CHAPTER II
CHARACTERISTICS OF RAIN AND RAIN SYSTEMS

2.1 INTRODUCTION

The attenuating and depolarizing effects of the troposphere, and the statistical nature of these effects, are chiefly determined by both the macroscopic and microscopic characteristics of rain systems. The macroscopic characteristics include items such as the size, distribution and movements of rain cells, the height of melting layers and the presence of ice crystals. The microscopic characteristics include the size distribution, density and oblateness of both rain drops and ice crystals. The combined effect of the characteristics on both scales leads to the cumulative distribution of attenuation and depolarization versus time, the duration of fades and depolarization periods, and the specific attenuation/depolarization versus frequency. In this chapter, we discuss how the characteristics are described and measured, and how the microscopic and macroscopic aspects are statistically related to each other. We also describe how one major propagation effect, specific attenuation, can be estimated. This information will serve as background for the rain and attenuation models of the next chapter.

2.2 TYPES AND SPATIAL DISTRIBUTIONS OF RAIN

2.2.1 Stratiform Rain

In the midlatitude regions, stratiform rainfall is the type of rain which typically shows stratified horizontal extents of hundreds of kilometers, durations exceeding one hour and rain rates less than about 25 mm/h (1 inch/h). This rain type usually occurs during the spring and fall months and results, because of the cooler temperatures, in vertical heights of 4 to 6 km. For communications applications, these stratiform rains represent a rain rate which occurs for a sufficiently long period that the link margin may be required to exceed the attenuation associated with a one-inch per hour (25 mm/h) rain rate. As shown below, this is much easier to do at frequencies below the 22 GHz water absorption line, than for frequencies above the H_2O line.

2.2.2 Convective Rain

Convective rains arise because of vertical atmospheric motions resulting in vertical transport and mixing. The convective flow occurs in a cell whose horizontal extent is usually several kilometers. The cell usually extends to heights greater than the average freezing layer at a given location because of the convective upwelling. The cell may be isolated or embedded in a thunderstorm region associated with a passing weather front. Because of the motion of the front and the sliding motion of the cell along the front, the high rain rate duration is usually only several minutes. These rains are the most common source of high rain rates in the U.S. and Canada.

2.2.3 Cyclonic Storm

Tropical cyclonic storms (hurricanes) often pass over the eastern seaboard during the August-October time period. These circular storms are typically 50 to 200 km in diameter, move at 10-

20 kilometers per hour, extend to melting layer heights up to 8 km and have high (greater than 25 mm/h) rain rates.

2.2.4 Long-Term Distributions

'The stratiform and cyclonic rain types cover large geographic locations and so the spatial distribution of total rainfall from one of these storms is expected to be uniform. Likewise the rain rate averaged over several hours is expected to be rather similar for ground sites located up to tens of kilometers apart.

Convective storms, however, are localized and tend to give rise to spatially nonuniform distributions of rainfall and rain rate for a given storm. S.C. Bloch, et al (1978) at EASCON 78, demonstrated an image-enhanced weather radar display which clearly showed the decay and redevelopment of a convective cell while passing over Tampa Bay. Clearly the total rainfall and rain rate varies significantly over the scale of 10 km for this region. The effect is attributed to the presence of the large water mass and the heat-island associated with Tampa.

Over more uniform terrain, Huff and Shipp (1969) have observed precipitation correlation coefficients of 0.95 over 5 mile extents for thunderstorms and rainshowers in Illinois. The correlation was also higher along the path of storm motion compared to perpendicular to the path, as would be expected. This correlation is computed for the period of the storm and is not the instantaneous spatial correlation coefficient required to estimate the effectiveness of ground station site diversity.

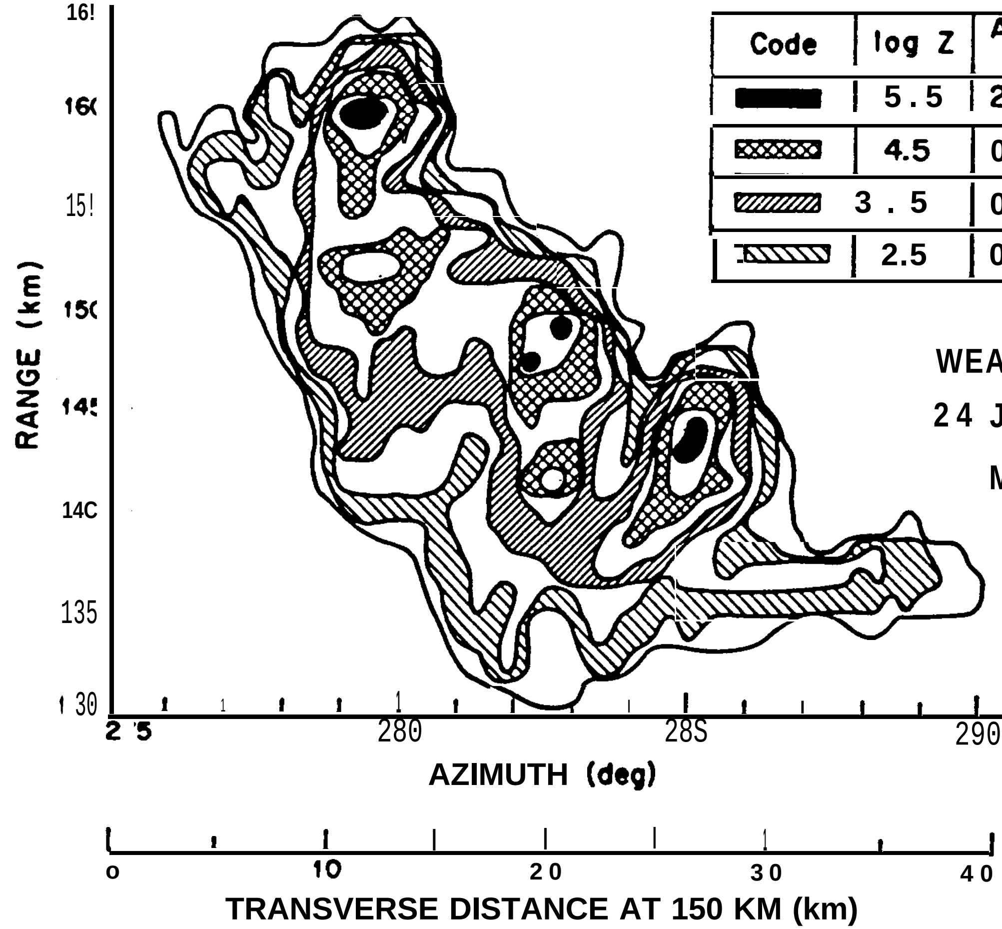
Goldhirsh (1983) evaluated five years of rain gauge measurements at Wallops Island, VA, and developed cumulative rain-rate distributions for yearly and combined average time periods. Year to year deviations in the measured rain rates, relative to the five year average, varied between 12 and 20 percent in the percentage interval between .01 and 1.0. The results also showed that the four year and five year averages fit a log normal distribution almost exactly down to 0.01 percent of the time, corresponding to rain rates up to about 50 mm/h. For larger rain rates, the distribution deviates from the log normal functional representation.

