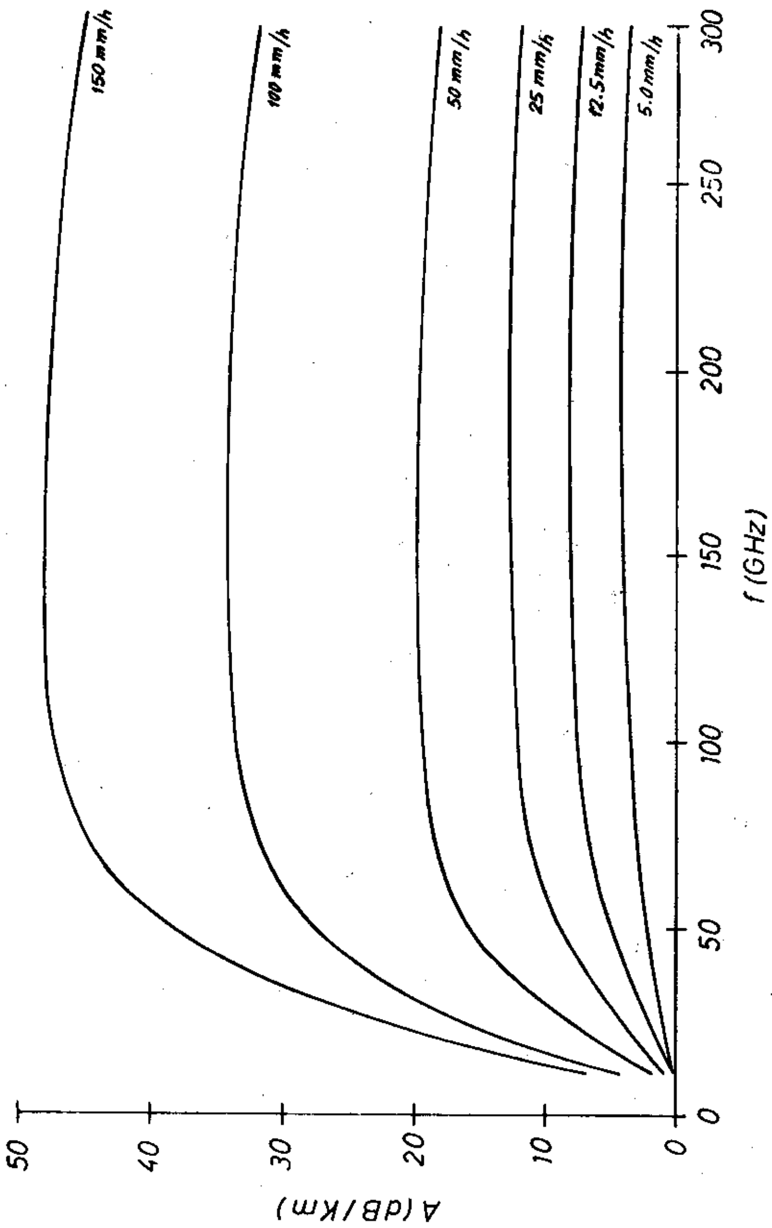
Drop-size distribution

Drop terminal velocity

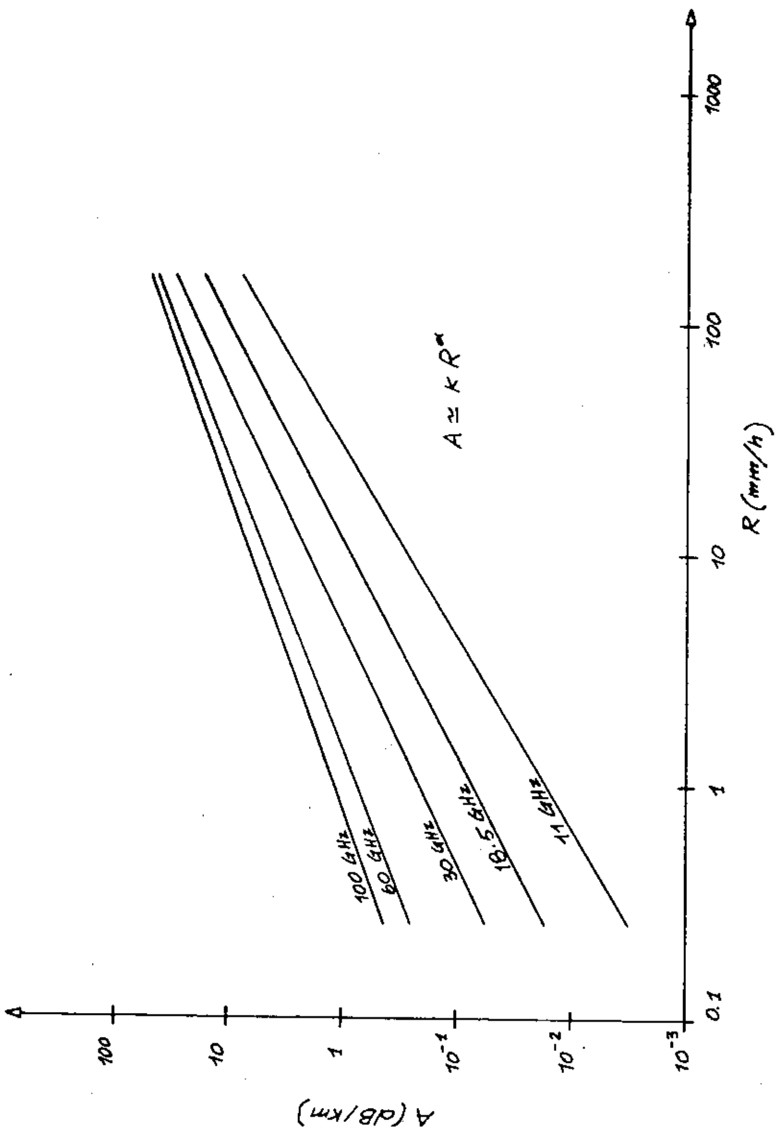




V (m/sec)
D (mm)
0
1
2
3
4
5
6
7
8
9
10
(from Best 1944)
(from Gunn-Kinzer 1949)
(Davies from Best 1950)



150 mm/h
100 mm/h
50 mm/h
25 mm/h
12.5 mm/h
5.0 mm/h
f (GHz)
0
50
100
150
200
250
300
A (dB/Km)
0
10
20
30
40
50



Relationship A-R

$$\boxed{A = \kappa R^{\alpha}}$$

A (dB/Km)

R (mm/h)

* κ, α coefficients depend on frequency (and not on the polarization)

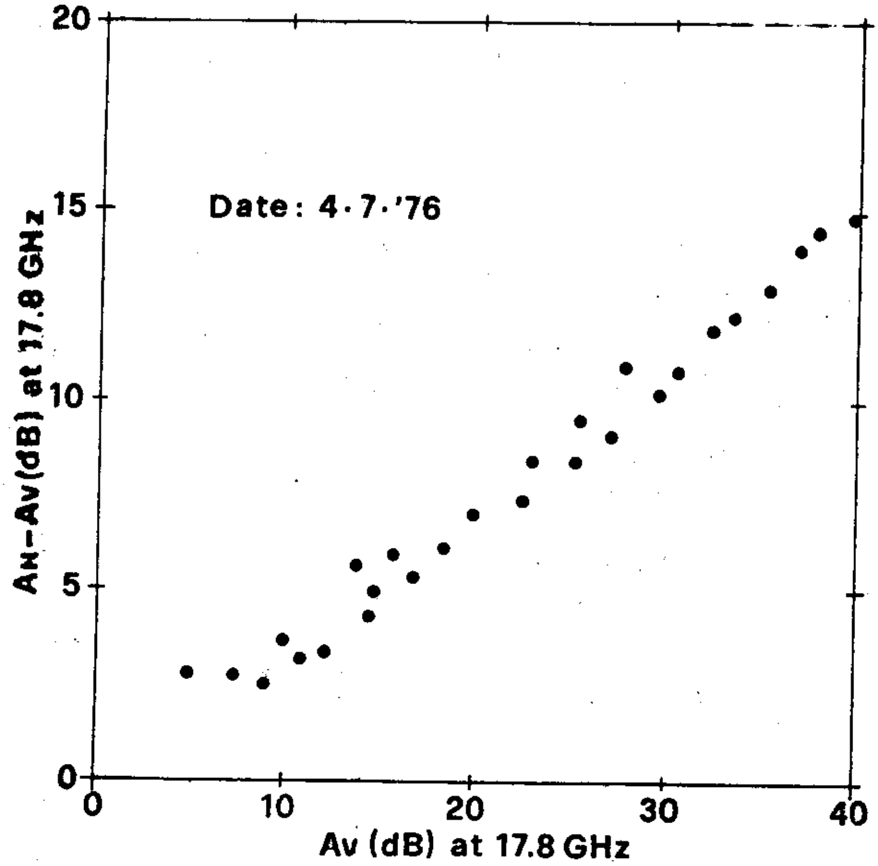
* $\alpha \to 1$ for those f for which

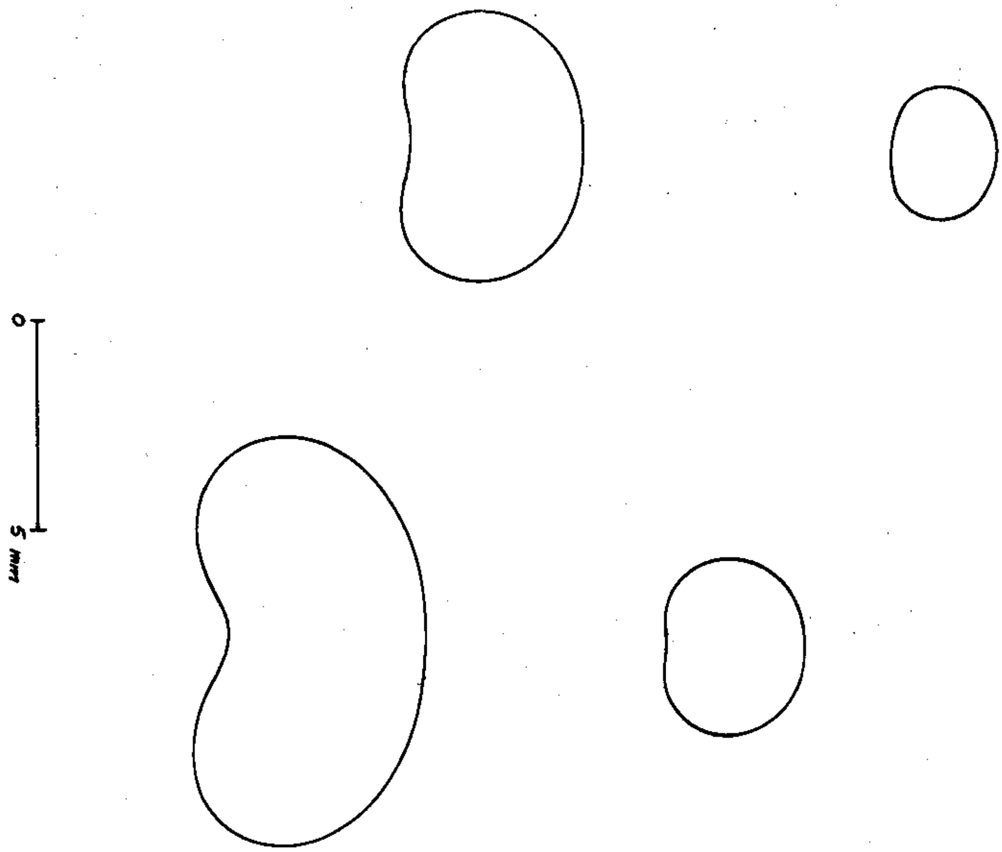
$\alpha = 1 \rightleftarrows$ A-R independent of m_Δ

* Hyp. $\to$ { Spherical drops / Single scattering

Parameters $\to$ { $\eta(\theta, \lambda)$ / v_Δ / m_Δ

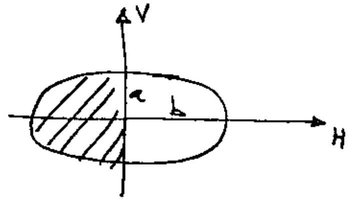
Fucino (Italy)





Oblate spheroidal raindrop (Oguchi, 1960)

oblate ellipsoid



$$Q_{H,V}\left[a,b;\lambda;\eta(\theta,\lambda)\right]$$

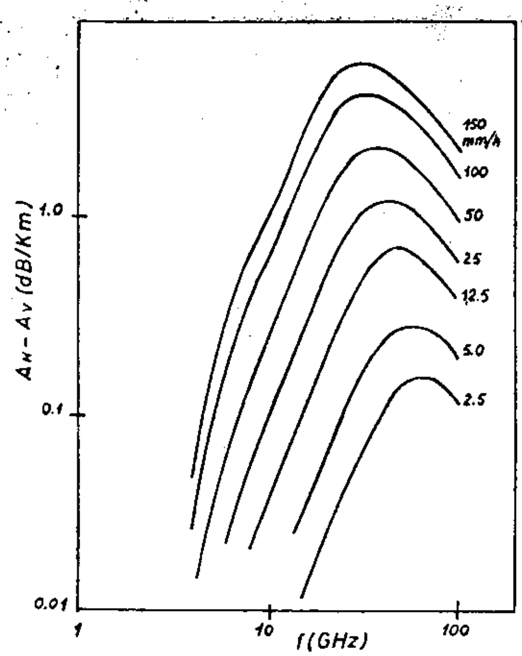
Specific attenuation versus R

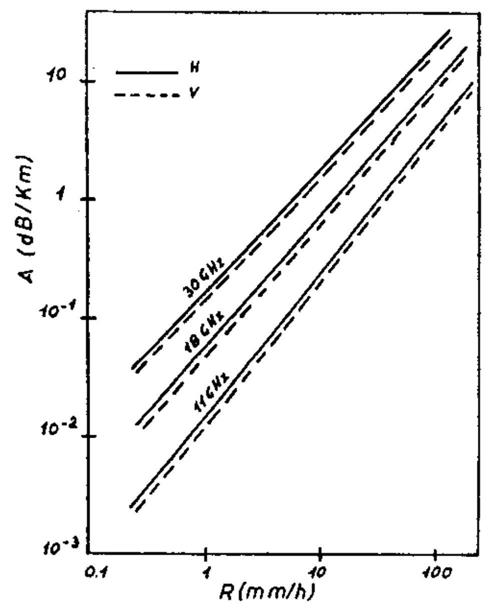
m_Δ, v_Δ for spherical drops

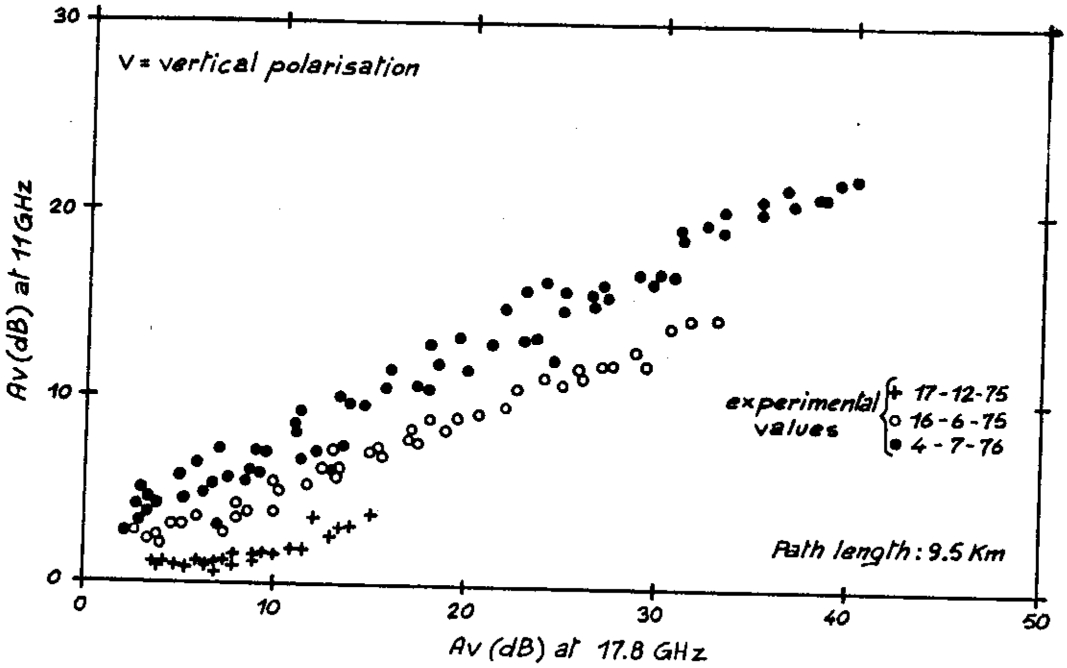
To find a, b of an oblate ellipsoid having the same volume of the spherical drop with diameter Δ:

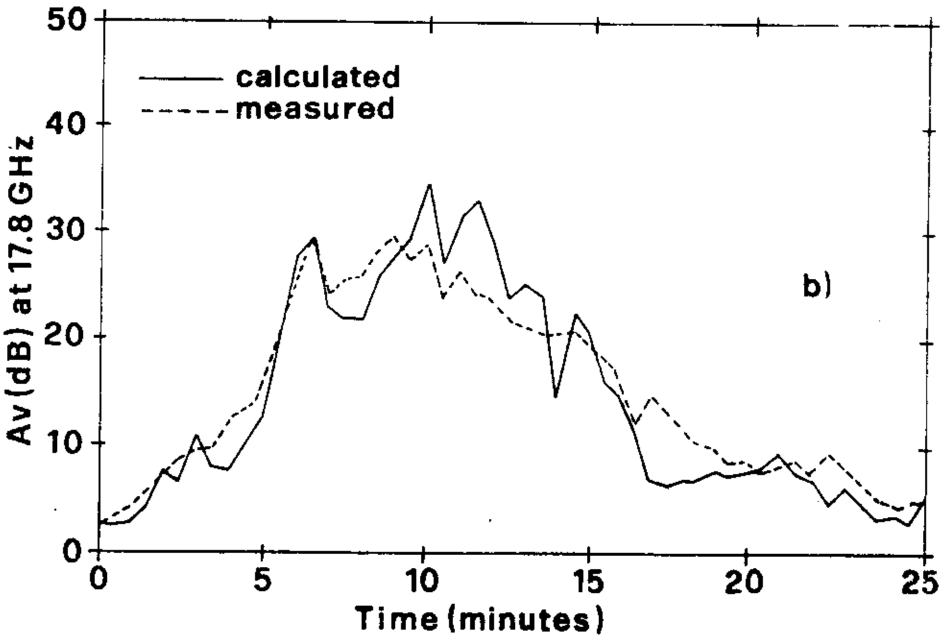
$$\begin{cases} \frac{4}{3}\pi a b^2 = \frac{\pi}{6}\Delta^3 \\ a/b \simeq 1 - f(\Delta) \end{cases}$$

$$\gamma_{H,V} = \frac{4.34}{\pi/6} R \int_0^\infty \frac{Q_{H,V}\left[a,b;\lambda;\eta(\theta,\lambda)\right]_{m_\Delta} d\Delta}{v_\Delta \, \Delta^3}$$

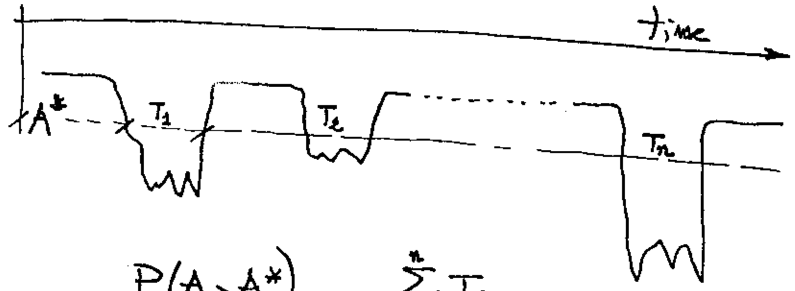




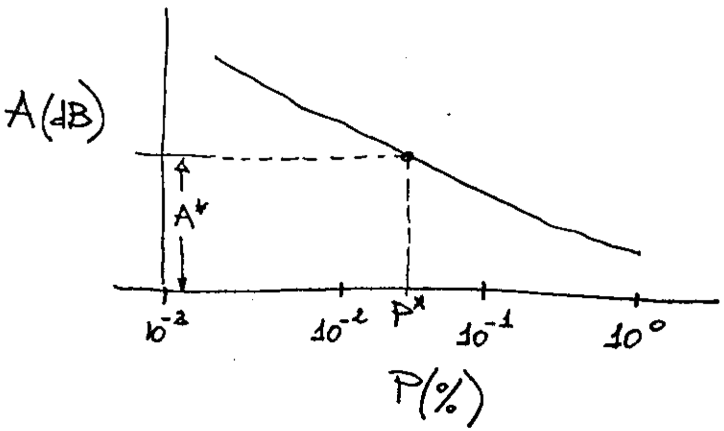

V = vertical polarisation
Av (dB) at 11GHz
Av (dB) at 17.8 GHz
experimental values
+ 17-12-75
○ 16-6-75
● 4-7-76
Path length: 9.5 Km
0
10
20
30
40
50

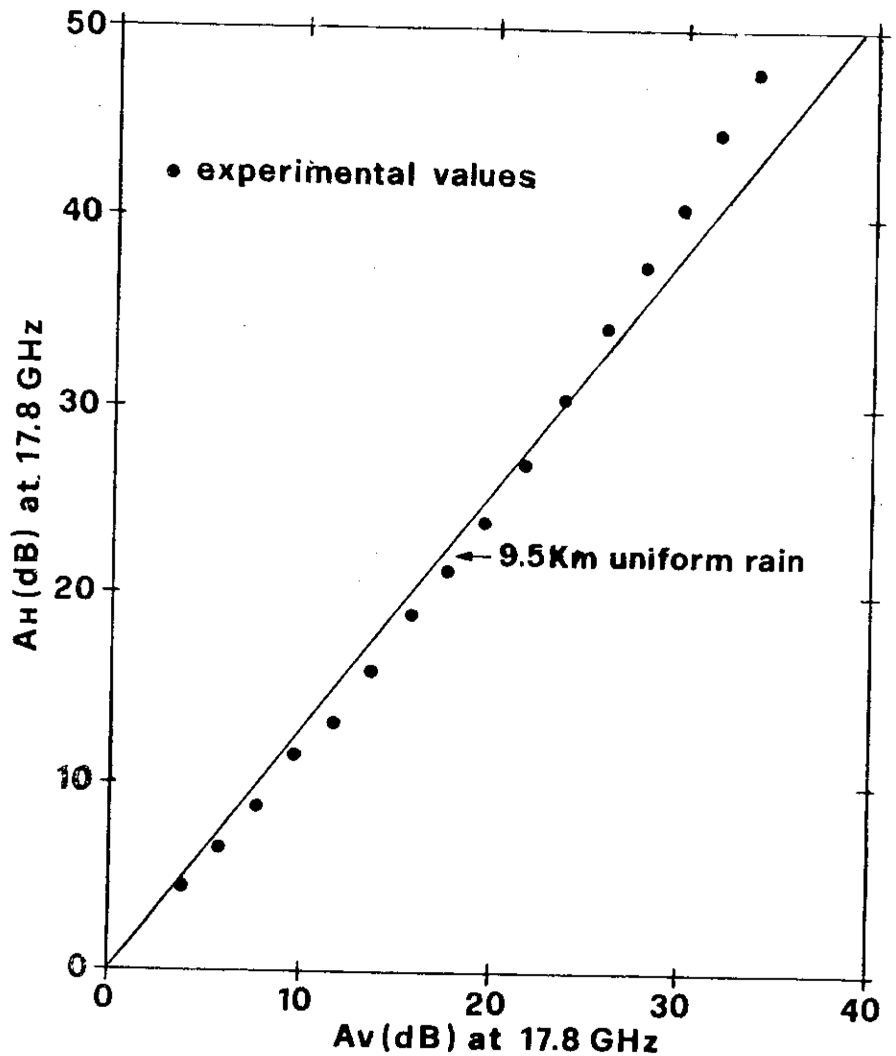

calculated
measured
b)
Av (dB) at 17.8 GHz
Time (minutes)
0
5
10
15
20
25
30
40
50

Cumulative distribution



$$P(A > A^*) = \frac{\sum_i^n T_i}{T_{total}} = P^*$$





CCIR Rep. 721-1 (Volume V)

TABLE 1 – *Regression coefficients for estimating specific attenuations in equation (?)***

Frequency (GHz)	k_H	k_V	α_H	α_V
1	0.0000387	0.0000352	0.912	0.880
2	0.000154	0.000138	0.963	0.923
4	0.000650	0.000591	1.121	1.075
6	0.00175	0.00155	1.308	1.265
7	0.00301	0.00265	1.332	1.312
8	0.00454	0.00395	1.327	1.310
10	0.0101	0.00887	1.276	1.264
12	0.0188	0.0168	1.217	1.200
15	0.0367	0.0335	1.154	1.128
20	0.0751	0.0691	1.099	1.065
25	0.124	0.113	1.061	1.030
30	0.187	0.167	1.021	1.000
35	0.263	0.233	0.979	0.963
40	0.350	0.310	0.939	0.929
45	0.442	0.393	0.903	0.897
50	0.536	0.479	0.873	0.868
60	0.707	0.642	0.826	0.824
70	0.851	0.784	0.793	0.793
80	0.975	0.906	0.769	0.769
90	1.06	0.999	0.753	0.754
100	1.12	1.06	0.743	0.744
120	1.18	1.13	0.731	0.732
150	1.31	1.27	0.710	0.711
200	1.45	1.42	0.689	0.690
300	1.36	1.35	0.688	0.689
400	1.32	1.31	0.683	0.684

* Raindrop size distribution [Laws and Parsons, 1943].
Terminal velocity of raindrops [Gunn and Kinzer, 1949].
Index of refraction of water at 20°C [Ray, 1972].

Values of k_H, k_V, α_H and α_V for spheroidal drops [Fedi, 1979; Maggiori, 1981] based on regression for the range 1 to 150 mm/h.

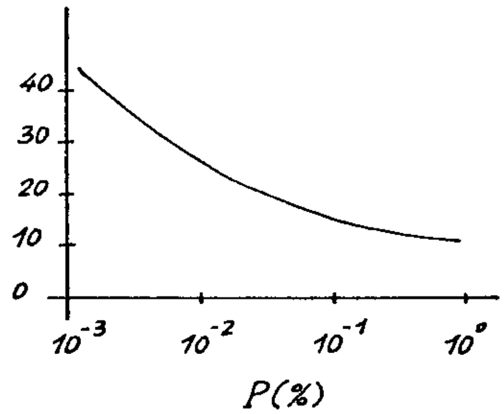
Terrestrial links

Information needed

given: location
frequency-polarisation
path length

obtain: A(P)

A(dB)



Direct methods

To obtain reliable statistics of A from direct measurements on radiolinks:

- at all frequencies of interest for various values of l
- repeated in all localities of interest
- prolonged for 10-15 years

Indirect methods

To obtain statistics of A from meteorological data available or easily obtainable in the various localities.

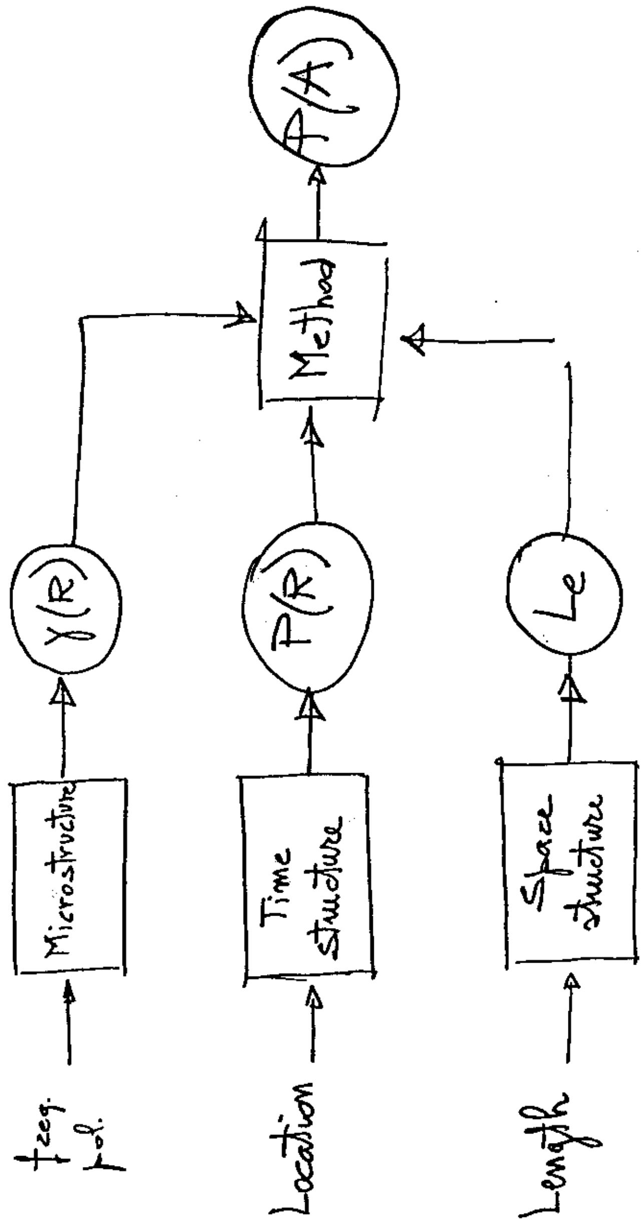
Attenuation per unit length $\rightarrow$ $\gamma = k R^{\alpha}$ (dB/km)

Attenuation on a path of length l:

$$A_l(t) = \int_0^l \gamma(x,t)\,dx = k \int_0^l R^{\alpha}(x,t)\,dx$$

P(A) obtainable from:

- k, α at the frequency and polarisation of interest
  $\Rightarrow$ (MICROSTRUCTURE)
- behaviour of $R(x,t)$ $\Rightarrow$ (TIME-SPACE STRUCTURE)



Relationship $\gamma(dB/Km)$ - $R(mm/h)$

Physical model for the microstructure :

* Shape : - oblate spheroidal raindrops
  - vertical rotational axis
  - dimension related to the equivolumic spherical drops

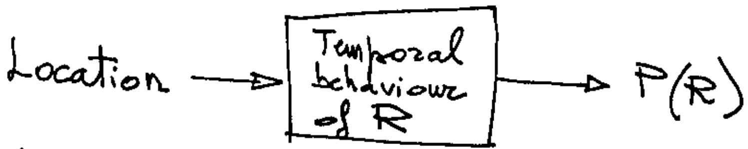
* Size distribution
* Terminal velocity
* Temperature

} experimental data

$$\gamma = \kappa R^{\alpha}$$

κ, α functions of frequency and polarisation tabulated by the CCIR.

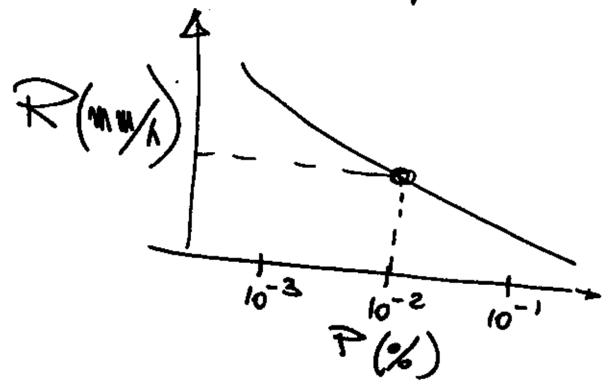
Time structure of R

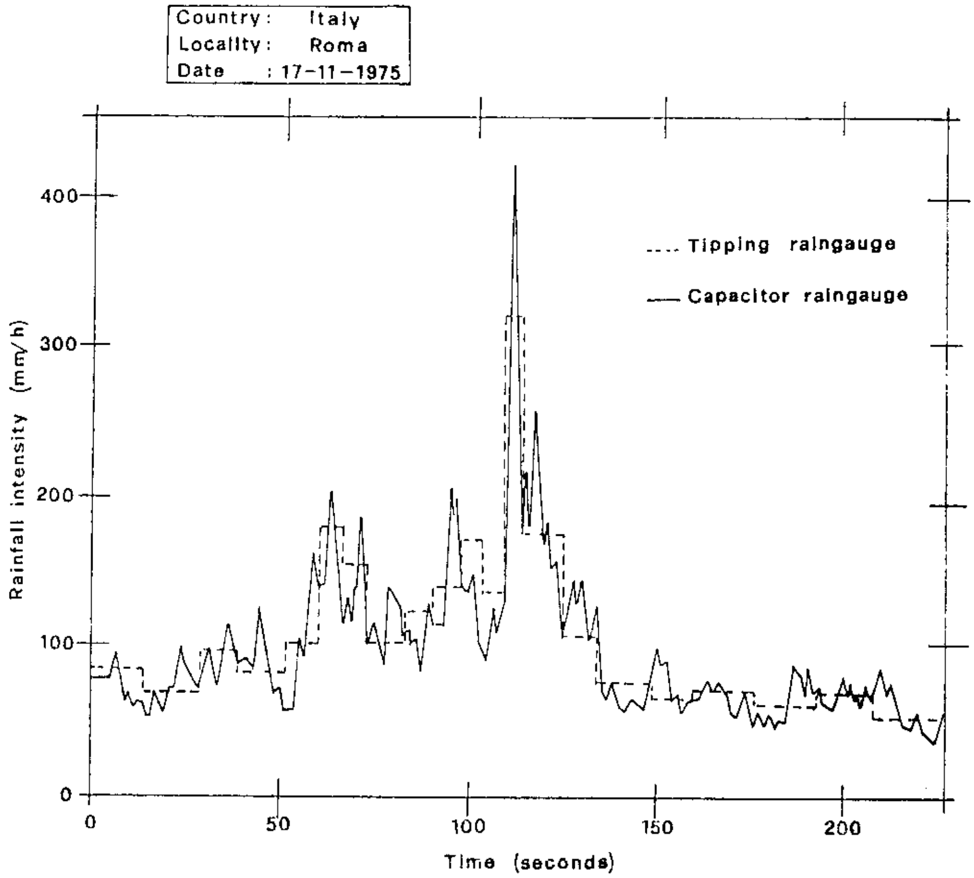


{ Variations of R in the same point in successive instants }

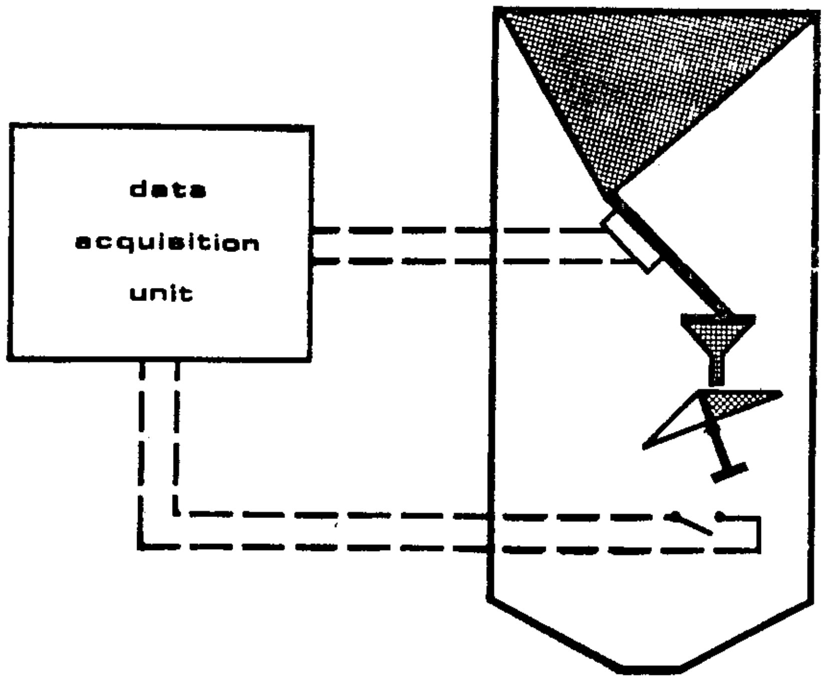
- Concentrated in short periods of time (few minutes)

Extraction of 1 min data from archives of Meteo Offices

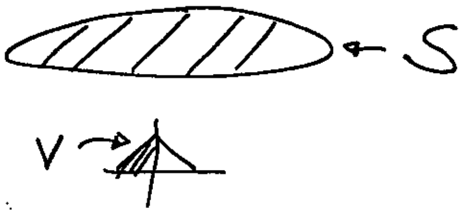




Example of time behaviour of rainfall intensity.



