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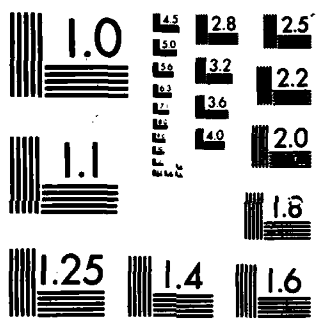

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PREDICTION OF POWER MARGINS ON SATELLITE COMMUNICATIONS LINKS AS A FUNCTION OF LOCAL RAIN RATE STATISTICS AND DESIRED AVAILABILITY

THESIS

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1

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THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Electrical Engineering

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PREFACE

This thesis describes a method to predict power margins on satellite communications links based on availability and local rainfall statistics. The problem of how much excess power to transmit is significant today because of the high cost involved in satellite communications. One decibel of power can cost a million dollars. In the future, the need for efficient use of transmitted power may be indirectly dictated by international regulation. As the number of satellites increases, the permissible level of output power per transmitter may decrease in order to maintain an acceptable level of microwave power density on earth and in space. Therefore, wasted power should be avoided by all means possible.

I selected this thesis topic with two goals in mind: first to gain experience in researching a problem that was directly related to the work I will be doing in my Air Force career, and, second, to create something that could be of immediate use. The nature of this project made both of these goals attainable.

The following people made vital contributions to this work which I greatly appreciate: Capt Glenn Prescott (AFIT/EN), my thesis advisor; Capt David King (AFIT/EN), thesis committee member; Major Elden Georg (Defense Communications Engineering Center/R430), thesis sponsor; 2Lt Phil Zuzolo (Air Weather Service/ETAC); and Mr Paul Tattelman (Air Force Geophysics Laboratory).

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ABSTRACT

This report presents an algorithm which can be used to predict the power margins needed to overcome the degrading effects of rain on satellite communications links in the 7 to 9 GHz frequency range. This algorithm employs established mathematical models which are used to characterize rain rate behavior and its effects on wave propagation. The algorithm accounts for each of the three ways in which the link can be degraded by rain: signal attenuation, signal depolarization, and increased noise power at the receiver input.

This algorithm is designed to give the link designer all the tools necessary to compute a reliable power margin. The power margin is tailor-made for each individual link by considering all the relevant variables which can distinguish one link from another including the specified value of link availability, the rain rate characteristics at the location of the satellite earth terminal, and the link configuration. Finally, the algorithm is implemented in a computer program to make it convenient to use.

SECTION I

INTRODUCTION

Background

Satellite communications links are required to maintain certain minimum levels of transmission quality usually defined in terms of signal-to-noise ratio (S/N) on analog communications links and bit-error-rate (BER) on digital links. A communications link which exceeds the minimum level of S/N or does not exceed the maximun level of BER is defined as "available"; otherwise, it is "unavailable". These values of S/N and BER are arbitrarily set. Communication over the link does not necessarily cease to exist if these levels are not met. They merely provide a standard to divide acceptable from unacceptable levels of transmission quality.

A link designer can estimate the transmitted power needed to achieve a specified level of S/N or BER with the knowledge of the deterministic parameters of the link such as antenna gains, number of information channels, link distance, and the modulation scheme. With this power set, there are two factors which can cause an unavailable link: equipment failures and propagation disturbances. The amount of unavailability due to these factors cannot be predetermined. It can only be estimated statistically. While equipment failures usually lead to a complete link outage, propagation disturbances tend to cause gradual and limited degradations. These degradations can be overcome with an increase in transmitted power. In practice, satellite communications links operate with an excess amount of transmitter output power called a "power margin" in order to maintain a specified percentage of time that the link is available. But there is a trade-off. Transmitter power can be limited by either regulation or the power generating capacity of the satellite. The available power must be shared by each of the information-carrying channels on the link. The allocated power per channel increases as the required power margin increases, therefore, the number of channels must decrease proportionally so the total available power is not exceeded. Thus, the restoration of the S/N or BER to an acceptable level in the midst of a propagation disturbance may entail the reduction of the link's information-carrying capacity. As the demand for satellite use increases, the satellite power becomes a critical resource. Power which is used in providing the power margin needed to maintain link quality could have been used to carry information. Therefore, the goal of the link designer is to have the smallest power margin which can achieve the specified amount of link availability.

By far, the most frequent and intense propagation disturbances on satellite communications links are those caused by rain. It is essential that a power margin be based on the expected rainfall at the site of the satellite earth terminal. However, rainfall is not deterministic, and rainfall behavior can vary greatly from one location to another. In addition, the amount of link degradation is dependent upon the configuration of the link itself which can also vary. Therefore, the optimal power margin, that is, one which is sufficient to meet the link availability requirements without excessively detracting from the information-carrying capacity, is one which is tailor-made to the specific conditions existing at each earth terminal.

Problem

Power margins on satellite communications links managed by the Defense Communications Agency (DCA) are generally set at one fixed value common to all links. However, there are large variations in the rainfall characteristics at the locations of the earth terminals and in link configurations. The problem is to develop an algorithm to predict reliable power margins as a function of local rainfall characteristics, link configuration, and specified link availability.

Scope

The algorithm described in this report is specifically designed for satellite communications links which use frequencies between 7.0 and 9.0 GHz. This is the range of frequencies used by the links that are managed by DCA, the

Defense Satellite Communications System (DSCS). A more universal algorithm would detract from its effectiveness at the very point that it should be optimized. However, it can easily be adapted to other frequency ranges. The algorithm can only be used on links where the availability is between 99.9% and 99.997%. This is the range in which all the models used in this algorithm are effective. DCA directives state that satellite links must operate with an availability of 99.9% (6:11-1). The allowable unavailability must be divided between the outages due to rain and equipment failures. Therefore, this range of availabilities should be sufficient to meet the needs of DCA.

Assumptions

This algorithm assumes that no adaptive power control schemes are employed on the satellite communications link. The power margins predicted by this algorithm remain constantly fixed.

Approach and Presentation

There has recently been an increase in research into the effects of rain on satellite communications links. This coincides with the increasing demand for satellite use. Models used to describe these effects are frequently updated and improved. Therefore, in order to develop the algorithm, it was necessary to survey the latest work in this field.

Then the most promising models were selected to be either used directly or adapted to the specific needs of this problem.

There are two major facets to this problem. One is the estimation of rainfall behavior at the location of the satellite earth terminal, and the other is the evaluation of the effects of this rainfall on the link. Consequently, Section I gives a background of the power margin problem including an outline of the algorithm, and Sections III and IV give detailed descriptions of each of these two major facets. Section V contains conclusions and recommendations. The algorithm is implemented in a computer program whose source code is presented in Appendix I.

SECTION II

STRUCTURE OF THE ALGORITHM

Introduction

This chapter presents the theory and structure of the algorithm used to predict the power margin for a satellite communications link. It is divided into three subsections. The first two subsections provide a background on the separate components of the algorithm. The third subsection assembles these components to form an outline of the algorithm. The mathematical models used to quantify these components are presented in Sections III and IV.

Estimation of Rain Rate

The first task in predicting a required power margin is to characterize the rain behavior at the location of the satellite earth terminal. The amount of link degradation is not directly related to the amount of rainfall at the location; rather, it is proportional to the intensity of the rainfall, that is, the rain rate. The higher the rain rate, the greater the degradation. Therefore, it is actually the rain rate behavior of the location that is of interest. Rain rates are commonly measured in units of inches per hour or millimeters per hour.

Link availabilities are specified in terms of annual percentages of time. For example, an availability of 99.9%

implies that a link outage during 0.1% of the year or less is acceptable. Some of this allowable outage time will be allotted to disruptions caused by rain. This availability is averaged over the entire year. Rainy months will generally have a much greater percent of outage time than relatively dry months.

The rain rate needed to determine the power margin is the rain rate which is equaled or exceeded the same percentage of time as the allowable percent of outage time due to rain. Based on this rain rate, the power margin will be sufficient to maintain the specified minimum of link quality for all rain rates less than this amount, and the link will be out during rain rates which are higher. Since these higher rain rates occur for a percentage of time not greater than that allowed, the requirement for link availability will be met. Rain rate models typically present the rain rates as a cumulative distribution, that is, as a function of their percents of time exceeded as illustrated in Figure 2-1. This format is well suited to the needs of the power margin problem. Given an allowable percent of outage time due to rain, the desired rain rate exceeded that percentage of time can be found directly from the cumulative distribution. Figure 2-1 includes an example for a percent outage time of 0.02%. A horizontal dotted line is drawn from 0.02% on the vertical axis (percent of time exceeded) to the curve and then straight down to the horizontal axis where the rain

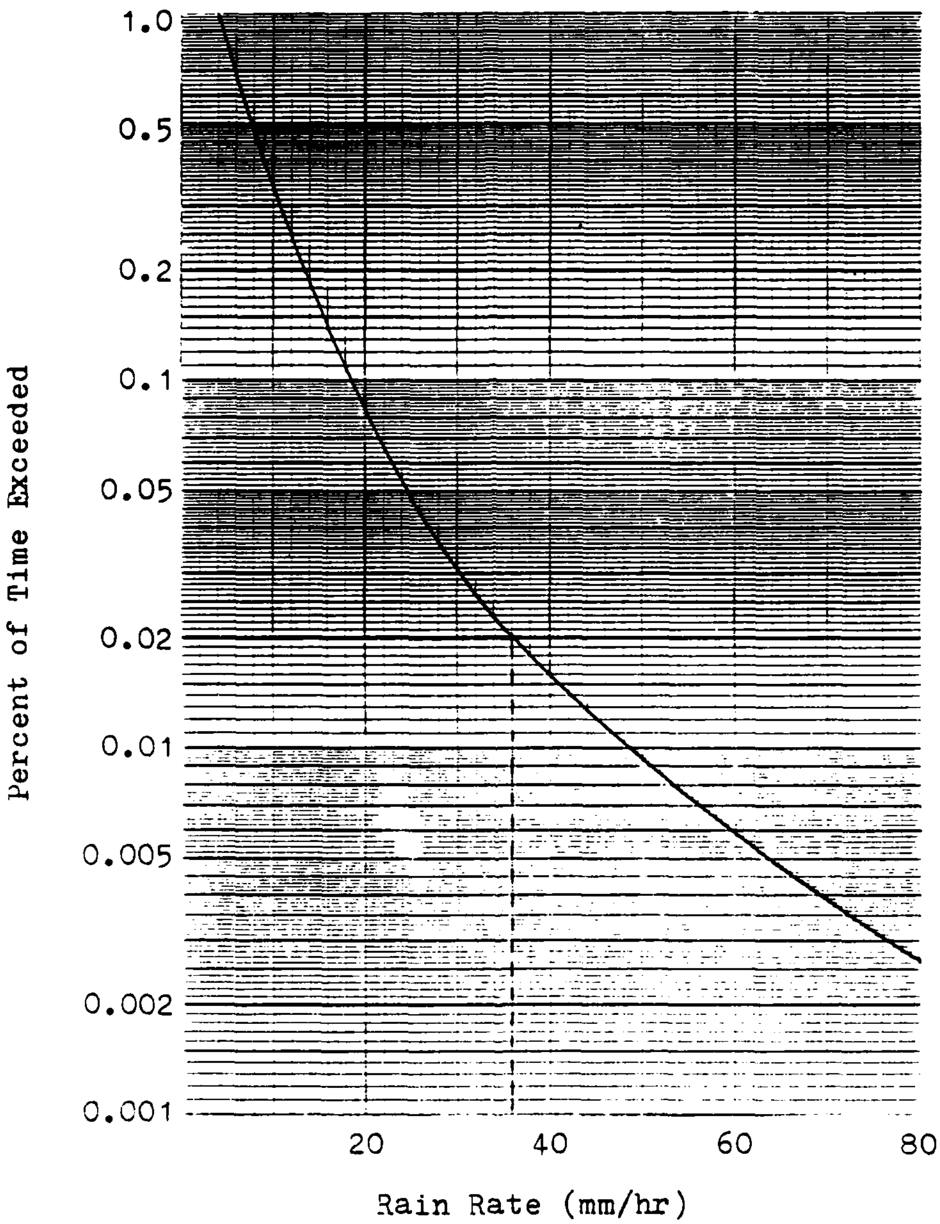

Figure 2-1. Cumulative distribution of rain rates.

rate is read, 36 mm/hr. Therefore, for this example, rain rates of 36 mm/hr and greater can be expected to occur 0.02% of the time. This is the rate used to compute the power margin.

Rain rate models are used to predict the rain rate characteristics of a location. These models give rain rates which are averaged over an interval of time. This is due to the nature of rainfall measuring devices used to collect statistical data from which these models are derived. Rain is collected during each interval of time and the amount measured. The average rain rate is the amount of rain divided by the length of the time interval. As the interval becomes shorter, the rain rates become greater due to the averaging effect of the longer intervals. Shorter intervals are more meaningful. For example, a moderate quantity of rain may have been recorded over a one-hour interval which consisted of 15 minutes of intense rain and none at all for the rest. If the power margin was designed to overcome the moderate rain rate averaged over the hour but not the actual rain rate in that 15 minutes, it might appear that there should be no outage at all when in fact there should. Therefore, it is desirable to use models with the shortest intervals possible. This power margin algorithm uses rain rates which are averaged over one-minute intervals called "one-minute rain rates".

There are a number of one-minute rain rate models available. In general, as the model becomes more complex and reliable it requires more meteorologic historical data as input. But the amount of such data available at a particular location can range from very extensive to none at all. To take advantage of whatever data is available, this power margin algorithm employs three rain rate models. The user will decide which model is most appropriate based on the amount of data available. These three models listed in their order of preference are:

1) The Davis-McMorrow model
2) The Tattelman-Scharr model
3) The CCIR global model

The Davis-McMorrow model, the most preferred model, relies on statistical data from the location, that is, actual measurements of rain rates taken over a period of at least several years. The Tattelman-Scharr model uses climatic data. The CCIR global model requires no data at all, only a knowledge of where the satellite terminal is to be located. It is only used if there is insufficient data to implement either of the other two. Each model is described in detail in Section III.

Estimation of the Power Margin

With the rain rate determined, it is necessary to estimate the amount of degradation this rain rate will cause the link. Rain can corrupt the link signal in three ways: it can attenuate the signal, it can increase the level of noise, and it can depolarize the signal. This power margin algorithm uses the mathematical models presented in Section IV to quantify each of these factors. These quantities are summed to determine the total degradation. This degradation, expressed in decibels, is the link power margin.

Electromagnetic waves used in link communications are attenuated by the process of absorption. As it passes through rain, some of the signal energy is absorbed by the raindrops and converted into heat energy. The greater the amount of rain in the path of the signal, the greater the absorption, and hence the greater the signal attenuation. This process is frequency dependent. As the wavelength approaches the dimensions of the raindrops, the attenuation increases. Snow causes a negligible amount of attenuation. Snowflakes are water crystals of very low density. The individual branches of snowflake crystals are very minute and don't compare at all with the wavelengths now used in satellite communications links.

The amount of rain that the signal must pass through is proportional to two variables: the rain rate and length of the signal path through the rain. The rain rate used in this computation is the one described above. The path length is a function of the physical geometries of the satellite earth terminal: the antenna elevation angle, the latitude, and the altitude above sea level. As the angle of antenna elevation measured from the horizontal decreases, the link path traverses more of the layer of atmosphere containing rain. Thus, the lower the elevation angle, the higher the attenuation. The latitude and the altitude above sea level are similar in that they are factors which effect the vertical distance of the path through the rain. Temperatures decrease as altitude increases to a point above which precipitation is frozen and no longer contributes to attenuation. This altitude is called the 0°C isotherm, and it tends to decrease as the latitude increases. Therefore, as the latitude increases, the vertical distance of the path through rain decreases. With the 0°C isotherm limiting the height of the path, it is obvious that the lower limit is the altitude of the earth terminal. As the altitude of the terminal increases, the length of the vertical path decreases.

Along with the decrease in signal power caused by attenuation is a simultaneous increase in the background noise. The satellite receiver will not be affected because of its distance from the rain, but the receiver at the earth terminal will. System performance is directly affected by this noise. An increase in noise brings an equivalent reduction in the signal-to-noise ratio (S/N), the fundamental measure of link quality.

The increase in background noise is due to the phenomenom of thermal noise which accompanies rain. The earth terminal antenna collects this noise, and it is added to the overall receiver noise. The impact of this noise depends on the normal noise level of the receiver. Low-noise systems will suffer greater degradation because the additional background noise will contribute a greater percentage to the total noise than in systems with relatively noisy receivers.

The mathematical model used to estimate the increase in noise in the presence of rain relies on only one link variable: attenuation. From this plus the values of the inherent receiver noise and the background sky noise without rain the percentage of increase in the total receiver noise is determined. This percentage of increase is then added to the power margin, that is, the transmitter power must be increased by this same amount to restore the S/N.

Depolarization is the third phenomenon which can degrade the link. Depolarization is any change in the polarization of the transmitted signal induced by the medium through which the wave travels (7:1232). It is caused by differential phase changes in the electric field vector as it passes through raindrops. Raindrops are not perfect spheres, however, they are approximately spheroidal in shape (an ellipse rotated about its minor axis) with an axis of symmetry. If the electromagnetic wave were to penetrate each raindrop exactly parallel or perpendicular to this axis, there would be no depolarization. But two factors can cause an oblique angle between the wave and the axis: the polarization angle of the transmitting antenna and the canting angle at which the rain falls. Depolarization reaches a maximum when the angle between the wave and the axis is 45 degrees.

Depolarization is only a factor on systems which use a linearly polarized wave because these systems are designed to receive the most signal power in one specific plane of polarization. The vector diagram of Figure 2-2 illustrates the principal of depolarization for a wave that was transmitted with linear polarization. At the transmitter, 100% of the transmitted power is in the plane in which the receiving antenna is oriented, the copolarized direction (Figure 2-2a). Therefore, the copolarized power at the transmitting antenna equals the total transmitted power P_t. The power present at the receiving antenna is P_r (Figure 2-2b). Because of depolarization, the vector P_r is tilted at some angle d from the copolarized plane. P_r is now the vector sum of the copolarized power P_c and a perpendicular component, the cross-polarized power P_x. But the receiving antenna only collects the component P_c which is equal to $P_r \cos d$. The power available to the receiver is, in effect, reduced by a factor of cos d. The power present at the receiving antenna and, therefore, the transmitted power must be increased by the reciprocal of cos d to restore the copolarized component to the value it would be without rain. The cosine of angle d is equal to P_c/P_r, and its reciprocal

a. Transmitted polarization vector.

b. Received polarization vector.

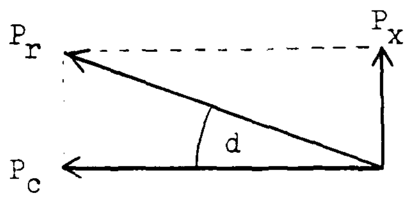

Figure 2-2. Depolarization of a linearly polarized wave.

is P_r/P_c. This factor, P_r/P_c, is added to the power margin to compensate for depolarization.

The degree of rain-induced depolarization is dependent upon four factors: the rain-induced attenuation, the transmitting antenna elevation angle, the transmitting antenna polarization (tilt) angle, and the link operating frequency. Attenuation is only indirectly related in that it is assumed that the same conditions which cause attenuation also cause depolarization. There are no models available at this time which use a joint distribution of attenuation and depolarization (7:1235). The antenna elevation angle influences the angle between the raindrop axis and the electromagnetic wave. This angle is minimized by a high antenna elevation angle. The angle between the axis and wave also increases as the tilt angle increases to a maximum at a tilt angle of 45 degrees. It is minimized for horizontal and vertical polarizations. Depolarization is inversely proportional to the frequency. It is reduced as frequencies increase if all other factors remain constant. However, it must be remembered that attenuation is highly frequency dependent. An increase in frequency will invariably bring about higher attenuation which has the opposite effect on depolarization.

A power margin for depolarization is of no use on systems which employ a dual polarization scheme, that is, separate transmission channels on each of two orthogonally polarized waves (frequency reuse). On such links, the cross-polarized vector of one channel is the copolarized vector of the other. Depolarization causes cross talk between them. An increase in transmitted power merely raises the cross talk along with the intended signal. The solution is to monitor the channels continuously for cross talk and temporarily shut one down if it reaches an unacceptable level (7:1234).

Structure of the Algorithm

The previous two subsections presented the components of the algorithm including the elements needed to execute each one. In this subsection the algorithm is outlined in a flowchart to show the relation of each component to the overall evaluation of the power margin.

Figure 2-3 is the algorithm flowchart. The algorithm begins with a search for the most appropriate rain rate model. The two decision points test for the type of data available at the location of the earth terminal. The algorithm will branch to the Davis-McMorrow model if long-term statistical data is available. If not, it will branch to the Tattelman-Scharr model if the necessary climatic data is available. If neither is available, the rain rate is estimated by the CCIR global model. Each of the three models requires the allowable link unavailability due to rain. The rain rate now becomes one of the inputs used to compute the attenuation. The user supplies the link frequency, the altitude of the 0°C isotherm, the altitude of the earth

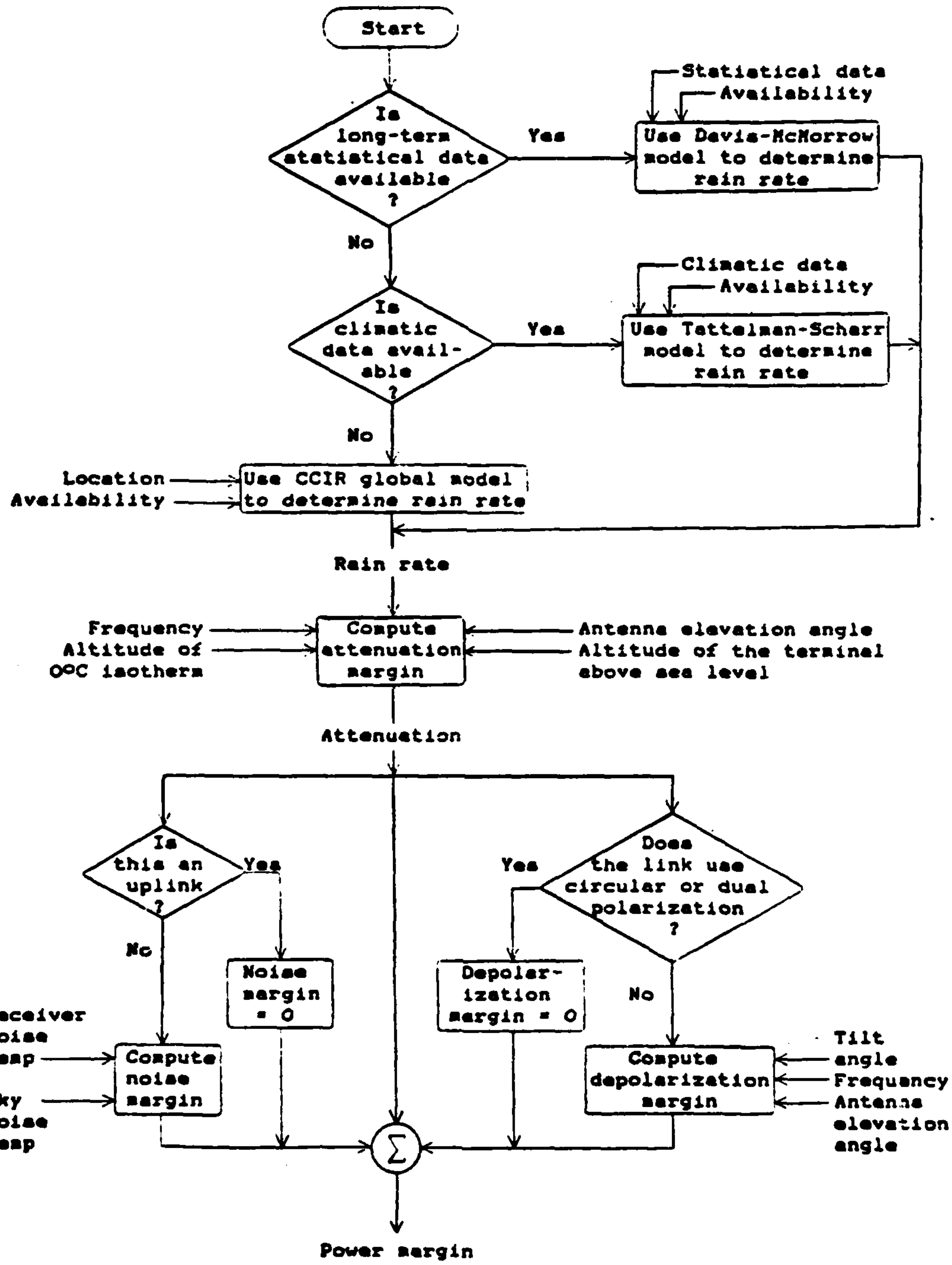

Figure 2-3. Flowchart of the power margin algorithm.

terminal, and the antenna elevation angle. The altitude of the 0°C isotherm is found by using Figure 4-2 in Section IV. The value of attenuation is then used to compute both the noise margin and the depolarization margin. For an uplink analysis (that is, the receiver antenna is on the satellite) the noise margin is zero. Otherwise the user supplies the receiver noise temperature and the sky noise temperature present at the receiving antenna to compute the noise margin. Similarly, if the link uses circular or dual polarization the depolarization margin is zero. Otherwise the user supplies the frequency, the tilt angle, and the antenna elevation angle to compute the depolarization margin. Finally, the power margin is the sum of the attenuation, noise, and depolarization margins.

The computation of the attenuation, noise, and depolarization power margins and their summation to give the total power margin can be accomplished with the aid of the computer program presented in Appendix I.

SECTION III

RAIN RATE ESTIMATION

Introduction

This section presents the methods used to estimate the rain rate required for the computation of attenuation. This algorithm employs three different models. The user will select the most appropriate model based on the amount and type of meteorologic historical data available from the location of the satellite earth terminal. These models are presented in this section in their order of preference. First, and most reliable, is the Davis-McMorrow model. Second is an annual application of the Tattelman-Scharr monthly model. And third is the CCIR global model. Because the application of the Tattelman-Scharr model on an annual basis is a novel approach, the greatest portion of this section will be devoted to its development.

Davis-McMorrow Model

The Davis-McMorrow model will produce a highly reliable estimate of one-minute rain rates for a given percent of time exceeded (1:371). It should be used if there are long-term clock-hour rainfall data available at or near the satellite earth terminal location.

The Davis-McMorrow model takes clock-hour statistical data (measurements of the amount of rainfall during the preceeding 60-minute interval taken every hour, on the hour) and extrapolates it into 1-minute or 4-minute (collectively called "instantaneous") rain rate distributions (2:1). The model was developed by taking instantaneous rain rate measurements at 13 locations. The data from each location was used to develop tables of percentages which show how the instantaneous rain rates were statistically distributed during each clock hour. The rain rates are divided into ten intervals for clock-hour rain rates less than 5 in/hr and into eight intervals for instantaneous rain rates less than 10 in/hr. Tables are provided for wet season, dry season, and annual for each of the 13 locations. The annual tables are the only ones of interest in this case because satellite communications link availabilities are specified in terms of annual percentages. These annual tables are presented in Appendix A. The 13 locations are climatically diverse to represent a cross-section of possible climatic regions.

The model is used in two steps. First, the user must determine the model location that is most climatically similar to the location of the satellite terminal. Second, each value of clock-hour data from the location of the satellite terminal is distributed into instantaneous rates using the percentages given in the table for the selected model location. The instantaneous rain rates thus determined can be presented in a useful format by plotting one-minute rain rates vs percent of time exceeded. Examples of these are included in Appendix E for 10 locations. Each graph shows plots for the wet season, dry season, and annual. The annual plots (the middle plot in each graph) are the ones used in determining power margins for satellite communications links.

The rain rate to be used in computing the power margin is taken directly from the annual plot where the percent of time exceeded is equal to the allowable percent outage time of the communications link due to rain. For example, if the link design specifies an availability of 99.98% for rain and the terminal is located in Indianapolis, Indiana, the percent time exceeded will be 0.02% (100.00% minus 99.98%) corresponding to a one-minute rain rate of about 47 mm/hr (from Figure E-6). This amount can then be entered directly into the power margin algorithm.

Implementing the Davis-McMorrow model can involve acquiring and processing an enormous amount of data. However, this is a standard model used by the USAF Environmental Technical Applications Center (ETAC) at Scott AFB, Illinois.

Tattelman-Scharr Monthly Model

In the absence of sufficient statistical rainfall data to implement the Davis-McMorrow model, the Tattelman-Scharr monthly model applied on an annual basis is preferred for this algorithm. Why should a monthly model be used on an annual basis? Because it is logical to characterize the annual rain rate behavior of a location with the combined knowledge of a number of subintervals. That is, a reliable estimate of the annual one-minute rain rates versus percent of time exceeded can be obtained by having a reliable estimate of the rain rates for each of its component months. This model uses climatic data which is available for many more areas than is clock-hour statistical data. Therefore, it fills the great void between statistical models and global models. This subsection presents the basic Tattelman-Scharr monthly model, the method used to apply it on an annual basis, and a demonstration of this application. This method is implemented in a computer program that is presented in the appendix.

Tattelman and Scharr have devised an equation which effectively estimates one-minute rain rates versus percent of time exceeded within a single month (3:1575). The equation makes use of climatic data and the latitude of the location. They have identified over 4000 locations worldwide for which this kind of data is available (4:10) (5:10). The relationship is

$$R_p = A + BT + CI + DF(L,T) \tag{1}$$

where R_p is the rain rate exceeded p percent of the time for a given month in millimeters per minute. T is the average temperature (deg F) for that month. I is the precipitation index defined as the average amount of precipitation (in millimeters) per rainy day (i.e. the average amount of precipitation divided by average number of rainy days). And F(L,T) is a function of both latitude (L) and temperature (T) defined as

$$F(L,T) = \begin{cases} 0 & \text{for } L < 23.5° \\ (L - 23.5)T & \text{for } 23.5° < L < 40° \\ 16.5T & \text{for } L > 40° \end{cases} \qquad (2)$$

The coefficients A, B, C, and D were derived by a stepwise multiple regression analysis using instantaneous rainfall rates at a number of locations. These coefficients have been tabulated for percentage levels of 0.01%, 0.05%, 0.1%, 0.5%, 1.0%, and 2.0% for each of three thresholds used to define a rainy day: 2.54 mm, 1.0 mm, and 0.25 mm.