2.2.5 Short-Term Horizontal Distributions

Radars operating at nonattenuating frequencies have been utilized to study both the horizontal and vertical spatial components of convective rain systems. A typical horizontal distribution (actually observed at 1.4 degrees elevation angle) is shown in Figure 2.2-1 for a thunder shower in New England (Crane and Blood - 1979). Here rain rate variations of 100:1 are observed over ranges of 10 km for a shower containing four intense cells. Similar measurements have been made by Goldhirsh (1976), at Wallops Island, VA. Goldhirsh (1976) has also observed that the rain cells are elongated along the northeast-southwest direction (the direction of motion). This direction also correlated well with the average or median wind directions. The impact of this result is that the fading was maximum and the space diversity gain a minimum in the northeast-southwest direction. (Space diversity is described in detail in Chapter VII).

2.2.6 Short-Term Vertical Distributions

The calibrated radars are also ideal for measurement of the vertical profile of rain events. The median reflectivity profiles for a group of rain cells measured from the ground as a function of rain rate is presented in Figure 2.2-2 (Goldhirsh and Katz - 1979). The numbers in parentheses are the number of cells measured and the abscissa is the reflectivity factor based on the relation $Z=200R^{1.6}$ mm^6/m^3. These experimental results clearly demonstrate that the rain rate is uniform up to 4 km altitude and then decreases dramatically at altitudes in the 6 to 8 km range. This decrease is also associated with the 0°C isotherm height. Note how the median isotherm height increases with the updraft, convective, high rain rate cells. This effect will be used later in a Global Rain Prediction Model along with the seasonal dependence of the median isotherm height.



Contours 5 dB Apart

Code	log Z	Attenuation (7.78 GHz)	Rate ($Z = 200R^{1.6}$)
(solid)	5.5	2.1 dB/km	4 in. /hr (100 mm/hr)
(cross-hatched)	4.5	0.3 dB/km	1 in./hr (24 mm/hr)
(dense hatched)	3.5	0.04 dB/km	0.2 in./hr (6 mm/hr)
(hatched)	2.5	0.006 dB/km	0.05 in./hr (1 mm/hr)

