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STATISTICS OF ATTENUATION DUE TO PRECIPITATION OF RADIO WAVES IN 12 GHz BAND AT HIGHER ANGLES OF ELEVATION

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by

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In continuation of the previous report[1] on a similar subject as above, this report describes several features of practical interest among the rainfall-attenuation characteristics at higher angles of elevation on the basis of a collective analysis of all basic data, at three different sites, of measurements performed so far. Statistics of rainfall-attenuation characteristics at these sites are presented numerically. In the light of the results thus obtained from the collective analysis, an approach is proposed to the derivation of a practical generalised prediction method for the characteristic in question at a given site.

1. INTRODUCTION

In response to a keen need for propagation information to assist in the establishment of design criteria for satellite to ground telecommunication links and broadcasting networks, studies on the above subject have been conducted since 1967 and are still being continued at the Laboratories.

As a means of collecting the basic data required to meet this need, parallel measurements of solar and sky noise at 12 GHz and instantaneous rainfall rate at a site near to the receiver (radiometer) have been brought to operation since June 1967 at the Laboratories. In addition, basic data of the same type for the years during 1965 through 1969, which had been collected at the Toyokawa Research Institute of Atmospherics,

Nagoya University, were used in an analysis for the present purpose. An interim report[1] was published on the basis of the analysis of the data collected up to the end of 1968.

In view of the nature of propagation aspects related to satellite telecommunication and broadcasting links, world-wide interest has been concentrated on the above subject and related studies have come to be conducted in many countries, especially in recent years. The sources of measurement data contributing to the practical objective, however, are confined as yet to countries in the Temperate Zone, although data from as widely different areas as possible are needed to discuss the problem on a global scale.

To compensate for such shortcomings entirely the same type of measurements as those made at the Laboratories were conducted in Malaysia during the period from late October 1970 through the end of October 1972 as a joint cooperative project by NHK and Radio & Television Malaysia (RTM) to collect basic data serving the present purpose from a representative site in the Tropical Zone.

On the basis of a continued analysis of all data referred to above, several interim reports including (1) describing summarised results have been published at proper opportunities[2].

This paper describes the summarised results of attenuation statistics related to surface rainfall-rate on the basis of the measurement data collected so far, and proposes an approach to the establishment of a generalised prediction method for the rainfall-attenuation characteristics.

2. OUTLINE OF MEASUREMENTS

Since the same type of equipment has been used throughout for measurements and the function and principle of measurement are described in the Ref. (1) in details, a repetition of these descriptions is omitted, but a list of fundamental parameters pertinent to the measurements is tabulated to provide information concerning the measurements in Malaysia, in particular, which were conducted after the previous report[1] was published:

The measuring equipment which had been used in Malaysia was installed at a place near to that used at NHK Labs. at the beginning of this year, and since then the two sets of equipment have been operated in parallel but in different ways for collecting basic data such as for different directions of sky-paths, etc.

Table 2.1 Parameters pertinent to measurements

Parameter \ Site Location	Toyokawa[1] RIA	Tokyo NHK	Klang, Malaysia RTM
	137.4°E 34.8°N	139.6°E 35.6°N	101.4°E 3.1°N
Height[2]	10 m	40. m[3]	5 m
Receiving aerial	Horn-feeding parabolic reflector with an aper- diameter of		
Diameter	1.2 m	1.0 m	1.5 m
Half-beam-width	2.0°	1.5°	1.3°
Frequency	9.4 GHz	11.8 GHz	11.8 GHz
Rainfall gauge	One-minute gauge (instantaneous rainfall-rate gauge) and tipping bucket type gauge run in parallel		

Remarks : (1) Measurements of solar signals at 9.4GHz and at other three fre-
quencies have been conducted since 1956 for a study of solar
physics.
(2) Height of ground above sea level.
(3) The receiving aerial is installed above the roof of the Labs.
building, and 20m high above ground level.

3. RESULTS OF MEASUREMENTS

3.1 General Trend of Rainfall Characteristics

In Malaysia

Roughly speaking, the rainfall pattern at the site of measurements during
the two years has followed that described in the meteorological literature[3].
Some aspect of variation in amount of monthly rainfall throughout the two
years is illustrated in Fig.1. A comparison between Fig.1(a) and Fig.1(b)
shows that the amount of monthly rainfall becomes a reasonable measure for
that of heavy rainfalls during the month.

Entering into more detail, with particular consideration for a correlation
with the attenuation characteristics to be developed on the basis thereof,
the following pronounced features were noticed in the rainfall pattern :

1) Heavy rainfalls were encountered frequently during the day-time hours
for the months October through December, and during the night-time hours
for the months late July through September 1971.*

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* An unusually long spell of rainfall which was experienced in the Kuala
Lumpur area in January 1971 is not included in Fig.1.

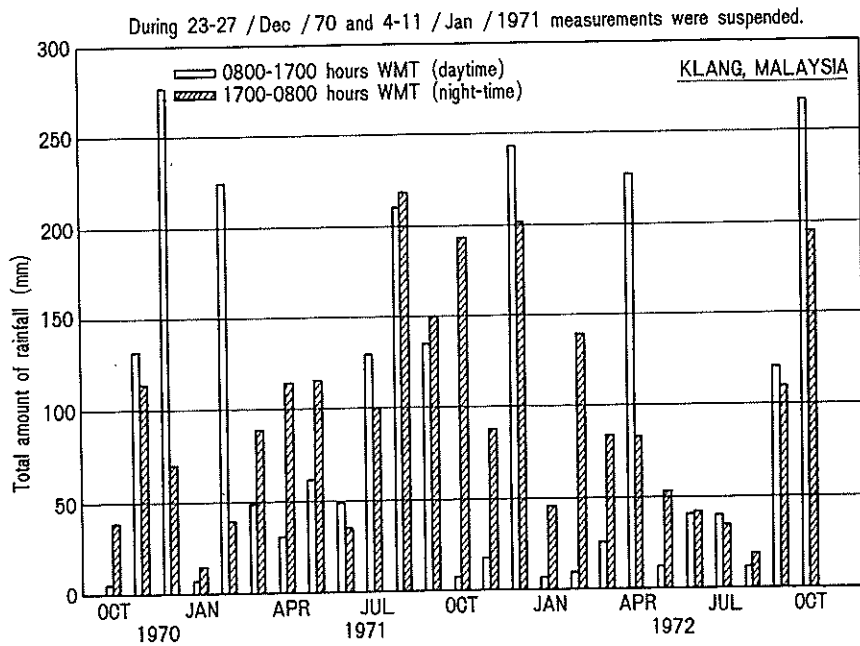During 23-27 / Dec / 70 and 4-11 / Jan / 1971 measurements were suspended.