Tattelman and Scharr have noted that there are three conditions under which the model is not valid:

1) $T \leq 32°F$
2) $I < 2$ mm/day
3) Number of rainy days < 1

They also noted that two anomalies, negative rain rates or increasing rates with increasing percentage level, may occur for T between 32°F and 40°F. However, any of these conditions would exist only in months with extremely low rain rates.

The computation of an annual rain rate from the individual monthly rain rates relies on two facts: 1) there is only one rain rate to be found, whether it be the resultant annual rain rate or one from any of the individual months, and 2) the average of the monthly percentage levels must be the same as the percentage level for the year, that is, the allowable percent of outage time for the satellite communications link due to rain. In other words, the objective is to find the one rain rate in all months whose corresponding percents of time exceeded averaged over the entire year equal the total allowable percent outage time for the year. Wet months will therefore contribute a much greater percentage of time than relatively dry months.

This technique is illustrated in Figure 3-1. Suppose at a particular location there are six months which are rainy enough and warm enough to meet the three minimum conditions listed above. For this example the plots of percent of time exceeded vs rain rate for all six months are on the same graph (Figure 3-1). The rain rate exceeded for an annual percentage of time can be found by placing a straightedge on the graph parallel to the vertical axis and sliding it across the graph. At some point the sum of the percents of time exceeded at the intersection of the straightedge and

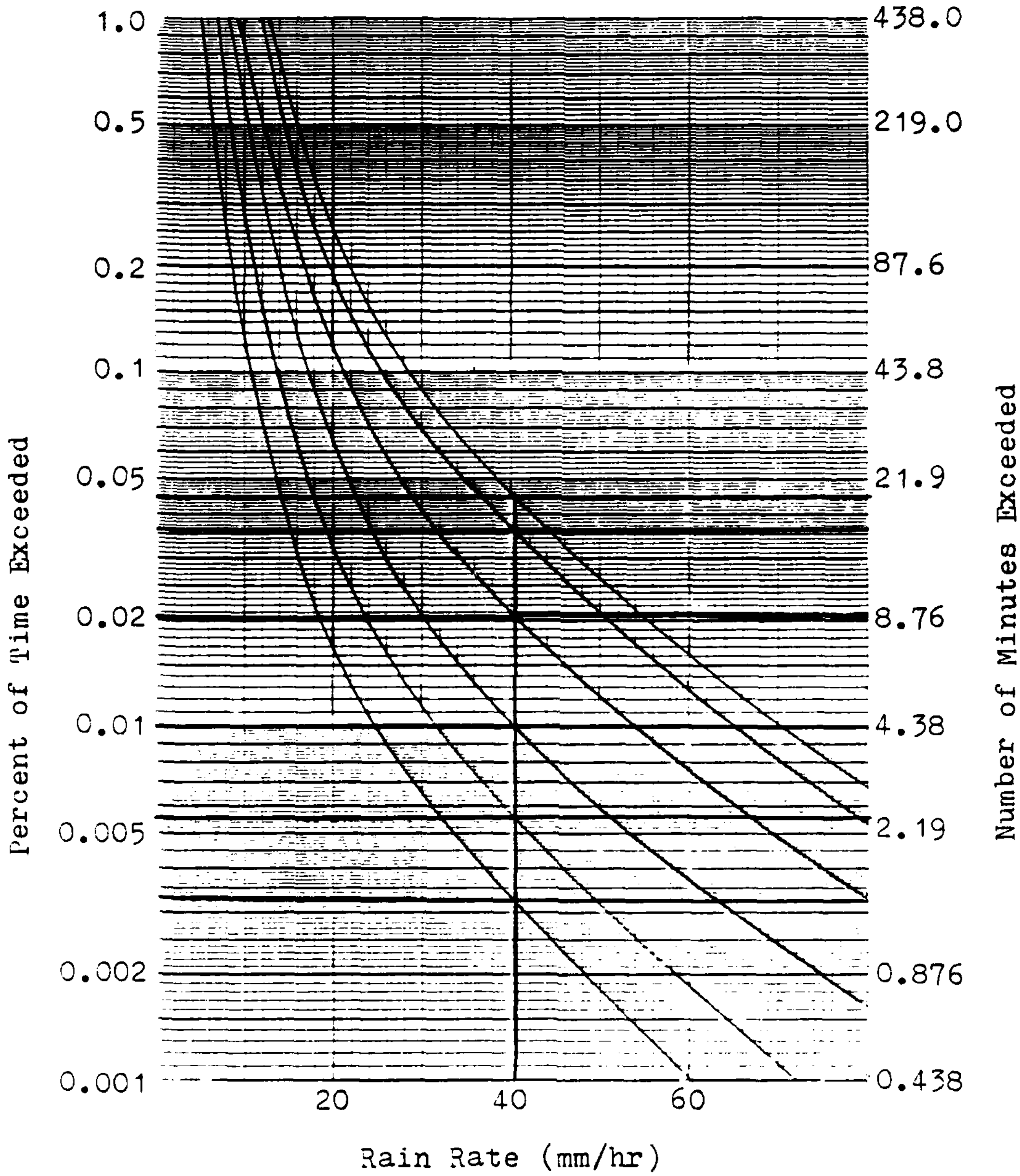

Figure 3-1. Percent of time exceeded vs rain rate for six months.

each plot divided by 12 will equal the desired annual percent of time exceeded. The monthly percentages are divided by 12 because each month is only one twelfth of a year.The rain rate at this point is the desired rain rate. It is the task of the program to find this point. Figure 3-1 shows a vertical line drawn across the six plots at the position of the straightedge for an annual percentage of 0.01% of the time. At the intersection of the vertical line with each plot a horizontal line is drawn to find the percents of time exceeded on the scale to the left: 0.045%, 0.036%, 0.020%, 0.01%, 0.0057%, and 0.0033%. The sum of these percents divided by twelve equals 0.01%, the desired annual percent of time exceeded. The vertical line intersects the horizontal axis at about 40.5 mm/hr. Therefore, the rain rate exceeded 0.01% of the year is 40.5 mm/hr. An alternate way of reaching the same result is to add up the number of minutes that each month contributes to this rain rate. Reading the number of minutes exceeded from the intersection of each horizontal line with the scale to the right of the graph gives times of 19.7, 15.8, 8.8, 4.4, 2.5, and 1.4 minutes. The sum of these is 52.6 minutes which is 0.01% of a year.

Three modifications were made to the model in order to adapt it to the needs of the power margin problem. First, the number of discrete percentage levels to choose from was increased from the original 6 to 21. The additional coefficients were determined by graphical interpolation. Tables of these coefficients and the graphs used to determine them are presented in Appendices B and C, respectively. The increased number of percentage levels provides greater accuracy. Second, two of the three conditions noted above whereby the model was invalid were increased and another one added. They are now

1) $T \leq 32°F$
2) $I < 3$ mm/day
3) Number of rainy days ≤ 2
4) Average precipitation < 20 mm

These conditions still indicate a month with very low rain rates. This modification was needed to prevent excessively high estimates in hot arid climates. There is a small possibility that no month will meet these conditions. The program will detect such a case and use the one month with the greatest average rainfall. Similarly, in any polar location, only the month with the greatest average rainfall is used. In either sort of location the power margin for precipitation would be nearly negligible. The third modification was an extension so that percentage levels less than 0.01% could be used. This was necessary because DCA directives state that DSCS satellite communications circuits must perform with at least 99.9% annual availability (6:11-1).

Most of the allowable outage time will be attributed to equipment failure (6:11-1). Therefore the outage due to rain will be less than 0.05%. If, for example, the specification called for only 0.01% outage due to rain there would quite possibly be some months contributing a significant percentage of time to the rain rate at a level below 0.01%. The extension uses the fact that the model becomes essentially a simple logarithmic function below the 0.05% percent level. This straight line on a semilogarithmic graph is simply extended below the 0.01% level. The rain rate R_p at any percent level p is found by using the fact that the slope between 0.05% and 0.01% is the same as the slope between 0.01% and any level p below 0.01%, that is

$$\frac{\text{Log } 0.05 - \text{Log } 0.01}{R_{0.05} - R_{0.01}} = \frac{\text{Log } 0.01 - \text{Log } p}{R_{0.01} - R_p} \qquad (3)$$

Solving for R_p gives

$$R_p = R_{0.01} + \left[\frac{(R_{0.01} - R_{0.05})(\text{Log } 0.01 - \text{Log } p)}{\text{Log } 0.05 - \text{Log } 0.01}\right] \qquad (4)$$

The addition of this extension gives the program an operating range of annual percentage levels from 0.003% to 0.5%.

The source code for the program to compute the annual rain rate at a particular percentage level and a user's manual are presented in Appendix F.

To demonstrate this program ETAC supplied the necessary data for 10 climatically diverse locations. Tables of this data are presented in Appendix D. The data was processed through the program, and the computed rain rates are presented in Table 3-1 for four percentage levels: 0.005%, 0.01%, 0.02%, and 0.05%. These percentage levels represent the range in which the allowable percent of outage time for rain would most likely occur. The standard used for comparison is the Davis-McMorrow model because, as described above, it has proved to be very reliable. ETAC supplied plots generated by the Davis-McMorrow model for the same 10 locations. They are presented in Appendix E. Table 3-1 shows the rain rates (mm/hr) produced by each of the models plus the percent of deviation of this program from the Davis-McMorrow model.

In the non-polar climates the average magnitude of the percent of deviation using this program is 9.5%. The polar locations present a special case. Because the rain rates are so low, a deviation of even a few mm/hr causes a large percent of deviation. Power margins for rain at polar locations are nearly negligible for two reasons: 1) the very low rain rates and, 2) the altitude of the 0°C isotherm above which precipitation is frozen (and therefore not contributing to attenuation) is much lower than in non-polar climates. The

Table 3-1: Rain rates produced by the annual application of the Tattelman-Scharr (T-S) model at four percentage levels for ten locations plus a comparison with those of the Davis-McMorrow (D-M) model.

Percentage Level (%)	Rain Rate (mm/hr) T-S	Rain Rate (mm/hr) D-M	% Deviation from D-M
Location: Balboa Heights, Panama Climate: Tropical maritime			
0.005	111.2	121	-8.1
0.01	98.1	102	-3.1
0.02	81.7	82	-0.4
0.05	58.7	59	-0.5
Location: Ubon, Thailand Climate: Tropical continental-monsoon			
0.005	117.5	122	-3.7
0.01	99.8	101	-1.2
0.02	82.4	81	+1.7
0.05	57.2	54	+5.9
Location: Jackson, Mississippi Climate: Subtropical wet			
0.005	87.0	114	-23.4
0.01	74.5	93	-19.9
0.02	60.9	70	-13.0
0.05	42.2	43	-1.9

Table 3-1 (continued).

Percentage Level (%)	Rain Rate (mm/hr) T-S	Rain Rate (mm/hr) D-M	% Deviation from D-M
Location: Bakersfield, California			
Climate: Subtropical arid			
0.005	23.3	24.0	-2.9
0.01	17.0	17.0	0.0
0.02	11.5	11.5	0.0
0.05	5.8	7.0	-17.1
Location: Denver, Colorado			
Climate: Temperate continental-semi arid			
0.005	47.1	45	+4.7
0.01	36.5	32	+14.1
0.02	26.3	21	+25.2
0.05	14.2	10.5	+40.0
Location: Saarbrucken, West Germany			
Climate: Temperate continental			
0.005	38.5	36.0	+6.9
0.01	30.5	28.0	+8.9
0.02	22.2	21.5	+3.3
0.05	12.2	13.0	-6.2
Location: Indianapolis, Indiana			
Climate: Temperate continental			
0.005	63.2	81.0	-22.5
0.01	50.8	64.0	-20.6

Table 3-1 (continued).

Percentage Level (%)	Rain Rate (mm/hr) T-S	Rain Rate (mm/hr) D-M	% Deviation from D-M
Location: Indianapolis, Indiana (continued)			
0.02	37.3	46.0	-18.9
0.05	22.4	26.0	-13.8
Location: Clearwater, Washington Climate: Temperate maritime			
0.005	44.9	50.0	-10.2
0.01	40.0	41.0	-2.4
0.02	33.5	32.5	+3.1
0.05	22.9	22.5	+1.8
Location: Anchorage, Alaska Climate: Polar maritime			
0.005	12.6	7.8	+61.5
0.01	8.2	7.1	+15.5
0.02	3.8	6.5	-41.5
0.05	1.9	5.2	-63.5
Location: Fairbanks, Alaska Climate: Polar continental			
0.005	10.4	7.5	+38.7
0.01	6.6	6.8	-2.9
0.02	2.8	6.2	-54.8
0.05	0.0	5.1	-100.0

program produces rain rates which adequately indicate the small order of the power margin needed which would probably be only a fraction of a decibel even at very low antenna elevation angles. The generally high correlation between the results of the Davis-McMorrow model and the annual application of the Tattelman-Scharr model, each obtained through completely independent means, induces a high level of confidence in each method.

An interesting case is that of Saarbrucken. At this location the threshold used to define a rainy day is 0.1 mm, however, the coefficients used were those for 0.25 mm. The very low percents of deviation imply that either the essential rain rate determining factors are preserved in spite of the different threshold or the number of days with more than 0.1 mm of rain is about the same as the number of days with more than 0.25 mm of rain. Either is a very small amount. Because of this, the 0.25 mm threshold will be used for any location with a threshold below 0.25 mm.

CCIR Global Model

The CCIR global model is the third and least preferred of the three methods used to estimate one-minute rain rates in this algorithm. Its most conspicuous feature is the fact that, as the name implies, it can be used anywhere. There is no place on earth for which it will not provide a rain rate.

This basic model divides the world into 14 rain rate regions. Rain rates for each region are tabulated for each of seven percentage levels (percents of year) between 0.001% and 1.0%. A map of these regions and the table of rain rates are in Appendix G. To determine the rain rate the rain climatic region for the location of the satellite earth terminal is first identified by using the maps in Figure G-1. The rain rate at a particular percentage level is found in Table G-1 in the column headed by the designation letter for that region. The CCIR model gives very few percentage levels in the range of interest to DCS satellite communication links. Therefore, for use in this algorithm, an expanded table was devised. The four rain rates at percentage levels between 0.003% and 0.1%, inclusive, were plotted for each region and curves drawn (Figures H-1 through H-6). From these curves interpolated values were taken and tabulated for 12 percentage levels (Table H-1). Rain rates can be found by using this expanded table or, if another percentage level is required, directly from the curves.

This model is useful as a catch-all for locations so remote that neither of the other two models can be used. However, two limitations must be recognized. First, variations within any of these large regions are not taken into account. For instance, rain rate behavior can change significantly from one side of a mountain range to another or from coastal to inland areas. And, second, boarderline cases can pose a dilemma. Rain rates can change greatly between adjacent regions. In such a case a compromise would be a logical solution as locations even close to a boarderline would probably exhibit some of the rain rate characteristics of the adjacent region.

SECTION IV

ESTIMATION OF THE POWER MARGIN

Introduction

This section presents the method used to determine the power margin of the satellite communications link. In each of the three subsections mathematical models are used to quantify each of the components of the power margin that were discussed in Section II: attenuation, noise and depolarization.

Attenuation

The estimation of rain-induced attenuation on a satellite communications link can be divided into two independent parts: the evaluation of the specific attenuation and the determination of the path length. Specific attenuation is the amount of attenuation per unit length given in units of decibels per kilometer (dB/km) in this case. The path length is the distance in kilometers that the link passes through rain. The product of these two is the total attenuation on the path and thus the power margin for attenuation.

Specific attenuation is a function of the rain rate and the link frequency. It is approximated by the exponential expression

$$A(dB/km) = B\ R^{C} \qquad (5)$$

where R is the rain rate in millimeters per hour (9:170). The coefficient B and the exponent C are based on the empirical estimates of raindrop size and shape distributions. They are dependent upon frequency and, to a lesser extent, the rain rate. It has been shown that there are significant changes in the distribution of raindrop size and shape between light and heavy rains (10:318). Therefore the values of B and C have been determined as a function of frequency for both high and low rain rates. Low rain rates are defined as 30 mm/hr or less and high rain rates as over 30 mm/hr. These values are given in Table 4-1 for frequencies of 7, 8, and 9 GHz. Linear interpolation is used determine B and C for other frequencies between 7 and 9 GHz.

Table 4-1. Values of B and C as a function of frequency and low and high rain rates (10:323)

Frequency	Low Rain Rate		High Rain Rate	
(GHz)	B	C	B	C
7.0	0.00455	1.180	0.00336	1.270
8.0	0.00649	1.187	0.00535	1.245
9.0	0.00888	1.185	0.00803	1.216

The estimation of the path length is somewhat more involved than the specific attenuation. It is complicated by variations in both the height of the 0°C isotherm and the rain rate along the path.

Figure 4-1 is a diagram of the signal beam as it passes through rain. The path length used to estimate attenuation is that portion of the link between the satellite earth terminal and the 0°C isotherm labeled L in Figure 4-1. L is computed from the expression

$$L = \frac{2H}{(\sin^2 E + 2H/8500)^{\frac{1}{2}} + \sin E} \qquad (6)$$

where H is the difference between the height of the 0°C isotherm above sea level, H_o, and the height of the terminal above sea level, H_g (11:335). However, this expression accounts for the curvature of the earth, and above 10° of antenna elevation the curvature is insignificant. Therefore, above 10° elevation, L can be simplified to

$$L = H/(\sin E) \qquad (7)$$

The height of the 0°C isotherm can be determined from Figure 4-2. This figure shows five separate curves: one for maritime climates and four for continental climates. The height of the 0°C isotherm in maritime climates is very stable with respect to local meteorological conditions.

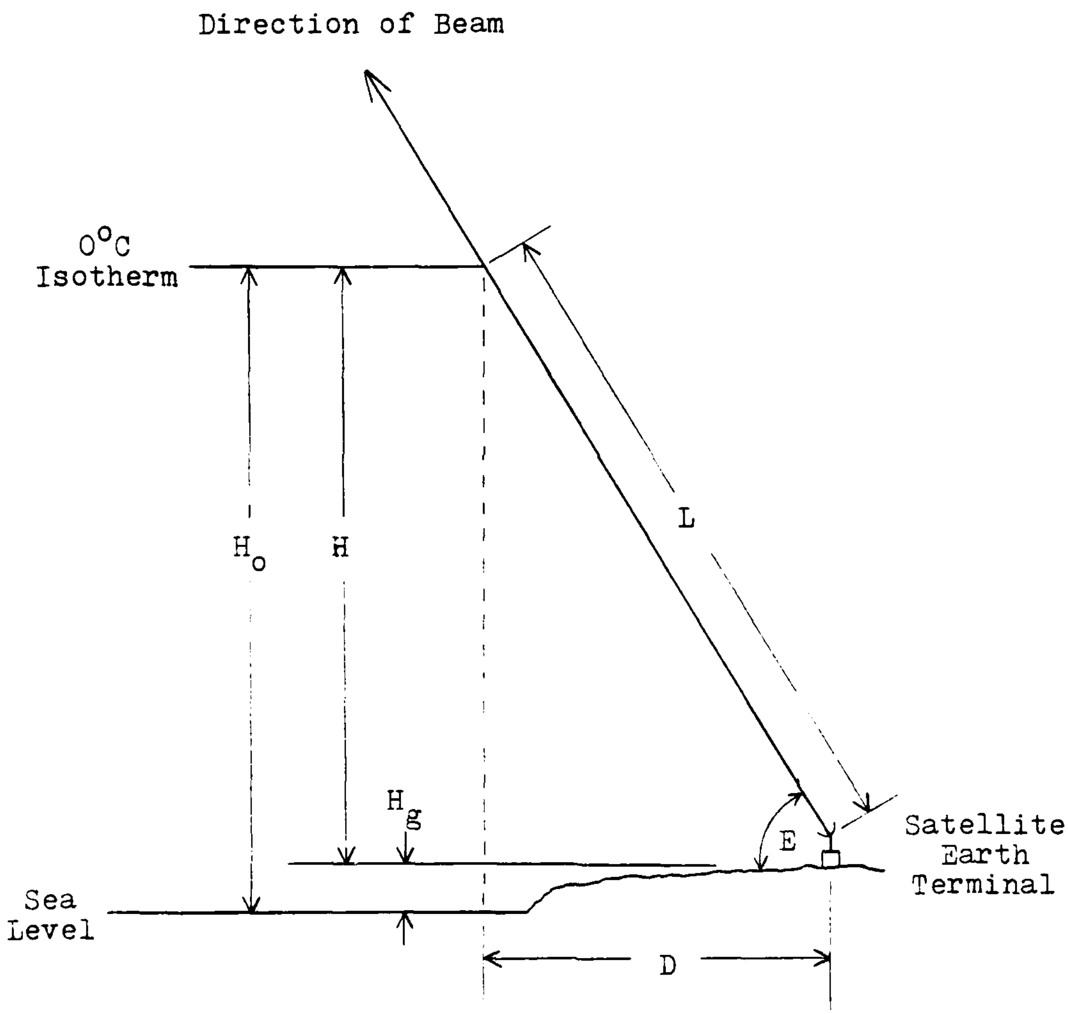

Figure 4-1. Geometry of the signal beam through rain

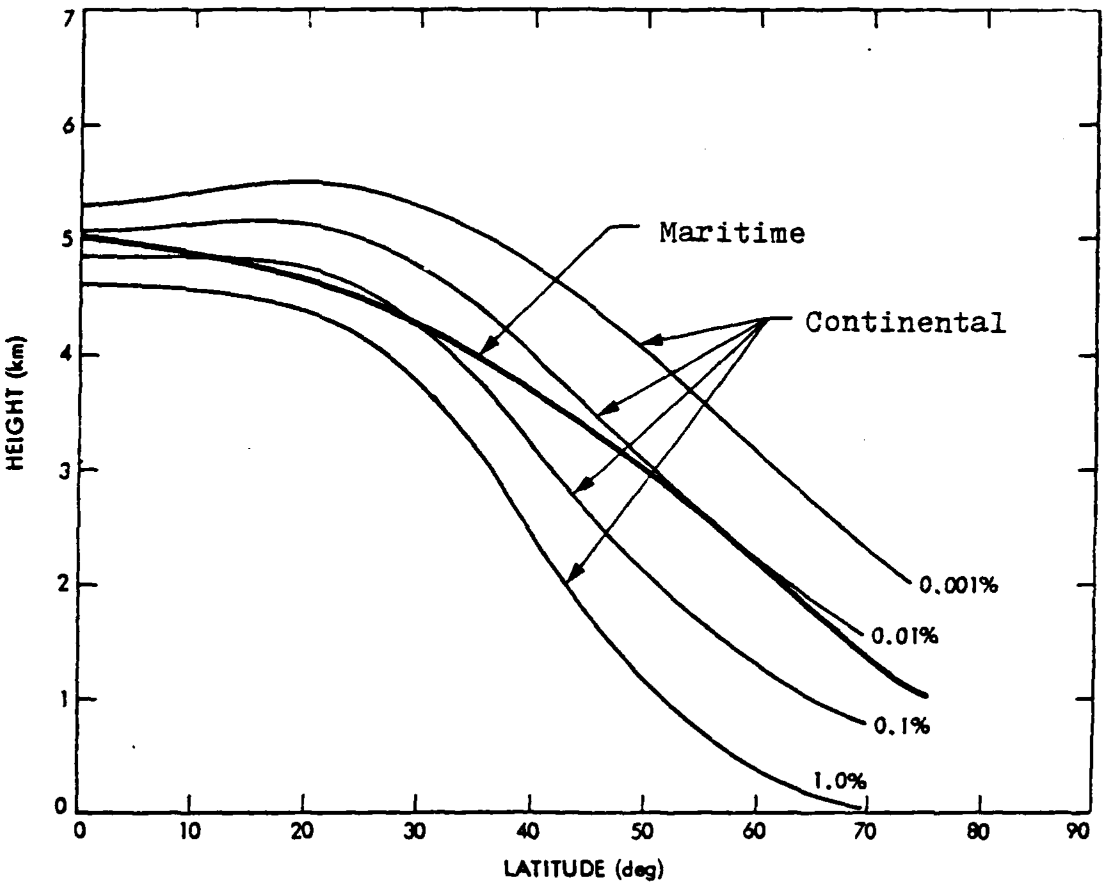

Figure 4-2. Height of the $0^{o}C$ isotherm as a function of latitude for maritime and continental climates. Source: (8:9-40)

Therefore, it is only dependent on the latitude, and only a single curve is needed. On the other hand, the 0°C isotherm in continental climates varies not only with latitude but also with the local meteorological conditions and is closely related to the probability of rain rate. These curves give the heights of the 0°C isotherm for annual percents of outage time due to rain of 1.0%, 0.1%, 0.01%, and 0.001%. If another value between 1.0% and 0.001% is needed, the user must interpolate.

The estimation of the path length through rain is complicated by the fact that the rain rate is not uniform along the entire path. The rain rate used to calculate the specific attenuation was that at the satellite earth terminal. But rain tends to be localized. Rain clouds group into cells which generally cover less surface area as the rain intensity increases. This leads to an effective reduction in the path length (11:336). To compensate for this, a path reduction factor RF is included in the path length. Again there are differences between maritime and continental climates. For continental climates

$$RF = \frac{90}{90 + C_p D} \tag{8}$$

where the coefficient C_p is found in Table 4-2 for three percents of outage time p: 0.1%, 0.01%, and 0.001%. Other values for $0.001 < p < 0.1$ are found by interpolation.

Table 4-2. Coefficient C_p as a function of annual percent of outage time p (11:336)

p (percent)	C_p
0.1	0.5
0.01	4.0
0.001	9.0

D is the horizontal projection of the path length L in Figure 4-1.

$$D = L \cos E \qquad (9)$$

In maritime climates

$$RF = \frac{90(p/0.01)^{-m}}{90 + 4D} \qquad (10)$$

where p is the percentage of outage time and $m = 0.33$ for $0.001 \leq p < 0.01$ and $m = 0.41$ for $0.01 < p \leq 0.1$. The actual path length is the product of RF and L. And, finally, the power margin for attenuation PM_a in decibels is

$$PM_a = A\ L\ RF \qquad (11)$$

Noise

The power margin needed to compensate for the increase in noise due to rain is the ratio of the total system noise with rain to the total system noise without rain. For this algorithm, noise will be expressed in terms of noise temperature in units of degrees Kelvin. The relationship between noise temperature T and actual noise power N in the system is

$$N = k\ T\ B \qquad (12)$$

where k is Boltzmann's constant, 1.38×10^{-23} joules/°K, and B is the receiver bandwidth in Hertz. The total noise temperature of the system T_s is the sum of the noise temperature collected by the receiving antenna T_a and the noise temperature contributed by the receiver T_r, that is,

$$T_s = T_a + T_r \qquad (13)$$

In the absence of rain, T_a consists only of the nominal sky noise T_{sn} . However, with rain, T_a increases by an amount T_{rain} to give

$$T_a = T_{sn} + T_{rain} \qquad (14)$$

Therefore, the power margin for rain-induced noise, PM_n, can be expressed in decibels as

$$PM_n = 10 \text{ Log} \left[\frac{T_r + T_{sn} + T_{rain}}{T_r + T_{sn}} \right] \tag{15}$$

T_{rain} can be estimated when the attenuation is known by the relation

$$T_{rain} = 288[1 - \exp(-PM_a/4.34)] \text{ °K} \tag{16}$$

where PM_a is the attenuation in decibels previously determined (12:1420). If the value of T_{sn} for the satellite earth terminal is known, it can be entered directly into the algorithm. Otherwise, it can be estimated using Figure 4-3. T_r can be found if the receiver noise figure (F) is known:

$$T_r = 290(F - 1) \tag{17}$$

where F is a pure ratio, that is, not in decibel form.

Depolarization

As was noted in Section II, the power margin for depolarization is the ratio of the total received power to copolarized power, P_r/P_c in Figure 2-2. The magnitudes of P_r and P_c can be found from a model which expresses the cross polarization discrimination (XPD) of the signal. XPD is

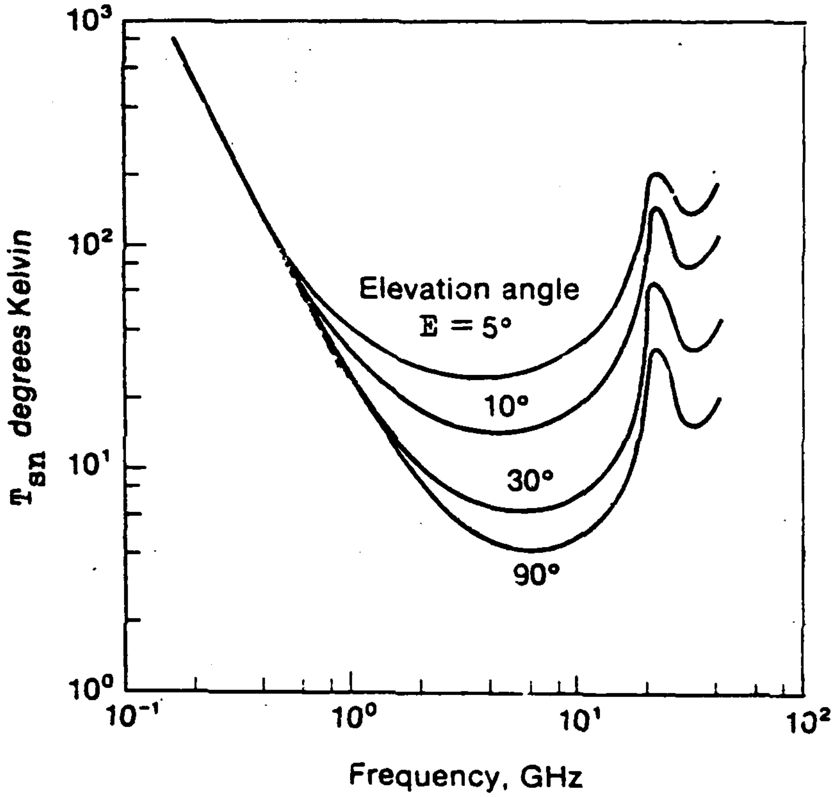

Figure 4-3. Sky noise temperature as a function of frequency and antenna elevation angle. Source: (13:103)

defined as the ratio of copolarized power to cross-polarized power. In decibels,

$$XPD = 20 \text{ Log } (P_c/P_x) \tag{18}$$

Solving for P_x gives

$$P_x = P_c \; 10^{-XPD/20} \tag{19}$$

Using the Pythagorean theorem

$$P_r = (P_c^{\;2} + P_x^{\;2})^{\frac{1}{2}} \tag{20}$$

Substituting equation (19) into equation (20)

$$P_r = (P_c^{\;2} + P_c^{\;2} \; 10^{-2XPD/20})^{\frac{1}{2}} \tag{21}$$

$$= P_c(1 + 10^{-XPD/10})^{\frac{1}{2}} \tag{22}$$

Therefore, the depolarization power margin PM_d in decibels is

$$PM_d = 10 \text{ Log } (P_r/P_c) \tag{23}$$

$$= 10 \text{ Log } \left[\frac{P_c(1 + 10^{-XPD/10})^{\frac{1}{2}}}{P_c}\right] \tag{24}$$

$$PM_d = 5 \text{ Log } (1 + 10^{-XPD/10}) \qquad (25)$$

XPD in decibels is approximated by the expression

$$XPD = 30 \text{ Log } f_{GHz} - 40 \text{ Log } (\cos E)$$

$$- 10 \text{ Log}\{0.5[1 - 0.9418 \cos (4T)]\}$$

$$- 20 \text{ Log } PM_a \qquad (26)$$

where f_{GHz} is the link frequency in gigahertz, E is the angle of antenna elevation, T is the polarization tilt angle measured from the horizontal, and PM_a is the attenuation estimated in the previous subsection (8:9-48). The coefficient 0.9418 is a term which accounts for the raindrop canting angle distribution. It assumes a Gaussian canting angle distribution with a zero mean and a standard deviation of 5°. The angle of elevation E is assumed to be equal to zero for angles less than 10° and equal to 60° for angles greater than 60°.