Figure 2.2-1. Weather Radar Map for New England Showers

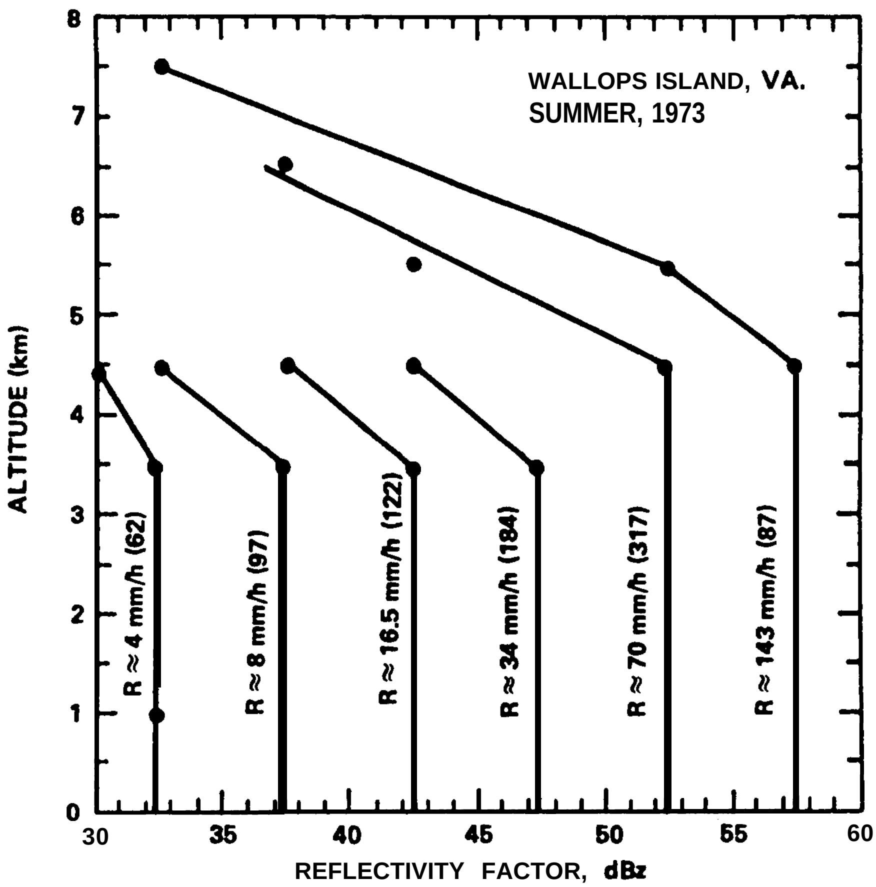


Figure 2.2-2. Median Reflectivity Factor Profiles for Given Rain Rates as Measured at Wallops Island, VA, During Summer of 1973

Above this isotherm, the hydrometers exist in the form of ice crystals and snow. These forms of hydrometers do not contribute significantly to the attenuation, but they can give rise to depolarization effects.

2.3 SPECIFIC RAIN ATTENUATION

2.3.1 Scattering

Rain drops both absorb and scatter microwave energy along an earth-space path. From the basic Rayleigh scattering criteria (the dimensions of the scatterer are much smaller than the wavelength) and the fact that the median rain drop diameter is approximately 1.5 mm, one would expect that Rayleigh scattering theory should be applied in the frequency (wavelength) range from 10 GHz (3cm) to 100 GHz (3mm). However, Rayleigh scattering also requires that the imaginary component of the refractive index be small, which is not the case for water drops (Kerker - 1969). Because of this effect and the wide distribution of rain drop diameters, the Rayleigh scattering theory appears to apply only up to 3 GHz (Rogers - 1978). Above 3 GHz Mie scattering applies and is the primary technique utilized for specific rain attenuation (attenuation per unit length, dB/km) calculations. Mie scattering accounts for the deficiencies of Rayleigh scattering and has proven to be the most accurate technique.

2.3.2 Drop Size Distributions

Several investigators have studied the distribution of rain drop sizes as a function of rain rate and type of storm activity. The three most commonly used distributions are

Laws and Parsons (LP)

Marshall-Palmer (MP)

Joss-thunderstorm (J-T) and drizzle (J-D)

In general the Laws and Parsons distribution (Laws and Parsons 1943) is favored for design purposes because it has been widely tested by comparison to measurements for both widespread (lower rain rates) and convective rain (higher rain rates). In the higher rain rate regime (>25 mm/hr) and at frequencies above 10 Ghz, the LP values give higher specific rain attenuations (Olsen, et al - 1978) than the J-T values (Joss, et al - 1968). It has been observed that the raindrop temperature is most accurately modeled by the 0°C data rather than 20°C, since for most high elevation angle earth-space links the raindrops are cooler at high altitudes and warm as they fall to earth.

An example of the measured number distribution of raindrops with drop diameter as a function of rain rate R (mm/h) is given in Figure 2.3-1. Here the measurements of Laws and Parsons (1943) and Marshall and Palmer (1948) are fitted by an exponential relation of the form

$$N_D = N_0 e^{-\Lambda D} \text{ cm}^{-4} \qquad (2.3\text{-}1)$$

where

$$N_0 = 0.08 \text{ cm}^{-4}$$

and

$$A = 41 \, R^{-0.21} \text{cm}^{-1}$$

Note that the units in the equations and Figure 2.3-1 are different. Multiply the N_D obtained from the above formula by 10^5 to convert to the units of Figure 2.3-1. The number of raindrops with diameters between D and D + δD in a volume V (cm^3) at rain rate R is

$$N_R = N_D \, (\delta D) V \qquad (2.3\text{-}2)$$

As shown in Figure 2.3-1, the measured data deviates from the exponential relation for diameters below 1.5 mm. However, the larger drops tend to dominate the specific attenuation at the higher rain rates of most concern for the system engineer, and so this deviation tends not to be reflected in the integral over drop diameters utilized in specific attenuation calculations.