Fig. 1(a) Total amount of monthly rainfall.
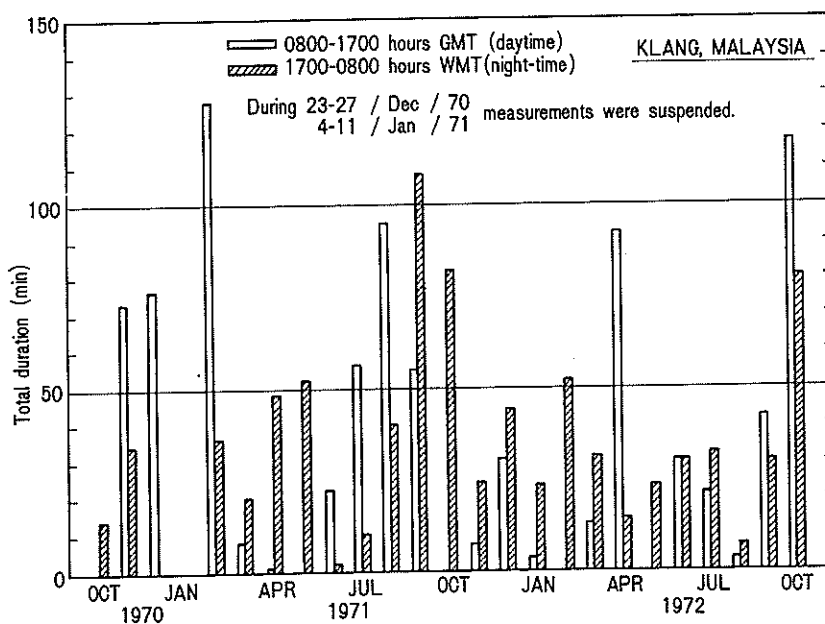(Seasonal variation of surface rainfall at the site of measurements)

Fig. 1(b) Total length of duration of monthly rainfall
with a rate of rainfall exceeding 40 mm/hr.
(Seasonal variation of surface rainfall at the site of measurements)

2) Throughout the period, the majority of the rainfall during the day-time
were characterised by higher rates of rainfall but comparatively shorter
durations (squall type), say about 20 minutes or less with a rainfall-
rate amounting to 100 mm/hr or more during the major part of a rainfall,

and with a rather regular occurrence during the mid to late afternoon hours.

3) During the months except those mentioned in 1), several types of rain-fall were encountered. The majority of the rainfall during the night-time hours with higher rates of rainfall were characterised by a less frequent occurrence but a longer duration than those during the day-time hours, say 40 minutes or more with a rainfall-rate of 70 mm/hr or more, occasionally amounting to 100 mm/hr or more, and the occurrence of rainfall mainly centred on early evening and early morning hours.

4) Among the several types of rainfall referred to in 3) are included the following: a single rainfall which lasted about two hours near midnight (0226-0410 WMT*) on 16 May 1971 and during which the total amount of rainfall reached about 90mm with a rate of rainfall exceeding 40 mm/hr for the most of the period; and another single rainfall which lasted about three hours (0440-0750 on 16 July 1971), the total amount of rain-fall reaching only 3 mm with a maximum rainfall-rate of 5 mm/hr.

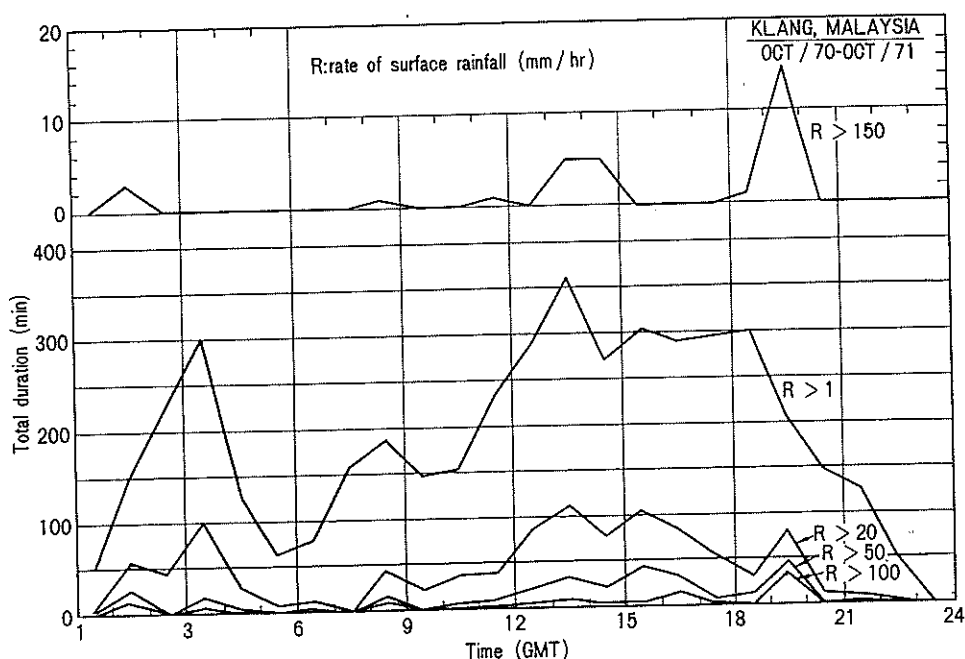Some of the above-mentioned aspects are reflected in Fig.2(a).

Fig. 2(a)   Total length of duration of surface rainfall with a rate of rainfall exceeding several specified values.
(Diurnal variation of surface rainfall at the site of measurements)

* Western Malaysian Time (GMT plus 7.5 hours)

In Tokyo

Various types of rainfall referred to meteorological aspects, rate of rainfall, duration and so forth, are encountered in Tokyo (and over a greater part of Japan).

On the average, the occurrence of rainfall in Tokyo is frequent during the months June through mid-July and mid-September through October. The amount of yearly rainfall is almost occupied by the rainfall during these periods. But, heavy rainfalls, say with a rate of rainfall of 30 mm/hr, are encountered during the period late July through September with the most frequent occurrence in September. The duration of an individual heavy rainfall specified above, for the most part remains within 8 minutes, amounting to about half an hour once or twice per year. A greater part of heavy rainfalls occur during early evening hours.

The most extreme case of rainfall that has been experienced since the measurements were commenced at the Labs. is a thunderstorm with a rate of rainfall exceeding 30 mm/hr for 15 minutes and during which 100 mm/hr was exceeded for 4 minutes (September 1968). Fig.2(b) is shown in entirely the same fashion as Fig.2(a) as an example of diurnal variation accumulated over one year of surface rainfall in Tokyo.
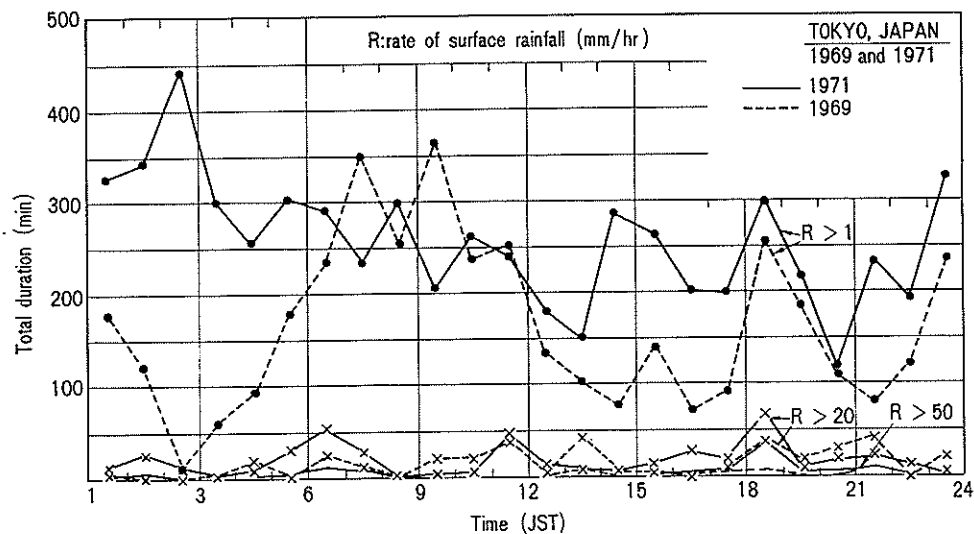

