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A Statistical Rain Attenuation Prediction Model With Application to the Advanced Communication Technology Satellite Project

I—Theoretical Development and Application to Yearly Predictions for Selected Cities in the United States

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SUMMARY

A rain attenuation prediction model is described for use in calculating satellite communication link availability for any specific location in the world that is characterized by a long-term meteorological record of rainfall. Such a formalism is necessary for the accurate assessment of such availability predictions in the case of the small user-terminal concept of the Advanced Communication Technology Satellite (ACTS) Project. The model employs the theory of extreme value statistics to generate the necessary statistical rain-rate parameters from rain data in the form compiled by the National Weather Service. These location dependent rain statistics are then applied to a rain attenuation model to obtain a yearly prediction of the occurrence of attenuation on any satellite link at that location. The predictions of this model are compared to those of the Crane Two-Component Rain Model and some empirical data and found to be very good. The model is then used to calculate rain attenuation statistics at 59 locations in the United States (including Alaska and Hawaii) for the 20 GHz downlinks and 30 GHz uplinks of the proposed ACTS system.

The flexibility of this modeling formalism is such that it allows a complete and unified treatment of the temporal aspects of rain attenuation that leads to the design of an optimum stochastic power control algorithm, the purpose of which is to efficiently counter such rain fades on a satellite link. This will form the subjects of Parts II and III.

E-3187

1. INTRODUCTION

As communication satellite technology becomes increasingly advanced, so do the technical problems with which one must deal. The increase in the complexity of these problems necessarily requires an attendant increase in the complexity of analysis procedures through which they are solved. This natural evolution of concepts - problems - analysis accounts for the plethora of rain attenuation prediction models found in the literature for use in calculating satellite communication system availability. Each calculational procedure entailed in these attenuation prediction models was originally formed to deal with whatever attenuation problems were posed by the then current satellite system technology. Refinements of prevailing modeling procedures also followed. Thus, one is lead from the Rice-Holmberg Rain Model (ref. 1) (Vintage 1973) to the Crane Two-Component Rain Attenuation Model (ref. 2) (Vintage

1982). For a good review of the relative merits and drawbacks of the various ad hoc modeling procedures in use, see reference 3.

The Advanced Communication Technology Satellite Program at NASA Lewis Research Center is addressing an entirely new set of problems never before appearing in an active communications satellite project. With its scanning spot beams and high data rate transmission and reception on a city-by-city basis, the Advanced Communication Technology Satellite (ACTS) requires the use of yet another rain attenuation prediction model for systems design and analysis. Each city (or at least each beam dwell area) must be differentiated from the others in terms of rain attenuation characteristics for the accurate availability predictions needed for the high data rate links. Existing models cannot provide this need; even the two-component rain attenuation model which divides the continental U.S. into eight rain zones does not possess the spatial "resolution" desired in the above-mentioned calculations. What is just as important, however, is an analysis of the adaptive control algorithms proposed for ACTS to combat losses in link availability due to rain, i.e., forward error correction (FEC) and adaptive power control (APC) at the ground station. These control methods, which are countermeasures to the very phenomena described by a rain attenuation model, should follow naturally from such a formalism. Especially in the case of APC, this requires a temporal description of the evolution of attenuation at a particular ground site. None of the existing models can satisfy this requirement.

What is ideally desired is a unified rain attenuation prediction model that can be applied to, and thus differentiate between, each city or location (based, for example, on the accumulated rain statistics for that location by the U.S. weather service), give temporal descriptions of the attenuation process and, ultimately, indicate an optimal control algorithm that would "undo" the attenuation process that the model would (hopefully) so well describe. Secondary to this, the format of the parameters characterizing each city should be such that, once calculated for a particular satellite link, they allow expeditious calculation of attenuation characteristics on the part of a systems engineer. Such a unified model is the subject of this study.

This first part of a three part report describes the theoretical development of a rain attenuation prediction model that is applicable to any city that has a long term meteorological record of rainrates, and its application to Earth-space communication links to ACTS for 59 cities in the U.S. Section 2 of the present work gives the theoretical structure of the attenuation portion of the model, including its major assumptions, its input parameters, and its output parameters. This portion of the model provides the necessary connection between the statistics of the attenuation observed along a slant path Earth-space communications link, with its distinguishing geometrical quantities, and the local rain statistics characterizing the particular location of interest.

The calculation of rain statistics for individual cities form the existing meteorological record is the subject of Section 3. This is accomplished via the theory of extreme value statistics. The theory is developed from first principles and detailed procedures are given for the derivation of rain statistics from available data.

The application of the results of the last two sections are the subjects of Sections 4 and 5. In Section 4, a comparison is made between experimentally observed attenuation distributions for various frequencies at several locations and the calculated distributions of the rain attenuation model applied at these locations. Simultaneous comparison with the Two-Component Rain Model is also made for these sites.

Section 5 presents calculations from the attenuation prediction model for 59 cities in the U.S. These attenuation statistics are calculated for both the 20 and 30 GHz links to ACTS. The use of this data to calculate availability, given the attenuation, or, to calculate the corresponding attenuation given the availability, is also described.

Various appendices are included to expand on certain results used within the model. A description of the software used to generate the results of sections 3 and 5 is also given.

Part II of this report, which exists under a separate cover, will concern itself with the temporal aspects of attenuation on a space communications link. The dynamic theory is based on the results of Part I and on the assumption that the attenuation process is a Markov Random Process. This development allows one to obtain time profiles of attenuation on a link, probability distributions of random "surges" of attenuation above given thresholds, etc. This information complements the static, yearly predictions of Part I.

The development of Part II relies on the derivation of a stochastic differential equation describing the behavior of attenuation as a function of time. The form of this equation is just that needed to design an optimal power control algorithm to counter rain fades on a communications link. Such a control algorithm is the subject of Part III which also exists under a separate cover.

Although this work is applied to the 30/20 GHz links of ACTS, it is applicable to any other satellite system and other frequencies; one could even apply it to terrestrial ground based point-to-point communications links.

2. STRUCTURE OF THE RAIN ATTENUATION MODEL

It is well known that the observation of rainrate values at a given point is described by a log-normal probability distribution. This situation is easily explained as follows: one can consider the rainrate observed at a point on the Earth to be the result of, and thus governed by, a large number of random, time-varying multiplicative components, i.e.,

$$R(t) = x_1(t)x_2(t)\ldots x_n(t) \tag{2.1}$$

Each of the contributing random processes $x_j(t)$ represents some random perturbation to the rain process giving the observed rainrate at the point of interest. These random perturbations could come by way of variations in wind velocity and thus the canting angle of the rain drops, etc. Taking logarithms of both sides of equation (2.1) gives

$$\ln R(t) = \ln x_1(t) + \ln x_2(t) + \ldots + \ln x_n(t) \tag{2.2}$$

indicating that the quantity $\ln R(t)$ is the sum of a large number of random variables $\ln x_j(t)$. For very large n, one has, by the central limit theorem (ref. 4), that the random variable is described by a normal (or Gaussian) probability distribution. Therefore, $R(t)$ is given by a log-normal distribution. That is

$$P(r < R) = \int_{-\infty}^{R} p(\ln R')\, d(\ln R') \tag{2.3}$$

gives the probability distribution that a rainrate smaller than R will occur. In equation (2.3), $p(\ln R')$ is the probability density of a normal distribution

$$p(\ln R) = \frac{C}{(2\pi)^{1/2}\,\sigma_{\ln R}} \exp\left[-\frac{(\ln R - \mu)^2}{2\sigma_{\ln R}^2}\right] \tag{2.4}$$

where μ is the mean of the logarithm of the corresponding mean rainrate R_m, i.e.,

$$\mu = \ln R_m, \tag{2.5}$$

$\sigma_{\ln R}$ is the standard deviation of the log-rainrate $\ln R$, and the normalization constant C is such that

$$\int_{-\infty}^{\infty} p(\ln R')\, d(\ln R') = P_0 \tag{2.6}$$

where P_0 is the probability that it will rain at the point of interest. It must be noted that the normalization condition of equation (2.6) is set equal to P_0, i.e., the probability that it rains, rather than equal to one, since equation (2.4) only describes the occurrence of rainrates under the hypothesis that it is raining. That is, equation (2.4) describes the occurrence of rainrates only during raining periods and does not apply to situations between rain events. Substituting equation (2.4) into equation (2.6) and performing the required integration yields

$$C = P_0 \tag{2.7}$$

This subtitle but important circumstance suggests that the probability density of equation (2.4) be rewritten as a conditional density $p(\ln R|\text{rain})$; this is the probability density that $\ln R$ occurs given (i.e., under hypothesis) that rain occurs at the point of interest. Thus, one has

$$p(\ln R) = p(\ln R|\text{rain})\, P_0 \tag{2.8}$$

i.e.,

$$p(\ln R|\text{rain}) = \left(\frac{1}{(2\pi)^{1/2}\,\sigma_{\ln R}}\right) \exp\left[-\frac{\left(\ln R - \ln R_m\right)^2}{2\sigma_{\ln R}^2}\right] \tag{2.9}$$

Substituting equation (2.8) into equation (2.3) gives

$$P(r < R) = P_0 \int_{-\infty}^{R} p(\ln R|\text{rain})\, d(\ln R') = P_0 p(r < R|\text{rain}) \tag{2.10}$$

where

$$P(r < R|\text{rain}) \equiv \int_{-\infty}^{R} p(\ln R|\text{rain})\, d(\ln R') \tag{2.11}$$

is the conditional probability that a rainrate smaller than R will occur given that it rains. Hence, in the sequel, conditional probabilities and their associated densities will be directly dealt with; contact with unconditional probabilities, such as $P(r < R)$, is made through P_0 and a relationship like that of equation (2.10).

Substituting equation (2.9) into equation (2.11), changing variables and splitting the integral gives

$$P(r < r|\text{rain}) = \frac{1}{(\pi)^{1/2}} \left[\int_0^{\infty} \exp(-t^2)\, dt + \int_0^{f(R)} \exp(-t^2)\, dt \right] \tag{2.12}$$

where

$$f(R) = \frac{\ln R - \ln R_m}{(2)^{1/2}\, \sigma_{\ln R}}$$

Using the relationships

$$\text{erf}(Z) = \frac{2}{(\pi)^{1/2}} \int_0^{Z} \exp(-t^2)\, dt$$

and

$$\text{erfc}(Z) = 1 - \text{erf}(Z),$$

Equation (2.12) becomes

$$P(r < R|\text{rain}) = 1 - \frac{1}{2}\, \text{erfc}\left(\frac{\ln R - \ln R_m}{(2)^{1/2}\, \sigma_{\ln R}} \right) \tag{2.13}$$

Of more interest, however, is the probability $P(r < R)$ that gives the occurrence of a rainrate larger than R. Since

$$P(r < R|\text{rain}) + p(r > R|\text{rain}) = 1$$

one has

$$P(r > R|\text{rain}) = \frac{1}{2}\,\text{erfc}\left(\frac{\ln R - \ln R_m}{(2)^{1/2}\,\sigma_{\ln R}}\right) \tag{2.14}$$

The connection between the attenuation along an Earth-space propagation path and the rainrate occurring at any point along that path is made via the specific attenuation (ref. 5), denoted here by Γ. The specific attenuation at a point and the prevailing rainrate R at that point is given by the well known relation (refs. 5 and 6)

$$\Gamma = aR^b \tag{2.15}$$

where a and b are coefficients that are functions of operating frequency, polarization, rain drop size, and temperature (ref. 6). (See also appendix A.) Taking logarithms of both sides of equation (2.15) and solving for $\ln R$ gives

$$\ln R = \frac{\ln \Gamma - \ln a}{b} \tag{2.16}$$

To obtain the governing probability distribution of $\ln \Gamma$ knowing that of $\ln R$ (i.e., eqs. (2.9) or (2.14)) and the relationship exhibited by equation (2.16), one makes use of the transformation properties of probability density functions for related variables (ref. 7), viz.,

$$p(\ln \Gamma|\text{rain}) = \left|\frac{d(\ln R)}{d(\ln \Gamma)}\right|\ p(\ln R|\text{rain}) \tag{2.17}$$

evaluated at $\ln R = (\ln \Gamma - \ln a)/b$. From equations (2.9) and (2.16), equation (2.17) becomes

$$p(\ln \Gamma|\text{rain}) = \left(\frac{1}{(2\pi)^{1/2}\,\sigma_{\ln R^b}}\right) \exp\left[-\frac{\left(\ln \Gamma - \ln(a\,R_m^b)\right)^2}{2b^2\,\sigma_{\ln R}^2}\right] \tag{2.18}$$

Defining

$$\Gamma_m \equiv a\,R_m^b \tag{2.19}$$

and

$$\sigma_{\ln \Gamma} \equiv b\,\sigma_{\ln R} \tag{2.20}$$

for the mean of Γ and the standard deviation of $\ln \Gamma$, equation (2.18) becomes

$$p(\ln \Gamma|\text{rain}) = \left(\frac{1}{(2\pi)^{1/2}\,\sigma_{\ln \Gamma}}\right) \exp\left[-\frac{(\ln \Gamma - \ln \Gamma_m)^2}{2\,\sigma_{\ln \Gamma}^2}\right] \tag{2.21}$$

Thus, Γ is governed by the same form of distribution as is R and, analogous to the result of equation (2.14),

$$P(r > \Gamma|\text{rain}) = \frac{1}{2}\,\text{erfc}\left(\frac{\ln \Gamma - \ln \Gamma_m}{(2)^{1/2}\,\sigma_{\ln \Gamma}}\right) \tag{2.22}$$

The attenuation incurred along a propagation path of length L is given by

$$A(L) = \int_0^L \Gamma(l)\,dl \tag{2.23}$$

where $\Gamma(l) = a\,R^b(l)$ is the specific attenuation at each point l along the propagation path, $0 \leq l \leq L$. It now remains to find an expression for the cumulative probability distribution of $A(L)$ knowing the quantities that define the propagation path geometry, i.e., the slant path angle (antenna elevation angle), θ, and the maximum height of precipitation H, and knowing the fact that the quantity $\Gamma(l)$ that enters into equation (2.23) is described by the distribution given by equation (2.22). To this end, assume that the cumulative probability distribution of $A(L,\theta)$ is given by the following expression:

$$P(a \geq A(L,\theta)) = P_0(L,\theta)\;P\,(a \geq A(L,\theta)|\text{rain on }\;L) \tag{2.24}$$

where $P_0(L,\theta)$ is the probability of rain occurring along the slant path of length L and elevation angle θ, and $P(a \geq A(L,\theta)|\text{rain on } L)$ is the conditional cumulative probability distribution that the attenuation $A(L,\theta)$ is exceeded along a slant path given that rain occurs along it. This later quantity is taken to be given by

$$P(a \geq A(L,\theta)|\text{rain on }\;L) = \frac{1}{2}\,\text{erfc}\left(\frac{\ln A - \ln A_m}{(2)^{1/2}\,\sigma_{\ln A}}\right) \tag{2.25}$$

analogous to that of equation (2.22), where $A \equiv A(L,\theta)$, $A_m \equiv A_m(L,\theta)$, and $\sigma_{\ln A} \equiv \sigma_{\ln A}(L,\theta)$ is the attenuation, mean attenuation, and standard deviation of $\ln A$, respectively, that are, in general, quantities dependent on L and θ. It is now required to relate the newly introduced quantities $P_0(L,\theta)$, A_m, and $\sigma_{\ln A}$ to those already known.

At the outset of achieving this goal, consider the scenario shown in figure 2.1; an Earth terminal, at height above sea level H_0, establishing a communications link to a satellite within a potential rain region characterized by a maximum height H (sometimes termed the 0°-isotherm height). From the geometry of the situation, one has for the projected propagation path length x on the Earth (ref. 5)

$$x = L \cos \theta \tag{2.26}$$

In terms of H and H_0, the total path length L is given by

$$L = (H - H_0)\csc \theta \tag{2.27}$$

FIGURE 2.1

Thus, equation (2.26) becomes

$$x = (H - H_0) \text{ ctn } \theta \tag{2.28}$$

It should be noted that H is an empirical function of the latitude of the ground terminal. Expressions for this relationship are given in appendix B.

Changing variables in equation (2.23) via the relation $x' = l \cos \theta$ and remembering equation (2.26) gives

$$A(L,\theta) = \sec \theta \int_0^{L \cos \theta} \Gamma(x')\, dx' \tag{2.29}$$

In order to relate the statistics of A with previously defined parameters, one commences with considering the ensemble average of A, viz $\langle A \rangle$, which, by assuming ergodicity, implies taking a long-term time average of the attenuation process along the propagation path. This implicit long-term time average allows events to occur such that rain falls everywhere along the propagation path, and necessarily at each point along the path, thus reconciling the interpretations given to equations (2.14) and (2.22) on the one hand, and to equation (2.25) on the other. Taking the ensemble average of equation (2.29) yields

$$\langle A \rangle = \langle A(L,\theta) \rangle = \sec \theta \int_0^{L \cos \theta} \langle \Gamma(x') \rangle\, dx' \tag{2.30}$$

The quantity $\langle \Gamma(x) \rangle$ is, of course, the result of all the contributions to the random process $\Gamma(x)$. By equation (2.15), this is directly related to the random variable $R(x)$, i.e., the rainrate at an intermediate point x. This rainrate depends on the particular structure of the rain cells that can occur along the projected path, their maximum rainrates R_0, and their relative positions $|y - x|$ with respect to x along the projected path (ref. 5). (The quantity y, i.e., the position of a rain cell, is reckoned from the ground terminal site, as is x.) All of these characteristics combine to yield a probability density $p_x(\Gamma)$ giving the probability that the value of the specific attenuation occurring between the values Γ and $\Gamma + d\Gamma$ at x which is $p_x(\Gamma)d\Gamma$. Thus, one has, upon evoking the statistical definition of ensemble average,

$$\langle \Gamma(x') \rangle = \int_{-\infty}^{\infty} \Gamma' p_{x'}(\Gamma')\, d\Gamma' \tag{2.31}$$

where the limits on the integration denote such an operation over all possible values Γ' of the random function $\Gamma(x')$. Assuming spatial homogeneity along the projected propagation path allows one to write

$$p_{x'}(\Gamma') = p(\Gamma) \tag{2.32}$$

i.e., the probability density is independent of the position x' along the projected path. This assumption implies that there are no major geographical variations along the path. Substitution of equation (2.32) into equation (2.31) then allows the quantity $\langle\Gamma(x')\rangle$ to become independent of x', i.e.,

$$\langle\Gamma(x')\rangle = \int_{-\infty}^{\infty} \Gamma' p(\Gamma')\, d\Gamma' = \langle\Gamma\rangle \tag{2.33}$$

Thus, equation (2.30) becomes

$$\langle A\rangle = \langle A(L,\theta)\rangle = \sec\theta \, \langle\Gamma\rangle \, L\cos\theta = \langle\Gamma\rangle L \tag{2.34}$$

where $\langle A(L,\theta)\rangle$ is still (implicitly) dependent on θ through the quantity L (See eq. (2.27)).

In the same way, one can consider the variance of A, σ_A given by

$$\sigma_A^2 = \langle A^2\rangle - \langle A\rangle^2 \tag{2.35}$$

From equation (2.29) one has

$$\langle A^2\rangle = \sec^2\theta \int_0^{L\cos\theta} \int_0^{L\cos\theta} \langle\Gamma(x')\Gamma(x'')\rangle \, dx'\, dx'' \tag{2.36}$$

Noting from equation (2.34) that one can write

$$\langle A\rangle^2 = \langle\Gamma\rangle^2 L^2 = \sec^2\theta \int_0^{L\cos\theta} \int_0^{L\cos\theta} \langle\Gamma\rangle^2 \, dx'\, dx''$$

and using equation (2.36), equation (2.35) becomes

$$\sigma_A^2 = \sigma_A^2(L,\theta) = \sec^2\theta \int_0^{L\cos\theta} \int_0^{L\cos\theta} \left\{\langle\Gamma(x')\,\Gamma(x'')\rangle - \langle\Gamma\rangle^2\right\} dx'\, dx'' \tag{2.37}$$

The correlation $\langle\Gamma(x')\,\Gamma(x'')\rangle$ is formally given by

$$\langle\Gamma(x')\,\Gamma(x'')\rangle = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Gamma'\Gamma'' \, p_{x',x''}(\Gamma',\Gamma'')\, d\Gamma'\, d\Gamma'' \tag{2.38}$$

where $p_{x',x''}(\Gamma',\Gamma'')$ is the probability density that specifies values Γ' and Γ'' of the random function $\Gamma(x)$ at positions x' and x'', respectively. Again, the function $p_{x',x''}(\Gamma',\Gamma'')$ is determined by the rain cell structure and the local geography. In the event that homogeneity prevails along the projected propagation path, one has that

$$p_{x',x''}(\Gamma',\Gamma'') = p_{x'-x''}(\Gamma',\Gamma'') \tag{2.39}$$

i.e., the statistics are only dependent on the separation of the two points x' and x'' under consideration.

If one further has complete decorrelation, then equation (2.39) becomes

$$p_{x',x''}(\Gamma',\Gamma'') = p_{x'}(\Gamma')\ p_{x''}(\Gamma'')$$

and, through equation (2.38), gives

$$\begin{aligned}
\langle\Gamma(x')\ \Gamma(x'')\rangle &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Gamma'\Gamma''\ p_{x'}(\Gamma')\ p_{x''}(\Gamma'')\ d\Gamma'\ d\Gamma'' \\
&= \left[\int_{-\infty}^{\infty} \Gamma'\ p_{x}(\Gamma')\ d\Gamma'\right]^2 \\
&= \left[\int_{-\infty}^{\infty} \Gamma'\ p(\Gamma')\ d\Gamma'\right]^2 \\
&= \langle\Gamma\rangle^2
\end{aligned} \tag{2.40}$$

Substitution of equation (2.40) into equation (2.37) then gives in this case

$$\sigma_A^2(L,\theta) = 0$$

However, in general, one can expect a nonzero variance of attenuation along the projected propagation path that is a function of the separation $|x' - x''|$ between two points along the path (due to the homogeneity assumption of equation (2.39).

Since the analytical form of the function $p_{x'-x''}(\Gamma',\Gamma'')$ is not known, it is expeditious to define a correlation function $C_\Gamma(x' - x'')$,

$$C_\Gamma(x' - x'') \equiv \langle\Gamma(x')\ \Gamma(x'')\rangle - \langle\Gamma\rangle^2 \tag{2.41}$$

so that equation (2.37) becomes

$$\sigma_A^2\ (L,\theta) = \sec^2\theta \int_0^{L\cos\theta}\int_0^{L\cos\theta} C_\Gamma(x' - x'')\ dx'\ dx'' \tag{2.42}$$

Defining a correlation coefficient $r_\Gamma(x' - x'')$ via

$$r_\Gamma(x' - x'') \equiv \frac{C_\Gamma(x' - x'')}{\sigma_\Gamma^2} \tag{2.43}$$

where

$$\sigma_\Gamma^2 = \langle\Gamma^2\rangle - \langle\Gamma\rangle^2, \tag{2.44}$$

equation (2.42) can be rewritten as

$$\sigma_A^2(L,\theta) = \sigma_\Gamma^2 \sec^2\theta \int_0^{L\cos\theta} \int_0^{L\cos\theta} r_\Gamma(x' - x'')\,dx'\,dx''$$

$$= \sigma_\Gamma^2 L^2 \left(\frac{1}{L^2 \cos^2\theta}\right) \int_0^{L\cos\theta} \int_0^{L\cos\theta} r_\Gamma(x' - x'')\,dx'\,dx''$$

$$= \sigma_\Gamma^2 L^2 K(L,\theta) \qquad (2.45)$$

where

$$K(L,\theta)\ \sigma \left(\frac{1}{L^2 \cos^2\theta}\right) \int_0^{L\cos\theta} \int_0^{L\cos\theta} r_\Gamma(x' - x'')\,dx'\,dx'' \qquad (2.46)$$

is the path correlation function.

The correlation coefficient $r_\Gamma(x' - x'')$ is taken to be given by

$$r_\Gamma(x' - x'') = \exp\left(- \frac{|x' - x''|}{L_c}\right) \qquad (2.47)$$

where L_c is a characteristic correlation length, the value of which is dependent on the temporal scale over which the rain probability P_0 describes the occurrence of rain at a point. In what is to follow later, this temporal scale (the rainrate integration time from which the statistics P_0, R_m, and $\sigma_{\ln R}$ are derived) is 5 min. The evaluation of equation (2.46) using equation (2.47) as well as an estimate of L_c is carried out in appendix C. The results are

$$K(L,\theta) = \left(\frac{2}{L^2}\right) L_c \sec\theta \left[L - L_c \sec\theta \left\{1 - \exp\left(- \frac{L\cos\theta}{L_c}\right)\right\}\right] \qquad (2.48)$$

and

$$L_c = 4.0 \text{ km} \qquad (2.49)$$

In the case where $\theta = 0°$ and $L \to 0$, $K(0,0) = 1$ as expected. Also, as $L \to \infty$, $K(\theta,\infty) = 0$.

Equations (2.34) and (2.45) provide the needed connection between the attenuation, which is a function of path length and angle, and the specific attenuation, a quantity related to a point on the path. With these, one can relate the quantities $A_m(L,\theta)$ and $\sigma_{\ln A}(L,\theta)$, introduced in equation (2.25), to those of the known Γ_m and $\sigma_{\ln \Gamma}$, given in equations (2.19) and (2.20). To this end, it will be expedient to look at the first and second moments of the probability densities leading to the distributions of equations (2.22) and (2.25).

Considering the conditional probability density given by equation (2.21), the j^{th} conditional moment $\langle\Gamma^j\rangle_c$ of the process described by it is given by

$$<Q^j>_c = \int_{-\infty}^{\infty} \Gamma^j \, p(\ln \Gamma | \text{rain}) \, d(\ln \Gamma)$$

$$= \frac{1}{(2\pi)^{1/2} \sigma_{\ln \Gamma}} \int_{-\infty}^{\infty} \Gamma^j \exp\left[- \frac{(\ln \Gamma - \ln \Gamma_m)^2}{2 \sigma^2_{\ln \Gamma}} \right] d(\ln \Gamma)$$

Letting $v = (\ln \Gamma - \ln \Gamma_m)/((2\pi)^{1/2} \sigma_{\ln \Gamma})$ gives

$$<\Gamma^j>_c = \frac{\Gamma_m^j}{\pi^{1/2}} \int_{-\infty}^{\infty} \exp\left(2^{1/2} j \sigma_{\ln \Gamma} v - v^2\right) dv \tag{2.50}$$

upon writing $\Gamma = \Gamma_m \exp(2^{1/2} \sigma_{\ln \Gamma} v)$. Completing the square of the argument of the exponential of equation (2.50) gives

$$<\Gamma^j>_c = \left(\frac{\Gamma_m^j}{\pi^{1/2}}\right) \exp\left(\frac{j\sigma^2_{\ln \Gamma}}{2}\right) \int_{-\infty}^{\infty} \exp(-v'^2) \, dv' = \exp(j \ln \Gamma_m) \exp\left(\frac{j^2 \sigma^2_{\ln \Gamma}}{2}\right) \tag{2.51}$$

Thus, the first conditional moment $<\Gamma>_c$ becomes

$$<\Gamma>_c = \exp\left(\ln \Gamma_m + \frac{\sigma^2_{\ln \Gamma}}{2}\right) \tag{2.52}$$

giving for the average

$$<\Gamma> = P_0 <\Gamma>_c = P_0 \exp\left(\ln \Gamma_m + \frac{\sigma^2_{\ln \Gamma}}{2}\right) \tag{2.53}$$

The second conditional moment $<\Gamma^2>_c$ is given by

$$<\Gamma^2>_c = \exp(2 \ln \Gamma_m) \exp 2\sigma^2_{\ln \Gamma} \tag{2.54}$$

yielding the second moment

$$<\Gamma^2> = P_0 <\Gamma^2>_c = P_0 \exp(2 \ln \Gamma_m) \exp\left(2\sigma^2_{\ln \Gamma}\right)$$

The variance σ_Γ^2 thus becomes

$$\sigma_\Gamma^2 = P_0 \exp(2 \ln \Gamma_m) \exp\left(2\sigma_{\ln \Gamma}^2\right) - P_0^2 \exp\left(2 \ln \Gamma_m + \sigma_{\ln \Gamma}^2\right)$$

$$= P_0 \exp\left(2 \ln \Gamma_m + \sigma_{\ln \Gamma}^2\right) \left[\exp\left(\sigma_{\ln \Gamma}^2\right) - P_0\right]$$

$$= \left(\frac{1}{P_0}\right) \langle\Gamma\rangle^2 \left[\exp\left(\sigma_{\ln \Gamma}^2\right) - P_0\right] = \langle\Gamma\rangle^2 \left[\frac{\exp\left(\sigma_{\ln \Gamma}^2\right)}{P_0} - 1\right] \qquad (2.55)$$

In an analogous manner, starting from the conditional probability density resulting in equation (2.25), i.e.,

$$p(\ln A|\text{rain}) = \frac{1}{(2\pi)^{1/2}\, \sigma_{\ln A}} \exp\left[-\frac{\left(\ln A - \ln A_m\right)^2}{2\sigma_{\ln A}^2}\right]$$

one obtains

$$\langle A(L,\theta)\rangle = P_0(L,\theta) \exp\left[\ln A_m + \frac{\sigma_{\ln A}^2}{2}\right] \qquad (2.56)$$

and

$$\sigma_A^2\,(L,\theta) = \langle A(L,\theta)\rangle^2 \left[\frac{\exp\left(\sigma_{\ln A}^2\right)}{P_0(L,\theta)} - 1\right] \qquad (2.57)$$

One can now solve for the quantities $\sigma_{\ln A}^2$ and A_m in terms of those those already known. Solving equation (2.57) for $\sigma_{\ln A}^2$ yields

$$\sigma_{\ln A}^2\,(L,\theta) = \ln\left[P_0(L,\theta) \left\{\frac{\sigma_A^2(L,\theta)}{\langle A(L,\theta)\rangle^2} + 1\right\}\right]$$

Substituting equations (2.34) and (2.45) into this relation gives

$$\sigma_{\ln A}^2(L,\theta) = \ln\left[P_0(L,\theta) \left\{\frac{\sigma_\Gamma^2}{\langle\Gamma\rangle^2} K(L,\theta) + 1\right\}\right]$$

Solving equation (2.55) for the ratio $\sigma_\Gamma^2/\langle\Gamma\rangle^2$ and employing this in the previous equation, one obtains

$$\sigma^2_{\ln A}(L,\theta) = \ln\left[P_0(L,\theta)\left\{K(L,\theta)\left(\frac{\exp\left(\sigma^2_{\ln \Gamma}\right)}{P_0} - 1\right) + 1\right\}\right] \tag{2.58}$$

relating $\sigma^2_{\ln A}(L,\theta)$ to the known quantities $\sigma^2_{\ln \Gamma}$ and $K(L,\theta)$ and the yet to be determined function $P_0(L,\theta)$.

To obtain an expression for $A_m(L,\theta)$, one solves equation (2.56) for $A_m(L,\theta)$ obtaining

$$A_m(L,\theta) = \frac{\langle A(L,\theta)\rangle}{P_0(L,\theta)} \exp\left(-\frac{\sigma^2_{\ln A}}{2}\right)$$

Substituting equations (2.34) and (2.53) into the above result gives

$$A_m(L,\theta) = \frac{P_0}{P_0(L,\theta)} L\,\Gamma_m \exp\left(\frac{\sigma^2_{\ln \Gamma} - \sigma^2_{\ln A}}{2}\right) \tag{2.59}$$

for an expression for $A_m(L,\theta)$ in terms of the known quantities and $\sigma^2_{\ln A} \equiv \sigma^2_{\ln A}(L,\theta)$ calculated in equation (2.58).

It should be noted that in the special case where there is total correlation between $\sigma^2_A(L,\theta)$ and σ^2_Γ, i.e., $K(L,\theta) = 1$ and $P_0 = P_0(L,\theta)$, equation (2.58) becomes

$$\sigma^2_{\ln A}(L,\theta) = \ln\left[\exp\left(\sigma^2_{\ln \Gamma}\right)\right] = \sigma^2_{\ln \Gamma}$$

and equation (2.59) thus gives

$$A_m(L,\theta) = \Gamma_m L$$

which are expected results.

It now only remains to determine the function $P_0(L,\theta)$. It is intuitively obvious that the probability of rain occurring on an extended path along the Earth will be greater than that at a point, P_0, and will be a nondecreasing function of the projected path length $L \cos\theta$. Although there are several ways to model the situation, it is expedient to appeal to empirical data, such as that obtained in the Florida Thunderstorm Project (ref. 8). This data has been used to obtain an expression for the probability $P_0(L,\theta)$ of precipitation occurring along a path length of $L \cos\theta$ in terms of the probability P_0 of rain occurring at any point along that path (ref. 9). It is given by

$$P_0(L,\theta) = 1 - (1 - P_0)\left[1 + \frac{L^2 \cos^2\theta}{21.5}\right]^{-0.014} \tag{2.60}$$

The basic structure of the rain attenuation model is now complete; given the statistical quantities P_0, R_m, and $\sigma_{\ln R}$ appearing in equations (2.10) and (2.14), one can obtain the log-normal attenuation parameters $P_0(L,\theta)$, $A_m(L,\theta)$, and $\sigma_{\ln A}(L,\theta)$ needed in equations (2.24) and (2.25), via equations (2.58) and (2.59) and the various intermediate quantities given in this section and in the appendices. A detailed calculational procedure will be given later. It will be shown in subsequent developments of the overall attenuation model that knowledge of these three statistical attenuation parameters, for a given satellite link, not only allows yearly (long term or stationary) attenuation predictions to be made (via eqs. (2.24) and (2.25)) but also play an important part in the short term (i.e., nonstationary) temporal descriptions of attenuation.

However, before any of this program can be carried out, one must have the parameters P_0, R_m, and $\sigma_{\ln R}$ for locations of interest. These parameters completely characterize the rain statistics at a location. These can be calculated from existing meteorological data for those sites of interest, as will be shown in the next section.

3. CALCULATION OF THE LOG-NORMAL DISTRIBUTION PARAMETERS FOR RAINRATE VIA THE STATISTICS OF EXTREME VALUES

(A) Development of Extreme Value Theory for Yearly Rainrate Data

Given $P(r \geq R)$, the probability of an observed rainrate r will equal or exceed a fixed value R, which is governed by a log-normal probability distribution as discussed at the outset of Section 2, viz,

$$P(r \geq R) = P_0 P(r \geq R|\text{rain}) = P_0 \left(\frac{1}{2}\right) \text{erfc}\left[\frac{\ln R - \ln R_m}{\sqrt{2}\ \sigma_{\ln R}}\right] \tag{3.1}$$

The following problem presents itself: How can the parameters P_0, R_m, and $\sigma_{\ln R}$ that enter into equation (3.1) be determined from available rain data, specific to the location of interest? Local rain statistics found in the long term (i.e., ≈50 yr of data) meteorological record are not in the form directly amenable to equation (3.1); rather, they are compiled in two different forms: (1) excessive short duration rainfall (ref. 10) giving the largest (or extreme) values of rainrate observed and averaged over time intervals of 5, 10, and 15 min, ... occurring at given locations over the course of a year; (2) rainfall intensity - duration-frequency curves (ref. 11) for rain fall observed and averaged over time intervals ranging from 5 min to 24 hr. (The rainrates mentioned above averaged or integrated over t-min intervals are simply called t-min rainrates. This is the average value of the randomly varying rainrate in a t-min interval and is given by $\Delta W/t$ where ΔW is the accumulated depth of rainfall in a t-min period. The period t is also called the rain gauge integration time.)