Tipping-bucket raingauge



$$R = \frac{V}{S\,T}$$

V (20 cm³) $S = 1000\ cm^2$

T (s)

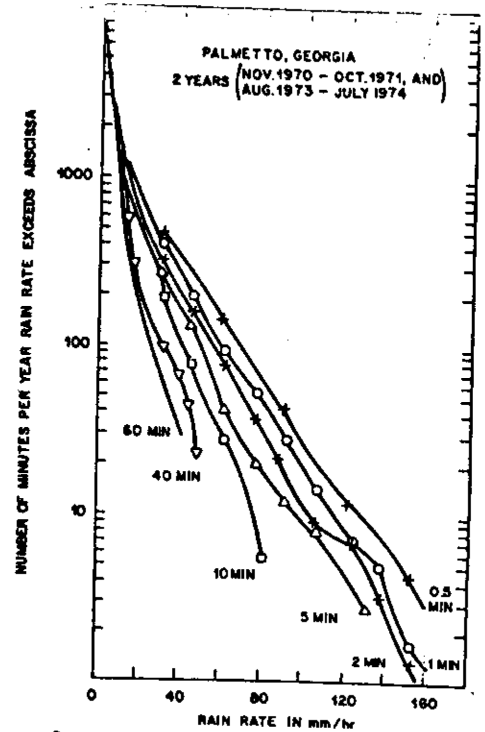
$$R = \frac{0.2\ (mm)}{T/3600} = \frac{720}{T}\ (mm/h)$$

$$T = \frac{720}{R}$$

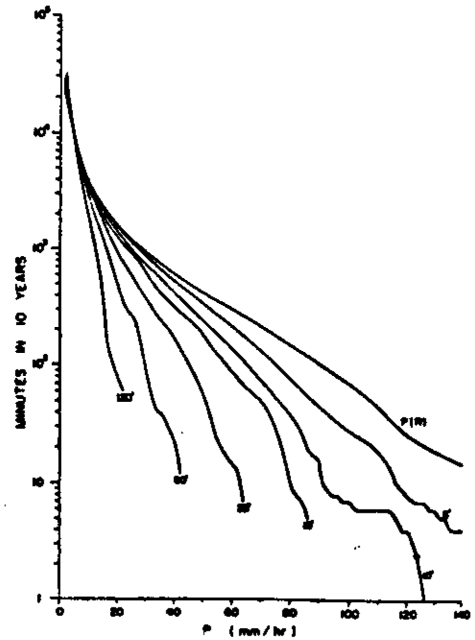
R = 100 mm/h → T ~ 7 s

R = 10 mm/h → T ~ 1 min

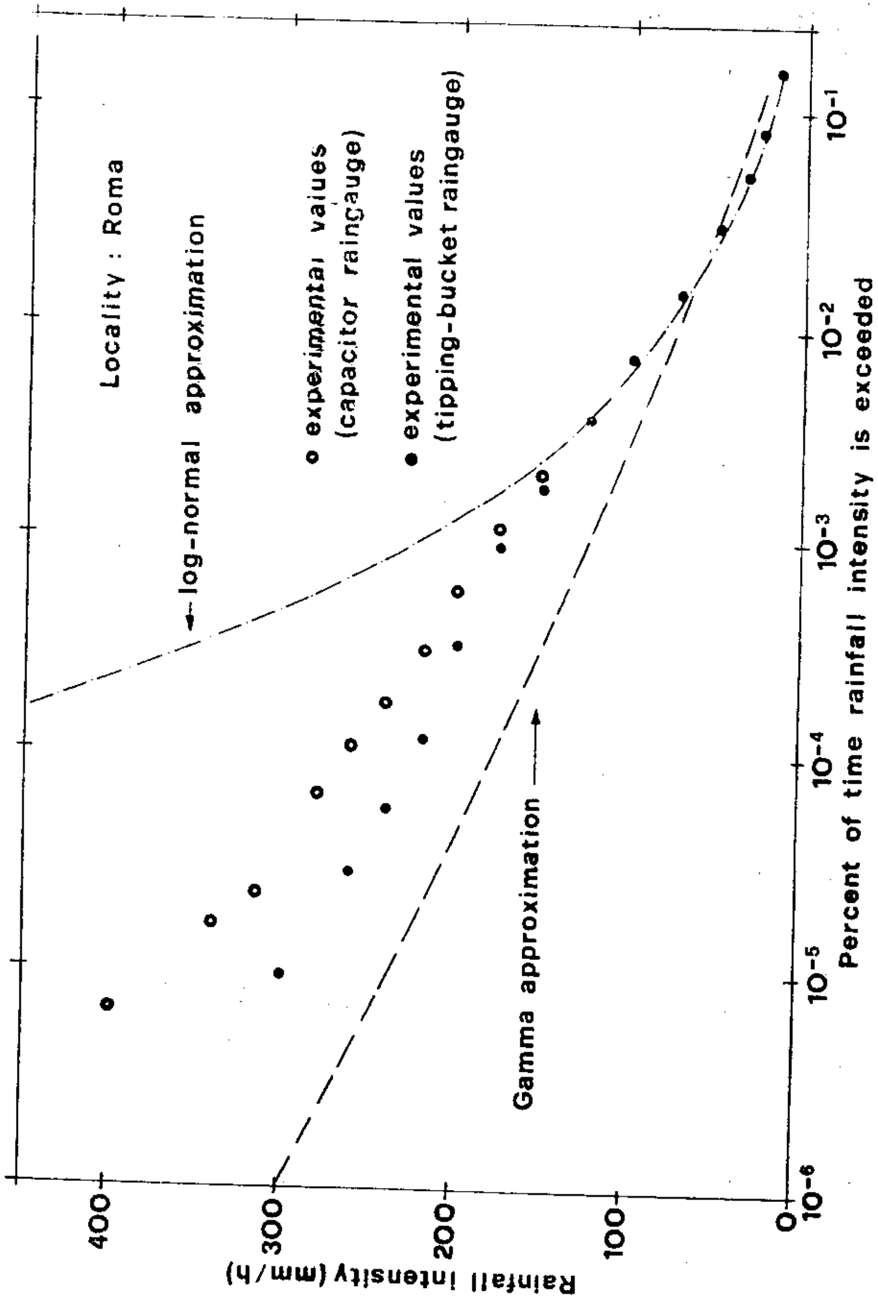
R = 0.2 mm/h → T ~ 1 h

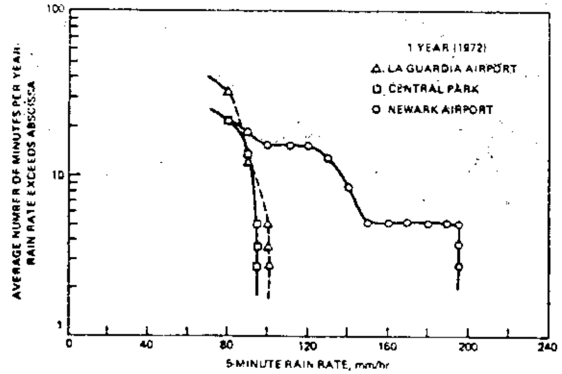


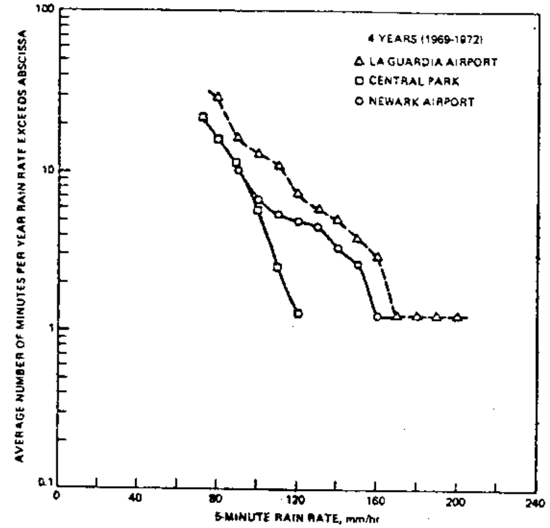
Dependence of rain rate distribution on rain gauge integration time from two years of measurement at Palmetto, Ga.

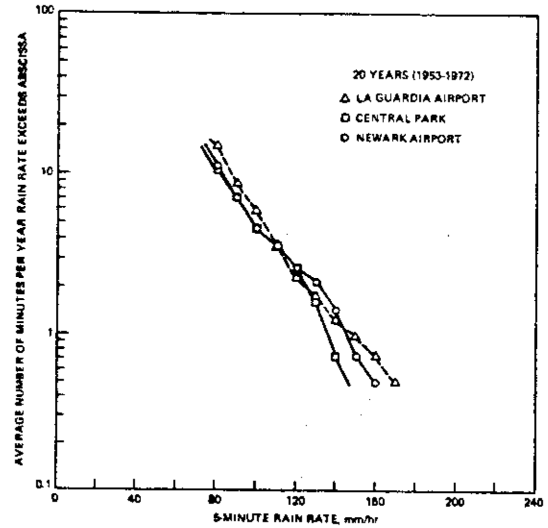


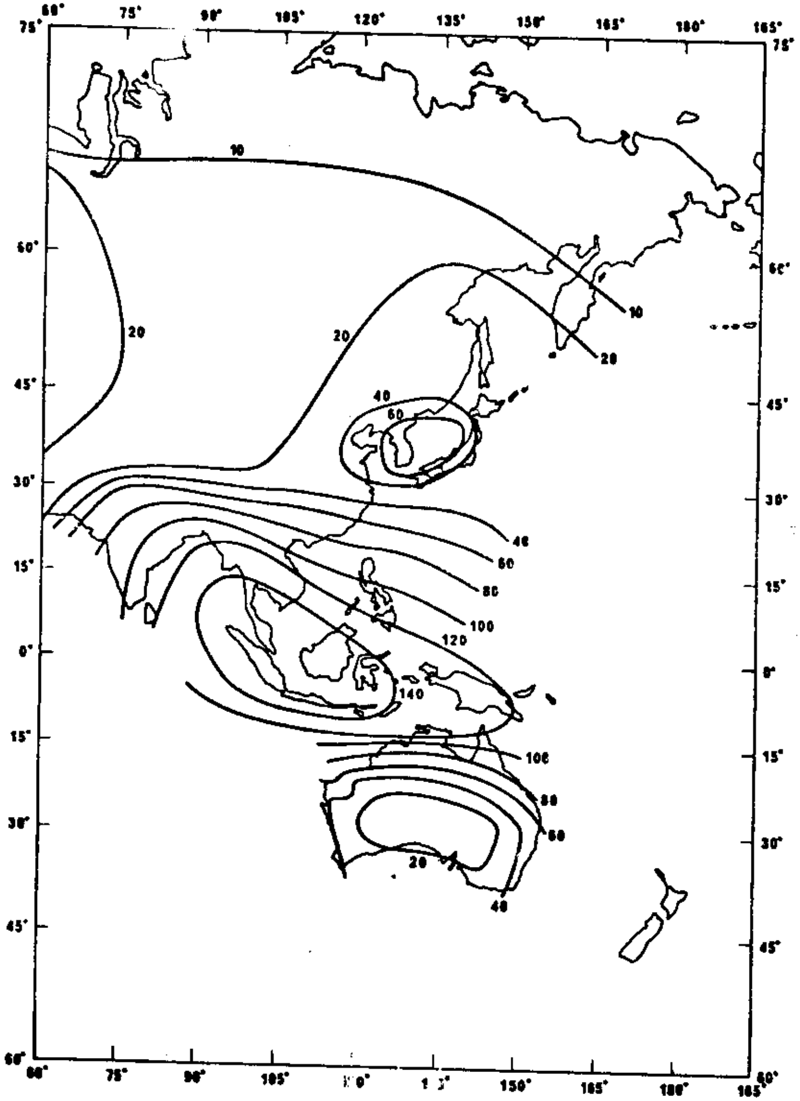
Rainfall probability curves for Montreal, based on ten years of summertime records, showing the effect of averaging on suppressing heavy rain rates


Locality : Roma
log-normal approximation
experimental values (capacitor raingauge)
experimental values (tipping-bucket raingauge)
Gamma approximation
Percent of time rainfall intensity is exceeded
Rainfall intensity (mm/h)
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
0 100 200 300 400


1 YEAR (1972)
LA GUARDIA AIRPORT
CENTRAL PARK
NEWARK AIRPORT
AVERAGE NUMBER OF MINUTES PER YEAR RAIN RATE EXCEEDS ABSCISSA
5-MINUTE RAIN RATE, mm/hr

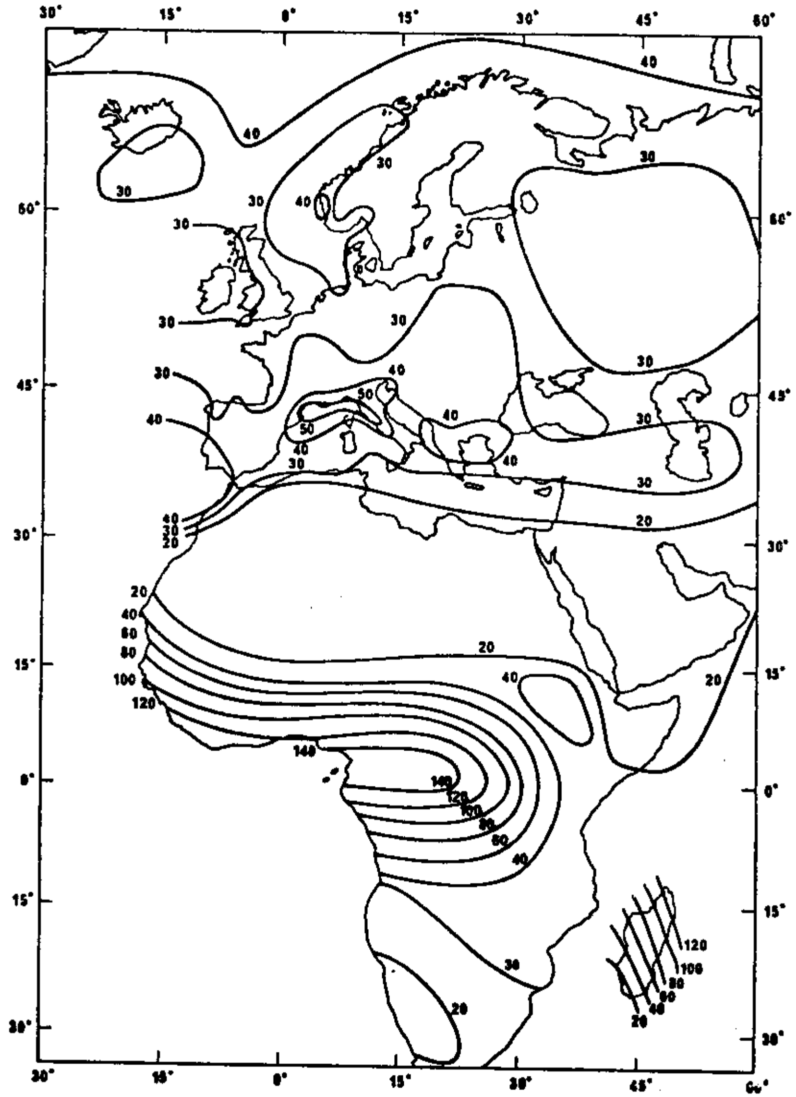

4 YEARS (1969-1972)
LA GUARDIA AIRPORT
CENTRAL PARK
NEWARK AIRPORT
AVERAGE NUMBER OF MINUTES PER YEAR RAIN RATE EXCEEDS ABSCISSA
5-MINUTE RAIN RATE, mm/hr


20 YEARS (1953-1972)
LA GUARDIA AIRPORT
CENTRAL PARK
NEWARK AIRPORT
AVERAGE NUMBER OF MINUTES PER YEAR RAIN RATE EXCEEDS ABSCISSA
5-MINUTE RAIN RATE, mm/hr