Fig. 2(b)   Total length of duration of surface rainfall with a rate
      of rainfall exceeding several specified values.
(Diurnal variation of surface rainfall at the site of measurements)

Since Morita[4] has conducted a thorough survey of rainfall aspects and statistics all over Japan, further detailed information on the matter

is referred to in (4).

   In Appendix 1 are shown graphically some examples of numerical statistics
of rainfall — number of occurrences as a function of duration for a range of
rainfall-rate exceeding a specified value — at the three sites of measurements.

3.2 Typical Examples of Parallelism of Heavy Rainfall and Attenuation

   Figs.3(a) through (d) show typical examples of parallelism of heavy
rainfall and attenuation at the three sites of measurements.

Fig.3(a)

   This result was obtained from the measurement made during the indicated
time interval during which a cold frontal type of rain (cell) traversed
the site of measurements. It is seen, especially when compared with
the examples (b) and (c), that the traces of rainfall and attenuation
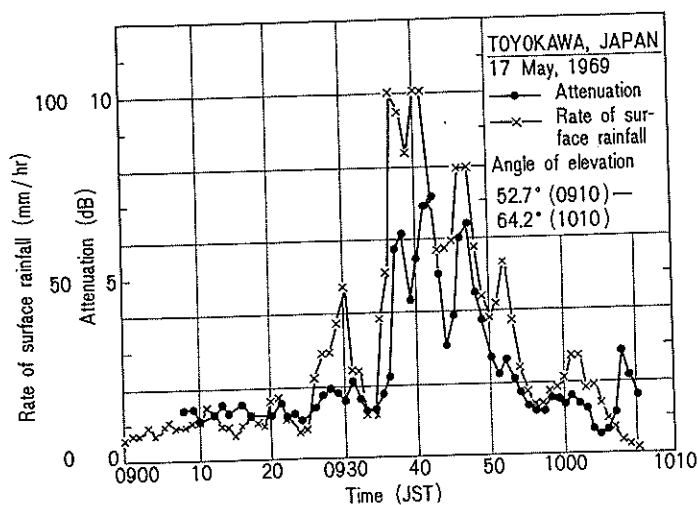are running reasonably in phase.

Fig. 3(a) Parallel observations of surface rainfall
           and attenuation during a heavy rainfall.

Fig.3(b)

   In this case a squall type of rain traversed the site of measurement.
As is shown in the figure, there is a difference in time of commencement
between rainfall and attenuation and a lack of similarity between the
variation pattern of the two parameters. Such a tendency is very usual,
and is attributed to a non-uniformity of rainfall with respect to time
and space and the location of the radio-path concerned. From a comparison
of the traces of the two parameters with reference to information of the

radiometeorological analysis of rain (such as (5)), it may safely be con-
cluded that, in this example, a very limited size of rain cell traversed
a portion of the radio path along a direction more or less opposite to
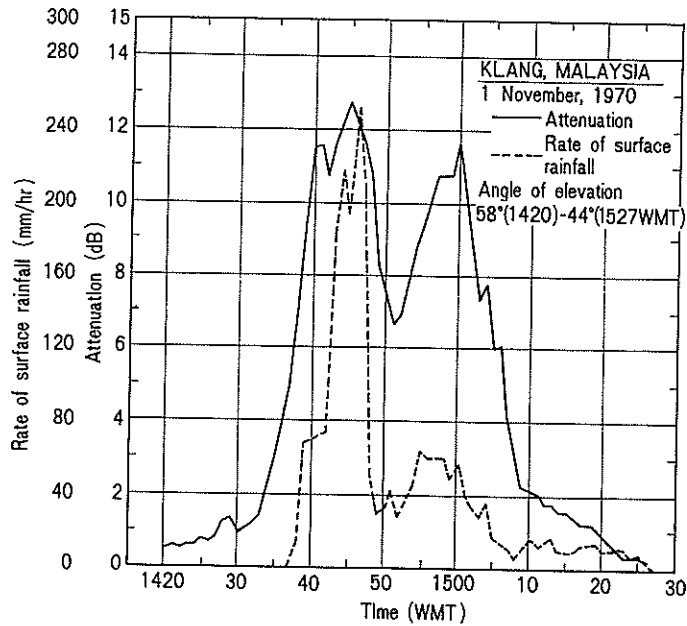the path.

Fig. 3(b) Parallel observations of surface rainfall
and attenuation during a heavy rainfall.

Fig.3(c)

This gives a very interesting result. The result was obtained from a
parallel operation of two radiometers*, of which one (A) was tracking
the sun and the other (B) was pointed along a fixed direction as
indicated. As is clearly noticed from the figure, the variation
pattern of the two parameters shows a reasonable similarity for B,
but no similarity at all for A. The rainfall in this case was of a
thunderstorm type accompanied by a cold front, and from a similar
consideration as in the previous case it is concluded that a rain cell
which belonged to an extensive rainfall region traversed the radio-
path at a portion markedly distant from the receiving site.
The above result produces evidence that a rain cell is considerably
limited in size as has been discussed recently by US workers[5].

Fig.3(d)

The figure shows an example obtained from measurements made at night.
The two radiometers were naturally pointed along a fixed direction.

* Refer to the statement made in the last paragraph of Section 2.