The data in the form of number 1 represents the occurrence of extreme, (i.e., large values) of rainrate, a process that is described by a probability distribution, different than that of the "parent" distribution of equation (3.1), that governs such extreme occurrences. The derivation and use of such an asymptotic probability distribution and the connection between this and that of equation (3.1) and the subsequent derivation of the parameters P_0, $\ln R_m$, and $\sigma_{\ln R}$ is the subject of this section.

The data in the form of number 2 gives essentially the same information as does form number 1 but in a more condensed form. The intensity-duration-frequency curves give plots of the extreme rainrate with selected "return periods" of N years, i.e., the rainrate which is exceeded once in N years, on the average, by yearly maximum t-min rainrates. In terms of the above mentioned asymptotic probability distribution $P_\infty (R_1 \geq r)$, where R_1 is the yearly maximum rainrate, the return period is simply $1/P_\infty (R_1 \geq r)$ years. This data covers ranges of return periods from 2 to 100 years.

In what is now to follow, a derivation of the theory of extreme value statistics, the formalism that deals with probabilities of the occurrences of extreme values of a process, will be given. This will follow the presentation of the original but hard to find work on the subject (refs. 12 and 13), with the specific application to rainrate occurrences. The application of the statistics of extremes to the problem of assessing the probability of rainrates was first noted just 10 years ago (ref. 14).

An expression for the asymptotic probability distribution governing the occurrences of extreme values of rainrates will now be derived (ref. 15). Other than some general characteristics, the asymptotic distribution is independent of the form of the parent distribution, i.e., equation (3.1). Let $P_1\ (r < R_1)$ be the cumulative probability distribution that an observed rainrate r is less than some given rainrate R_1. (At this point, the integration time associated with the rainrate R_1 is also arbitrary but, of course, taken to be fixed throughout this discussion.) Also, let $p_1(R_1)$ be the corresponding probability density. Let there be n independent observations of the rainrate r such that $r < R_1$. The probability that this will occur is

$$P_{1,n}(r < R_1) = P_1^n(r < R_1) \tag{3.2}$$

since the events $r < R_1$ are taken to be independent. Equation (3.2) can also be interpreted as the probability for the rainrate R_1 to be the largest rainrate observed among the n independent observations in a year, i.e., the extreme rainrate in a years' worth of rain events. Also, the quantity

$$\begin{aligned} p_{1,n}(R_1) &= \frac{d}{dR_1} P_{1,n}(r < R_1) \\ &= \frac{d}{dR_1} P_1^n(r < R_1) \\ &= n\, P_1^{n-1}(r < R_1)\, p_1(R_1) \end{aligned} \tag{3.3}$$

is the corresponding density governing the occurrence of the largest rainrate R_1 among the n independent observations.

With the goal of obtaining a general expression for $P_1(r < R_1)$, consider first the relative maximum of equation (3.3) at which the average of P_1, i.e., R_1, occurs. (Actually, in the log-normal case, this is more properly denoted $\ln R_1$.) Differentiating equation (3.3) with respect to R_1, equating the result to zero, and rearranging terms gives

$$\frac{(n-1)\, p_1(\bar{R}_1)}{P_1(r < \bar{R}_1)} = -\left[\frac{1}{p_1(R_1)} \frac{dp_1(R_1)}{dR_1}\right]\Bigg|_{R_1 = \bar{R}_1} \tag{3.4}$$

Solution of this equation yields the mean value for the extreme rainrate, R_1. At this point one notes that as $R \to \infty$ (or at least some very large limiting value) the quantity, formed from equation (3.1)

$$1 - P(r < R) = P(r \geq R) = \frac{P_0}{2} \operatorname{erfc}\left(\frac{\ln R - \ln R_m}{\sqrt{2}\, \sigma_{\ln R}}\right) \tag{3.5}$$

tends to zero. So too does the associated probability density

$$p(R) = \frac{P_0}{\sigma_{\ln R}\sqrt{2\pi}} \exp\left[-\left(\frac{\ln R - \ln R_m}{2\sigma^2_{\ln R}}\right)\right]$$

Thus, the ratio $p(R_1)/(1 - P(r < R_1))$ can be expressed via L'Hospital's Rule as

$$\frac{p(R)}{1 - P(r < R)} \approx - \frac{\dfrac{dp\ (R)}{dR}}{\dfrac{dP(r < R)}{dR}} = -\frac{p'(R)}{p(R)}\ . \tag{3.6}$$

where, as usual, $p'(R) = dp(R)/dR$. The above operation is permissible since the function $p(R)$ is unbounded. Since this holds for the parent distribution of equation (3.1), it must also be true for the asymptotic distribution. Thus, substituting equation (3.6) into equation (3.4) gives

$$\frac{(n-1)\, p_1(\bar{R}_1)}{P_1(r < \bar{R}_1)} = \frac{p_1(\bar{R}_1)}{1 - P_1(r < \bar{R}_1)}$$

Solving this expression for $P_1(r < \bar{R}_1)$ yields

$$P_1(r < \bar{R}_1) = 1 - \frac{1}{n} \tag{3.7}$$

where $\bar{R}_1$ is an implicit function of n. Equation (3.7) has a simple interpretation: rewriting the expression gives

$$n = \frac{1}{1 - P_1(r < \bar{R}_1)} = \frac{1}{P_1(\ r \geq \bar{R}_1)} \tag{3.8}$$

which, as mentioned above, is the definition of the return period for the rainrate R_1. It is the number of observations such that, on the average, there is one observation equaling or exceeding R_1.

In a similar way, since the variable R_1 is unbounded (actually, it is $\ln R_1$ that enters into the calculations) one has that all derivatives $p^{(m)}(R_1)$ tend to zero. Thus, again by L'Hospital's Rule, one has

$$\frac{p_1'(R_1)}{p_1(R_1)} = \frac{p_1''(R_1)}{p_1'(R_1)} \tag{3.9}$$

or, more generally,

$$\frac{p_1^{(m)}(R_1)}{p_1^{(m-1)}(R_1)} = \frac{p_1^{(m+1)}(R_1)}{p_1^{(m)}(R_1)} \tag{3.10}$$

Considering once again the probability $P_1(r < R_1)$, for any R_1, one can use the properties just derived by expanding $P_1(R < R_1)$ about the mean $\bar{R}_1$ thus obtaining

$$P_1(r < R_1) = P_1(r < \bar{R}_1) + \frac{(\ln R_1 - \ln \bar{R}_1)}{1!} p_1(\bar{R}_1) + \frac{(\ln R_1 - \ln \bar{R}_1)^2}{2!} p_1'(\bar{R}_1)$$

$$+ \frac{(\ln R_1 - \ln R_1)^3}{3!} p_1''(\bar{R}_1) + \ldots \tag{3.11}$$

Now from equations (3.6) and (3.8) one has

$$p_1'(\bar{R}_1) = - \frac{p_1^2(\bar{R}_1)}{1 - P_1(r < \bar{R}_1)} = - np_1^2(\bar{R}_1) \tag{3.12}$$

Similarly, from equation (3.9)

$$p_1''(\bar{R}_1) = \frac{(p_1'(\bar{R}_1))^2}{p_1(\bar{R}_1)} = \frac{n^2 p_1^4(\bar{R}_1)}{p_1(\bar{R}_1)} = n^2 p_1^3(\bar{R}_1) \tag{3.13}$$

In general,

$$p_1^{(m)}(\bar{R}_1) = (-1)^m n^m p_1^{(m+1)}(\bar{R}_1) \tag{3.14}$$

Substituting equations (3.12) to (3.14) into equation (3.11) yields

$$P_1(r < R_1) = 1 - \frac{1}{n}\left[1 - \frac{(\ln R_1 - \ln \bar{R}_1)}{1!} n\, p_1(R_1) + \frac{(\ln R_1 - \ln \bar{R}_1)^2}{2!} n^2 p_1^2(\bar{R}_1) - \frac{(\ln R_1 - \ln \bar{R}_1)^3}{3!} n^3 p_1^3(\bar{R}_1) + \ldots + \frac{(\ln R_1 - \ln \bar{R}_1)^m}{m!} (-1)^{m-1} n^{m+1} p_1^{m+1}(R_1) + \ldots\right]$$

In the ideal (but unrealistic) case that $n \to \infty$, this expression becomes

$$P_1(r < R_1) = 1 - \frac{1}{n} \exp\left[- np_1(\bar{R}_1)(\ln R_1 - \ln \bar{R}_1)\right] \tag{3.15}$$

assuming that the expansion converges with an infinite number of terms. The probability that all n observations (i.e., rain events) are less than R_1 is given by substituting equation (3.15) into equation (3.2),

$$P_{1,n}(r < R_1) = \left\{1 - \frac{1}{n} \exp\left[- n\, p_1(\bar{R}_1)(\ln R_1 - \ln \bar{R}_1)\right]\right\}^n \xrightarrow[n\to\infty]{} \exp\left[-\exp[-np_1(\bar{R}_1)(\ln R_1 - \ln \bar{R}_1)]\right] = \exp[-\exp(-Y_n)] \tag{3.16}$$

where

$$Y_n \equiv \alpha(\ln R - U), \quad \alpha \equiv np_1(\bar{R}_1), \quad U = \ln \bar{R}_1 \tag{3.17}$$

Equation (3.16) is well known (refs. 12, 13, and 15) in the theory of extreme value statistics and is called the Type I Asymptotic Distribution For Maximum Values. It is also sometimes called Gumbel's Extreme Value Distribution. Unlike the parent log-normal distribution which is characterized by three parameters, equation (3.16) has two parameters: the location parameter U and the scale parameter α. These parameters will now be related to the two forms of meteorological data bases. The connection between α and U and the log-normal parameters P_0, $\ln R_m$, and $\sigma_{\ln R}$ will be made in the next section.

Treating the quantity Y_n, called the reduced variate, as a random variable (by virtue of the random variable $\ln R$, occurring in its definition of equation (3.17)), one has

$$P_n(y < Y_n) = \exp[-\exp(-Y_n)] \tag{3.18}$$

for the probability distribution of values y and for the corresponding density

$$p(Y_n) = \frac{dP(y < Y_n)}{dY_n} = \exp[-Y_n - \exp(-Y_n)] \tag{3.19}$$

The mean value $\bar{Y}_n$ and the variance $\sigma^2_{Y_n}$ of Y_n are then found via equation (3.19) to be (refs. 12 and 13)

$$\bar{Y}_n = \gamma = 0.57722 \tag{3.20}$$

and

$$\sigma^2_{Y_n} = \frac{\pi^2}{6} \tag{3.21}$$

where γ is the Euler constant. The problem of obtaining α and U from the available meteorological data reduces to fitting the equation

$$Y_n = \alpha(\ln R_1 - U)$$

to observed statistics of Y_n and $\ln R_1$. In a tedious but straightforward curve fitting procedure (that will not be detailed here but, if necessary, can be found elsewhere (refs. 12 and 13) one finds that

$$\alpha = \frac{\sigma_Y}{\sigma_{\ln R_1}}, \quad U = \overline{\ln R_1} - \frac{\bar{Y}}{\alpha} \tag{3.22}$$

where, given a finite number of yearly extreme value observations, say, subtending N years,

$$\overline{\ln R_1} = \frac{1}{N} \sum_{i=1}^{N} x_i \tag{3.23}$$

and

$$\sigma_{\ln R_1} = \left\{ \frac{1}{N-1} \sum_{i=1}^{N} \left(x_i - \overline{\ln R_1}\right)^2 \right\}^{1/2} \tag{3.24}$$

where

$$x_i = (\ln R_1)_i \tag{3.25}$$

is the extreme value observed in the i^{th} year.

The values of $\bar{Y}_n$ and $\sigma^2_{Y_n}$ given in equations (3.20) and (3.21) hold for the ideal situation of an infinite number of observations, i.e., rain events. In practice, however, these parameters should reflect and be derived from the fact that a finite number of observations make up the meteorological data base. This can be accomplished as follows. Let the observations x_i be placed in nondecreasing order, i.e., $x_j, x_k, x_l, \ldots$ where $x_j \leq x_k \leq x_l \ldots$. These N ordered extreme values, which are of course random variables, have values that fluctuate from one sample to the next according to some probability distribution whose expectation value should correspond to the theoretically derived distribution $P_{1,n}(r < R_1)$ (or, what is the same thing, $P_n(y < Y_n)$). To obtain this expectation value, one notes that for the j^{th} ordered extreme, $j - 1$ extremes occurred each with probability $P_1(r < (R_1)_j)$ one occurred with probability $dP_1 = P_1(R_1 < r \leq R_1 + dR_1)$, and the remaining $N - j$ occurred each with probability $P_1(r > (R_1)_j) = 1 - P_1(r > (R_1)_j)$. Since this ordering procedure is analogous to a generalized Bernoulli trial, the total probability density of the j^{th} ordered extreme is given by

$$p(x_j) = \frac{N!}{(j-1)\cdot 1\cdot(N-j)} P_1^{j-1}(1 - P_1)^{N-j}\, dP_1$$

The expectation value of P_1 can then be found from

$$\overline{P_1} = \frac{N!}{(j-1)(N-j)} \int_0^1 P_1 P_1^{j-1}(1 - P_1)^{N-j}\, dP_1 = \frac{j}{N+1} \tag{3.26}$$

upon repeatedly integrating by parts. Thus, each of the N rain events, $1 \leq j \leq N$, is governed by a different "average probability" of occurring.

Even though the order in which these observations occurred was used in deriving equation (3.26), the ordering of these events is immaterial in terms of the curve fitting equations of equation (3.22). What is significant, however, is that equation (3.26) can be used for what was desired at the outset, i.e., evaluation of Y_n and $\sigma^2_{Y_n}$ for finite sized samples. To this end, equating equation (3.26) to equation (3.18) gives

$$\frac{j}{N+1} = \exp\left[-\exp(-Y_{n_j})\right]$$

for each corresponding value Y_{n_j}. Solving this equation for Y_{n_j} yields

$$Y_{n_j} = -\ln\left(-\ln\left(\frac{j}{N+1}\right)\right) \tag{3.27}$$

One then has, by definition of the sample mean and variance,

$$\bar{Y}_n = \frac{1}{N}\sum_{i=1}^{N} Y_{n_i} \tag{3.28}$$

$$\sigma_{Y_n} = \left[\frac{1}{N-1}\sum_{i=1}^{N}\left(Y_{n_i} - \bar{Y}\right)^2\right]^{1/2} \tag{3.29}$$

Therefore, if individual values of R_1 are available one each year for N years for a particular location of interest, as they are in the excessive short duration rainfall data mentioned earlier, then equations (3.23) and (3.24) along with equations (3.27) to (3.29) can be used to obtain the corresponding values of α and U.

If, however, intensity-duration-frequency curves are used, one must proceed differently. As mentioned earlier, this form of the data gives values of extreme rainrates with various return periods. Thus, one has pairs of numbers (r_{1i}, T_i) where R_{1i} is the i^{th} extreme rainrate corresponding to the return period T_i. By the definition of return period,

$$T_i = \frac{1}{1 - P(r < R_{1i})}$$

Using equations (3.16) and (3.17), one has

$$T_i = 1 - \exp\left[-\exp(-\alpha(\ln R_{1i} - U))\right] \tag{3.30}$$

Hence, two such pairs of values (R_{1i},T_i) can be used and, via equation (3.30), one can solve for α and U directly. However, these values also derive from a finite speed data base that was created using the theory of the statistics of extreme values (refs. 12 and 13) but only in its asymptotic form (ref. 11). In other words, even though a finite number (albeit, a large number) of rain events were used to construct the data base, the treatment of the data assumed that it is infinite. To rectify this problem, let α' and U' be the asymptotic values of α and U derived from the intensity-duration-frequency curves by two pairs of data, (R_{11},T_1) and (R_{12},T_2). From equation (3.30), one has

$$T_1 = [1 - \exp(-\exp(-\alpha'(\ln R_{11} - U')))]$$

$$T_2 = [1 - \exp(-\exp(-\alpha'(\ln R_{12} - U')))]$$

Solving these equations for α' and U' gives

$$U' = \frac{C_1 \ln R_{12} - C_2 \ln R_{11}}{C_1 - C_2} \tag{3.31}$$

$$\alpha' = \frac{C_1 - C_2}{\ln R_{12} - \ln R_{11}} \tag{3.32}$$

where

$$C_1 \equiv -\ln\left(-\ln\left(\frac{T_1}{T_1 - 1}\right)\right), \quad C_2 \equiv -\ln\left(-\ln\left(\frac{T_2}{T_2 - 1}\right)\right) \tag{3.33}$$

To correct for the fact that the rainfall intensity-duration-frequency curves originally derived from a finite number of rainfall observations, one can demand that the ratio α/α', i.e., the ratio of the value of α for a finite data base to that of an assumed infinite one, be equal to the corresponding ratio

$$\frac{\dfrac{\sigma_{Y_n}}{\sigma_{\ln R}}}{\dfrac{\sigma_{Y'_n}}{\sigma_{\ln R}}} = \frac{\sigma_{Y_n}}{\sigma_{Y'_n}}$$

where $\sigma_{Y'_n}$ is the asymptotic value of σ_Y given by equation (3.21); thus

$$\alpha = \left(\frac{(6)^{1/2}}{\pi}\right)\alpha'\sigma_Y \tag{3.34}$$

where σ_Y is found from equation (3.29).

Similarly, for U', one has from equation (3.22)

$$U' = \overline{\ln R_1} - \frac{\gamma}{\alpha'}$$

using the asymptotic values for α and $\bar{Y}_n$. However, in the finite sample case

$$U = \overline{\ln R_1} - \frac{\bar{Y}_n}{\alpha}$$

where $\bar{Y}_n$ is now given by equation (3.28). Solving one of these relations for $\overline{\ln R_1}$ and substituting the result into the other gives

$$U = U' + \frac{\gamma}{\alpha'} - \frac{\bar{Y}_n}{\alpha}$$

using equation (3.34), one has

$$U = U' + \frac{1}{\alpha'}\left[\gamma - \frac{\pi}{(6)^{1/2}}\ \frac{\bar{Y}_n}{\sigma_{Y_n}}\right] \tag{3.35}$$

Hence in the case of using the rainfall intensity-duration-frequency curves, one uses to sets of data, (R_{11},T_1) and (R_{12},T_2), taken from the curves for a given location, at a particular t-min integration time, and uses equations (3.31) to (3.33) to calculate α' and U'. These values are then used in equations (3.34) and (3.35), with the help of equations (3.28) and (3.29) to obtain the final values of α and U. The number of years to be used in the later two equations corresponds to the total number of years the data was taken at the particular location of interest.

In the next section to follow, it will be shown how knowledge of the values of α and U can be used to obtain the desired log-normal parameters P_0, R_m, and $\sigma_{\ln R}$.

(B) Application of the Foregoing to the Calculation of the Log-Normal

Rainrate Parameters

The first step in relating the quantities P_0, R_m, and $\sigma_{\ln R}$ to α and U naturally commences with employing the definition of the return period to the conditional probability found from equation (3.1), i.e.,

$$\frac{P(r > R)}{P_0} = p(r > R|\text{rain}) = \left(\frac{1}{2}\right) \text{erfc}\left[\frac{\ln R - \ln R_m}{\sqrt{2}\,\sigma_{\ln R}}\right] \tag{3.36}$$

an expression that holds only during the raining time. (In what is to follow, it is necessary to use the conditional probability $P(r \geq R|\text{rain})$ since this function is normalized to 1, whereas as discussed in Section 2, the quantity $P(r \geq R)$ is normalized to P_0.) It must be remembered that P_0 is the yearly probability that it rains, i.e., it is the ratio of total raining time to the time within an average year. As mentioned earlier, this probability must necessarily be linked to a rain gauge integration time τ; for reasons that will be detailed in Subsection (c), this integration time will be taken to be equal to 5 min. Letting n_5 be the total number of 5-min intervals in a year, one has that the product n_5P_0 is the total number of 5-min intervals in a year that it rains. Thus, there is a total number

$$n = n_5P_0 \tag{3.37}$$

of (5-min) observations in a year that it rains. By equations (3.8), (3.17), (3.36), and (3.37) one has

$$\frac{1}{2}\,\text{erfc}\left[\frac{U - \ln R_m}{\sqrt{2}\,\sigma_{\ln R}}\right] = \frac{1}{n_5P_0} = \frac{1}{105\ 120\ P_0}$$

where $n_5 = 105\ 120$ is the number of 5-min intervals in a year. In order to facilitate the calculations to follow, this relation will be written in terms of the normal probability function η:

$$1 - \frac{1}{2}\,\text{erfc}\left[\frac{U - \ln R_m}{\sqrt{2}\,\sigma_{\ln R}}\right] \equiv \eta\left(\frac{\ln \bar{R}_1 - \ln R_m}{\sigma_{\ln R}}\right) = 1 - \frac{1}{105\ 120\ P_0} \tag{3.38}$$

where

$$\eta(x) \equiv 1 - \frac{1}{2}\,\text{erfc}\ \frac{x}{\sqrt{2}} \tag{3.39}$$

Another relationship that can be written comes from equation (3.17). Using the corresponding conditional probability density

$$p(\bar{R}_1|\text{rain}) = \frac{1}{\sqrt{2\pi}\,\sigma_{\ln R}} \exp\left[-\frac{\left(\ln \bar{R}_1 - \ln R_m\right)^2}{2\,\sigma^2_{\ln R}}\right]$$

the definition for α in equations (3.17) and (3.37) gives

$$\alpha = \frac{105\ 120\ P_0}{\sqrt{2\pi}\,\sigma_{\ln R}} \exp\left[-\frac{(U - \ln R_m)^2}{2\,\sigma^2_{\ln R}}\right] \tag{3.40}$$

Equations (3.38) and (3.40) are two independent equations for the three unknowns P_0, R_m, and $\sigma_{\ln R}$. To obtain one more independent equation, one uses the average yearly accumulated rainfall depth, W_{avg}, for the location of interest. This can be related to the average rainrate $\langle R\rangle$, and the total raining time T_{rain} in a year,

$$W_{avg} = \langle R\rangle\, T_{rain}$$

If $\langle R\rangle$ is expressed in terms of depth of rainfall per hour, then T_{rain} is related to P_0 via

$$T_{rain} = 8760\ P_0$$

where T_{rain} is in hours, P_0 is, of course, the fraction of raining time per year and 8760 is the number of hours in an average year. Hence, one has

$$W_{avg} = 8760\ \langle R\rangle\ P_0 \tag{3.41}$$

An expression for the first moment of the rainrate $\langle R\rangle$ is analogous to that of the specific attenuation $\langle\Gamma\rangle$ given by equation (2.52) since both quantities are governed by log-normal distributions. Thus, one has

$$\langle R\rangle = \exp\left[\ln R_m + \frac{\sigma^2_{\ln R}}{2}\right]$$

giving

$$W_{avg} = 8760\ P_0 R_m \exp\left(\frac{\sigma^2_{\ln R}}{2}\right) \tag{3.42}$$

Hence, given the geographical dependent rain parameters α, U, and W_{avg}, equations (3.38), (3.40), and (3.42) can be solved for the desired quantities P_0, R_m, and $\sigma_{\ln R}$. The method of solution will now be detailed.

From equation (3.38) one has

$$\frac{U - \ln R_m}{\sigma_{\ln R}} = \eta^{-1}\left(1 - \frac{1}{105120\ P_0}\right) \tag{3.43}$$

where $n^{-1}(\ldots)$ is the inverse normal probability function (ref. 16). Substituting this result into equation (3.40) and solving for $\sigma_{\ln R}$ gives

$$\sigma_{\ln R} = \frac{105120\ P_0}{2\pi\ \alpha} \exp\left[-\frac{\left\{n^{-1}\left(1 - \frac{1}{105120\ P_0}\right)\right\}^2}{2}\right]$$

$$= \frac{105120\ P_0}{\alpha}\ \phi, \quad \phi \equiv \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{\{n^{-1}(\ )\}^2}{2}\right] \tag{3.44}$$

Solving equation (3.43) for R_m yields

$$R_m = \exp\left[U - \sigma_{\ln R}\ n^{-1}\left(1 - \frac{1}{105120\ P_0}\right)\right] \tag{3.45}$$

Equations (3.42), (3.44), and (3.45) constitute a system of simultaneous transcendental equations to be solved for P_0, R_m, and $\sigma_{\ln R}$. Substituting equation (3.45) into equation (3.42) gives

$$W_{avg} = 8760\ P_0 \exp\left[U - \sigma_{\ln R}\ n^{-1}\left(1 - \frac{1}{105120\ P_0}\right)\right] \exp\left(\frac{\sigma^2_{\ln R}}{2}\right) \tag{3.46}$$

Substituting equation (3.44) into this relation, i.e.,

$$W_{avg} = 8760\ P_0 \exp\left[U - \frac{105120\ P_0}{\alpha}\ \phi\ n^{-1}\left(1 - \frac{1}{105120\ P_0}\right)\right] \exp\left[\frac{1}{2}\left(\frac{105120\ P_0}{\alpha}\ \phi\right)^2\right]$$

re-arranging factors and making the natural logarithm of both sides

$$\ln\left(\frac{W_{avg}}{8760\ P_0}\right) = U - \left(\frac{105120\ P_0}{\alpha}\right)\left[\phi n^{-1}\left(1 - \frac{1}{105120\ P_0}\right) - \left(\frac{1}{2}\right)\left(\frac{105120\ P_0}{\alpha}\right)\phi^2\right]$$

and solving for the P_0 factor in the coefficient of the second term gives for the final result

$$P_0 = \left(\frac{\alpha}{105120}\right) \frac{\left[U - \ln\left(\frac{W_{avg}}{8760\ P_0}\right)\right]}{\left[\phi n^{-1}\left(1 - \frac{1}{105120\ P_0}\right) - \left(\frac{1}{2}\right)\left(\frac{105120\ P_0}{\alpha}\phi\right)^2\right]} \tag{3.47}$$

which involves only one unknown, P_0. Numerically solving this equation for P_0 via, e.g., the Newton-Raphson Method, one can then use equation (3.44) to obtain $\sigma_{\ln R}$ and, with P_0 and $\sigma_{\ln R}$ calculated, solve equation (3.42) for R_m to obtain this value. Alternatively, equation (3.45) can be used to find R_m but this may allow an increased incidence of systematic errors to enter the calculation.

(C) Selection and Use of the City-by-City Meteorological Data Base To Obtain α and U

Now that the formalism has been established relating the available extreme value statistics of rainrate to the scale and location parameters (i.e., α and U) of the prevailing asymptotic probability distribution and thus, relating these to the desired log-normal parameters P_0, R_m, and $\sigma_{\ln R}$, it only remains to select one of the two data bases for site characterization. Of the two different types of data available, the intensity-duration-frequency representation is more attractive. In addition to being in a condensed format (unlike that of the separate extreme value rainrates that must be analyzed on a year-by-year basis for as long as 30 yr for each location of interest), this data set extends over a time period of 50 yr for some locations; these statistics therefore offer more stability against long-term temporal variations. For example, it is known (ref. 17) that variations in rainfall data are correlated with the 11-yr solar cycle. In addition, it has been shown (ref. 18) that rainfall and other climatic effects may be influenced by the movement of the entire solar system through interstellar dust clouds.

Of the wide range of rain gauge integration times to use, ranging from 5-min to 24 hr, the 5-min rainrate will be used. The reason for this is that the implicit 5-min time averaging takes into account the fact that the communications link slant path represents a spatial average over nonuniform rainrates (refs. 19 and 20). Assuming a rain drop descent velocity of 7 m/s, a 5-min time average corresponds to a vertical spatial average of 2.1 km. The resulting horizontal spatial average represented by a 5-min time average must also be taken into account in the attenuation model of Section 2. This is done through the use of the spatial correlation function $K(L,\theta)$ of equation (2.48) and dictates the selection of the spatial correlation coefficient L_c calculated in appendix C. This approach implicitly averages over the various size and shape parameters describing rain cells that are needed in and complicate the use of other modeling procedures (refs. 2 and 4).

A typical set of rainfall intensity duration frequency curves is shown in figure 3.1. Five such curves exist for return periods of 2, 5, 10, 25, 50, and 100 yr. As detailed earlier, however, only two curves need be used at a given rain gauge integration time (duration). The selection of which two to use is dictated as follows. To gain as much "resolution" as possible and, at the same time to assure the most temporally stable statistics, one of the curves to be used is the 2-yr return period. The other curve should be as far removed as possible from this one, e.g., the 100-yr return period curve. This would assure the inclusion of the less frequent, large rainrate events. However, most of the compiled curves for various locations are based on 40 to 50 yr of observations and some only one about 20 yr of events. Thus, it seems that use of a curve with a return period of larger than 20 yr is unjustified. Thus, the second curve to be used is the one corresponding to the 10 yr return period.

Thus, as per the remarks made above and the calculational procedure outlined in Subsection (A), one obtains from these curves the rainrates with 5-min durations (integration time) on the curves corresponding to the 2- and 10-yr return periods. In the example of figure 3.1 for Detroit, Michigan, one thus has $T_1 = 2$ yr, and $T_2 = 10$ yr with corresponding 5-min rainrates of $R_{11} = 4.10$ in./hr and $R_{12} = 6.45$ in./hr. In this case, the time base

FIGURE 3.1

extends from the years 1903 to 1949; hence, N = 46 yr. The only other parameter needed is the average yearly total rainfall. This is also a well documented statistic (ref. 21); for Detroit, one has W_{avg} = 30.97 in. These values are then used with equations (3.28), (3.29), and (3.31) to (3.35) to obtain values for α and U. The results, obtained with the algorithm and BASIC program detailed in appendix D, are α = 3.781 and U = 4.552. These values are obtained after converting the above parameters to mm/hr and mm, where applicable. These values are then introduced into equation (3.47) which is solved for P_0 via the Newton-Raphson method. This procedure is also part of the algorithm and program given in appendix D. Equations (3.44) and (3.42) are then used to obtain $\sigma_{\ln R}$ and R_m, respectively. The results are as follows: P_0 = 1.032 %, R_m = 5.831 mm/hr, and $\sigma_{\ln R}$ = 0.895 nepers. These are the only parameters needed to characterize the rainrate statistics for Detroit.

In appendix E, similar calculations are presented for 59 cities within the U.S. For each city, the input parameters are summarized: the 2- and 10-yr return period for the 5-min rainrates in millimeter/hour, the average yearly total rainfall in millimeters, and the time base. The raw rainrate statistics are then presented which constitute the scale parameter α and the location parameter U. Finally, the calculated log-normal rain statistics P_0, R_m, and $\sigma_{\ln R}$ ($\equiv$ SR) are shown.

4. APPLICATION OF THE FOREGOING TO SOME EXPERIMENTALLY OBSERVED DATA AND COMPARISON WITH PREDICTIONS OF THE TWO-COMPONENT RAIN ATTENUATION MODEL

The rain attenuation prediction model detailed in Section 2 along with the rain statistics compiled in appendix E will now be applied to satellite links along which experimentally observed attenuation events have been recorded. Ten such observed attenuation distributions will be used that range in frequencies from 12 to 30 GHz and have a range of elevation angles from 24° to 57°. Application of the attenuation prediction model of Section 2 to these situations proceeds as follows. For each city of interest, the rain statistics P_0, R_m, and $\sigma_{\ln R}$ are obtained from the compilation in appendix E. The latitude of the city determines the maximum rain height H_0, as given by equation (B.1) of appendix B. This value along with the known elevation angle θ are used in equation (2.27) to calculate the slant path range L. Equations (2.48) and (2.60) are then employed to obtain $K(L,\theta)$ and $P_0(L,\theta)$ respectively. Knowing the frequency, one then uses Table A.1 to find the corresponding values of a_v, a_h, b_v, and b_h to be used in conjunction with θ and the polarization angle τ in equation (A.1) giving the coefficients a and b; the value of τ = 45° was used throughout these calculations since this was not available from the published results. Equations (2.19) and (2.20) are then used to get Γ_m and $\sigma_{\ln R}$. One can then use equations (2.58) and (2.59) to calculate $\sigma^2_{\ln A}$ and $A_m(L,\theta)$. These two quantities along with $P_0(L,\theta)$ calculated earlier define the attenuation statistics for the particular satellite link. Equations (2.24) and (2.25) are then used to obtain $P(a \geq A)$ for any given attenuation A. Simultaneous comparison is also made with the two-component rain attenuation model applied to the satellite links in question. The detailed application of this model is given elsewhere (ref. 2) and will not be reiterated here. Figures 4.1 to 4.10 and the corresponding Tables 4.1 to 4.10 show the results of the present model (denoted there by RM 2) and that of the two-component model (denoted by 2C-RM), as applied to these links. The figures also show the

FIGURE 4.1

FIGURE 4.2

FIGURE 4.3

FIGURE 4.4

FIGURE 4.5

FIGURE 4.6

FIGURE 4.7

FIGURE 4.8

FIGURE 4.9

FIGURE 4.10

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TABLE 4.1

WALTHAM, MA. (BOSTON RAIN DATA)

FREQ = 12.00 GHz
ANTENNA ELEV. ANGLE = 24.00 DEGREES
STATION HEIGHT = 0.005 KM
STATION LATITUDE = 42.37 DEGREES
P0 = 1.566 %
RM = 5.729 mm/hr
SR (STANDARD DEVIATION OF RAINRATE) = 0.834
GLOBAL RAIN REGION: D2
POLARIZATION ANGLE = 45.0 DEGREES

PL = 3.448 %
AM = 0.521 dB
SA (STANDARD DEVIATION OF ATTEN.) = 1.116

ATTENUATION dB	PROBABILITY % (RM2)	PROBABILITY % (2C-RM)
1.0	0.96E+00	0.34E+00
3.0	0.20E+00	0.72E-01
5.0	0.73E-01	0.33E-01
7.0	0.34E-01	0.18E-01
9.0	0.18E-01	0.11E-01
11.0	0.11E-01	0.66E-02
13.0	0.68E-02	0.43E-02
15.0	0.45E-02	0.28E-02
17.0	0.31E-02	0.19E-02
19.0	0.22E-02	0.13E-02
21.0	0.16E-02	0.87E-03
23.0	0.12E-02	0.61E-03
25.0	0.90E-03	0.44E-03
27.0	0.69E-03	0.31E-03
29.0	0.54E-03	0.23E-03
31.0	0.43E-03	0.17E-03
33.0	0.34E-03	0.13E-03
35.0	0.28E-03	0.10E-03
37.0	0.23E-03	0.78E-04
39.0	0.19E-03	0.62E-04
41.0	0.16E-03	0.50E-04

TABLE 4.2

HOLMDEL, NJ. (TRENTON RAIN DATA)

FREQ = 12.00 GHz
ANTENNA ELEV. ANGLE = 27.00 DEGREES
STATION HEIGHT = 0.005 KM
STATION LATITUDE = 40.33 DEGREES
P0 = 0.659 %
RM =14.928 mm/hr
SR (STANDARD DEVIATION OF RAINRATE) = 0.666
GLOBAL RAIN REGION: D2
POLARIZATION ANGLE = 45.0 DEGREES

PL = 2.400 %
AM = 0.725 dB
SA (STANDARD DEVIATION OF ATTEN.) = 1.189

ATTENUATION dB	PROBABILITY % (RM2)	PROBABILITY % (2C-RM)
1.0	0.94E+00	0.11E+01
3.0	0.28E+00	0.26E+00
5.0	0.13E+00	0.12E+00
7.0	0.68E-01	0.65E-01
9.0	0.41E-01	0.39E-01
11.0	0.27E-01	0.26E-01
13.0	0.18E-01	0.17E-01
15.0	0.13E-01	0.12E-01
17.0	0.96E-02	0.87E-02
19.0	0.72E-02	0.64E-02
21.0	0.56E-02	0.49E-02
23.0	0.44E-02	0.37E-02
25.0	0.35E-02	0.29E-02
27.0	0.28E-02	0.23E-02
29.0	0.23E-02	0.19E-02
31.0	0.19E-02	0.15E-02
33.0	0.16E-02	0.12E-02
35.0	0.13E-02	0.10E-02
37.0	0.11E-02	0.88E-03
39.0	0.97E-03	0.74E-03
41.0	0.83E-03	0.60E-03

TABLE 4.3

HOLMDEL, NJ. (TRENTON RAIN DATA)

FREQ = 20.00 GHz
ANTENNA ELEV. ANGLE = 38.60 DEGREES
STATION HEIGHT = 0.005 KM
STATION LATITUDE = 40.33 DEGREES
P0 = 0.659 %
RM =14.928 mm/hr
SR (STANDARD DEVIATION OF RAINRATE) = 0.666
GLOBAL RAIN REGION: D2
POLARIZATION ANGLE = 45.0 DEGREES

PL = 1.641 %
AM = 2.466 dB
SA (STANDARD DEVIATION OF ATTEN.) = 1.038

ATTENUATION dB	PROBABILITY % (RM2)	PROBABILITY % (2C-RM)
1.0	0.13E+01	0.27E+01
3.0	0.70E+00	0.73E+00
5.0	0.41E+00	0.34E+00
7.0	0.26E+00	0.20E+00
9.0	0.17E+00	0.13E+00
11.0	0.12E+00	0.91E-01
13.0	0.90E-01	0.67E-01
15.0	0.67E-01	0.51E-01
17.0	0.52E-01	0.39E-01
19.0	0.40E-01	0.31E-01
21.0	0.32E-01	0.25E-01
23.0	0.26E-01	0.20E-01
25.0	0.21E-01	0.17E-01
27.0	0.17E-01	0.14E-01
29.0	0.14E-01	0.11E-01
31.0	0.12E-01	0.94E-02
33.0	0.10E-01	0.79E-02
35.0	0.87E-02	0.66E-02
37.0	0.75E-02	0.56E-02
39.0	0.64E-02	0.47E-02
41.0	0.56E-02	0.40E-02

TABLE 4.4

HOLMDEL, NJ. (TRENTON RAIN DATA)

FREQ = 30.00 GHz
ANTENNA ELEV. ANGLE = 38.60 DEGREES
STATION HEIGHT = 0.005 KM
STATION LATITUDE = 40.33 DEGREES
P0 = 0.659 %
RM =14.928 mm/hr
SR (STANDARD DEVIATION OF RAINRATE) = 0.666
GLOBAL RAIN REGION: D2
POLARIZATION ANGLE = 45.0 DEGREES

PL = 1.641 %
AM = 4.989 dB
SA (STANDARD DEVIATION OF ATTEN.) = 1.006

ATTENUATION dB	PROBABILITY % (RM2)	PROBABILITY % (2C-RM)
1.0	0.16E+01	0.54E+01
3.0	0.11E+01	0.20E+01
5.0	0.82E+00	0.10E+01
7.0	0.60E+00	0.63E+00
9.0	0.46E+00	0.42E+00
11.0	0.35E+00	0.30E+00
13.0	0.28E+00	0.23E+00
15.0	0.22E+00	0.18E+00
17.0	0.18E+00	0.14E+00
19.0	0.15E+00	0.11E+00
21.0	0.13E+00	0.94E-01
23.0	0.11E+00	0.79E-01
25.0	0.89E-01	0.67E-01
27.0	0.76E-01	0.57E-01
29.0	0.66E-01	0.49E-01
31.0	0.57E-01	0.42E-01
33.0	0.49E-01	0.37E-01
35.0	0.43E-01	0.32E-01
37.0	0.38E-01	0.28E-01
39.0	0.34E-01	0.25E-01
41.0	0.30E-01	0.22E-01

TABLE 4.5

AUSTIN, TX.