The total link power margin PM is equal to the sum of the three individual components:

$$PM = PM_a + PM_n + PM_d \qquad (27)$$

The mathematical models previously presented are organized in a computer program to make the determination of the link power margin as convenient as possible and to minimize the risk of error. The program is written in Microsoft Basic and can be run with a Basic interpreter or compiled to decrease the run time. The source code for this program and a user's manual are presented in Appendix I.

SECTION V

CONCLUSION AND RECOMMENDATIONS

The algorithm presented in this report is designed to provide the satellite communications link designer with all the tools needed to determine the link power margin. It utilizes models which have recently been developed to estimate rain rate and its effect on link attenuation, noise, and depolarization. However, each of these models is based on empirical statistics, and variances from the actual degradations of the link are possible. In addition, these models often make assumptions and simplifications which may not always apply. As models become more sophisticated, they are able to depend on fewer assumptions and simplifications, and they become more reliable. Rain and its effect on communications links are very complex. Most research in the area of modeling link phenomena is relatively recent as is the demand for satellite use and efficient utilization of transmitted power. Existing models are continually being updated and new models devised. Because of this, the following two recommendations are made:

1. This algorithm should be upgraded as promising new models or revisions to old models become available. The algorithm is highly modularized; one element can be modified or replaced without disturbing the operation of another.

2. The accuracy of this algorithm should be tested by

comparing it with actual link degradations. Data consisting of rainfall, outage time, and fading measurements should be compiled over the lifetime of the link. It would take several years of data at a particular location to judge whether the models are adequate or not because of the large variances in meteorologic conditions from one year to the next. Such long-term statistics can be used to adjust the power margin and possibly as a basis for a modification of the algorithm itself.

APPENDIX A

ANNUAL TABLES OF THE DAVIS-MCMORROW MODEL

Table A-1: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Urbana, Illinois.

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	96.02	3.43	0.51	0.04	0.0	0.0	0.0	0.0	0.0
0.01	87.56	10.38	1.96	0.06	0.04	0.0	0.0	0.0	0.0
0.02-0.09	59.17	29.16	10.17	1.16	0.25	0.08	0.01	0.0	0.0
0.10-0.24	27.34	19.24	37.58	11.82	2.82	1.05	0.15	0.0	0.0
0.25-0.49	23.50	11.28	23.01	23.14	12.16	5.33	1.58	0.0	0.0
0.50-0.99	20.45	8.53	14.74	16.28	16.99	13.53	8.65	0.83	0.0
1.00-1.99	6.67	5.56	8.89	13.33	19.44	20.00	25.56	0.56	0.0
2.00-2.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.00-3.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00-4.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
over 5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-2: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Majuro Atoll, Marshall Islands.

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	93.71	4.15	1.64	0.44	0.06	0.0	0.0	0.0	0.0
0.01	88.79	6.39	3.13	1.49	0.20	0.0	0.0	0.0	0.0
0.02-0.09	70.65	15.00	10.03	2.87	1.12	0.29	0.03	0.0	0.0
0.10-0.24	43.42	14.27	25.96	9.03	4.98	1.92	0.41	0.01	0.0
0.25-0.49	35.86	9.08	16.47	18.06	11.02	6.51	2.96	0.04	0.0
0.50-0.99	22.53	6.61	14.78	15.32	18.60	14.35	7.35	0.27	0.0
1.00-1.99	9.38	0.62	3.75	18.33	24.37	23.12	20.21	0.21	0.0
2.00-2.99	0.0	0.0	0.0	6.67	23.33	15.00	53.33	1.67	0.0
3.00-3.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00-4.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
over 5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-3: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Miami, Florida.

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	93.55	4.60	1.49	0.33	0.04	0.0	0.0	0.0	0.0
0.01	85.31	9.44	4.01	1.17	0.06	0.0	0.0	0.0	0.0
0.02-0.09	65.67	19.97	11.13	2.30	0.66	0.26	0.01	0.0	0.0
0.10-0.24	39.21	16.40	29.82	9.84	2.21	2.14	0.38	0.0	0.0
0.25-0.49	29.81	11.52	18.64	22.42	9.47	5.87	2.23	0.04	0.0
0.50-0.99	34.04	6.32	16.67	10.61	10.00	11.14	10.18	1.05	0.0
1.00-1.99	15.50	12.17	7.50	12.33	13.17	13.67	20.83	4.83	0.0
2.00-2.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.00-3.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00-4.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
over 5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-4: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Franklin, North Carolina.

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	91.62	6.57	1.65	0.14	0.02	0.0	0.0	0.0	0.0
0.01	83.72	11.92	3.87	0.46	0.03	0.0	0.0	0.0	0.0
0.02-0.09	55.66	29.20	13.36	1.47	0.28	0.03	0.0	0.0	0.0
0.10-0.24	19.57	20.63	42.88	14.23	2.08	0.56	0.06	0.0	0.0
0.25-0.49	9.89	6.07	27.41	41.15	12.61	2.42	0.46	0.0	0.0
0.50-0.99	8.47	6.94	11.11	22.36	35.56	11.94	3.61	0.0	0.0
1.00-1.99	32.50	2.50	5.83	10.00	10.42	18.75	12.08	7.92	0.0
2.00-2.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.00-3.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00-4.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
over 5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-5: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Island Beach State Park, New Jersey

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	93.79	5.45	0.71	0.05	0.0	0.0	0.0	0.0	0.0
0.01	80.57	16.59	2.80	0.04	0.0	0.0	0.0	0.0	0.0
0.02-0.09	50.05	37.54	11.28	0.95	0.14	0.04	0.01	0.0	0.0
0.10-0.24	16.00	23.87	47.98	9.49	2.17	0.45	0.04	0.0	0.0
0.25-0.49	16.23	11.32	29.39	20.53	14.04	7.19	1.32	0.0	0.0
0.50-0.99	36.25	5.42	16.67	9.17	7.50	10.83	12.92	1.25	0.0
1.00-1.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.00-2.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.00-3.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00-4.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
over 5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-6: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Woody Island, Alaska.

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	95.62	3.73	0.59	0.05	0.0	0.0	0.0	0.0	0.0
0.01	85.95	12.23	1.65	0.16	0.0	0.0	0.0	0.0	0.0
0.02-0.09	46.07	48.21	5.60	0.11	0.01	0.0	0.0	0.0	0.0
0.10-0.24	2.90	21.27	72.63	3.20	0.0	0.0	0.0	0.0	0.0
0.25-0.49	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.50-0.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.00-1.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.00-2.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.00-3.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00-4.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
over 5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-7: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Freiburg, Germany.

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	97.10	2.84	0.06	0.0	0.0	0.0	0.0	0.0	0.0
0.01	88.32	10.55	1.10	0.03	0.0	0.0	0.0	0.0	0.0
0.02-0.09	57.39	33.61	8.27	0.66	0.06	0.01	0.0	0.0	0.0
0.10-0.24	23.82	22.61	39.45	10.12	3.76	0.24	0.0	0.0	0.0
0.25-0.49	15.71	15.24	21.90	21.43	18.57	6.67	0.48	0.0	0.0
0.50-0.99	0.0	0.0	13.33	40.00	26.67	20.00	0.0	0.0	0.0
1.00-1.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.00-2.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.00-3.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00-4.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
over 5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-8: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Koblenz, Germany.

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	96.73	3.06	0.21	0.0	0.0	0.0	0.0	0.0	0.0
0.01	85.28	12.96	1.76	0.0	0.0	0.0	0.0	0.0	0.0
0.02-0.09	60.10	28.53	9.99	1.24	0.12	0.02	0.0	0.0	0.0
0.10-0.24	33.59	14.87	32.05	13.85	4.62	1.03	0.0	0.0	0.0
0.25-0.49	37.33	10.67	14.00	14.67	13.33	8.00	2.00	0.0	0.0
0.50-0.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.00-1.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.00-2.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.00-3.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00-4.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
over 5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-9: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Pleiku, Vietnam.

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	96.13	3.57	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.01	85.59	12.11	2.30	0.0	0.0	0.0	0.0	0.0	0.0
0.02-0.09	63.57	22.57	11.46	1.81	0.56	0.03	0.0	0.0	0.0
0.10-0.24	40.32	17.27	23.47	11.99	5.09	1.81	0.05	0.0	0.0
0.25-0.49	32.13	9.60	12.67	23.47	14.13	6.27	1.73	0.0	0.0
0.50-0.99	28.46	8.97	10.51	14.36	10.00	16.15	10.51	1.03	0.0
1.00-1.99	13.33	3.89	10.00	13.89	10.00	11.67	19.44	7.78	0.0
2.00-2.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.00-3.99	0.0	0.0	6.67	0.0	0.0	26.67	53.33	13.33	0.0
4.00-4.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
over 5.00	20.00	26.67	0.0	13.33	6.67	0.0	0.0	13.33	20.00

Table A-10: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Saigon, Vietnam.

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	93.87	5.12	1.01	0.0	0.0	0.0	0.0	0.0	0.0
0.01	80.53	16.80	2.13	0.53	0.0	0.0	0.0	0.0	0.0
0.02-0.09	64.37	21.42	10.83	2.50	0.88	0.0	0.0	0.0	0.0
0.10-0.24	44.44	13.26	25.07	9.03	5.76	2.22	0.21	0.0	0.0
0.25-0.49	38.04	9.02	15.69	14.71	12.94	8.04	1.57	0.0	0.0
0.50-0.99	31.94	5.83	9.17	10.83	12.78	20.56	8.61	0.28	0.0
1.00-1.99	12.73	3.64	6.06	6.67	21.82	15.76	29.70	3.64	0.0
2.00-2.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.00-3.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00-4.99	13.33	0.0	0.0	0.0	0.0	13.33	20.00	40.00	13.33
over 5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-11: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Da Nang, Vietnam.

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	95.93	3.58	0.49	0.0	0.0	0.0	0.0	0.0	0.0
0.01	85.95	11.55	2.38	0.12	0.0	0.0	0.0	0.0	0.0
0.02-0.09	63.64	23.53	10.48	2.02	0.29	0.04	0.0	0.0	0.0
0.10-0.24	32.85	16.74	32.07	12.36	4.77	1.12	0.10	0.0	0.0
0.25-0.49	29.33	9.23	16.62	22.05	13.74	6.77	2.26	0.0	0.0
0.50-0.99	23.60	9.55	11.53	14.05	18.74	14.59	7.57	0.36	0.0
1.00-1.99	15.00	1.11	6.11	7.22	22.22	28.33	18.33	1.11	0.56
2.00-2.99	2.22	0.0	2.22	4.44	20.00	31.11	33.33	2.22	4.44
3.00-3.99	43.33	10.00	10.00	3.33	16.67	0.0	0.0	0.0	16.67
4.00-4.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
over 5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-12: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Naha, Okinawa.

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	94.99	4.57	0.43	0.0	0.0	0.0	0.0	0.0	0.0
0.01	83.66	13.87	2.47	0.0	0.0	0.0	0.0	0.0	0.0
0.02-0.09	58.75	26.81	12.20	1.86	0.36	0.02	0.0	0.0	0.0
0.10-0.24	24.57	20.62	37.56	12.92	3.58	0.70	0.05	0.0	0.0
0.25-0.49	17.68	9.42	24.65	29.24	12.11	6.12	0.80	0.0	0.0
0.50-0.99	8.94	4.96	16.17	21.42	24.68	18.44	4.68	0.57	0.14
1.00-1.99	5.33	6.00	8.00	6.67	22.00	31.33	20.00	0.67	0.0
2.00-2.99	0.0	0.0	0.0	0.0	26.67	26.67	40.00	6.67	0.0
3.00-3.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00-4.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
over 5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table A-13: Percent contribution of instantaneous precipitation rate to clock-hour precipitation rates for Bet Dagan, Israel.

Clock-Hour Rates (in/hr)	Instantaneous Rates (in/hr) 0.00-0.03	0.04-0.09	0.10-0.24	0.25-0.49	0.50-0.99	1.00-1.99	2.00-4.99	5.00-9.99	over 10.00
Trace	94.92	4.75	0.34	0.0	0.0	0.0	0.0	0.0	0.0
0.01	84.09	10.97	4.52	0.43	0.0	0.0	0.0	0.0	0.0
0.02-0.09	62.47	22.39	12.47	2.39	0.27	0.0	0.0	0.0	0.0
0.10-0.24	38.71	16.92	27.16	11.24	4.28	1.59	0.10	0.0	0.0
0.25-0.49	28.25	9.21	22.86	19.37	13.33	6.03	0.95	0.0	0.0
0.50-0.99	13.33	13.33	20.00	0.0	33.33	20.00	0.0	0.0	0.0
1.00-1.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.00-2.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.00-3.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00-4.99	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
over 5.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX B

INTERPOLATED COEFFICIENTS FOR THE TATTELMAN-SCHARR RAIN RATE MODEL

Table B-1: Interpolated coefficients for locations where a threshold of 2.54 mm of rain is used to define a rainy day.

Percentage Level (%)	A	B	C	D
0.01	-0.91	0.028	0.023	-0.00034
0.015	-0.81	0.025	0.0225	-0.00033
0.02	-0.73	0.023	0.0222	-0.000323
0.025	-0.67	0.021	0.0217	-0.00032
0.03	-0.63	0.020	0.021	-0.000317
0.04	-0.55	0.018	0.020	-0.00031
0.05	-0.50	0.016	0.019	-0.00031
0.06	-0.45	0.0145	0.018	-0.000308
0.07	-0.41	0.013	0.017	-0.000305
0.08	-0.37	0.0125	0.016	-0.000303
0.1	-0.31	0.011	0.014	-0.00030
0.12	-0.26	0.010	0.0125	-0.000293
0.15	-0.21	0.0085	0.011	-0.00028
0.2	-0.15	0.0067	0.0095	-0.00027
0.25	-0.11	0.0055	0.0084	-0.00025

Table B-1 (continued):

Percentage Level (%)	A	B	C	D
0.3	-0.08	0.0046	0.0077	-0.00023
0.4	-0.03	0.0033	0.0064	-0.00019
0.5	-0.01	0.0025	0.0054	-0.00015
0.7	0.01	0.0014	0.0042	-0.00011
1.0	0.03	0.00074	0.0029	-0.000076
2.0	0.04	-0.0002	0.0015	-0.000032

Table B-2: Interpolated coefficients for locations where a threshold of 1.0 mm of rain is used to define a rainy day.

Percentage Level (%)	A	B	C	D
0.01	-1.0	0.028	0.036	-0.00022
0.015	-0.89	0.025	0.033	-0.000227
0.02	-0.81	0.023	0.031	-0.000232
0.025	-0.75	0.021	0.0297	-0.000233
0.03	-0.70	0.020	0.0285	-0.000237
0.04	-0.62	0.018	0.0265	-0.000240
0.05	-0.56	0.016	0.025	-0.00024
0.06	-0.51	0.015	0.0237	-0.000242
0.07	-0.46	0.0135	0.0225	-0.00024
0.08	-0.42	0.0125	0.0216	-0.000242
0.1	-0.36	0.011	0.020	-0.00024
0.12	-0.31	0.010	0.0187	-0.000233
0.15	-0.26	0.0085	0.017	-0.000225
0.2	-0.19	0.0067	0.015	-0.00021
0.25	-0.15	0.0055	0.013	-0.000193
0.3	-0.11	0.0045	0.0115	-0.000175
0.4	-0.06	0.0032	0.0094	-0.000145
0.5	-0.03	0.0024	0.0078	-0.00012
0.7	-0.01	0.0014	0.0057	-0.000088
1.0	0.02	0.00069	0.0042	-0.000062
2.0	0.04	-0.00018	0.0020	-0.000026

Table B-3: Interpolated coefficients for locations where a threshold of 0.25 mm of rain is used to define a rainy day.

Percentage Level (%)	A	B	C	D
0.01	-1.0	0.028	0.042	-0.00022
0.015	-0.89	0.025	0.039	-0.00022
0.02	-0.81	0.023	0.037	-0.000225
0.025	-0.75	0.021	0.036	-0.000225
0.03	-0.70	0.020	0.034	-0.00023
0.04	-0.62	0.018	0.032	-0.00023
0.05	-0.56	0.016	0.030	-0.00023
0.06	-0.51	0.0145	0.028	-0.00023
0.07	-0.47	0.0135	0.027	-0.00023
0.08	-0.43	0.0125	0.026	-0.00023
0.1	-0.36	0.011	0.024	-0.00023
0.12	-0.31	0.010	0.022	-0.000226
0.15	-0.26	0.0084	0.020	-0.00022
0.2	-0.19	0.0066	0.017	-0.000205
0.25	-0.14	0.0053	0.015	-0.00019
0.3	-0.10	0.0043	0.014	-0.00018
0.4	-0.06	0.0032	0.012	-0.00015
0.5	-0.03	0.0023	0.010	-0.00012
0.7	-0.01	0.0013	0.0080	-0.000083
1.0	0.01	0.00056	0.0060	-0.000056
2.0	0.03	-0.00023	0.0028	-0.000024

APPENDIX C

GRAPHS OF COEFFICIENTS OF THE TATTELMAN-SCHARR MONTHLY RAIN RATE MODEL VS PERCENT OF TIME EXCEEDED FOR THREE THRESHOLDS USED TO DEFINE A RAINY DAY: 2.54 MM, 1.0 MM, AND 0.25 MM.

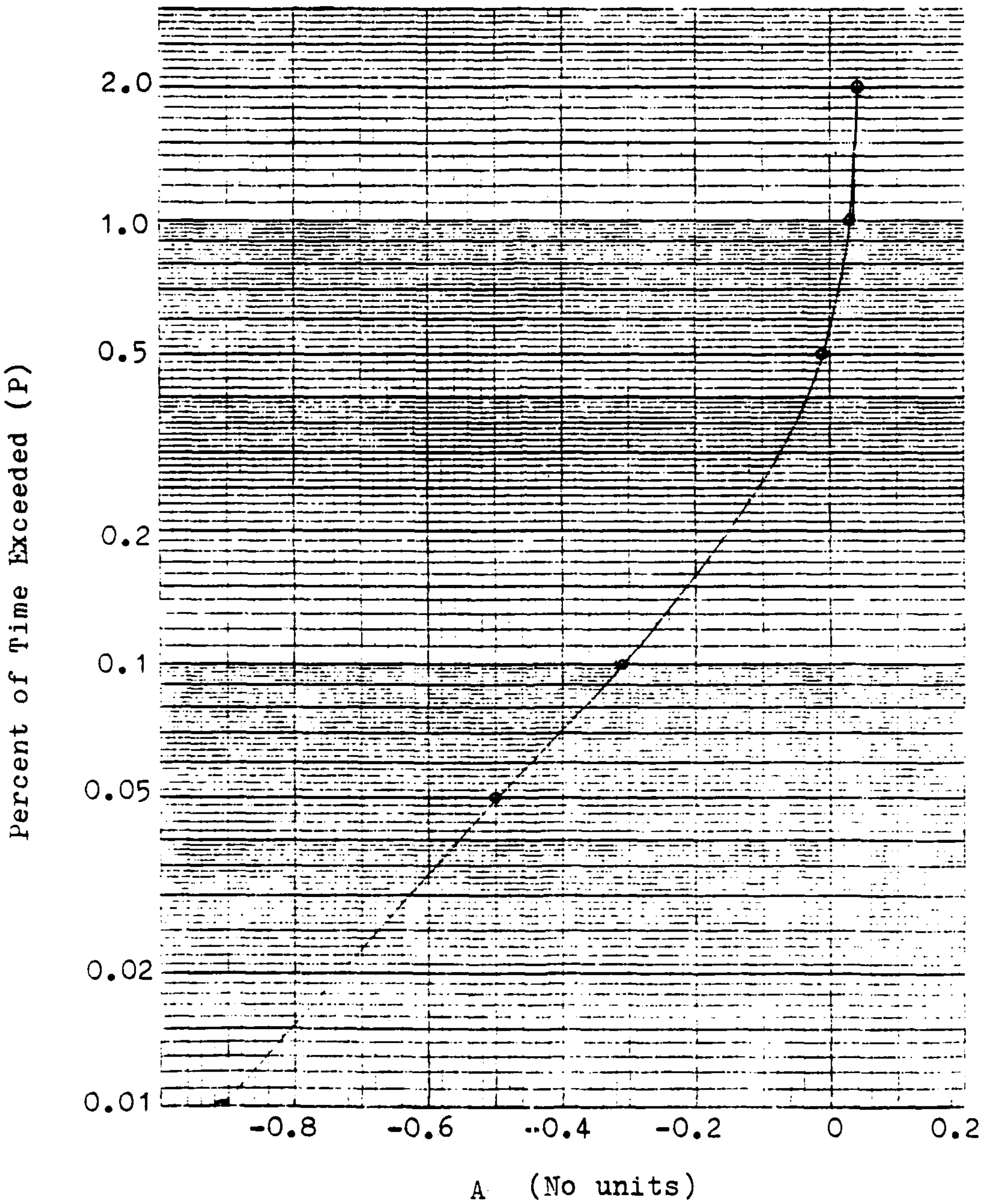

Figure C-1: Coefficient A (threshold=2.54mm) vs percent (P).

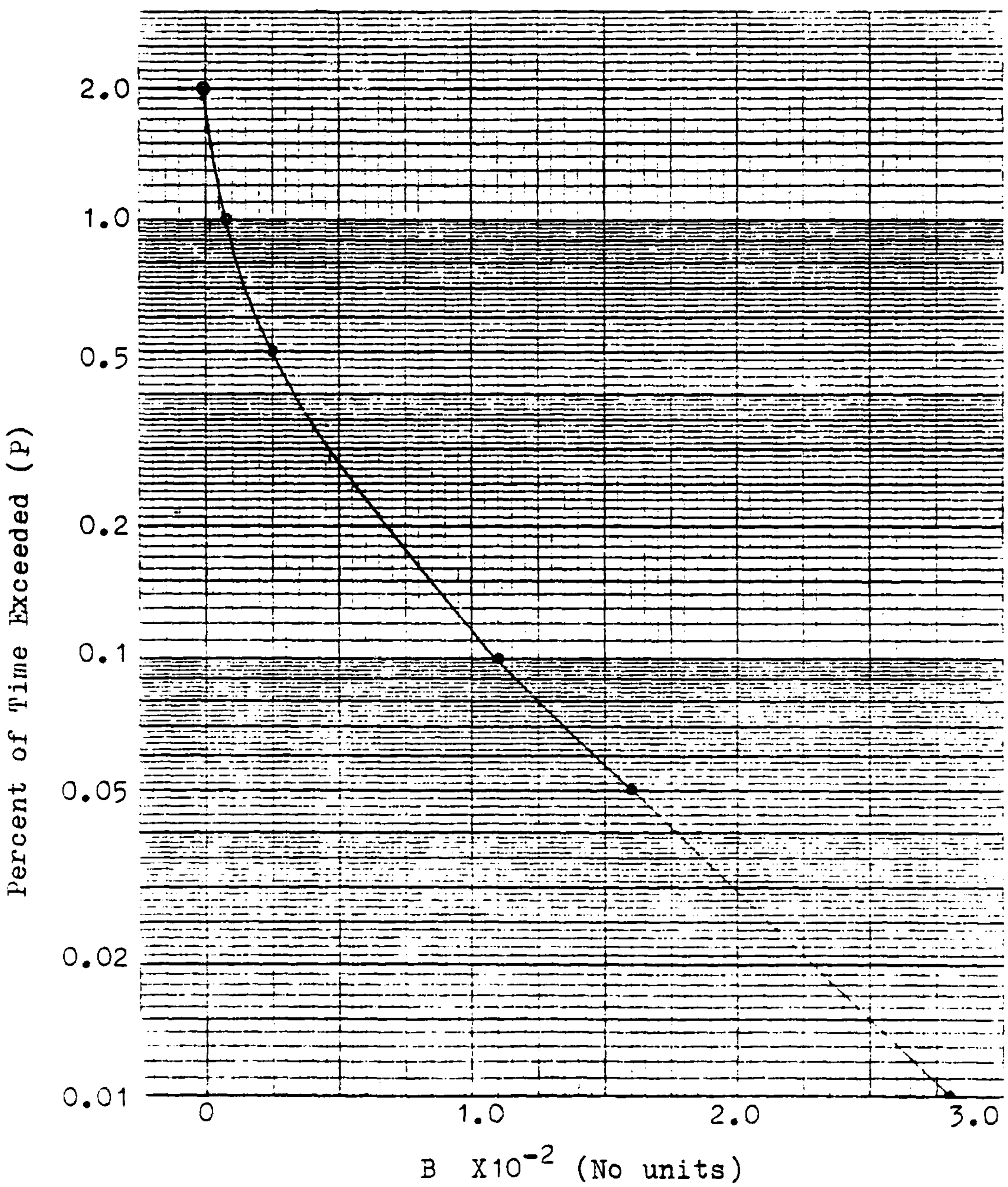

Figure C-2: Coefficient B (threshold=2.54mm) vs percent (P).

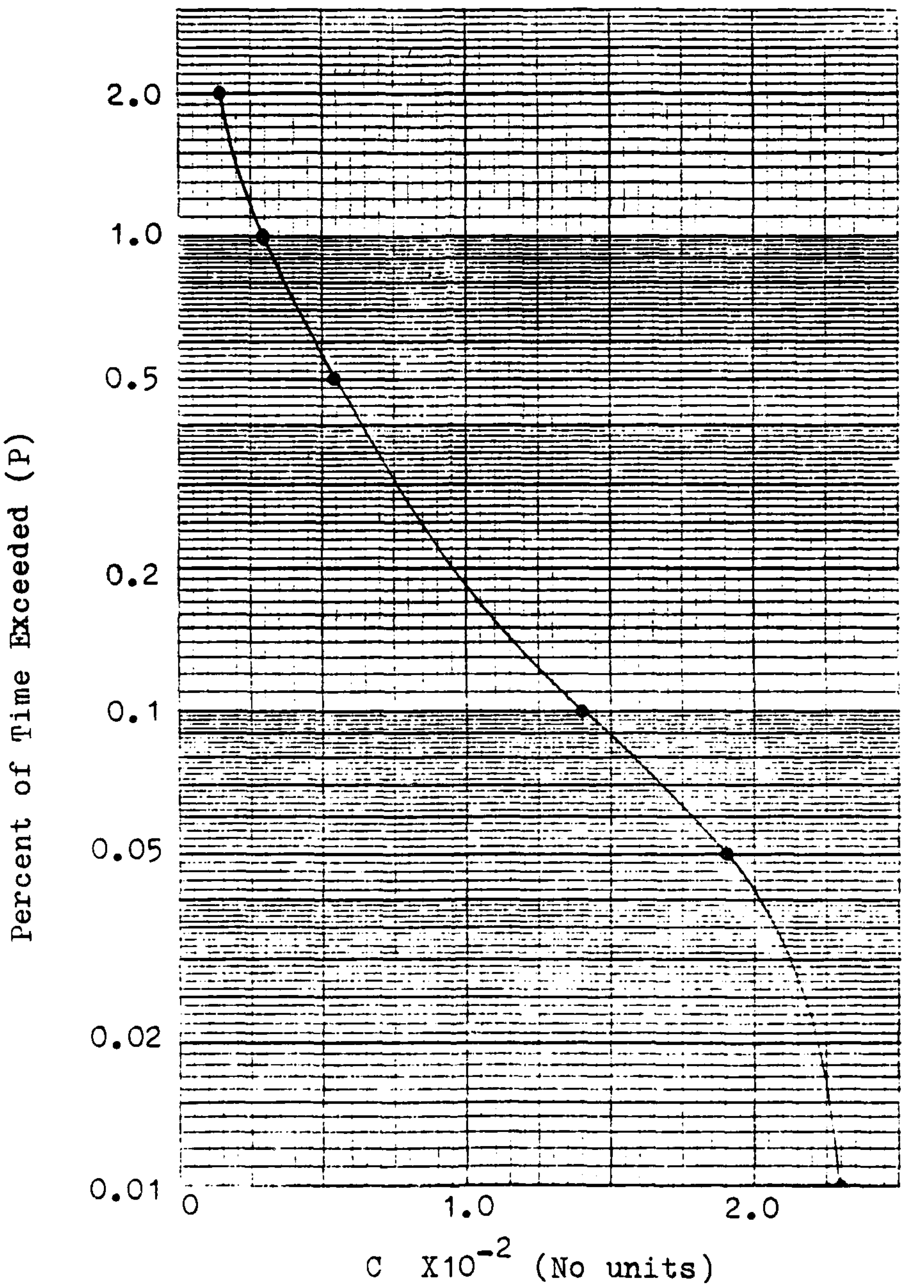

Figure C-3: Coefficient C (threshold=2.54mm) vs percent (P).