The rainfall in this case was of a thunderstorm type accompanied by a Baiu front. It is evident from the direction of the radio-path (at a very high angle of elevation) that a rain cell traversed the radio-path for a short time interval.
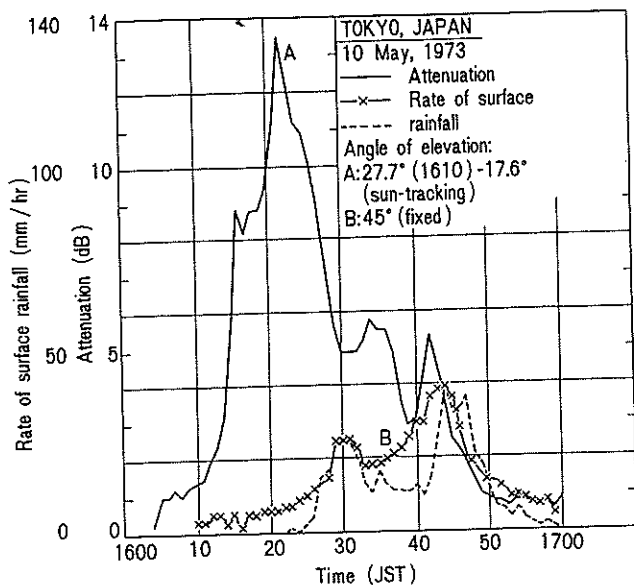

Fig. 3(c) Parallel observations of surface rainfall and attenuation during a heavy rainfall.
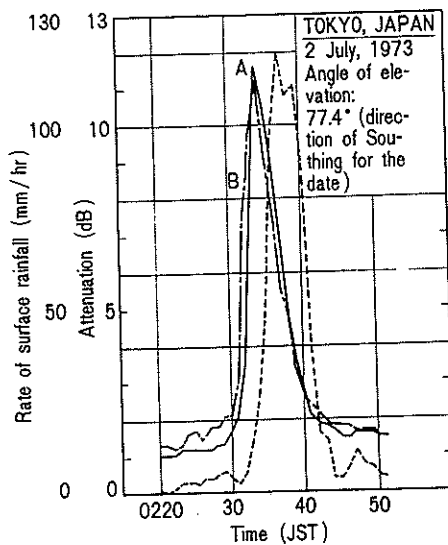

Fig. 3(d) Parallel observations of surface rainfall and attenuation during a heavy rainfall.

3.3 Typical Examples of Frequency Distribution of Rainfall and Attenuation

The general trend of rainfall patterns as has been described in 3.1 was well reflected in that of the attenuation at the respective sites. To visualise this aspect and for practical application, several typical examples of frequency distribution of rainfall and attenuation at 11.8 GHz are summarised in Fig.4, in which the values of attenuation have been computed for a converted angle of elevation of 45°. This conversion is based on the assumption that the region of precipitation is uniform (at a rate of surface rainfall measured) and concentric with the earth's surface. A detailed description on the "conversion" is referred to in 3.4.1.

In Malaysia, so far as the "rainy season" (October through December) is concerned, most of the values of the aforesaid conversion factor are close to unity, since the occurrence of heavy rainfalls during the season was mainly concentrated in the mid to late afternoon hours during which the angles of elevation did not differ greatly from 45°, as may be understood

from Fig.3(b) (also refer to 3.1 1)).

3.4 Statistics of Rainfall-Attenuation Characteristics

In 3.2 and 3.3 have been presented the merely numerical results for several specified time intervals and years, individually, although the presentation in Fig.4(b) is based on the result of an analysis to be developed in the following.
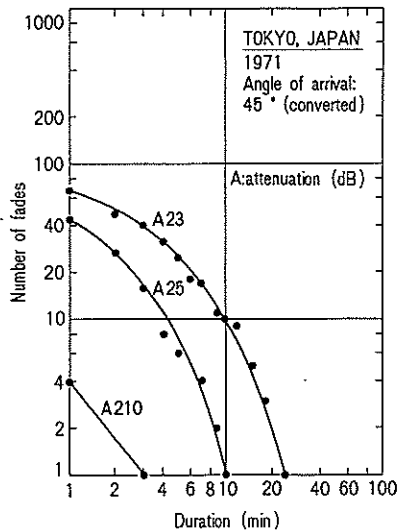

Fig. 4(a) Number of occurrence
vs. duration of attenuation
exceeding a specified level
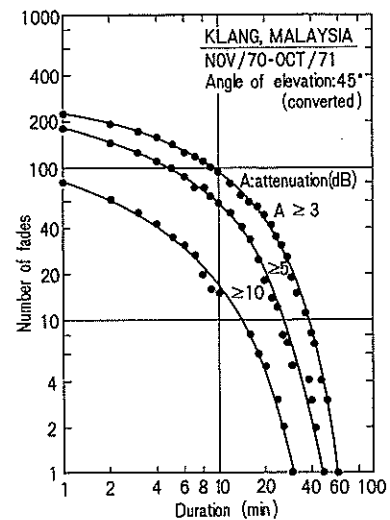of the radio waves at 12GHz.

Fig. 4(b) Number of occurrence
vs. duration of attenuation
exceeding a specified level
of the radio waves at 12GHz.

3.4.1 Angle dependence of attenuation

Since the basic data on radio signals during daytime hours are obtained by sun-tracking measurement, the angle of elevation of a radio-path at any receiving site changes from time to time. Therefore, the heading subject was analysed in the following manner.

1) The angle of elevation of a radio-path was computed for the full period of hours of a day, during which sun-tracking measurements were made.

2) The range of angles of elevation thus worked out were divided into several intervals as is seen in Fig.5.

3) The basic data on rainfall and attenuation, which were obtained during the respective intervals mentioned in 2), were selected.

4) A cumulative distribution was derived for the rainfall (with a rate of rainfall R mm/hr) and attenuation (A dB), respectively.

5) At a same value of per centage of time of the cumulative distribution of the two parameters, a pair of values of R and A were read out from the curves made by the procedure in 4).

Fig.5 has been made by following the above procedures; i,e., the values of A are plotted against the angle of elevation for a specified value of R.

Fig.5(a) shows an example obtained from measurements at the Labs. in 1971. In this and other like figures the scatter plot of A against angle of elevation is made in such a way that the best fit curve obtained therefrom passes through the point A_{rel}=1 at an angle of elevation of 45°. Namely the values of attenuation are _normalised_ to those at an angle of 45°.

It may be noticed from the figure that a general trend of the A_{rel}- ϕ curves is represented by the cosec-curve* for a range of angles greater than about 15°. Figures corresponding to Fig.5(a) for another year at the Labs. and at the other sites of measurement are given in Appendix 2. A similar trend to the above-mentioned one concerning the A_{rel}- ϕ characteristic is noticed in the figures given in Appendix 2. But, in Malaysia, the range of angles of elevation over which a cosecant approximation can be applied is limited to $\phi \gtrsim 30^\circ$ approximately for higher rates of rainfall, say exceeding about 20 mm/hr.

Allowing for such a similarity between the A_{rel}- ϕ curves, Fig.5(b) summarises the characteristic of angle dependence of attenuation for the respective sites of measurement and for a specified year, each by a single zigzag curve. Each plot of the values of a pair of A_{rel} and ϕ represents the average of the values of A_{rel} at ϕ for several values of R as are plotted in Fig.5(a).

At any site of measurements, scarcity of basic data for cases of rain- falls heavier than those indicated in the respective figure makes it pro- hibitive to draw the corresponding A_{rel}- ϕ curves. The aforesaid "scaricity" of course originates from a very infrequent occurrence of the heavier rain- falls in question. In addition, a possible considerable difference in occur- rence from year to year of very high rates of rainfall should be accounted for separately.