FREQ = 12.00 GHz
ANTENNA ELEV. ANGLE = 49.00 DEGREES
STATION HEIGHT = 0.170 KM
STATION LATITUDE = 30.25 DEGREES
P0 = 0.251 %
RM =31.549 mm/hr
SR (STANDARD DEVIATION OF RAINRATE) = 0.535
GLOBAL RAIN REGION: D2
POLARIZATION ANGLE = 45.0 DEGREES

PL = 1.026 %
AM = 0.995 dB
SA (STANDARD DEVIATION OF ATTEN.) = 1.233

ATTENUATION dB	PROBABILITY % (RM2)	PROBABILITY % (2C-RM)
1.0	0.51E+00	0.72E-01
3.0	0.19E+00	0.15E-01
5.0	0.98E-01	0.61E-02
7.0	0.58E-01	0.28E-02
9.0	0.38E-01	0.13E-02
11.0	0.26E-01	0.67E-03
13.0	0.19E-01	0.34E-03
15.0	0.14E-01	0.18E-03
17.0	0.11E-01	0.10E-03
19.0	0.86E-02	0.57E-04
21.0	0.68E-02	0.33E-04
23.0	0.56E-02	0.20E-04
25.0	0.46E-02	0.12E-04
27.0	0.38E-02	0.81E-05
29.0	0.32E-02	0.55E-05
31.0	0.27E-02	0.38E-05
33.0	0.23E-02	0.28E-05
35.0	0.20E-02	0.21E-05
37.0	0.17E-02	0.16E-05
39.0	0.15E-02	0.13E-05
41.0	0.13E-02	0.10E-05

TABLE 4.6

AUSTIN, TX.

FREQ = 20.00 GHz
ANTENNA ELEV. ANGLE = 52.00 DEGREES
STATION HEIGHT = 0.170 KM
STATION LATITUDE = 30.25 DEGREES
P0 = 0.251 %
RM =31.569 mm/hr
SR (STANDARD DEVIATION OF RAINRATE) = 0.535
GLOBAL RAIN REGION: D2
POLARIZATION ANGLE = 45.0 DEGREES

PL = 0.907 %
AM = 2.960 dB
SA (STANDARD DEVIATION OF ATTEN.) = 1.159

ATTENUATION dB	PROBABILITY % (RM2)	PROBABILITY % (2C-RM)
1.0	0.75E+00	0.33E+00
3.0	0.45E+00	0.57E-01
5.0	0.30E+00	0.26E-01
7.0	0.21E+00	0.15E-01
9.0	0.15E+00	0.96E-02
11.0	0.12E+00	0.63E-02
13.0	0.91E-01	0.42E-02
15.0	0.73E-01	0.28E-02
17.0	0.60E-01	0.19E-02
19.0	0.49E-01	0.13E-02
21.0	0.41E-01	0.93E-03
23.0	0.35E-01	0.65E-03
25.0	0.30E-01	0.45E-03
27.0	0.26E-01	0.32E-03
29.0	0.22E-01	0.23E-03
31.0	0.19E-01	0.16E-03
33.0	0.17E-01	0.11E-03
35.0	0.15E-01	0.82E-04
37.0	0.13E-01	0.60E-04
39.0	0.12E-01	0.43E-04
41.0	0.11E-01	0.32E-04

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TABLE 4.7

AUSTIN, TX.

FREQ = 30.00 GHz
ANTENNA ELEV. ANGLE = 52.00 DEGREES
STATION HEIGHT = 0.170 KM
STATION LATITUDE = 30.25 DEGREES
P0 = 0.251 %
RM =31.569 mm/hr
SR (STANDARD DEVIATION OF RAINRATE) = 0.535
GLOBAL RAIN REGION: D2
POLARIZATION ANGLE = 45.0 DEGREES

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PL = 0.907 %
AM = 5.675 dB
SA (STANDARD DEVIATION OF ATTEN.) = 1.140

ATTENUATION dB	PROBABILITY % (RM2)	PROBABILITY % (2C-RM)
1.0	0.85E+00	0.10E+01
3.0	0.65E+00	0.17E+00
5.0	0.49E+00	0.72E-01
7.0	0.39E+00	0.42E-01
9.0	0.31E+00	0.28E-01
11.0	0.25E+00	0.20E-01
13.0	0.21E+00	0.15E-01
15.0	0.18E+00	0.12E-01
17.0	0.15E+00	0.90E-02
19.0	0.13E+00	0.70E-02
21.0	0.11E+00	0.55E-02
23.0	0.10E+00	0.44E-02
25.0	0.88E-01	0.35E-02
27.0	0.78E-01	0.27E-02
29.0	0.69E-01	0.22E-02
31.0	0.62E-01	0.17E-02
33.0	0.56E-01	0.14E-02
35.0	0.50E-01	0.11E-02
37.0	0.45E-01	0.88E-03
39.0	0.41E-01	0.71E-03
41.0	0.38E-01	0.57E-03

TABLE 4.8

TAMPA, FL.

FREQ = 20.00 GHz
ANTENNA ELEV. ANGLE = 57.00 DEGREES
STATION HEIGHT = 0.005 KM
STATION LATITUDE = 27.95 DEGREES
P0 = 0.449 %
RM =25.101 mm/hr
SR (STANDARD DEVIATION OF RAINRATE) = 0.608
GLOBAL RAIN REGION: E
POLARIZATION ANGLE = 45.0 DEGREES

PL = 0.966 %
AM = 4.829 dB
SA (STANDARD DEVIATION OF ATTEN.) = 0.979

ATTENUATION dB	PROBABILITY % (RM2)	PROBABILITY % (2C-RM)
1.0	0.91E+00	0.45E+01
3.0	0.66E+00	0.17E+01
5.0	0.47E+00	0.96E+00
7.0	0.34E+00	0.64E+00
9.0	0.25E+00	0.47E+00
11.0	0.19E+00	0.36E+00
13.0	0.15E+00	0.28E+00
15.0	0.12E+00	0.23E+00
17.0	0.96E-01	0.19E+00
19.0	0.78E-01	0.16E+00
21.0	0.64E-01	0.13E+00
23.0	0.53E-01	0.11E+00
25.0	0.45E-01	0.96E-01
27.0	0.38E-01	0.83E-01
29.0	0.32E-01	0.72E-01
31.0	0.28E-01	0.63E-01
33.0	0.24E-01	0.55E-01
35.0	0.21E-01	0.49E-01
37.0	0.18E-01	0.43E-01
39.0	0.16E-01	0.38E-01
41.0	0.14E-01	0.34E-01

TABLE 4.9

CLARKSBURG, MD. (BALTIMORE RAIN DATA)

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FREQ = 20.00 GHz
ANTENNA ELEV. ANGLE = 43.50 DEGREES
STATION HEIGHT = 0.050 KM
STATION LATITUDE = 39.25 DEGREES
P0 = 0.827 %
RM =10.680 mm/hr
SR (STANDARD DEVIATION OF RAINRATE) = 0.796
GLOBAL RAIN REGION: D2
POLARIZATION ANGLE = 45.0 DEGREES

PL = 1.605 %
AM = 2.244 dB
SA (STANDARD DEVIATION OF ATTEN.) = 1.048

ATTENUATION dB	PROBABILITY % (RM2)	PROBABILITY % (2C-RM)
1.0	0.13E+01	0.62E+00
3.0	0.63E+00	0.11E+00
5.0	0.36E+00	0.51E-01
7.0	0.22E+00	0.30E-01
9.0	0.15E+00	0.20E-01
11.0	0.10E+00	0.14E-01
13.0	0.75E-01	0.10E-01
15.0	0.56E-01	0.74E-02
17.0	0.43E-01	0.55E-02
19.0	0.33E-01	0.41E-02
21.0	0.26E-01	0.31E-02
23.0	0.21E-01	0.23E-02
25.0	0.17E-01	0.18E-02
27.0	0.14E-01	0.13E-02
29.0	0.12E-01	0.10E-02
31.0	0.98E-02	0.78E-03
33.0	0.83E-02	0.60E-03
35.0	0.70E-02	0.46E-03
37.0	0.60E-02	0.36E-03
39.0	0.52E-02	0.28E-03
41.0	0.45E-02	0.22E-03

TABLE 4.10

CLARKSBURG, MD. (BALTIMORE RAIN DATA)

FREQ = 30.00 GHz
ANTENNA ELEV. ANGLE = 43.50 DEGREES
STATION HEIGHT = 0.050 KM
STATION LATITUDE = 39.25 DEGREES
P0 = 0.827 %
RM =10.680 mm/hr
SR (STANDARD DEVIATION OF RAINRATE) = 0.796
GLOBAL RAIN REGION: D2
POLARIZATION ANGLE = 45.0 DEGREES

PL = 1.605 %
AM = 4.650 dB
SA (STANDARD DEVIATION OF ATTEN.) = 1.002

ATTENUATION dB	PROBABILITY % (RM2)	PROBABILITY % (2C-RM)
1.0	0.15E+01	0.18E+01
3.0	0.11E+01	0.36E+00
5.0	0.76E+00	0.15E+00
7.0	0.55E+00	0.85E-01
9.0	0.41E+00	0.57E-01
11.0	0.31E+00	0.41E-01
13.0	0.24E+00	0.31E-01
15.0	0.19E+00	0.24E-01
17.0	0.16E+00	0.20E-01
19.0	0.13E+00	0.16E-01
21.0	0.11E+00	0.13E-01
23.0	0.89E-01	0.11E-01
25.0	0.75E-01	0.90E-02
27.0	0.64E-01	0.75E-02
29.0	0.54E-01	0.63E-02
31.0	0.47E-01	0.53E-02
33.0	0.40E-01	0.44E-02
35.0	0.35E-01	0.37E-02
37.0	0.31E-01	0.31E-02
39.0	0.27E-01	0.27E-02
41.0	0.24E-01	0.22E-02

observed attenuation distributions on these links. It must be remembered that these observations span a time period of no more than 2 yr, whereas the rain statistics from which the theoretical predictions are made cover a period of about 50 yr. Thus, some statistical instability can be expected. This is demonstrated in figures 4.1 and 4.2 where two consecutive years of observations are shown. This is an implicit problem (and potential danger) of applying <u>average</u> yearly predictions to <u>actual</u> yearly observations.

These results show that for cities in regions where the two-component model was extensively tested during its development, the present model agrees well with it and the observed data. However, cases do exist where the results of the two-component model diverge from those of the present one and the observed data; in particular, those cases for Austin, TX and Clarksburg, MD. This is probably due to the fact that the two-component model assigns typical rain statistics parameters over wide spatial regions and thus does not account for small-scale (on the order of about 100 mi) variations of geography that may perturb rainfall, e.g., changes of elevation, lakes, etc. On the other hand, the model formulated here is specific for each city that has a long term meteorological record of rainfall and assigns rain statistics parameters on this basis. It should be noted that in some cases, e.g., Holmdel, NJ, cities are encountered that do not have such a record. In this case, the closest city must of course be considered, but these are usually well within 100 mi of the location of interest.

These few examples are not enough to rigorously critique any rain model (if, indeed such is possible due to the implicit time averaging mentioned earlier) but they do serve as examples of the results of the two different approaches.

5. APPLICATION OF THE RAIN ATTENUATION MODEL FOR THE 30/20 GHz ACTS PROJECT

In this section, application of the results of Sections 2 and 3 will be made to the proposed Advanced Communication Technology Satellite with uplinks at 30 GHz and downlinks at 20 GHz. The satellite is taken to be located in a geosynchronous orbit longitude 100° W. Yearly attenuation predictions for the 59 cities, the rain statistics of which appear in appendix E, will be calculated.

At the outset, it is necessary to obtain the link elevation angles to ACTS for a given city. As shown in appendix F, letting L_S be the longitude of the geostationary satellite, L_E be the longitude of the Earth station, and Λ be the latitude of the Earth station, one has for the antenna elevation angle at this site

$$\theta = \sin^{-1}\left\{\frac{R \cos \Lambda \cos w - R_0}{\left(R^2 + R_0^2 - 2R_0 R \cos \Lambda \cos w\right)^{1/2}}\right\} \tag{5.1}$$

where $R_0 = 6370$ km is the radius of the Earth and $R = 42\ 230$ km is the radius of the geostationary orbit with respect to the center of the Earth. The quantity w is the relative longitude of the Earth station, given by

$$w = |L_E - L_S| \tag{5.2}$$

The elevation angle θ, as well as the rain statistics P_0, R_m, and $\sigma_{\ln R}$, the maximum rain height H (determined from the latitude of the site Λ and eq. (B.1)) and the height of the station above sea level are the parameters needed in the rain attenuation model to completely characterize the Earth station. The operating frequency and polarization angle τ determine the coefficients a and b by the procedure outlined in appendix A. At this point, the calculational procedure is the same as outlined in section 4. A typical flow chart of the algorithm is shown in Figure 5.1.

In the 59 tables that follow, probabilities of attenuations are shown for values ranging from 5 to 25 dB for 20 and 30 GHz communications links of ACTS. In addition to the yearly probabilities shown (in percent of an average year - 8766 hr), a "worst month" probability is also calculated (in percent of an average month = 730.5 hr); since the occurrence of rain is variable from month to month, there is an agreed upon procedure set forth by CCIR (refs. 29 and 30) to estimate the percent of an average month that has the <u>largest</u> occurrence of rain, i.e., the worst month. The relationship giving the worst month probability P_W in terms of the corresponding yearly probability P is

$$P_W = (3.448\ P)^{0.8696} \tag{5.3}$$

Also shown is the atmospheric molecular absorption ("clear air") attenuation, due mostly to the presence of water vapor on oxygen. This parameter, which is a constant for a given propagation link, is calculated from (ref. 31)

$$A_G = \frac{\gamma_o h_o \exp\left(\dfrac{-h_w}{h_o}\right) + \gamma_w h_w}{\sin\theta} \tag{5.4}$$

where γ_O and γ_W are the specific attenuations due to, respectively, oxygen and water vapor and h_O and h_W are the apparent heights of vertically uniform oxygen and water vapor with loss characteristics identical to those of the actual atmosphere. These four parameters are related to the operating frequency f and water vapor density ρ_W by

$$\gamma_o = 10^{-3}\left[\frac{7.1}{f^2 + 0.36} + \frac{4.5}{(f - 57)^2 + 0.98}\right] f^2 \tag{5.5}$$

$$\gamma_w = 10^{-4}\left[0.067 + \frac{3}{(f - 22.3)^2 + 7.3}\right]\rho_w f^2 \tag{5.6}$$

$$h_o = 6\ . \tag{5.7}$$

and

$$h_w = 2.2 + \frac{3}{(f - 22.3)^2 + 3} \tag{5.8}$$

It must be noted (refs. 30 and 31) that equations (5.4) to (5.8) only hold for elevation angles $\theta > 10°$ and frequencies $f < 50$ GHz.

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The water vapor density ρ_W is a function of the location of the Earth station, time of year, and time of day (refs. 30 and 31). However, for the cases here, a typical value of $\rho_W = 10$ g/m^3 was assumed.

The description and use of the data shown in these tables will now be given. The computer software used to generate this information is the subject of appendix G.

Figure 5.2 shows an example of the format of typical attenuation prediction, in this case for Cleveland, Ohio.

Lines 1 to 3 are the input data to the model characterizing the terminal location. Line 1 is the station height, in kilometers, above sea level. Lines 2 and 3 are the latitude and longitude of the site. From these data and given a satellite in a geosynchronous orbit at longitude 100° W, an antenna elevation angle is calculated and displayed in line 4. Based on his data and the maximum rain height data built into the model algorithm, lines 5 and 6 are calculated. The data in lines 7 to 9 are, like those of lines 1 to 3, basic input data into the model characterizing the terminal site in terms of its rain statistics P_0, R_m, and S_R. The quantity P_0 is the probability that it will rain at the terminal site, R_m is the median (or mean) rainrate that will occur and S_R is the standard deviation of the logarithm of this rainrate.

Line 10 is also a basic input into the model specifying the polarization tilt of the incident wave field at the terminal antenna. In this case, as in all other cases, it shows a polarization tilt of 45° which represents a circularly polarized wave.

All of the data shown in lines 1 to 10 enter into the rain attenuation model calculations to give the output data that is of interest to a system designer performing link power budget calculations; these are the log-normal attenuation statistics for the 20 GHz downlink, shown in lines 11 to 15, and the 30 GHz uplink, shown in lines 16 to 20.

Consider lines 11 to 13; these give the log-normal attenuation statistics for the 20 GHz ACTS downlink at the terminal site characterized by the data in lines 1 to 10. The probability of attenuation PL in line 11 is the probability that attenuation (i.e., rain) will occur along the extended slant path. The median attenuation A_m is listed in line 12 and the standard deviation S_A of the logarithm of the attenuation is given in line 13. Now since the probability density of attenuation occurring along the link is taken to be log-normal the cumulative probability distribution of an observed attenuation, a, being equal to or greater than some given attenuation, A, is

$$P(a \geq A) = \left(\frac{1}{2}\right)(PL)\ \mathrm{erfc}(X) \tag{5.9}$$

where

$$X = \frac{\ln A - \ln A_m}{\sqrt{2}\ S_A} \tag{5.10}$$

FIGURE 5.2

where erfc(...) is the complementary error function. In this particular example, P_L = 2.097 percent, A_m = 1.319 dB and S_A = 1.097; thus, equations (5.9) and (5.10) become

$$P(a \geq A) = 1.049 \text{ erfc}(X) \tag{5.11}$$

with

$$X = \frac{\ln A - 0.2769}{1.5514} \tag{5.12}$$

giving the attenuation statistics (in percent of a year) for the Cleveland 20 GHz downlink. Line 14 is a computation of equations (5.11) and (5.12) for selected attenuations A of 5, 10, 15, 20, and 25 dB. These values appear in the second column. For example, an attenuation of 5 dB will be equaled or exceeded for 0.236 percent of the year which corresponds to about 20.7 min out of an average year. (There are 8766 hr/average year of 365.25 days.) The third column gives the probability of the selected attenuations being observed in the "worst month." Finally, line 15 gives the constant "clear air" attenuation along the link due to atmospheric molecular absorption. This is the attenuation that will exist along the link whether or not it is raining.

The information contained in equations (5.11) and (5.12) can be used to find the availability given any attenuation (the direct problem) or the attenuation given the availability (the inverse problem). The direct problem can be evaluated using equations (5.11) and (5.12) in conjunction with tabulations of the erfc function given in Table 5.1. For example, suppose it is desired to find the availability for an attenuation of A = 18 dB. Substituting this value into equation (5.12) gives

$$X = 1.685$$

From table I, one has for X = 1.685, by linear interpolation,

$$\text{erfc}(1.685) = 0.0172$$

Thus, by equation (5.11),

$$P(a \geq 18 \text{ dB}) = 0.018 \text{ percent}$$

The worst month probability is, from equation (5.3), P_W = 0.089 percent of a month.

For the inverse problem, consider the availability of 0.018 percent as calculated above; suppose it is required to find the corresponding attenuation. To solve this problem, one must consider the expression that is the inverse to that of equation (5.9), i.e., given $P(a \geq A)$ what is the corresponding X and, by equation (5.10), the corresponding attenuation A. This problem is solved via the following procedure. Given $P(a \geq A)$ one forms the quantity

$$t = (-2 \ln p)^{1/2} \tag{5.13}$$

where

TABLE 5.1

COMPLEMENTARY ERROR FUNCTION TABLE

X	ERFC(X)	X	ERFC(X)	X	ERFC(X)	X	ERFC(X)
-2.00	1.9953	-1.50	1.9661	-1.00	1.8427	-0.50	1.5205
-1.99	1.9951	-1.49	1.9649	-0.99	1.8385	-0.49	1.5117
-1.98	1.9949	-1.48	1.9637	-0.98	1.8342	-0.48	1.5027
-1.97	1.9947	-1.47	1.9624	-0.97	1.8299	-0.47	1.4937
-1.96	1.9944	-1.46	1.9611	-0.96	1.8254	-0.46	1.4847
-1.95	1.9942	-1.45	1.9597	-0.95	1.8209	-0.45	1.4755
-1.94	1.9939	-1.44	1.9583	-0.94	1.8163	-0.44	1.4662
-1.93	1.9937	-1.43	1.9569	-0.93	1.8116	-0.43	1.4569
-1.92	1.9934	-1.42	1.9554	-0.92	1.8068	-0.42	1.4475
-1.91	1.9931	-1.41	1.9539	-0.91	1.8019	-0.41	1.4380
-1.90	1.9928	-1.40	1.9523	-0.90	1.7969	-0.40	1.4284
-1.89	1.9925	-1.39	1.9507	-0.89	1.7918	-0.39	1.4187
-1.88	1.9922	-1.38	1.9490	-0.88	1.7867	-0.38	1.4090
-1.87	1.9918	-1.37	1.9473	-0.87	1.7814	-0.37	1.3992
-1.86	1.9915	-1.36	1.9456	-0.86	1.7761	-0.36	1.3893
-1.85	1.9911	-1.35	1.9438	-0.85	1.7707	-0.35	1.3794
-1.84	1.9907	-1.34	1.9419	-0.84	1.7651	-0.34	1.3694
-1.83	1.9903	-1.33	1.9400	-0.83	1.7595	-0.33	1.3593
-1.82	1.9899	-1.32	1.9381	-0.82	1.7538	-0.32	1.3491
-1.81	1.9895	-1.31	1.9361	-0.81	1.7480	-0.31	1.3389
-1.80	1.9891	-1.30	1.9340	-0.80	1.7421	-0.30	1.3286
-1.79	1.9886	-1.29	1.9319	-0.79	1.7361	-0.29	1.3183
-1.78	1.9882	-1.28	1.9297	-0.78	1.7300	-0.28	1.3079
-1.77	1.9877	-1.27	1.9275	-0.77	1.7238	-0.27	1.2974
-1.76	1.9872	-1.26	1.9252	-0.76	1.7175	-0.26	1.2869
-1.75	1.9867	-1.25	1.9229	-0.75	1.7112	-0.25	1.2763
-1.74	1.9861	-1.24	1.9205	-0.74	1.7047	-0.24	1.2657
-1.73	1.9856	-1.23	1.9181	-0.73	1.6981	-0.23	1.2550
-1.72	1.9850	-1.22	1.9155	-0.72	1.6914	-0.22	1.2443
-1.71	1.9844	-1.21	1.9130	-0.71	1.6847	-0.21	1.2335
-1.70	1.9838	-1.20	1.9103	-0.70	1.6778	-0.20	1.2227
-1.69	1.9832	-1.19	1.9076	-0.69	1.6708	-0.19	1.2118
-1.68	1.9825	-1.18	1.9048	-0.68	1.6638	-0.18	1.2009
-1.67	1.9818	-1.17	1.9020	-0.67	1.6566	-0.17	1.1900
-1.66	1.9811	-1.16	1.8991	-0.66	1.6494	-0.16	1.1790
-1.65	1.9804	-1.15	1.8961	-0.65	1.6420	-0.15	1.1680
-1.64	1.9796	-1.14	1.8931	-0.64	1.6346	-0.14	1.1569
-1.63	1.9788	-1.13	1.8900	-0.63	1.6270	-0.13	1.1459
-1.62	1.9780	-1.12	1.8868	-0.62	1.6194	-0.12	1.1348
-1.61	1.9772	-1.11	1.8835	-0.61	1.6117	-0.11	1.1236
-1.60	1.9763	-1.10	1.8802	-0.60	1.6039	-0.10	1.1125
-1.59	1.9755	-1.09	1.8768	-0.59	1.5959	-0.09	1.1013
-1.58	1.9745	-1.08	1.8733	-0.58	1.5879	-0.08	1.0901
-1.57	1.9736	-1.07	1.8698	-0.57	1.5798	-0.07	1.0789
-1.56	1.9726	-1.06	1.8661	-0.56	1.5716	-0.06	1.0676
-1.55	1.9716	-1.05	1.8624	-0.55	1.5633	-0.05	1.0564
-1.54	1.9706	-1.04	1.8586	-0.54	1.5549	-0.04	1.0451
-1.53	1.9695	-1.03	1.8548	-0.53	1.5465	-0.03	1.0338
-1.52	1.9684	-1.02	1.8508	-0.52	1.5379	-0.02	1.0226
-1.51	1.9673	-1.01	1.8468	-0.51	1.5292	-0.01	1.0113
-1.50	1.9661	-1.00	1.8427	-0.50	1.5205	0.00	1.0000

TABLE 5.1 (CONTINUED)

COMPLEMENTARY ERROR FUNCTION TABLE

X	ERFC(X)	X	ERFC(X)	X	ERFC(X)	X	ERFC(X)
0.00	1.0000	0.50	0.4795	1.00	0.1573	1.50	0.0339
0.01	0.9887	0.51	0.4708	1.01	0.1532	1.51	0.0327
0.02	0.9774	0.52	0.4621	1.02	0.1492	1.52	0.0316
0.03	0.9662	0.53	0.4535	1.03	0.1452	1.53	0.0305
0.04	0.9549	0.54	0.4451	1.04	0.1414	1.54	0.0294
0.05	0.9436	0.55	0.4367	1.05	0.1376	1.55	0.0284
0.06	0.9324	0.56	0.4284	1.06	0.1339	1.56	0.0274
0.07	0.9211	0.57	0.4202	1.07	0.1302	1.57	0.0264
0.08	0.9099	0.58	0.4121	1.08	0.1267	1.58	0.0255
0.09	0.8987	0.59	0.4041	1.09	0.1232	1.59	0.0245
0.10	0.8875	0.60	0.3961	1.10	0.1198	1.60	0.0237
0.11	0.8764	0.61	0.3883	1.11	0.1165	1.61	0.0228
0.12	0.8652	0.62	0.3806	1.12	0.1132	1.62	0.0220
0.13	0.8541	0.63	0.3730	1.13	0.1100	1.63	0.0212
0.14	0.8431	0.64	0.3654	1.14	0.1069	1.64	0.0204
0.15	0.8320	0.65	0.3580	1.15	0.1039	1.65	0.0196
0.16	0.8210	0.66	0.3506	1.16	0.1009	1.66	0.0189
0.17	0.8100	0.67	0.3434	1.17	0.0980	1.67	0.0182
0.18	0.7991	0.68	0.3362	1.18	0.0952	1.68	0.0175
0.19	0.7882	0.69	0.3292	1.19	0.0924	1.69	0.0168
0.20	0.7773	0.70	0.3222	1.20	0.0897	1.70	0.0162
0.21	0.7665	0.71	0.3153	1.21	0.0870	1.71	0.0156
0.22	0.7557	0.72	0.3086	1.22	0.0845	1.72	0.0150
0.23	0.7450	0.73	0.3019	1.23	0.0819	1.73	0.0144
0.24	0.7343	0.74	0.2953	1.24	0.0795	1.74	0.0139
0.25	0.7237	0.75	0.2888	1.25	0.0771	1.75	0.0133
0.26	0.7131	0.76	0.2825	1.26	0.0748	1.76	0.0128
0.27	0.7026	0.77	0.2762	1.27	0.0725	1.77	0.0123
0.28	0.6921	0.78	0.2700	1.28	0.0703	1.78	0.0118
0.29	0.6817	0.79	0.2639	1.29	0.0681	1.79	0.0114
0.30	0.6714	0.80	0.2579	1.30	0.0660	1.80	0.0109
0.31	0.6611	0.81	0.2520	1.31	0.0639	1.81	0.0105
0.32	0.6509	0.82	0.2462	1.32	0.0619	1.82	0.0101
0.33	0.6407	0.83	0.2405	1.33	0.0600	1.83	0.0097
0.34	0.6306	0.84	0.2349	1.34	0.0581	1.84	0.0093
0.35	0.6206	0.85	0.2293	1.35	0.0562	1.85	0.0089
0.36	0.6107	0.86	0.2239	1.36	0.0544	1.86	0.0085
0.37	0.6008	0.87	0.2186	1.37	0.0527	1.87	0.0082
0.38	0.5910	0.88	0.2133	1.38	0.0510	1.88	0.0078
0.39	0.5813	0.89	0.2082	1.39	0.0493	1.89	0.0075
0.40	0.5716	0.90	0.2031	1.40	0.0477	1.90	0.0072
0.41	0.5620	0.91	0.1981	1.41	0.0461	1.91	0.0069
0.42	0.5525	0.92	0.1932	1.42	0.0446	1.92	0.0066
0.43	0.5431	0.93	0.1884	1.43	0.0431	1.93	0.0063
0.44	0.5338	0.94	0.1837	1.44	0.0417	1.94	0.0061
0.45	0.5245	0.95	0.1791	1.45	0.0403	1.95	0.0058
0.46	0.5153	0.96	0.1746	1.46	0.0389	1.96	0.0056
0.47	0.5063	0.97	0.1701	1.47	0.0376	1.97	0.0053
0.48	0.4973	0.98	0.1658	1.48	0.0363	1.98	0.0051
0.49	0.4883	0.99	0.1615	1.49	0.0351	1.99	0.0049
0.50	0.4795	1.00	0.1573	1.50	0.0339	2.00	0.0047

$$p \equiv \frac{P(a \geq A)}{PL} \qquad (5.14)$$

The quantity X is then calculated from the expression (ref. 16)

$$X = \frac{1}{\sqrt{2}} \left[t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right] \qquad (5.15)$$

where

$$\begin{aligned} c_0 &= 2.515517 & d_1 &= 1.432788 \\ c_1 &= 0.802853 & d_2 &= 0.189269 \\ c_2 &= 0.010328 & d_3 &= 0.001308 \end{aligned}$$

Equations (5.13) to (5.15) hold so long as the condition

$$0 < p \leq 0.5 \qquad (5.16)$$

is satisfied.

Using the above example, one has $P(a \geq A) = 0.018$ percent and $PL = 2.097$ percent. Thus

$$p = \frac{0.018}{2.097} = 8.584 \times 10^{-3}$$

This quantity satisfies the condition of equation (5.16). Equations (5.13) and (5.15) thus give

$$t = 3.0848$$

$$X = 1.6854 \qquad (5.17)$$

Using equation (5.17) in equation (5.12) (the latter is specific only to this problem; the more general relation to use is equation (5.10)) and solving for A gives

$$1.6854 = \frac{\ln A - 0.2769}{1.5514}$$

$$\Rightarrow \ln A = 2.892$$

$$A = 18.00 \text{ dB}$$

The same procedure applies for lines 16 to 20 for the 30 GHz uplink. In this case for Cleveland, the parameters to use here are $PL = 2.097$ %, $A_m = 2.869$ dB, and $S_R = 1.037$. These parameters are then used in equations (5.9) and (5.10) for the direct problem, and in equations (5.13) to (5.15) and equation (5.10) for the inverse problem.

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CITY, STATE OF TERMINAL: JUNEAU, AK.

STATION HEIGHT IN KM = 0.005
STATION LATITUDE IN DEG. N. = 58.30
TERMINAL LONGITUDE IN DEG. W. = 134.42
ANTENNA ELEV. ANGLE = 17.41
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.57
SLANT PATH PROJECTION ON EARTH IN KM = 6.27
PO IN % =36.390
RM IN mm/hr = 0.209
SR = 1.189
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 37.309 %
MEAN ATTENUATION Am = 0.103 dB
STANDARD DEV. OF ATTENUATION = 1.124

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.010	0.055
10.00	0.001	0.006
15.00	0.000	0.002
20.00	0.000	0.001
25.00	0.000	0.000

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 1.045 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 37.309 %
MEAN ATTENUATION Am = 0.282 dB
STANDARD DEV. OF ATTENUATION = 1.029

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.098	0.389
10.00	0.010	0.053
15.00	0.002	0.014
20.00	0.001	0.005
25.00	0.000	0.002

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.758 dB

CITY, STATE OF TERMINAL: PHOENIX, AZ.