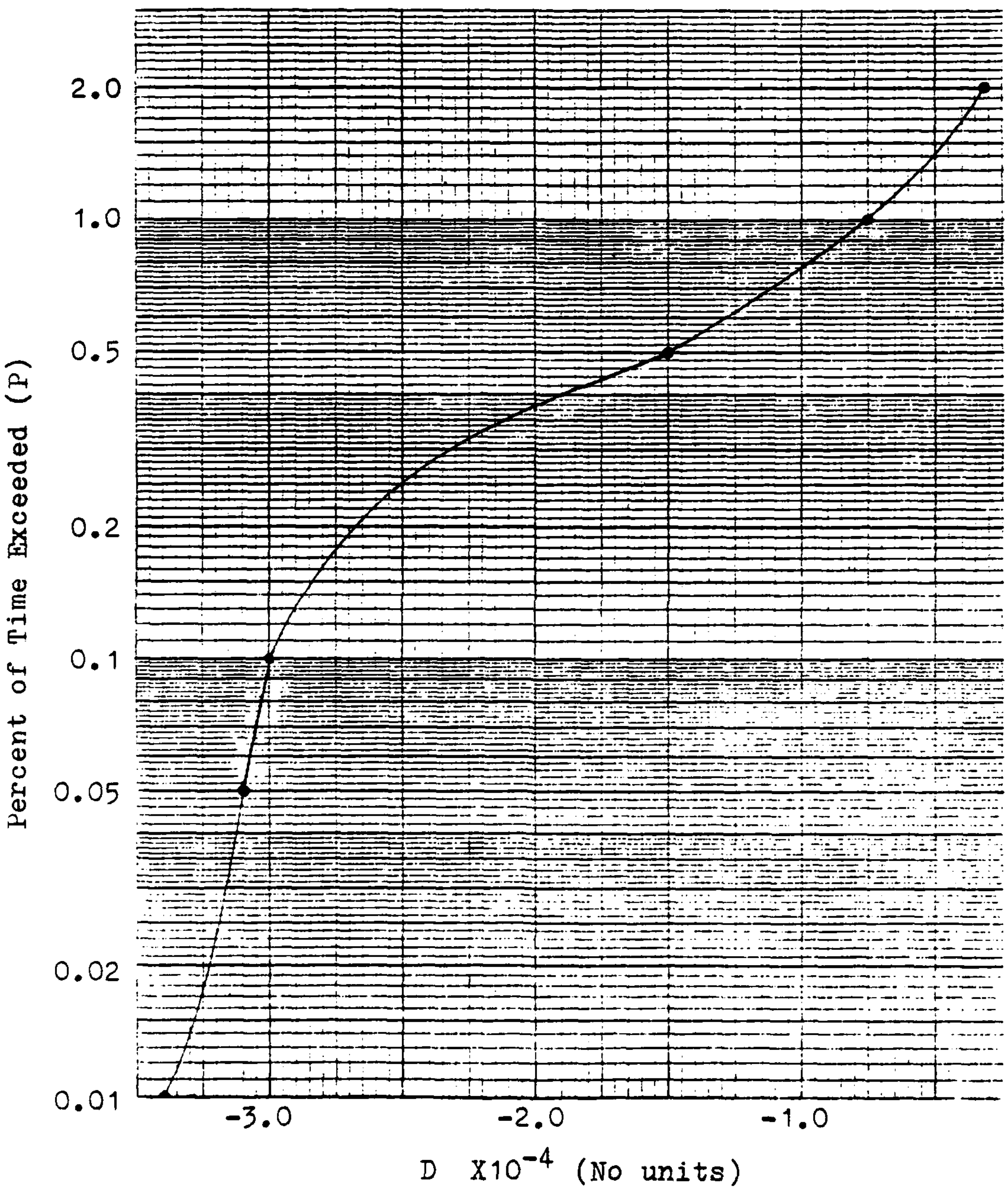

Figure C-4: Coefficient D (threshold=2.54mm)
vs percent (P).

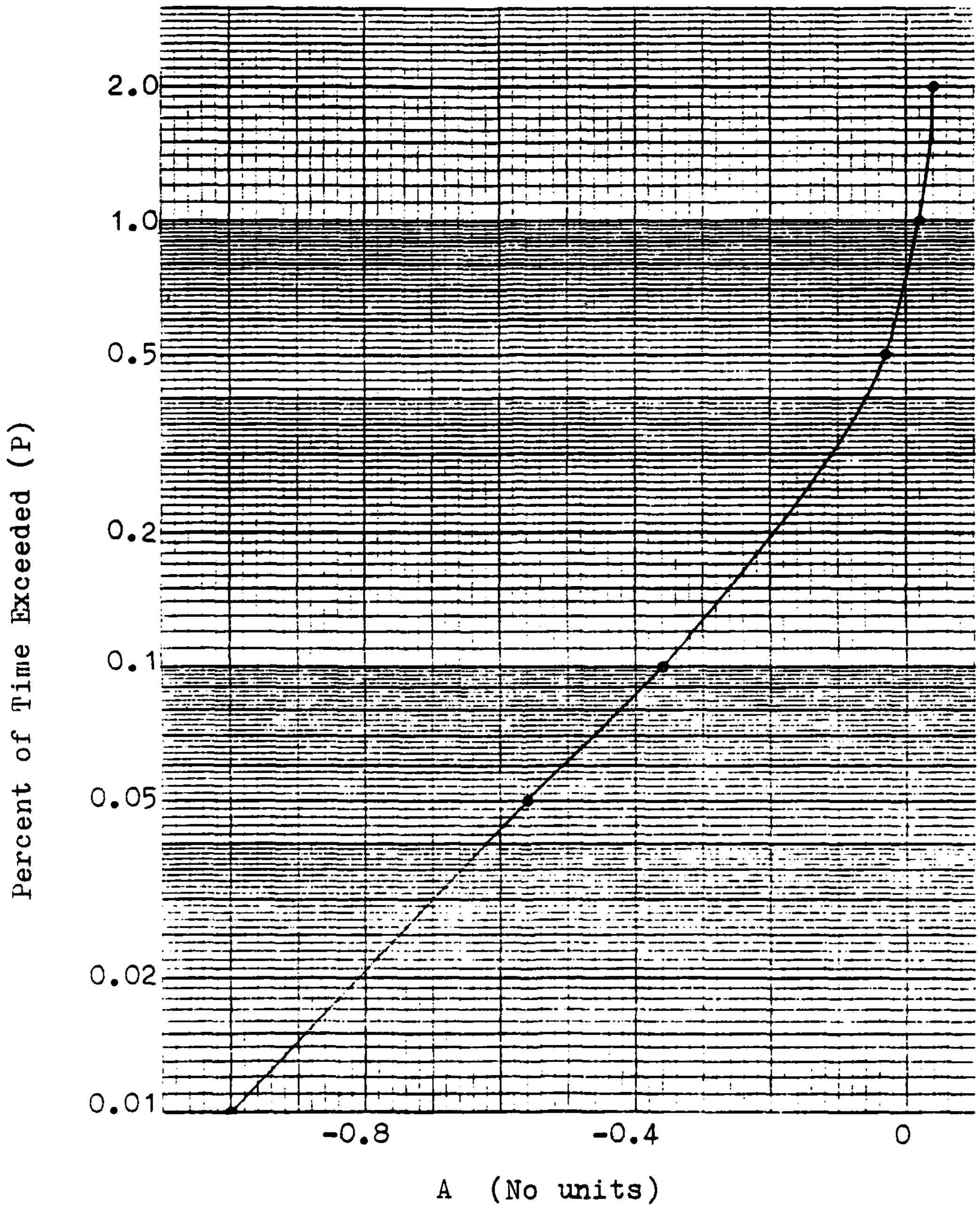

Figure C-5: Coefficient A (threshold=1.0mm) vs percent (P).

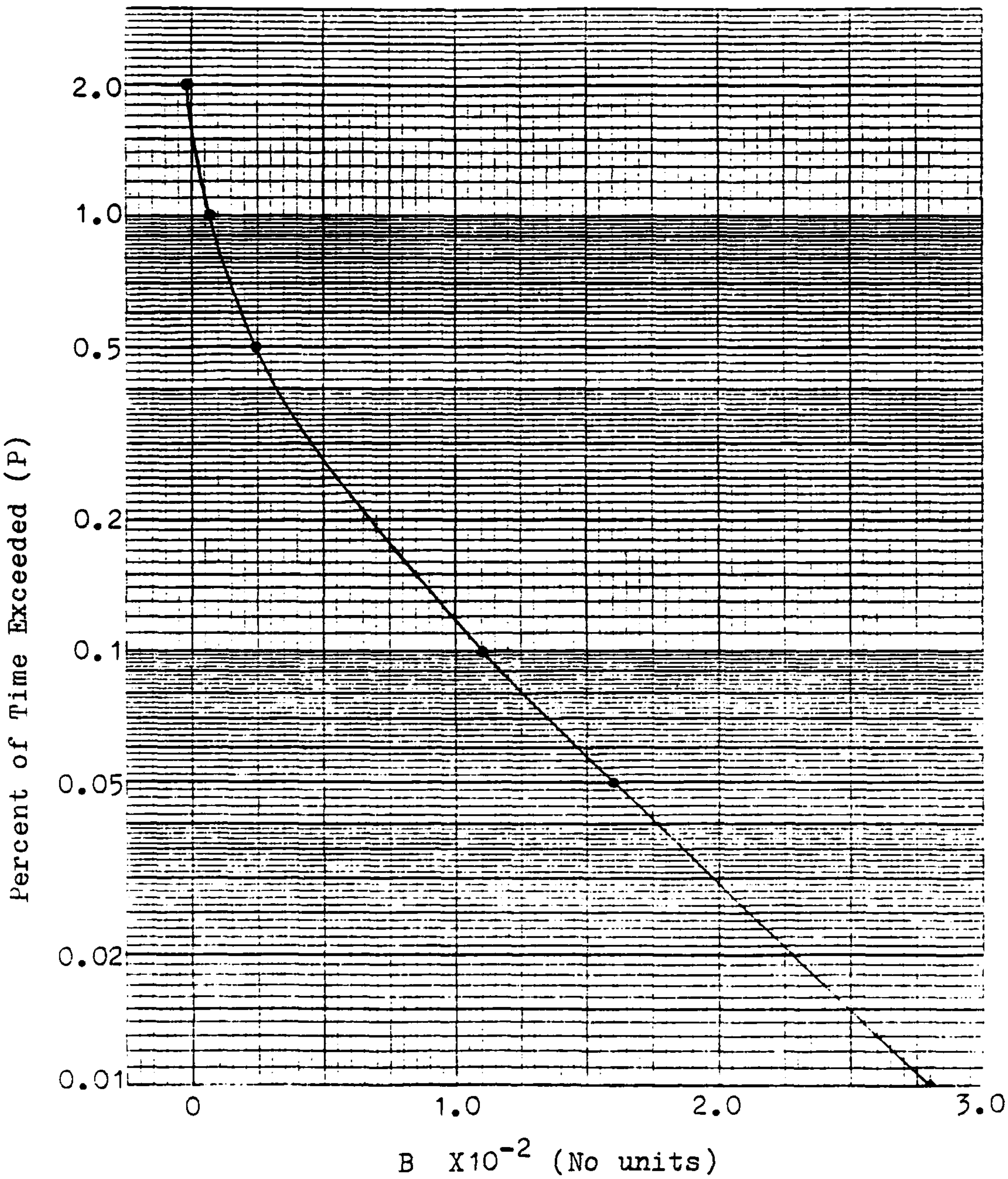

Figure C-6: Coefficient B (threshold=1.0mm) vs percent (P).

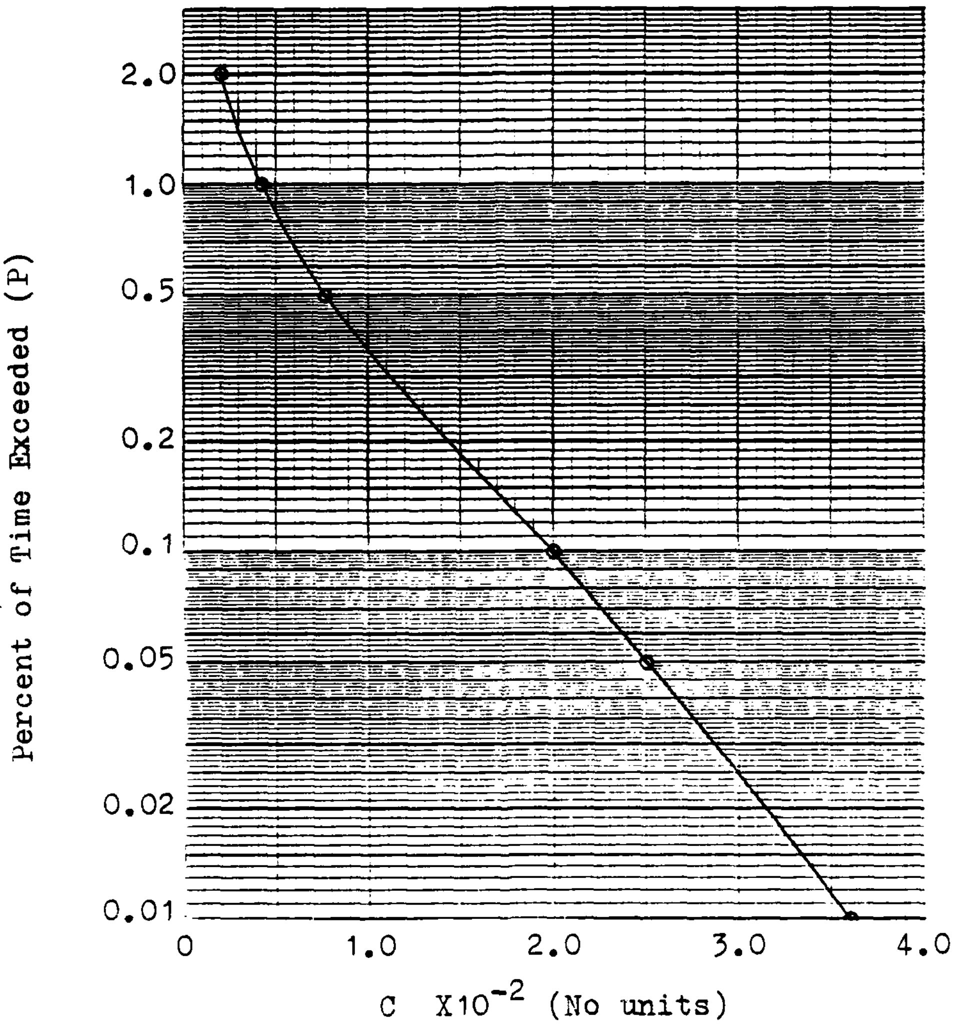

Figure C-7: Coefficient C (threshold=1.0mm) vs percent (P).

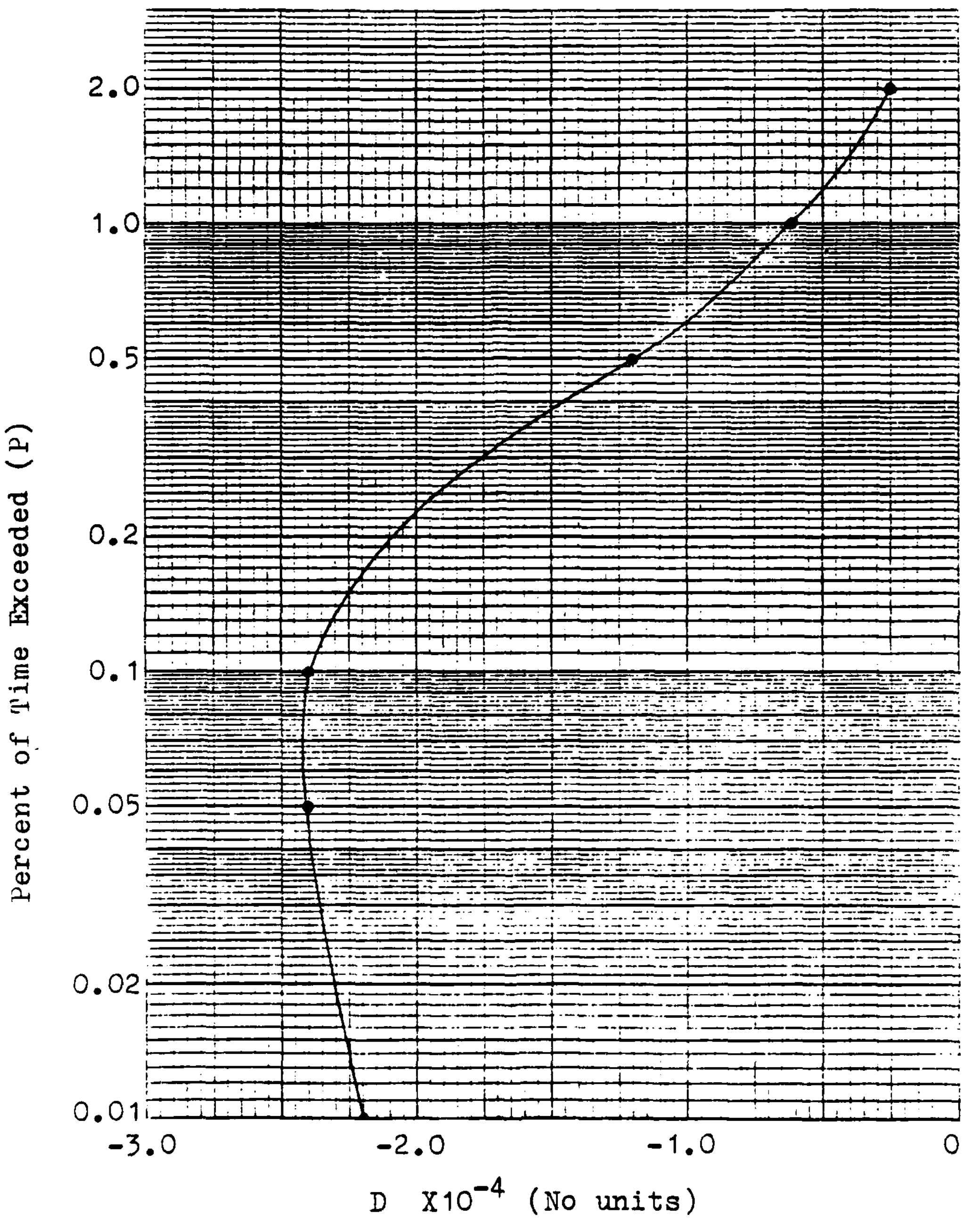

Figure C-8: Coefficient D (threshold=1.0mm) vs percent (P).

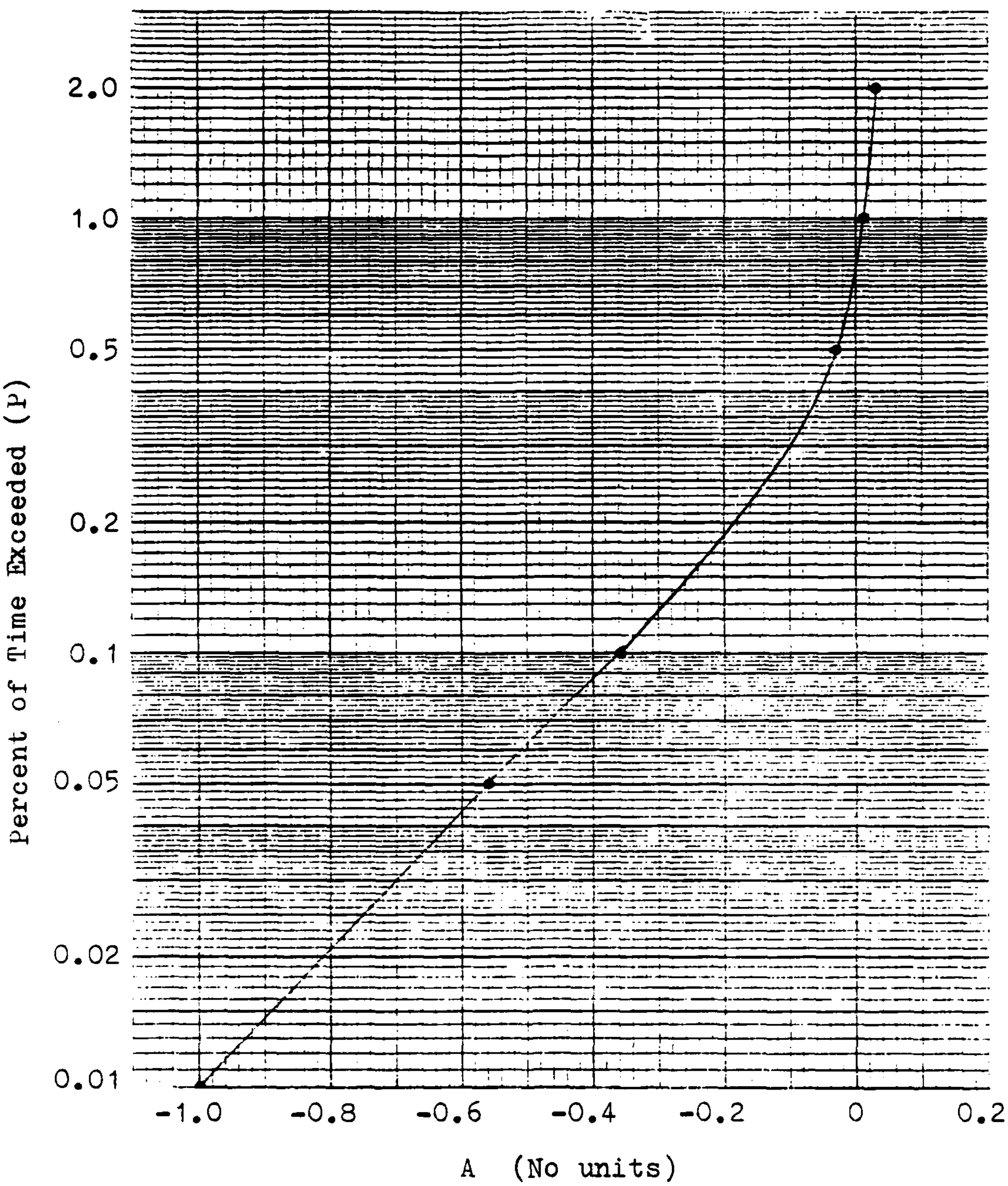

Figure C-9: Coefficient A (threshold=0.25mm) vs percent (P).

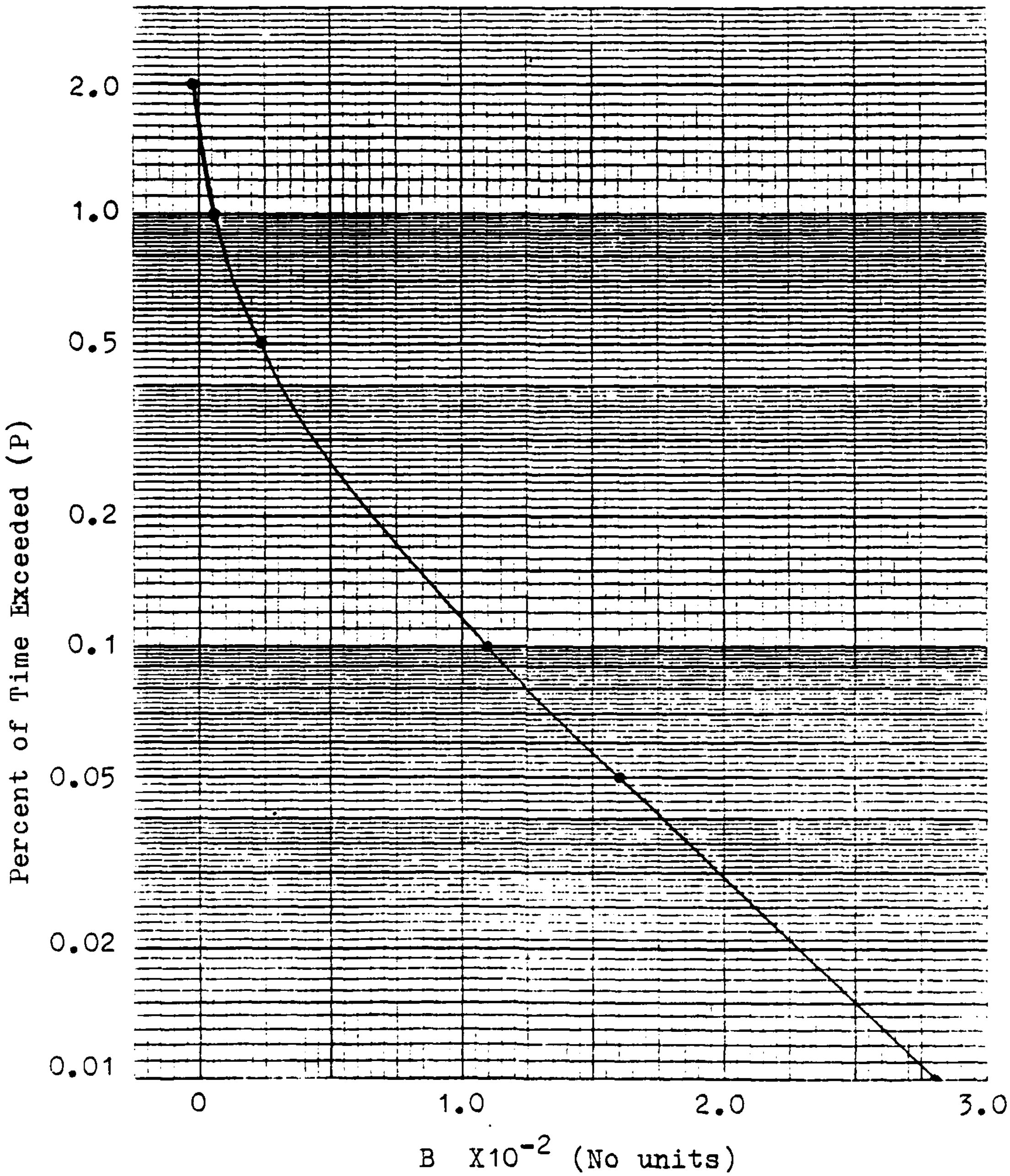

Figure C-10: Coefficient B (threshold=0.25mm) vs percent (P).

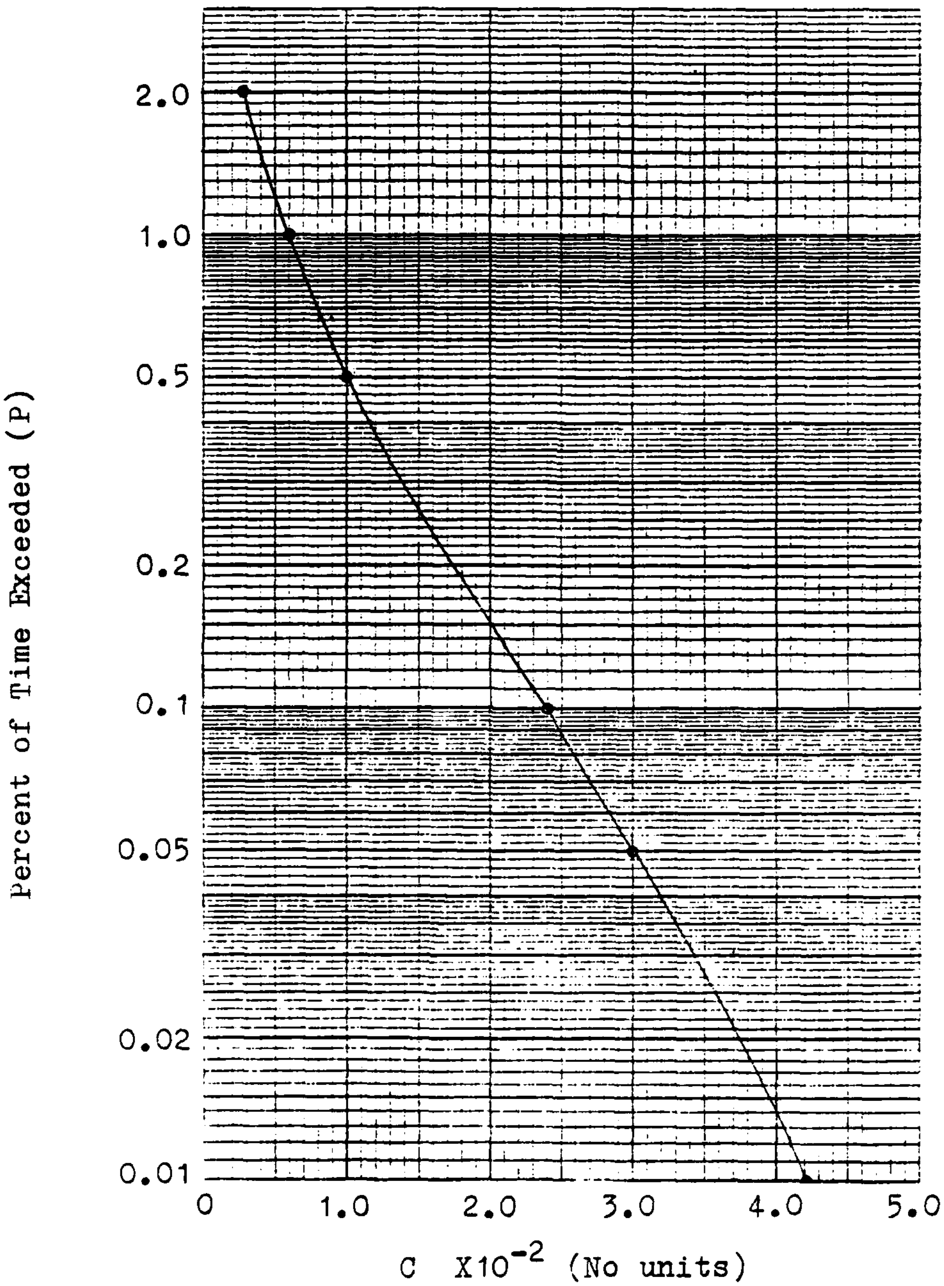

Figure C-11: Coefficient C (threshold=0.25mm) vs percent (P).