The _effective distance_, a parameter which was introduced in (1) and is repeated in more detail in Appendix 3 for ready reference, is derived from

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* Cosec-curve represents the characteristic of angle dependence for an ideal case in which a rainfall is uniform with respect to intensity and with height above the earth's surface of the rainy region.
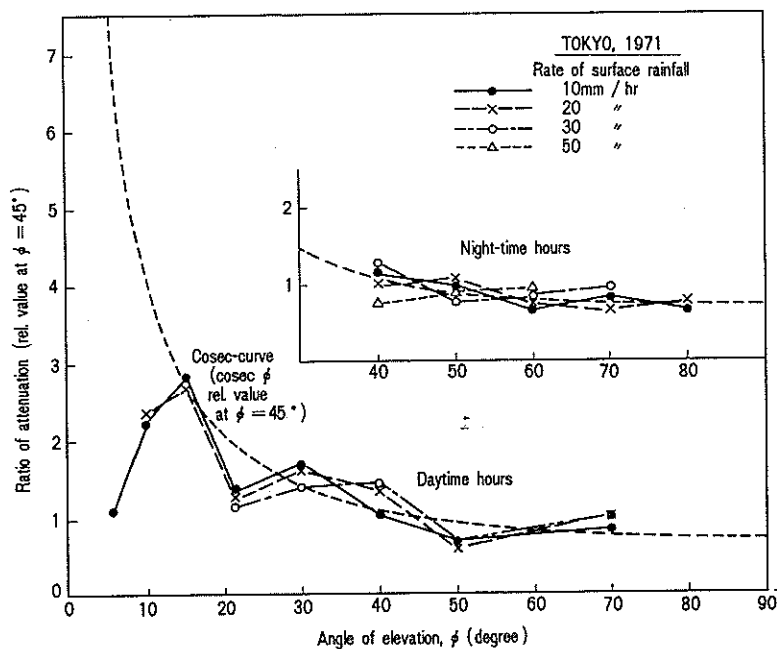
Fig. 5(a) Scatter plot of relative values of
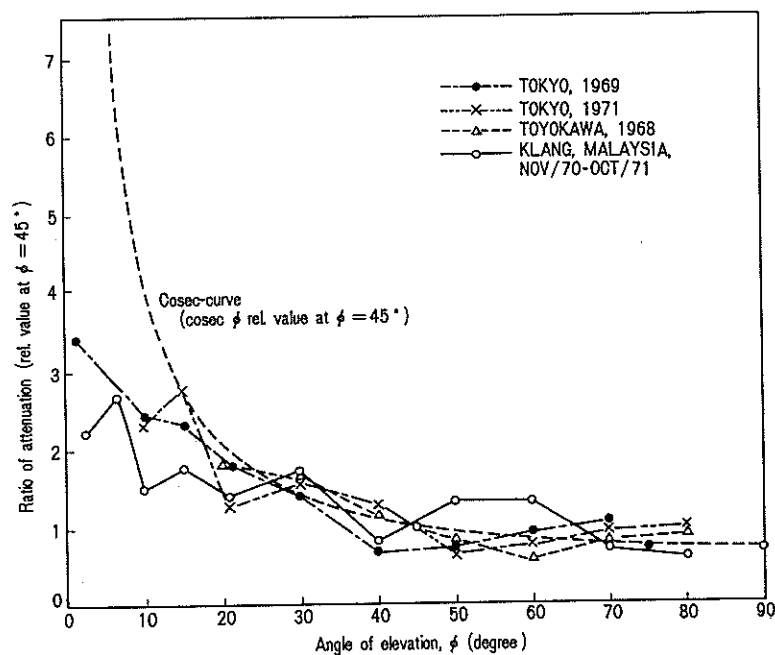attenuation against angle of elevation.

Fig. 5(b) Scatter plot of relative values of attenuation
against angle of elevation. (Yearly average)

the results of angle dependence such as are given in Figs. 5 and A2. Of
course, a reference value of attenuation at an angle of elevation of $45°$ is
needed, and the scatter plots for a respectively specified range of rates

of rainfall and the scatter plots of effective distance derived therefrom
should ultimately be represented by a best fit curve, especially for practical
purposes. However, since the following subject 3.4.2 is closely related to
the present subject of angle dependence and the same conclusion concerning
the effective distance ensues from the result in either section, a discussion
on the matter is deferred to 3.4.3.

3.4.2 Yearly cumulative distribution of rate of surface rainfall and attenuation

The cumulative distribution of the two parameters : rate of surface
rainfall and attenuation for an individual one-year-period was derived by
a) extending the procedures itemised in 3.4.1 and b) using the results
summarised in Fig.5(b). That is, (numbering is continued from that in the
previous section)

6) The angle dependence of attenuation, which was originally given by a
scatter plot for a specified one year period, was represented by a best fit
curve.

7) The magnitude of attenuation (dB) of each sample falling in a specified
interval of angle of elevation, each sample being classified by the pro-
cedures 1) through 3), was modified (multiplied) by the factor which is
read out from the best fit curve obtained by procedure 6) at the angle in
question. In other words, the magnitude of attenuation of each sample was
converted to that at an angle of elevation of 45 degrees.

8) An ensemble was thus made from the above converted samples for a specified
year.

9) At the same time an ensemble was made from the samples of instantaneous
(1-min) rate of surface rainfall for the same one year.

10) Finally a statistical result on the rainfall-attenuation characteristic
was represented in a form of culmulative distribution of the two parameters
concerned.

Fig.6 shows the results obtained by the above procedures for the three sites
of measurements and for different years[*].

It may be worth emphasising that, in deriving the results in Fig.6,
the conversion of the magnitude of attenuation to that at an angle of
elevation of 45° is based on the result of analysis of measurement data

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[*] The same type of figures as in Fig.6 are presented in (1) and elsewhere.
But, in the previous cases, the cosec-approximation was employed a priori
with neither theoretical nor experimental evidence.
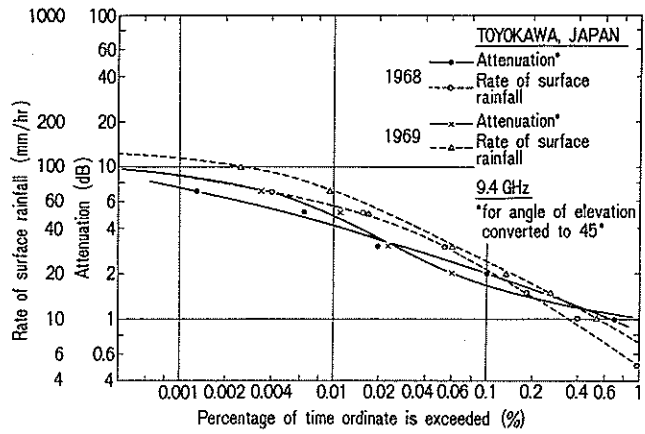
Fig. 6(a) Yearly cumulative distribution of rate of surface
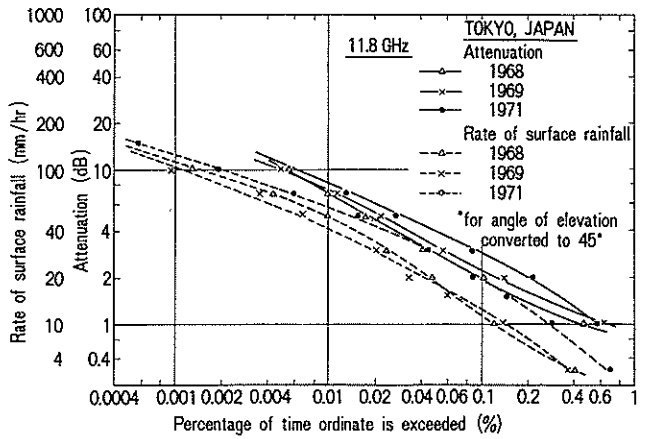   rainfall and attenuation of radio waves at 9.4 GHz.