[redacted] - Rainfall contours 0.01 % of the time

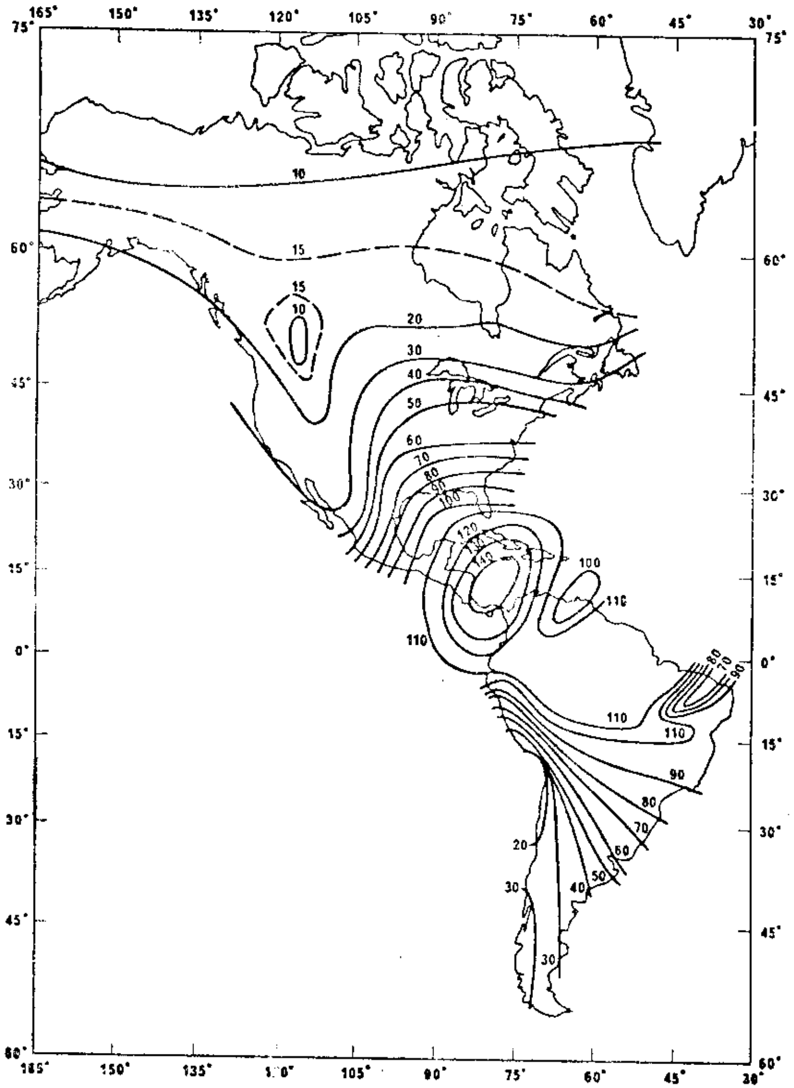
CCIR



[redacted] - Rainfall contours 0.01 % of the time

CCIR

(Doc. 5/1024-E)



~~FIGURE 11~~ - Rainfall contours 0.01 % of the time

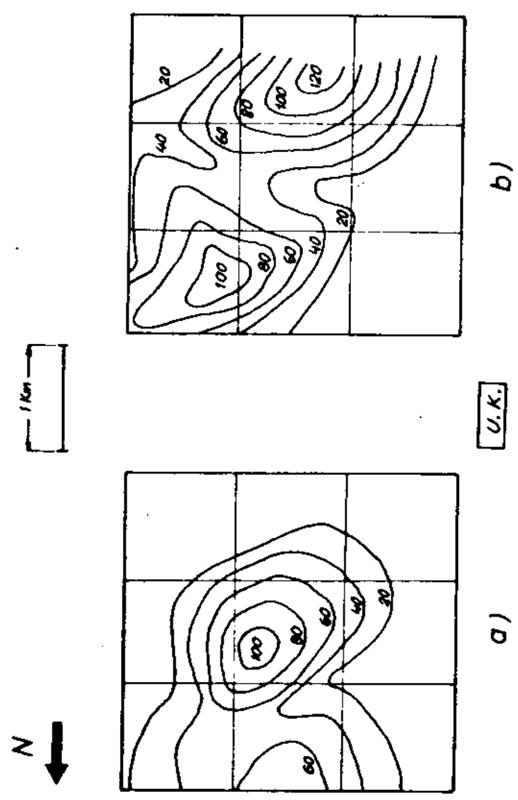
CCIR

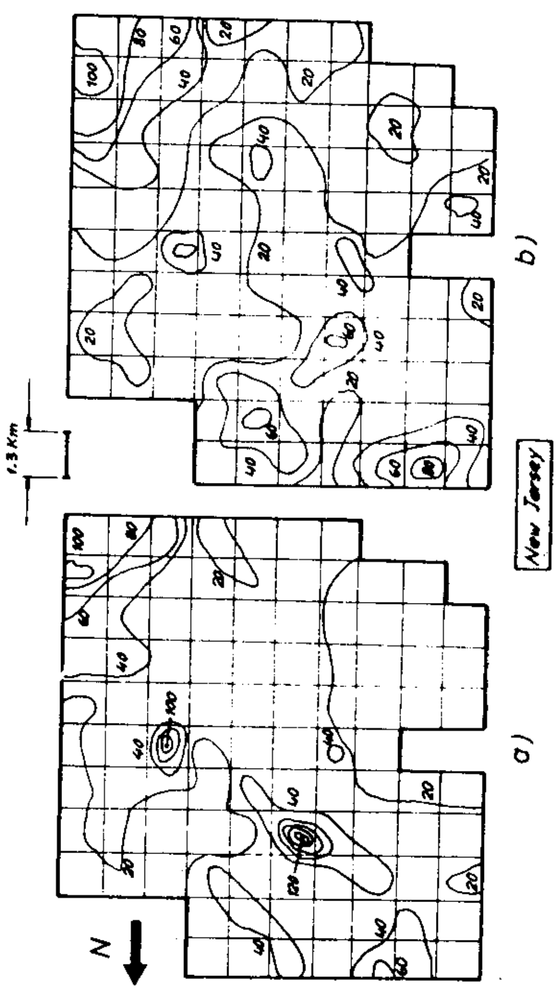
Space structure of R

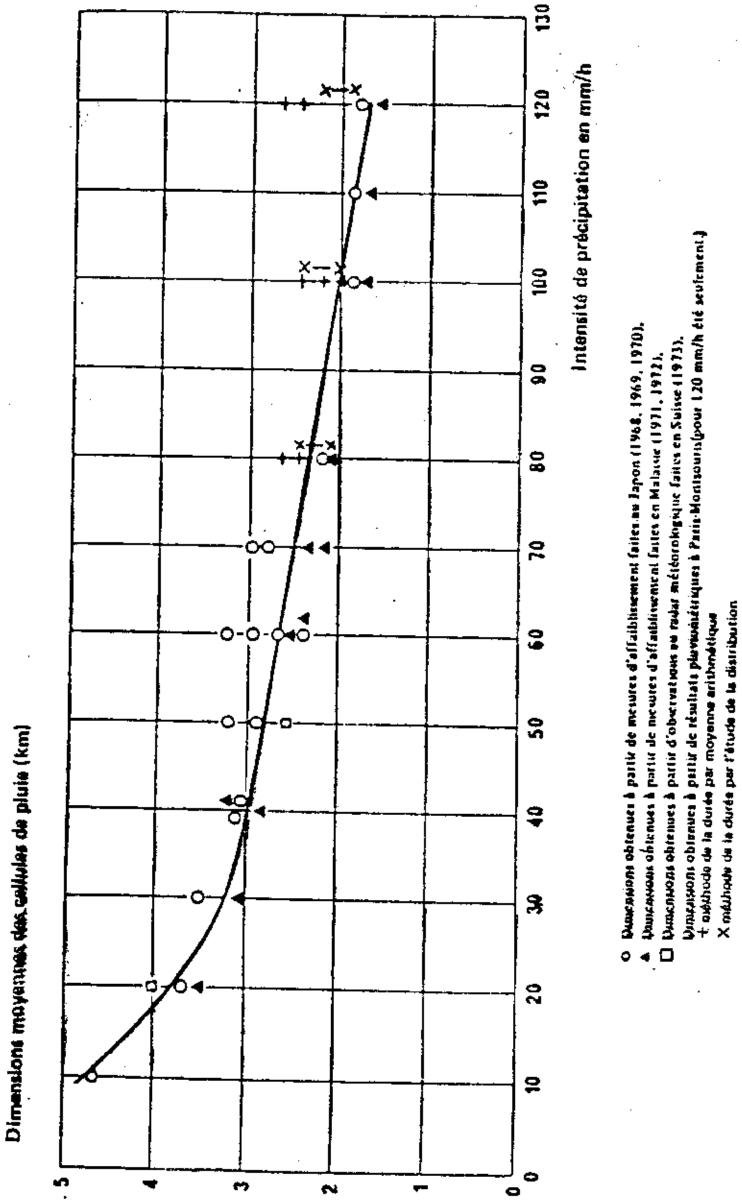
Path length L (km) → Spatial behaviour of R → Effective path length Le (km)

Variations of R in the same instant in the various points of a certain area (along the path)

- Concentrated in space → rain cells (100m – some Km)
  - that may shift (wind)
  - that may appear and disappear


N
1 Km
U.K.
a)
b)


N
1.3 Km
New Jersey
a)
b)



Even when distribution of R $P(R)$ is the same in all points the max values of R will not occur simultaneously in all points

$$\Downarrow$$

$$R(x) = \text{constant} \rightarrow A_{L\,MAX} = \int_0^L k R^{\alpha}(x)\, dx = k R^{\alpha} L$$

$$\text{actual } R(x) \longrightarrow A_L = A_{L\,MAX} \cdot r$$

$$r \leq 1$$

$$A_L(P) = k R^{\alpha}(P)\, \underline{L\, r(P)}$$

$$L_e = L\, r(P)$$

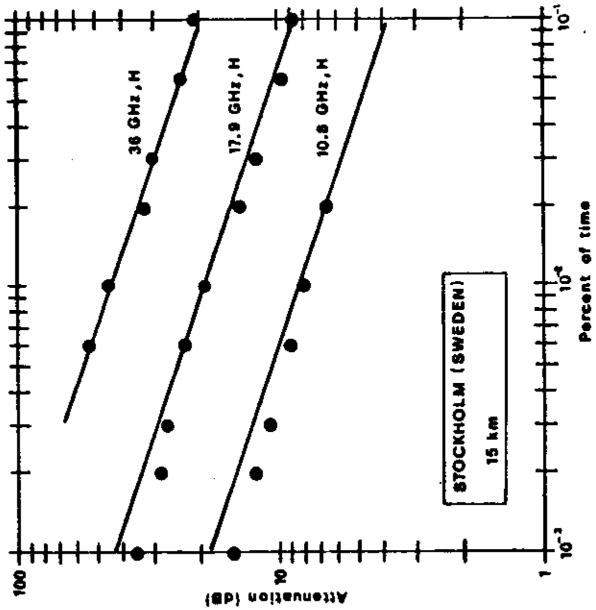
L_e and r depend on P

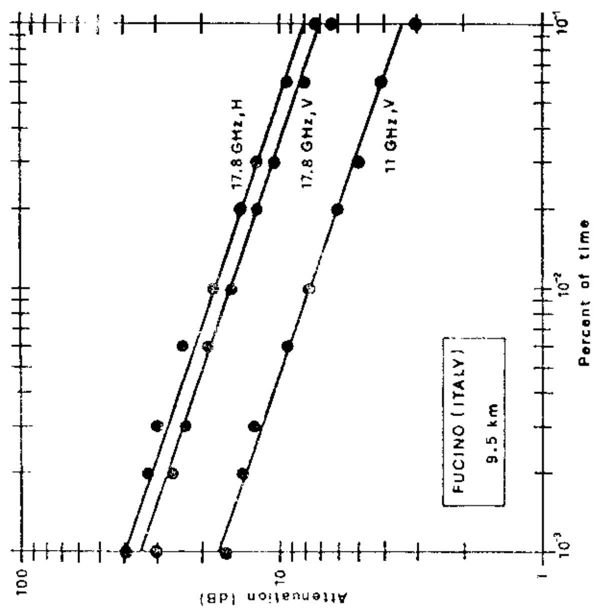
Prediction method

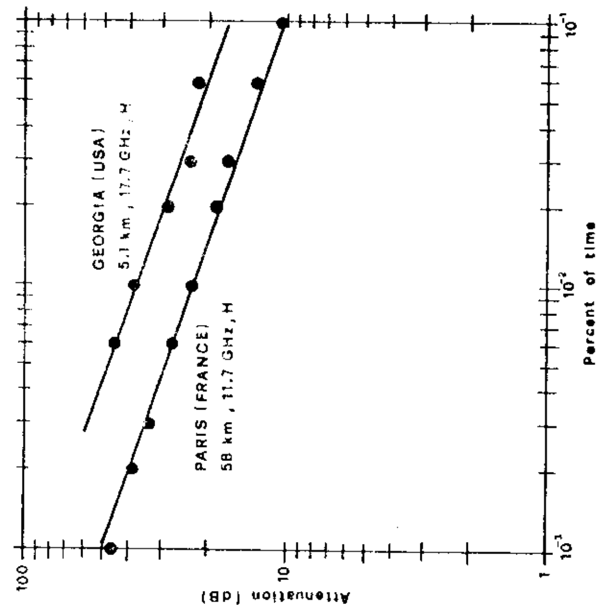
$$A(P) = K\, R^{\alpha}(P)\, L\, r(P)$$

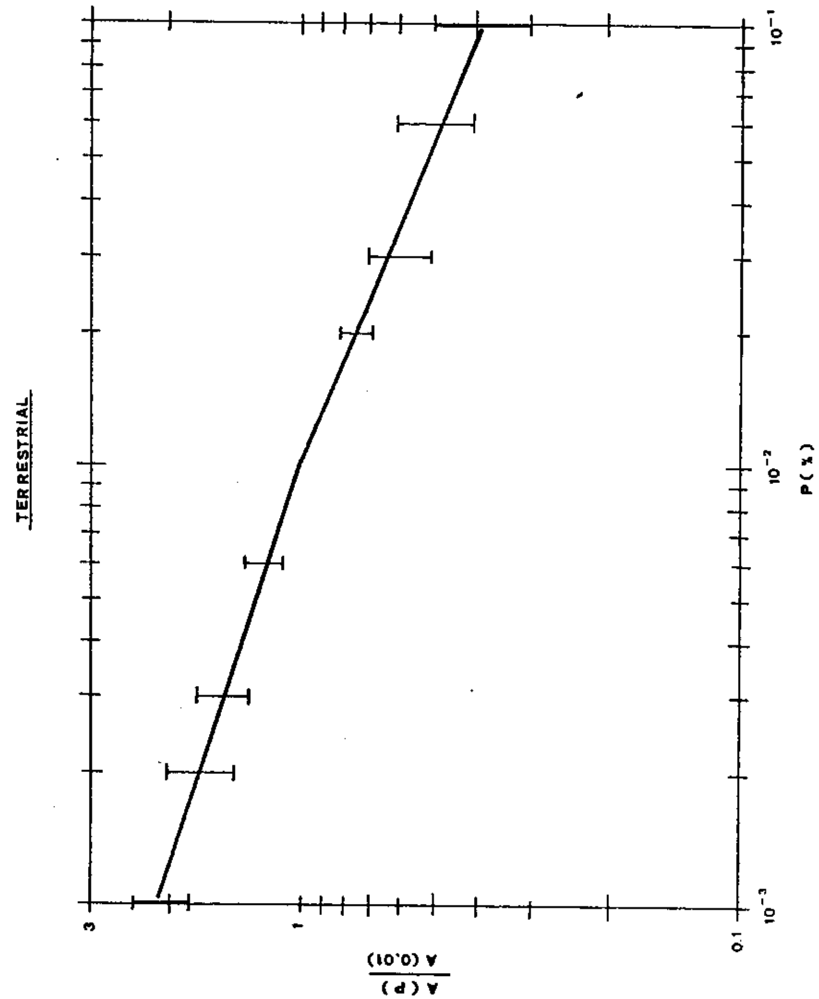
Most reliable data for R
for $P = 10^{-2}\%$

Develop a method for predicting $A(P)$ on the basis of the only value $R(0.01)$




17.8 GHz, H
17.8 GHz, V
11 GHz, V
FUCINO (ITALY)
9.5 km
Attenuation (dB)
Percent of time
100
10
1
10^{-3}
10^{-2}
10^{-1}


GEORGIA (USA)
5.1 km, 17.7 GHz, H
PARIS (FRANCE)
58 km, 11.7 GHz, H
Attenuation (dB)
Percent of time
100
10
1
10^{-3}
10^{-2}
10^{-1}



CCIR Procedure

(Fedi, 1981)

$$A(0.01) = \kappa\, R^{\alpha}(0.01)\, L\, r$$

$$r = \frac{1}{1 + L/25}$$

$$A(P) = A(0.01)\, b\, P^{-a}$$

b, a tabulated.