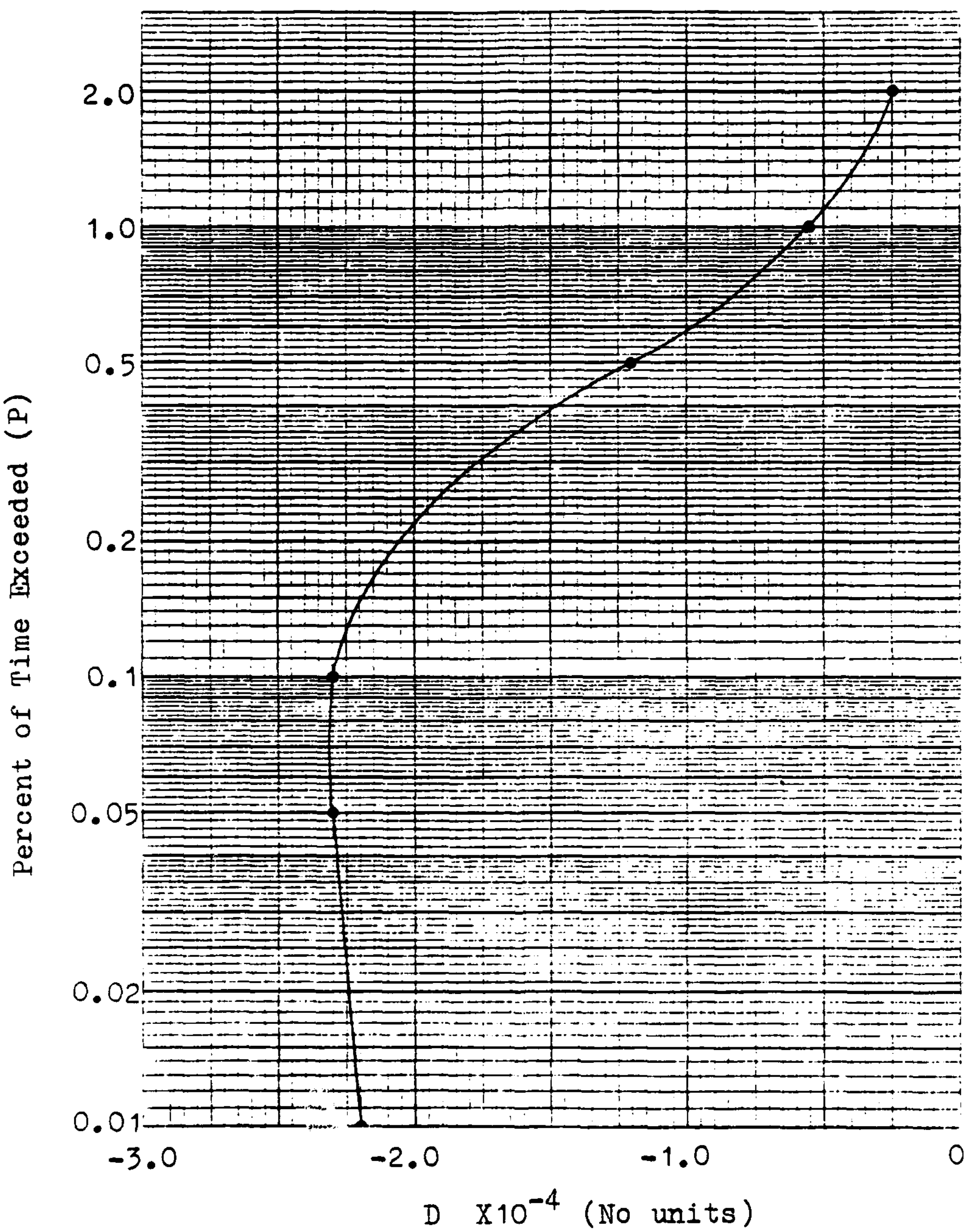

Figure C-12: Coefficient D (threshold=0.25mm) vs percent (P).

APPENDIX D

CLIMATIC DATA FOR 10 LOCATIONS

Table D-1

Location name: Balboa Heights, Panama

Location latitude: 9.0°N

Threshold used to define a rainy day: 0.25 mm

Month	Mean Precipitation (mm)	Mean Number of Days With Precipitation	Mean Temperature (deg F)
Jan	38	6	79.88
Feb	16	3	80.42
Mar	17	0.5	81.68
Apr	76	5	82.22
May	198	17	80.96
Jun	203	17	80.24
Jul	183	20	80.42
Aug	190	20	80.24
Sep	193	15	79.88
Oct	254	22	79.16
Nov	249	24	79.16
Dec	130	12	79.88

Table D-2

Location name: Ubon, Thailand

Location latitude: 15.3°N

Threshold used to define a rainy day: 0.25 mm

Month	Mean Precipitation (mm)	Mean Number of Days With Precipitation	Mean Temperature (deg F)
Jan	13	0.5	76.0
Feb	12	1	78.5
Mar	20	2	84.0
Apr	102	8	84.5
May	257	14	84.5
Jun	244	18	82.5
Jul	310	20	82.0
Aug	292	21	81.0
Sep	305	20	80.5
Oct	58	7	80.0
Nov	23	2	78.0
Dec	13	0.5	75.0

Table D-3

Location name: Jackson, Mississippi

Location latitude: 32.3°N

Threshold used to define a rainy day: 0.25 mm

Month	Mean Precipitation (mm)	Mean Number of Days With Precipitation	Mean Temperature (deg F)
Jan	127	11	45.7
Feb	114	9	49.1
Mar	149	11	56.3
Apr	149	9	65.1
May	123	9	72.5
Jun	75	8	79.2
Jul	112	11	81.9
Aug	94	10	81.2
Sep	90	9	76.4
Oct	67	6	65.0
Nov	106	9	54.9
Dec	137	10	48.6

Table D-4

Location name: Bakersfield, California

Location latitude: 35.4°N

Threshold used to define a rainy day: 0.25 mm

Month	Mean Precipitation (mm)	Mean Number of Days With Precipitation	Mean Temperature (deg F)
Jan	25	6	48.2
Feb	27	6	53.2
Mar	22	7	57.1
Apr	18	4	62.7
May	6	2	70.6
Jun	1.8	1	78.3
Jul	0.3	1	84.5
Aug	1.3	1	82.4
Sep	3.3	1	77.3
Oct	7.6	2	68.0
Nov	16.5	3	56.2
Dec	16.5	5	48.2

AD-A164 097 PREDICTION OF POWER MARGINS ON SATELLITE COMMUNICATIONS 2/2
LINKS AS A FUNCTI..(U) AIR FORCE INST OF TECH
WRIGHT-PATTERSON AFB OH SCHOOL OF ENGI.. M J NAVAS
UNCLASSIFIED DEC 85 AFIT/GE/ENG/85D-29 F/G 17/2 NL

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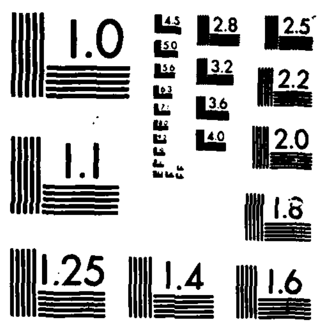


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Table D-5

Location name: Denver, Colorado

Location latitude: 39.8°N

Threshold used to define a rainy day: 0.25 mm

Month	Mean Precipitation (mm)	Mean Number of Days With Precipitation	Mean Temperature (deg F)
Jan	14	6	30.02
Feb	18	6	32.54
Mar	31	8	37.94
Apr	54	9	47.48
May	69	11	56.66
Jun	37	9	66.92
Jul	39	9	73.40
Aug	33	8	71.96
Sep	29	6	63.50
Oct	26	6	52.34
Nov	18	5	39.20
Dec	12	4	33.08

Table D-6

Location name: Indianapolis, Indiana

Location latitude: 39.7°N

Threshold used to define a rainy day: 0.25 mm

Month	Mean Precipitation (mm)	Mean Number of Days With Precipitation	Mean Temperature (deg F)
Jan	77	12	29.12
Feb	58	10	31.10
Mar	87	12	38.84
Apr	95	12	50.72
May	101	13	61.34
Jun	117	11	71.06
Jul	89	9	75.20
Aug	77	8	73.76
Sep	82	7	66.56
Oct	67	8	55.40
Nov	78	10	40.82
Dec	68	10	31.10

Table D-7

Location name: Saarbrucken, West Germany

Location latitude: 49.2°N

Threshold used to define a rainy day: 0.1 mm

Month	Mean Precipitation (mm)	Mean Number of Days With Precipitation	Mean Temperature (deg F)
Jan	72	17.5	32.1
Feb	64	15.9	35.3
Mar	54	14.8	39.9
Apr	63	15.1	48.3
May	76	14.2	54.8
Jun	82	13.8	60.1
Jul	66	12.6	62.8
Aug	99	14.8	62.3
Sep	69	11.5	58.0
Oct	55	11.3	50.4
Nov	88	12.7	40.1
Dec	77	12.0	32.0

Table D-8

Location name: Clearwater, Washington

Location latitude: 47.6°N

Threshold used to define a rainy day: 0.25 mm

Month	Mean Precipitation (mm)	Mean Number of Days With Precipitation	Mean Temperature (deg F)
Jan	383	23	39.0
Feb	307	20	41.7
Mar	286	21	42.2
Apr	180	19	46.0
May	119	16	51.0
Jun	78	15	55.1
Jul	59	12	59.0
Aug	72	11	59.2
Sep	134	13	56.8
Oct	267	18	50.4
Nov	354	22	43.8
Dec	414	24	40.8

Table D-9

Location name: Anchorage, Alaska

Location latitude: 61.2°N

Threshold used to define a rainy day: 0.25 mm

Month	Mean Precipitation (mm)	Mean Number of Days With Precipitation	Mean Temperature (deg F)
Jan	20	7	12.38
Feb	18	6	17.96
Mar	13	7	23.36
Apr	11	4	35.78
May	13	5	45.86
Jun	25	7	54.50
Jul	47	11	57.02
Aug	65	15	55.58
Sep	64	15	47.84
Oct	47	11	35.06
Nov	26	8	22.28
Dec	24	7	14.36

Table D-10

Location name: Fairbanks, Alaska

Location latitude: 64.8°N

Threshold used to define a rainy day: 0.25 mm

Month	Mean Precipitation (mm)	Mean Number of Days With Precipitation	Mean Temperature (deg F)
Jan	23	9	-11.02
Feb	13	7	-2.29
Mar	10	7	8.96
Apr	6	4	29.48
May	18	8	47.12
Jun	35	11	58.46
Jul	47	13	59.72
Aug	56	15	54.32
Sep	28	10	43.52
Oct	22	11	26.24
Nov	15	9	3.92
Dec	14	8	-7.78

APPENDIX E

GRAPHS OF ONE-MINUTE RAIN RATES VS PERCENT OF TIME EXCEEDED FROM THE DAVIS-MCMORROW MODEL FOR 10 LOCATIONS

(Source: ETAC)