Fig. 6(b) Yearly cumulative distribution of rate of surface
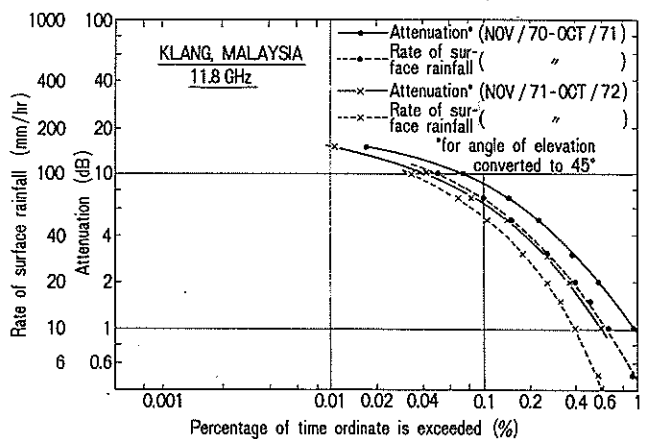   rainfall and attenuation of radio waves at 11.8 GHz.

Fig. 6(c) Yearly cumulative distribution of rate of surface
        rainfall and attenuation of radio waves at 11.8 GHz.

but not merely on the so-called cosec-approximation", although each of the
empirically and heuristically derived conversion curves and the cosec-curve
are similar to one another at higher angles of elevation as have been stated
in the previous section.

3.4.3 Effective distance of rainfall region

As has been stated in 3.4.1, the effective distance is derived from
whichever result is reached by the analysis in 3.4.1 or by the one in 3.4.2,
which itself has been developed in continuation of the analysis in 3.4.1.
In deriving the effective distance, the attenuation coefficient for a uniform
rainfall has been referred to published literatures (ref. Appendix 3).
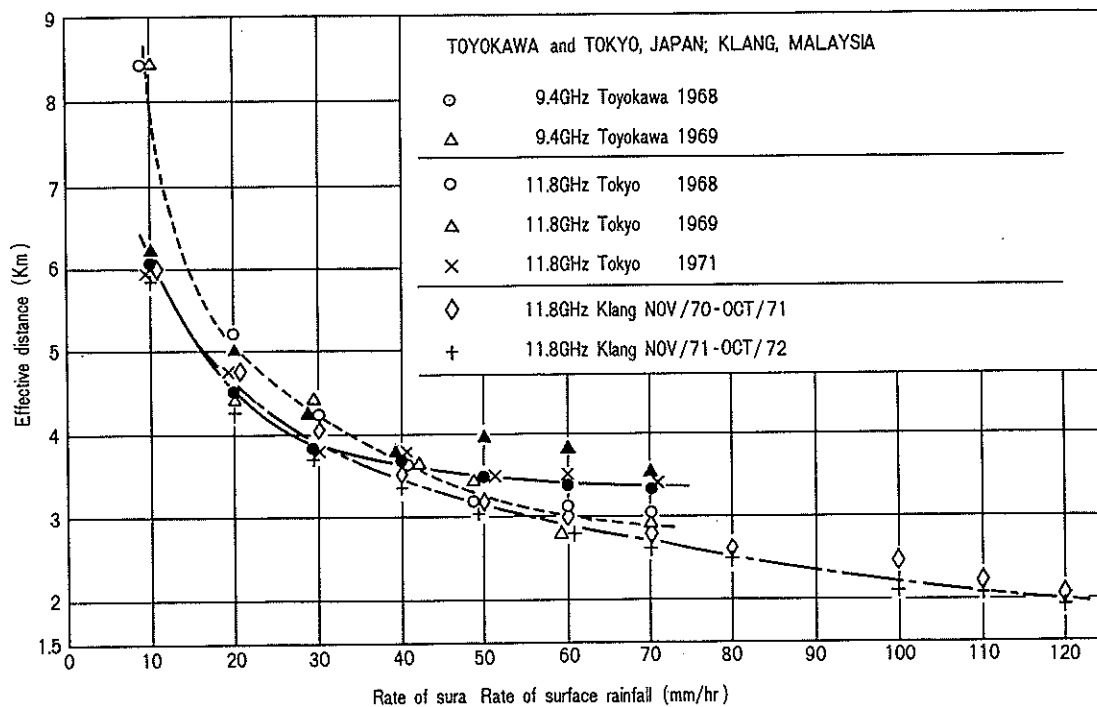
The result is summarised collectively in Fig.7.

Fig. 7 Effective distance for attenuation vs. angle
of elevation at an angle of elevation of 45°.

This figure shows that,

1) The relationship between effective distance and rate of surface rainfall, with a rate exceeding a specified level, can be represented by a single curve at a given site to a sufficient to reasonable degree of approximation, although the yearly cumulative distribution of rate of surface rainfall and consequently that of attenuation may vary from year to year and/or site to site as are illustrated in Figs.6(a) through (b).

2) There appears a general tendency that the effective distance increases/ decreases with a decrease/increase in the rate of surface rainfall, the gradient of an increase being markedly enhanced compared with that of a decrease, especially at lower rates of rainfall, say less than about 20 mm/hr or less.

3) Even at the same frequency of 11.8GHz, the effective distance in Malaysia decreases progressively with an increase in rainfall-rate at a steeper gradient than that at Tokyo.

4) A quite marked difference is noticed between the characteristic of effective distance vs. rainfall rate at Toyokawa (9.4 GHz) and that at Tokyo (11.8 GHz), although the two sites are separated by approximately only 230 km and are located on the side facing the Pacific Ocean (ref. Table/2.1).

The tendency that has been pointed out in 2) may be attributed to the difference in the character of a rainfall. As is well known, a region of rainfall with a very low rainfall-rate is usaully extended over a very wide area. On the contrary, that with a very high rainfall-rate, or rainfall of a convective type such as a squall or thunderstorm rain, etc., is extremely limited[5]. The aspect stated in 3) may also be attributed to the same reasoning as above, since the area in which the site of measurements was located is subject to frequent rainfalls of the squall type.

But a further discussion on the matter in association with meteorological aspects is beyond the scope of this report.