STATION HEIGHT = 0.335
STATION LATITUDE IN DEG. N. = 33.45
TERMINAL LONGITUDE IN DEG. W. = 112.07
ANTENNA ELEV. ANGLE = 49.00
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.46
SLANT PATH PROJECTION ON EARTH IN KM = 3.58
P0 IN % =0.280
RM IN mm/hr = 4.847
SR = 0.916
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 0.931 %
MEAN ATTENUATION Am = 0.412 dB
STANDARD DEV. OF ATTENUATION = 1.381

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.033	0.151
10.00	0.010	0.052
15.00	0.004	0.026
20.00	0.002	0.015
25.00	0.001	0.010

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.415 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 0.931 %
MEAN ATTENUATION Am = 0.903 dB
STANDARD DEV. OF ATTENUATION = 1.335

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.093	0.372
10.00	0.033	0.152
15.00	0.016	0.082
20.00	0.009	0.051
25.00	0.006	0.034

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.300 dB

CITY, STATE OF TERMINAL: FRESNO, CA.

STATION HEIGHT = 0.101
STATION LATITUDE IN DEG. N. = 36.73
TERMINAL LONGITUDE IN DEG. W. = 119.78
ANTENNA ELEV. ANGLE = 42.57
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.95
SLANT PATH PROJECTION ON EARTH IN KM = 4.38
PO IN % = 15.087
RM IN mm/hr = 0.043
SR = 1.765
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 15.842%
MEAN ATTENUATION Am = 0.016 dB
STANDARD DEV. OF ATTENUATION = 1.835

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.013	0.068
10.00	0.003	0.021
15.00	0.001	0.010
20.00	0.001	0.006
25.00	0.000	0.004

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.462 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 15.842%
MEAN ATTENUATION Am = 0.048 dB
STANDARD DEV. OF ATTENUATION = 1.704

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.051	0.219
10.00	0.014	0.070
15.00	0.006	0.034
20.00	0.003	0.020
25.00	0.002	0.013

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.335 dB

CITY, STATE OF TERMINAL: LOS ANGELES, CA.

STATION HEIGHT = 0.061
STATION LATITUDE IN DEG. N. = 34.07
TERMINAL LONGITUDE IN DEG. W. = 118.25
ANTENNA ELEV. ANGLE = 45.85
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.04
SLANT PATH PROJECTION ON EARTH IN KM = 4.21
P0 IN % =1.087
RM IN mm/hr = 2.195
SR = 0.933
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.915 %
MEAN ATTENUATION Am = 0.512 dB
STANDARD DEV. OF ATTENUATION = 1.126

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.041	0.183
10.00	0.008	0.044
15.00	0.003	0.016
20.00	0.001	0.008
25.00	0.001	0.004

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.436 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.915 %
MEAN ATTENUATION Am = 1.187 dB
STANDARD DEV. OF ATTENUATION = 1.066

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.170	0.628
10.00	0.044	0.193
15.00	0.017	0.083
20.00	0.008	0.043
25.00	0.004	0.025

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.316 dB

CITY, STATE OF TERMINAL: SAN DIEGO, CA.

STATION HEIGHT = 0.006
STATION LATITUDE IN DEG. N. = 32.72
TERMINAL LONGITUDE IN DEG. W. = 117.15
ANTENNA ELEV. ANGLE = 47.68
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.12
SLANT PATH PROJECTION ON EARTH IN KM = 4.12
P0 IN % =0.558
RM IN mm/hr = 3.174
SR = 0.920
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.364 %
MEAN ATTENUATION Am = 0.471 dB
STANDARD DEV. OF ATTENUATION = 1.254

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.041	0.181
10.00	0.010	0.054
15.00	0.004	0.024
20.00	0.002	0.013
25.00	0.001	0.008

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.423 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.364 %
MEAN ATTENUATION Am = 1.065 dB
STANDARD DEV. OF ATTENUATION = 1.202

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.135	0.515
10.00	0.043	0.189
15.00	0.019	0.093
20.00	0.010	0.054
25.00	0.006	0.034

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.307 dB

CITY, STATE OF TERMINAL: SAN FRANSICSO, CA.

STATION HEIGHT = 0.009
STATION LATITUDE IN DEG. N. = 37.78
TERMINAL LONGITUDE IN DEG. W. = 112.42
ANTENNA ELEV. ANGLE = 44.33
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.74
SLANT PATH PROJECTION ON EARTH IN KM = 4.11
P0 IN % =2.104
RM IN mm/hr = 1.654
SR = 0.987
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 2.895 %
MEAN ATTENUATION Am = 0.517 dB
STANDARD DEV. OF ATTENUATION = 1.072

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.050	0.215
10.00	0.008	0.045
15.00	0.002	0.016
20.00	0.001	0.007
25.00	0.000	0.003

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.448 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 2.895 %
MEAN ATTENUATION Am = 1.224 dB
STANDARD DEV. OF ATTENUATION = 1.002

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.232	0.823
10.00	0.052	0.225
15.00	0.018	0.089
20.00	0.008	0.042
25.00	0.004	0.023

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.324 dB

CITY, STATE OF TERMINAL: DENVER, CO.

STATION HEIGHT = 1.600
STATION LATITUDE IN DEG. N. = 39.73
TERMINAL LONGITUDE IN DEG. W. = 104.98
ANTENNA ELEV. ANGLE = 43.75
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 3.22
SLANT PATH PROJECTION ON EARTH IN KM = 2.33
PO IN % =2.714
RM IN mm/hr = 0.646
SR = 1.363
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 3.019 %
MEAN ATTENUATION Am = 0.135 dB
STANDARD DEV. OF ATTENUATION = 1.449

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.019	0.094
10.00	0.004	0.027
15.00	0.002	0.012
20.00	0.001	0.006
25.00	0.000	0.004

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.452 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 3.019 %
MEAN ATTENUATION Am = 0.342 dB
STANDARD DEV. OF ATTENUATION = 1.350

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.071	0.294
10.00	0.019	0.092
15.00	0.008	0.043
20.00	0.004	0.024
25.00	0.002	0.015

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.328 dB

CITY, STATE OF TERMINAL: HARTFORD, CT.

STATION HEIGHT = 0.030
STATION LATITUDE IN DEG. N. = 41.77
TERMINAL LONGITUDE IN DEG. W. = 72.68
ANTENNA ELEV. ANGLE = 34.35
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.37
SLANT PATH PROJECTION ON EARTH IN KM = 5.26
P0 IN % =1.457
RM IN mm/hr = 6.168
SR = 0.848
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 2.591 %
MEAN ATTENUATION Am = 1.687 dB
STANDARD DEV. OF ATTENUATION = 1.014

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.368	1.230
10.00	0.103	0.406
15.00	0.040	0.180
20.00	0.019	0.094
25.00	0.010	0.054

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.554 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 2.591 %
MEAN ATTENUATION Am = 3.635 dB
STANDARD DEV. OF ATTENUATION = 0.960

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.958	2.827
10.00	0.378	1.259
15.00	0.181	0.664
20.00	0.098	0.389
25.00	0.058	0.245

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.402 dB

CITY, STATE OF TERMINAL: WASHINGTON, D.C.

STATION HEIGHT = 0.013
STATION LATITUDE IN DEG. N. = 38.90
TERMINAL LONGITUDE IN DEG. W. = 77.03
ANTENNA ELEV. ANGLE = 39.04
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.19
SLANT PATH PROJECTION ON EARTH IN KM = 4.80
PO IN % =0.477
RM IN mm/hr =19.892
SR = 0.622
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.488 %
MEAN ATTENUATION Am = 2.470 dB
STANDARD DEV. OF ATTENUATION = 1.109

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.391	1.295
10.00	0.154	0.578
15.00	0.077	0.317
20.00	0.044	0.195
25.00	0.027	0.129

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.497 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.488 %
MEAN ATTENUATION Am = 4.895 dB
STANDARD DEV. OF ATTENUATION = 1.083

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.732	2.238
10.00	0.379	1.262
15.00	0.224	0.799
20.00	0.144	0.544
25.00	0.098	0.390

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.360 dB

CITY, STATE OF TERMINAL: JACKSONVILLE, FL.

STATION HEIGHT = 0.006
STATION LATITUDE IN DEG. N. = 30.33
TERMINAL LONGITUDE IN DEG. W. = 81.65
ANTENNA ELEV. ANGLE = 49.37
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.27
SLANT PATH PROJECTION ON EARTH IN KM = 4.08
PO IN % =0.271
RM IN mm/hr =52.649
SR = 0.377
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.070 %
MEAN ATTENUATION Am = 4.925 dB
STANDARD DEV. OF ATTENUATION = 1.108

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.529	1.687
10.00	0.280	0.969
15.00	0.168	0.623
20.00	0.110	0.431
25.00	0.076	0.313

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.412 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.070 %
MEAN ATTENUATION Am = 9.103 dB
STANDARD DEV. OF ATTENUATION = 1.098

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.757	2.302
10.00	0.498	1.601
15.00	0.347	1.170
20.00	0.253	0.889
25.00	0.191	0.696

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.299 dB

CITY, STATE OF TERMINAL: MIAMI, FL.

STATION HEIGHT = 0.002
STATION LATITUDE IN DEG. N. = 25.78
TERMINAL LONGITUDE IN DEG. W. = 80.18
ANTENNA ELEV. ANGLE = 52.65
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.04
SLANT PATH PROJECTION ON EARTH IN KM = 3.66
PO IN % =0.318
RM IN mm/hr =48.374
SR = 0.399
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 0.992 %
MEAN ATTENUATION Am = 6.063 dB
STANDARD DEV. OF ATTENUATION = 1.021

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.570	1.800
10.00	0.310	1.058
15.00	0.186	0.679
20.00	0.120	0.465
25.00	0.082	0.333

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.394 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 0.992 %
MEAN ATTENUATION Am = 11.273 dB
STANDARD DEV. OF ATTENUATION = 1.009

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.783	2.373
10.00	0.543	1.725
15.00	0.385	1.281
20.00	0.283	0.978
25.00	0.213	0.766

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.285 dB

CITY, STATE OF TERMINAL: TAMPA, FL.

STATION HEIGHT = 0.006
STATION LATITUDE IN DEG. N. = 27.95
TERMINAL LONGITUDE IN DEG. W. = 82.45
ANTENNA ELEV. ANGLE = 52.06
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.08
SLANT PATH PROJECTION ON EARTH IN KM = 3.74
P0 IN % =0.449
RM IN mm/hr =25.101
SR = 0.608
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.144 %
MEAN ATTENUATION Am = 4.075 dB
STANDARD DEV. OF ATTENUATION = 1.040

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.483	1.558
10.00	0.222	0.793
15.00	0.120	0.465
20.00	0.072	0.298
25.00	0.046	0.203

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.397 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.144 %
MEAN ATTENUATION Am = 7.942 dB
STANDARD DEV. OF ATTENUATION = 1.013

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.774	2.347
10.00	0.469	1.520
15.00	0.303	1.040
20.00	0.207	0.746
25.00	0.147	0.555

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.287 dB

CITY, STATE OF TERMINAL: ATLANTA, GA.

STATION HEIGHT = 0.305
STATION LATITUDE IN DEG. N. = 33.75
TERMINAL LONGITUDE IN DEG. W. = 84.38
ANTENNA ELEV. ANGLE = 47.34
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.60
SLANT PATH PROJECTION ON EARTH IN KM = 3.80
P0 IN % =1.267
RM IN mm/hr = 7.698
SR = 0.858
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.974 %
MEAN ATTENUATION Am = 2.190 dB
STANDARD DEV. OF ATTENUATION = 1.008

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.407	1.343
10.00	0.130	0.498
15.00	0.055	0.237
20.00	0.028	0.130
25.00	0.015	0.078

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.425 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.974 %
MEAN ATTENUATION Am = 4.644 dB
STANDARD DEV. OF ATTENUATION = 0.952

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.926	2.744
10.00	0.415	1.365
15.00	0.215	0.771
20.00	0.123	0.475
25.00	0.076	0.312

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.308 dB

CITY, STATE OF TERMINAL: HONOLULU, HI.

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STATION HEIGHT IN KM = 0.002
STATION LATITUDE IN DEG. N. = 21.32
TERMINAL LONGITUDE IN DEG. W. = 157.87
ANTENNA ELEV. ANGLE = 21.64
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 13.01
SLANT PATH PROJECTION ON EARTH IN KM = 12.09
P0 IN % = 0.349
RM IN mm/hr =16.167
SR = 0.612
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 3.174 %
MEAN ATTENUATION Am = 1.032 dB
STANDARD DEV. OF ATTENUATION = 1.363

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.392	1.300
10.00	0.152	0.570
15.00	0.079	0.322
20.00	0.047	0.206
25.00	0.031	0.142

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.848 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 3.174 %
MEAN ATTENUATION Am = 2.076 dB
STANDARD DEV. OF ATTENUATION = 1.343

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.814	2.452
10.00	0.383	1.275
15.00	0.223	0.797
20.00	0.145	0.548
25.00	0.101	0.401

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.615 dB

CITY, STATE OF TERMINAL: CAIRO, IL.

STATION HEIGHT = 0.096
STATION LATITUDE IN DEG. N. = 37.05
TERMINAL LONGITUDE IN DEG. W. = 89.18
ANTENNA ELEV. ANGLE = 45.56
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.60
SLANT PATH PROJECTION ON EARTH IN KM = 3.92
P0 IN % =0.883
RM IN mm/hr =12.173
SR = 0.708
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.629 %
MEAN ATTENUATION Am = 2.802 dB
STANDARD DEV. OF ATTENUATION = 0.949

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.441	1.440
10.00	0.147	0.553
15.00	0.063	0.264
20.00	0.031	0.144
25.00	0.017	0.086

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.438 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.629 %
MEAN ATTENUATION Am = 5.752 dB
STANDARD DEV. OF ATTENUATION = 0.909

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.914	2.714
10.00	0.442	1.443
15.00	0.237	0.840
20.00	0.139	0.526
25.00	0.086	0.348

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.318 dB

CITY, STATE OF TERMINAL: CHICAGO, IL.

STATION HEIGHT = 0.186
STATION LATITUDE IN DEG. N. = 41.88
TERMINAL LONGITUDE IN DEG. W. = 87.63
ANTENNA ELEV. ANGLE = 40.02
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.33
SLANT PATH PROJECTION ON EARTH IN KM = 4.08
P0 IN % =0.806
RM IN mm/hr = 8.475
SR = 0.833
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.599 %
MEAN ATTENUATION Am = 1.624 dB
STANDARD DEV. OF ATTENUATION = 1.090

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.242	0.853
10.00	0.076	0.313
15.00	0.033	0.151
20.00	0.017	0.085
25.00	0.010	0.052

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.486 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.599 %
MEAN ATTENUATION Am = 3.421 dB
STANDARD DEV. OF ATTENUATION = 1.041

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.572	1.805
10.00	0.242	0.855
15.00	0.124	0.479
20.00	0.072	0.297
25.00	0.045	0.197

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.353 dB

CITY, STATE OF TERMINAL: PEORIA, IL.

STATION HEIGHT = 0.199
STATION LATITUDE IN DEG. N. = 40.70
TERMINAL LONGITUDE IN DEG. W. = 89.60
ANTENNA ELEV. ANGLE = 41.76
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.30
SLANT PATH PROJECTION ON EARTH IN KM = 3.95
PO IN % =0.386
RM IN mm/hr =22.407
SR = 0.560
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.145 %
MEAN ATTENUATION Am = 2.521 dB
STANDARD DEV. OF ATTENUATION = 1.074

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.300	1.029
10.00	0.114	0.445
15.00	0.055	0.237
20.00	0.031	0.142
25.00	0.019	0.092

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.470 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.145 %
MEAN ATTENUATION Am = 4.953 dB
STANDARD DEV. OF ATTENUATION = 1.052

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.569	1.796
10.00	0.289	0.996
15.00	0.167	0.620
20.00	0.106	0.415
25.00	0.071	0.294

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.340 dB

CITY, STATE OF TERMINAL: SPRINGFIELD, IL.

STATION HEIGHT = 0.183
STATION LATITUDE IN DEG. N. = 39.80
TERMINAL LONGITUDE IN DEG. W. = 89.65
ANTENNA ELEV. ANGLE = 42.73
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.36
SLANT PATH PROJECTION ON EARTH IN KM = 3.94
PO IN % =0.449
RM IN mm/hr =17.737
SR = 0.644
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.203 %
MEAN ATTENUATION Am = 2.306 dB
STANDARD DEV. OF ATTENUATION = 1.082

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.285	0.986
10.00	0.105	0.414
15.00	0.050	0.217
20.00	0.028	0.129
25.00	0.017	0.083

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.461 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.203 %
MEAN ATTENUATION Am = 4.607 dB
STANDARD DEV. OF ATTENUATION = 1.053

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.564	1.783
10.00	0.278	0.963
15.00	0.158	0.588
20.00	0.098	0.390
25.00	0.065	0.272

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.334 dB

CITY, STATE OF TERMINAL: EVANSVILLE, IN.

STATION HEIGHT = 0.117
STATION LATITUDE IN DEG. N. = 37.97
TERMINAL LONGITUDE IN DEG. W. = 87.58
ANTENNA ELEV. ANGLE = 44.13
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.58
SLANT PATH PROJECTION ON EARTH IN KM = 4.01
PO IN % =0.423
RM IN mm/hr =24.913
SR = 0.518
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.197 %
MEAN ATTENUATION Am = 3.201 dB
STANDARD DEV. OF ATTENUATION = 1.024

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.397	1.314
10.00	0.159	0.594
15.00	0.079	0.322
20.00	0.044	0.194
25.00	0.027	0.126

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.449 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.197 %
MEAN ATTENUATION Am = 6.242 dB
STANDARD DEV. OF ATTENUATION = 1.004

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.703	2.161
10.00	0.382	1.272
15.00	0.229	0.815
20.00	0.147	0.555
25.00	0.100	0.396

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.326 dB

CITY, STATE OF TERMINAL: FORT WAYNE, IN.

STATION HEIGHT = 0.244
STATION LATITUDE IN DEG. N. = 41.67
TERMINAL LONGITUDE IN DEG. W. = 86.50
ANTENNA ELEV. ANGLE = 39.94
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.28
SLANT PATH PROJECTION ON EARTH IN KM = 4.05
PO IN % =0.841
RM IN mm/hr = 8.650
SR = 0.794
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.624 %
MEAN ATTENUATION Am = 1.711 dB
STANDARD DEV. OF ATTENUATION = 1.043

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.247	0.869
10.00	0.074	0.303
15.00	0.030	0.141
20.00	0.015	0.076
25.00	0.008	0.045

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.487 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.624 %
MEAN ATTENUATION Am = 3.599 dB
STANDARD DEV. OF ATTENUATION = 0.997

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.602	1.888
10.00	0.248	0.873
15.00	0.124	0.476
20.00	0.069	0.288
25.00	0.042	0.187

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.353 dB

CITY, STATE OF TERMINAL: INDIANAPOLIS, IN.

STATION HEIGHT = 0.229
STATION LATITUDE IN DEG. N. = 39.77
TERMINAL LONGITUDE IN DEG. W. = 86.15
ANTENNA ELEV. ANGLE = 41.82
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.39
SLANT PATH PROJECTION ON EARTH IN KM = 4.02
PO IN % =0.610
RM IN mm/hr =14.936
SR = 0.663
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.386 %
MEAN ATTENUATION Am = 2.471 dB
STANDARD DEV. OF ATTENUATION = 1.015

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.338	1.142
10.00	0.117	0.453
15.00	0.052	0.226
20.00	0.027	0.128
25.00	0.016	0.079

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.469 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.386 %
MEAN ATTENUATION Am = 4.997 dB
STANDARD DEV. OF ATTENUATION = 0.982

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.693	2.133
10.00	0.333	1.126
15.00	0.182	0.667
20.00	0.109	0.428
25.00	0.070	0.291

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.340 dB

CITY, STATE OF TERMINAL: LEXINGTON, KY.

STATION HEIGHT = 0.298
STATION LATITUDE IN DEG. N. = 38.50
TERMINAL LONGITUDE IN DEG. W. = 84.50
ANTENNA ELEV. ANGLE = 42.57
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.40
SLANT PATH PROJECTION ON EARTH IN KM = 3.97
PO IN % =0.921
RM IN mm/hr =11.209
SR = 0.707
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.682 %
MEAN ATTENUATION Am = 2.511 dB
STANDARD DEV. OF ATTENUATION = 0.941

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.390	1.295
10.00	0.119	0.462
15.00	0.048	0.211
20.00	0.023	0.111
25.00	0.012	0.064

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.462 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.682 %
MEAN ATTENUATION Am = 5.185 dB
STANDARD DEV. OF ATTENUATION = 0.900

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.868	2.595
10.00	0.392	1.299
15.00	0.200	0.724
20.00	0.112	0.439
25.00	0.068	0.282

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.335 dB

CITY, STATE OF TERMINAL: LOUISVILLE, KY.

STATION HEIGHT = 0.140
STATION LATITUDE IN DEG. N. = 38.25
TERMINAL LONGITUDE IN DEG. W. = 85.77
ANTENNA ELEV. ANGLE = 43.26
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.60
SLANT PATH PROJECTION ON EARTH IN KM = 4.07
P0 IN % =0.819
RM IN mm/hr =11.705
SR = 0.743
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.610 %
MEAN ATTENUATION Am = 2.452 dB
STANDARD DEV. OF ATTENUATION = 1.006

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.386	1.281
10.00	0.131	0.500
15.00	0.058	0.246
20.00	0.030	0.138
25.00	0.017	0.085

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.456 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.610 %
MEAN ATTENUATION Am = 5.046 dB
STANDARD DEV. OF ATTENUATION = 0.964

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.811	2.446
10.00	0.385	1.280
15.00	0.208	0.750
20.00	0.123	0.476
25.00	0.078	0.320

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.331 dB

CITY, STATE OF TERMINAL: NEW ORLEANS, LA.

STATION HEIGHT = 0.002
STATION LATITUDE IN DEG. N. = 29.97
TERMINAL LONGITUDE IN DEG. W. = 90.07
ANTENNA ELEV. ANGLE = 53.42
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.98
SLANT PATH PROJECTION ON EARTH IN KM = 3.56
P0 IN % =0.444
RM IN mm/hr =34.272
SR = 0.507
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.088 %
MEAN ATTENUATION Am = 5.914 dB
STANDARD DEV. OF ATTENUATION = 0.961

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.620	1.935
10.00	0.318	1.084
15.00	0.181	0.664
20.00	0.111	0.435
25.00	0.073	0.300

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.390 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.088 %
MEAN ATTENUATION Am = 11.272 dB
STANDARD DEV. OF ATTENUATION = 0.941

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.877	2.618
10.00	0.599	1.879
15.00	0.414	1.363
20.00	0.295	1.015
25.00	0.216	0.774

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.282 dB

CITY, STATE OF TERMINAL: BALTIMORE, MD.

STATION HEIGHT = 0.024
STATION LATITUDE IN DEG. N. = 39.28
TERMINAL LONGITUDE IN DEG. W. = 76.62
ANTENNA ELEV. ANGLE = 38.49
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.18
SLANT PATH PROJECTION ON EARTH IN KM = 4.84
PO IN % =0.827
RM IN mm/hr =10.680
SR = 0.796
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.844 %
MEAN ATTENUATION Am = 2.084 dB
STANDARD DEV. OF ATTENUATION = 1.087

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.388	1.289
10.00	0.138	0.523
15.00	0.064	0.269
20.00	0.035	0.157
25.00	0.021	0.100

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.503 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.844 %
MEAN ATTENUATION Am = 4.318 dB
STANDARD DEV. OF ATTENUATION = 1.043

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.819	2.467
10.00	0.388	1.288
15.00	0.214	0.769
20.00	0.130	0.499
25.00	0.085	0.344

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.364 dB

CITY, STATE OF TERMINAL: BOSTON, MA.

STATION HEIGHT = 0.005
STATION LATITUDE IN DEG. N. = 42.37
TERMINAL LONGITUDE IN DEG. W. = 71.07
ANTENNA ELEV. ANGLE = 33.02
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.53
SLANT PATH PROJECTION ON EARTH IN KM = 5.48
P0 IN % =1.566
RM IN mm/hr = 5.729
SR = 0.834
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 2.762 %
MEAN ATTENUATION Am = 1.628 dB
STANDARD DEV. OF ATTENUATION = 0.989

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.355	1.191
10.00	0.092	0.368
15.00	0.034	0.156
20.00	0.016	0.078
25.00	0.008	0.044

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.574 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 2.762 %
MEAN ATTENUATION Am = 3.527 dB
STANDARD DEV. OF ATTENUATION = 0.935

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.979	2.881
10.00	0.366	1.225
15.00	0.168	0.622
20.00	0.088	0.354
25.00	0.050	0.217

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.416 dB

CITY, STATE OF TERMINAL: ALPENA, MI.

STATION HEIGHT = 0.179
STATION LATITUDE IN DEG. N. = 45.07
TERMINAL LONGITUDE IN DEG. W. = 83.45
ANTENNA ELEV. ANGLE = 35.56
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.35
SLANT PATH PROJECTION ON EARTH IN KM = 4.36
PO IN % =2.558
RM IN mm/hr = 1.692
SR = 1.145
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 3.417 %
MEAN ATTENUATION Am = 0.521 dB
STANDARD DEV. OF ATTENUATION = 1.223

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.110	0.431
10.00	0.027	0.126
15.00	0.010	0.055
20.00	0.005	0.029
25.00	0.003	0.017

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.538 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 3.417 %
MEAN ATTENUATION Am = 1.232 dB
STANDARD DEV. OF ATTENUATION = 1.141

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.375	1.249
10.00	0.113	0.442
15.00	0.049	0.211
20.00	0.025	0.118
25.00	0.014	0.072

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.390 dB

CITY, STATE OF TERMINAL: DETRIOT, MI.

STATION HEIGHT = 0.198
STATION LATITUDE IN DEG. N. = 42.33
TERMINAL LONGITUDE IN DEG. W. = 83.05
ANTENNA ELEV. ANGLE = 38.19
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.45
SLANT PATH PROJECTION ON EARTH IN KM = 4.28
P0 IN % =1.032
RM IN mm/hr = 5.831
SR = 0.895
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.883 %
MEAN ATTENUATION Am = 1.265 dB
STANDARD DEV. OF ATTENUATION = 1.102

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.200	0.724
10.00	0.057	0.244
15.00	0.023	0.112
20.00	0.012	0.061
25.00	0.006	0.036

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.506 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.883 %
MEAN ATTENUATION Am = 2.737 dB
STANDARD DEV. OF ATTENUATION = 1.047

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.532	1.694
10.00	0.203	0.734
15.00	0.098	0.389
20.00	0.054	0.232
25.00	0.033	0.149

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.367 dB

CITY, STATE OF TERMINAL: GRAND RAPIDS, MI.

STATION HEIGHT = 0.198
STATION LATITUDE IN DEG. N. = 42.97
TERMINAL LONGITUDE IN DEG. W. = 85.67
ANTENNA ELEV. ANGLE = 38.36
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.33
SLANT PATH PROJECTION ON EARTH IN KM = 4.18
PO IN % =0.793
RM IN mm/hr = 9.411
SR = 0.760
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.615 %
MEAN ATTENUATION Am = 1.755 dB
STANDARD DEV. OF ATTENUATION = 1.035

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.252	0.884
10.00	0.075	0.308
15.00	0.031	0.142
20.00	0.015	0.076
25.00	0.008	0.045

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.504 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.615 %
MEAN ATTENUATION Am = 3.669 dB
STANDARD DEV. OF ATTENUATION = 0.992

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.610	1.908
10.00	0.252	0.885
15.00	0.126	0.484
20.00	0.071	0.292
25.00	0.043	0.190

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.365 dB

CITY, STATE OF TERMINAL: HOUGHTON, MI.

STATION HEIGHT = 0.191
STATION LATITUDE IN DEG. N. = 47.12
TERMINAL LONGITUDE IN DEG. W. = 88.57
ANTENNA ELEV. ANGLE = 34.71
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.09
SLANT PATH PROJECTION ON EARTH IN KM = 4.18
PO IN % =0.822
RM IN mm/hr = 7.253
SR = 0.785
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.645 %
MEAN ATTENUATION Am = 1.298 dB
STANDARD DEV. OF ATTENUATION = 1.048

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.163	0.606
10.00	0.042	0.187
15.00	0.016	0.081
20.00	0.007	0.041
25.00	0.004	0.024

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.549 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.645 %
MEAN ATTENUATION Am = 2.765 dB
STANDARD DEV. OF ATTENUATION = 1.003

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.456	1.483
10.00	0.164	0.610
15.00	0.075	0.310
20.00	0.040	0.178
25.00	0.023	0.111

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.398 dB

CITY, STATE OF TERMINAL: LANSING, MI.

STATION HEIGHT = 0.261
STATION LATITUDE IN DEG. N. = 42.73
TERMINAL LONGITUDE IN DEG. W. = 84.55
ANTENNA ELEV. ANGLE = 38.27
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.27
SLANT PATH PROJECTION ON EARTH IN KM = 4.14
PO IN % =0.753
RM IN mm/hr = 8.260
SR = 0.802
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.564 %
MEAN ATTENUATION Am = 1.462 dB
STANDARD DEV. OF ATTENUATION = 1.082

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.200	0.724
10.00	0.059	0.250
15.00	0.025	0.117
20.00	0.012	0.064
25.00	0.007	0.038

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.505 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.564 %
MEAN ATTENUATION Am = 3.086 dB
STANDARD DEV. OF ATTENUATION = 1.036

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.502	1.610
10.00	0.201	0.726
15.00	0.099	0.394
20.00	0.056	0.238
25.00	0.034	0.155

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.366 dB

CITY, STATE OF TERMINAL: SAULT STE. MARIE, MI.

STATION HEIGHT = 0.220
STATION LATITUDE IN DEG. N. = 46.50
TERMINAL LONGITUDE IN DEG. W. = 84.35
ANTENNA ELEV. ANGLE = 34.36
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.19
SLANT PATH PROJECTION ON EARTH IN KM = 4.29
PO IN % =1.126
RM IN mm/hr = 6.205
SR = 0.811
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.977 %
MEAN ATTENUATION Am = 1.366 dB
STANDARD DEV. OF ATTENUATION = 1.005

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.194	0.705
10.00	0.047	0.205
15.00	0.017	0.084
20.00	0.007	0.041
25.00	0.004	0.023

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.554 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.977 %
MEAN ATTENUATION Am = 2.942 dB
STANDARD DEV. OF ATTENUATION = 0.954

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.572	1.804
10.00	0.197	0.716
15.00	0.087	0.350
20.00	0.044	0.194
25.00	0.025	0.117

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.402 dB

CITY, STATE OF TERMINAL: TRENTON, NJ

STATION HEIGHT IN kM = 0.017
STATION LATITUDE IN DEG. N. = 40.23
TERMINAL LONGITUDE IN DEG. W. = 74.77
ANTENNA ELEV. ANGLE = 36.73
LINK SLANT PATH LGTH. THRU RAIN REGION IN kM = 6.29
SLANT PATH PROJECTION ON EARTH IN kM = 5.04
P0 IN % = 0.659
RM IN mm/hr =14.928
SR = 0.666
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.737 %
MEAN ATTENUATION Am = 2.386 dB
STANDARD DEV. OF ATTENUATION = 1.055

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.420	1.379
10.00	0.151	0.568
15.00	0.071	0.293
20.00	0.038	0.171
25.00	0.023	0.108

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.523 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.737 %
MEAN ATTENUATION Am = 4.827 dB
STANDARD DEV. OF ATTENUATION = 1.023

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.845	2.534
10.00	0.414	1.362
15.00	0.232	0.825
20.00	0.143	0.541
25.00	0.094	0.374

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.379 dB

CITY, STATE OF TERMINAL: KANSAS CITY, MO.

STATION HEIGHT = 0.226
STATION LATITUDE IN DEG. N. = 39.10
TERMINAL LONGITUDE IN DEG. W. = 94.58
ANTENNA ELEV. ANGLE = 44.40
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.24
SLANT PATH PROJECTION ON EARTH IN KM = 3.74
P0 IN % =0.458
RM IN mm/hr =16.256
SR = 0.675
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.154 %
MEAN ATTENUATION Am = 2.230 dB
STANDARD DEV. OF ATTENUATION = 1.082

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.263	0.919
10.00	0.096	0.381
15.00	0.045	0.198
20.00	0.025	0.117
25.00	0.015	0.075

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.447 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.154 %
MEAN ATTENUATION Am = 4.484 dB
STANDARD DEV. OF ATTENUATION = 1.050

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.530	1.688
10.00	0.257	0.900
15.00	0.144	0.545
20.00	0.089	0.359
25.00	0.059	0.249

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.324 dB

CITY, STATE OF TERMINAL: OMAHA, NEB.

STATION HEIGHT = 0.299
STATION LATITUDE IN DEG. N. = 41.28
TERMINAL LONGITUDE IN DEG. W. = 96.02
ANTENNA ELEV. ANGLE = 42.14
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.03
SLANT PATH PROJECTION ON EARTH IN KM = 3.73
PO IN % =0.880
RM IN mm/hr = 6.674
SR = 0.891
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.570 %
MEAN ATTENUATION Am = 1.371 dB
STANDARD DEV. OF ATTENUATION = 1.106

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.190	0.692
10.00	0.057	0.242
15.00	0.024	0.114
20.00	0.012	0.063
25.00	0.007	0.038

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.466 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.570 %
MEAN ATTENUATION Am = 2.938 dB
STANDARD DEV. OF ATTENUATION = 1.051

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.481	1.553
10.00	0.191	0.696
15.00	0.095	0.378
20.00	0.053	0.229
25.00	0.033	0.150

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.338 dB

CITY, STATE OF TERMINAL: ALBANY, NY.

STATION HEIGHT = 0.006
STATION LATITUDE IN DEG. N. = 42.65
TERMINAL LONGITUDE IN DEG. W. = 73.75
ANTENNA ELEV. ANGLE = 34.10
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.30
SLANT PATH PROJECTION ON EARTH IN KM = 5.21
PO IN % =0.674
RM IN mm/hr =12.040
SR = 0.700
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.804 %
MEAN ATTENUATION Am = 1.862 dB
STANDARD DEV. OF ATTENUATION = 1.082

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.326	1.107
10.00	0.108	0.425
15.00	0.049	0.211
20.00	0.025	0.121
25.00	0.015	0.075

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.558 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.804 %
MEAN ATTENUATION Am = 3.825 dB
STANDARD DEV. OF ATTENUATION = 1.047

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.720	2.205
10.00	0.324	1.100
15.00	0.173	0.639
20.00	0.103	0.407
25.00	0.066	0.276

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.404 dB

CITY, STATE OF TERMINAL: BINGHAMTON, NY.

STATION HEIGHT = 0.366
STATION LATITUDE IN DEG. N. = 42.10
TERMINAL LONGITUDE IN DEG. W. = 75.92
ANTENNA ELEV. ANGLE = 35.59
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.54
SLANT PATH PROJECTION ON EARTH IN KM = 4.50
PO IN % =0.881
RM IN mm/hr = 9.028
SR = 0.766
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.799 %
MEAN ATTENUATION Am = 1.757 dB
STANDARD DEV. OF ATTENUATION = 1.030

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.279	0.967
10.00	0.082	0.334
15.00	0.034	0.154
20.00	0.016	0.082
25.00	0.009	0.049

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.537 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.799 %
MEAN ATTENUATION Am = 3.685 dB
STANDARD DEV. OF ATTENUATION = 0.987

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.681	2.101
10.00	0.280	0.971
15.00	0.139	0.528
20.00	0.078	0.318
25.00	0.047	0.206

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.390 dB

CITY, STATE OF TERMINAL: BUFFALO, NY.