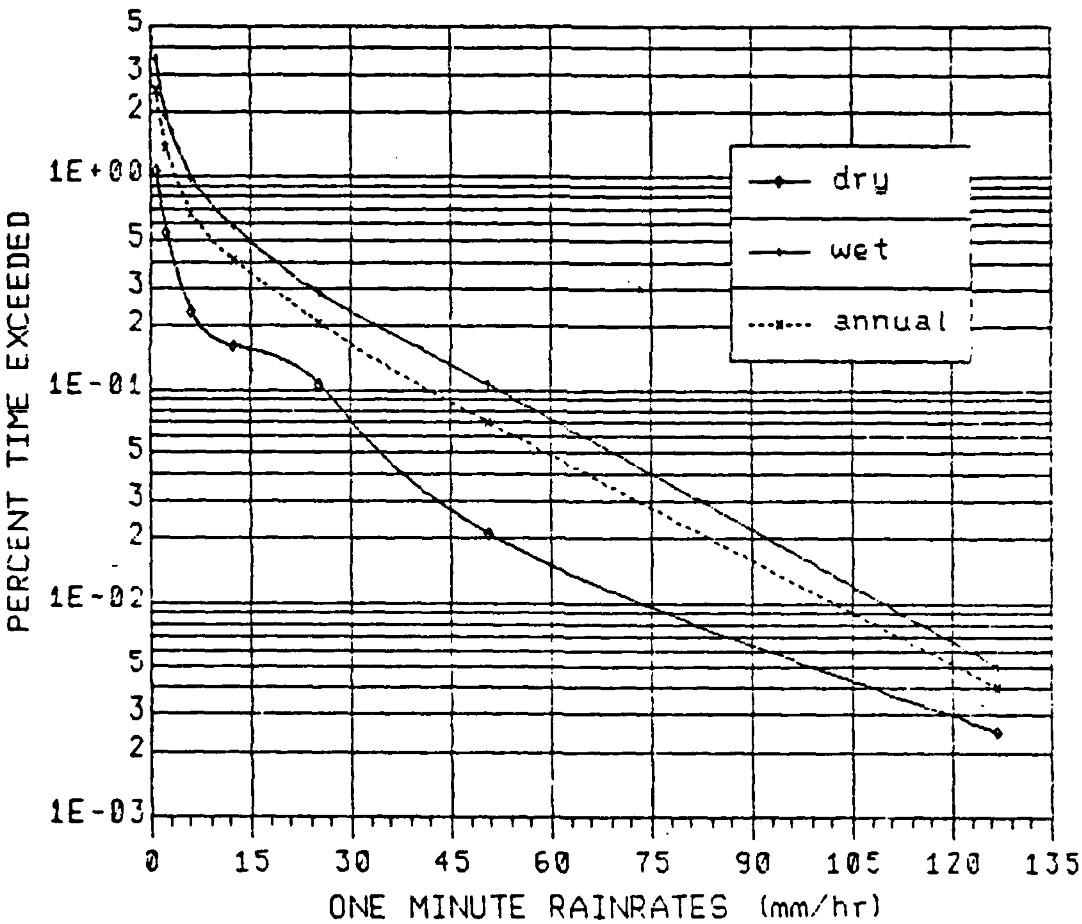


Figure E-1: Balboa Heights, Panama

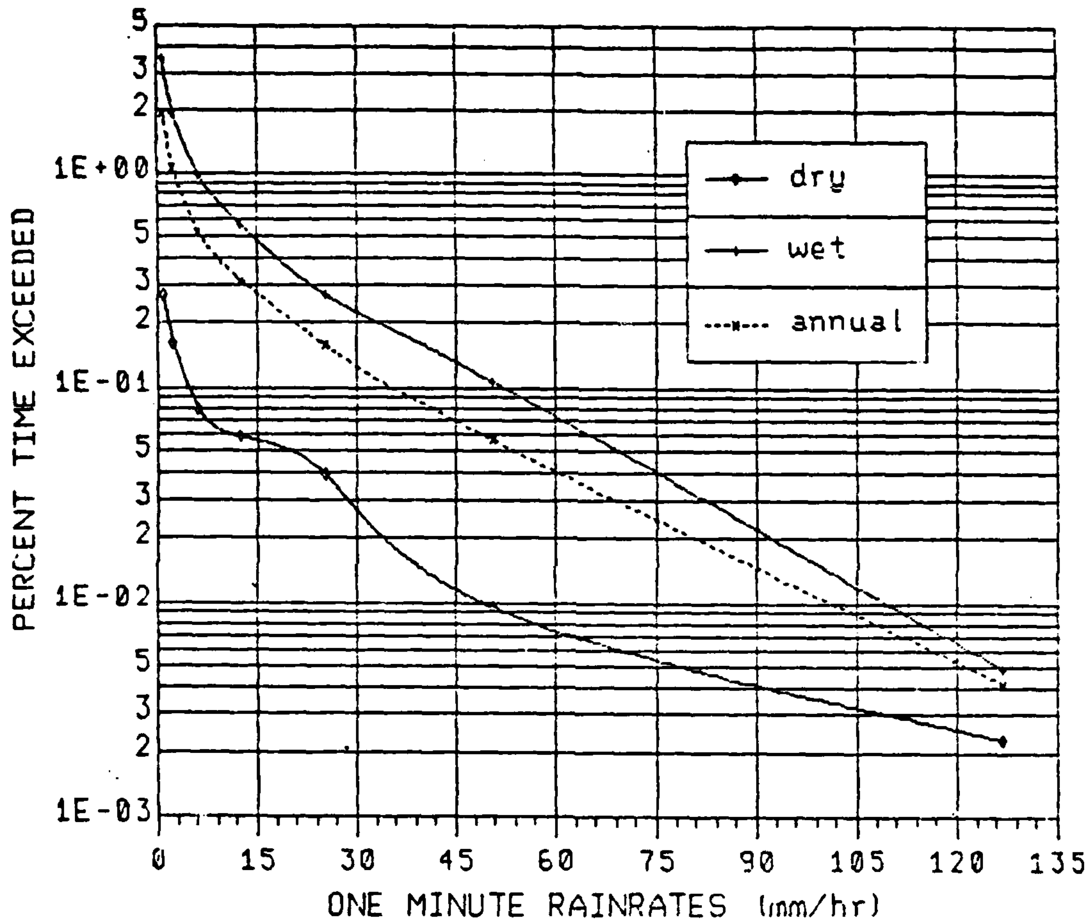


Figure E-2: Ubon, Thailand

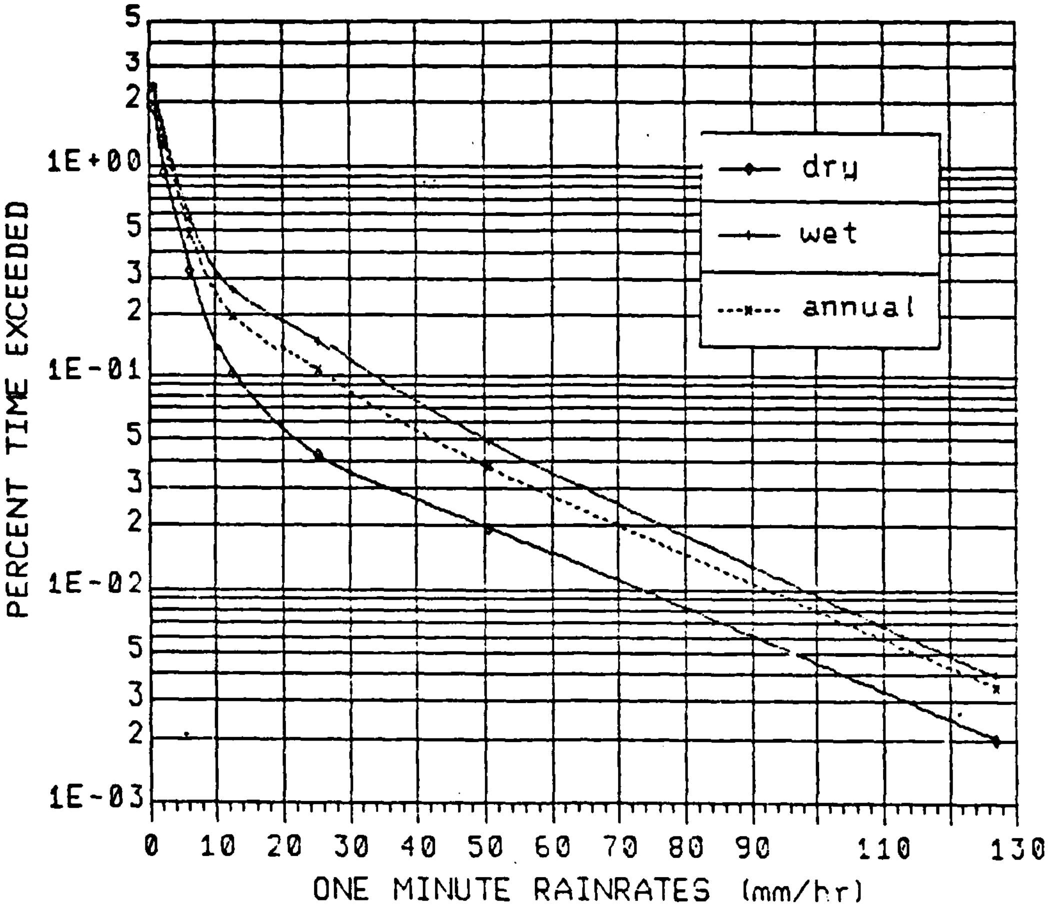


Figure E-3: Jackson, Mississippi

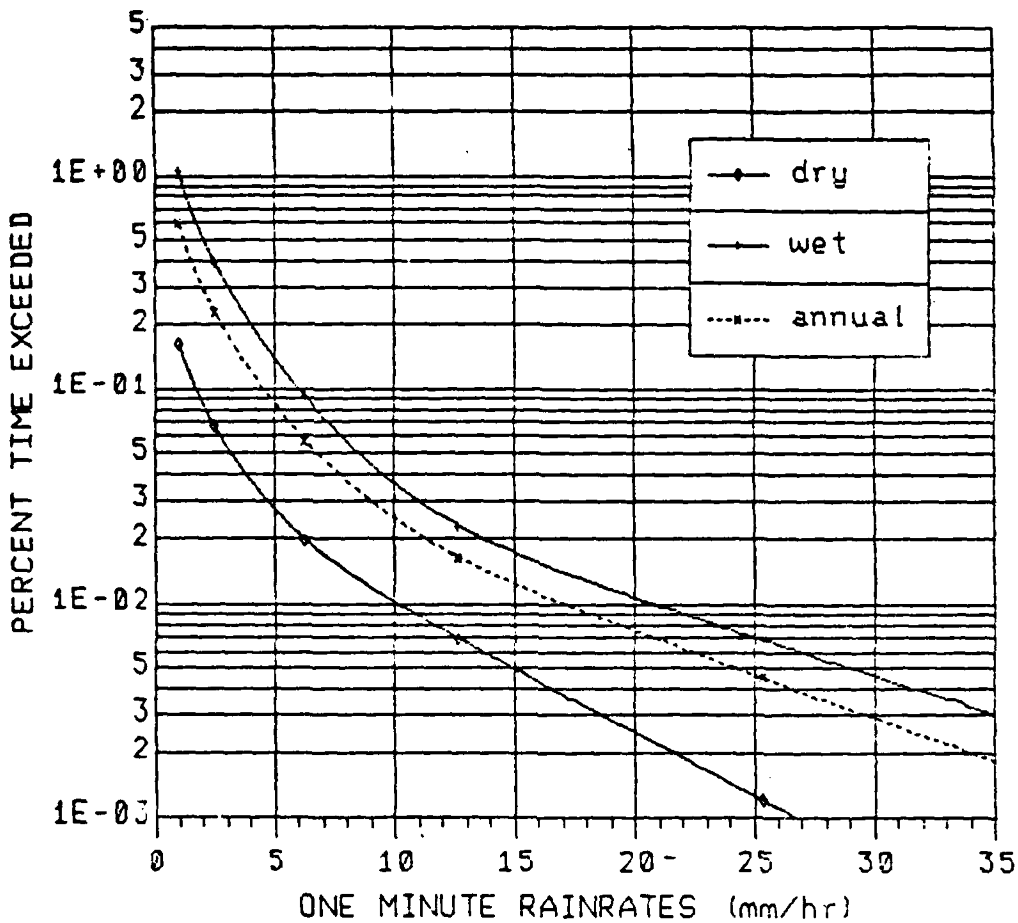


Figure E-4: Bakersfield, California

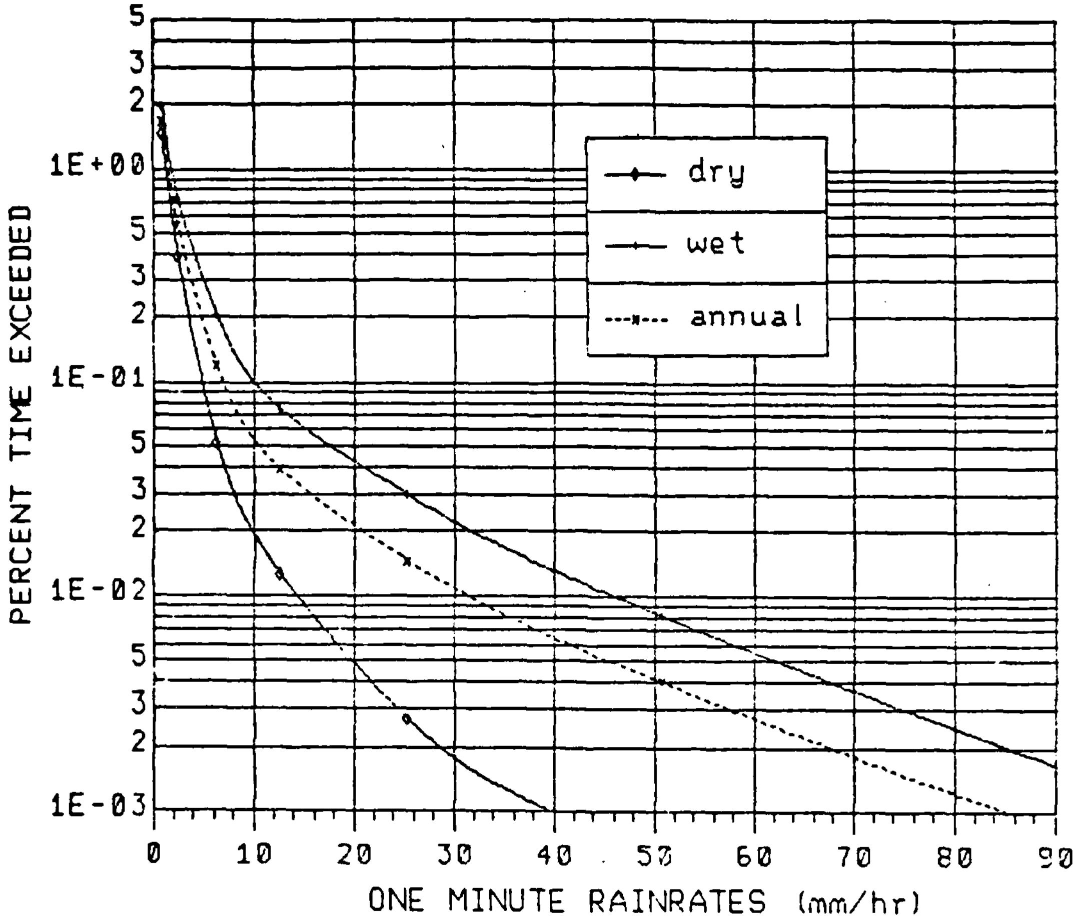


Figure E-5: Denver, Colorado

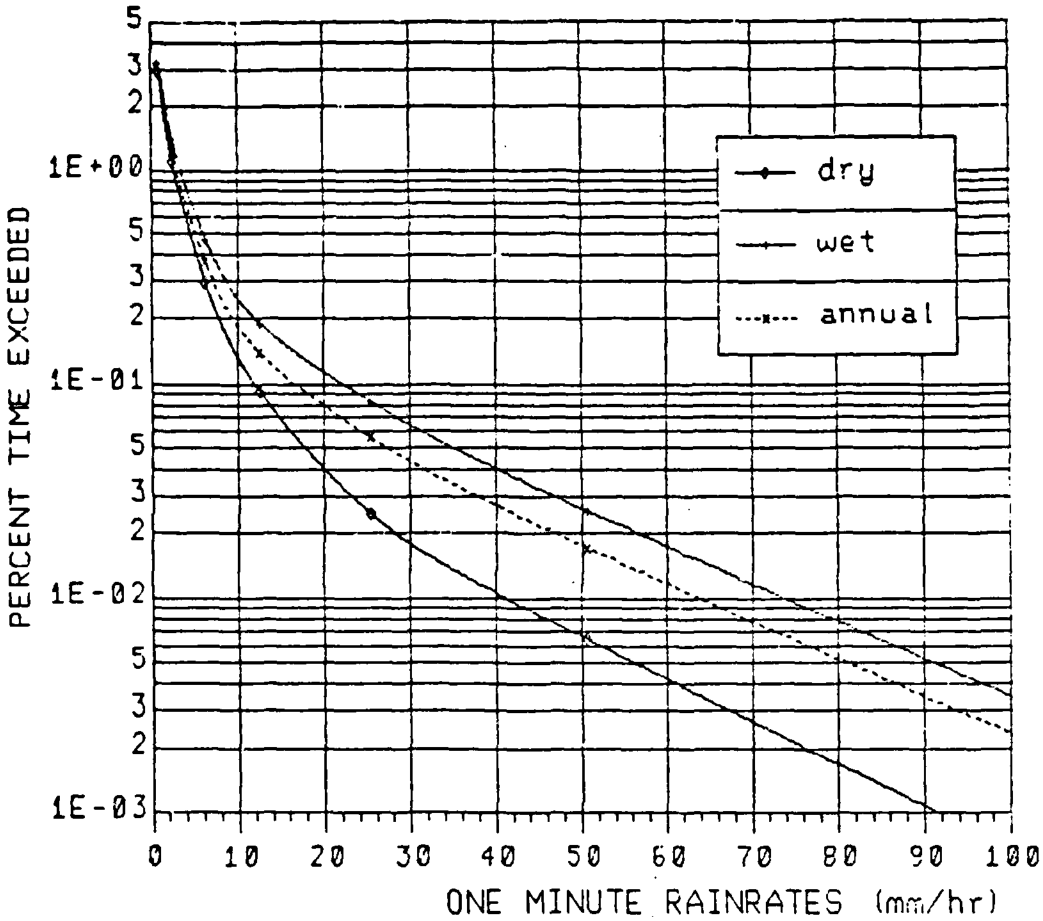


Figure E-6: Indianapolis, Indiana

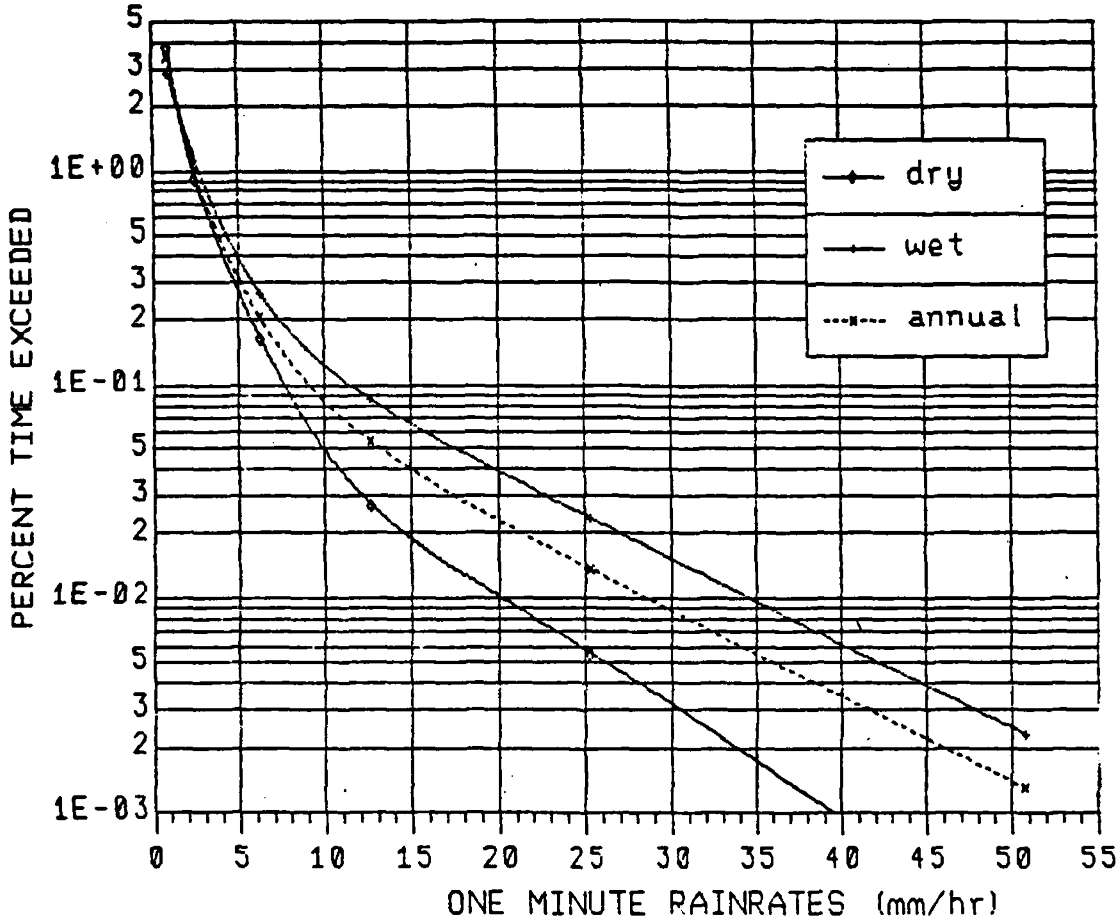


Figure E-7: Saarbrucken, West Germany

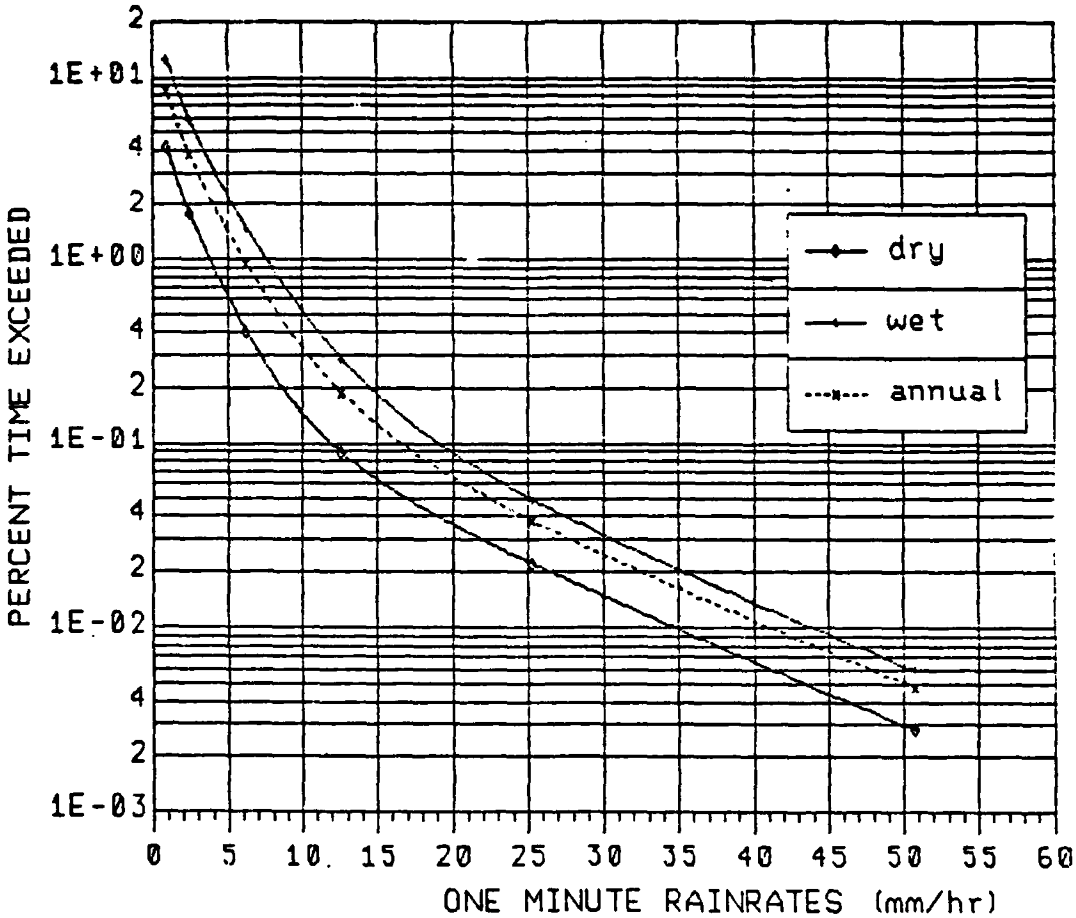


Figure E-8: Clearwater, Washington

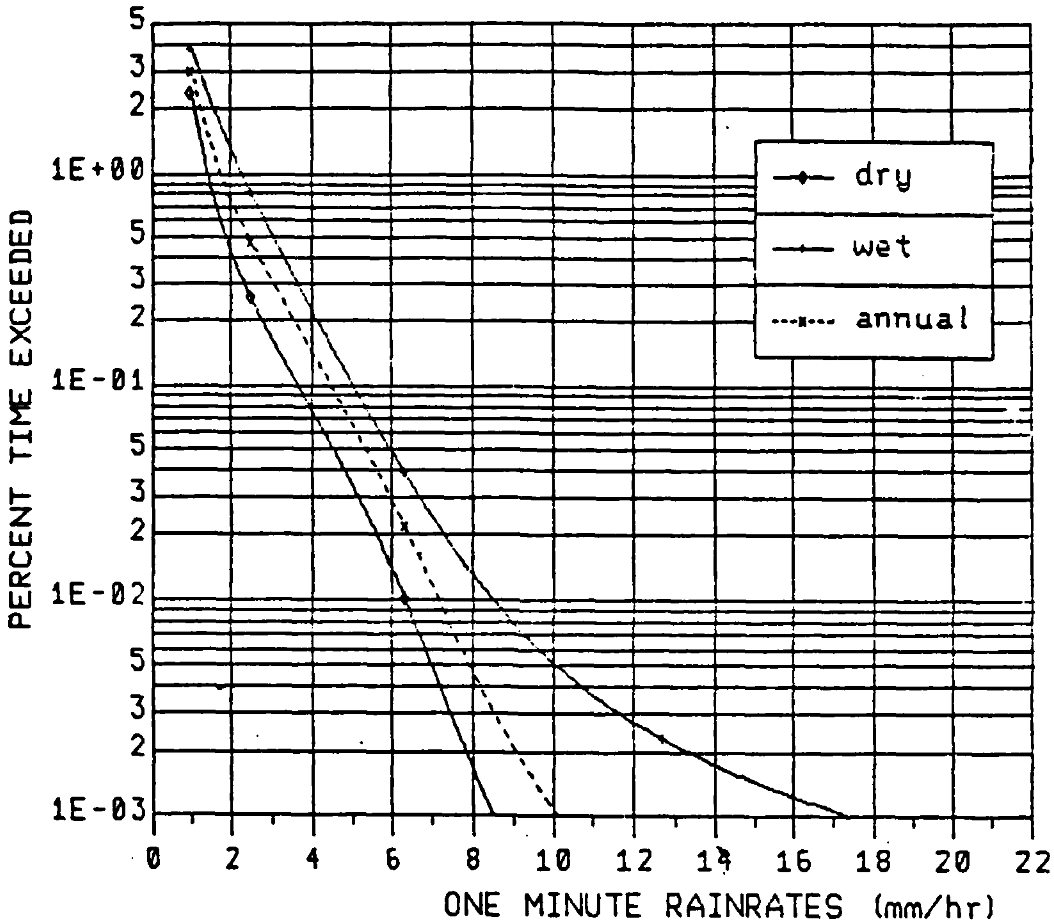


Figure E-9: Anchorage, Alaska

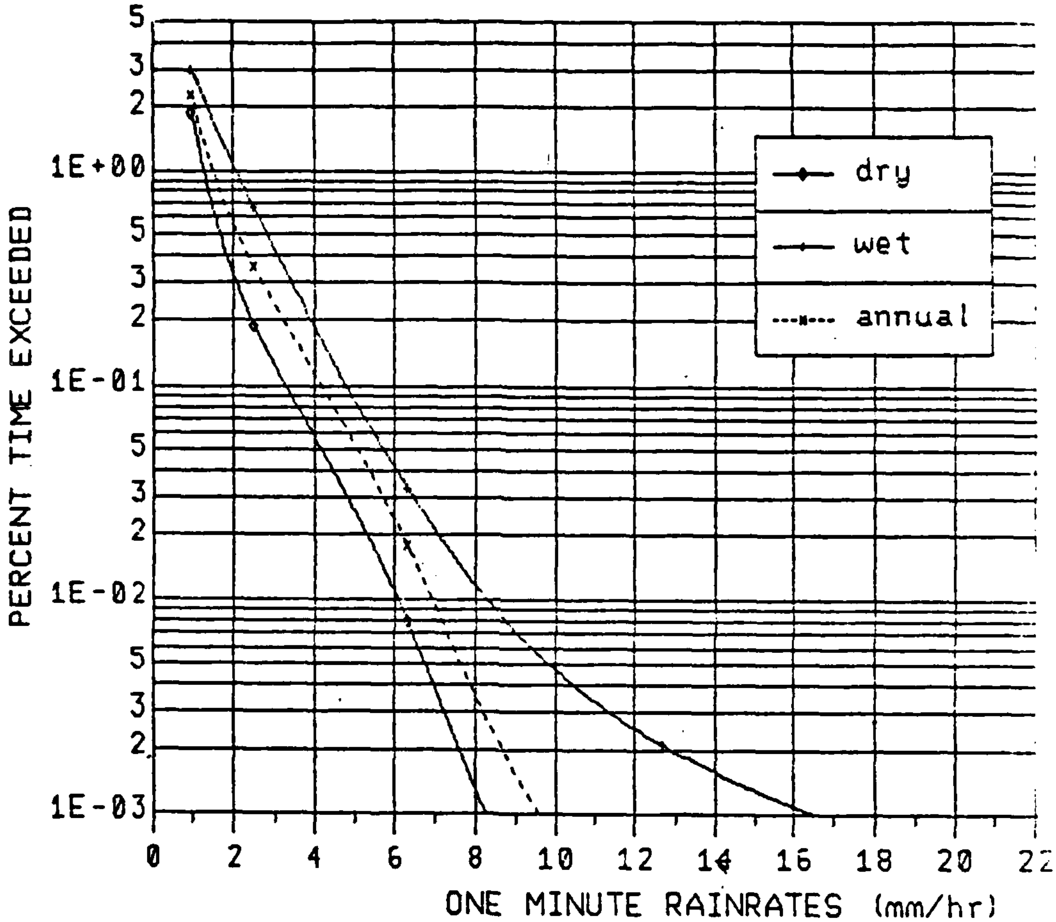


Figure E-10: Fairbanks, Alaska

APPENDIX F

PROGRAM TO COMPUTE RAIN RATES EXCEEDED A PERCENTAGE OF A YEAR USING THE TATTELMAN-SCHARR MONTHLY RAIN RATE MODEL

Introduction

This appendix presents a program that computes the rain rate exceeded a given percentage of the year. The program achieves this by applying the Tattelman-Scharr monthly rain rate model on an annual basis. The basic theory behind the application is presented in Section III of this thesis. This appendix contains two parts: first, a user's manual and, second, the source code of the program.

User's Manual

General Information.

This user's manual describes how the program accomplishes the task of applying a monthly rain rate model on an annual basis. The manual is divided into seven subsections:

- General Information
- Program Algorithm
- Illustration of the Adjustment Process
- Special Mechanisms
- Monthly Rain Rate Distribution
- Testing the Monthly Rain Rates
- Program Documentation

The program was written in Microsoft Basic and has been checked out on two microcomputers: the Zenith Z-100 in both compiled and interpreted form and the Sanyo MBC-550, interpreted only. Both machines were using MS-DOS 2.11 operating systems.

Throughout the manual the term "percentage level" is used. It refers to the discrete percentages of a month that are used to calculate monthly rain rates. These percentage levels are fixed, and the monthly rain rate model is bound to these levels.

Program Algorithm.

Figure F-1 shows the flow graph of this program. The program begins by prompting the user to enter the following information:

- Location latitude
- Polar climate? (yes or no)
- Threshold used to define a rainy day
- Average monthly temperature for each of 12 months
- Average number of rainy days for each of 12 months
- Average monthly precipitation for each of 12 months
- The allowable percent of outage time for the communications link due to rain

The program loads the applicable coefficients of the

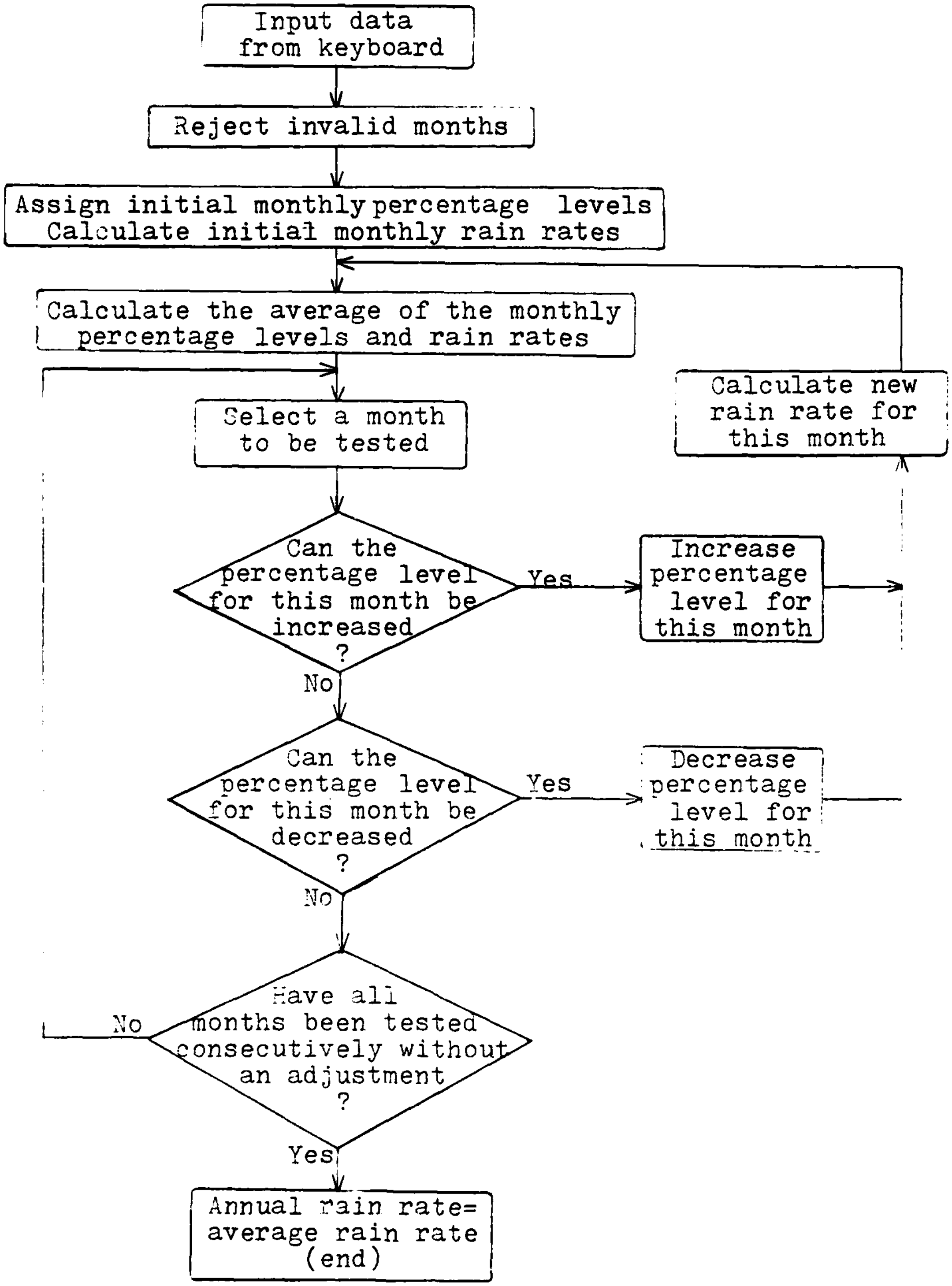


Figure F-1. Program flowchart.

Tattelman-Scharr equation (depending on the threshold) and other array constants. Then the information that was entered is scanned to determine whether this is a polar climate or if none of the months meets the four minimum conditions of temperature, precipitation index, number of rainy days, and precipitation required. In either case, the rainiest month is found, and the annual rain rate is based on this one month. If neither is the case, any months which do not meet the four minimum conditions are found and rejected. Each of the remaining months are then assigned an initial percentage level which is the closest percentage level to the allowable percent of outage time. Initial monthly rain rates are computed using the model equation at these initial percentage levels. Then the averages of the monthly percentage levels and rain rates are calculated. The percentage levels are averaged over the entire year, that is, each is divided by 12 then summed whereas each rain rate is divided by the number of months not rejected and then summed. The program then enters the adjustment loop. Here each individual rain rate and the average percentage level are tested to determine if the percentage level for that particular month should be adjusted. This is done one month at a time. An adjustment to the month being tested can be made if one of two conditions exists:

1) Its rain rate is above the average rain rate and the average percentage level is less than or equal to the allow-

able percent of outage time, or

2) Its rain rate is below the average rain rate and the average percentage level is greater than or equal to the allowable percent of outage time.

If condition 1 exists the percentage level for this month is increased to the next higher percentage level causing the rain rate to decrease while the average percentage level increases slightly. If condition 2 exists it is decreased to the next lower level causing its rain rate to increase and the average percentage level to decrease slightly. The new rain rate for this month is calculated using the model equation (1) or, if the percentage level is below 0.01%, the extension equation (4). New averages for percentage levels and rain rates are then determined, and, following this, the next month is tested. If neither condition 1 nor 2 exists, the program tests whether all months have been consecutively tested without an adjustment. If not, the next month is tested. If so, the program is finished, and the annual rain rate is the last computed value of the average rain rate. The rain rate is multiplied by 60 to give units of mm/hour. In addition to this annual rain rate, the program displays the rain rate for each month not rejected along with the percentage level used to compute it.

<u>Illustration of the Adjustment Process.</u>

This process of small adjustments can be visualized with the use of Figure F-2. This figure shows an example of

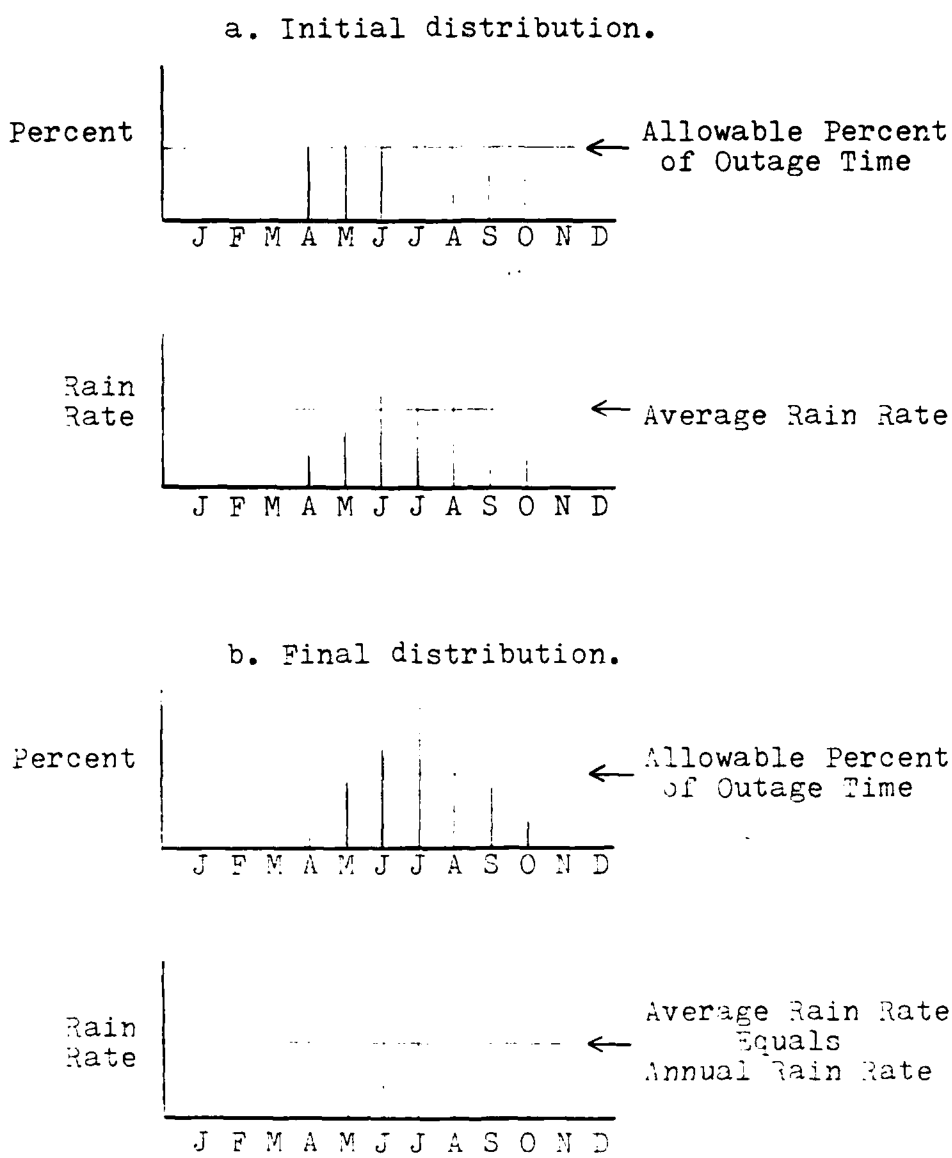


Figure F-2. Monthly distribution of percents and rain rates.

how the monthly percents and rain rates might be distributed for a location where seven months, April through October (each month abbreviated by its first letter), met the minimum conditions. Initially, each monthly percent is set at the level closest to the allowable percent of outage time (Figure F-2a). The initial rain rate distribution shows that the relatively rainy months of June, July, and August are above the average rain rate while the other, less rainy months are below the average. During the program, each monthly percentage level is adjusted one step at a time so that its rain rate moves toward the average. A new average rain rate is determined after each adjustment. An increase in one month's percentage results in a decrease in the rain rate for that month, and a decrease in the percentage results in an increase in the rain rate. A percent is adjusted a step higher only if the average percents of all 12 months (in this case five months have percents constantly equal to zero) is below or equal to the allowable percent of outage time. The converse is true for a step lower. The program ends when all the monthly rain rates are the same (Figure F-2b). The last average rain rate is the product of the program, that is, the annual rain rate exceeded the percent of time equal to the allowable percent of outage time.

Special Mechanisms.

The program contains several special mechanisms.

Because the percentage levels are in discrete steps, the rain rates for all months will seldom equal the average rain rate exactly. To prevent an infinite loop situation of rain rates and percentage levels oscillating about their averages, a "tolerance" is added to the average rain rate in condition 1 and subtracted from the average rain rate in condition 2. The tolerance is zero until 20 adjustments have been made and then increases slowly. This allows the average rain rate to converge to its optimum value and allows the monthly rain rates to approach as close to the average as possible. Another feature is a test for either a negative rain rate or an increasing rain rate with a increasing percentage level (anomalies mentioned in Section III). These tests are performed after any adjustment. Either anomaly will cause the month to be rejected.

Because some months are larger than others each month is weighted by its relative size in the computation of the average percentage level. For example, the percentage level for July with 31 days is weighted by 31/365 instead of being weighted simply by 1/12. Another point is that the percentage levels are converted into integers because the intervals between these levels are not equal. There are a total of 31 percentage levels ranging from 0.001% to 2.0%. The lowest percentage level is converted to 1, the next lowest is 2, and so on to where the highest level is 31. This conversion makes it possible for any adjustment to be either +1 or -1.

These integers are converted back into their respective percentage values when computing the average percentage level.

Monthly Rain Rate Distribution.

As noted above, the individual monthly rain rates will rarely equal the average rain rate exactly, however they will be close. Table F-1 shows the monthly rain rate distribution for an allowable percent outage time of 0.01% at Indianapolis, Indiana. The climatic data used here is tabulated in Appendix D. The average percentage is actually 0.0103%. This is because the model uses only discrete values for percentage levels. However, the method used to test if an adjustment can be made guarantees that this

Table F-1. Monthly distribution of percentage levels and rain rates for an allowable percent of outage time of 0.01% at Indianapolis, Indiana. Average rain rate=50.8 mm/hr.

Month	Rain Rate(mm/hr)	Percentage Level(%)
Apr	48.9	0.0025
May	49.0	0.01
Jun	49.1	0.03
Jul	51.4	0.03
Aug	53.7	0.025
Sep	55.2	0.02
Oct	48.0	0.006

average will be very close to the desired allowable percent of outage time. An advantage is that the allowable percent of outage time is not bound to these same discrete levels. Any percent can be used. The average percentage will always approach it. At the end of the program the actual percentage will be displayed with the rain rate.

Testing the Monthly Rain Rates.

The validity of the monthly rain rates can be tested by applying the basic Tattelman-Scharr equation (1) for each of the months. For example, the rain rate for June in Table F-1 was calculated using the coefficients at a percentage level of 0.03%. The threshold used to define a rainy day at Indianapolis is 0.25 mm. Therefore, the coefficients in Table B-3 are used giving:

$$A = -0.70$$

$$B = 0.020$$

$$C = 0.034$$

$$D = -0.00023$$

The climatic data for June at Indianapolis is found in Table D-6:

$$T = 71.06^{\circ}F$$

$$I = 117/11 = 10.64 \text{ mm/day}$$

$$F = (39.7 - 23.5) \times 71.06 = 1151.2$$

Using the Tattelman-Scharr equation

$$R_p = A + BT + CI + DF(L,T)$$

$$R_{0.03} = -0.70 + 0.020 \times 71.06 + 0.034 \times 10.64 - 0.00023 \times 1151.2$$

$$= 0.818 \text{ mm/min}$$

$$= 49.1 \text{ mm/hr}$$

Program Documentation.

The first 31 statements of the program contain comments that define the variables used throughout the program. The arrays are defined first followed by non-array "other" variables. The program contains many other comments. Each is preceeded by an apostrophe and three asterisks ('***). These comments describe the operations immediatly following them.