The marked difference that has been stated in 4) may be attributed to the fact that, in this report and also in the previous report[1], the "attenuation" includes that due to the factors other than rainfall, such as elevated precipitations of various kinds : rainy cloud, cloud, fog, etc., and the magnitudes of attenuation due to rainfall are less than those at 11.8 GHz, say a little less than half (in dB unit) of the latter over the whole range of rainfall intensities considered at present. If a division of an amount of attenuation

between rainfall and the other kinds of precipitaions is detected rigorously, more light it is believed will be brought to bear on the matter. Of course, the problem of this division should also be applied to the cases of 11.8 GHz to discuss the matter on a unified basis. At any rate, Fig.7 shows just a practical result, and a further information in this regard is reserved until a succeeding report is published.

The result given plays the role of offering a very useful means for deriving a practical generalised prediction method for the rainfall-attenuation characteristic at higher angles of elevation. This subject is discussed in the following section.

3.4.4 An approach to the derivation of the generalised prediction method for rainfall-attenuation characteristic

From the above results, which have been reached on the basis of an analysis of the basic data of measurements performed at different sites over a prolonged period, it may safely be concluded that an approach is suggested to the derivation of a generalised prediction method for the rainfall-attenuation characteristic at a given site.

That is, as is evident from the previous discussions, the characteristic can be predicted if the following basic information is provided : yearly cumulative distribution of instantaneous rate of surface rainfall at a given frequency, such as that in Fig.6, and the effective distance as a function of rate of surface rainfall, such as Fig.7, for the respective climatic region over which the statistically same or very similar rainfall pattern prevails. The magnitude of attenuation for a specified percentage of time is computed as a product of the attenuation coefficient (readily available from published literatures) and the effective distance at the rate of (hypothetical) uniform rainfall for the same percentage of time, respectively.

Provided that the aforesaid basic information for the climatic region including a given site is available yet only the basic information on rainfall is available at the site, a highly approximated prediction can be made by a combined use of the characteristic of effective distance versus rate of surface rainfall to be applied to the region, and the cumulative distribution of instantaneous rate of surface rainfall collected at the site.

Even in the absence of rainfall data, collection of the data can be made easily. In addition, works of several specialists including Morita[4] have made it possible to estimate the distribution of an instantaneous rate of rainfall from a 10-min rate of rainfall. The estimation method developed

by Morita is based on the concept of space-correlation of rainfall. These estimation methods facilitate an efficient and quick derivation of the rainfall statistics required for a site concerned.

4. CONCLUSION AND ACKNOWLEDGEMENT

On the basis of a collective analysis of all data on measurements performed so far, this report has made clear several features, which are closely associated with practical purposes, of the rainfall-attenuation characteristic at higher angles of elevation, mainly at 11.8 GHz and partly at 9.4 GHz.

The statistics for the rainfall-attenuation characteristic at the sites of measurement have been derived, and in the light of the results obtained from the present analysis an approach has been proposed for the derivation of a generalised prediction method from a practical standpoint for the rainfall-attenuation characteristic.

The authors would like to take this opportunity to express their hearty gratitude to Mr. T. Nomura, Chairman of Research and Development Committee of NHK, who had advocated conducting measurements in a Tropical Zone to collect basic data relevant to the present subject literally for the first time therefrom, to Mr. Dol Ramli, Director-General, Department of Broadcasting, Ministry of Information and Culture, Malaysia, who accepted the conducting of measurements at the Central Monitoring Station of Radio and Television Malaysia (Radio Telivishen Malaysia), Klang, Selangor, in reponse to a proposal from NHK for an execution of measurements, under a "joint cooperative project of NHK and RTM", and helped and encouraged all those involved in the way of conducting the full two years' measurements smoothly. The authors' thanks also are dedicated to many of his staff. In particular, the authors would like to express their hearty gratitude to Mr. Thoo Kim Lan, Engineer-in-Charge, who coordinated the project throughout the period of measurements for a smooth progress in each piece of work involved, to Mr. Marcus N. Sundram, Technical Assistant-in-Charge, Monitoring Station, Mr. Teoh Yan Sing, Technical Assistant-in-Charge, who succeeded to Mr. Marcus in April 1971, and their juniors of the Technical Group of the Monitoring Station, who maintained a satisfactory operation of the equipment, collected the data and worked hard in handling the various tasks involved throughout the period of measurements.

REFERENCES

(1) Kinase, A. and Kinpara, A.: Statistics of Attenuation due to Precipitation of Radio Waves in 10 GHz Band at Higher Angles of Elevation, NHK Laboratories Note, No.130, August 1969.

(2) Kinase, A. and Kinpara, A.: Statistics of Attenuation due to Precipitation of Radio Waves in the 12 GHz Band at Higher Angles of Elevation in a Tropical Zone, (in Japanese) Rep. AP Res. Commit., Elec. and Com. Eng. of Japan, 23 March 1972.
" " " " (in English version) submitted to Interim Meeting of SG 5, CCIR, Geneva 1972.

(3) "Meteorological Service Malaysia" Summary of Observations for Malays, Sabah and Sarawak (yearly issue).

(4) Morita, K. and Higuti, I.: Statistical Studies on Electromagnetic Wave Attenuation due to Rain, Review of the Electrical Communication Labs., Vol. 19, No.1, January 1970; Vol.19, Nos.7-8, JULY-AUGUST, 1971 (English version).

(5) C.C.I.R. Report AB/5, Radioclimatological Data, Conclusions of the Interim Meeting of Study Group 5, Geneva, April 1972.

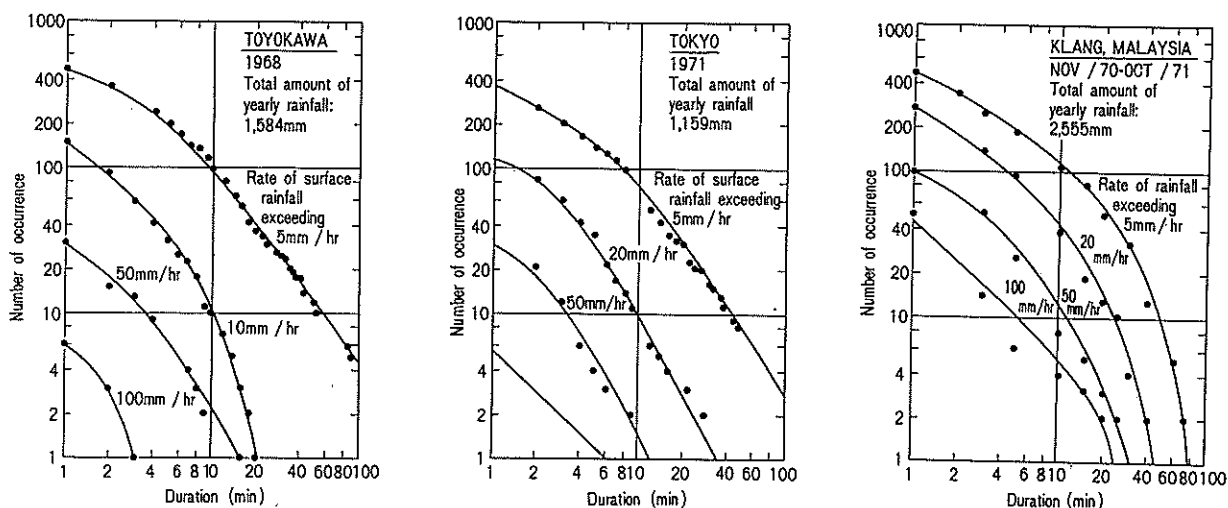## Appendix 1   Examples of Rainfall Statistics, Supplement to 3.3