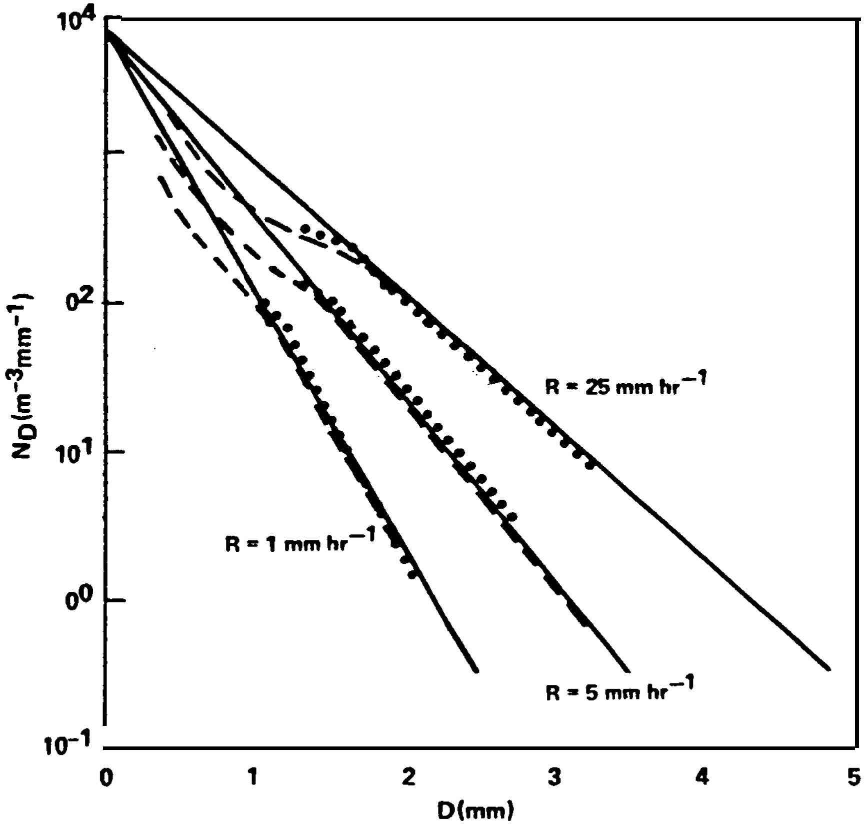


Figure 2.3-1. Rain Drop Size Distribution Function Compared with Experimental Results

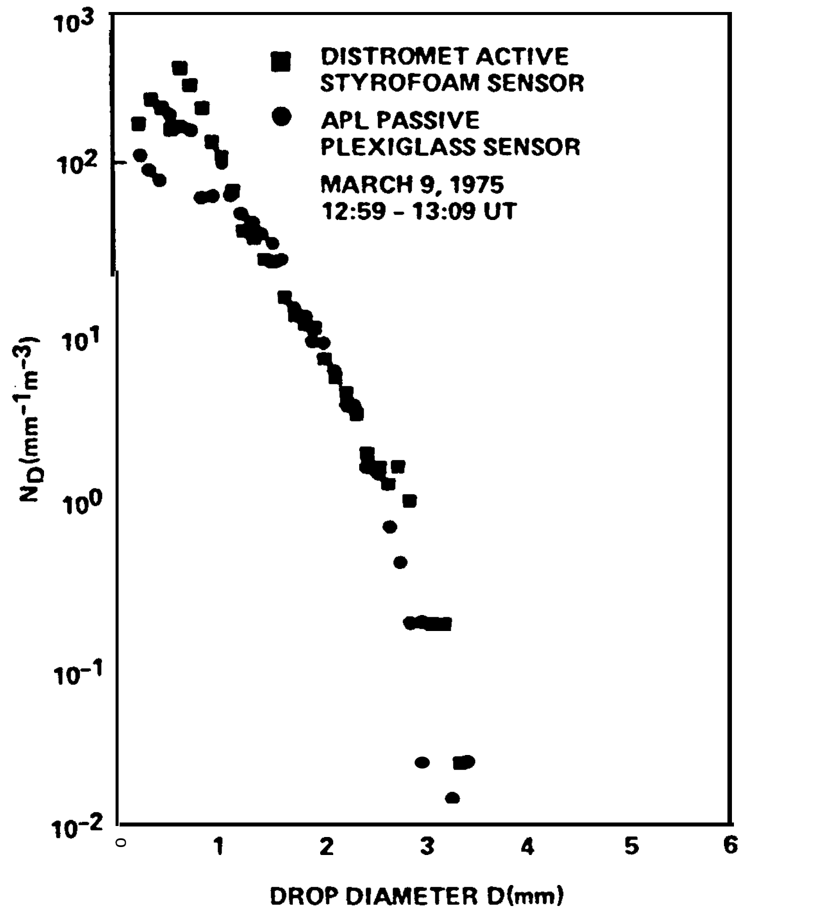


Figure 2.3-2. Raindrop Size Distribution Measured With Two Disdrometers

Joss, et al (1968) have found significant variations of N_D and A for different types of rainfall based on one year's measurements at Locarno, Switzerland. These results are presented in Table 2.3-1; however, the climatic regions where the Joss statistics apply have not been determined. Therefore, it appears best to utilize the Laws and Parsons results, realizing that in certain areas of the U.S. and Canada they have not been verified.

Table 2.3-1. Values of N_0, A Versus Rain Event as Determined by Joss, et al (1968)

Rainfall Type	N_0 (cm^{-4})	A (cm^{-1})
drizzle	0.3	$57R^{-0.21}$
widespread	0.07	$41R^{-0.21}$
thunderstorm	0.014	$30R^{-0.21}$

2.3.3 Measurement Techniques for Drop Size Distributions

Experimenters have employed a wide variety of techniques to measure raindrop size distributions in situ. These include: (1) optical systems requiring imaging or scattering light from raindrops, (2) replicating techniques where a permanent record of each drop size is made such as the flour method (Laws and Parsons - 1943), dyed filter paper (Marshall and Palmer - 1948), sugar coated nylon or foil impactors, (3) capacitive techniques due to changing dielectric constant, and (4) impact types of sensors (Rowland - 1976) .

Today the impact-type of sensor (called a disdrometer after drop distribution meter), is the favored technique. The Applied physics Laboratory has developed two styles of disdrometer with decided advantages over the commercially available Distromet Ltd unit. These three types have been described by Rowland (1976) and their calibration has been compared. A typical experimental result for two disdrometers measuring the same rain event on 9 March 1975, is shown in Figure 2.3-2. Note that the data for the APL passive plexiglas sensor which utilizes a piezoelectric crystal to "hear" the impact of raindrops may be invalid below a 1 mm\h rain rate because of noise in the preamplifier. Normally, this data would more clearly follow the Distromet active styrofoam sensor data.