Program Source Code

```
10 '*** PROGRAM TO COMPUTE ANNUAL 1-MIN RAIN RATES AS A
        FUNCTION OF A DESIRED PERCENTAGE OF TIME EXCEEDED
        USING THE TATTELMAN-SCHARR MONTHLY MODEL
20 '*** This program is written in Microsoft Basic
30 '*** DEFINITION OF ARRAY VARIABLES:
40 ' * A,B,C,D=T-S equation coefficients
50 ' * T=Temperature
```

```
60 ' * ND=Number of rainy days
70 ' * PR=Mean precipitation
80 ' * I=Precipitation index (PR/ND)
90 ' * F=Latitude factor
100 '* RR=Rain rate for one month
110 '* P=Percent of time exceeded in one month
120 '* PL=Percentage level, the integer conversion of P
130 '* MO$=Month name
140 '* WT=Weight for each month, ie, the number of days in
       each month divided by 365 days in a year
150 '
160 '***DEFINITION OF OTHER VARIABLES:
170 '* Q=Counter for adjustment loop
180 '* X=Number of months not yet rejected
190 '* Z=Counter for no-adjustment loop
200 '* L$=Location name
210 '* THLD=Threshold used to define a rainy day
220 '* TOL=Tolerance to decide on RR adjustment
230 '* AVL=Required link unavailability
240 '* CAVL=Compensated availability used to set PIN close
       to the annual availability
250 '* NM=Counter used in testing if no months meet minimum
       climatic conditions
260 '* RRA=Rain rate at P=0.01%
270 '* RRE=Rain rate at P=0.05%
280 '* PIN=Initial percent levels
```

```
290 '* PAVG=Average of the monthly percentages
300 '* RRAVG=Average of the monthly rain rates
310 '* RRTEMP=Temporary storage of the rain rate to be
      compared with new rate
320 DIM A(25),B(25),C(25),D(25),T(12),ND(12),PR(12),I(12),
    F(12),RR(12),PL(12),P(35),MO$(12),WT(12):CLS
330 '*** Enter data from keyboard
340 INPUT "Enter location name: ",L$
350 PRINT:INPUT "Enter location latitude: ",LAT
360 PRINT:INPUT "Enter the specified value of link
    unavailability (percent): ",AVL
370 PRINT:INPUT "Does this location have a polar climate?
    (Y or N): ",YN$
380 PRINT:INPUT "Enter threshold used to define a rainy
    day (2.54mm, 1.0mm, or .25mm): ",THLD
390 IF THLD=1! GOTO 550
400 IF THLD=.25 GOTO 680
410 IF THLD<>2.54 GOTO 380
420 FOR K=1 TO 21:READ A(K):NEXT
430 '*** Load Tattelman-Scharr coefficients
440 DATA -.91,-.81,-.73,-.67,-.63,-.55,-.50,-.45,-.41,-.37,
    -.31,-.26,-.21,-.15,-.11,-.08,-.03,-.01,.01,.03,.04
450 RESTORE 470
460 FOR K=1 TO 21:READ B(K):NEXT
470 DATA .028,.025,.023,.021,.02,.018,.016,.0145,.0135,
    .0125, .011,.01,.0085,.0067,.0055,.0046,.0033,.0025,
```

```
     .0014,.00074,-.0002
480 RESTORE 500
490 FOR K=1 TO 21:READ C(K):NEXT
500 DATA .023,.0225,.0222,.0217,.021,.020,.019,.018,.017,
     .016,.014,.0125,.011,.0095,.0084,.0077,.0064,.0054,
     .0042,.0029,.0015
510 RESTORE 530
520 FOR K=1 TO 21:READ D(K):NEXT
530 DATA -.00034,-.00033,-.000323,-.00032,-.000317,-.00031,
     -.00031,-.000308,-.000305,-.000303,-.0003,-.000293,
     -.00028,-.00027,-.00025,-.00023,-.00019,-.00015,
     -.00011,-.000076,-.000032
540 GOTO 810
550 RESTORE 570
560 FOR K=1 TO 21:READ A(K):NEXT
570 DATA -1.0,-.89,-.81,-.75,-.7,-.62,-.56,-.51,-.46,-.42,
     -.36,-.31,-.26,-.19,-.15,-.11,-.06,-.03,-.01,.02,.04
580 RESTORE 600
590 FOR K=1 TO 21:READ B(K):NEXT
600 DATA .028,.025,.023,.021,.02,.018,.016,.015,.0135,
     .0125,.011,.01,.0085,.0067,.0055,.0045,.0032,.0024,
     .0014,.00069,-.00018
610 RESTORE 630
620 FOR K=1 TO 21:READ C(K):NEXT
630 DATA .036,.033,.031,.0297,.0285,.0265,.025,.0237,
     .0225,.0216,.02,.0187,.017,.015,.013,.0115,.0094,.0078,
```

```
.0057,.0042,.002
640 RESTORE 660
650 FOR K=1 TO 21:READ D(K):NEXT
660 DATA -.00022,-.000227,-.000232,-.000233,-.000237,
    -.00024,-.00024,-.000242,-.00024,-.000242,-.00024,
    -.000233,-.000225,-.00021,-.000193,-.000175,-.000145,
    -.00012,-.000088,-.000062,-.000026
670 GOTO 810
680 RESTORE 700
690 FOR K=1 TO 21:READ A(K):NEXT
700 DATA -1,-.89,-.81,-.75,-.7,-.62,-.56,-.51,-.47,-.43,
    -.36,-.31,-.26,-.19,-.14,-.1,-.06,-.03,-.01,.01,.03
710 RESTORE 730
720 FOR K=1 TO 21:READ B(K):NEXT
730 DATA .028,.025,.023,.021,.02,.0177,.016,.0145,.0135,
    .0125,.011,.010, .0084,.0066,.0053,.0043,.0032,.0023,
    .0013,.00056,-.00023
740 RESTORE 760
750 FOR K=1 TO 21:READ C(K):NEXT
760 DATA .042,.039,.037,.036,.034,.032,.03,.028,.027,.026,
    .024,.022,.02,.017,.015,.014,.012,.01,.008,.006,.0028
770 RESTORE 790
780 FOR K=1 TO 21:READ D(K):NEXT
790 DATA -.00022,-.00022,-.000225,-.000225,-.00023,
    -.00023,-.00023,-.00023,-.00023,-.00023,-.00023,
    -.000226,-.00022,-.000205,-.00019,-.00018,-.00015,
```

```
-.00012,-.000083,-.000056,-.000024
800 '*** Load discrete percentage levels, month weightings,
    and month names
810 RESTORE 830
820 FOR K=1 TO 31:READ P(K):NEXT
830 DATA .001,.0015,.002,.0025,.003,.004,.005,.006,.007,
    .008,.01,.015,.02,.025,.03,.04,.05,.06,.07,.08,.1,.12,
    .15,.2,.25,.3,.4,.5,.7,1.0,2.0
840 RESTORE 860
850 FOR K=1 TO 12:READ WT(K):NEXT
860 DATA .08493,.07671,.08493,.08219,.08493,.08219,.08493,
    .08493,.08219,.08493,.08219,.08493
870 FOR K=1 TO 12:READ MO$(K):NEXT
880 DATA "Jan","Feb","Mar","Apr","May","Jun","Jul","Aug",
    "Sep","Oct","Nov","Dec"
890 '*** Enter climatic data from keyboard
900 PRINT:PRINT "Enter mean monthly temperature (degrees F)"
910 INPUT; "     Jan: ",T(1):INPUT; "     Feb: ",T(2)
920 INPUT; "     Mar: ",T(3):INPUT "     Apr: ",T(4)
930 INPUT; "     May: ",T(5):INPUT; "     Jun: ",T(6)
940 INPUT; "     Jul: ",T(7):INPUT "     Aug: ",T(8)
950 INPUT; "     Sep: ",T(9):INPUT; "     Oct: ",T(10)
960 INPUT; "     Nov: ",T(11):INPUT "     Dec: ",T(12)
970 PRINT:PRINT "Enter mean number of rainy days per month"
980 INPUT; "     Jan: ",ND(1):INPUT; "     Feb: ",ND(2)
990 INPUT; "     Mar: ",ND(3):INPUT "     Apr: ",ND(4)
```

```
1000 INPUT; "     May: ",ND(5):INPUT; "     Jun: ",ND(6)
1010 INPUT; "     Jul: ",ND(7):INPUT "     Aug: ",ND(8)
1020 INPUT; "     Sep: ",ND(9):INPUT; "     Oct: ",ND(10)
1030 INPUT; "     Nov: ",ND(11):INPUT "     Dec: ",ND(12)
1040 PRINT:PRINT "Enter mean monthly precipitation (mm)"
1050 INPUT; "     Jan: ",PR(1):INPUT; "     Feb: ",PR(2)
1060 INPUT; "     Mar: ",PR(3):INPUT "     Apr: ",PR(4)
1070 INPUT; "     May: ",PR(5):INPUT; "     Jun: ",PR(6)
1080 INPUT; "     Jul: ",PR(7):INPUT "     Aug: ",PR(8)
1090 INPUT; "     Sep: ",PR(9):INPUT; "     Oct: ",PR(10)
1100 INPUT; "     Nov: ",PR(11):INPUT "     Dec: ",PR(12)
1110 '*** Calculate I's and F's for each month
1120 FOR K=1 TO 12:IF ND(K)=0 THEN ND(K)=1
1130 NEXT K
1140 FOR K=1 TO 12:I(K)=PR(K)/ND(K):NEXT K
1150 FOR K=1 TO 12:IF LAT>23.5 THEN F(K)=(LAT-23.5)*T(K):
     IF LAT>40 THEN F(K)=16.5*T(K)
1160 NEXT
1170 '*** Test for polar climate
1180 IF YN$="Y" OR YN$="y" GOTO 1240
1190 '*** Test if no month meets minimum climatic conditions
1200 FOR K=1 TO 12:IF I(K)<3 OR T(K)<=32 OR PR(K)<20
     OR ND(K)<=2 THEN NM=NM+1
1210 NEXT
1220 IF NM<12 GOTO 1300
1230 '*** Find the rainiest month
```

```
1240 X=1
1250 FOR K=2 TO 12
1260 IF PR(K)>PR(1) THEN PR(1)=PR(K):I(1)=I(K):T(1)=T(K):
     F(1)=F(K):MO$(1)=MO$(K):WT(1)=WT(K)
1270 NEXT
1280 GOTO 1440
1290 '*** Set initial tolerance
1300 Y=0
1310 X=12
1320 '*** Test for extreme climatic data
1330 FOR K=1 TO 12
1340 IF T(K)<=32 OR PR(K)<20 OR I(K)<3 OR ND(K)<=2
     GOTO 1370 ELSE NEXT K
1350 GOTO 1440
1360 '*** Reject months which don't meet minimum conditions
1370 IF K=X THEN X=X-1:GOTO 1440 ELSE J=K
1380 Q=J+1:IF K=12 GOTO 1420
1390 T(J)=T(Q):ND(J)=ND(Q):I(J)=I(Q):PR(J)=PR(Q):F(J)=F(Q):
     MO$(J)=MO$(Q):WT(J)=WT(Q)
1400 J=J+1
1410 IF J<>12 GOTO 1380
1420 X=X-1:IF X>=K GOTO 1340 ELSE
1430 '*** Average the unavailability over the number of
     months not rejected
1440 CAVL=AVL*12/X
1450 '*** Convert unavailability into an integer
```

```
1460 IF CAVL>=.009 THEN PIN=11:IF CAVL>=.0125 THEN PIN=12:
     IF CAVL>=.0175 THEN PIN=13:IF CAVL>=.0225 THEN PIN=14:
     IF CAVL>=.0275 THEN PIN=15:IF CAVL>=.035 THEN PIN=16:
     IF CAVL>=.045 THEN PIN=17
1470 IF CAVL>=.055 THEN PIN=18:IF CAVL>=.066 THEN PIN=19:
     IF CAVL>=.075 THEN PIN=20:IF CAVL>=.09 THEN PIN=21:
     IF CAVL>=.11 THEN PIN=22:IF CAVL>=.135 THEN PIN=23
1480 IF CAVL>=.175 THEN PIN=24:IF CAVL>=.225 THEN PIN=25:
     IF CAVL>=.275 THEN PIN=26:IF CAVL>=.35 THEN PIN=27:
     IF CAVL>=.45 THEN PIN=28:IF CAVL>=.6 THEN PIN=29:
     IF CAVL>=.85 THEN PIN=30:IF CAVL>=1.5 THEN PIN=31
1490 '*** Set initial monthly percent levels
1500 FOR K=1 TO X
1510 PL(K)=PIN
1520 NEXT K
1530 '*** Set initial rain rates
1540 FOR K=1 TO X:PL=PL(K)-10
1550 RR(K)=A(PL)+B(PL)*T(K)+C(PL)*I(K)+D(PL)*F(K):NEXT K
1560 '*** Initialize counters
1570 Z=0:Q=0:S=0:V=0:W=0:J=0
1580 '*** Calculate the average of the monthly percentages
1590 PAVG=0
1600 FOR H=1 TO X:PL=PL(H)
1610 PAVG=PAVG+P(PL)*WT(H)
1620 NEXT H
1630 '*** Calculate the average of the monthly rain rates
```

```
1640 RRSUM=0
1650 FOR H=1 TO X
1660 RRSUM=RRSUM+RR(H)
1670 NEXT H
1680 RRAVG=RRSUM/X
1690 '*** Program is finished if only one month left
1700 IF X=1 GOTO 2210
1710 '*** Increment or reset month index J
1720 IF J>=X THEN J=1 ELSE J=J+1
1730 '*** Test if adjustment can be made
1740 IF RR(J)>(RRAVG+TOL) AND PAVG<=AVL GOTO 1800
1750 IF RR(J)<(RRAVG-TOL) AND PAVG>=AVL GOTO 1950
1760 '*** Adjustment can't be made; try next month
1770 Z=Z+1
1780 IF Z>=X GOTO 2210 ELSE GOTO 1720
1790 '*** Adjustment can be made; test if this month has
     reached max percent
1800 IF PL(J)=31 GOTO 1770
1810 '*** If not, store current rain rate
1820 RRTEMP=RR(J)
1830 '*** Increase the percent level
1840 PL(J)=PL(J)+1:Z=0:PP=PL(J):PL=PL(J)-10
1850 '*** Branch to extension if percentage is <0.01%
1860 IF PL(J)<=10 GOTO 1900
1870 '*** Calculate the new rain rate using T-S equation
1880 RR(J)=A(PL)+B(PL)*T(J)+C(PL)*I(J)+D(PL)*F(J):GOTO 1930
```

```
1890 '*** Calculate new rain rate using extension
1900 RRA=A(1)+B(1)*T(J)+C(1)*I(J)+D(1)*F(J):
     RRE=A(7)+B(7)*T(J)+C(7)*I(J)+D(7)*F(J):PT=P(PP)
1910 RR(J)=RRA+(RRE-RRA)*1.43068*(LOG(PT)*.43429+2)
1920 '*** Test if the new rain rate increased
1930 IF RR(J)-RRTEMP>0 THEN W=W+1:GOTO 2150 ELSE GOTO 2100
1940 '*** Test if this month has reached minimum percentage
1950 IF PL(J)=1 THEN V=V+1:GOTO 2150 ELSE
1960 '*** If not, store the current rain rate
1970 RRTEMP=RR(J)
1980 '*** Decrease the percent level
1990 PL(J)=PL(J)-1:Z=0:PP=PL(J):PL=PL(J)-10
2000 '*** Branch to extension if percentage is <.01%
2010 IF PL(J)<=10 GOTO 2050
2020 '*** Calculate new rain rate using T-S equation
2030 RR(J)=A(PL)+B(PL)*T(J)+C(PL)*I(J)+D(PL)*F(J):GOTO 2080
2040 '*** Calculate new rain rate using extension
2050 RRA=A(1)+B(1)*T(J)+C(1)*I(J)+D(1)*F(J):
     RRE=A(7)+B(7)*T(J)+C(7)*I(J)+D(7)*F(J):PT=P(PP)
2060 RR(J)=RRA+(RRE-RRA)*1.43068*(LOG(PT)*.43429+2)
2070 '*** Test if new RR decreased
2080 IF RR(J)-RRTEMP<0 THEN W=W+1:GOTO 2150 ELSE
2090 '*** Increment Q; loosen tolerance if Q>20
2100 Q=Q+1:IF Q>20 THEN TOL=TOL+.0005:IF Q>30 THEN
     TOL=TOL+.001:IF Q>40 THEN TOL=TOL+.001
2110 '*** Test for negative rain rates
```

```
2120 IF Q<25 GOTO 1590 ELSE
2130 IF RR(J)>0 GOTO 1590 ELSE S=S+1
2140 '*** Reject months
2150 G=J:X=X-1
2160 NN=G+1:IF NN>12 GOTO 2180
2170 T(G)=T(NN):I(G)=I(NN):F(G)=F(NN):PL(G)=PL(NN):
     RR(G)=RR(NN):MO$(G)=MO$(NN):WT(G)=WT(NN)
2180 G=G+1
2190 IF G<=X GOTO 2160 ELSE GOTO 1590
2200 '*** Program is finished; display results
2210 CLS:IF RRAVG<0 THEN RRAVG=0 ELSE:RRAVG=RRAVG*60:PRINT
"           ****************** RESULTS ******************"
2220 PRINT "Rain rate exceeded "PAVG"% of the year for
     "L$" ="RRAVG"mm/hr"
2230 PRINT :PRINT ,"        Monthly Distributions"
2240 PRINT :PRINT ," Month","Rain Rate","Percent level"
2250 PRINT:FOR H=1 TO X:AA=PL(H):RR(H)=RR(H)*60
2260 PRINT ,"  "MO$(H),RR(H),"    "P(AA):NEXT H
2270 IF YN$="Y" OR YN$="y" THEN PRINT:PRINT "This location
     has a polar climate, and, therefore, only the rainiest
     month is  used."
2280 END
```

APPENDIX G

CCIR GLOBAL MODEL

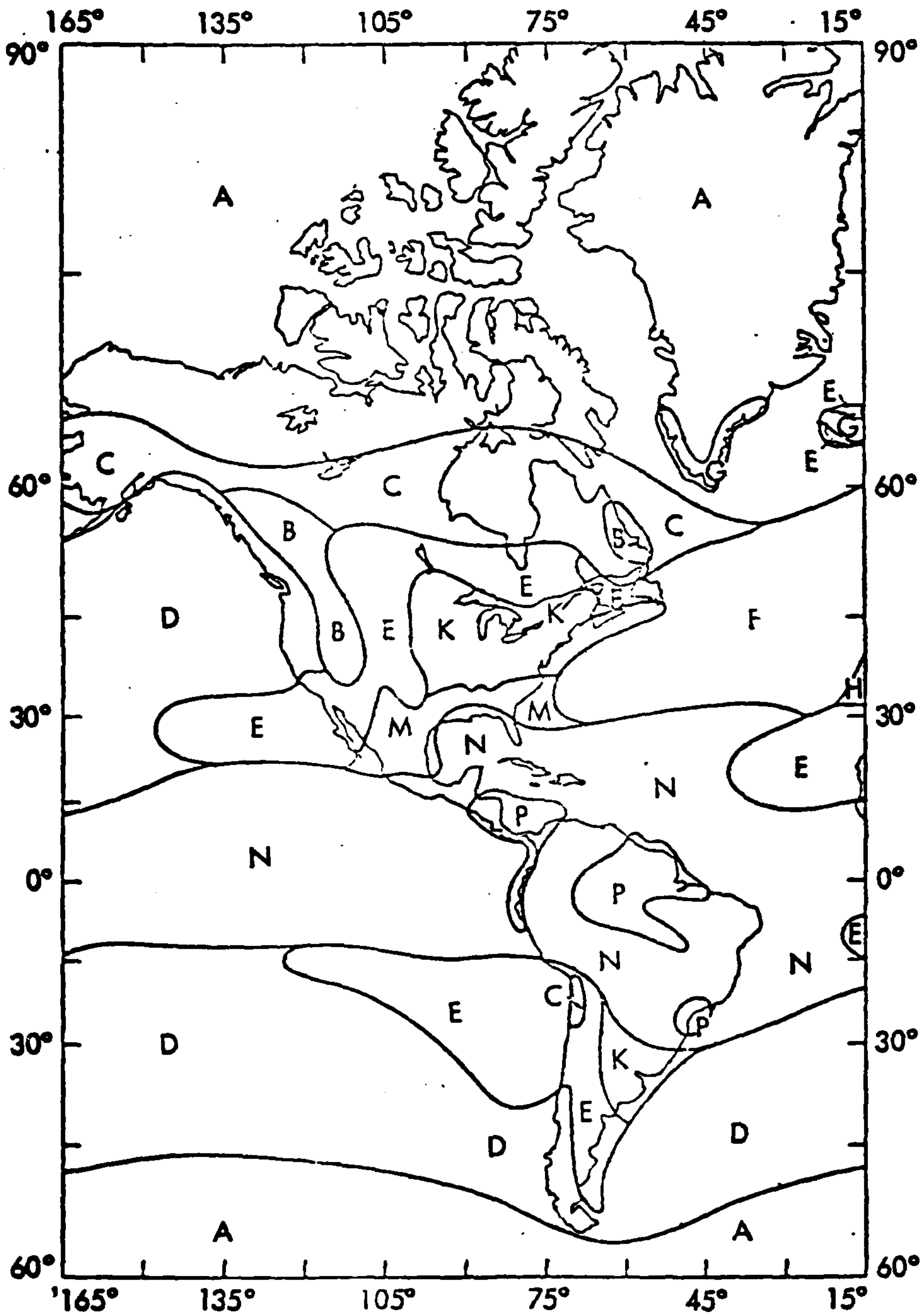


Figure G-1: Rain rate regions of the Americas (CCIR, 1982).

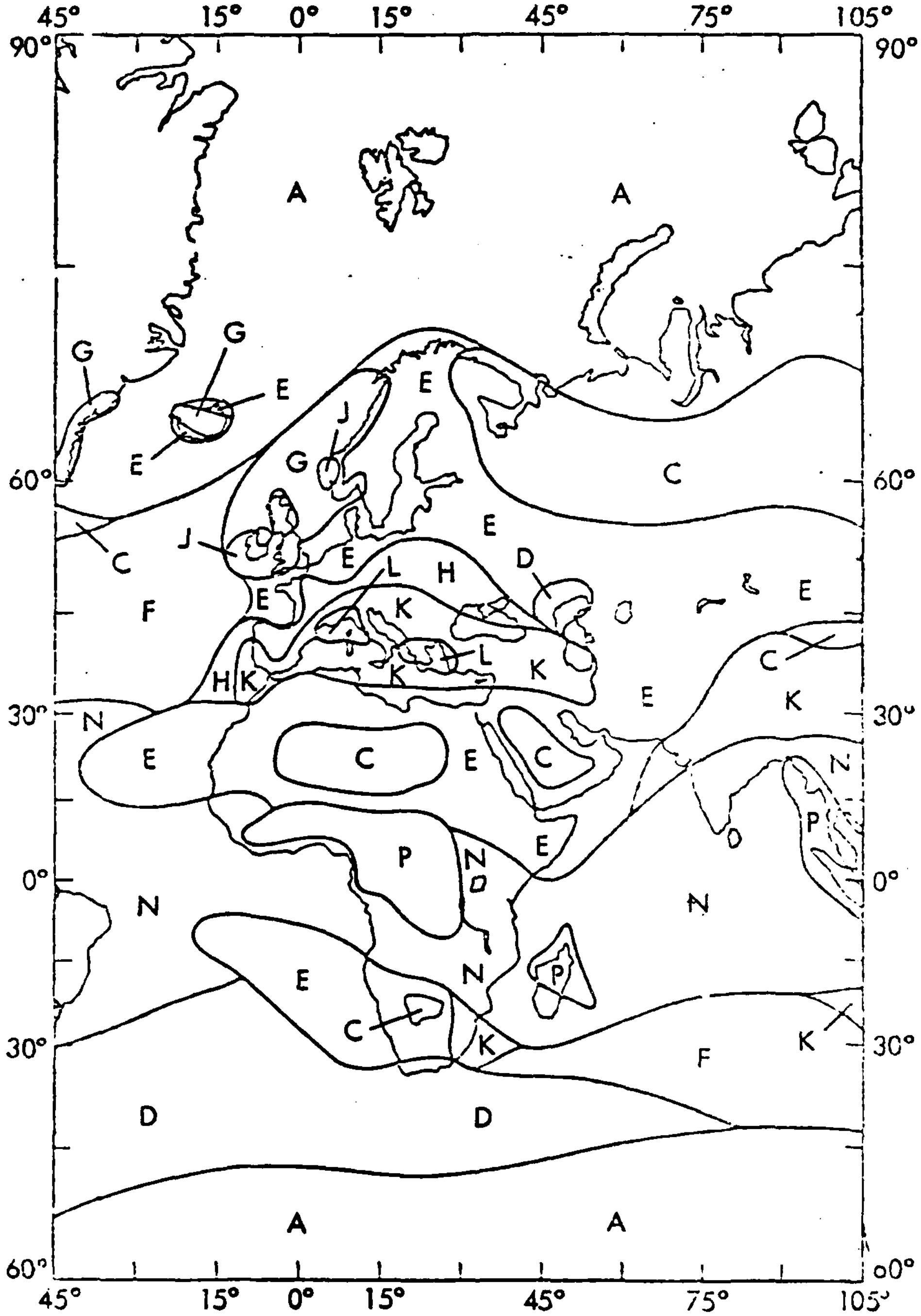


Figure G-2: Rain rate regions of Europe and Africa (CCIR, 1982).

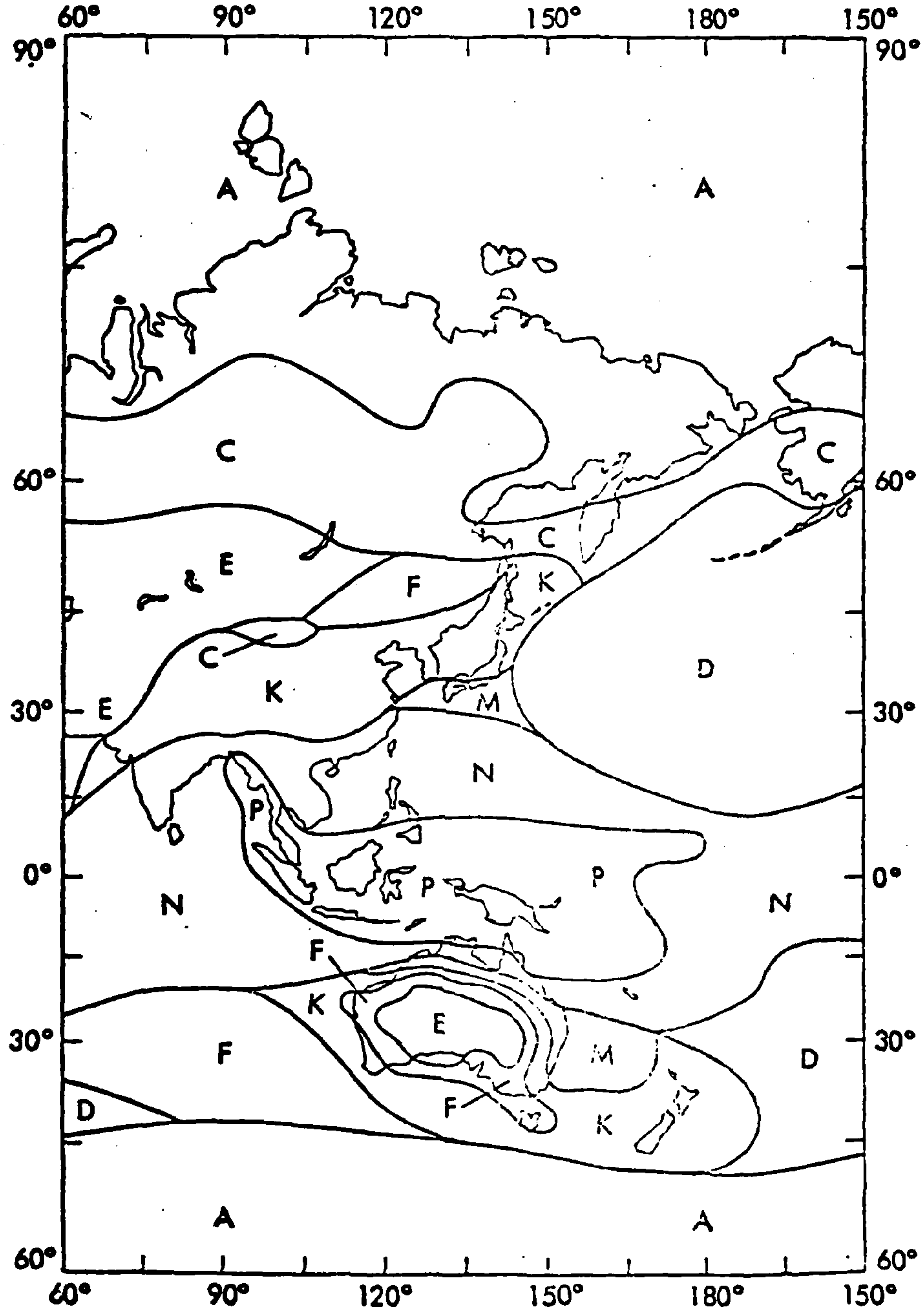


Figure G-3: Rain rate regions of Asia and Oceania (CCIR, 1982).

Table G-1: Rain rates of the CCIR global model (mm/hr). (CCIR,1982)

% of Time Exceeded	Regions A	B	C	D	E	F	G
1.0	-	1	-	3	1	2	-
0.3	1	2	3	5	3	4	7
0.1	2	3	5	8	6	8	12
0.03	5	6	9	13	12	15	20
0.01	8	12	15	19	22	28	30
0.003	14	21	26	29	41	54	45
0.001	22	32	42	42	70	78	65

Table G-1 (continued):

% of Time Exceeded	Regions H	J	K	L	M	N	P
1.0	-	-	2	-	4	5	12
0.3	4	13	6	7	11	15	34
0.1	10	20	12	15	22	35	65
0.03	18	28	23	33	40	65	105
0.01	32	35	42	60	63	95	145
0.003	55	45	70	105	95	140	200
0.001	83	55	100	150	120	180	250

APPENDIX H

EXPANDED TABLE OF RAIN RATES FOR THE CCIR GLOBAL MODEL AND THE GRAPHS USED TO INTERPOLATE THESE RAIN RATES

Table H-1: Expanded table of rain rates for the CCIR global model (mm/hr).

% of Time Exceeded	Regions						
	A	B	C	D	E	F	G
0.1	2	3	5	8	6	8	12
0.07	3	4	6	9	7	10	14
0.05	4	4	7	10	9	11	16
0.04	4	5	8	12	10	13	18
0.03	5	6	9	13	12	15	20
0.02	6	8	11	15	15	18	23
0.015	7	10	13	17	18	22	26
0.01	8	12	15	19	22	28	30
0.007	10	15	18	22	27	34	34
0.005	11	17	21	24	32	41	38
0.004	12	19	23	26	36	47	41
0.003	14	21	26	29	41	54	45

Table H-1 (continued):

% of Time	Regions						
Exceeded	H	J	K	L	M	N	P
0.1	10	20	12	15	22	35	65
0.07	11	22	14	19	26	43	77
0.05	13	25	17	24	31	52	88
0.04	15	26	20	28	35	57	96
0.03	18	28	23	33	40	65	105
0.02	22	30	29	42	48	76	120
0.015	26	32	34	49	54	83	130
0.01	32	35	42	60	63	95	145
0.007	38	37	49	71	72	106	160
0.005	44	40	57	83	80	118	174
0.004	49	42	63	92	87	126	185
0.003	55	45	70	105	95	140	200

The following figures were used to interpolate rain rates between the exceedance levels given in the CCIR global model. The highest point on each curve represents 0.1% of the year, and the lowest point represents 0.003% of the year.

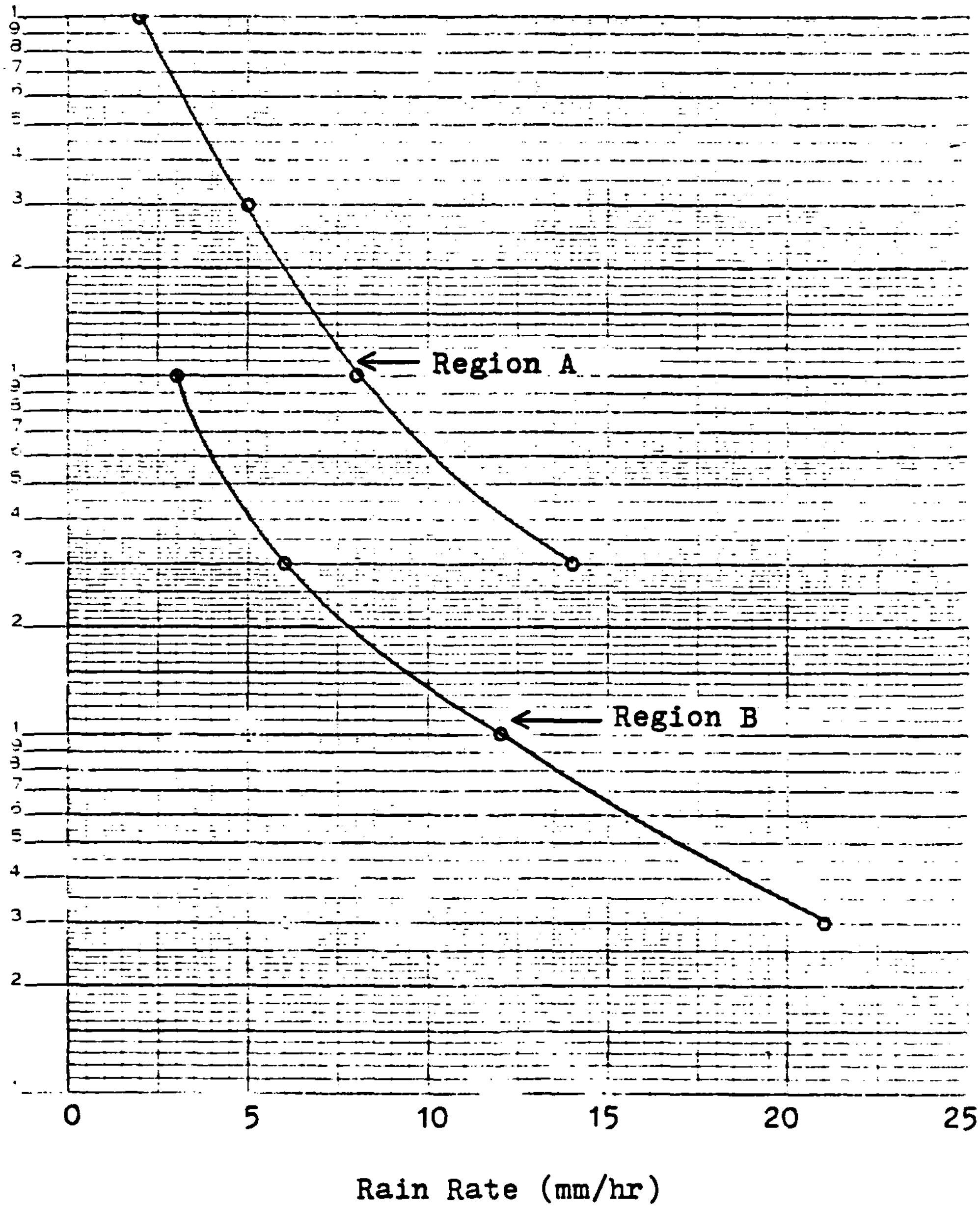


Figure H-1: CCIR global model regions A and B.