Accuracy

- Data base:

attenuation — 10 - 80 GHz
40 links
2 - 60 Km path length
90 site / years
Europe, Japan, North-America, Africa

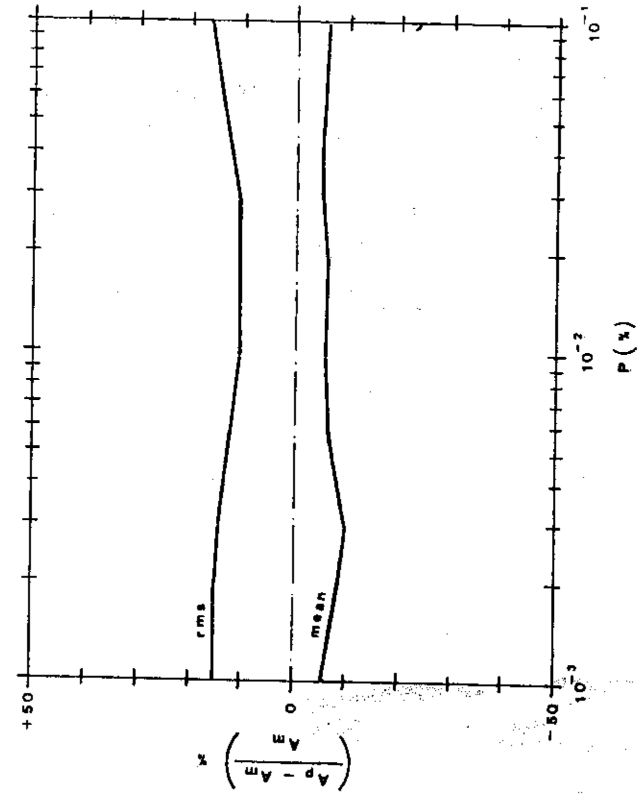
rainfall intensity — concurrently measured

- For selected values of P (10^{-3} - 10^{-1} %) the relative error:

$$e = \frac{A_p - A_m}{A_m} \times 100$$

has been calculated for each link and the average and rms values of e over the whole sample have been obtained.

TERRESTRIAL



Method

Applicability

Simple → only R(0.01)
- } easy identification
- } replacement of H(mm)

Value of R exceeded for $10^{-2}\%$
- intermediate in $10^{-3}\%$ – $10^{-1}\%$
- more stable and accurate than R(0.001)
- allows a better characterization than values R(0.1)
- allows utilization of archives of Meteo Offices.

Physical significance

* γ-R → physical model for microstructure (oblate spheroidal raindrops, aligned with vertical rotational axis, dimensions increasing with size) built on purely meteorological data (distribution, terminal velocity and temperature of drops)

* L_e ⇒ from radio data (depends on horizontal structure)

Considerable achievement - radio data derived in many different climatic regions - Validation of the method on the basis of a model developed from independently measured meteo parameters desirable.

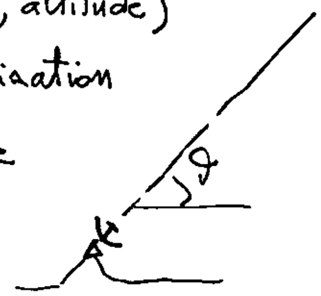
Accuracy

- R.M.S. error → 15%
- Ultimate limit for accuracy is accuracy of input R data → refinement of R characterization
- Same microstructure } in all locations
  Same horizontal structure } in all locations

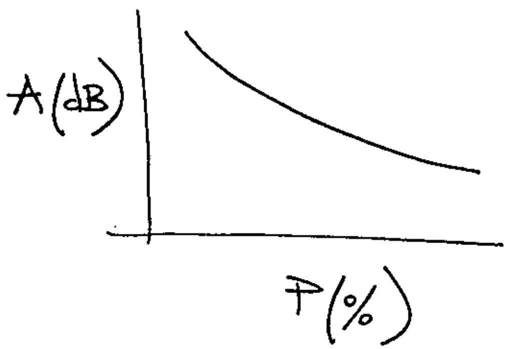
Earth-space links

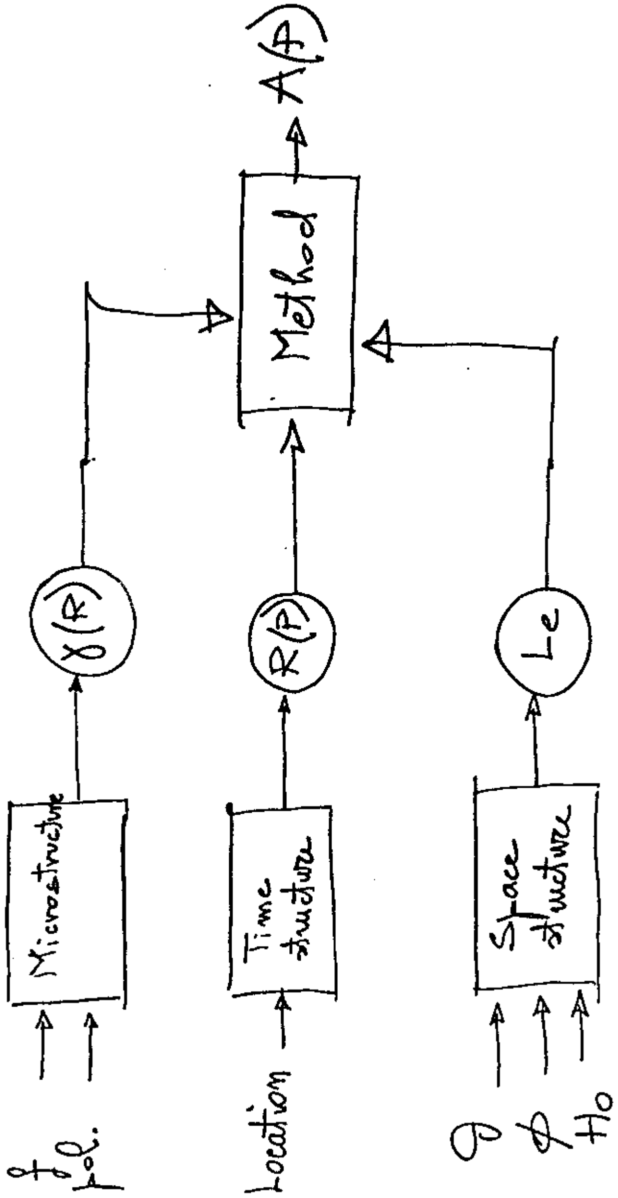
Information needed

given: { location (latitude, altitude), frequency, polarization, elevation angle

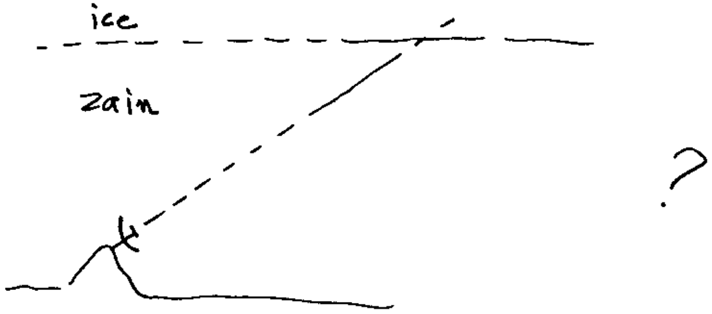


obtain A(P)

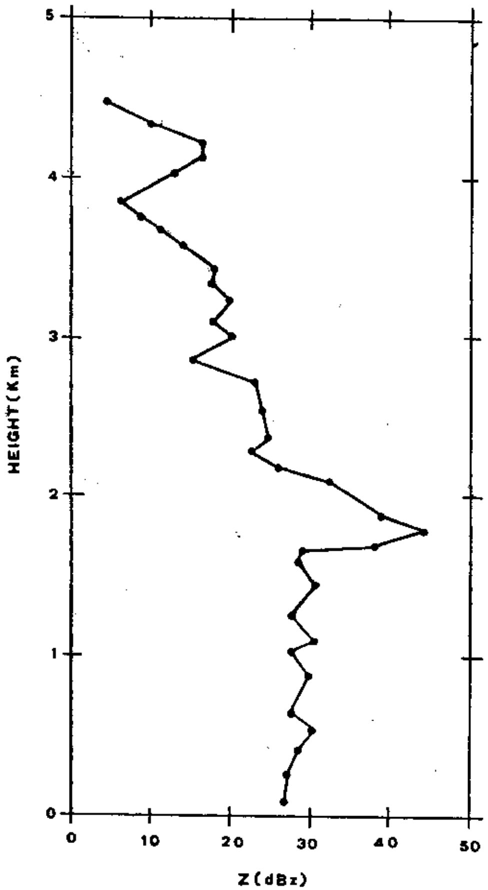




Microstructure

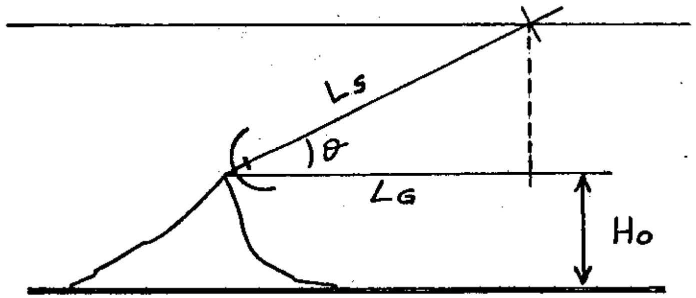


- Microstructure aloft
- Relationship between microstructure measured at the ground and aloft



Earth-space links

elevation angle (θ) → latitude (ϕ) → altitude (H_o) → **[Horizontal Vertical structure]** → effective path length (L_e)

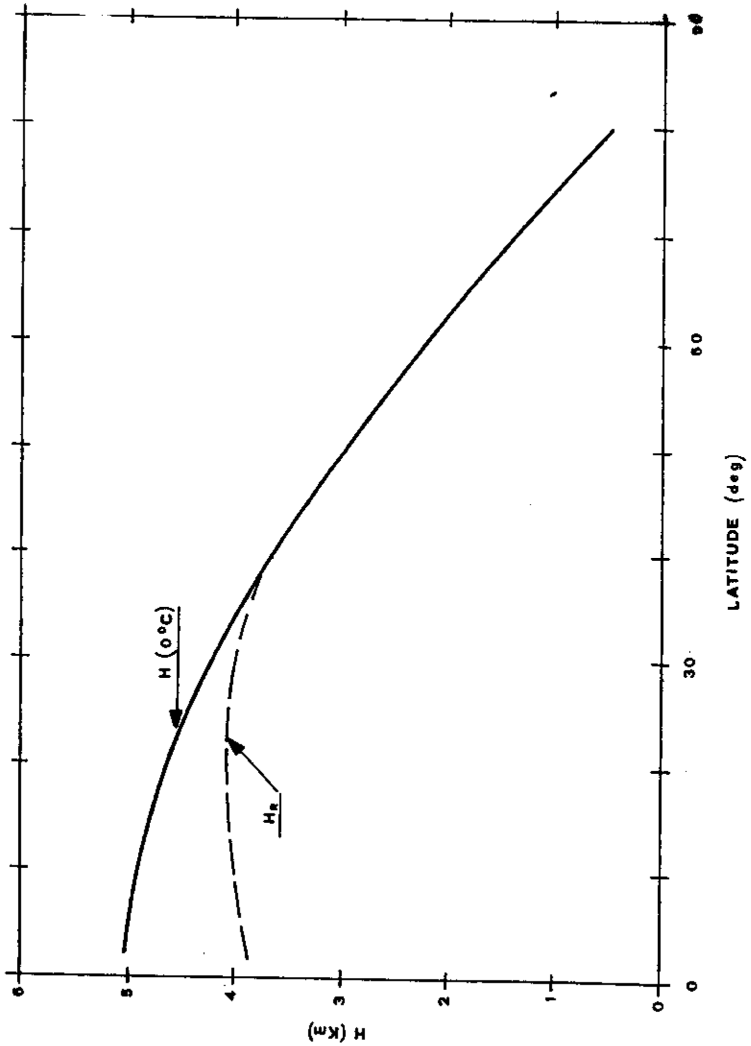


Vertical structure → "rain height" H_R (km) below which the specific attenuation is assumed constant

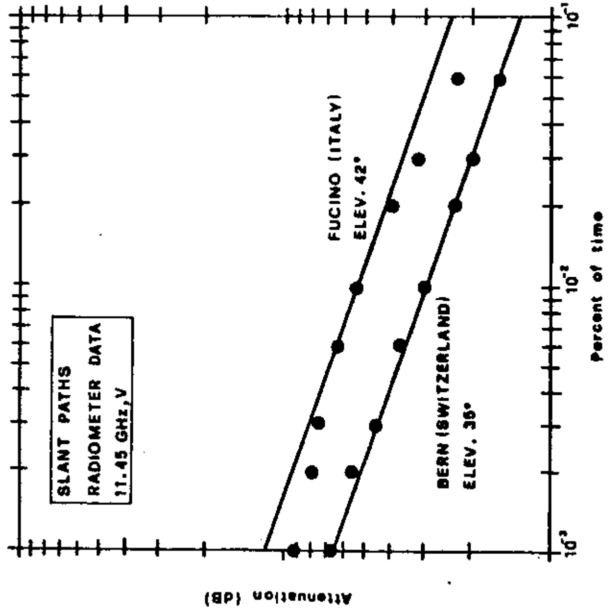
$$L_e = \frac{H_R - H_o}{\sin\theta} \cdot r = L_S \cdot r$$

$$r = \frac{1}{1 + L_G/25}$$

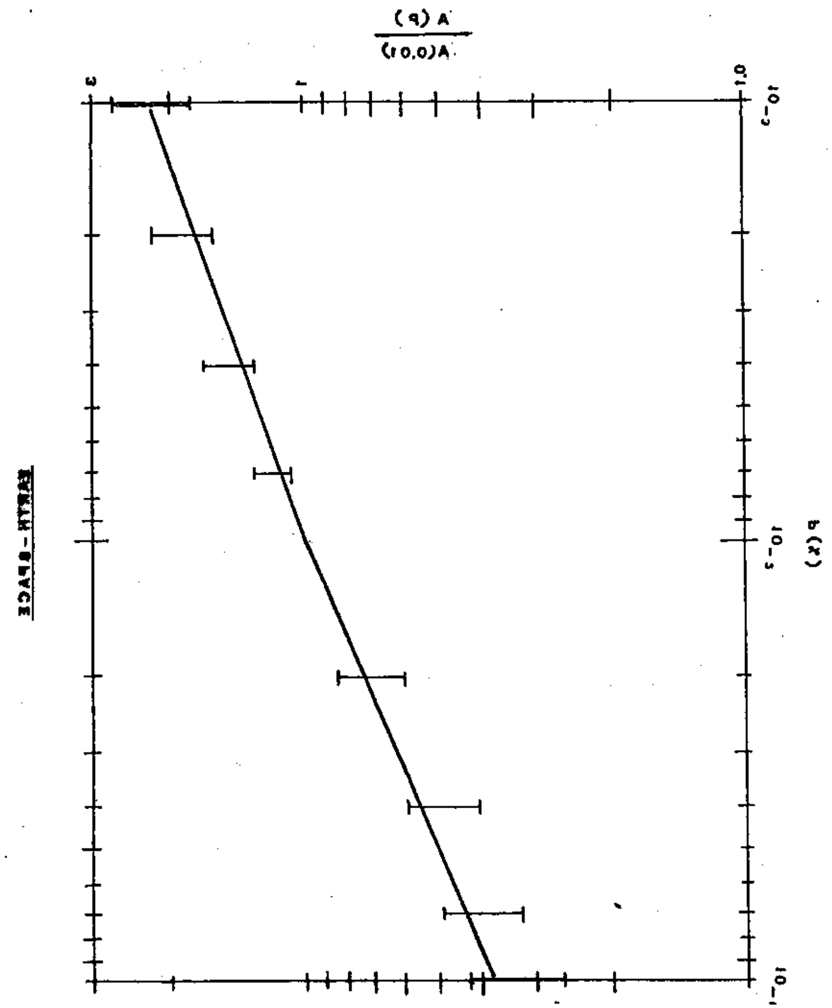
CCIR Procedure (Fedi, 1981)


H (0°C)
H_R
LATITUDE (deg)
H (Km)
0
30
60
90
0
1
2
3
4
5
6

75


SLANT PATHS
RADIOMETER DATA
11.45 GHz, V
FUCINO (ITALY)
ELEV. 42°
BERN (SWITZERLAND)
ELEV. 35°
Percent of time
Attenuation (dB)

76



Accuracy

- Consolidated data base not yet available

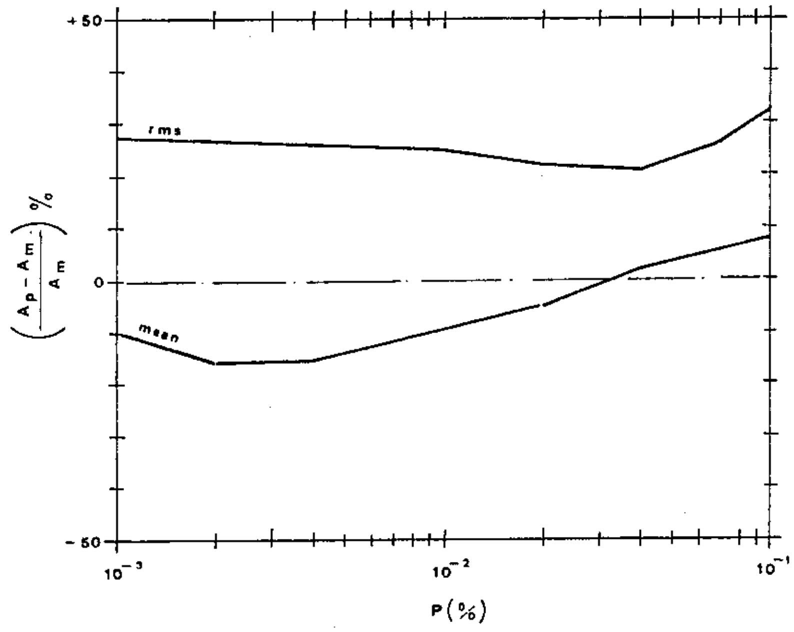
- Preliminary results

European region	(Project COST 205)
OTS - SIRIO	11 - 18 GHz band

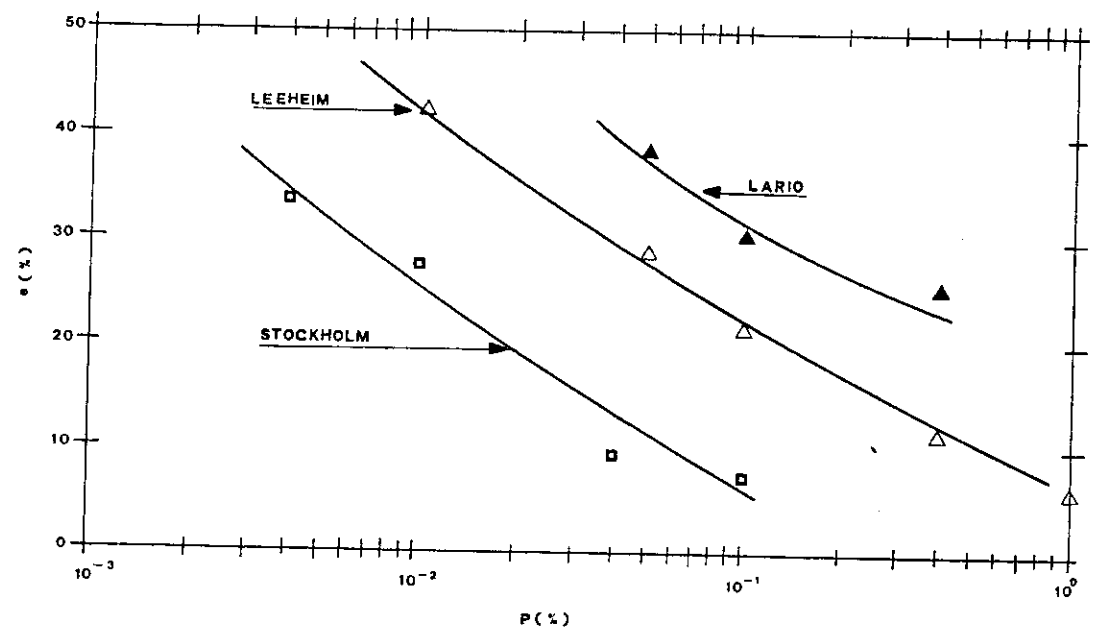
- Data base :

attenuation	11 - 18 GHz
	13 locations
	55 site/years
rainfall intensity	concurrently measured

EARTH - SPACE



YEAR - TO - YEAR VARIABILITY



Concluding remarks

- Applicability
- Limit for accuracy $\frac{\Delta A}{A} \simeq \frac{\Delta R}{R}$
  - Accuracy in characterizing a given location with a certain R(P).
- Terrestrial links
  - Advantage in utilizing the whole R(P)
  - Validation of Le with a physical model
- Earth-space links

Radiometeorological data about HR especially for tropical climates

- Assessment of accuracy obtainable
- Effect of hydrometeors other than rain in the melting layer.