2.3.4 Estimates of the Specific Attenuation

The scattering properties of raindrops and the dropsize distributions are inputs for the calculation of the attenuation per kilometer (specific attenuation) of a uniform rain at rain rate R.

It has been empirically observed (Ryde and Ryde - 1945, Kerr - 1951) that the specific attenuation a (dB/km) is related to the rain rate R (mm/h) by a relation

$$\alpha = a(f)R^{b(f)} \qquad (2.3\text{-}3)$$

where the coefficients a and b are functions of frequency.

Olsen, et al (1978) have made extensive calculations of the a and b coefficients. These calculations extend from 1 to 1000 GHz and have been presented in both tabular and graphical format for several raindrop distributions and temperatures. For the U.S. and Canada the 0°C numbers are most applicable (Rogers - 1978). Table 2.3-2 (Olsen, et al 1978) is given below for selected frequencies of interest. The LP_L and LP_H refer to Laws and Parsons drop size distributions associated with rain rates R from 1.27 to 50.8 mm/h and 25.4 to 152.4 mm/h, respectively. Olsen, et al (1978) have also provided analytic approximations for a(f) and b(f) which are quite adequate for systems engineering applications. These are

$$a(f) = 4.21 \times 10^{-5}(f)^{2.42} \qquad 2.9 \le f \le 54 \text{ GHz}$$

$$\qquad = 4.09 \times 10^{-2}(f)^{0.699} \qquad 54 \le f \le 180 \text{ GHz} \qquad (2.3\text{-}4)$$

and

$$b(f) = 1.41\,(f)^{-0.0779} \qquad 8.5 \le f \le 25 \text{ GHz}$$

$$\qquad = 2.63\,(f)^{-0.272} \qquad 25 \le f \le 164 \text{ GHz} \qquad (2.3\text{-}5)$$

Table 2.3-2. Regression Calculations for a and b in $\alpha = aR^b$ (dB/km) as Functions of Frequency and Dropsize Distribution, Rain Temperature = 0^oC

FREQ. (GHz)	a					b				
	LP_L	LP_H	MP	J-T	J-D	LP_L	LP_H	MP	J-T	J-D
10 “	1.17X10^{-2}	1.14X10^{-2}	1.36X10^{-2}	1.69x10^{-2}	1.14X10^{-2}	1.178	1.189	1.150	1.076	0.%8
11	1.50x10^{-2}	1.52x10^{-2}	1.73X10-2	2.12X10-2	1.41X10-*	1.171	1.167	1.143	1.065	0.977
12	1.86X10^{-2}	1.96x10^{-2}	2.15x10^{-2}	2.62x10^{-2}	1.72x10^{-2}	1.162	1.150	1.136	1.052	0.985
15	3.21x10^{-2}	3.47X10^{-2}	3.68x10^{-2}	4.66x10^{-2}	2.82x10^{-2}	1.142	1.119	1.118	1.010	1.003
19.04	5.59X10^{-2}	6.24x10^{-2}	6.42x10^{-2}	8.68X10^{-2}	4.76x10^{-2}	1.123	1.091	1.001	0.957	1.017
19.3	5.77X10^{-2}	6.46x10^{-2}	6.62x10^{-2}	8.99x10^{-2}	4.90X10-2	1.122	1.089	1.100	0.954	1.018
20	6.26x10^{-2}	7.09X10-*	7.19X10-2	9.83x10^{-2}	5.30X10-*	1.119	1.083	1.097	0.946	1.020
25	0.105	0.132	0.121	0.173	8.61X10^{-2}	1.094	1.029	1.074	0.884	1.033
28.56	0.144	0.196	0.166	0.243	0.115	1.071	0.983	1.052	0.839	1.041
30	0.162	0.226	0.186	0.274	0.128	1.061	0.964	1.043	0.823	1.044
34.8	0.229	0.340	0.264	0.368	0.177	1.023	0.909	1.008	0.784	1.053
35	0.232	0.345	0.268	0.372	0.180	1.022	0.907	1.007	0.783	1.053
40	0.313	0.467	0.362	0.451	0.241	0.981	0.864	0.972	0.760	1.058
50	0.489	0.669	0.579	0.629	0.387	0.907	0.815	0.905	0.709	1.053
60	0.658	0.796	0.801	0.804	0.558	0.850	0.794	0.851	0.682	1.035
70	0.801	0.869	1.00	0.833	0.740	0.809	0.784	0.812	0.661	1.009
80	0.924	0.913	1.19	0.809	0.922	0.778	0.780	0.781	0.674	0.980
90	1.02	0,945	1.35	0.857	1.10	0.756	0.776	0.153	0.663	0.953
100	1.08	0.966	1,48	0.961	1.26	0.742	0.774	0.730	0.637	0.928

Note: Values for 19.04, 19.3, 28.56 and 34.8 GHz obtained from D. V. Rogers, Comsat Lab., Clarksburg, MO where f is in GHz. Thus for 20 GHz

$$a = a(f)R^{b(f)} \text{ db/km} \quad (2.3\text{-}6)$$

$$= 4.21 \times 10^{-5}(20)^{2.42}R^{1.41(20)^{-000779}} \text{ dB/km}$$

$$= 0.059\ R^{1.117} = 2.19 \text{ dB/km @ } R = 25.4 \text{ mm/hr.}$$

The value in Table 2.3-2 for this frequency is 0.0626 $R^{1.119}$ = 2.34 dB/km @ R = 25.4 mm/hr, an error of 6%.