Fig. A1   Number of occurrence vs. duration of surface rainfall with a rate of rainfall exceeding a specified level.
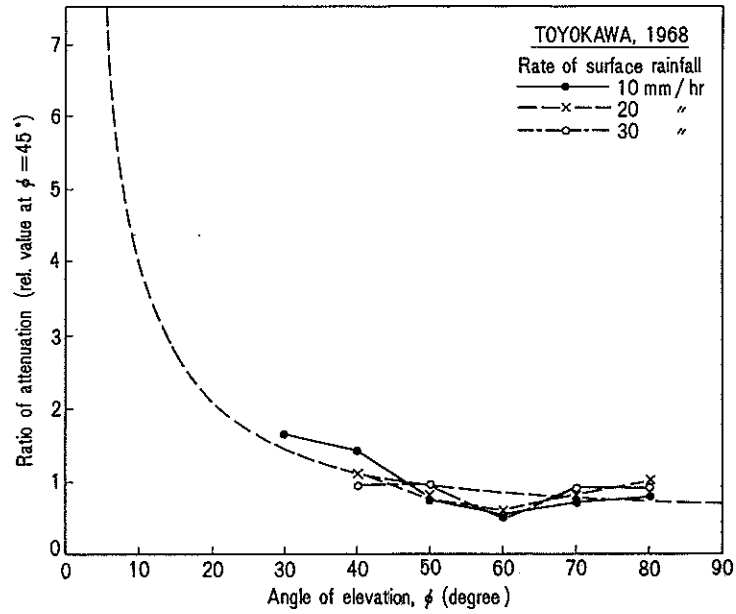
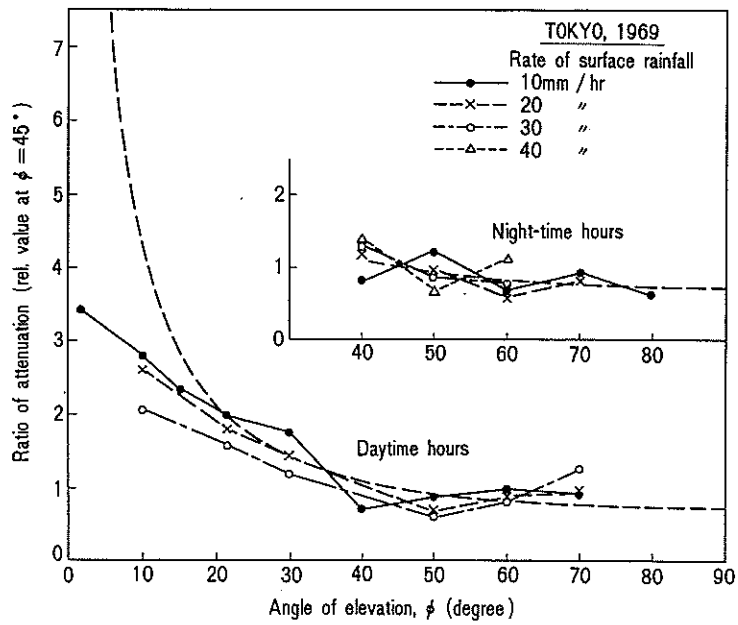Fig. A2(a)   Scatter plot of relative values of attenuation against angle of elevation.

Fig. A2(b)   Scatter plot of relative values of attenuation against angle of elevation.
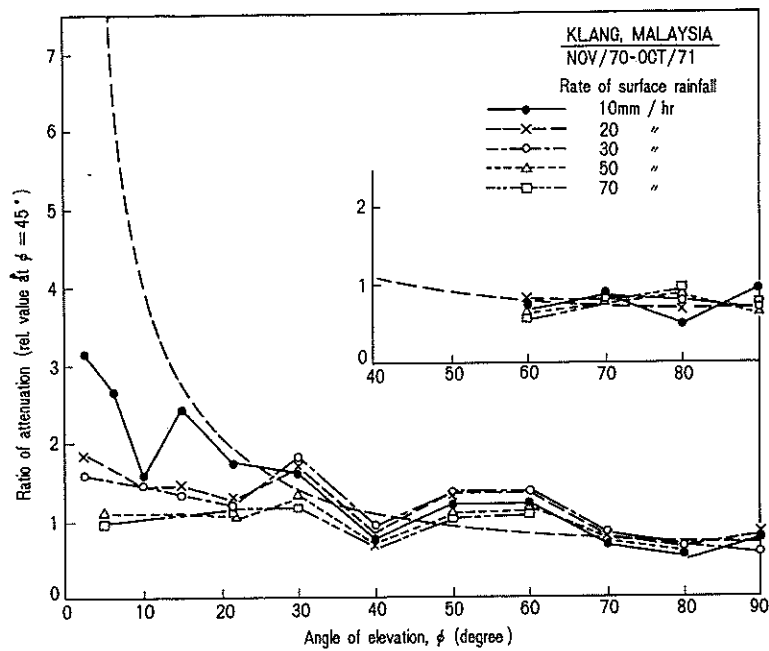
Fig. A2(c) Scatter plot of relative values of attenuation
against angle of elevation.

Appendix 3 Effective Distance

The term effective distance originates from the following equation :

$$A_P = \gamma_{so}\, r_{eo} \qquad\qquad \cdots (A3.1)$$

where A_p = attenuation (in dB) for a specified percentage (p %) of time over a period of one year;

γ_{so} = attenuation coefficient (in dB/km) for the rainfall as determined at the earth's surface at a rate exceeding p % of time;

r_{eo} = effective distance (in km) of the earth-space path through the atmosphere at a specified angle of elevation, being 45° in this report.

When the angle is different from 45°,

$$A_{p,\phi} = A_{p,\phi=45°}\, \frac{\sin 45°}{\sin\phi}, \quad \phi \geq 5°. \qquad \cdots (A3.2)$$

As may be understood from Eqns. (A3.1) and (A3.2), the effective distance is the distance a radio wave travels through a hypothetical uniform rainfall extending from the earth's surface upwards to a height of r_{eo}

sin 45° km with a vacuum above. The other parameter γ_{so} can be readily referred to in published literatures, such as Fig.4 of Report 233-2 (Rev. 72 Draft), Conclusions of the Interim Meeting of S.G. 5, C.C.I.R., Geneva 1972.

In the above discussion the curvature of the earth's surface and that of the atmosphere have been neglected. This approximation is justified for a range of $\phi \geq 5^{\circ}$. But when $\phi < 5^{\circ}$ further corrections to r_{eo} should be made to allow for the aforesaid curvatures and a refraction effect caused by the atmosphere.