Radio Science, Volume 16, Number 5, pages 731-743, September-October 1981

Prediction of attenuation due to rainfall on terrestrial links

Francesco Fedi

Fondazione Ugo Bordoni, Viale Trastevere 108, 00153 Rome, Italy

(Received May 26, 1980; accepted January 26, 1981.)

In this review, attention is confined to rain attenuation and to its influence on the availability of terrestrial radiocommunication systems operating at frequencies above 10 GHz. The availability objectives recently established by the Comité Consultatif International des Radiocommunications for digital systems, the information necessary, and a calculation procedure applicable for system design are examined. Various methods for predicting attenuation due to rain are compared and reviewed. Present trends for the use of frequencies above 10 GHz in terrestrial systems are illustrated, and areas in which further study is needed are indicated.

INTRODUCTION

The progressive saturation of the spectrum at lower microwave frequencies and the increasing demand for new services have resulted in pressures to utilize frequencies above 10 GHz for terrestrial radiocommunication networks. Following the present evolution of existing analog networks toward an integrated digital network, the wide frequency bands available in the upper portion of the spectrum will very likely be used for the transmission of digital information.

In the past years this emerging requirement has provided the impetus for an extensive series of studies of the atmospheric phenomena which might impair the availability and performance of the new systems.

Rainfall can cause noticeable attenuation in the received signal and has received considerable attention, since this is a phenomenon peculiar to the frequency range beyond about 10 GHz. Multipath activity causes both a decrease in the received signal and an increase in intersymbol interference; its influence has been newly appreciated in connection with the possibility of using existing facilities for digital systems in the 11-GHz band. Both rainfall and multipath can induce cross-polarization and hence interference between two orthogonally polarized radio channels at the same frequency. This phenomenon has received careful consideration in connection with the possibility of frequency reuse.

All of these phenomena influence system design and, for a given value of the fading margin, impose a limit on the maximum value of the repeater spacing which may be used in radio relay systems to meet prefixed availability and performance objectives.

In this review, attention is confined to rain attenuation and to its influence on the availability of terrestrial radiocommunication systems operating at frequencies above 10 GHz. The availability objectives recently established by the Comité Consultatif International des Radiocommunications (CCIR) for digital systems, the information necessary, and a calculation procedure applicable for system design are examined. Various methods for predicting attenuation due to rain are compared and reviewed. Present trends for the use of frequencies above 10 GHz in terrestrial systems are illustrated, and areas in which further study is needed are indicated.

INFLUENCE OF RAIN ATTENUATION

For a given frequency and polarization, rain attenuation increases with the length of the radio link and depends on the rainfall climatic conditions in the region where the link is to be installed. Given a certain value of the system fading margin, a maximum value of the hop length therefore has to be established for each rain climate region to meet prefixed availability objectives.

Availability and performance objectives

Availability and performance objectives recently established by the CCIR for large-capacity digital radio relay systems [*CCIR*, 1978*a*] refer to a hypothetical reference digital path (HRDP) of 2500

Paper number 1S0195.
0048-6604/81/0910-0195$01.00

km and to a maximum acceptable value for the bit error rate (MBER) of 10^{-3}. The value of 2500 km for the HRDP has been chosen to adhere to Comité Consultatif International Télégraphique et Téléphonique specifications. The value of 10^{-3} for the MBER corresponds to a minimum acceptable performance in telephony.

The event

$$\text{BER} \geq \text{MBER} = 10^{-3} \quad (1)$$

is referred to as an outage of the system.

A HRDP is considered unavailable if the duration of the outage is at least 10 consecutive seconds. The availability objective *Pa* is defined as the maximum percent of the time in an average year for which the system may be unavailable. For a HRDP, *Pa* has tentatively been established as

$$Pa = 0.3\% \quad (2)$$

The value of 0.3% is provisional, and it is recognized that in practice the availability objective may fall in the range 0.5–0.1%. This objective should not take into account the improvements which could be obtained by rerouting over other systems and should include all causes which are statistically predictable and unintentional.

The considerable attenuation induced by rainfall in the received signal usually lasts longer than 10 s. Consequently, rain is included among the major causes of unavailability of digital radio relay systems.

The performance objective *Pp* is defined as the maximum outage probability, expressed in percent of time in any month, allowed when the system is available. For a HRDP, *Pp* has tentatively been fixed as

$$Pp = 0.05\% \quad (3)$$

The value of 0.05% refers to any 1-s outages, is provisional, and should take account of fading, interference, and all other sources of degradation of performance. In view of the short duration of the induced outages, multipath activity is included among the causes of degradation of system performance.

Procedure for the calculation of the maximum hop length

Taking into account the CCIR recommendation for a HRDP (equation (2)), the availability objective for a multihop digital radio relay system of total length *L* (kilometers) may be written as [*Fedi and Peroni*, 1974]

$$Pa(L) = 0.3(L/2500) = 1.2 \times 10^{-4} L \quad (4)$$

If the system is composed of *n* hops in tandem of length l_i (kilometers), then

$$\sum_{i=1}^{n} l_i = L \quad (5)$$

Whenever the attenuation due to rain $A_R(l_i)$ (decibels) on any of the *n* hops exceeds the fading margin $M(l_i)$ (decibels), the system is unavailable. The fading margin is defined as

$$M(l_i) = W(l_i) - W_t = M_0 - 20 \log (l_i/l_0) \quad (6)$$

where

$W(l_i)$ received power under normal conditions, dB;
W_t threshold received power at which BER = MBER = 10^{-3}, dB;
l_0 hop length chosen for reference, km;
M_0 fading margin at $l_i = l_0$, dB.

In the case of rain attenuation, outage probability is equal to the probability of attenuation exceeding the fading margin:

$$P[\text{BER}(l_i) \geq 10^{-3}] = P[A_R(l_i) \geq M(l_i)] \quad (7)$$

Assuming repeaters of the regenerative type and under the conservative hypothesis that the events of attenuation $A_R(l_i)$ exceeding $M(l_i)$ are disjoint in the different hops, the condition which has to be imposed to meet availability objectives is therefore

$$\sum_{i=1}^{n} P[A_R(l_i) \geq M(l_i)] \leq Pa(L) \quad (8)$$

If the whole region traversed by the system can be assumed to belong to the same rain climate, then the hop length is a constant *l*, and the above expressions become

$$l = \text{const} = L/n \quad (9)$$

$$P[A_R(l) \geq M(l)] \leq Pa(l) \quad (10)$$

$$Pa(l) = 1.2 \times 10^{-4} l \quad (11)$$

$$M(l) = M_0 - 20 \log (l/l_0) \quad (12)$$

If, on the other hand, a number of distinct rain climate subregions can be identified, then the total length of the system can be subdivided into sections relative to the different subregions.

If the fading margin can be exceeded simultaneously over several successive hops, then outage events are not disjoint, and (10) becomes

$$Pa(l) = 1.2 \times 10^{-4} l\eta \quad (13)$$

where $\eta > 1$.

The maximum value of the hop length can easily be calculated from (10), (11), and (12). It is worth recalling that (10) and (11) are expressed in percent of time in an average year.

First, given the frequency and polarization, the cumulative distribution of rain attenuation must be estimated for various values of the hop length for the region where the system is to be installed. For prefixed values of *l* it is then possible to calculate the probabilities at which $A_R(l) = M(l)$ and hence to obtain the outage probability $P[A_R(l) \geq M(l)]$ curve as a function of *l*. The intersection of this curve with the availability objective $Pa(l)$ curve gives the maximum value of the hop length (and hence the minimum number of hops) for the region under consideration.

Even if it is outside the scope of this review, it is interesting to note that a similar calculation procedure may be applied to evaluate the maximum value of the hop length resulting from the influence of multipath to meet the CCIR performance objectives. In this case, however, outage probability is expected to be higher than the probability of multipath attenuation A_M (decibels) exceeding the fading margin (12):

$$P[\text{BER}(l) \geq 10^{-3}] > P[A_M(l) \geq M(l)] \quad (14)$$

and it has to be evaluated from the transfer function of the channel [e.g., *Andreucci et al.*, 1980].

Therefore, taking into account (3) and (14), expressions (10) and (11) become, respectively,

$$P[\text{BER}(l) \geq 10^{-3}] \leq Pp(l) \quad (15)$$

$$Pp(l) = 2 \times 10^{-5} l \quad (16)$$

Note that (11) is a yearly percentage, whereas (16) is expressed in percent of time in the worst month.

PREDICTION OF RAIN ATTENUATION STATISTICS FROM RAINFALL INTENSITY DATA

From the calculation procedure outlined in the previous section it is clear that for the design of terrestrial systems the cumulative distribution of rain attenuation for an 'average' year is needed, at a given frequency and polarization and for various values of the path length, for the region where the system is to be installed.

The possibility and the advantages of estimating this distribution from rainfall intensity data seem at present to be well established. The estimating procedure of all the prediction methods based on the use of point rainfall intensity cumulative distribution is based on the following steps.

A relationship between specific attenuation and rainfall intensity is to be established on the basis of a model for the microstructure of rainfall (i.e., size distribution, temperature, terminal velocity, and shape of the raindrops). This topic is reviewed in the following subsection, but it can be stated in anticipation that given the frequency and polarization, the use of the same relationship has been recommended for every region. This implies that the microstructure of rainfall is assumed, on average, to be the same in every region.

The rain attenuation over a hop is computed by integrating the specific attenuation over the path length: the rain intensity profile along the path is therefore needed. Owing to the nonuniformity of this profile, the value of rain attenuation exceeded for a certain percentage of the year increases in less than linear proportion with path length. A statistical model of the rain intensity profile is generally employed to take account of the nonuniformity of this profile. Unless different parameters of the model are chosen for every region, the underlying assumption is that the spatial structure of rainfall intensity is statistically the same in every region.

Consequently, rain attenuation cumulative distributions at a given frequency and polarization will differ from one region to another only because the point cumulative distributions of rainfall intensity assumed for the two regions are different. The entire prediction procedure is therefore based on the rainfall intensity data which are usually acquired, for a certain region, at one or several points with instruments having a collecting surface generally less than 1000 cm^2.

On the one hand, this prediction methodology represents a considerable achievement of the efforts which have been made by a number of scientists in various parts of the world. On the other hand, it has to be recognized that the accuracy of attenuation predictions strongly depends on the accuracy of the instrument used, on how closely the rapid temporal variation of rainfall intensity can be recorded and processed, and on how stable and representative the assumed cumulative rain intensity distribution is for the region concerned.

Relationship between specific attenuation and rainfall intensity

Particular attention has been given in the past years to the possibility of calculating the relationship between specific attenuation and rainfall intensity, to the applicability of this relationship to real rainfall situations, to the influence of the hypotheses and parameters adopted in the calculations, and to the limitations of the experimental techniques used to ascertain its validity. Extensive reviews on this subject are available in the literature [*Crane*, 1971, 1975; *Fedi and Mandarini*, 1973, 1974; *Waldteufel*, 1973; *Fedi et al.*, 1974; *Rogers*, 1976].

For practical applications, the relationship between specific attenuation γ_R (decibels per kilometer) and rainfall intensity R (millimeters per hour) appears at present to be well established in the form of the power law

$$\gamma_R = kR^\alpha \qquad (17)$$

where the parameters k and α depend only on frequency and polarization once a particular model for the microstructure of rainfall is assumed [*Olsen et al.*, 1978].

Values of k and α for any frequency in the range 1–400 GHz and any linear and circular polarization have recently been adopted by the CCIR [*CCIR*, 1980]. They have been obtained by assuming oblate spheroidal raindrops randomly distributed in space aligned with a vertical rotational axis and dimensions related to the equivolumic spherical drops and the Laws-Parsons raindrop size distribution, the Gunn-Kinzer terminal velocity, and the Ray model for the index of refraction of water at 20°C [*Fedi*, 1979*b*; *Nowland et al.*, 1977].

The use of these values has been recommended for evaluating the statistical characteristics of rain attenuation in any region. However, in view of the complexity and variability of the real rainfall microstructure, caution has been suggested in applying the proposed relationship between specific attenuation and rainfall intensity to individual rain events [*Fedi et al.*, 1977].

Cumulative distributions of rainfall intensity

A number of rain climatic regions, each characterized by the same cumulative distribution of rainfall intensity, have to be identified for system design. Data on this point are still too scarce to allow a sufficiently refined rainfall climatic characterization for many countries.

Variability in the cumulative distribution from year to year has been shown to be extremely high; a long observation period is therefore needed to obtain statistical stability [*Lin*, 1977]. Using 5-min-averaged rain data, it has also been shown that more than 10 years of observations are required to estimate the rain intensity value exceeded for 0.001% of the time with an uncertainty of less than 10% of the estimated value [*Crane*, 1977].

Variability is also expected from location to location within a certain region. However, it has been found that the use of data pooled from different locations within a region can provide improved statistical estimates: this suggests a time-space ergodicity for the cumulative distribution of rainfall intensity [*Drufuca*, 1974*a*; *Lin*, 1977; *Crane*, 1977].

Moreover, since the entire procedure for predicting rain attenuation statistics relies on rainfall intensity data, particular care must be devoted to ensuring the accuracy of the experimental techniques used to collect these data.

Rapid response rain gauges or tipping bucket rain gauges with adequate time resolution measuring systems [*Fedi*, 1979*a*] have indicated that rainfall of high intensity tends to be concentrated in short periods of time, typically a few minutes. Even 1-min average values may be considerably lower than the actual peaks of rain intensity [*Fedi and Merlo*, 1977; *Breuer and Kreuels*, 1977; *Norbury and White*, 1973], and the cumulative distribution is strongly influenced by the integration time employed [*Fedi*, 1979*a*; *Lin*, 1979; *Segal*, 1979].

Although theoretical and experimental results [*Lin*, 1976; *Morita*, 1978*a*; *Fedi*, 1979*a*] have been presented on the effect of integration time on the cumulative distribution, no definite conclusion on a relation of general validity between 'quasi-instantaneous' and 'time-averaged' rainfall intensity seems to be established as a function of time percentage (or rainfall intensity) and for various integration times. This may be due in part to the fact that the term of reference 'quasi-instantaneous rainfall intensity' is difficult to define and to measure.

Cumulative distributions of rainfall intensity can be obtained with sufficient accuracy by means of rapid response rain gauges up to rather high intensity values. However, the problem of accurately measuring the tail of the distribution for intensities

higher than about 50 mm/h appears to be still unsolved, since rainfall of high intensity is very difficult to measure and varies considerably from year to year. Moreover, data with rapid response rain gauges have been obtained in only a few regions and are still limited to time periods of a few years. A rainfall climatic classification for the European region has been attempted on the basis of data mostly obtained with rapid response rain gauges in 37 locations throughout Europe for periods ranging from 1 to 12 years [*Fedi*, 1979*a*]. This classification has been further refined for Italy [*Barbaliscia and Fedi*, 1980].

In many instances, use has to be made of the data contained in the archives of meteorological services. A direct approach is to process, through optical magnification to increase time resolution, the pen charts where the tips of tipping bucket rain gauges have been recorded [*Segal*, 1979]. This approach permits data to be acquired for a number of years. The rapidity of response of the instrument up to rain intensities typically of about 20 mm/h may be exploited by measuring with sufficient accuracy the time intervals between tips. For higher rates, where the tip intervals become very small, integration has to be performed over several tips; high-intensity rainfall therefore tends to be underestimated. Data obtained with this procedure in 47 locations for periods of up to 20 years allowed the development of a detailed rain climatic map for Canada, based on the two parameters of a power law distribution [*Segal*, 1980*c*].