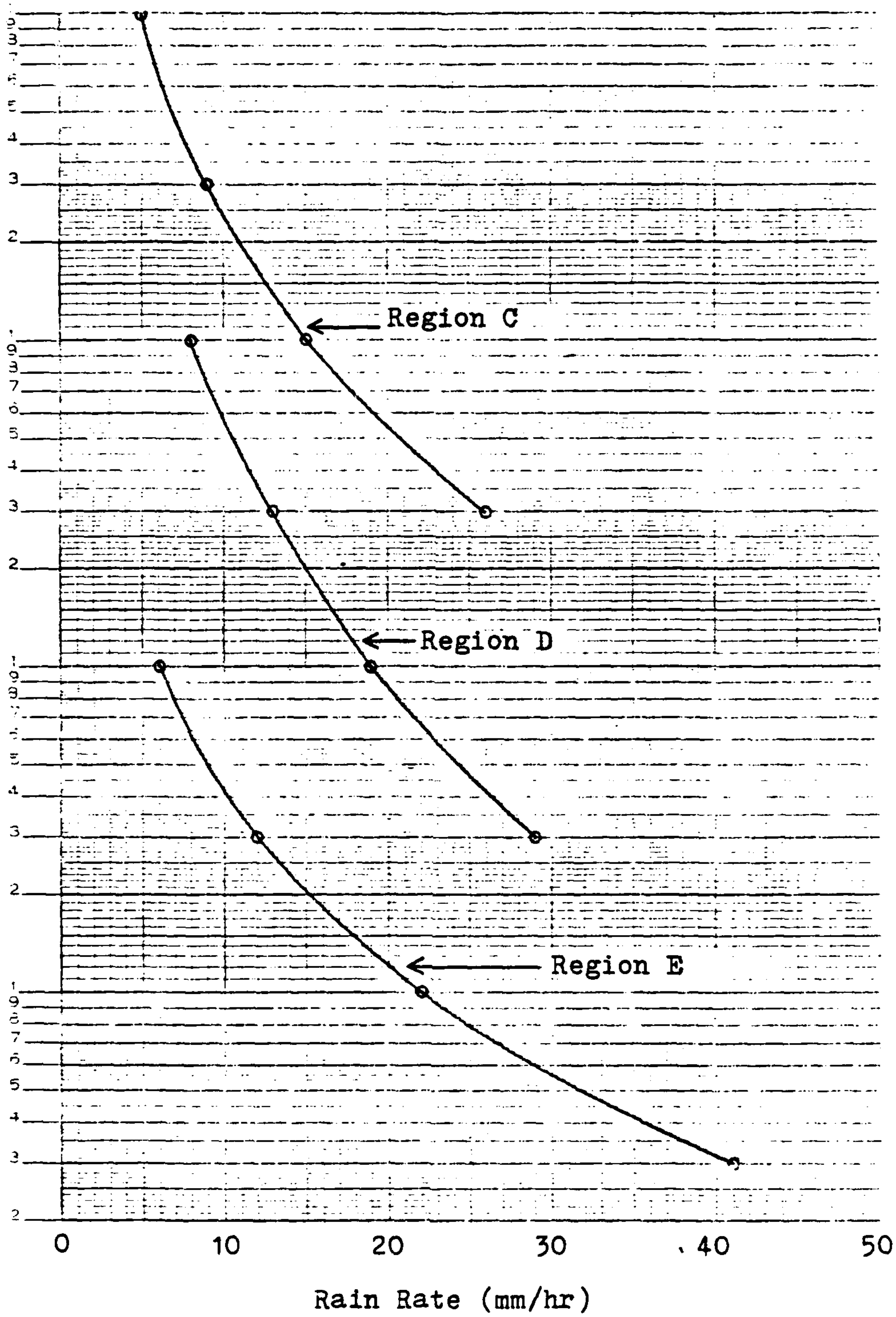


Figure H-2: CCIR global model regions C, D, and E.

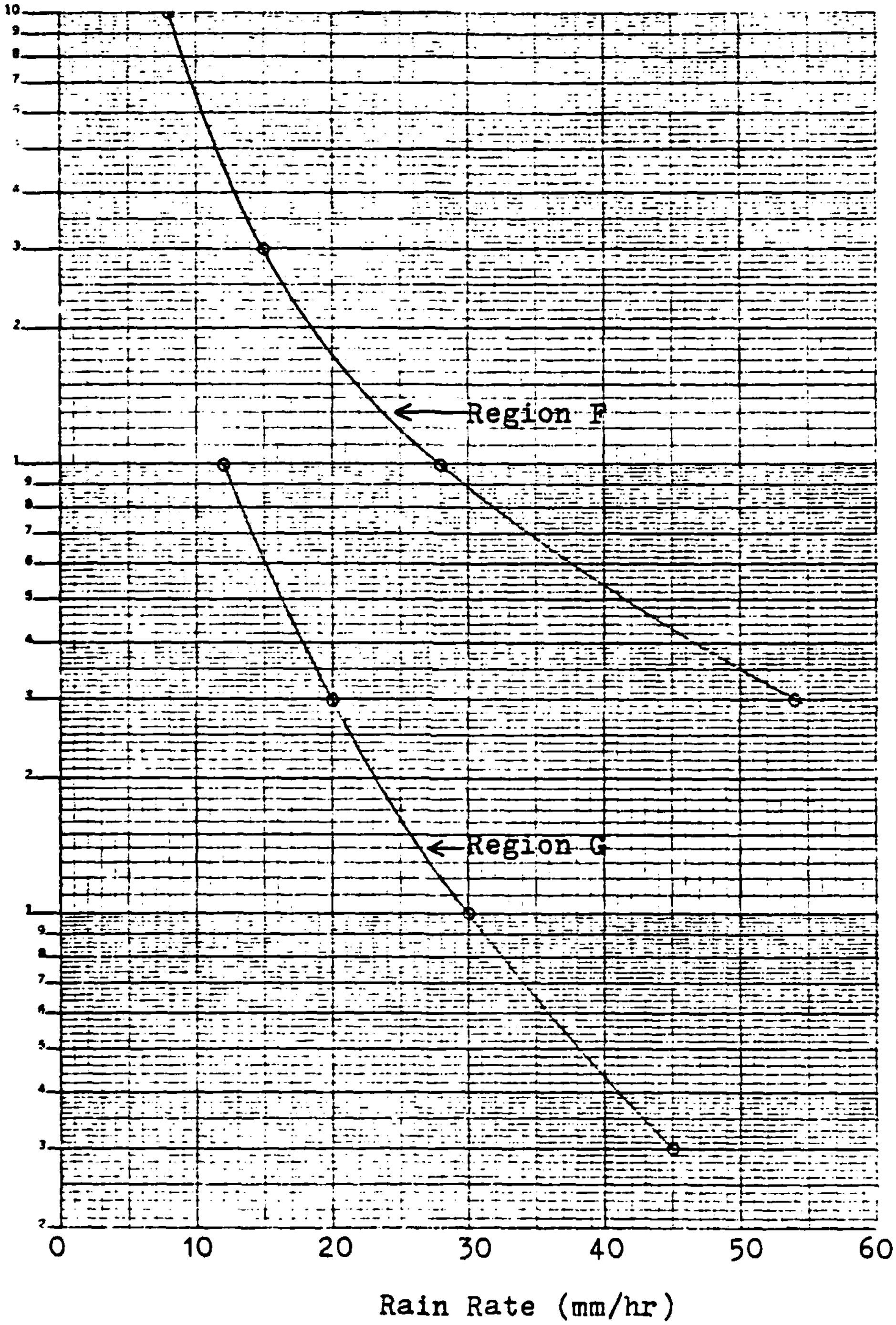


Figure H-3: CCIR global model regions F and G.

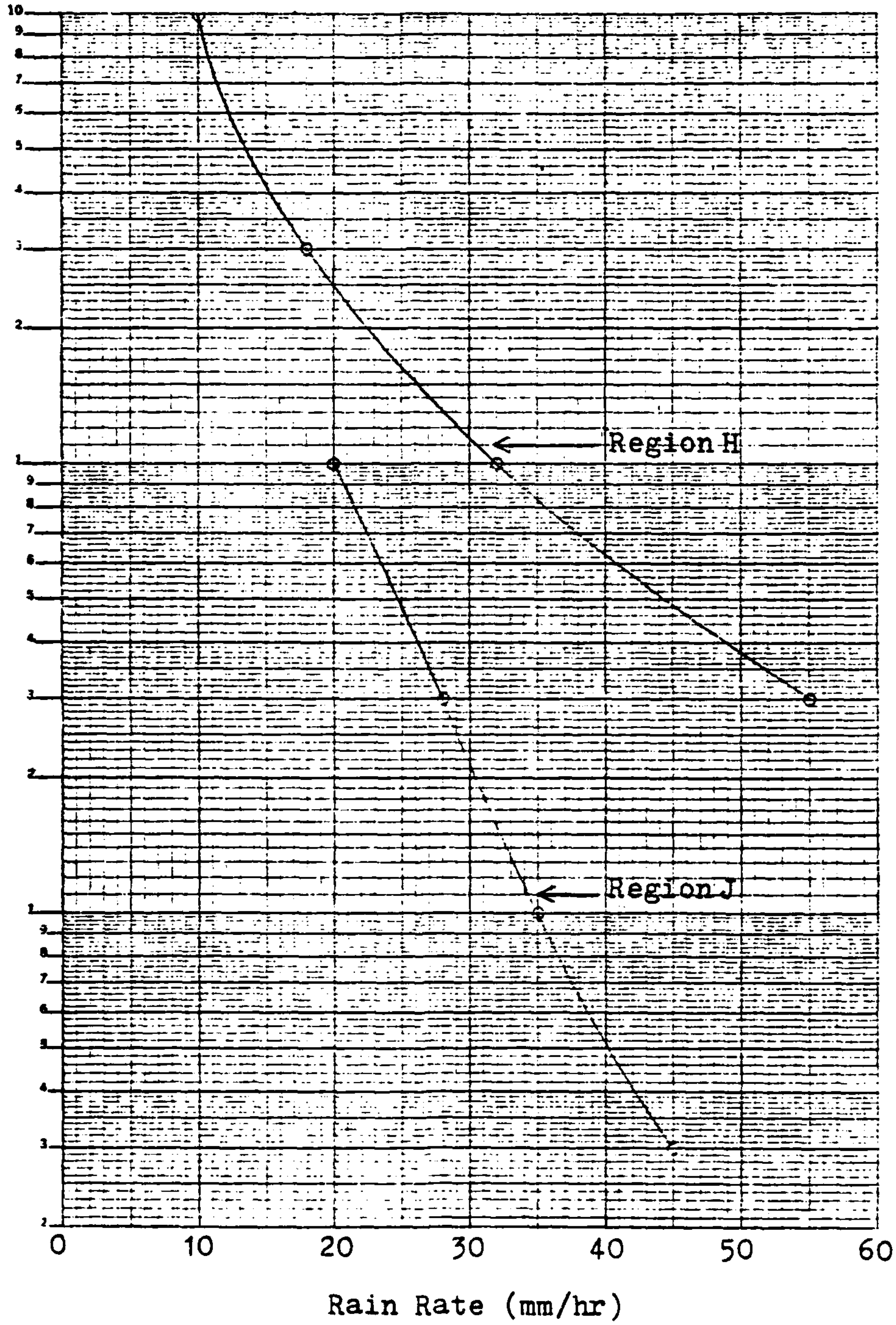


Figure H-4: CCIR global model regions H and J.

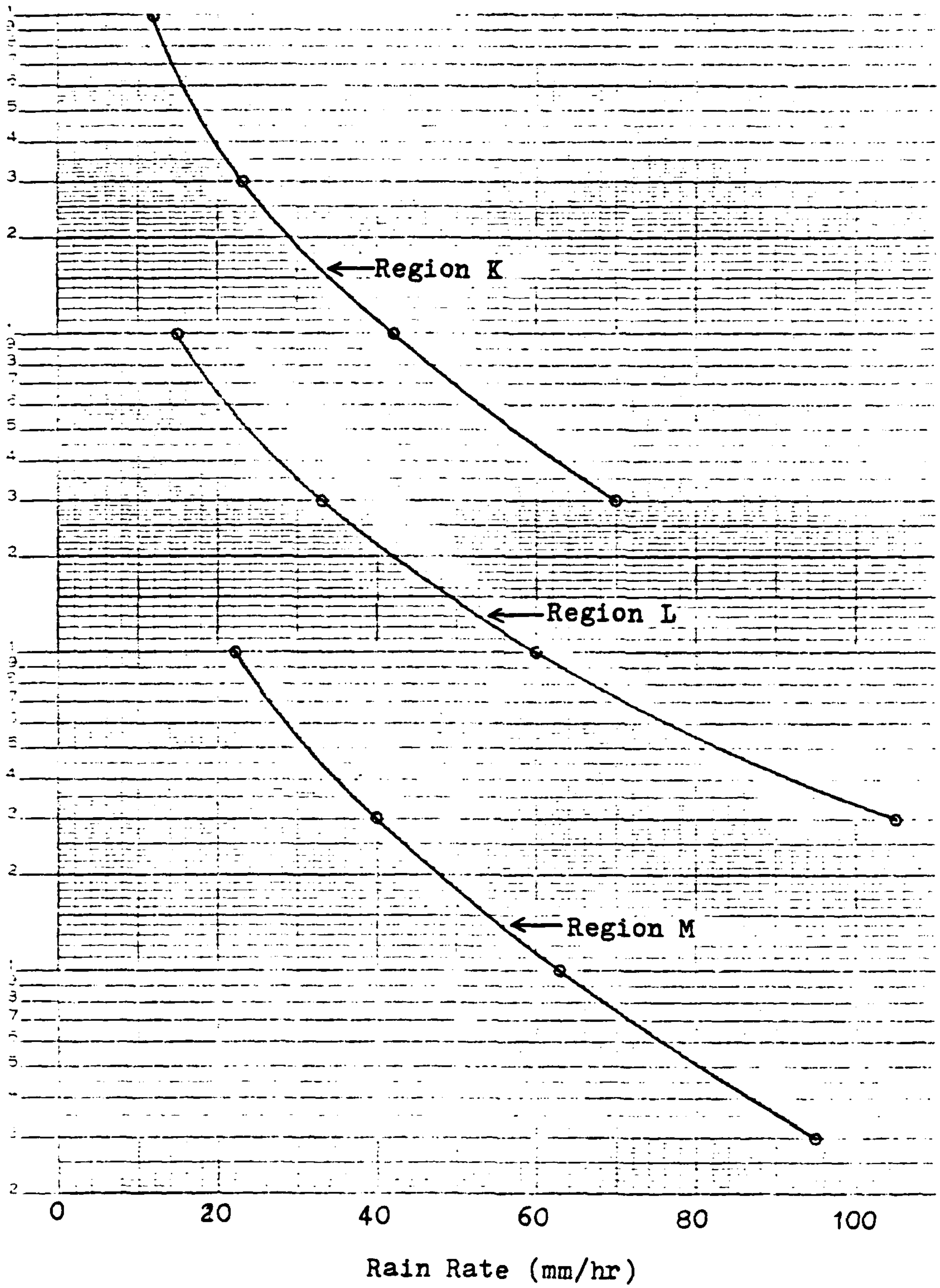
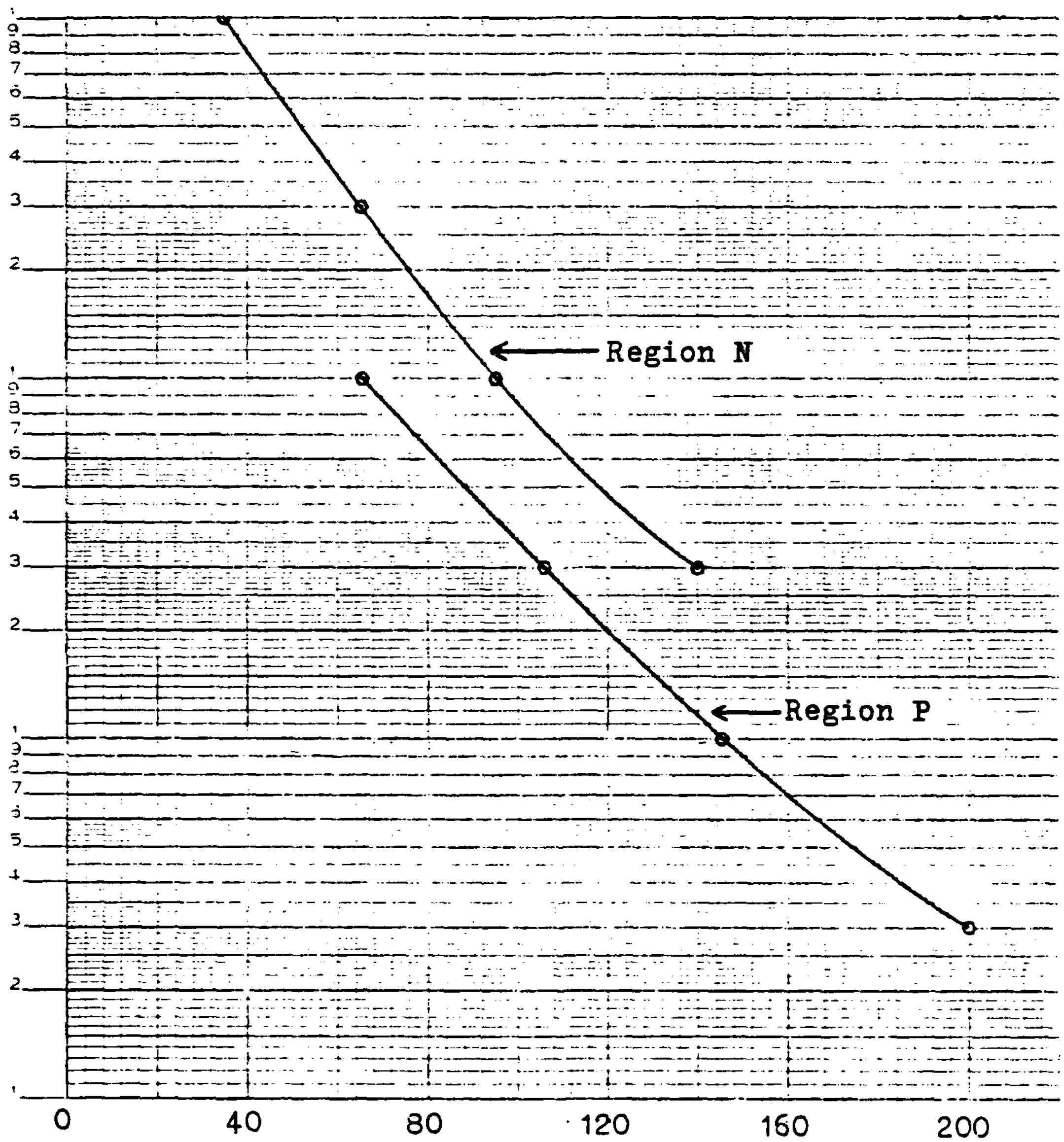


Figure H-5: CCIR global model regions K, L, and M.



Rain Rate (mm/hr)

Figure H-6: CCIR global model regions N and P.

APPENDIX I

PROGRAM TO COMPUTE THE POWER MARGIN

Introduction

The mathematical models presented in Section IV are organized in a computer program to make the determination of the link power margin as convenient as possible and to minimize the risk of error. This appendix contains a user's manual for the program and the source code.

User's Manual

General Information.

This user's manual describes how the program computes the power margin on a satellite communications link as a function of rain rate statistics. desired availability, and link configuration. The manual contains five sections:

- General Information
- Program Algorithm
- Conversions
- Program Test
- Program Documentation

The program was written in Microsoft Basic. It has been checked out on two microcomputers: the Zenith Z-100 and the Sanyo MBC-550. Both machines were using basic interpreters, and both were using MS-DOS 2.11 operating systems.

Program Algorithm.

The program begins by prompting the user to enter the following information at the keyboard:

- Rain rate (mm/hr)
- Height of the 0°C isotherm (km)
- Altitude of the earth terminal above sea level (km)
- Link frequency (GHz)
- Antenna elevation angle (degrees)
- Percent of outage time (%)
- Whether the climate is continental or maritime
- Whether it is an uplink or not
- Whether there is circular or dual polarization or not

If this is not an uplink, the user is then asked to enter the values of the sky noise temperature T_{sn} and the receiver noise temperature T_r. If neither circular nor dual polarization is used, the user is asked to enter the polarization tilt angle T. The required units are specified in all cases involving numerical inputs. The inputs must consist only of numbers without units. In each of the three questions, the possible answers are also specified: C for continental climate, M for maritime climate, Y for yes, and N for no. All letters can be either upper or lower case.

The program makes all the calculations and decisions discussed in Section IV needed to compute the link power margin. The link power margin and the power margins for each of the three separate components are presented under the RESULTS display.

Conversions.

The LOG function is the natural logarithm. To convert it to a base 10 logarithm, each is multiplied by a factor of 0.4343. Angular measures are converted from degrees to radians for use in trigonometric functions by multiplying degree measures by 0.01745 (rad/deg).

Program Test.

The operation of the program is demonstrated with an example that uses the following set of link information:

- Rain rate (R) = 45 mm/hr
- Altitude of the 0°C isotherm (H_o) = 4 km
- Altitude of the terminal (H_g) = 0.3 km
- Frequency (F) = 7.8 GHz
- Antenna elevation angle (E) = 20°
- Percent of allowable outage time (p) = 0.009%
- Maritime climate
- Downlink
- Link uses a single linearly-polarized wave
- Sky noise temperature (T_{sn}) = 12°K
- Receiver noise temperature (T_r) = 200°K
- Polarization tilt angle (T) = 30°

The program will determine the power margin by means of the methods presented in Section IV:

Coefficient B and exponent C are found by linear interpolation of the values in Table 4-1:

$$B = 0.00336 + (0.00535 - 0.00336) \times (7.8 - 7.0)$$
$$= 0.004952$$
$$C = 1.270 + (1.245 - 1.270) \times (7.8 - 7.0)$$
$$= 1.250$$

From equation (5) the specific attenuation (A) is

$$A = 0.004952 \times 45^{1.250} \text{ (dB/km)}$$
$$= 0.55716 \text{ (dB/km)}$$

The path length (L) is found using equation (7) with $H = H_o - H_g$:

$$L = (4.0 - 0.3)/(\sin 20°)$$
$$= 10.82 \text{ km}$$

Equation (10) is used to find the path reduction factor (RF) in a maritime climate:

$$RF = \frac{90(0.009/0.01)^{-0.33}}{90 + 4(10.82 \cos 20°)}$$

$$= 0.713$$

From equation (11) the power margin for attenuation (PM_a) is

$$PM_a = 0.55716 \times 10.82 \times 0.713$$

$$= 4.45 \text{ dB}$$

The noise temperature contributed by rain (T_{rain}) is found using equation (16):

$$T_{rain} = 288[1 - \exp(-4.45/4.34)]$$

$$= 184.7°K$$

The power margin for noise PM_n from equation (15) is

$$PM_n = 10 \text{ Log} \left[\frac{200 + 12 + 184.7}{200 + 12}\right]$$

$$= 2.72 \text{ dB}$$

The cross polarization discrimination (XPD) from equation (26) is

$$XPD = 30 \text{ Log } 7.8 - 40 \text{ Log } (\cos 20°) - 10 \text{ Log} \left\{0.5[1 - 0.9418 \cos (4 \times 30°)]\right\}$$

$$- 20 \text{ Log } 4.45$$
$$= 16.20 \text{ dB}$$

The power margin for depolarization (PM_d) is found from equation (25):

$$PM = 5 \text{ Log } (1 + 10^{-16.20/10})$$
$$= 0.05 \text{ dB}$$

The total power margin (PM) is the sum of the three components:

$$PM = PM_a + PM_n + PM_d$$
$$= 4.45 + 2.72 + 0.05$$
$$= 7.22 \text{ dB}$$

These values are the same as those produced by the program.

Program Documentation.

All variables in the program are identical to those used in Section IV except that all letters are capitalized and none are subscripted. There are a number of comment statements indicating the function of the following executable statements. Comments are preceeded by an apostrophe and three asterisks ('***).

Program Source Code

```
10 'PROGRAM TO COMPUTE POWER MARGIN FOR RAIN ON A SATELLITE
   COMMUNICATIONS LINK
20 '
30 '*** Input data from keyboard
40 CLS:INPUT "Enter the rain rate (mm/hr): ",R
50 INPUT "Enter the height of the 0 degree C isotherm (km):
   ",HO
60 INPUT "Enter the altitude of the earth terminal above sea
   level (km): ",HG
70 INPUT "Enter the link frequency (GHz): ",F:IF F<7 OR
   F>9 THEN PRINT:PRINT "Frequency must be between 7 and
   9 GHz.":PRINT:GOTO 70 ELSE
80 INPUT "Enter the antenna elevation angle (degrees):
   ",EDEG:E=EDEG*.01745
90 INPUT "Enter the allowable percent of outage time due to
   rain (%): ",P:IF P>.1 OR P<.001 THEN PRINT:PRINT "Percent
   must be between 0.1% and 0.001%.":PRINT:GOTO 90 ELSE
100 INPUT "Is the climate continental (C) or maritime (M)?
    ",CM$
110 INPUT "Is this an uplink? (Y/N): ",YNU$
120 INPUT "Does the link use circular or dual polarization?
    (Y/N): ",YNP$
130 '*** Interpolate to find coefficient B and exponent C
140 IF R>30 GOTO 180
```

```
150 IF F<8 THEN B=.00455+.00194*(F-7):C=1.18+.007*
    (F-7) ELSE
160 IF F>=8 THEN B=.00649+.00239*(F-8):C=1.187-.002*
    (F-8) ELSE
170 GOTO 210
180 IF F<8 THEN B=.00336+.00199*(F-7):C=1.27-.025*
    (F-7) ELSE
190 IF F>=8 THEN B=.00535+.00268*(F-8):C=1.245-.029*
    (F-8) ELSE
200 '*** Calculate the specific attenuation A
210 A=B*R•C
220 '*** Determine the path length L through rain
230 H=HO-HG:IF E>=10 THEN L=H/SIN(E) ELSE L=2*H/(((SIN(E))•2
    +(2*H/8500))•.5+SIN(E))
240 D=L*COS(E):IF CM$="M" OR CM$="m" GOTO 300
250 '*** Interpolate to find coefficient CP
260 IF P>.01 THEN CP=-1.52*LOG(P)-3
270 IF P<=.01 THEN CP=-2.1715*LOG(P)-6
280 '*** Calculate the path reduction factor RF for a
    continental climate
290 RF=90/(90+CP*D):GOTO 340
300 IF P>=.01 THEN M=.41 ELSE M=.33
310 '*** Calculate the path reduction factor RF for a
    maritime climate
320 RF=(P/.01)•-M*90/(90+4*D)
330 '*** Calculate the power margin for attenuation PMA
```

```
340 PMA=A*L*RF
350 IF YNU$="Y" OR YNU$="y" GOTO 420
360 INPUT "Enter the sky noise temperature (degrees K):
    ",TSN
370 INPUT "Enter the receiver noise temperature (degrees K)
    : ",TR
380 '*** Use PMA to find the noise temperature of rain
    TRAIN
390 TRAIN=288*(1-EXP(-PMA/4.34))
400 '*** Calculate the power margin for noise PMN
410 PMN=4.343*LOG((TSN+TRAIN+TR)/(TSN+TR))
420 IF YNP$="Y" OR YNP$="y" GOTO 510
430 INPUT "Enter the polarization tilt angle (degrees from
    horizontal): ",TDEG:T=TDEG*.01745
440 IF E>1.0472 THEN E=1.0472
450 IF E<.1745 THEN E=0
460 '*** Determine the cross-polarization descrimination XPD
470 XPD=13.029*LOG(F)-17.372*LOG(COS(E))-4.343*LOG(.5*
    (1-.9418*COS(4*T)))-8.686*LOG(PMA)
480 '*** Calculate the power margin for depolarization PMD
490 PMD=2.1715*LOG(1+10·(-XPD/10))
500 '*** Determine the link power margin PM by adding the
    three components
510 PM=PMA+PMN+PMD
520 '*** Display the results
530 PRINT:PRINT "            ******************** RESULTS **
```

```
    ******************"
540 PRINT:PRINT "                    Link power margin = "PM "dB"
550 PRINT:PRINT "                    Power margin for attenuation
    = "PMA "dB"
560 PRINT:PRINT "                    Power margin for noise = "PMN
    "dB"
570 PRINT:PRINT "                    Power margin for
    depolarization = "PMD "dB"
580 END
```

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This thesis presents an algorithm which can be used to predict power margins needed to overcome the degrading effects of rain on satellite communications links in the 7 to 9 GHz frequency range. This algorithm employs established mathematical models which are used to characterize rain rate behavior and its effects on wave propagation. The algorithm accounts for each of the three ways in which the link can be degraded by rain: signal attenuation, signal depolarization, and increased noise power at the receiver input.

This algorithm is designed to give the link designer all the tools necessary to compute a reliable power margin. The power margin is tailor-made for each individual link by considering all the relevant variables that can distinguish one link from another including the specified value of link availability, the rain rate characteristics at the location of the satellite earth terminal, and the link configuration. Finally, the algorithm is implemented in a computer program to make it convenient to use.

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