The specific attenuations for several of the common earth-space bands are shown in Figure 2.3-3 for rain rates from 0.1 to 10 inches/h (2.54 to 254 mm/h), calculated using the approximate equations given. The 85 and 94 GHz curves overlap the 50 GHz data because of inaccuracies in the approximations. More accurate results are obtained from interpolation of Table 2.3-2. The CCIR (1986) has recently published tables of coefficients for specific attenuation that show the dependence of specific attenuation on wave polarization. These coefficients are given in Table 2.3-3. The H and V subscripts refer to horizontal and vertical polarization, respectively.

An earlier calculation of the specific attenuation coefficients by Crane (1966) may be compared to the results listed above. Crane employed the Laws and Parsons (1943) number density model to obtain the aR^b power law relation coefficients. The results of these earlier calculations are given in Chapter 3.

2.4 RAINFALL DATA

The largest long-term sources of rainfall data in the U.S. and Canada are their respective weather services. The data collected by these agencies is an excellent starting data base for rain rate estimation. However, in situ measurements are still the most accurate, but quite expensive technique for acquiring rain rate statistics.

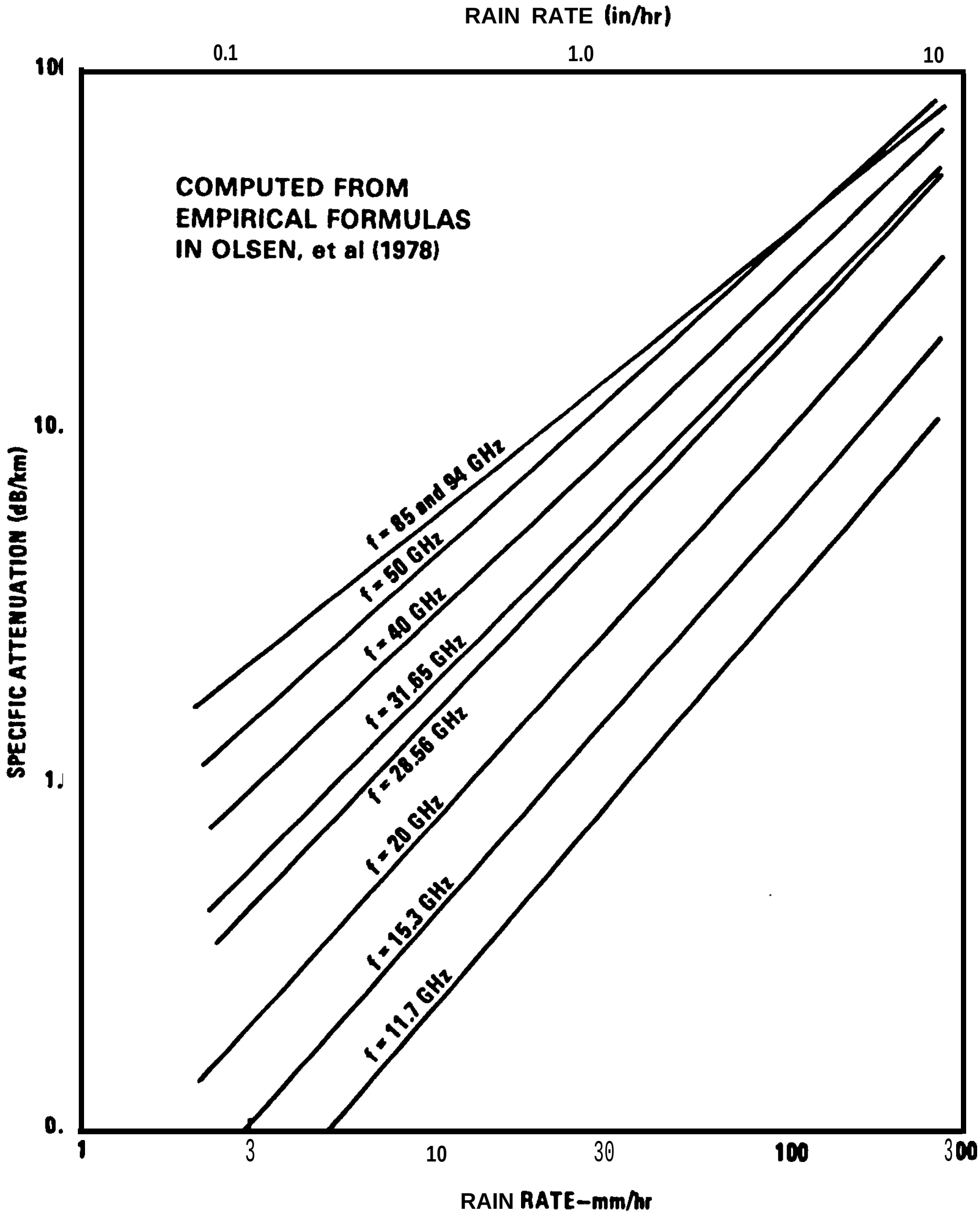


Figure 2.3-3. Specific Attenutation Versus Rain Rate for Common Earth-Space Frequencies

Table 2.3-3. Specific Attenuation Coefficients* (CCIR-1986)