STATION HEIGHT = 0.211
STATION LATITUDE IN DEG. N. = 42.88
TERMINAL LONGITUDE IN DEG. W. = 78.88
ANTENNA ELEV. ANGLE = 36.12
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.60
SLANT PATH PROJECTION ON EARTH IN KM = 4.52
P0 IN % =1.846
RM IN mm/hr = 3.826
SR = 0.930
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 2.760 %
MEAN ATTENUATION Am = 1.119 dB
STANDARD DEV. OF ATTENUATION = 1.037

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.206	0.741
10.00	0.048	0.209
15.00	0.017	0.085
20.00	0.008	0.042
25.00	0.004	0.023

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.531 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 2.760 %
MEAN ATTENUATION Am = 2.495 dB
STANDARD DEV. OF ATTENUATION = 0.973

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.655	2.032
10.00	0.212	0.761
15.00	0.090	0.361
20.00	0.045	0.197
25.00	0.025	0.117

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.385 dB

CITY, STATE OF TERMINAL: NEW YORK, NY.

STATION HEIGHT = 0.006
STATION LATITUDE IN DEG. N. = 40.72
TERMINAL LONGITUDE IN DEG. W. = 74.00
ANTENNA ELEV. ANGLE = 35.92
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.34
SLANT PATH PROJECTION ON EARTH IN KM = 5.14
PO IN % =0.935
RM IN mm/hr =10.133
SR = 0.755
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 2.040 %
MEAN ATTENUATION Am = 2.110 dB
STANDARD DEV. OF ATTENUATION = 1.032

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.411	1.355
10.00	0.134	0.512
15.00	0.059	0.249
20.00	0.030	0.139
25.00	0.017	0.085

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.533 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 2.040 %
MEAN ATTENUATION Am = 4.388 dB
STANDARD DEV. OF ATTENUATION = 0.990

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.913	2.710
10.00	0.413	1.361
15.00	0.219	0.782
20.00	0.128	0.491
25.00	0.080	0.328

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.386 dB

CITY, STATE OF TERMINAL: ROCHESTER, NY.

STATION HEIGHT = 0.166
STATION LATITUDE IN DEG. N. = 43.17
TERMINAL LONGITUDE IN DEG. W. = 77.62
ANTENNA ELEV. ANGLE = 35.34
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.74
SLANT PATH PROJECTION ON EARTH IN KM = 4.68
PO IN % =0.441
RM IN mm/hr =17.264
SR = 0.592
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.415 %
MEAN ATTENUATION Am = 1.876 dB
STANDARD DEV. OF ATTENUATION = 1.106

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.266	0.926
10.00	0.092	0.369
15.00	0.043	0.189
20.00	0.023	0.110
25.00	0.014	0.070

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.541 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.415 %
MEAN ATTENUATION Am = 3.755 dB
STANDARD DEV. OF ATTENUATION = 1.082

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.560	1.772
10.00	0.259	0.905
15.00	0.142	0.537
20.00	0.086	0.349
25.00	0.056	0.241

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.392 dB

CITY, STATE OF TERMINAL: SYRACUSE, NY.

STATION HEIGHT = 0.129
STATION LATITUDE IN DEG. N. = 43.05
TERMINAL LONGITUDE IN DEG. W. = 76.15
ANTENNA ELEV. ANGLE = 34.83
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.89
SLANT PATH PROJECTION ON EARTH IN KM = 4.84
P0 IN % =1.353
RM IN mm/hr = 5.706
SR = 0.877
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 2.365 %
MEAN ATTENUATION Am = 1.452 dB
STANDARD DEV. OF ATTENUATION = 1.048

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.281	0.974
10.00	0.078	0.317
15.00	0.031	0.141
20.00	0.015	0.074
25.00	0.008	0.043

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.548 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 2.365 %
MEAN ATTENUATION Am = 3.147 dB
STANDARD DEV. OF ATTENUATION = 0.991

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.757	2.304
10.00	0.288	0.994
15.00	0.136	0.518
20.00	0.073	0.303
25.00	0.043	0.191

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.397 dB

CITY, STATE OF TERMINAL: OKLAHOMA CITY, OK.

STATION HEIGHT = 0.384
STATION LATITUDE IN DEG. N. = 35.50
TERMINAL LONGITUDE IN DEG. W. = 97.50
ANTENNA ELEV. ANGLE = 48.71
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.15
SLANT PATH PROJECTION ON EARTH IN KM = 3.39
P0 IN % =0.254
RM IN mm/hr =31.098
SR = 0.499
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 0.852 %
MEAN ATTENUATION Am = 2.848 dB
STANDARD DEV. OF ATTENUATION = 1.113

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.261	0.913
10.00	0.110	0.432
15.00	0.058	0.246
20.00	0.034	0.155
25.00	0.022	0.105

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.416 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 0.852 %
MEAN ATTENUATION Am = 5.466 dB
STANDARD DEV. OF ATTENUATION = 1.096

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.453	1.475
10.00	0.248	0.872
15.00	0.152	0.570
20.00	0.101	0.399
25.00	0.070	0.292

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.302 dB

CITY, STATE OF TERMINAL: CLEVELAND, OH.

STATION HEIGHT = 0.213
STATION LATITUDE IN DEG. N. = 41.50
TERMINAL LONGITUDE IN DEG. W. = 81.70
ANTENNA ELEV. ANGLE = 38.55
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.51
SLANT PATH PROJECTION ON EARTH IN KM = 4.31
PO IN % =1.239
RM IN mm/hr = 5.395
SR = 0.926
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 2.097 %
MEAN ATTENUATION Am = 1.319 dB
STANDARD DEV. OF ATTENUATION = 1.097

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.236	0.834
10.00	0.068	0.284
15.00	0.028	0.131
20.00	0.014	0.071
25.00	0.008	0.043

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.502 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 2.097 %
MEAN ATTENUATION Am = 2.869 dB
STANDARD DEV. OF ATTENUATION = 1.037

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.621	1.939
10.00	0.240	0.848
15.00	0.116	0.451
20.00	0.064	0.270
25.00	0.039	0.173

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.364 dB

CITY, STATE OF TERMINAL: COLUMBUS, OH.

STATION HEIGHT = 0.229
STATION LATITUDE IN DEG. N. = 39.97
TERMINAL LONGITUDE IN DEG. W. = 83.00
ANTENNA ELEV. ANGLE = 40.55
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.50
SLANT PATH PROJECTION ON EARTH IN KM = 4.18
PO IN % =0.679
RM IN mm/hr =12.413
SR = 0.694
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.502 %
MEAN ATTENUATION Am = 2.159 dB
STANDARD DEV. OF ATTENUATION = 1.020

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.308	1.055
10.00	0.100	0.396
15.00	0.043	0.191
20.00	0.022	0.106
25.00	0.012	0.064

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.481 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.502 %
MEAN ATTENUATION Am = 4.426 dB
STANDARD DEV. OF ATTENUATION = 0.984

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.677	2.090
10.00	0.306	1.048
15.00	0.161	0.601
20.00	0.094	0.376
25.00	0.059	0.250

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.349 dB

CITY, STATE OF TERMINAL: PORTLAND, OR.

STATION HEIGHT = 0.009
STATION LATITUDE IN DEG. N. = 45.53
TERMINAL LONGITUDE IN DEG. W. = 122.62
ANTENNA ELEV. ANGLE = 33.02
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.94
SLANT PATH PROJECTION ON EARTH IN KM = 4.98
P0 IN % = 17.325
RM IN mm/hr = 0.273
SR = 1.288
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 18.208%
MEAN ATTENUATION Am = 0.117 dB
STANDARD DEV. OF ATTENUATION = 1.277

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.030	0.138
10.00	0.005	0.027
15.00	0.001	0.009
20.00	0.001	0.004
25.00	0.000	0.002

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.574 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 18.208%
MEAN ATTENUATION Am = 0.314 dB
STANDARD DEV. OF ATTENUATION = 1.177

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.171	0.631
10.00	0.030	0.139
15.00	0.009	0.050
20.00	0.004	0.023
25.00	0.002	0.012

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.416 dB

CITY, STATE OF TERMINAL: HARRISBURG, PA.

STATION HEIGHT = 0.102
STATION LATITUDE IN DEG. N. = 40.27
TERMINAL LONGITUDE IN DEG. W. = 76.88
ANTENNA ELEV. ANGLE = 37.72
LINK SLANT PATH LGTH. THRU RAIN REGION IN kM = 6.00
SLANT PATH PROJECTION ON EARTH IN kM = 4.75
PO IN % =1.329
RM IN mm/hr = 5.636
SR = 0.911
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 2.314 %
MEAN ATTENUATION Am = 1.463 dB
STANDARD DEV. OF ATTENUATION = 1.082

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.296	1.019
10.00	0.088	0.353
15.00	0.036	0.165
20.00	0.018	0.090
25.00	0.010	0.054

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.511 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 2.314 %
MEAN ATTENUATION Am = 3.173 dB
STANDARD DEV. OF ATTENUATION = 1.023

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.760	2.311
10.00	0.303	1.039
15.00	0.149	0.561
20.00	0.083	0.338
25.00	0.051	0.219

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.371 dB

CITY, STATE OF TERMINAL: MEMPHIS, TN.

STATION HEIGHT = 0.081
STATION LATITUDE IN DEG. N. = 35.13
TERMINAL LONGITUDE IN DEG. W. = 90.05
ANTENNA ELEV. ANGLE = 47.85
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.67
SLANT PATH PROJECTION ON EARTH IN KM = 3.81
PO IN % =1.437
RM IN mm/hr = 7.344
SR = 0.835
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 2.145 %
MEAN ATTENUATION Am = 2.246 dB
STANDARD DEV. OF ATTENUATION = 0.963

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.435	1.424
10.00	0.130	0.497
15.00	0.052	0.225
20.00	0.025	0.118
25.00	0.013	0.068

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.422 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 2.145 %
MEAN ATTENUATION Am = 4.779 dB
STANDARD DEV. OF ATTENUATION = 0.907

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	1.030	3.011
10.00	0.446	1.454
15.00	0.222	0.794
20.00	0.123	0.474
25.00	0.073	0.302

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.306 dB

CITY, STATE OF TERMINAL: NASHVILLE, TN.

STATION HEIGHT = 0.176
STATION LATITUDE IN DEG. N. = 36.17
TERMINAL LONGITUDE IN DEG. W. = 86.78
ANTENNA ELEV. ANGLE = 45.77
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.59
SLANT PATH PROJECTION ON EARTH IN KM = 3.90
P0 IN % =0.658
RM IN mm/hr =17.330
SR = 0.647
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.400 %
MEAN ATTENUATION Am = 3.311 dB
STANDARD DEV. OF ATTENUATION = 0.973

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.470	1.522
10.00	0.179	0.658
15.00	0.084	0.342
20.00	0.045	0.199
25.00	0.026	0.125

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.437 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.400 %
MEAN ATTENUATION Am = 6.625 dB
STANDARD DEV. OF ATTENUATION = 0.940

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.865	2.585
10.00	0.463	1.502
15.00	0.269	0.938
20.00	0.168	0.622
25.00	0.111	0.432

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.316 dB

CITY, STATE OF TERMINAL: AUSTIN,TX

STATION HEIGHT IN KM = 0.187
STATION LATITUDE IN DEG. N. = 30.28
TERMINAL LONGITUDE IN DEG. W. = 97.75
ANTENNA ELEV. ANGLE = 54.63
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.62
SLANT PATH PROJECTION ON EARTH IN KM = 3.25
P0 IN % = 0.251
RM IN mm/hr =31.569
SR = 0.535
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 0.809 %
MEAN ATTENUATION Am = 3.341 dB
STANDARD DEV. OF ATTENUATION = 1.119

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.291	1.002
10.00	0.132	0.505
15.00	0.073	0.300
20.00	0.044	0.196
25.00	0.029	0.136

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.384 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 0.809 %
MEAN ATTENUATION Am = 6.405 dB
STANDARD DEV. OF ATTENUATION = 1.100

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.476	1.540
10.00	0.277	0.961
15.00	0.178	0.653
20.00	0.122	0.469
25.00	0.087	0.352

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.278 dB

CITY, STATE OF TERMINAL: DALLAS, TX.

STATION HEIGHT = 0.148
STATION LATITUDE IN DEG. N. = 32.78
TERMINAL LONGITUDE IN DEG. W. = 96.82
ANTENNA ELEV. ANGLE = 51.72
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.57
SLANT PATH PROJECTION ON EARTH IN KM = 3.45
PO IN % =0.326
RM IN mm/hr =21.608
SR = 0.622
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 0.939 %
MEAN ATTENUATION Am = 2.615 dB
STANDARD DEV. OF ATTENUATION = 1.116

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.264	0.920
10.00	0.108	0.423
15.00	0.055	0.236
20.00	0.032	0.147
25.00	0.020	0.099

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.399 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 0.939 %
MEAN ATTENUATION Am = 5.151 dB
STANDARD DEV. OF ATTENUATION = 1.089

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.480	1.550
10.00	0.255	0.894
15.00	0.153	0.575
20.00	0.100	0.396
25.00	0.069	0.287

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.289 dB

CITY, STATE OF TERMINAL: EL PASO, TX.

STATION HEIGHT = 1.195
STATION LATITUDE IN DEG. N. = 31.75
TERMINAL LONGITUDE IN DEG. W. = 106.48
ANTENNA ELEV. ANGLE = 52.38
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 4.33
SLANT PATH PROJECTION ON EARTH IN KM = 2.64
P0 IN % =0.250
RM IN mm/hr = 6.416
SR = 0.834
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 0.642 %
MEAN ATTENUATION Am = 0.630 dB
STANDARD DEV. OF ATTENUATION = 1.245

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.031	0.143
10.00	0.008	0.046
15.00	0.003	0.021
20.00	0.002	0.012
25.00	0.001	0.007

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.395 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 0.642 %
MEAN ATTENUATION Am = 1.353 dB
STANDARD DEV. OF ATTENUATION = 1.203

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.089	0.358
10.00	0.031	0.143
15.00	0.015	0.074
20.00	0.008	0.044
25.00	0.005	0.029

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.286 dB

CITY, STATE OF TERMINAL: FORT WORTH, TX.

STATION HEIGHT = 0.183
STATION LATITUDE IN DEG. N. = 32.75
TERMINAL LONGITUDE IN DEG. W. = 97.28
ANTENNA ELEV. ANGLE = 51.80
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.53
SLANT PATH PROJECTION ON EARTH IN KM = 3.42
PO IN % =0.306
RM IN mm/hr =23.731
SR = 0.568
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 0.910 %
MEAN ATTENUATION Am = 2.736 dB
STANDARD DEV. OF ATTENUATION = 1.097

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.265	0.924
10.00	0.108	0.423
15.00	0.055	0.235
20.00	0.032	0.146
25.00	0.020	0.097

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.398 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 0.910 %
MEAN ATTENUATION Am = 5.354 dB
STANDARD DEV. OF ATTENUATION = 1.075

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.478	1.544
10.00	0.255	0.895
15.00	0.154	0.575
20.00	0.100	0.396
25.00	0.069	0.287

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.289 dB

CITY, STATE OF TERMINAL: HOUSTON, TX.

STATION HEIGHT = 0.015
STATION LATITUDE IN DEG. N. = 29.77
TERMINAL LONGITUDE IN DEG. W. = 95.37
ANTENNA ELEV. ANGLE = 54.94
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.85
SLANT PATH PROJECTION ON EARTH IN KM = 3.36
P0 IN % =0.379
RM IN mm/hr =29.284
SR = 0.561
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 0.965 %
MEAN ATTENUATION Am = 4.572 dB
STANDARD DEV. OF ATTENUATION = 1.022

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.449	1.462
10.00	0.214	0.768
15.00	0.118	0.458
20.00	0.072	0.297
25.00	0.046	0.204

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.382 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 0.965 %
MEAN ATTENUATION Am = 8.813 dB
STANDARD DEV. OF ATTENUATION = 0.998

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.690	2.125
10.00	0.434	1.420
15.00	0.287	0.990
20.00	0.199	0.720
25.00	0.143	0.541

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.277 dB

CITY, STATE OF TERMINAL: SAN ANTONIO, TX.

STATION HEIGHT = 0.241
STATION LATITUDE IN DEG. N. = 29.42
TERMINAL LONGITUDE IN DEG. W. = 98.50
ANTENNA ELEV. ANGLE = 55.67
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.52
SLANT PATH PROJECTION ON EARTH IN KM = 3.11
P0 IN % =0.467
RM IN mm/hr =13.702
SR = 0.745
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 0.984 %
MEAN ATTENUATION Am = 2.499 dB
STANDARD DEV. OF ATTENUATION = 1.074

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.255	0.894
10.00	0.097	0.385
15.00	0.047	0.205
20.00	0.026	0.123
25.00	0.016	0.079

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.379 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 0.984 %
MEAN ATTENUATION Am = 5.085 dB
STANDARD DEV. OF ATTENUATION = 1.035

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.499	1.602
10.00	0.253	0.887
15.00	0.146	0.549
20.00	0.091	0.366
25.00	0.061	0.257

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.275 dB

CITY, STATE OF TERMINAL: SALT LAKE CITY, UT.

STATION HEIGHT = 1.289
STATION LATITUDE IN DEG. N. = 40.75
TERMINAL LONGITUDE IN DEG. W. = 111.88
ANTENNA ELEV. ANGLE = 41.34
LINK SLANT PATH LGTH. THRU RAIN REGION IN km = 3.69
SLANT PATH PROJECTION ON EARTH IN km = 2.77
PO IN % =3.292
RM IN mm/hr = 0.630
SR = 1.233
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 3.704 %
MEAN ATTENUATION Am = 0.151 dB
STANDARD DEV. OF ATTENUATION = 1.298

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.013	0.067
10.00	0.002	0.015
15.00	0.001	0.005
20.00	0.000	0.003
25.00	0.000	0.001

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.474 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 3.704 %
MEAN ATTENUATION Am = 0.382 dB
STANDARD DEV. OF ATTENUATION = 1.207

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.061	0.258
10.00	0.013	0.065
15.00	0.004	0.026
20.00	0.002	0.013
25.00	0.001	0.007

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.343 dB

CITY, STATE OF TERMINAL: NORFOLK, VA.

STATION HEIGHT IN KM = 0.006
STATION LATITUDE IN DEG. N. = 36.85
TERMINAL LONGITUDE IN DEG. W. = 76.28
ANTENNA ELEV. ANGLE = 40.52
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.32
SLANT PATH PROJECTION ON EARTH IN KM = 4.81
P0 IN % = 1.093
RM IN mm/hr = 8.694
SR = 0.802
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 2.098 %
MEAN ATTENUATION Am = 2.134 dB
STANDARD DEV. OF ATTENUATION = 1.023

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.425	1.394
10.00	0.137	0.522
15.00	0.059	0.252
20.00	0.030	0.139
25.00	0.017	0.084

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.481 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 2.098 %
MEAN ATTENUATION Am = 4.486 dB
STANDARD DEV. OF ATTENUATION = 0.974

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.956	2.822
10.00	0.431	1.411
15.00	0.226	0.805
20.00	0.131	0.502
25.00	0.082	0.333

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.349 dB

CITY, STATE OF TERMINAL: RICHMOND, VA

STATION HEIGHT = 0.049
STATION LATITUDE IN DEG. N. = 37.55
TERMINAL LONGITUDE IN DEG. W. = 77.45
ANTENNA ELEV. ANGLE = 40.48
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 6.15
SLANT PATH PROJECTION ON EARTH IN KM = 4.68
P0 IN % =0.656
RM IN mm/hr =15.384
SR = 0.686
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.628 %
MEAN ATTENUATION Am = 2.610 dB
STANDARD DEV. OF ATTENUATION = 1.053

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.437	1.429
10.00	0.164	0.611
15.00	0.079	0.322
20.00	0.043	0.191
25.00	0.026	0.123

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.482 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.628 %
MEAN ATTENUATION Am = 5.267 dB
STANDARD DEV. OF ATTENUATION = 1.019

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.847	2.541
10.00	0.431	1.411
15.00	0.248	0.872
20.00	0.155	0.580
25.00	0.103	0.406

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.349 dB

CITY, STATE OF TERMINAL: SEATTLE, WA.

STATION HEIGHT IN KM = 0.004
STATION LATITUDE IN DEG. N. = 47.60
TERMINAL LONGITUDE IN DEG. W. = 122.33
ANTENNA ELEV. ANGLE = 31.17
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.86
SLANT PATH PROJECTION ON EARTH IN KM = 5.02
P0 IN % =52.991
RM IN mm/hr = 0.076
SR = 1.432
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 53.498 %
MEAN ATTENUATION Am = 0.031 dB
STANDARD DEV. OF ATTENUATION = 1.435

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.010	0.054
10.00	0.001	0.010
15.00	0.000	0.003
20.00	0.000	0.002
25.00	0.000	0.001

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.604 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 53.498 %
MEAN ATTENUATION Am = 0.090 dB
STANDARD DEV. OF ATTENUATION = 1.326

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.065	0.274
10.00	0.010	0.054
15.00	0.003	0.019
20.00	0.001	0.009
25.00	0.001	0.005

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.438 dB

CITY, STATE OF TERMINAL: MILWAUKEE, WI.

STATION HEIGHT = 0.195
STATION LATITUDE IN DEG. N. = 43.03
TERMINAL LONGITUDE IN DEG. W. = 87.92
ANTENNA ELEV. ANGLE = 38.88
LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.26
SLANT PATH PROJECTION ON EARTH IN KM = 4.09
P0 IN % =0.856
RM IN mm/hr = 7.363
SR = 0.840
POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

PROBABILITY OF ATTENUATION PL = 1.653 %
MEAN ATTENUATION Am = 1.435 dB
STANDARD DEV. OF ATTENUATION = 1.083

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.206	0.742
10.00	0.060	0.255
15.00	0.025	0.119
20.00	0.012	0.064
25.00	0.007	0.039

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.498 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

PROBABILITY OF ATTENUATION PL = 1.653 %
MEAN ATTENUATION Am = 3.053 dB
STANDARD DEV. OF ATTENUATION = 1.033

ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH)
5.00	0.523	1.670
10.00	0.207	0.747
15.00	0.102	0.403
20.00	0.057	0.243
25.00	0.035	0.157

ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.361 dB

APPENDIX A

CALCULATION OF THE COEFFICIENTS a AND b IN EQUATION (2.15)

Values of a and b for a Laws-Parsons rain drop size distribution and a rain drop temperature of 20 °C have been calculated by assuming oblate spheroidal drops aligned with a vertical rotation axis and with dimensions related to the equivolumic spherical rain drops (refs. 32 and 33). These values, which are appropriate for horizontal (H) and vertical (V) polarizations are shown in Table A.1. Values of a_H, a_V, b_H, and b_V at other frequencies between those shown in Table A.1 can be obtained by interpolation using a logarithmic scale for frequency and a_H and a_V and a linear scale for b_H and b_V.

For general linear and circular polarizations, the coefficients a and b appearing in equation (2.15) and subsequent relations can be calculated using the values in Table A.1 and the following relationships (ref. 34):

$$\left.\begin{aligned} a &= \frac{\left[a_H + a_V + (a_H - a_V)\cos^2\theta\cos 2\tau\right]}{2} \\ b &= \frac{\left[a_H b_H + a_V b_V + (a_H b_H - a_V b_V)\cos^2\theta\cos 2\tau\right]}{(2a)} \end{aligned}\right\} \qquad (A.1)$$

where θ is the slant path elevation angle and τ is the polarization tilt angle relative to the horizontal. The value $\tau = 45°$ holds for circular polarization.

The values appearing in Table A.1 and equation (A.1) are used in this model. This is a recommended procedure appearing in CCIR Report 721-1 "Attenuation By Hydrometers, in Particular Precipitation and Other Atmospheric Particles," 15 Plenary Assembly, 1982, pp. 170-171.

TABLE A.1

Frequency, GHz	a_H	a_V	b_H	b_V
1	0.0000387	0.0000352	0.912	0.880
2	.000154	.000138	.963	.923
4	.000650	.000591	1.121	1.075
6	.00175	.00155	1.308	1.265
7	.00301	.00265	1.332	1.312
8	.00454	.00395	1.327	1.310
10	.0101	.00887	1.276	1.264
12	.0188	.0168	1.217	1.200
15	.0367	.0335	1.154	1.128
20	.0751	.0691	1.099	1.065
25	.124	.113	1.061	1.030
30	.187	.167	1.021	1.000
35	.263	.233	.979	.963
40	.350	.310	.939	.929
45	.442	.393	.903	.897
50	.536	.479	.873	.868
60	.707	.642	.826	.824
70	.851	.784	.793	.793
80	.975	.906	.769	.769
90	1.06	.999	.753	.754
100	1.12	1.06	.743	.744
120	1.18	1.13	.731	.732
150	1.31	1.27	.710	.711
200	1.45	1.42	.689	.690
300	1.36	1.35	.688	.689
400	1.32	1.31	.683	.684

APPENDIX B

DETERMINATION OF 0 °C ISOTHERM RAIN HEIGHTS

The size and number of raindrops per unit volume varies with the height in the atmosphere. The variation is small up to a height corresponding to the 0 °C isotherm height, where the number density decreases significantly. The rainrate may be assumed to be constant to the height of the 0 °C isotherm and this height may be used to define the upper boundary of the attenuation region (i.e., the potential rain region).

The average height of the 0° isotherm for days with rain was taken to correspond to the height to be expected one percent of the year. The highest height observed with rain is taken to correspond to the value to be expected 0.001 percent of the year, i.e., the average summer height of the -5 °C isotherm. These heights, which depend on the latitude of interest are known and have been compiled (ref. 35). The seasonal average height H, in kilometers, is related to the latitude Λ by (ref. 36)

$$H = \begin{cases} 4.8, & |\Lambda| \leq 30° \\ 7.8 - 0.1\ |\Lambda|, & |\Lambda| > 30° \end{cases} \tag{B.1}$$

This representation is used throughout the rain attenuation model.

APPENDIX C

EVALUATION OF EQUATION (2.46) AND ESTIMATION OF THE CHARACTERISTIC CORRELATION LENGTH

Substituting equation (2.47) for the spatial correlation coefficient of specific attenuation into equation (2.46) yields

$$K(L,\theta) = \left(\frac{1}{L \cos \theta}\right)^2 \int_0^{L \cos \theta} \int_0^{L \cos \theta} \exp\left(- \frac{|x' - x''|}{L_c}\right) dx' \, dx''$$

$$= \left(\frac{1}{L}\right)^2 \int_0^{L} \int_0^{L} \exp\left(\frac{|l' - l''|}{L_c} \cos \theta\right) dl' \, dl'' \qquad \text{(C.1)}$$

upon evoking the change of variables given by $x = l \cos \theta$ for $0 \leq l \leq L$. Evaluation of equation (C.1) is facilitated by noting the regions of the l', l'' plane in which $|l' - l''| > 0$ and making use of the symmetry of the argument of the exponential, i.e.,

$$K(L,\theta) = \frac{2}{L^2} \int_0^{L} \int_0^{l'} \exp\left[- \frac{l' - l''}{L_c} \cos \theta\right] dl' \, dl''$$

$$= \frac{2}{L^2} \int_0^{L} \exp\left[- \frac{l'}{L_c} \cos \theta\right] \int_0^{l'} \exp\left[- \frac{l''}{L_c} \cos \theta\right] dl'' \, dl'$$

$$= \left(\frac{2}{L^2}\right)\left(\frac{L_c}{\cos \theta}\right) \int_0^{L} \exp\left[- \frac{l' \cos \theta}{L_c}\right] \left(\exp\left[\frac{l' \cos \theta}{L_c}\right] - 1\right) dl'$$

$$= \left(\frac{2}{L^2}\right)\left(\frac{L_c}{\cos \theta}\right) \left\{1 - \frac{L_c}{\cos \theta}\left[1 - \exp\left(- \frac{L \cos \theta}{L_c}\right)\right]\right\}$$

$$= \left(\frac{2}{L^2}\right) L_c \sec \theta \left\{L - L_c \sec \theta \left[1 - \exp\left(- \frac{L \cos \theta}{L_c}\right)\right]\right\} \qquad \text{(C.2)}$$

which is equation (2.48). In the special case where $\theta = 0$ (i.e., terrestrial propagation), equation (C.2) becomes

$$K(L,0) = \frac{2Lc}{L}\left[1 - \frac{Lc}{L}\left\{1 - \exp\left(- \frac{L}{L_c}\right)\right\}\right]$$

Further, as $L \to 0$, one has

$$K(0,0) = \lim_{L \to 0} K(L,0) = 1$$

which is the expected result.

It now remains to determine the value of L_c. This spatial characteristic is invariably linked to the average speed of rain cells and the time over which the observation is made. This characteristic time is essentially the integration time over which the rainrate statistics, calculated in section 3, apply. There, for the reasons given, the rainrate integration time is 5 min. Thus, to make an estimate of L_c that is consistent with the rainrate statistics, one must have the time over which Lc corresponds be equal to 5 min.

The characteristic average speed of the rain cell can be estimated as follows (ref. 37). The total mass M of the atmosphere is about 1.0×10^{19} kg and its total kinetic energy E_k is on the order of 1.0×10^{21} J. Hence, one can write for its characteristic velocity V

$$V = \sqrt{\frac{2E_k}{M}} = \sqrt{\frac{2 \times 10^{21}}{1.0 \times 10^{19}}} = 14 \text{ m/sec}$$

In a characteristic time T_c of 5-min, i.e., $T_c = 300$ sec, this corresponds to a characteristic length L_c of

$$L_c = VT_c = (14)(300) = 4200 \text{ m} = 4.2 \text{ km}$$

Here, a nominal value of $L_c = 4.0$ km will be used.

APPENDIX D

RAINRATE STATISTICAL PARAMETER ALGORITHM

This appendix details the computer algorithm used to find the parameters of the log-normal distribution for rainrate from rainfall intensity-duration-frequency curves. The relevant equations employed are equations (3.28), (3.29), (3.31) to (3.35), (3.42), (3.44), and (3.47). The flow-chart is shown in figure D.1 and the MS-BASIC Version 2.0 computer program follows.

The inputs into the program are the time base (in years), the 2-yr return period of the 5-min rainrate and the 10-yr return period of the same rainrate (both in inches/hour) and finally the average yearly rainfall (in inches). These inputs are specific to the location of interest and are obtained from the available curves and comparative meteorological data. The location at which these statistics have been observed is also an input for printing purposes of the compiled calculated statistical parameters. After the data is converted to millimeters of rainfall/hour (mm/hr) or just millimeters of rainfall (mm) the scale and location parameters, α and U, respectively, are calculated with all their associated quantities. Equation (3.47) is then numerically solved for P_0 via the Newton-Raphson Method. Two subroutines are used to expedite the calculation. The first, subroutine "FCTN," calculates the function ϕ defined in equation (3.44). This, however, requires the inverse normal probability function n^{-1} to be calculated. This is done in the subroutine "INVERT" where use is made of the rational approximation (ref. 16)

$$n^{-1}\left(1 - \frac{1}{105\ 120\ P_0}\right) = t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} + E$$

where

$$c_0 = 2.515517 \qquad d_1 = 1.432788$$

$$c_1 = 0.802853 \qquad d_2 = 0.189269$$

$$c_2 = \ .010328 \qquad d_3 = \ .001308,$$

$$t \equiv (2|\ln(105120\ P_0))^{1/2}$$

and

$$|E| < 4.5 \times 10^{-4}$$

With a value for P_0 obtained, the remaining parameters $\sigma_{\ln R}$ and R_m are then calculated. The printout routine then follows where the units of the quantities are as noted.

This algorithm was applied to meteorological data for 59 cities throughout the U.S., the results of which are given in appendix E.