In some countries, rainfall accumulations over 5- and 10-min intervals are readily available for a considerable number of years in the publications of meteorological services. In the cumulative distributions obtained from these data, high values of rain intensity tend to be increasingly underestimated as the integration time increases.

In the United States a methodology for estimating 5-min rain rate distributions from data on yearly maximum 5-min rain rate and yearly total accumulated rainfall, published by the National Climatic Center, has been proposed and applied to extract this information for several U.S. locations and for periods of time of up to 50 years [*Lee*, 1979; *Lin*, 1976, 1977, 1978]. Cumulative distributions of 10-min rain rate were obtained in Japan in 10 locations based on an observation period of 10 years [*Morita*, 1978*a*].

In the absence of more refined data an empirical method, which makes use of the total annual rainfall height and the ratio between thunderstorm or convective rainfall and the total annual height, has been proposed to derive estimates of cumulative distributions of rainfall intensity [*Rice and Holmberg*, 1973]. Detailed mapping of the parameters of this method for the North American and European regions has been obtained as well as information on year-to-year variability of cumulative distribution of rain rate [*Dutton and Dougherty*, 1979]. Based on this method, a global rain climatic model has been developed with eight regions to represent variation in rain rate on a world basis. The climate region boundaries were established using total rain accumulation and the number of thunderstorm days provided by the World Meteorological Organization. Satellite cloud data and microwave radiometer observations were used to extend rain climatic regions over the oceans [*Crane*, 1980]. Estimates of year-to-year and location-to-location variations have been made; within a certain region, year-to-year variations should be limited by the curves of the two adjacent regions.

An attempt to introduce the additional parameter 'number of rainy days caused by typhoon' has been made in Japan, and a rain climatic classification for that country has been developed [*Morita*, 1978*b*].

On the basis of the above mentioned data [*Fedi*, 1979*a*; *Segal*, 1980*c*; *Crane*, 1980] a rain climate classification on a world basis has recently been attempted by the CCIR [*CCIR*, 1980]. Each continent and the oceans have been divided into climatic regions, each characterized by a specific rainfall intensity distribution. It may be expected that in practice, the transition from one region to the next will not be abrupt and that rainfall rate distribution will vary from one location to another within a given region and may display considerable variability from year to year.

Models for the cumulative distribution of rainfall intensity may be very useful both for rain classification maps and for use in rain attenuation prediction methods.

Examining rainfall intensity data, it has been found that experimental point rainfall rate distributions could be well approximated by a lognormal law. The parameters of the lognormal conditional distribution (median value and standard deviation) were estimated through *Po* (probability of rain) and a least squares analysis of the experimental values.

The agreement was very satisfactory up to intensities of about 100 mm/h: deviations for rates higher than this value were attributed to the limited data base. The experimental data examined had been obtained with integration times up to 2 min and were converted to 2-s data through an empirical conversion factor [*Lin,* 1975].

Using fast response rain gauges, the validity of the lognormal approximation was confirmed for low intensities, but it was noted that for high intensities, experimental data tended to be lower than the lognormal approximation [*Fedi and Merlo,* 1977]. In examining a considerable data sample collected in Europe with fast response rain gauges [*Fedi,* 1979*a*] it was suggested [*Fedi,* 1979*b*] that this phenomenon might be due to the unavoidable integration time which in any rain gauge is needed to collect the rainwater into the funnel and to direct it into the sensor. This integration process, especially for high intensities, might cause an underestimation of the actual values of rain rate even with fast response rain gauges. The effect of the integration time, especially on the underestimation of the standard deviation of the lognormal approximation, has recently been confirmed [*Barbaliscia and Fedi,* 1980; *Damosso et al.,* 1980]. It was thus suggested [*Fedi,* 1979*a*] that fast response rain gauges use values of up to only about 50 mm/h for the estimation of the parameters of the lognormal law: below this value the effect of the integration time was not significant, and the number of occurrences generally was high enough to give statistical stability to this portion of the statistics. However, the explanation of the disagreement between experimental data and predictions beyond 50 mm/h is still controversial, mainly because the problem of accurately measuring the tail of the distribution appears to be still unsolved.

The suitability of the lognormal approximation to the cumulative distribution below about 50 mm/h has been confirmed using 5- and 10-min data [*Segal,* 1980*b*; *Lin,* 1977; *Morita and Higuti,* 1978]. Moreover, the lognormal hypothesis has been further circumstantiated by noting that the environmental parameters affect the rain rate in a proportional fashion [*Lin,* 1978].

It is well known that for a lognormal distribution it is quite easy to construct a probability graph in such a way that the theoretical distribution appears as a straight line. This allows a simple graphical test for the goodness of fit and for the estimation of the parameters for the distribution. In the case of rainfall intensity data the mean and the standard deviation derived in this way with a least squares analysis have been shown to be in good agreement with the same parameters estimated from the experimental distribution [*Fedi,* 1979*b*]. The same is not always true for a gamma distribution [*Morita and Higuti,* 1976]. If the mean and standard deviation are estimated from the experimental distribution, the agreement between experimental values and the gamma approximation is, in general, poor. If these parameters are estimated by an elaborate curve-fitting method, the agreement is better, but they do not agree with parameters determined from the experimental distribution [*Fedi,* 1979*b*; *Segal,* 1980*b*].

Although the lognormal distribution is recognized as providing a very good fit for low rainfall rates, a straight line approximation in log-log coordinates, that is, a power law relationship, has been shown to approximate satisfactorily the entire experimental cumulative distribution beyond about 5 mm/h [*Segal,* 1980*b*].

Prediction methods

With only one exception, all methods which will be reviewed in this paper make use of the point cumulative distribution of rainfall intensity to predict rain attenuation statistics. Attention is focused in this section on the models for the spatial structure of rainfall, assumed in each method to take into account the nonuniformity of rainfall intensity profile along the path.

A first group of methods makes use of the 'path average' rain rate and its relationship with rainfall rate measured at a point as determined experimentally by a network of rain gauges [*Hogg,* 1969; *Battesti et al.,* 1971; *Harden et al.,* 1978*b*]. The behavior of this relationship is similar to that between quasi-instantaneous and time-averaged rain rate both measured at a point. This approach would be precisely applicable only in the case of specific attenuation proportional to rain intensity. The influence of the exponent in (17) and the fact that the reduction factor is frequency and path length dependent are well recognized [*Misme and Fimbel,* 1975; *Kheirallah et al.,* 1980*a*]. *Battesti and Boithias* [1978] elaborated further on this approach by proposing the use of two coefficients.

Crane and Blood [1980] and *Crane* [1980] used the concept of path average rain rate to establish a power law relationship with point rain rate, based on measurements carried out with networks of rain gauges in both Europe and the United States. To take the nonlinearity between specific attenuation and rain rate into account, the rain path profile was reconstructed by differentiating the established power relationship between path average and point rainfall intensity. The resulting path profile was then integrated, taking into account the relationship between specific attenuation and rain rate. An attempt to place error bounds on the mean attenuation predictions was also made in the analysis.

Misme and Fimbel [1975] assumed a single rain cell having the same probability of occurrence for all the points in the region. The cell is cylindrical with dimensions related to rainfall intensity and is surrounded by an area of 'residual' rainfall, which depends on the intensity in the cell and which extends for about 33 km. The cumulative distribution of rainfall intensity is assumed to be lognormal, although this assumption is not strictly necessary.

Morita and Higuti assumed an exponential spatial correlation for rainfall intensity and the same law for the cumulative distribution of point rainfall intensity and of rain attenuation. The parameters of the two distributions are related through the spatial correlation of rain intensity. Originally, a gamma distribution was assumed [*Morita and Higuti,* 1976], and later a lognormal one was assumed [*Morita and Higuti,* 1978]. Also, *Lin* [1975] assumed both lognormal rainfall intensity and rain attenuation cumulative distributions. Their parameters were related through empirically adjusted coefficients.

The 'synthetic storm' method [*Drufuca,* 1974*b*] generates rain attenuation statistics by converting rain rate/time profiles recorded at a point to rain rate/distance profiles, using the translation velocity of the rain pattern, a good estimate of which seems to be the wind speed at the 700-mbar level as derived by a conventional radiosonde. Although this method requires not only the cumulative distribution of rainfall intensity but also the actual rain intensity recordings and information on wind velocity aloft and therefore needs a more detailed data analysis and processing, it allows one to investigate other attenuation characteristics such as durations and joint probability distributions [*Drufuca and Torlaschi,* 1977]. Moreover, although several assumptions on the spatial structure of rainfall have to be made [*Kheirallah et al.,* 1980*a*], the method does not need to assume the same spatial structure of rainfall in all the regions. It is interesting to note that if the relationship between specific attenuation and rain intensity is assumed to be linear and if the wind velocity is supposed to be constant, the same results proposed earlier by *Bussey* [1950] are found.

Comparison between predicted and experimental results

The most extensive comparison between predicted and experimental results for terrestrial links has been performed in Europe as a result of a joint research project on radio propagation above 10 GHz [*Fedi,* 1979*b*]. Average cumulative distributions of rain attenuation have been obtained in the 10- to 40-GHz band for vertical and horizontal polarizations on 53 radio links with path lengths from about 2 to 60 km set up in 12 European localities. For each of the 12 localities, cumulative distributions of point rainfall intensity were obtained with one or more rapid response rain gauges or with traditional rain gauges with a typical integration time of 1 min. The methods tested were those proposed by Misme and Fimbel, Lin, and Morita and Higuti. For comparison, predictions obtained by supposing a uniform rain rate along the path were also obtained. Of these methods, only the models concerning the spatial structure of rainfall were maintained. Both the parameters of the relationship between specific attenuation and rainfall intensity and the procedures for estimating the lognormal and gamma approximations for the cumulative distribution of point rainfall intensity were modified and standardized. The result was that if the cumulative distribution was sufficiently representative of the region where the link was installed, the Misme-Fimbel method provided the most satisfactory results. This method, however, was very sensitive to the value of the standard deviation of the lognormal approximation for the cumulative distribution of rain intensity. Additional comparisons carried out in Italy [*Damosso et al.,* 1980] and Denmark [*Mogensen and Stephansen,* 1978], with similar procedures, confirmed these findings and indicated the important influence of rain rate integration time on the standard deviation of the lognormal approximation.

Good agreement was reported by *Lin* [1975] in comparing his predictions with experimental results obtained in the United States on three links in the

18-GHz band with path lengths of 4–6 km and on one link in the 11-GHz band with a path length of about 42 km. However, this method, when applied in Europe, tended to overestimate attenuation [*Fedi*, 1979*b*; *Damosso et al.*, 1980].

Good agreement was also reported by Morita and Higuti in comparing predictions obtained in Japan with gamma approximations on two links in the 19-GHz band (2–4 km) [*Morita and Higuti*, 1976] and with lognormal approximation [*Morita and Higuti*, 1978]. However, probably because of the poor gamma approximation used for the distribution of rainfall intensity, the gamma method applied in the European region did not give satisfactory results [*Fedi*, 1979*b*]. The lognormal method, when applied in Italy, tended to overestimate attenuation, and the results were very close to predictions obtained with Lin's method [*Damosso et al.*, 1980].

The synthetic storm method provided satisfactory results when used in Canada and in Italy [*Drufuca*, 1974*b*; *Bertok et al.*, 1977]. It has to be noted, however, that the values of the parameters in (17) were chosen to fit the experimental distribution in 1 year, and the method was tested for the remaining years. If recommended values of the parameters in (17) are chosen independently, in some cases the results obtained may not be satisfactory [*Damosso et al.*, 1980].

Crane [1980] reported agreement within expected variation of his predictions with experimental data obtained in the United Kingdom. However, the same method applied in Italy [*Damosso et al.*, 1980] and Denmark [*CCIR*, 1978*c*] did not provide similarly good results.

OTHER PREDICTION TECHNIQUES FOR RAIN ATTENUATION

Frequency scaling

Frequency scaling is a promising technique to derive rain-induced attenuation statistics at higher frequencies from available data at lower frequencies, for both terrestrial and satellite radio links. The problem is to estimate A_2 (decibels) at f_2 (gigahertz) given A_1 (decibels) at f_1 (gigahertz), where generally $f_2 > f_1$.

A first group of techniques needs only the values of the two frequencies to predict A_2 once A_1 is known [*Drufuca*, 1974*b*; *CCIR*, 1978*b*].

A second group of techniques makes use of the parameters k and α of (17) for the two frequencies f_2 and f_1 and of statistical models for the rainfall intensity profile to predict A_2 once A_1 is known [*Hodge*, 1977; *Rue*, 1980; *Kheirallah et al.*, 1980*b*; *Barbaliscia et al.*, 1980].

A third group makes use of both A_2 and A_1 to derive the parameters of assumed statistical models for the rainfall intensity profile and hence to predict attenuation statistics at another frequency [*Muller*, 1977; *Hogg*, 1973; *Harris and Hyde*, 1977].

Results so far obtained are encouraging and seem to indicate that the techniques of the second group are an acceptable compromise between complexity and accuracy. To select a procedure which might have a worldwide application, a relative assessment of the different approaches proposed should be made on the basis of data presently available. A comparison between results obtained with earth-satellite links and those obtained with terrestrial links would also be interesting and give a better understanding of the phenomenon, as in the latter case a wider dynamic measurement range can be more easily obtained [*Barbaliscia et al.*, 1980].

Caution should be exercised in deriving information on the spatial structure of rainfall intensity from purely radio measurements owing to the considerable variability of the microstructure of rainfall [*Fedi et al.*, 1977; *Harden et al.*, 1978*a*; *Debrunner*, 1980].

Radar observations and other techniques

Radar observations have been widely used to obtain information on rain attenuation along slant paths. Extensive reviews on advantages and limitations of radar techniques are available in the literature [e.g., *Crane*, 1971, 1977; *Fedi et al.*, 1974; *Rogers*, 1976]. In some cases, radar observations have also been used to derive rain attenuation statistics on terrestrial links [*Drufuca*, 1974*a*; *Ferguson and Rogers*, 1978].

The possibility of estimating attenuation statistics from the thermodynamic variables in regions where pluviometric data are not available has recently been suggested [*Torlaschi and Zawadzki*, 1980].

PATH DIVERSITY

Rainfall intensity data obtained with networks of rain gauges [*Freeny and Gabbe*, 1969] or derived from simulated profiles of rain rate versus distance [*Drufuca and Zawadzki*, 1975] have shown that the probability that the same rain rate is jointly

exceeded at two points decreases with increasing separation. In the limiting case the joint probability would be equal to the product of the individual probabilities.

Consequently, path diversity appears to be an effective means for increasing the maximum hop length while still meeting prefixed availability objectives [*Hogg*, 1969].

These findings have recently been confirmed from attenuation data collected with a network of radio links [*Blomquist and Norbury*, 1979]. It appears that for path lengths of 4–12 km the diversity improvement increases as the path separation increases from 4 to 8 km but there is no further significant improvement as the separation increases from 8 to 12 km. These data show similar trends to those previously estimated on the basis of radar observations [*Drufuca*, 1974*a*].

More information on the statistical structure of rain intensity over an area is still required to develop models for predicting path diversity improvement from statistics of rainfall rate measured at a point.

WORST MONTH STATISTICS

Recently established CCIR availability objectives for terrestrial radio relay systems at frequencies above 10 GHz refer to an average year. Consequently, statistics of rain attenuation for the worst month are no longer required for the design of these systems. However, the concept of worst month can still be useful for other types of services or in radiometeorological studies.

The annual worst month distribution of any radiometeorological quantity is defined as the envelope of the highest monthly probability values of 12 calendar monthly distributions [*Crane and Debrunner*, 1978]. From theoretical and experimental studies [*Brussaard and Watson*, 1979; *Brussaard*, 1979] it appears that a useful definition for practical applications is the ratio

$$Q_{j1} = X_{jh}/Y_j \tag{18}$$

where X_{jh} is the average annual worst month percentage of time in 1 year and Y_j is the average annual percentage during which the same level j is exceeded. In order to establish the expected range of variation for Q_{j1} this ratio can be plotted as a function of the average monthly probability of exceeding the level j, Co_j, with M as a parameter, assuming an exponential model for the tail of the probability distribution. M is the average number of months during which the phenomenon occurs. Experimental findings both in the case of point rainfall intensity [*Fedi*, 1979*a*; *Mawira*, 1980] and in the case of rain attenuation [*Mawira*, 1980; *Debrunner*, 1980; *Damosso et al.*, 1980; *Brussaard*, 1979] confirm the calculated range of variation for Q_{j1}.

It is interesting to note that for rain attenuation the relationship between worst month and yearly cumulative distribution seems to be independent of frequency, polarization, and path length [*Damosso et al.*, 1980] and in countries where attenuation due to wet snow is not predominant, appears to be similar to that established for rainfall intensity [*Mawira*, 1980].

Empirical expressions for the relationship between Y_j and X_{jh} and also available in the literature [*Morita*, 1978*b*; *Segal*, 1980*a*].

PRESENT TRENDS IN THE USE OF FREQUENCIES ABOVE 10 GHz

The possibility of using the 10.7- to 11.7-GHz band to establish large-capacity (typically 140 Mbit/s) long-haul digital radio relay systems utilizing existing facilities for the lower-frequency bands is presently being carefully considered by various telecommunication administrations. Rain attenuation seems to be an obstacle to the use of existing facilities, and therefore to hop lengths of up to about 50–60 km, in only a few regions. On the other hand, multipath fading might be the limiting factor in many regions and might require the use of antenna height diversity.