Frequency (GHz)	a_H	a_V	b_H	b_V
1	0.0000387	0.0000352	“0.912	0.880
, 2	0.000154	0.000138	0.963	0.923
3	0.000650	0.000591	1.121	1.075
6	0.00175	0.00155	1.308	1.265
7	0.00301	0.00265	1.332	1.312
8	0.00454	0.00395	1.327	1.310
10	0.0101	0.00887	1.276	1.264
12	0.0188	0.0168	1.21.7	1.200
15	0.0367	0.0347	1.154	1.128
20	0.0751	0.0691	1.099	1.065
25	0.124	0.113	1.061	1.030
30	0.187	0.167	1.021	1.000
35	0.263	0.233	0.979	0.963
40	0.350	0.310	0.939	0.929
45	0.442	0.393	0.903	0.897
50	0.536	0.479	0.873	0.868
60	0.707	0.642	0.826	0.824
70	0.851	0.784	0.793	0.793
80	0.975	0.906	0.769	0.769
90	1.06	0.999	9.753	0.754
100	1.12	1.06	0.743	0.744
120	1.18	1.13	0.731	0.732
150	1.31	1.27	0.710	0.711
200	1.45	1.42	0.689	0.690
300	1.36	1.35	0.688	0.689
400	1.32	1.31	0.683	0.684

* Values for a and b at other frequencies can be obtained by interpolation using a logarithmic scale for a and frequency and a linear scale for b.

2.4.1 U.S. Sources

2.4.1.1 Published Data. In the U.S., the National Weather Service's National Climatic Center* prepares and maintains extensive precipitation records obtained from Weather Service Offices and over 12,000 observers and agencies. This rain data is available in several documents available from the National Climatic Center. Several of the key publications of interest to the earth-space path engineer are:

- Hourly Precipitation Data (HPD)
  - 15 minute rain rate resolution
  - published monthly by state
  - District of Columbia included in the Virginia HPD
  - available about 6 months following date of recording
  - $1.95 per copy
  - $25.40 per year

- Climatological Data (CD)
  - 1 hour rain rate resolution
  - published monthly by state(s)
  - District of Columbia included in the Maryland and Delaware CD
  - Washington National Airport WSO included in the Virginia CD
  - available about 3 months following date of recording
  - $1.50 per copy
  - $19.50 per year

- Climatological Data - National Summary, Annual Summary
  - one 5 minute rain rate resolution event per month
  - available about 18 months following last date of recording
  - $1.50 per copy

*National Climatic Data Center, Federal Building, Asheville, North Carolina 28801, phone (704) 259-0682

- Local Climatological Data (LCD)
  - hourly rain rate resolution
  - published monthly by location
  - available about 4 months following date of recording
  - $0.65 per copy, $8.45 per year
  - annual issue also published for each location, $0.65

- Storm Data
  - published monthly for the U.S.
  - describes type of storm and extent of damage.
  - $1.05 per copy, $12.60 per year

The local Climatological Data is available for the 287 stations shown in Table 2.4-1; however, the Hourly Precipitation Data is available for many more stations.

Examples of the precipitation-related data available in each of these publications are given in Figures 2.4-1 to 2.4-4. Comparing the results for either the Baltimore Weather Station Office (WSO) at the Airport (AP) or the Beltsville results, one observes that precipitation data up to 15-minute resolution is available in the HPD's, while the monthly CD lists only the total precipitation per day (see Figure 2.4-2). In the Annual Summary of the National CD (see Figure 2.4-3) the total precipitation, snowfall (all frozen precipitation except hailstones) and the amount and date(s) of the highest precipitation accumulation during the year for periods of 5 to 180 minutes are given. Unfortunately it only includes one 5 minute event per month, only the highest will be indicated in the data, Additional techniques to retrieve more data will be described below.

The Local Climatological Data (LCD) provides the rainfall by hour at each of the 287 stations shown in Table 2.4-1. An example for Asheville, NC, is shown in Figure 2.4-4. In this publication the type of weather is provided so that one can ascertain if the rainfall is from a thunderstorm or a general wide-coverage weather system. The water equivalent of the snow is shown in the hourly

Table 2.4-1. Logical Climatological Data Stations

U.S.DEPARTMENTOF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL ENVIRONMENTAL SATELLITE , DATA AND INFORMATION SERVICE

(Stations for which Local Climatological Data are issued, as of January 1, 1982)

ALABAMA

abc ● IRUINGWAW AIRPORT
. BIRMINGHAM CITY OFFICE
abc HUNTSVILLE
abc MOBILE
abc MONTGOMERY

ALASKA

abc ANCHORAGE
abc ANNETTE
abc BARROW
abc BARTER ISLAND
abc BETHEL
abc BETTLES
abc BIG DELTA
abc COLD BAY
abc FAIRBANKS
abc GULKANA
abc HOMER
ac JUNEAU
abc KING SALMON
abc KODIAK
abc KOTZEBUE
abc McGRATH
abc NOME
abc ST PAUL ISLAND
abc TALKEETNA
abc UNALAKLEET
abc VALDEZ
abc YAKUTAT

ARIZONA

abc FLAGSTAFF
abc PHOENIX
abc TUCSON
ac WINSLOW
ac YUMA

ARKANSAS

abc FORT SMITH
abc LITTLE ROCK
. No LITTLE ● m!!