PROGRAM D.1

```
REM                   RAIN STATS/I-D FREQ CRVS
REM                          VERSION 1.0
REM                          MAY 5, 1986
REM
REM  STATISTICAL RAIN PARAMETER ALGORITHM: FINDS LOG-NORMAL
REM  DISTRIBUTION PARAMETERS GIVEN LOCAL RAIN DATA IN TERMS OF
REM  5-MINUTE RAINFALL INTENSITY-DURATION FREQUENCY CURVES
REM  FOR 2 AND 10 YEAR RETURN PERIODS, AND THE AVERAGE YEARLY
REM  RAINFALL DEPTH.
REM
OPTION BASE 1
DIM Z(56)
210 CLS
M1=0
5 PRINT"ENTER CITY,STATE"
LINE INPUT CTY$
7 INPUT"EDIT INPUT ? (YES/NO)",EDT$
IF EDT$="YES" THEN GOTO 5
IF EDT$="NO" THEN GOTO 6
GOTO 7
6 CLS
12 INPUT"ENTER TIME BASE IN YEARS (<=55 YRS) :",YR
IF YR>55 THEN GOTO 12
INPUT"ENTER 2-YEAR RETURN PERIOD OF 5-MIN RAINRATE IN in/hr :",RNRT2
INPUT"ENTER 10-YEAR RETURN PERIOD OF 5-MIN RAINRATE IN in/hr :",RNRT10
INPUT"ENTER AVERAGE YEARLY RAINFALL IN inches :",WAVG
REM
REM  EDIT INPUT
REM
11 INPUT"EDIT INPUT ? (YES/NO)",EDT$
IF EDT$="YES" THEN GOTO 12
IF EDT$="NO" THEN GOTO 120
GOTO 11
REM
REM  CONVERT INPUT PARAMETERS TO mm/hr OR mm AND CALCULATE STATISTICS
REM
120 ZSUM=0
RNRT2=25.4*RNRT2
RNRT10=25.4*RNRT10
WAVG=25.4*WAVG
FOR I=1 TO YR
Z(I)=-LOG(-LOG(I/(YR+1)))
ZSUM=ZSUM+Z(I)
 NEXT I
ZAVG=ZSUM/YR
ZDSQ=0
ZDSQSUM=0
```


127, 128, 129

PROGRAM D.1 (CONTINUED)

```
FOR I=1 TO YR
ZDSQ=(Z(I)-ZAVG)^2
ZDSQSUM=ZDSQSUM+ZDSQ
 NEXT I
SIGMAZ=SQR(ZDSQSUM/(YR-1))
RETPRD1=2'YEARS
RETPRD2=10'YEARS
COEF1=-LOG(LOG(RETPRD1/(RETPRD1-1)))
COEF2=-LOG(LOG(RETPRD2/(RETPRD2-1)))
ALPHASYMP=(COEF1-COEF2)/(LOG(RNRT2)-LOG(RNRT10))
UASYMP=(COEF1*LOG(RNRT10)-COEF2*LOG(RNRT2))/(COEF1-COEF2)
ALPHA=ALPHASYMP*SIGMAZ*SQR(6)/3.14159
U=UASYMP+(.5772-(ZAVG/SIGMAZ)*3.14159/SQR(6))/ALPHASYMP
REM
REM SOLVE TRANSCENDENTAL EQUATION FOR P0
REM
160 INPUT"ENTER INITIAL GUESS FOR P0: (0<P0<=.09)",P0
 IF (P0<=0) OR (P0>.09) THEN GOTO 160
FOR J=1 TO 50
GOSUB FCTN'CALCULATE TRANSCENDENTAL FUNCTION
FUNC0=FUNC
P00=P0
P0=P00-.00001
GOSUB FCTN
FUNC1L=FUNC
P0=P00+.00001
GOSUB FCTN
FUNC1R=FUNC
P0=P00
SLOPE=(FUNC1R-FUNC1L)/(2*.00001)
P1=P0-FUNC0/SLOPE
IF P1>0 THEN GOTO 165
PRINT"CHOOSE A SMALLER P0."
GOTO 160
165 IF ABS(P1-P0)<.0001*P0 THEN GOTO 180
P0=P1
NEXT J
PRINT"ROOT NOT FOUND OF DESIRED ACCURACY IN 50 ITERATIONS"
STOP
REM
REM SOLVE FOR RAINRATE MEAN AND VARIANCE
REM
180 SIGMAR=(105120!*P0/ALPHA)*PSI
RM=WAVG/(8760*P0*EXP((SIGMAR^2)/2))
REM
REM  PRINTOUT RESULTS
REM
```

```
LPRINT
LPRINT
LPRINT
LPRINT
LPRINT
LPRINT TAB(30);"PROPAGATION PARAMETERS FOR ";CTY$
LPRINT
LPRINT
LPRINT TAB(30);"INPUT PARAMETERS:"
LPRINT
LPRINT TAB(35);"2 YEAR RETURN PERIOD 5-MIN RAINRATE = ";USING "####.##";RNRT2;
LPRINT TAB(82);"mm/hr"
LPRINT TAB(35);"10 YEAR RETURN PERIOD 5-MIN RAINRATE = ";USING"####.##";RNRT10;
LPRINT TAB(83);"mm/hr"
LPRINT TAB(35);"AVG. YEARLY TOTAL RAINFALL =";USING"####.##";WAVG;
LPRINT TAB(71);"mm"
LPRINT TAB(35);"TIME BASE = ";YR;
LPRINT TAB(52);"YEARS"
LPRINT
LPRINT
LPRINT TAB(30);"RAW RAINRATE STATISTICS FOR SITE:"
LPRINT
LPRINT TAB(35);"SCALE PARAMETER (ALPHA) =";USING "##.###";ALPHA
LPRINT TAB(35);"LOCATION PARAMETER (U) =";USING"##.###";U
LPRINT
LPRINT
LPRINT TAB(30);"LOG-NORMAL RAIN STATISTICS:"
LPRINT
LPRINT TAB(35);"PROBABILITY OF RAIN P0 = ";USING"##.###";P0*100;
LPRINT TAB(67)"% OF YEAR"
LPRINT TAB(35);"MEAN RAINRATE Rm = ";USING"##.###";RM;
LPRINT TAB(61)"mm/hr"
LPRINT TAB(35);"STANDARD DEV. OF LOG-RAINRATE SR = ";USING"#.###";SIGMAR;
LPRINT TAB(76)"NEPERS"
LPRINT
CLS
200 INPUT"CONTINUE WITH ANOTHER LOCATION ? (YES/NO)",ANS$
IF ANS$="YES" THEN GOTO 210
IF ANS$="NO" THEN GOTO 220
GOTO 200
220 END

FCTN:
GOSUB INVERT'CALCULATE INVPHI FUNCTION
PSI=(1/(SQR(2*3.14159)))*EXP(-(INVPHI^2)/2)
NUM=(ALPHA/105120!)*(U-LOG(WAVG/(8760*P0)))
DEN1=PSI*INVPHI
```

PROGRAM D.1 (CONTINUED)

```
DEN2=(P0/2)*(105120!/ALPHA)*(PSI^2)
FUNC=P0-NUM/(DEN1-DEN2)
RETURN

INVERT:
T=SQR(2*LOG(105120!*P0))
NUMER=2.515517+.802853*T+.010328*(T^2)
DENOM=1+1.432788*T+.189269*(T^2)+.001308*(T^3)
INVPHI=T-(NUMER/DENOM)
RETURN
```

APPENDIX E

PROPAGATION PARAMETERS FOR SELECTED CITIES IN THE UNITED STATES

PROPAGATION PARAMETERS FOR JUNEAU, AK.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 28.19 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 43.94 mm/hr
AVG. YEARLY TOTAL RAINFALL =1350.01 mm
TIME BASE = 19 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.590
LOCATION PARAMETER (U) = 3.243

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 36.390 % OF YEAR
MEAN RAINRATE Rm = 0.209 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 1.189 NEPERS

PROPAGATION PARAMETERS FOR PHOENIX, AZ.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 64.77 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 109.22 mm/hr
AVG. YEARLY TOTAL RAINFALL = 180.59 mm
TIME BASE = 45 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.274
LOCATION PARAMETER (U) = 4.062

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.280 % OF YEAR
MEAN RAINRATE Rm = 4.847mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.916 NEPERS

PROPAGATION PARAMETERS FOR LOS ANGELES, CA.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 54.61 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 90.17 mm/hr
AVG. YEARLY TOTAL RAINFALL = 342.14 mm
TIME BASE = 47 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.421
LOCATION PARAMETER (U) = 3.896

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 1.087 % OF YEAR
MEAN RAINRATE Rm = 2.195mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.993 NEPERS

PROPAGATION PARAMETERS FOR SAN DIEGO, CA.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 52.07 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 85.09 mm/hr
AVG. YEARLY TOTAL RAINFALL = 236.73 mm
TIME BASE = 46 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.489
LOCATION PARAMETER (U) = 3.851

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.558 % OF YEAR
MEAN RAINRATE Rm = 3.174 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.920 NEPERS

PROPAGATION PARAMETERS FOR FRESNO, CA.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 43.18 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 90.93 mm/hr
AVG. YEARLY TOTAL RAINFALL = 267.21 mm
TIME BASE = 47 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 2.304
LOCATION PARAMETER (U) = 3.611

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 15.087 % OF YEAR
MEAN RAINRATE Rm = 0.043 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 1.765 NEPERS

PROPAGATION PARAMETERS FOR SAN FRANSICSO, CA.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 48.26 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 77.47 mm/hr
AVG. YEARLY TOTAL RAINFALL = 495.81 mm
TIME BASE = 47 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.625
LOCATION PARAMETER (U) = 3.779

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 2.104 % OF YEAR
MEAN RAINRATE Rm = 1.654mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.987 NEPERS

PROPAGATION PARAMETERS FOR DENVER, CO.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 74.93 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 142.24 mm/hr
AVG. YEARLY TOTAL RAINFALL = 388.87 mm
TIME BASE = 46 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 2.673
LOCATION PARAMETER (U) = 4.184

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 2.714 % OF YEAR
MEAN RAINRATE Rm = 0.646mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 1.363 NEPERS

PROPAGATION PARAMETERS FOR HARTFORD, CT.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 102.87 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 156.21 mm/hr
AVG. YEARLY TOTAL RAINFALL =1127.51 mm
TIME BASE = 46 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.102
LOCATION PARAMETER (U) = 4.547

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 1.457 % OF YEAR
MEAN RAINRATE Rm = 6.168 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.848 NEPERS

PROPAGATION PARAMETERS FOR WASHINGTON, D.C.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 128.27 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 180.34 mm/hr
AVG. YEARLY TOTAL RAINFALL =1007.87 mm
TIME BASE = 55 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 5.083
LOCATION PARAMETER (U) = 4.784

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.477 % OF YEAR
MEAN RAINRATE Rm = 19.892 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.622 NEPERS

PROPAGATION PARAMETERS FOR MIAMI, FL.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 152.40 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 190.50 mm/hr
AVG. YEARLY TOTAL RAINFALL =1461.77 mm
TIME BASE = 40 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 7.608
LOCATION PARAMETER (U) = 4.980

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.318 % OF YEAR
MEAN RAINRATE Rm = 48.374 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.399 NEPERS

PROPAGATION PARAMETERS FOR TAMPA, FL.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 153.67 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 214.63 mm/hr
AVG. YEARLY TOTAL RAINFALL =1186.94 mm
TIME BASE = 52 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 5.166
LOCATION PARAMETER (U) = 4.966

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.449 % OF YEAR
MEAN RAINRATE Rm = 25.101 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.608 NEPERS

PROPAGATION PARAMETERS FOR JACKSONVILLE, FL.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 152.40 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 189.23 mm/hr
AVG. YEARLY TOTAL RAINFALL =1340.10 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 7.936
LOCATION PARAMETER (U) = 4.982

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.271 % OF YEAR
MEAN RAINRATE Rm = 52.649 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.377 NEPERS

PROPAGATION PARAMETERS FOR ATLANTA, GA.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 128.27 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 196.85 mm/hr
AVG. YEARLY TOTAL RAINFALL =1234.69 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.011
LOCATION PARAMETER (U) = 4.765

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 1.267 % OF YEAR
MEAN RAINRATE Rm = 7.698 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.858 NEPERS

PROPAGATION PARAMETERS FOR HONOLULU, HI.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 95.25 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 133.10 mm/hr
AVG. YEARLY TOTAL RAINFALL = 596.14 mm
TIME BASE = 34 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 5.016
LOCATION PARAMETER (U) = 4.486

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.349 % OF YEAR
MEAN RAINRATE Rm = 16.167 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.612 NEPERS

PROPAGATION PARAMETERS FOR CAIRO, IL.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 115.57 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 166.37 mm/hr
AVG. YEARLY TOTAL RAINFALL =1210.31 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.715
LOCATION PARAMETER (U) = 4.674

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.883 % OF YEAR
MEAN RAINRATE Rm = 12.173 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.708 NEPERS

PROPAGATION PARAMETERS FOR PEORIA, IL.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 115.57 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 157.48 mm/hr
AVG. YEARLY TOTAL RAINFALL = 886.21 mm
TIME BASE = 46 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 5.537
LOCATION PARAMETER (U) = 4.686

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.386 % OF YEAR
MEAN RAINRATE Rm = 22.407 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.560 NEPERS

PROPAGATION PARAMETERS FOR SPRINGFIELD, IL.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 120.65 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 171.45 mm/hr
AVG. YEARLY TOTAL RAINFALL = 858.01 mm
TIME BASE = 47 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.882
LOCATION PARAMETER (U) = 4.720

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.449 % OF YEAR
MEAN RAINRATE Rm = 17.737 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.644 NEPERS

PROPAGATION PARAMETERS FOR CHICAGO, IL.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 116.84 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 177.80 mm/hr
AVG. YEARLY TOTAL RAINFALL = 846.84 mm
TIME BASE = 32 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.978
LOCATION PARAMETER (U) = 4.673

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.806 % OF YEAR
MEAN RAINRATE Rm = 8.475 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.833 NEPERS

PROPAGATION PARAMETERS FOR INDIANAPOLIS, IN.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 114.30 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 162.56 mm/hr
AVG. YEARLY TOTAL RAINFALL = 993.65 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.877
LOCATION PARAMETER (U) = 4.666

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.610 % OF YEAR
MEAN RAINRATE Rm = 14.936 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.663 NEPERS

PROPAGATION PARAMETERS FOR EVANSVILLE, IN.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 115.57 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 153.67 mm/hr
AVG. YEARLY TOTAL RAINFALL =1055.37 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 6.029
LOCATION PARAMETER (U) = 4.691

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.423 % OF YEAR
MEAN RAINRATE Rm = 24.913 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.518 NEPERS

PROPAGATION PARAMETERS FOR FORT WAYNE, IN.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 106.68 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 160.02 mm/hr
AVG. YEARLY TOTAL RAINFALL = 873.76 mm
TIME BASE = 40 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.187
LOCATION PARAMETER (U) = 4.585

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.841 % OF YEAR
MEAN RAINRATE Rm = 8.650 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.794 NEPERS

PROPAGATION PARAMETERS FOR LEXINGTON, KY.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 106.68 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 152.40 mm/hr
AVG. YEARLY TOTAL RAINFALL =1160.27 mm
TIME BASE = 38 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.743
LOCATION PARAMETER (U) = 4.595

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.921 % OF YEAR
MEAN RAINRATE Rm = 11.209 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.707 NEPERS

PROPAGATION PARAMETERS FOR LOUISVILLE, KY.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 121.92 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 179.07 mm/hr
AVG. YEARLY TOTAL RAINFALL =1106.42 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.469
LOCATION PARAMETER (U) = 4.724

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.819 % OF YEAR
MEAN RAINRATE Rm = 11.705 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.743 NEPERS

PROPAGATION PARAMETERS FOR NEW ORLEANS, LA.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 154.94 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 204.47 mm/hr
AVG. YEARLY TOTAL RAINFALL =1517.40 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 6.193
LOCATION PARAMETER (U) = 4.986

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.444 % OF YEAR
MEAN RAINRATE Rm = 34.272 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.507 NEPERS

PROPAGATION PARAMETERS FOR BOSTON, MA.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 92.71 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 139.70 mm/hr
AVG. YEARLY TOTAL RAINFALL =1112.77 mm
TIME BASE = 49 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.195
LOCATION PARAMETER (U) = 4.445

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 1.566 % OF YEAR
MEAN RAINRATE Rm = 5.729 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.834 NEPERS

PROPAGATION PARAMETERS FOR BALTIMORE, MD.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 132.08 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 199.39 mm/hr
AVG. YEARLY TOTAL RAINFALL =1062.74 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.171
LOCATION PARAMETER (U) = 4.798

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.827 % OF YEAR
MEAN RAINRATE Rm = 10.680 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.796 NEPERS

PROPAGATION PARAMETERS FOR LANSING, MI.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 101.60 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 153.67 mm/hr
AVG. YEARLY TOTAL RAINFALL = 751.33 mm
TIME BASE = 41 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.110
LOCATION PARAMETER (U) = 4.535

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.753 % OF YEAR
MEAN RAINRATE Rm = 8.260 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.802 NEPERS

PROPAGATION PARAMETERS FOR ALPENA, MI.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 90.17 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 153.67 mm/hr
AVG. YEARLY TOTAL RAINFALL = 730.50 mm
TIME BASE = 37 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.167
LOCATION PARAMETER (U) = 4.390

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 2.558 % OF YEAR
MEAN RAINRATE Rm = 1.692 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 1.145 NEPERS

PROPAGATION PARAMETERS FOR DETRIOT, MI.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 104.14 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 163.83 mm/hr
AVG. YEARLY TOTAL RAINFALL = 786.64 mm
TIME BASE = 46 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.781
LOCATION PARAMETER (U) = 4.552

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 1.032 % OF YEAR
MEAN RAINRATE Rm = 5.831 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.895 NEPERS

PROPAGATION PARAMETERS FOR GRAND RAPIDS, MI.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 102.87 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 152.40 mm/hr
AVG. YEARLY TOTAL RAINFALL = 872.49 mm
TIME BASE = 45 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.353
LOCATION PARAMETER (U) = 4.552

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.793 % OF YEAR
MEAN RAINRATE Rm = 9.411 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.760 NEPERS

PROPAGATION PARAMETERS FOR HOUGHTON, MI.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 86.36 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 127.00 mm/hr
AVG. YEARLY TOTAL RAINFALL = 710.95 mm
TIME BASE = 24 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.227
LOCATION PARAMETER (U) = 4.376

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.822 % OF YEAR
MEAN RAINRATE Rm = 7.253 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.785 NEPERS

PROPAGATION PARAMETERS FOR SAULT STE. MARIE, MI.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 86.36 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 129.54 mm/hr
AVG. YEARLY TOTAL RAINFALL = 850.39 mm
TIME BASE = 42 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.201
LOCATION PARAMETER (U) = 4.374

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 1.126 % OF YEAR
MEAN RAINRATE Rm = 6.205 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.811 NEPERS

PROPAGATION PARAMETERS FOR KANSAS CITY, MO.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 121.92 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 176.53 mm/hr
AVG. YEARLY TOTAL RAINFALL = 818.39 mm
TIME BASE = 52 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.664
LOCATION PARAMETER (U) = 4.727

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.458 % OF YEAR
MEAN RAINRATE Rm = 16.256 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.675 NEPERS

PROPAGATION PARAMETERS FOR OMAHA, NEB.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 113.03 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 177.80 mm/hr
AVG. YEARLY TOTAL RAINFALL = 765.56 mm
TIME BASE = 40 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.748
LOCATION PARAMETER (U) = 4.633

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.880 % OF YEAR
MEAN RAINRATE Rm = 6.674 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.891 NEPERS

PROPAGATION PARAMETERS FOR TRENTON, NJ.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 116.84 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 165.10 mm/hr
AVG. YEARLY TOTAL RAINFALL =1075.44 mm
TIME BASE = 38 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.893
LOCATION PARAMETER (U) = 4.689

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.659 % OF YEAR
MEAN RAINRATE Rm = 14.928 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.666 NEPERS

PROPAGATION PARAMETERS FOR ALBANY, NY.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 105.41 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 152.40 mm/hr
AVG. YEARLY TOTAL RAINFALL = 907.80 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.660
LOCATION PARAMETER (U) = 4.582

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.674 % OF YEAR
MEAN RAINRATE Rm = 12.040 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.700 NEPERS

PROPAGATION PARAMETERS FOR BINGHAMTON, NY.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 102.87 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 152.40 mm/hr
AVG. YEARLY TOTAL RAINFALL = 934.21 mm
TIME BASE = 46 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.359
LOCATION PARAMETER (U) = 4.552

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.881 % OF YEAR
MEAN RAINRATE Rm = 9.028 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.766 NEPERS

PROPAGATION PARAMETERS FOR BUFFALO, NY.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 88.90 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 139.70 mm/hr
AVG. YEARLY TOTAL RAINFALL = 953.01 mm
TIME BASE = 50 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.810
LOCATION PARAMETER (U) = 4.394

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 1.846 % OF YEAR
MEAN RAINRATE Rm = 3.826 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.930 NEPERS

PROPAGATION PARAMETERS FOR ROCHESTER, NY.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 100.33 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 138.43 mm/hr
AVG. YEARLY TOTAL RAINFALL = 794.26 mm
TIME BASE = 43 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 5.300
LOCATION PARAMETER (U) = 4.542

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.441 % OF YEAR
MEAN RAINRATE Rm = 17.264 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.592 NEPERS

PROPAGATION PARAMETERS FOR NEW YORK, NY.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 113.03 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 166.37 mm/hr
AVG. YEARLY TOTAL RAINFALL =1104.14 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.444
LOCATION PARAMETER (U) = 4.648

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.935 % OF YEAR
MEAN RAINRATE Rm = 10.133 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.755 NEPERS

PROPAGATION PARAMETERS FOR SYRACUSE, NY.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 102.87 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 158.75 mm/hr
AVG. YEARLY TOTAL RAINFALL = 993.39 mm
TIME BASE = 45 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.944
LOCATION PARAMETER (U) = 4.543

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 1.353 % OF YEAR
MEAN RAINRATE Rm = 5.706 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.877 NEPERS

PROPAGATION PARAMETERS FOR OKLAHOMA CITY, OK.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 125.73 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 167.64 mm/hr
AVG. YEARLY TOTAL RAINFALL = 784.61 mm
TIME BASE = 46 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 5.956
LOCATION PARAMETER (U) = 4.775

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.254 % OF YEAR
MEAN RAINRATE Rm = 31.098 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.499 NEPERS

PROPAGATION PARAMETERS FOR CLEVELAND, OH.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 111.76 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 177.80 mm/hr
AVG. YEARLY TOTAL RAINFALL = 899.16 mm
TIME BASE = 50 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.709
LOCATION PARAMETER (U) = 4.620

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 1.239 % OF YEAR
MEAN RAINRATE Rm = 5.395 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.926 NEPERS

PROPAGATION PARAMETERS FOR COLUMBUS. OH.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 106.68 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 153.67 mm/hr
AVG. YEARLY TOTAL RAINFALL = 939.04 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.707
LOCATION PARAMETER (U) = 4.594

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.679 % OF YEAR
MEAN RAINRATE Rm = 12.413 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.694 NEPERS

PROPAGATION PARAMETERS FOR PORTLAND, OR.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 44.45 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 76.20 mm/hr
AVG. YEARLY TOTAL RAINFALL = 949.71 mm
TIME BASE = 47 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.183
LOCATION PARAMETER (U) = 3.683

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 17.325 % OF YEAR
MEAN RAINRATE Rm = 0.273 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 1.288 NEPERS

PROPAGATION PARAMETERS FOR HARRISBURG, PA.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 113.03 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 177.80 mm/hr
AVG. YEARLY TOTAL RAINFALL = 992.89 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.792
LOCATION PARAMETER (U) = 4.634

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 1.329 % OF YEAR
MEAN RAINRATE Rm = 5.636 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.911 NEPERS

PROPAGATION PARAMETERS FOR MEMPHIS, TN.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 116.84 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 176.53 mm/hr
AVG. YEARLY TOTAL RAINFALL =1309.88 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.163
LOCATION PARAMETER (U) = 4.675

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 1.437 % OF YEAR
MEAN RAINRATE Rm = 7.344 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.835 NEPERS

PROPAGATION PARAMETERS FOR NASHVILLE, TN.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 128.27 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 180.34 mm/hr
AVG. YEARLY TOTAL RAINFALL =1231.65 mm
TIME BASE = 46 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 5.029
LOCATION PARAMETER (U) = 4.784

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.658 % OF YEAR
MEAN RAINRATE Rm = 17.330 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.647 NEPERS

PROPAGATION PARAMETERS FOR DALLAS, TX.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 129.54 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 182.88 mm/hr
AVG. YEARLY TOTAL RAINFALL = 748.28 mm
TIME BASE = 37 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.897
LOCATION PARAMETER (U) = 4.792

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.326 % OF YEAR
MEAN RAINRATE Rm = 21.608 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.622 NEPERS

PROPAGATION PARAMETERS FOR AUSTIN, TX.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 140.97 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 189.23 mm/hr
AVG. YEARLY TOTAL RAINFALL = 800.10 mm
TIME BASE = 24 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 5.537
LOCATION PARAMETER (U) = 4.886

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.251 % OF YEAR
MEAN RAINRATE Rm = 31.569 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.535 NEPERS

PROPAGATION PARAMETERS FOR EL PASO, TX.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 66.04 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 106.68 mm/hr
AVG. YEARLY TOTAL RAINFALL = 198.63 mm
TIME BASE = 42 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.552
LOCATION PARAMETER (U) = 4.091

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.250 % OF YEAR
MEAN RAINRATE Rm = 6.416 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.834 NEPERS

PROPAGATION PARAMETERS FOR HOUSTON, TX.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 151.13 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 205.74 mm/hr
AVG. YEARLY TOTAL RAINFALL =1136.90 mm
TIME BASE = 41 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 5.513
LOCATION PARAMETER (U) = 4.954

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.379 % OF YEAR
MEAN RAINRATE Rm = 29.284 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.561 NEPERS

PROPAGATION PARAMETERS FOR SAN ANTONIO, TX.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 127.00 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 190.50 mm/hr
AVG. YEARLY TOTAL RAINFALL = 739.90 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.237
LOCATION PARAMETER (U) = 4.760

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.467 % OF YEAR
MEAN RAINRATE Rm = 13.702 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.745 NEPERS

PROPAGATION PARAMETERS FOR FORT WORTH, TX.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 120.65 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 166.37 mm/hr
AVG. YEARLY TOTAL RAINFALL = 748.28 mm
TIME BASE = 45 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 5.325
LOCATION PARAMETER (U) = 4.726

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.306 % OF YEAR
MEAN RAINRATE Rm = 23.731 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.568 NEPERS

PROPAGATION PARAMETERS FOR SALT LAKE CITY, UT.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 49.53 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 87.63 mm/hr
AVG. YEARLY TOTAL RAINFALL = 388.87 mm
TIME BASE = 44 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 2.995
LOCATION PARAMETER (U) = 3.784

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 3.292 % OF YEAR
MEAN RAINRATE Rm = 0.630 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 1.233 NEPERS

PROPAGATION PARAMETERS FOR RICHMOND, VA.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 128.27 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 184.15 mm/hr
AVG. YEARLY TOTAL RAINFALL =1119.38 mm
TIME BASE = 47 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.744
LOCATION PARAMETER (U) = 4.779

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.656 % OF YEAR
MEAN RAINRATE Rm = 15.384 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.686 NEPERS

PROPAGATION PARAMETERS FOR NORFOLK, VA.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 116.84 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 175.26 mm/hr
AVG. YEARLY TOTAL RAINFALL =1148.59 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 4.237
LOCATION PARAMETER (U) = 4.677

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 1.093 % OF YEAR
MEAN RAINRATE Rm = 8.694 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.802 NEPERS

PROPAGATION PARAMETERS FOR SEATTLE, WA.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 31.75 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 55.88 mm/hr
AVG. YEARLY TOTAL RAINFALL = 983.49 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.039
LOCATION PARAMETER (U) = 3.341

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 52.991 % OF YEAR
MEAN RAINRATE Rm = 0.076 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 1.432 NEPERS

PROPAGATION PARAMETERS FOR MILWAUKEE, WI.

INPUT PARAMETERS:

2 YEAR RETURN PERIOD 5-MIN RAINRATE = 105.41 mm/hr
10 YEAR RETURN PERIOD 5-MIN RAINRATE = 162.56 mm/hr
AVG. YEARLY TOTAL RAINFALL = 785.88 mm
TIME BASE = 48 YEARS

RAW RAINRATE STATISTICS FOR SITE:

SCALE PARAMETER (ALPHA) = 3.966
LOCATION PARAMETER (U) = 4.568

LOG-NORMAL RAIN STATISTICS:

PROBABILITY OF RAIN P0 = 0.856 % OF YEAR
MEAN RAINRATE Rm = 7.363 mm/hr
STANDARD DEV. OF LOG-RAINRATE SR = 0.840 NEPERS

APPENDIX F

DERIVATION OF THE SATELLITE SLANT PATH ELEVATION ANGLE EQUATION

Consider a geostationary satellite as a longitude L_S and an Earth terminal at a longitude L_E and a latitude Λ, as depicted in figure F.1. Let R_0 be the radius of the Earth and R be the distance of the satellite from the center of the Earth G. In the figure, the point S is the subsatellite point on the equator and E is the substation point on the equator where it is intersected by the plane of the major circle passing through the Earth station. Let w be the relative longitude of the Earth station with respect to the satellite; hence

$$w = |L_E - L_S| \tag{F.1}$$

From the construction shown in the figure, the angles w, Λ and α are related by

$$\cos \alpha = \cos \Lambda \cos w. \tag{F.2}$$

Applying the law of cosines to the triangle formed by the satellite, the Earth station, and the point G, one has that

$$d^2 = R^2 + R_0^2 - 2RR_0 \cos \alpha \tag{F.3}$$

where d is the distance of the Earth station from the satellite. Substituting equation (F.2) into equation (F.3) yields

$$d^2 = R^2 + R_0^2 - 2RR_0 \cos \Lambda \cos w. \tag{F.4}$$

Figure F.2 shows a detail of the above-mentioned triangle and its relationship to the local horizontal at the Earth station. The link elevation angle θ is the angle existing between the local horizontal and the direction to the satellite. Since the local horizontal forms a right angle to the radius vector of the Earth at the Earth station, one can write, again by employing the law of cosines,

$$R^2 = R_0^2 + d^2 - 2R_0 d \cos\left(\frac{\pi}{2} + \theta\right) = R_0^2 + d^2 + 2R_0 d \sin \theta \tag{F.5}$$

Solving this equation for $\sin \theta$ gives

$$\sin \theta = \frac{R^2 - R_0^2 - d^2}{2R_0 d} \tag{F.6}$$

Substituting equation (F.4) into this expression finally gives

$$\theta = \sin^{-1}\left\{\frac{R \cos \Lambda \cos w - R_0}{\left(R^2 + R_0^2 - 2R_0 R \cos \Lambda \cos w\right)^{1/2}}\right\}, \tag{F.7}$$

relating θ to known quantities of the problem. The constant R_0 is given by

FIGURE F.1

FIGURE F.2

$$R_0 = 6370 \text{ km}$$

For the geostationary case considered here, the constant R is

$$R = 42\ 230 \text{ km}$$

APPENDIX G

ACTS ATTENUATION PREDICTION ALGORITHM

This appendix details the algorithm and computer software used to generate the ACTS attenuation predictions which are the subject of Section 5. The algorithm is specific to the ACTS in that it assumes a satellite position of 100° W in a geostationary orbit with an uplink of 30 GHz and downlink of 20 GHz. It can, however, be easily modified for application to any other satellite in a geostationary orbit.

The algorithm configuration is essentially that given in the flow chart of Figure 5.1, with the addition of the calculations required by equations (5.3) to (5.8). The only other difference is that the coefficients a_V, a_H, b_V, and b_H corresponding to the frequencies of 20 and 30 GHz are preassigned within the program. The portion of the program which assigns these values must be changed if it is to be applied to other frequencies.

The MS-BASIC computer code used to generate the results of Section 5 is given in program G.1. The subroutine "ERRORFUNC" evalutes the error function, and hence the complementary error function, as required by the model.

PROGRAM G.1

```
REM                     ACTS ATTEN PREDICTION
REM                          VERSION 1.0
REM                          MAY 5,1986
REM
REM   RAIN ATTENUATION CALCULATION ALGORITHM FOR SPACE COMMUNIC-
REM  ATION LINK TO GEOSYNCHRONUS SATELLITE FOR 20 GHz (DOWNLINK)
REM   AND 30 GHz (UPLINK).
REM
FLG$="NBP"'BYPASS/NO BYPASS FLAG FOR ENTERING RAINRATE STATISTICS
110 CLS
PRINT"ENTER CITY (OR SITE LOCATION),STATE OF TERMINAL :"
LINE INPUT CTY$
INPUT"ENTER TERMINAL HEIGHT IN FEET ABOVE SEA LEVEL :",HT
HT=(.0003048)*HT' CONVERT TO kM
INPUT"ENTER TERMINAL LATITUDE IN THE FORM ' DEG. MIN ' NORTH :",LAT
INPUT"ENTER TERMINAL LONGITUDE IN THE FORM ' DEG.MIN ' WEST :",LNG
LAT=100*(LAT-INT(LAT))/60+INT(LAT)' CONVERT LATITUDE TO DECIMAL REPRESENTATION
LNG=100*(LNG-INT(LNG))/60+INT(LNG)' CONVERT LONGITUDE TO DECIMAL REPRESENTATION
INPUT"ENTER POLARIZATION ANGLE IN DEGREES :",TAU
IF FLG$="BP" THEN GOTO 115
INPUT"ENTER PROBABILITY (%) OF RAIN FOR TERMINAL CITY :",PO
INPUT"ENTER MEAN RAINRATE (IN mm/hr) FOR TERMINAL CITY :",RM
INPUT"ENTER RAINRATE STANDARD DEVIATION FOR TERMINAL CITY :",SR
REM
REM  CALCULATE ANTENNA ELEVATION ANGLE TO SATELLITE
REM
115 REARTH=6370'RADIUS OF EARTH IN kM
RORBIT=42230!'RADIUS OF GEOSYNC. ORBIT IN kM
SLNG=100'SATELLITE LONGITUDE IN DEG. W. (ACTS)
CONV=3.14159/180'CONVERSION FACTOR TO RADIAN MEASURE
RELLONG=ABS(LNG-SLNG)'STATION/SATELLITE RELATIVE LONGITUDE
DIST=SQR(REARTH^2+RORBIT^2-2*REARTH*RORBIT*COS(CONV*LAT)*COS(CONV*RELLONG))'DISTANC
E INkM FROM TERMINAL TO SATELLITE
AGMT=(RORBIT^2-REARTH^2-DIST^2)/(2*REARTH*DIST)
ELEV=(1/CONV)*ATN(AGMT/(SQR(1-AGMT^2)))'CALC ELEVATION ANGLE VIA ARCTAN FUNCTION.
REM
REM CONVERT ANGLES TO RADIANS
REM
ELEVR=(3.14159/180)*ELEV
TAUR=(3.14159/180)*TAU
REM
REM CALCULATE 0-DEGREE ISOTHERM HEIGHT
REM
IF LAT<=30 THEN H=4.8
IF LAT>30 THEN H=7.8-.1*LAT
REM
REM DETERMINE SLANT PATH RANGE
```

PROGRAM G.1 (CONTINUED)

```
REM
L=(H-HT)/SIN(ELEVR)
REM
REM DETERMINE PROBABILITY (%) OF RAIN ALONG PATH PROJECTION
REM
PL=(1-(1-(P0/100))/((1+((L*COS(ELEVR))^2)/21.5)^.014))*100'%
LPRINT
LPRINT TAB(25)" CITY, STATE OF TERMINAL: ";CTY$
LPRINT
LPRINT
LPRINT TAB(5)"STATION HEIGHT IN kM = ";USING"#.###";HT
LPRINT TAB(5)"STATION LATITUDE IN DEG. N. =";USING"###.##";LAT
LPRINT TAB(5)"TERMINAL LONGITUDE IN DEG. W. = ";USING"###.##";LNG
LPRINT TAB(5)"ANTENNA ELEV. ANGLE = ";USING"##.##";ELEV
LPRINT TAB(5)"LINK SLANT PATH LGTH. THRU RAIN REGION IN kM = ";USING"##.##";L
LPRINT TAB(5)"SLANT PATH PROJECTION ON EARTH IN kM = ";USING"##.##";L*COS(ELEVR)
LPRINT TAB(5)"P0 IN % =";USING"##.###";P0
LPRINT TAB(5)"RM IN mm/hr =";USING"##.###";RM
LPRINT TAB(5)"SR = ";USING"#.###";SR
LPRINT TAB(5)"POLARIZATION ANGLE IN DEGREES = ";USING"##.#";TAU
REM
REM CALCULATE a AND b COEFFICIENTS
REM
FREQ=20'GHz
LINK$="DOWNLINK"
10 IF FREQ=20 THEN GOTO 30
IF FREQ=30 THEN GOTO 40
GOTO 10
30 KH=.0751
KV=.0691
AH=1.099
AV=1.065
GOTO 50
40 KH=.187
KV=.167
AH=1.021
AV=1!
50 A=(KH+KV+(KH-KV)*((COS(ELEVR))^2)*COS(2*TAUR))/2
B=(KH*AH+KV*AV+(KH*AH-KV*AV)*((COS(ELEVR))^2)*COS(2*TAUR))/(2*A)
REM
REM CALCULATE SPECIFIC ATTENUATION STATISTICS
REM
GM=A*(RM^B)' MEAN SPECIFIC ATTENUATION
SG=B*SR' STANDARD DEVIATION OF SPECIFIC ATTENUATION
REM
REM DETERMINE PATH CORRELATION FUNCTION
REM
```

PROGRAM G.1 (CONTINUED)

```
LC=4' CHARACTERISTIC CORRELATION LENGTH IN kM
HL=(2/(L^2))*(LC/COS(ELEVR))*(L-(LC/COS(ELEVR))*(1-EXP(-(L*COS(ELEVR))/LC)))' kM
REM
REM CALCULATE SLANT PATH ATTENUATION STATISTICS
REM
SA2=LOG((PL/100)*(HL*((EXP(SG^2))/(PO/100)-1)+1))
AM=(PO/PL)*L*GM*EXP((SG^2-SA2)/2)
REM
REM  ATMOSPHERIC MOLECULAR ABSORPTION
REM
RHO=10' AVG. WATER VAPOR CONCENTRATION IN g-m^(-3)
GAMMO=(7.1/(FREQ^2+.36)+4.5/((FREQ-57)^2+.98))*FREQ^2*.001'SPECIFIC ATTENUATION DUE TO OXYGE
N
GAMMAW=(.067+3/((FREQ-22.3)^2+7.3))*RHO*FREQ^2*.0001' SPECIFIC ATTENUATION DUE TO WATER V
APOR
HO=6' EFFECTIVE HEIGHT OF OXYGEN IN kM
HW=2.2+3/((FREQ-22.3)^2+3)' EFFECTIVE HEIGHT OF WATER VAPOR IN kM
ATTENG=(GAMMAO*HO*EXP(-HT/HO)+GAMMAW*HW)/SIN(ELEVR)' ATTENUATION DUE TO MOLECULAR A
BSORPTION IN dB
REM
REM  PRINT ATTENUATION PARAMETERS AND CALCULATE PROBABILITIES
REM
LPRINT
LPRINT
LPRINT
LPRINT
LPRINT TAB(21)"LOG-NORMAL ATTENUATION STATISTICS FOR";FREQ;"GHz ";LINK$
LPRINT
LPRINT TAB(30)"PROBABILITY OF ATTENUATION PL = ";USING"##.###";PL;
LPRINT TAB(69)"%"
LPRINT TAB(30)"MEAN ATTENUATION Am = ";USING"##.###";AM;
LPRINT TAB(59)"dB"
LPRINT TAB(30)"STANDARD DEV. OF ATTENUATION = ";USING"##.###";SQR(SA2)
FOR ATTEN=5 TO 25 STEP 5
ARG=(LOG(ATTEN)-LOG(AM))/(SQR(2*SA2))
GOSUB ERRORFUNC
PA=(PL/2)*ERFC
IF ATTEN>5 THEN GOTO 70
LPRINT
LPRINT TAB(5)"ATTENUATION (dB)";TAB(23)"PROBABILITY (% OF YEAR)";TAB(49)"WORST MONTH PRO
BABILITY (% OF MONTH)"
LPRINT
70 LPRINT TAB(9);USING"##.##";ATTEN;
LPRINT TAB(31);USING"##.###";PA;
LPRINT TAB(65);USING"##.###";(PA/.29)^(1/1.15)
NEXT ATTEN
LPRINT
```