The use of the 13-GHz and in some regions of the 15-GHz bands seems suitable for medium-capacity (typically 34 Mbit/s) radio relay systems for use in regional and local areas with typical hop lengths of 20–30 km.

In many regions the use of the 20-GHz band for medium- and long-distance radiocommunications would require a large number of repeaters with high system cost due also to the great reliability required. For this reason, the wide-scale use of this frequency band is not foreseen in the immediate future for this kind of application, although experiments are in progress in various countries. An interesting use of this frequency range has been made in Japan for a large-capacity (400 Mbit/s) radio relay system with typical hop lengths of 5 km [*Ninomiya*, 1972].

The growing cost of cables and ducts in urban and metropolitan areas provides a strong incentive for the introduction of large-capacity digital radio transmission media in junction networks in metropolitan and urban areas. Use of the 30- and 60-GHz bands has been suggested for this application. In the latter case, interference problems might be alleviated by making use of the high oxygen attenuation, which makes it possible to use the same frequency in radio links with separations of about 5 km also under clear sky conditions.

CONCLUDING REMARKS

Availability objectives for terrestrial radiocommunication systems at frequencies above 10 GHz have recently been established by the CCIR as the maximum percentage of time in an average year during which an outage of the system is tolerated.

Rain attenuation is a major limitation to system availability and imposes a maximum value for the hop length in order to meet availability objectives. Given the availability objectives and the fading margin of the system, the evaluation of the maximum value of the hop length is possible if the yearly cumulative distributions of rain attenuation for various values of the path length are provided for the region where the system is to be installed at the frequency and polarization envisaged.

The possibility and advantages of estimating these distributions from rainfall intensity data appear well established at present.

Various prediction methods have been proposed to estimate rain attenuation distributions from (1) the distribution of point rainfall intensity for the region under consideration, (2) a relationship between specific attenuation and rainfall intensity, which depends on the microstructure of rainfall, and (3) a model for the spatial structure of rainfall intensity. If the rainfall microstructure and the spatial structure of rainfall intensity are assumed to be statistically the same in every region, then the distributions of rain attenuation (for a given frequency, polarization, and path length) will differ from one region to another only because the distributions of point rainfall intensity are different.

The hypothesis concerning the statistical constancy of the microstructure of rainfall seems to be appropriate to many regions. Consequently, values of the parameters for the relationship between specific attenuation and rainfall intensity for any frequency and polarization have recently been recommended by the CCIR. On the other hand, the choice of a particular statistical model for the spatial structure of rainfall intensity and its applicability to all regions are still controversial questions.

In order to be widely used, a prediction method should be easy to apply, preferably should have a physical significance, should give good agreement when tested with experimental results obtained in different regions, and should not be too critically dependent on the techniques used for obtaining the rainfall intensity data. From the results so far obtained, although some methods seem to give better results than others, no one method simultaneously satisfies all of the above conditions. Consequently, possible refinements in the proposed methods should be introduced, and a relative assessment among the various methods should be made on the basis of the considerable amount of experimental data which now exist for many regions. In this comparison the recommended values for the parameters of the relationship between specific attenuation and rain intensity should be used. Moreover, careful attention should be given to the experimental techniques used to obtain data on rainfall intensity.

With the above refinements it appears that establishing a suitable method to predict rain attenuation statistics from point rainfall intensity distributions is not beyond reach, and present CCIR activities are directed toward this aim. Once the applicability of this method is tested satisfactorily worldwide, the sensitivity of the method to various input parameters should be evaluated in order to derive confidence limits for the rain attenuation predictions.

In this regard, the possibility of identifying the various rain climatic regions and of characterizing each of them with a statistically stable cumulative distribution of rainfall intensity valid for all the locations in the region appears to be of the utmost importance. Although a number of rain climatic regions have been tentatively identified by the CCIR, data are still needed to obtain a sufficiently refined rain climatic characterization in many countries.

Frequency scaling appears to be a promising technique to derive rain attenuation statistics at higher frequencies if data at lower frequencies are available. Again, this possibility does not seem far from being well established. For this purpose a relative assessment of the different approaches which have been proposed should be made on the

basis of data presently available. In deriving information on the spatial structure of rainfall intensity from purely radio measurements the influence of the variability of the rainfall microstructure and, in particular, of the raindrop size distribution should be carefully considered.

Statistics of rain attenuation and rainfall intensity in the worst month, although no longer directly relevant to the design of terrestrial radiocommunication systems, are still needed for other services or in radiometeorological studies. The most suitable definition for practical applications and the expected range of variation for the ratio between average worst month and annual percentages now appear to be well established. The relationship between worst month and annual percentages appears to be similar both for point rainfall intensity and for rain attenuation at any frequency and polarization, and, with certain limitations, at any path length.

As far as present trends for the use of frequencies above 10 GHz in terrestrial systems are concerned, the situation appears to be the following.

Careful consideration is being given to the possibility of using the 11-GHz band for large-capacity long-haul digital radio relay systems utilizing existing facilities at lower frequencies and therefore hop lengths up to 50–60 km. In addition to the limitations imposed by rain attenuation in some regions, the influence of multipath fading should be carefully considered in all regions.

The 13-GHz band and, in some regions, the 15-GHz band are being presently considered for medium-capacity radio relay systems for use in regional and local areas.

The introduction on a wide scale of the 20-GHz band for long-haul large-capacity digital radio relay systems is not foreseen in the immediate future, especially because of the large number of repeaters which would be necessary in many regions. In this context the possibility of adopting switched path diversity has received considerable attention.

The 30-GHz band and, in some cases, the 60-GHz band have been suggested for large-capacity digital radio transmission media in junction networks in metropolitan and urban areas.

REFERENCES

Andreucci, F., F. Fedi, and P. G. Marchetti (1980), An analytical method to evaluate the effect of multipath fading on long-haul high-capacity digital radio-relay systems, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., Lennoxville, Que.

Barbaliscia, F., and F. Fedi (1980), Rainfall intensity, statistical properties and prediction techniques, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., Lennoxville, Que.

Barbaliscia, F., F. Fedi, D. Maggiori, and P. Migliorini (1980), Frequency scaling of rain induced attenuation at 11, 18 and 30 GHz, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., Lennoxville, Que.

Battesti, J., and L. Boithias (1978), Method for calculating rain attenuation on a microwave path, paper presented at 6th Colloquium on Microwave Communications, Sci. Soc. for Telecommun., Budapest.

Battesti, J., L. Boithias, and P. Misme (1971), Détermination de l'affaiblissement dû à la pluie pour les fréquences supérieures à 10 GHz, *Ann. Telecommun.*, *26*, 439–444.

Bertok, E., G. De Renzis, and G. Drufuca (1977), Estimate of attenuation due to rain at 11 GHz from raingauge data, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., La Baule, France.

Blomquist, A., and J. P. Norbury (1979), Attenuation due to rain on series, parallel and convergent terrestrial paths, *Alta Freq.*, *66*(4), 185–191.

Breuer, L. I., and R. K. Kreuels (1977), Rainfall drop spectra intensities and fine structures on different time bases, *Ann. Telecommun.*, *32*(11–12), 430–436.

Brussaard, G. (1979), Attenuation due to rain on a slant path, *Alta Freq.*, *66*(4), 210–215.

Brussaard, G., and P. A. Watson (1979), Annual and annual-worst month statistics of fading on earth-satellite paths at 11.5 GHz, *Electron. Lett.*, *14*(9), 278–280.

Bussey, H. E. (1950), Microwave attenuation statistics estimated from rainfall and water vapor statistics, *Proc. IEEE*, *38*, 781–785.

CCIR (1978*a*), Fixed service using radio-relay systems, *Rep. 378-3*, vol. 9, Recom. 556, 557, pp. 20–21, 43–44, 164, Geneva.

CCIR (1978*b*), Prediction of attenuation by rain, *Doc. 5/75*, Geneva.

CCIR (1978*c*), Estimation of attenuation by rain on a terrestrial path from rainfall rate data, *Doc. 5/87*, Geneva.

CCIR (1980), Conclusions of the interim meeting of study group 5, *Doc. 5/206*, Geneva.

Crane, R. K. (1971), Propagation phenomenon affecting satellite communication systems operating in the centimeter and millimeter wavelength bands, *Proc. IEEE*, *59*, 173–188.

Crane, R. K. (1975), Attenuation due to rain—A mini review, *IEEE Trans. Antennas Propag.*, *AP-23*, 750–752.

Crane, R. K. (1977), Prediction of the effects of rain on satellite communication systems, *Proc. IEEE*, *65*, 456–474.

Crane, R. K. (1980), Prediction of attenuation by rain, *IEEE Trans. Commun.*, *COM-28*, 1717–1733.

Crane, R. K., and D. W. Blood (1980), Application of the global rain attenuation model and deviation bounds in terrestrial and slant path prediction, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., Lennoxville, Que.

Crane, R. K., and W. E. Debrunner (1978), Worst-month statistics, *Electron. Lett.*, *14*(2), 38–40.

Damosso, E., G. De Renzis, F. Fedi, and P. Migliorini (1980), A systematic comparison of rain attenuation and prediction methods for terrestrial paths, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., Lennoxville, Que.

Debrunner, W. E. (1980), The prediction of rain attenuation

statistics, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., Lennoxville, Que.
Drufuca, G. (1974*a*), Rain attenuation statistics for frequencies above 10 GHz from radar observations, *J. Rech. Atmos.*, *8*(1-2), 413–420.
Drufuca, G. (1974*b*), Rain attenuation statistics for frequencies above 10 GHz from raingauge observations, *J. Rech. Atmos.*, *8*(1-2), 339-411.
Drufuca, G., and E. Torlaschi (1977), Rain outage performance of tandem and route diversity systems at 11 GHz, *Radio Sci.*, *12*, 63–74.
Drufuca, G., and I. Zawadzki (1975), Statistics of raingauge data, *J. Appl. Meteorol.*, *14*, 1419–1429.
Dutton, E. J., and H. T. Dougherty (1979), Year-to-year variability of rainfall for microwave applications in the USA, *IEEE Trans. Commun.*, *COM-27*, 829–832.
Fedi, F. (1979*a*), Rainfall characteristics across europe, *Alta Freq.*, *66*(4), 158-166.
Fedi, F. (1979*b*), Attenuation due to rain on a terrestrial path, *Alta Freq.*, *66*(4), 167–184.
Fedi, F., and P. Mandarini (1973), Analysis of the influence of the various parameters on the attenuation-rain rate relation, in *Modern Topics in Microwave Propagation and Air-Sea Interaction*, D. Reidel, Hingham, Mass.
Fedi, F., and P. Mandarini (1974), Influence of spacing and integration time of the raingauges on the attenuation rain rate relationship, *J. Rech. Atmos.*, *8*(1-2), 267–274.
Fedi, F., and U. Merlo (1977), Statistical data on point rainfall intensity for radio-relay systems, *Ann. Telecommun.*, *32*(11-12), 487–491.
Fedi, F., and B. Peroni (1974), The calculation of the hop length of digital radio-relay systems at frequencies above 19 GHz, *Alta Freq.*, *43*(9), 634–639.
Fedi, F., et al. (1974), Attenuation theory and measurements, *J. Rech. Atmos.*, *8*(1-2), 465–472.
Fedi, F., U. Merlo, and P. Migliorini (1977), Effect of rain structure on rain induced attenuation, *Ann. Telecommun.*, *32*(11-12), 459–464.
Ferguson, A., and R. R. Rogers (1978), Joint statistics of rain attenuation on terrestrial and earth-space propagation paths, *Radio Sci.*, *13*, 471–479.
Freeny, A. E., and J. D. Gabbe (1969), A statistical description of intense rainfall, *Bell Syst. Tech. J.*, *48*, 1789–1852.
Harden, B. N., J. R. Norbury, M. A. Tracey, and W. J. K. White (1978*a*), Attenuation ratios and path-diversity gains observed in rain on a network of short terrestrial links at frequencies near 11, 20 and 36 GHz, *IEE Conf. Publ.*, *169*.
Harden, B. N., J. I. Norbury, and W. J. K. White (1978*b*), Estimation of attenuation by rain on terrestrial radio links in the UK at frequencies from 10 to 100 GHz, *Microwaves Opt. Acoust.*, *2*(4), 97–104.
Harris, J. M., and G. Hyde (1977), Preliminary results of COMSTAR 19/29 GHz beacon measurements at Clarksburg, Maryland, *COMSAT Tech. Rev.*, *7*, 599–629.
Hodge, D. B. (1977), Frequency scaling on rain attenuation, *IEEE Trans. Antennas Propag.*, *AP-25*(3), 446–447.
Hogg, D. (1969), Statistics on attenuation of microwaves by intense rain, *Bell Syst. Tech. J.*, *48*, 2449–2962.
Hogg, D. (1973), Intensity and extent of rain on earth—Space paths, *Nature*, *43*, 337–338.
Kheirallah, H. N., B. Segal, and R. L. Olsen (1980*a*), Application of synthetic storm data to evaluate path average rain rate techniques for predicting rain attenuation statistics, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., Lennoxville, Que.
Kheirallah, H. N., J. P. Knight, R. L. Olsen, K. S. McCornick, and B. Segal (1980*b*), Frequency dependence of effective path length in the prediction of rain attenuation statistics, *Electron. Lett.*, *16*, 448–450.
Lee, W. C. Y. (1979), An approximate method for obtaining rain rate statistics for use in signal attenuation estimating, *IEEE Trans. Antennas Propag.*, *AP-27*, 407–413.
Lin, S. H. (1975), A method for calculating rain attenuation distribution on microwave paths, *Bell Syst. Tech. J.*, *54*, 5.
Lin, S. H. (1976), Rain rate distributions and extreme value statistics, *Bell Syst. Tech. J.*, *55*, 8.
Lin, S. H. (1977), Nationwide long-term rain statistics and empirical calculation of 11 GHz microwave rain attenuation, *Bell Syst. Tech. J.*, *56*, 1581-1604.
Lin, S. H. (1978), More on rain rate distributions and extreme value statistics, *Bell Syst. Tech. J.*, *57*, 5.
Lin, S. H. (1979), Empirical rain attenuation model for earth-satellite paths, *IEEE Trans. Commun.*, *COM-27*(5), 812–817.
Mawira, A. (1980), Statistics of rain rates, some worst month considerations, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., Lennoxville, Que.
Misme, P., and J. Fimbel (1975), Détermination théorique et expérimentale de l'affaiblissement par la pluie sur un trajet radioéléctrique, *Ann. Telecommun.*, *30*, 149–158.
Mogensen, G., and E. Stephansen (1978), An estimation of methods for prediction of rain induced attenuation on L.O.S. paths, *IEE Conf. Publ.*, *169*(2), 97–101.
Morita, K. (1978*a*), Study on rain rate distribution, *Rev. Electr. Commun. Lab.*, *26*(1-2), 268–277.
Morita, K. (1978*b*), A method for estimating year and worst-month rain rate distribution, *Trans. Inst. Electron. Commun. Eng. Jpn.*, *E61*, 8, 618–624.
Morita, K., and I. Higuti (1976), Prediction methods for rain attenuation distribution of micro and millimeter waves, *Rev. Electr. Commun. Lab.*, *54*(7-8), 651–668.
Morita, K., and I. Higuti (1978), Statistical studies on rain attenuation and site diversity effect on earth to satellite links in microwave and millimeter wavebands, *Trans. Inst. Electron. Commun. Eng. Jpn.*, *E61*, 425–432.
Muller, E. E. (1977), Long-term rain attenuation observations at 13, 19 and 28 GHz, *Eur. Space Agency Spec. Publ.*, *ESA SP-138*.
Ninomiya, Y. (1972), Data to speed over 20 GHz radio relay, *Electronics*, 81-85.
Norbury, J. R., and W. J. K. White (1973), Correlation between measurements of rainfall rate and microwave attenuation at 36 GHz, *IEE Conf. Publ.*, *98*.
Nowland, W. L., R. L. Olsen, and I. P. Shkarofsky (1977), Theoretical relationship between rain depolarisation and attenuation, *Electron. Lett.*, *13*, 676–678.
Olsen, R. L., D. V. Rogers, and D. B. Hodge (1978), The aR^b relation in the calculation of rain attenuation, *IEEE Trans. Antennas Propag.*, *AP-26*, 318–329.
Rice, P. L., and N. R. Holmberg (1973), Cumulative time statistics of surface-point rainfall rates, *IEEE Trans. Commun.*, *COM-21*, 1131-1136.
Rogers, R. R. (1976), Statistical rainstorm models: Their theoretical and physical foundations, *IEEE Trans. Antennas Propag.*, *AP-24*, 547–566.

Rue, O. (1980), Electromagnetic wave propagation at frequencies above 10 GHz, New formulas for attenuation in rain, *Telecommun. Radio Eng.*, Engl. Transl., *Part I*.
Segal, B. (1979), High-intensity rainfall statistics for Canada, *CRC Rep.*, *1329*.
Segal, B. (1980*a*), An examination of the worst-month precipitation attenuation criteria for radio system design, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., Lennoxville, Que.
Segal, B. (1980*b*), An analytical examination of mathematical models for the rainfall rate distribution function, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., Lennoxville, Que.
Segal, B. (1980*c*), A new procedure for the determination and classification of rainfall rate climatic zones, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., Lennoxville, Que.
Torlaschi, E., and I. Zawadzki (1980), Mesoscale thermodynamic variable as stratifier of microwave attenuation by rain, paper presented at URSI Commission F Symposium, Union Radio Sci. Int., Lennoxville, Que.
Waldteufel, P. (1973), Atténuation des ondes hyperfréquences par la pluie: Une mise au point, *Ann. Telecommun.*, *28*, 255–272.