PROGRAM G.1 (CONTINUED)

```
LPRINT TAB(5)"ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = ";USING"##.###";ATTENG;
LPRINT TAB(61)"dB"
IF FREQ=30 THEN GOTO 80
FREQ=30
LINK$="UPLINK"
GOTO 10
CLS
80 INPUT"CALCULATE FOR ANOTHER TERMINAL SITE ? (YES/NO) :";ANS$
IF ANS$="YES" THEN GOTO 100
IF ANS$="NO" THEN GOTO 90
GOTO 80
100 INPUT"ARE THE RAINRATE STATISTICS FOR THE SITE THE SAME ? (YES/NO) :";ANS$
IF ANS$="YES" THEN GOTO 105
IF ANS$="NO" THEN GOTO 106
GOTO 100
105 LET FLG$="BP"
GOTO 110
106 LET FLG$="NBP"
GOTO 110
90 END


ERRORFUNC:
TOL=.00001
IF ARG<0 THEN LET K1=-1
IF ARG>0 THEN LET K1=1
IF ARG=0 THEN GOTO 1000
ARG=K1*ARG
ARG2=ARG^2
IF (ARG>1.5) THEN GOTO 1100
T0=ARG
T1=ARG
J=0
REM BEGIN LOOP
1200 J=J+1
T2=T0
T1=2*T1*ARG2/(1+2*J)
T0=T1+T2
IF (T1>TOL*T0) THEN GOTO 1200
ERF=K1*2*T0*EXP(-ARG2)/SQR(3.14159)
ERFC=1-ERF
GOTO 1300
1000 ERF=0
ERFC=1
GOTO 1300
1100 REM COMPLEMENTARY ERROR FUNCTION
T3=12
```

PROGRAM G.1 (CONTINUED)

```
V=.5/ARG2
U=1+V*(T3+1)
FOR J=T3 TO 1 STEP -1
T0=1+J*V/U
U=T0
NEXT J
ERFC=EXP(-ARG2)/(ARG*T0*SQR(3.14159))
ERF=1-ERFC
IF K1=1 THEN GOTO 1300
ERF=-ERF
ERFC=1-ERF
1300 RETURN
```

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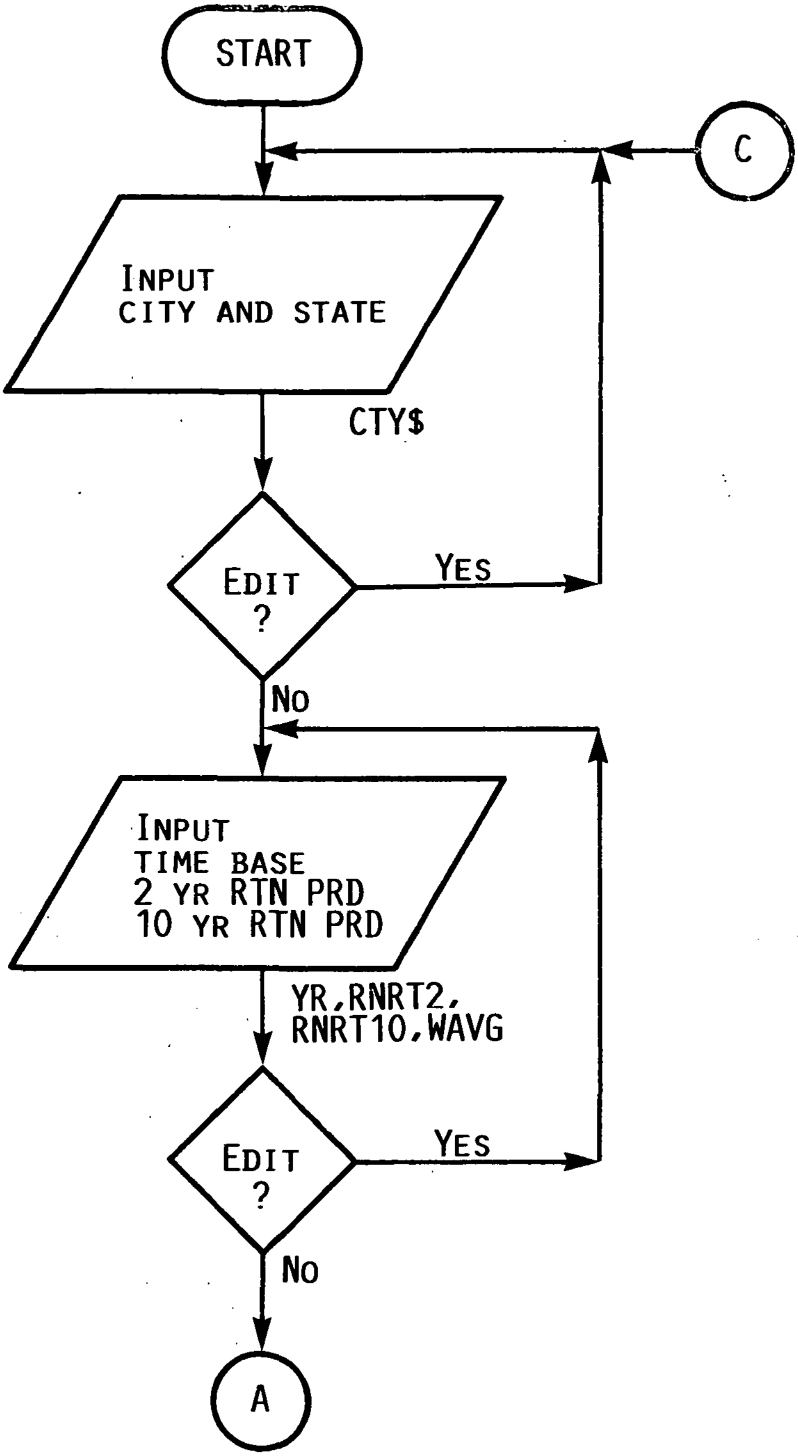

START
C
INPUT
CITY AND STATE
CTY$
EDIT
?
YES
NO
INPUT
TIME BASE
2 YR RTN PRD
10 YR RTN PRD
YR,RNRT2,
RNRT10,WAVG
EDIT
?
YES
NO
A

FIGURE D.1

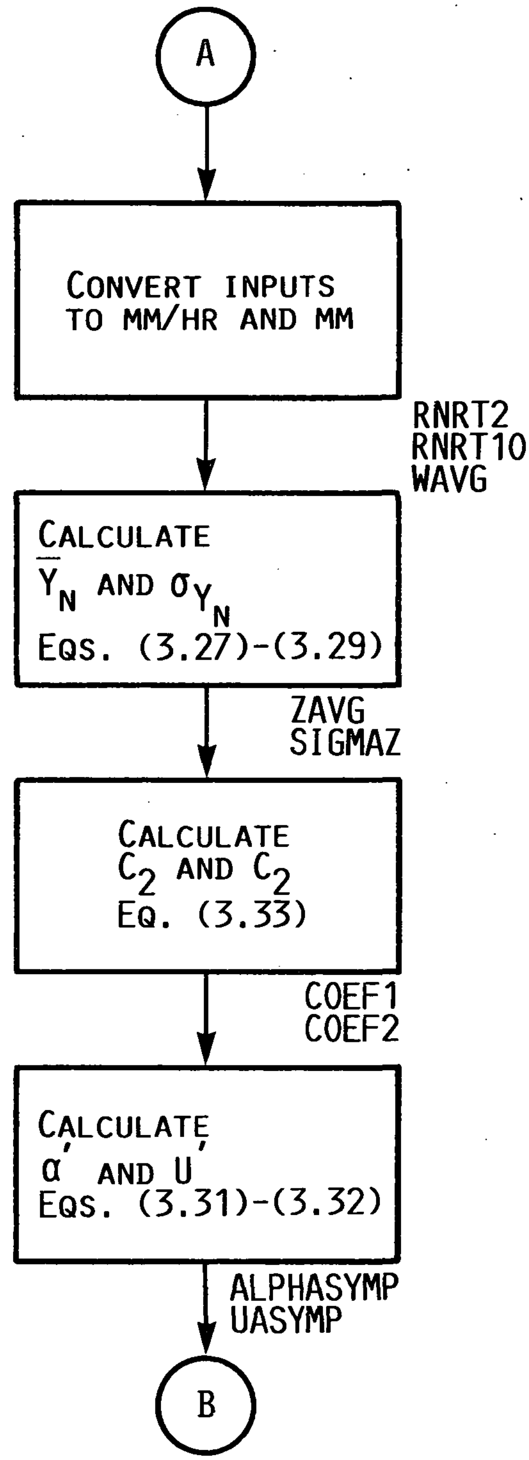


FIGURE D-1 - CONTINUED

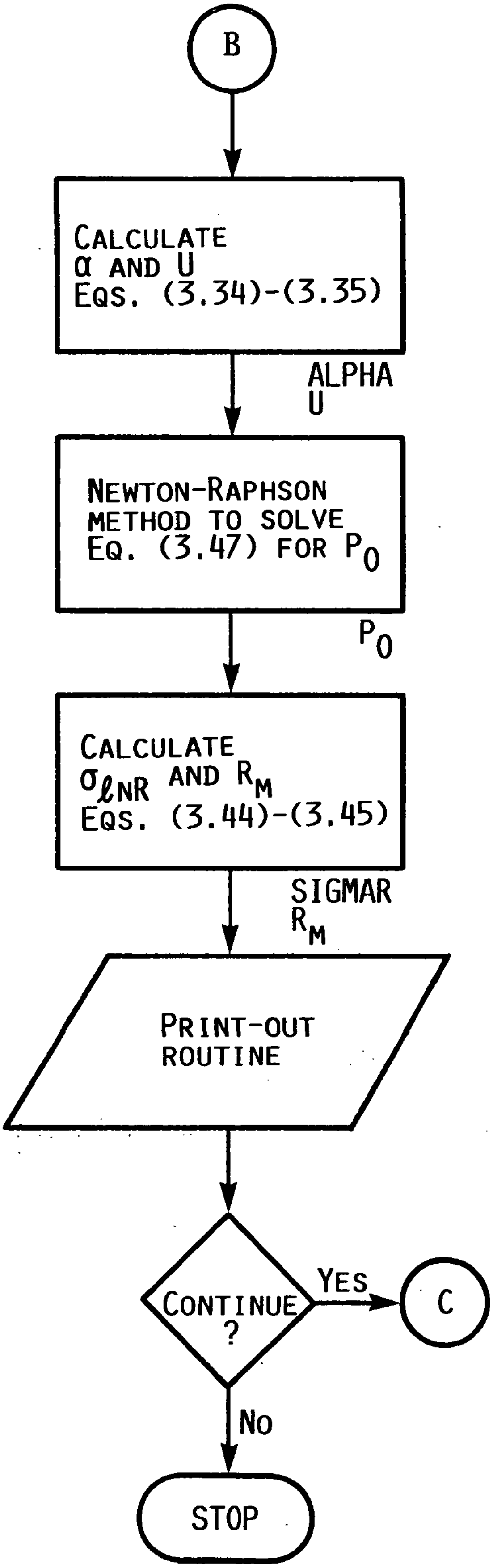


FIGURE D-1 - CONCLUDED

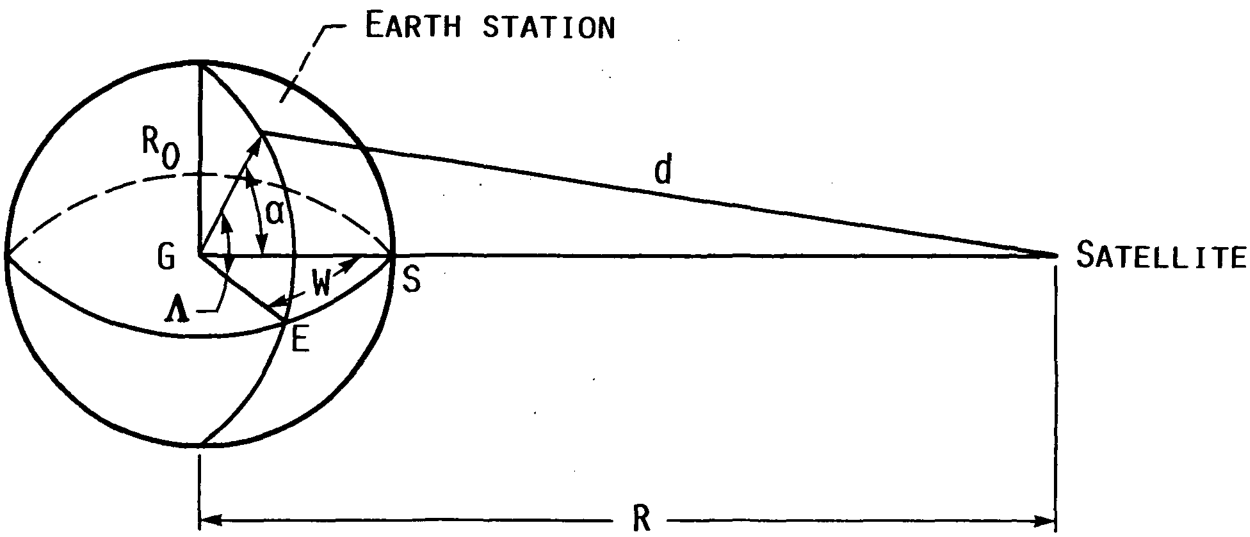


FIGURE F.1

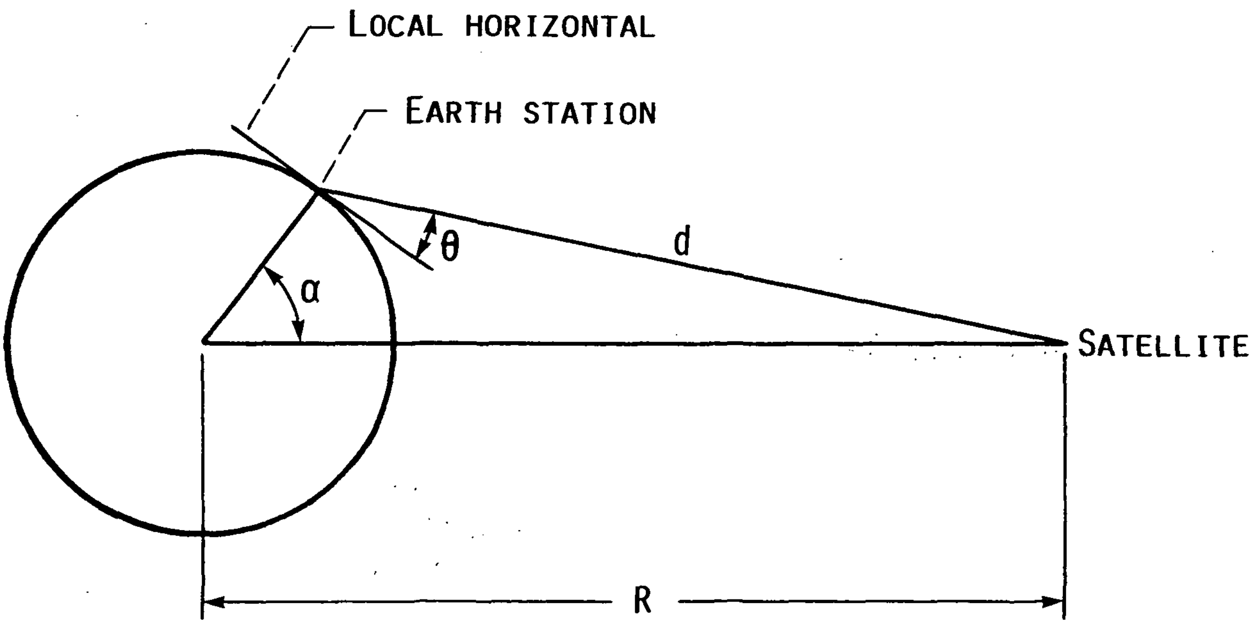


FIGURE F.2

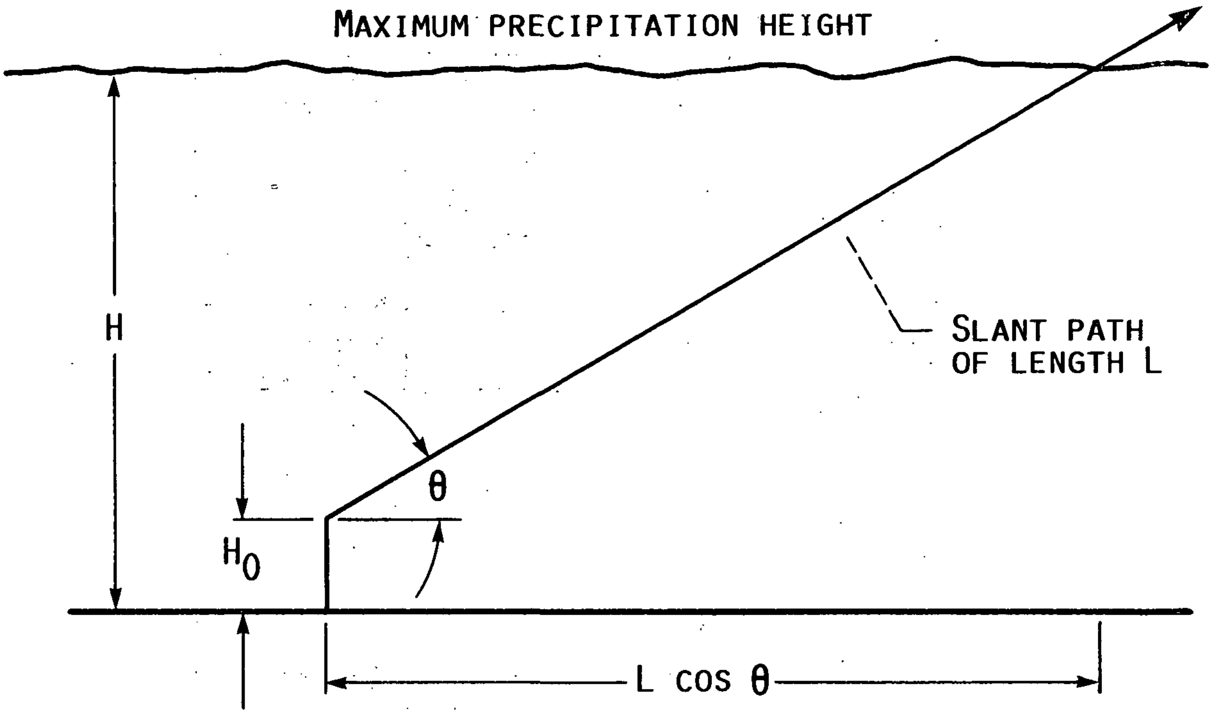


FIGURE 2.1. - PROPAGATION SCENARIO.

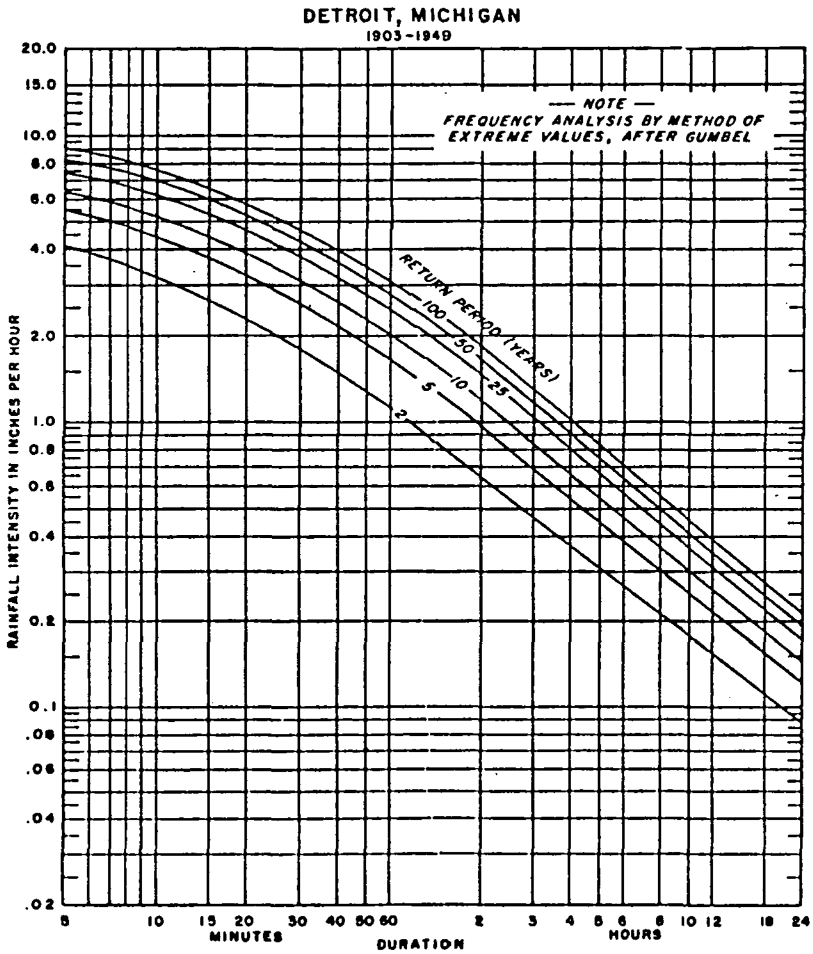
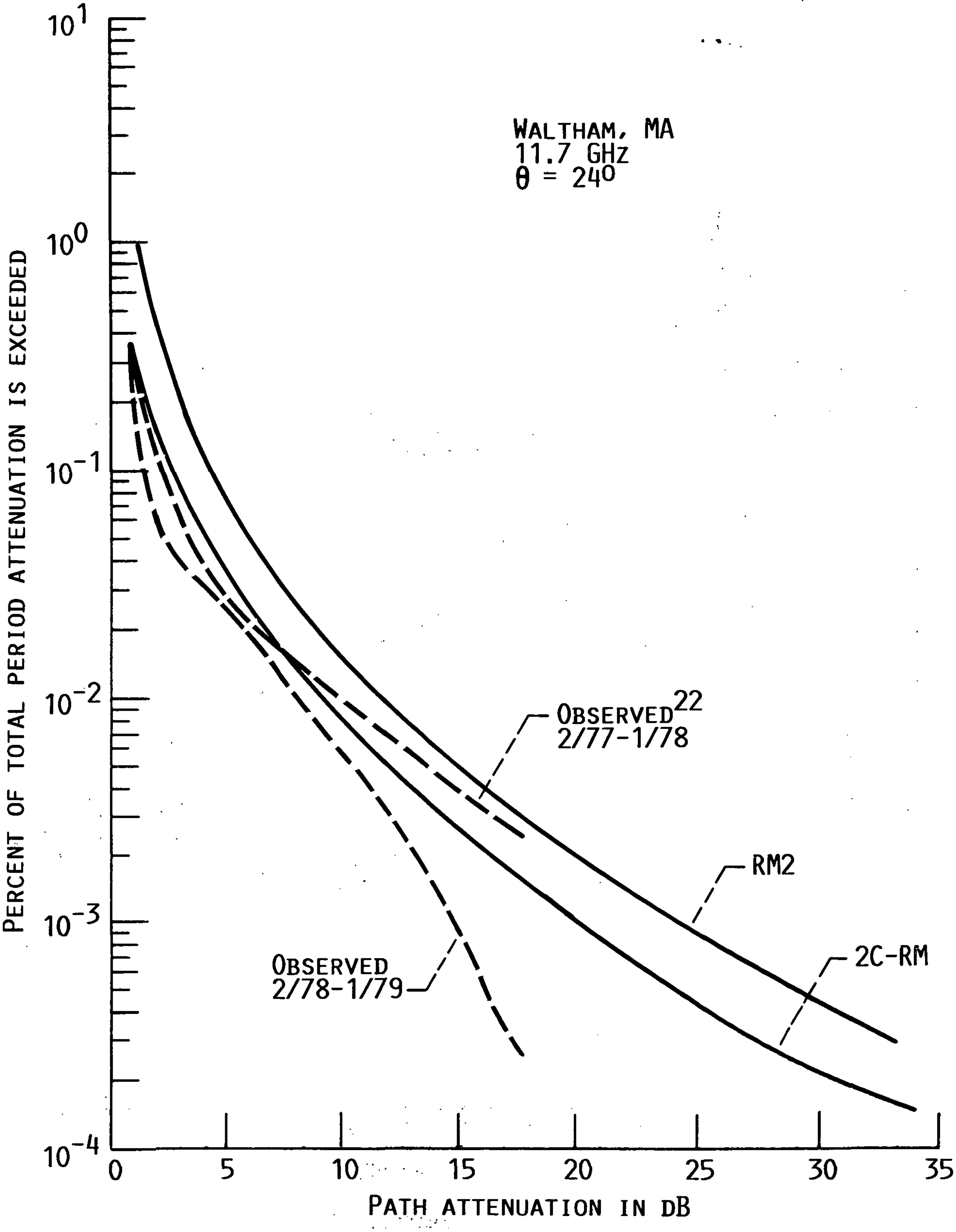
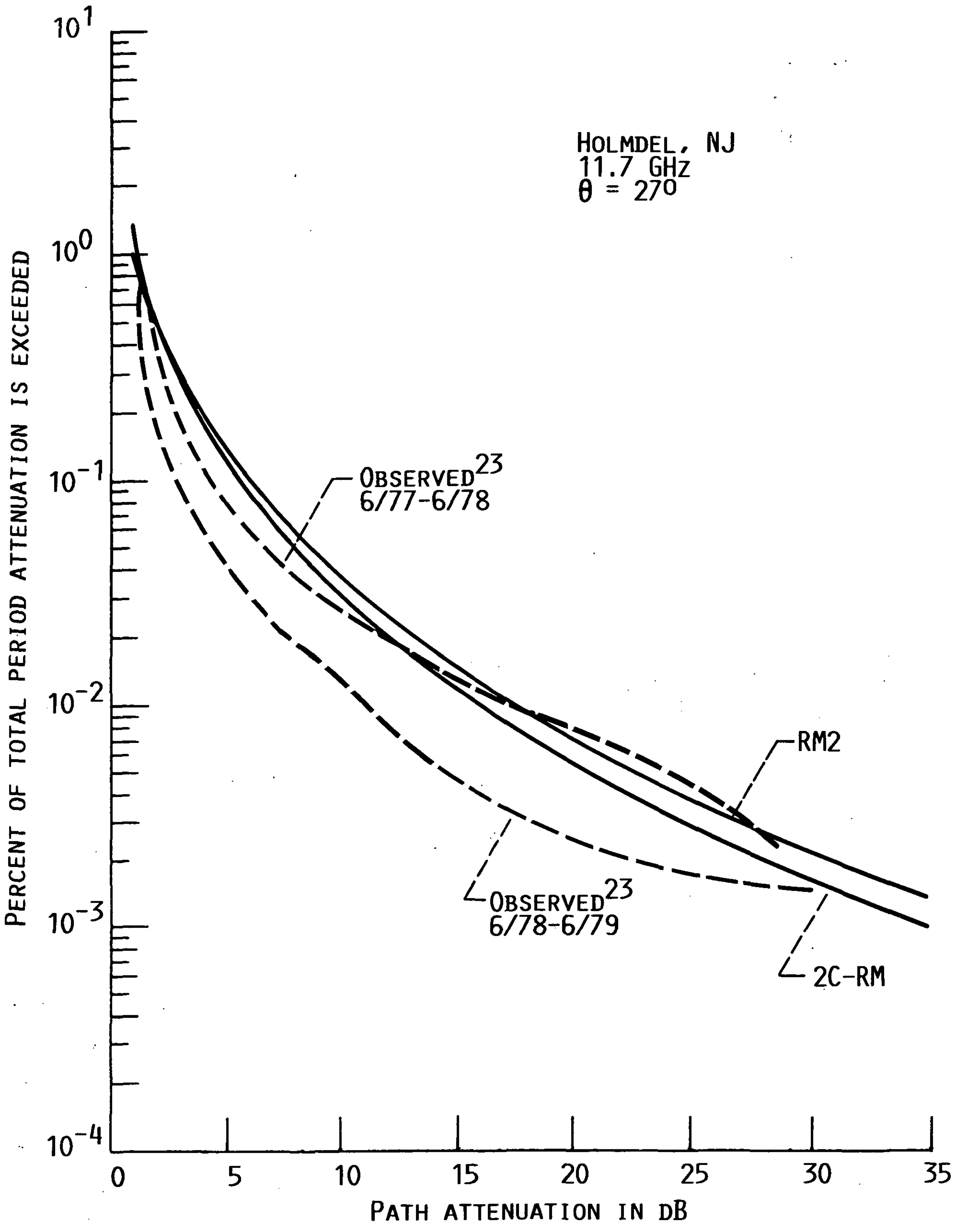


FIGURE 3.1. - EXAMPLE OF RAINRATE INTENSITY-DURATION FREQUENCY CURVES.



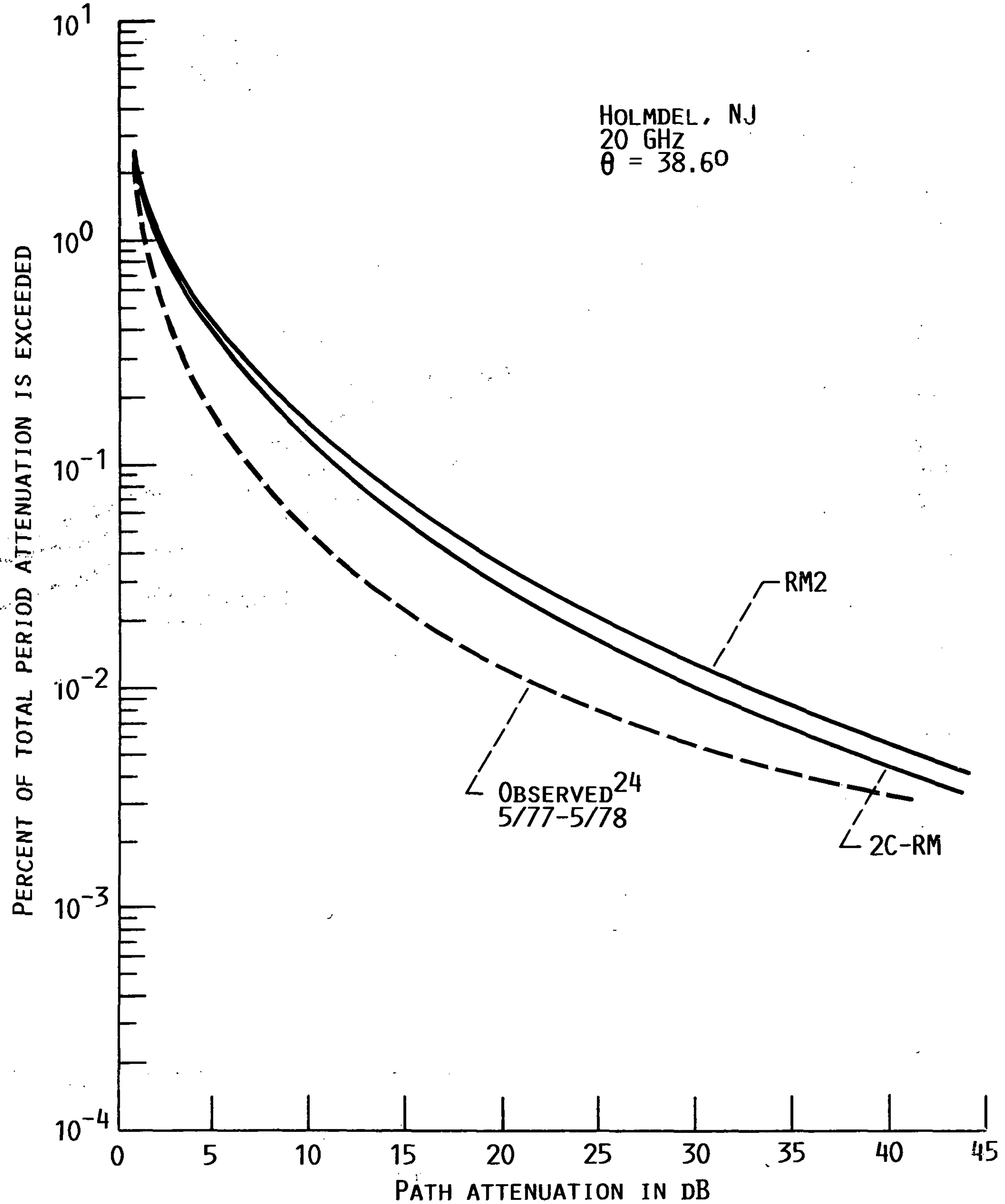
WALTHAM, MA
11.7 GHz
θ = 24°
OBSERVED[22]
2/77-1/78
OBSERVED
2/78-1/79
RM2
2C-RM
PERCENT OF TOTAL PERIOD ATTENUATION IS EXCEEDED
PATH ATTENUATION IN dB
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0
5
10
15
20
25
30
35

FIGURE 4.1



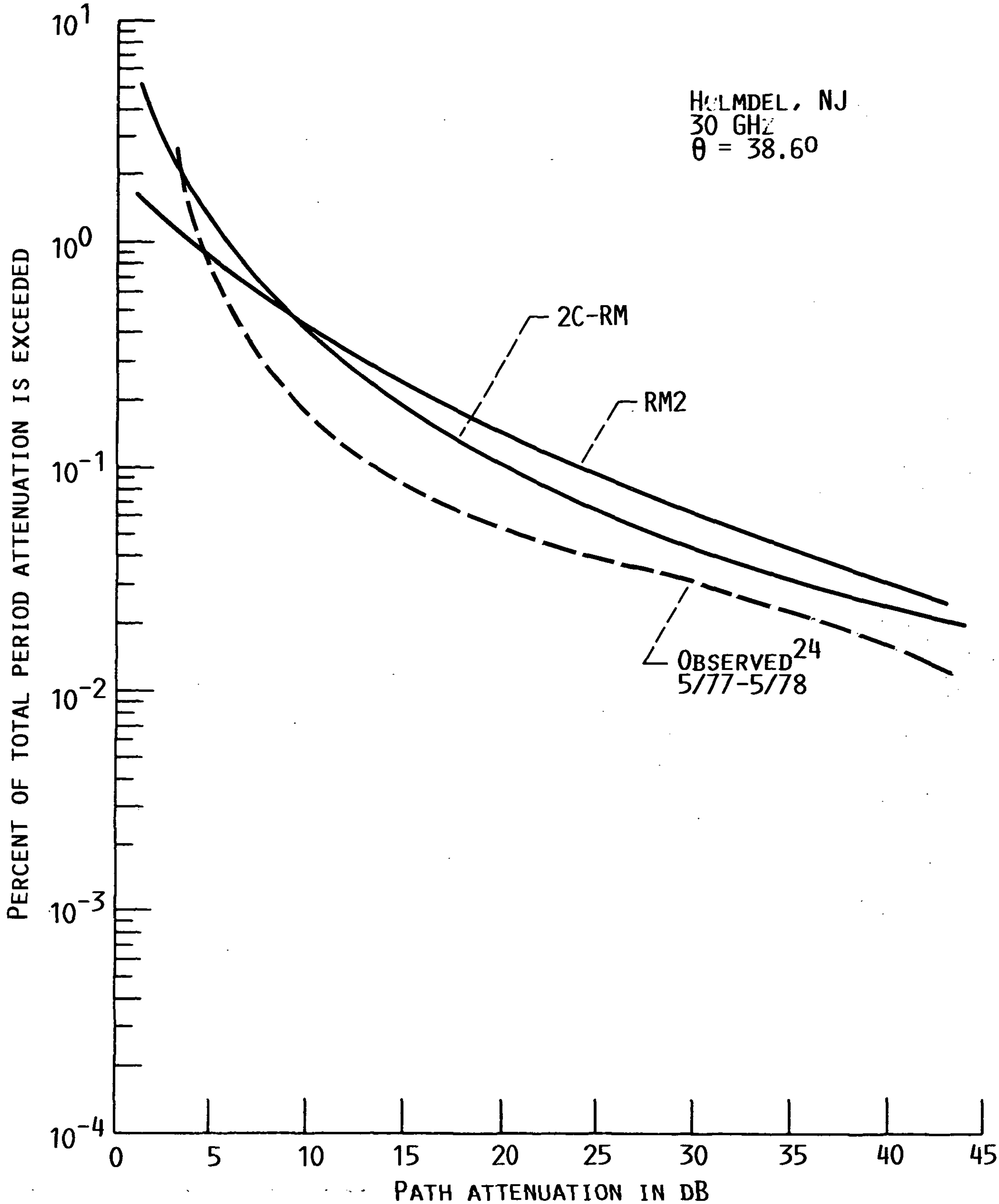
HOLMDEL, NJ
11.7 GHz
θ = 27°
OBSERVED[23]
6/77-6/78
OBSERVED[23]
6/78-6/79
RM2
2C-RM
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
5
10
15
20
25
30
35
PERCENT OF TOTAL PERIOD ATTENUATION IS EXCEEDED
PATH ATTENUATION IN dB

FIGURE 4.2



HOLMDEL, NJ
20 GHz
θ = 38.6°
RM2
OBSERVED[24]
5/77-5/78
2C-RM
PERCENT OF TOTAL PERIOD ATTENUATION IS EXCEEDED
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
5
10
15
20
25
30
35
40
45
PATH ATTENUATION IN dB

FIGURE 4.3



HOLMDEL, NJ
30 GHZ
θ = 38.6°
2C-RM
RM2
OBSERVED24
5/77-5/78
PERCENT OF TOTAL PERIOD ATTENUATION IS EXCEEDED
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0
5
10
15
20
25
30
35
40
45
PATH ATTENUATION IN DB

FIGURE 4.4

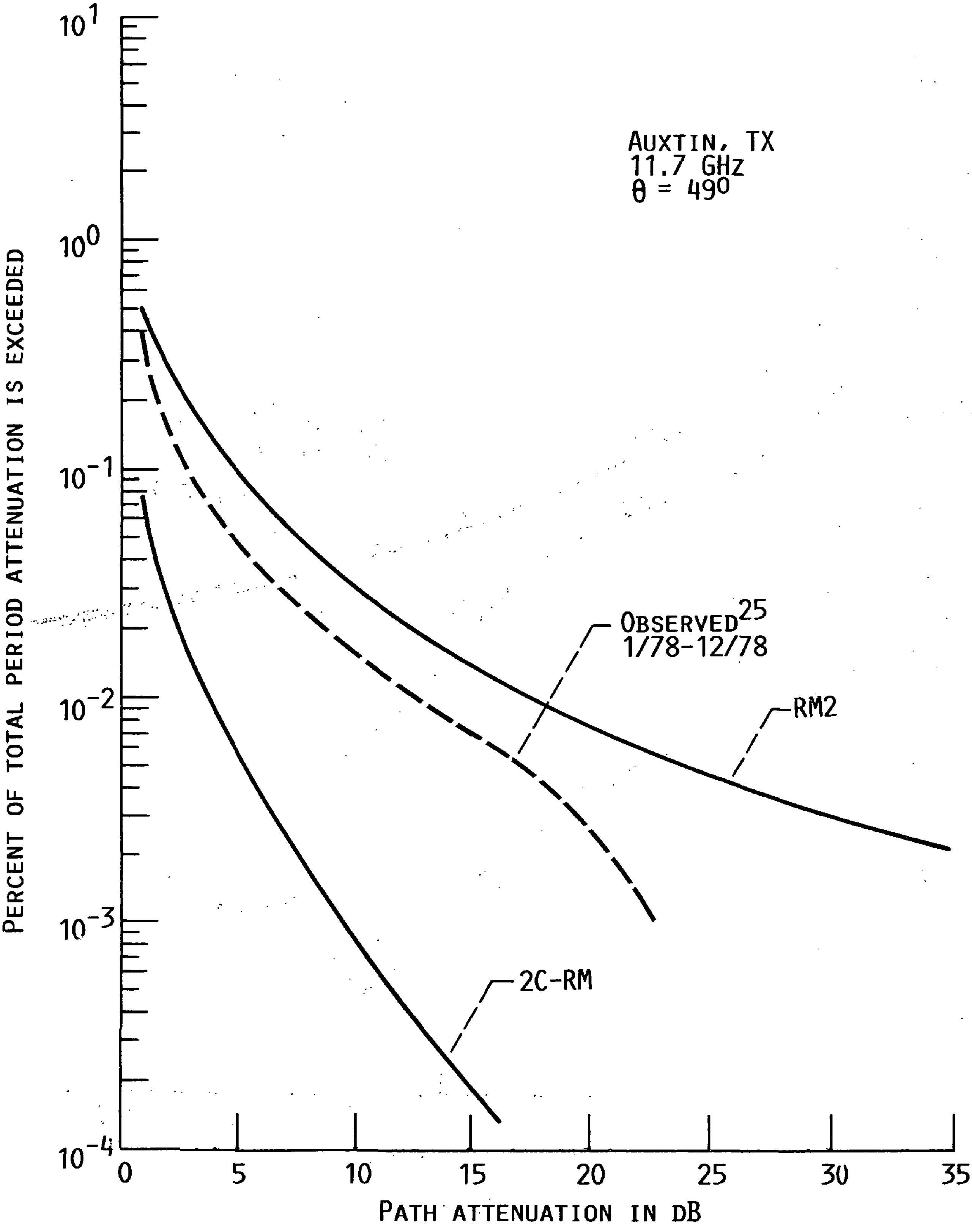
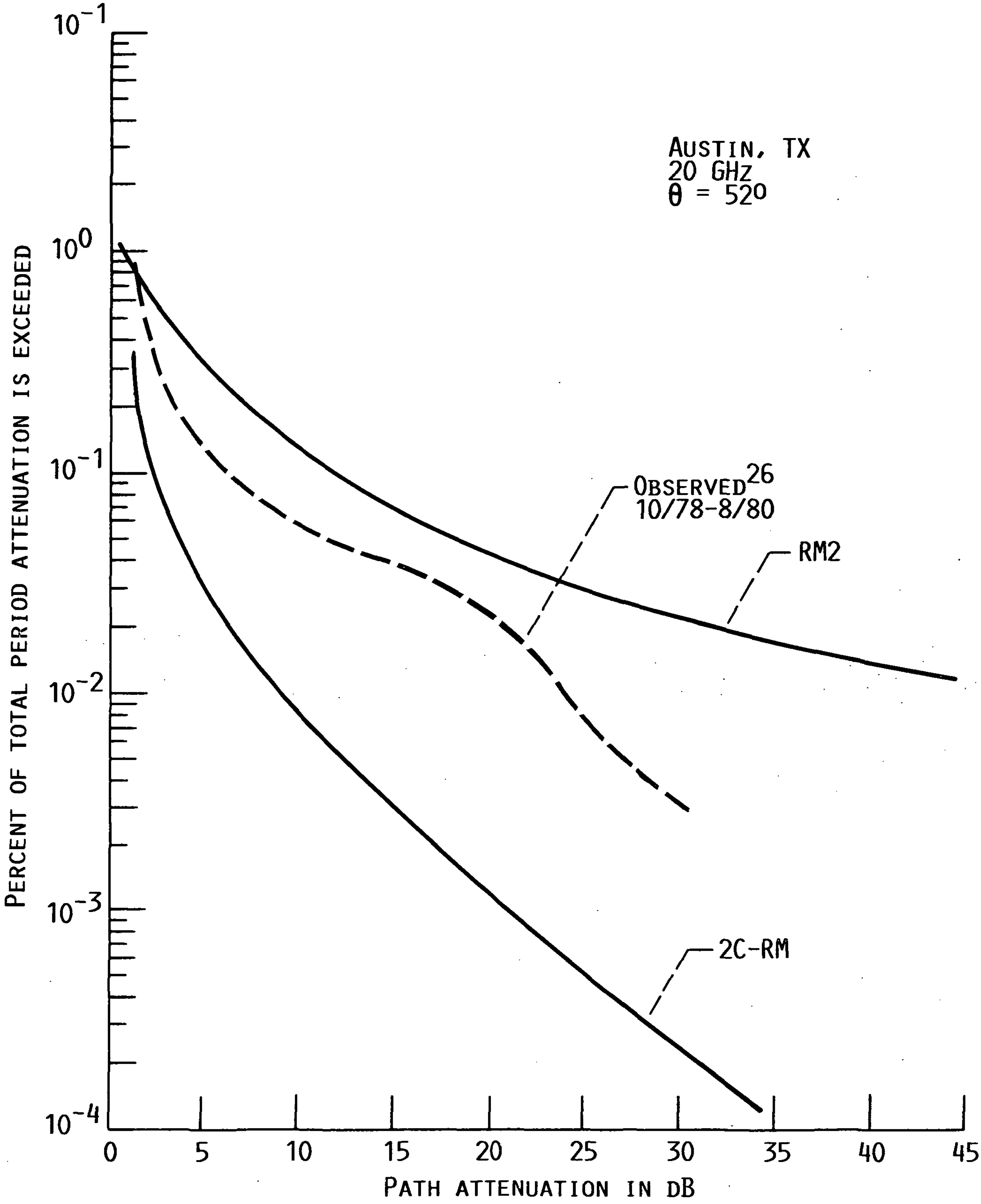

AUXTIN, TX
11.7 GHz
θ = 49°
OBSERVED25
1/78-12/78
RM2
2C-RM
PERCENT OF TOTAL PERIOD ATTENUATION IS EXCEEDED
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0
5
10
15
20
25
30
35
PATH ATTENUATION IN dB

FIGURE 4.5



AUSTIN, TX
20 GHz
θ = 52°
OBSERVED[26]
10/78-8/80
RM2
2C-RM
PERCENT OF TOTAL PERIOD ATTENUATION IS EXCEEDED
10^-1
10^0
10^-1
10^-2
10^-3
10^-4
0
5
10
15
20
25
30
35
40
45
PATH ATTENUATION IN dB

FIGURE 4.6

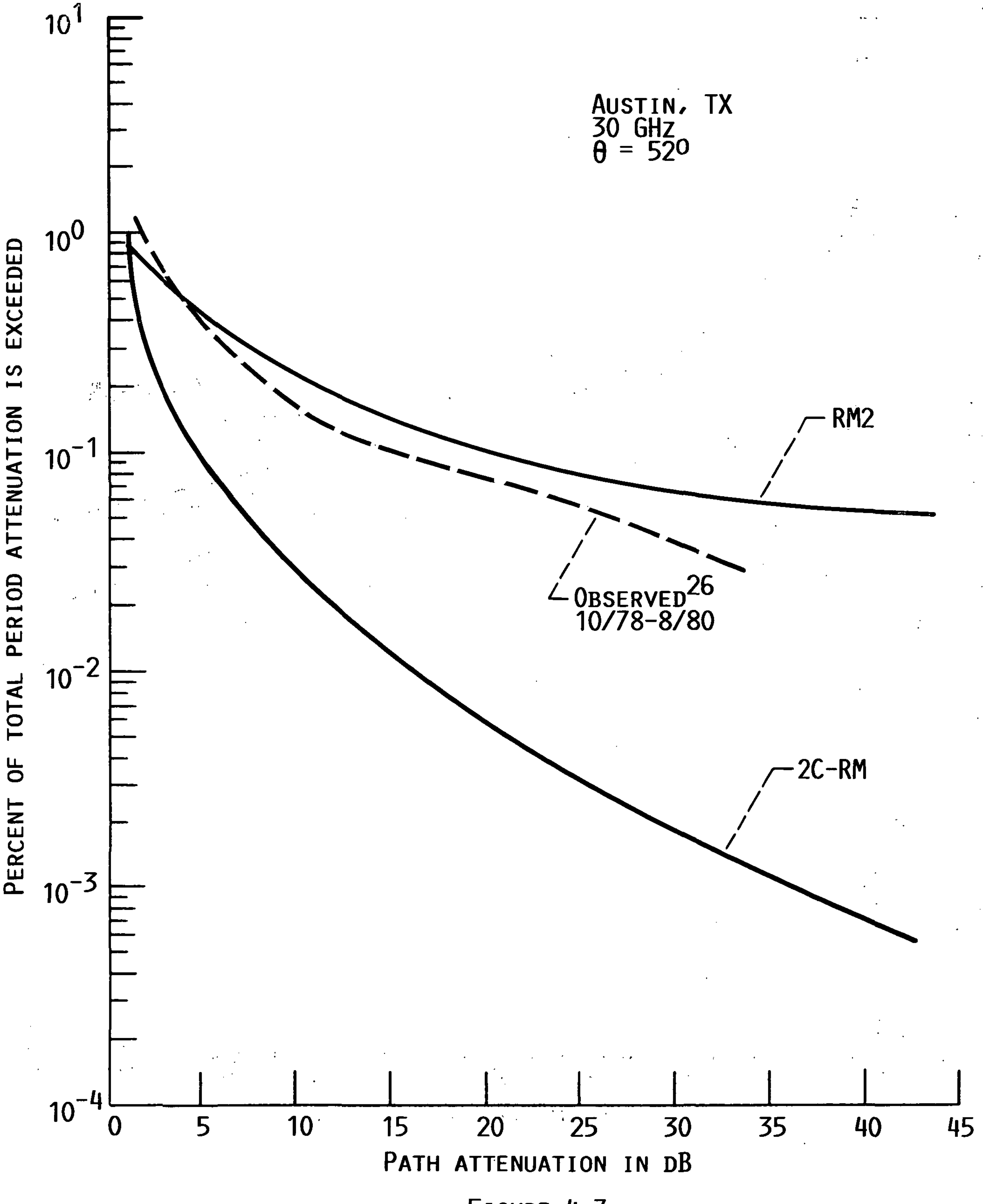
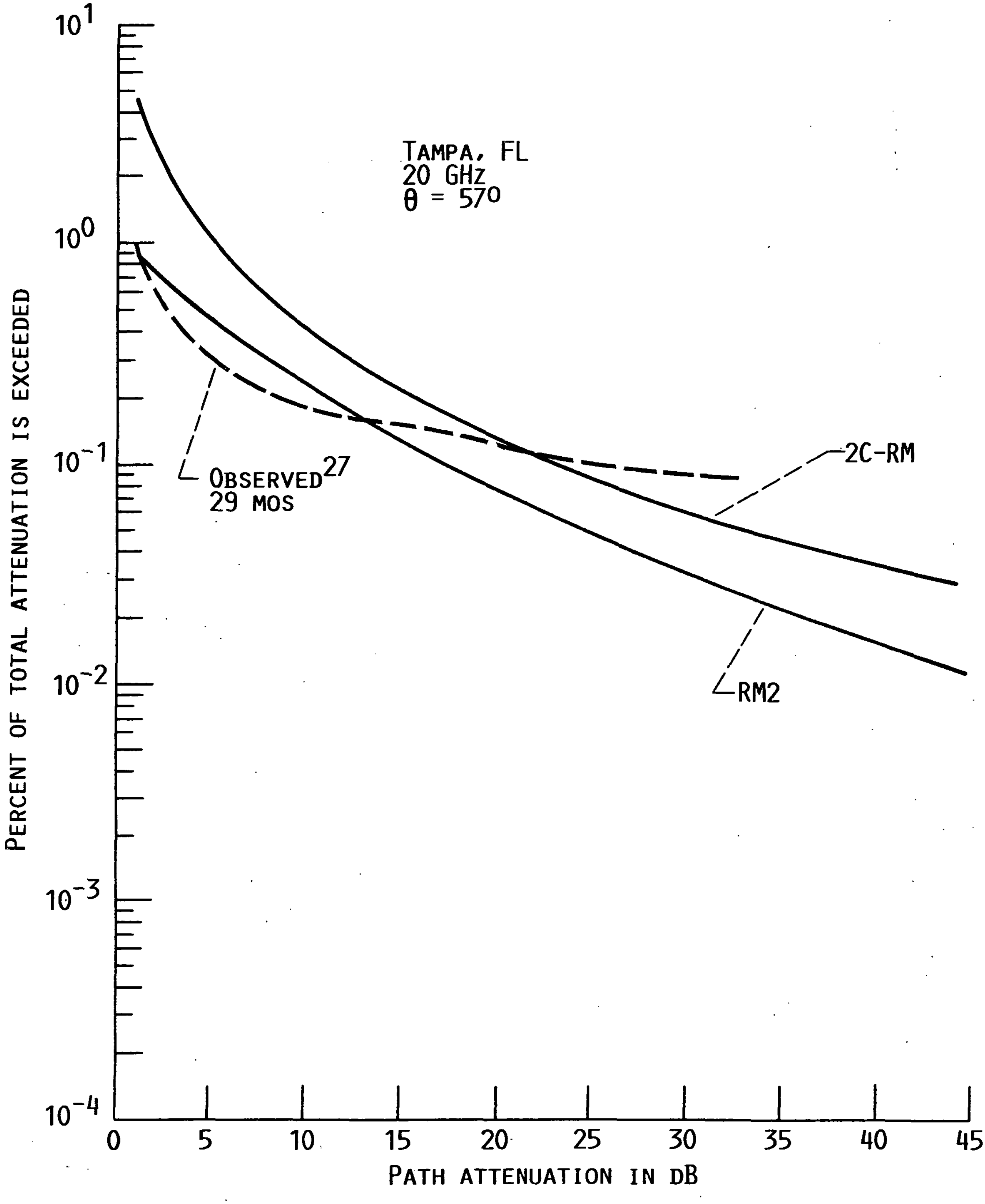

AUSTIN, TX
30 GHz
θ = 52°
RM2
OBSERVED26
10/78-8/80
2C-RM
PERCENT OF TOTAL PERIOD ATTENUATION IS EXCEEDED
PATH ATTENUATION IN dB
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0
5
10
15
20
25
30
35
40
45

FIGURE 4.7



Tampa, FL
20 GHz
θ = 57°
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Percent of total attenuation is exceeded
Observed[27]
29 mos
2C-RM
RM2
0
5
10
15
20
25
30
35
40
45
Path attenuation in dB

Figure 4.8

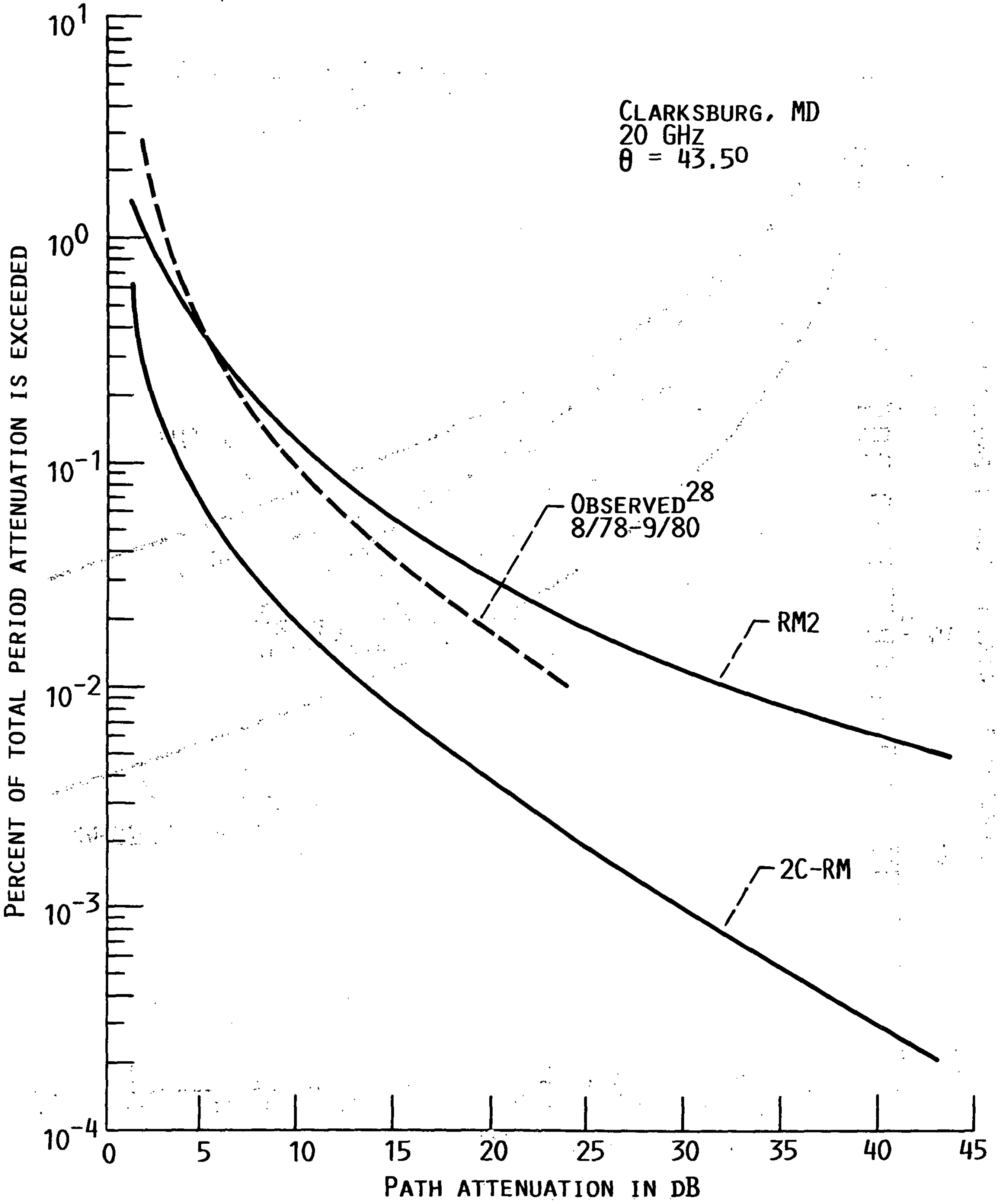

CLARKSBURG, MD
20 GHz
θ = 43.5°
OBSERVED[28]
8/78-9/80
RM2
2C-RM
PERCENT OF TOTAL PERIOD ATTENUATION IS EXCEEDED
PATH ATTENUATION IN DB
10^1
10^0
10^-1
10^-2
10^-3
10^-4
0
5
10
15
20
25
30
35
40
45

FIGURE 4.9

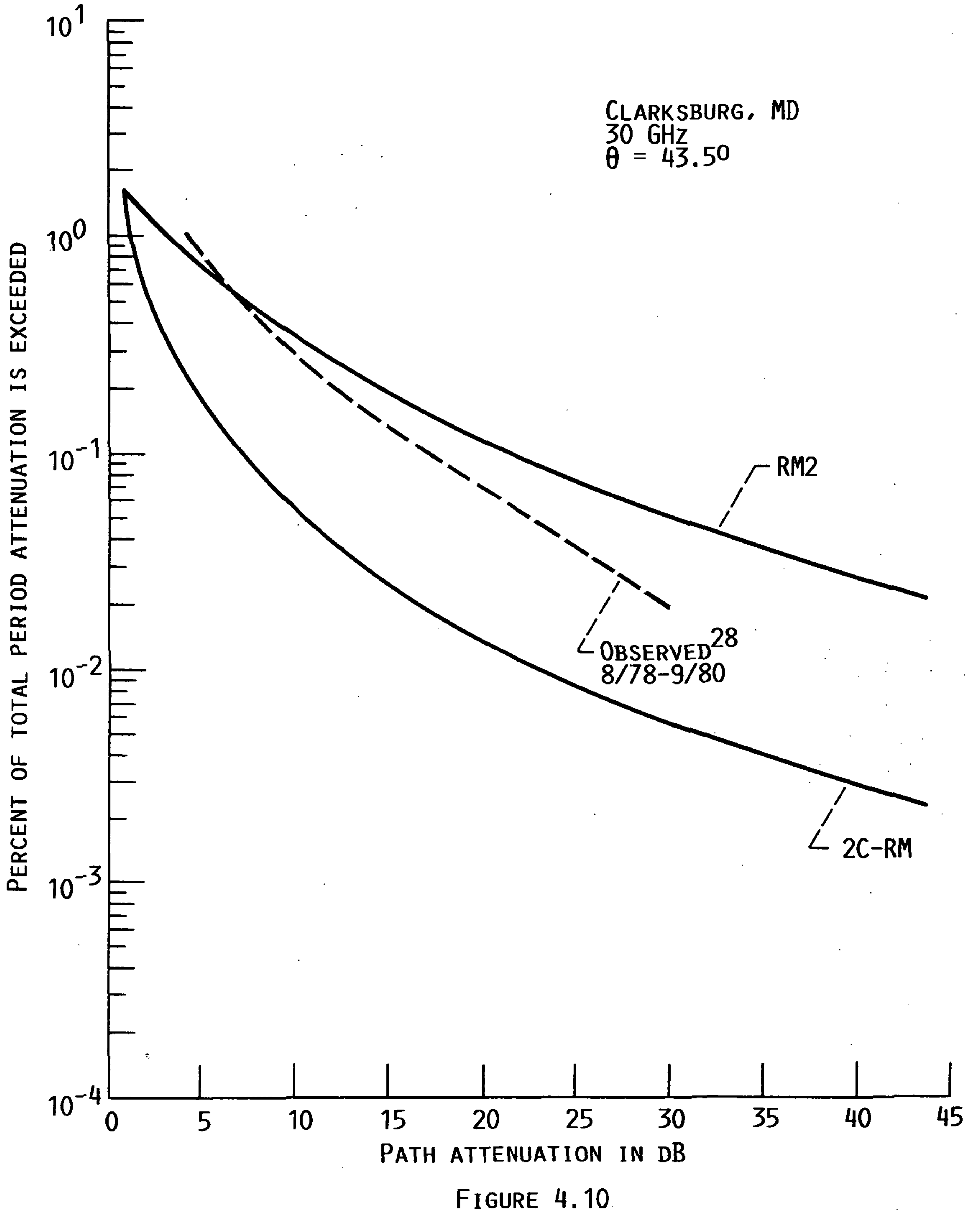

CLARKSBURG, MD
30 GHz
θ = 43.5°
RM2
OBSERVED[28]
8/78-9/80
2C-RM
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
PERCENT OF TOTAL PERIOD ATTENUATION IS EXCEEDED
0
5
10
15
20
25
30
35
40
45
PATH ATTENUATION IN dB

FIGURE 4.10

INPUTS: TERMINAL PARAMETERS

TERMINAL HEIGHT (IN KM), H_0

TERMINAL LATITUDE (DEG), Λ

TERMINAL LONGITUDE (DEG), L_E

POLARIZATION ANGLE (DEG), τ

OPERATING FREQUENCY (GHZ), F

SITE PARAMETERS

PROBABILITY OF RAIN (%), P_0

MEAN RAINRATE (MM/HR), R_M

STANDARD DEVIATION OF RAINRATE, $\sigma_{\ell NR}$

SATELLITE PARAMETERS

LONGITUDE IN GEOSTATIONARY ORBIT (DEG), L_S

↓

CONVERT L_E, L_S, AND τ TO RADIANS
(LEAVE Λ IN DEGREES)

↓

A

FIGURE 5.1

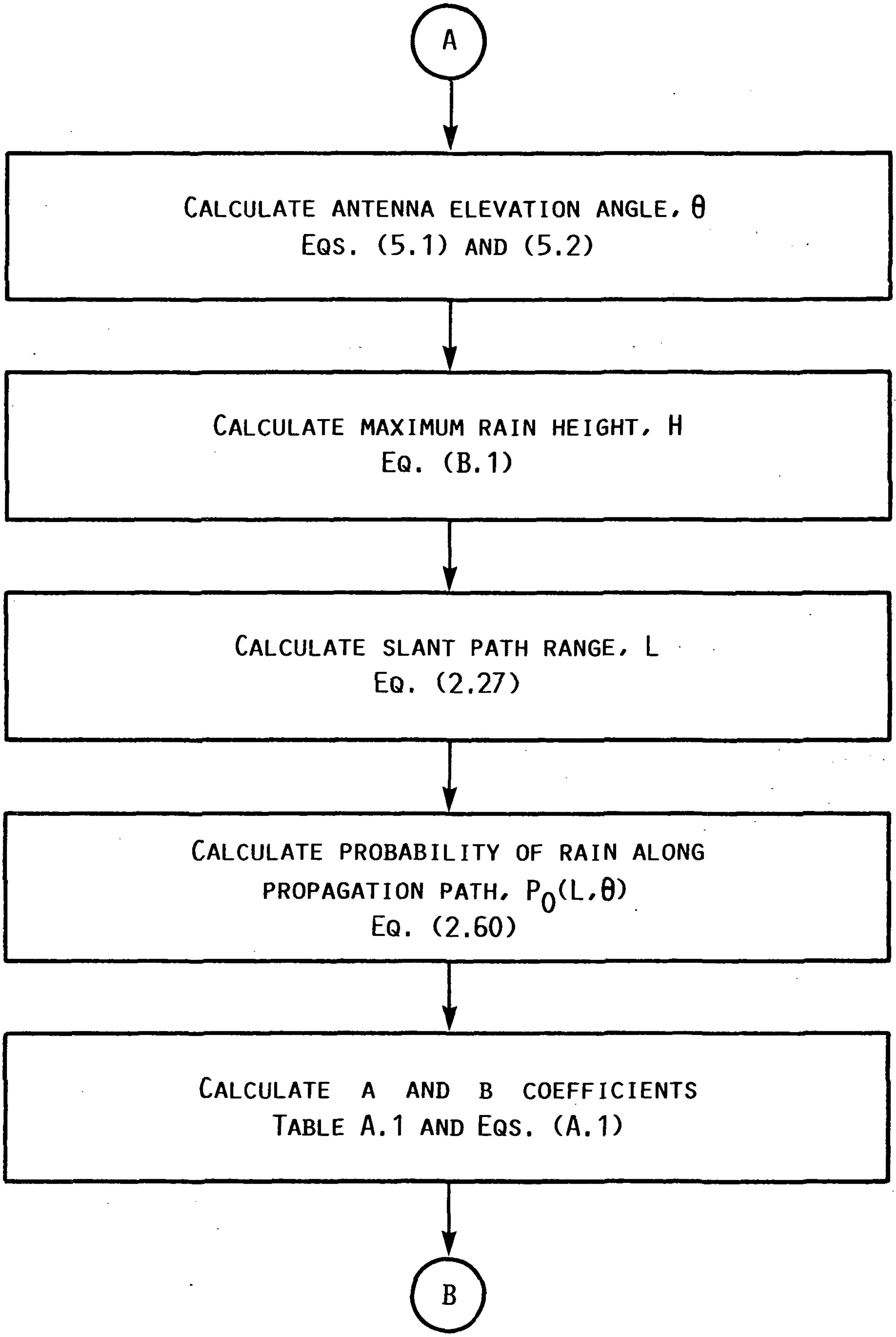


FIGURE 5.1 - CONTINUED

B

CALCULATE SPECIFIC ATTENUATION STATISTICS, Γ_M AND $\sigma_{\ell N \Gamma}$
EQS. (2.19) AND (2.20)

↓

CALCULATE PATH CORRELATION FUNCTION, $K(L,\theta)$
EQS. (2.48) AND (2.49)

↓

CALCULATE SLANT PATH ATTENUATION STATISTICS, $A_M(L,\theta)$ AND $\sigma^2_{\ell NA}(L,\theta)$
EQS. (2.58) AND (2.59)

↓

CALCULATE CUMULATIVE PROBABILITY DISTRIBUTION FOR ATTENUATION, $P(A \geq A)$
EQS. (2.24) AND (2.25)

NOTE: $P_0(L,\theta)$, $A_M(L,\theta)$, AND $\sigma^2_{\ell NA}(L,\theta)$ COMPLETELY CHARACTERIZE THE ATTENUATION STATISTICS FOR THE PARTICULAR TERMINAL, SITE, AND SATELLITE PARAMETERS; IF ANY OF THESE PARAMETERS CHANGE, SOME OR ALL OF THE ABOVE QUANTITIES MUST BE RE-CALCULATED.

FIGURE 5.1 - CONCLUDED

CITY, STATE OF TERMINAL: CLEVELAND, OH.

1 → STATION HEIGHT = 0.213
2 → STATION LATITUDE IN DEG. N. = 41.50
3 → TERMINAL LONGITUDE IN DEG. W. = 81.70
4 → ANTENNA ELEV. ANGLE = 38.55
5 → LINK SLANT PATH LGTH. THRU RAIN REGION IN KM = 5.51
6 → SLANT PATH PROJECTION ON EARTH IN KM = 4.31
7 → PO IN % =1.239
8 → RM IN mm/hr = 5.395
9 → SR = 0.926
10 → POLARIZATION ANGLE IN DEGREES = 45.0

LOG-NORMAL ATTENUATION STATISTICS FOR 20 GHz DOWNLINK

11 → PROBABILITY OF ATTENUATION PL = 2.097 %
12 → MEAN ATTENUATION Am = 1.319 dB
13 → STANDARD DEV. OF ATTENUATION = 1.097

	ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH
14	5.00	0.236	0.834
	10.00	0.068	0.284
	15.00	0.028	0.131
	20.00	0.014	0.071
	25.00	0.008	0.043

15 → ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.502 dB

LOG-NORMAL ATTENUATION STATISTICS FOR 30 GHz UPLINK

16 → PROBABILITY OF ATTENUATION PL = 2.097 %
17 → MEAN ATTENUATION Am = 2.869 dB
18 → STANDARD DEV. OF ATTENUATION = 1.037

	ATTENUATION (dB)	PROBABILITY (% OF YEAR)	WORST MONTH PROBABILITY (% OF MONTH
19	5.00	0.621	1.939
	10.00	0.240	0.848
	15.00	0.116	0.451
	20.00	0.064	0.270
	25.00	0.039	0.173

20 → ATMOSPHERIC MOLECULAR ABSORPTION FOR THIS LINK = 0.364 dB

FIGURE 5.2

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15. Supplementary Notes

Project Manager, Richard T. Gedney, ACTS Project Office, NASA Lewis Research Center.

16. Abstract

A rain attenuation prediction model is described for use in calculating satellite communication link availability for any specific location in the world that is characterized by a long-term meteorological record of rainfall. Such a formalism is necessary for the accurate assessment of such availability predictions in the case of the small user-terminal concept of the Advanced Communication Technology Satellite (ACTS) Project. The model employs the theory of extreme value statistics to generate the necessary statistical rainrate parameters from rain data in the form compiled by the National Weather Service. These location dependent rain statistics are then applied to a rain attenuation model to obtain a yearly prediction of the occurrence of attenuation on any satellite link at that location. The predictions of this model are compared to those of the Crane Two-Component Rain Model and some empirical data and found to be very good. The model is then used to calculate rain attenuation statistics at 59 locations in the United States (including Alaska and Hawaii) for the 20 GHz downlinks and 30 GHz uplinks of the proposed ACTS system. The flexibility of this modeling formalism is such that it allows a complete and unified treatment of the temporal aspects of rain attenuation that leads to the design of an optimum stochastic power control algorithm, the purpose of which is to efficiently counter such rain fades on a satellite link. This will form the subjects of parts II and III.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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