CALIFORNIA

abc ● ilKRwli LD
abc ● ISHOP
abc BLUE CANYON
. EUREKA
abc FRESNO
abc LONG BEACH
abc LOS ANGELES AIRPORT
ac LOS ANGELES CIVIC CENTER
abc MT SHASTA
abc RED BLUFF
abc SACRAUEN1O
abc SAN DIEGO
abc SAN FRANCISCO AIRPORT
. SAN FRANCISCO CITY
abc SANTA MARIA
. STOCKTON

COLORADO

abc ALAMOSA
abc COLORADO SPRINGS
abc DENVER
abc GRAND JUNCTION
abc PUEBLO (4)

CONNECTICUT

abc BRIDGEPORT
abc HARTFORD

DELAWARE

abc WI LMINC1OM

DISTRICT OS COLUMBIA

abc WASHINGTON NATIONAL AP
abc WASHINGTON - DULLES INT'L AP

FLORIDA

abc APALACHICOLA
abc DAYTONA BEACH
abc FORT MYERS
abc JACKSONVILLE
abc KEY WEST
abc MIAMI
abc ORLANDO
abc PENSACOLA
abc TALLAHASSEE
abc TAMPA
abc WEST PALM BEACH

GEORGIA

abc ATHENS
abc ATLANTA
abc AUGUSTA
abc COLUMBUS
abc MACON
abc SAVANNAH

abc HILO
abc HONOLULU
abc KAHULUI
abc LIHUE

IDAHO

abc BOISE
abc LEWISTON
abc POCATELLO

ILLINOIS

ac CAIRO
abc CHICAGO O'HARE AIRPORT
abc MOLINE
abc PEORIA
abc ROCKFORD
abc SPRINGFIELD

INDIANA

abc EVANSVILLE
abc FORT WAYNE
abc INDIANAPOLIS
abc SOUTH BEND

IOWA

abc DES MOINES
abc DUBUQUE (2)
abc SIOUX CITY
abc WATERLOO

abc CONCORDIA
abc DODGE CITY
abc GOODLAND
abc TOPEKA
abc WICHITA

KENTUCKY

abc JACKSON
abc LEXINGTON
abc LOUISVILLE

LOUISIANA

abc BATON ■ offic
abc LAKE CHARLES
abc NEW ORLEANS
abc SHREVEPORT

MAINE

abc CARIBOU
abc PORTLAND

MARYLAND

abc BALTIMORE

abc BOSTON
ac BLUE HILL OBS.
abc WORCESTER

abc ALPENA
abc DETROIT CITY AIRPORT
abc DETROIT METRO AP
abc FLINT
abc GRAND RAPIDS
abc HOUGHTON LAKE
abc LANSING
ac MARQUETTE
abc MUSKEGON
abc SAULT STE MARIE

MINNESOTA

abc DULUTH
abc INTERNATIONAL FALLS
abc MINNEAPOLIS - ST PAUL
abc ROCHESTER
abc ST CLOUD

MISSISSIPPI

● W JACKSON
abc MERIDIAN

MISSOURI

abc COLUMBIA
abc KANSAS COT" INT'LAP
abc KANSAS CITY DOWNTOWN AP
abc ST JOSEPH (3)
abc ST LOUIS
#01 SPRINGFIELD

abc BILLINGS
abc GLASGOW
abc GREAT FALLS
abc HAVRE
abc HELENA
abc KALISPELL
abc MILES CITY
abc MISSOULA

NEBRASKA

abc GRAND ISLAND
abc LINCOLN
abc NORFOLK
abc NORTH PLATTE
abc OMAHA
ac OMAHA (NORTH)
● W SCOTTSBLUFF
. VALENTINE

NEVADA

abc ELKO
abc ELY
abc LAS VEGAS
abc RENO
abc WINNEMUCCA

NEW HAMPSHIRE

abc CONCORD
. MT WASHINGTON

NEW JERSEY

abc ATLANTIC CITY AIRPORT
ac ATLANTIC CITY STATE MARINA
abc NEWARK
ac TRENTON (5)

NEW MEXICO

abc ALBUQUERQUE
abc CLAYTON
abc ROSWELL

NEW YORK

abc ALBANY
abc BINGHAMTON
abc BUFFALO
abc NEW YORK CENTRAL PARK
abc N Y , F KENNEDY INT'L AIRPORT
abc N Y LaGUARDIA FIELD
abc ROCHESTER
abc SYRACUSE

NORTH CAROLINA

abc ASHEVILLE
abc CAPE HATTERAS
abc CHARLOTTE
abc GREENSBORO
● W RALEIGH
abc WILMINGTON

NORTH DAKOTA

abc BISMARCK
abc FARGO
abc WILLISTON

OHIO

. AKRON-CANTON
ac CINCINNATI ABBE OBS
abc CINCINNATI AIRPORT
abc CLEVELAND
abc COLUMBUS
abc DAYTON
abc MANSFIELD
abc TOLEDO
abc YOUNGSTOWN

OKLAHOMA

abc OKLAHOMA CITY
abc TULSA

OREGON

abc ASTORIA
abc BURNS
abc EUGENE
abc MEDFORD
abc PENDLETON
abc PORTLAND
abc SALEM
ac SEXTON SUMMIT

PACIFIC ISLANDS

abc GUAM
abc JOHNSTON
abc KOROR
abc KWAJALEIN
abc MAJURO
abc PAGO PAGO
abc PONAPE
abc TRUK (MOEN)
abc WAKE
abc YAP

PENNSYLVANIA

abc ALLENTOWN
abc AVOCA, WILKES-BARRE SCRANTON AP
abc ERIE
abc HARRISBURG
abc PHILADELPHIA
abc PITTSBURGH AIRPORT
abc WILLIAMSPORT

RHODE ISLAND

ac BLOCK ISLAND
abc PROVIDENCE

SOUTH CAROLINA

abc CHARLESTON AIRPORT
a CHARLESTON CITY
. COLUMBIA
abc GREENVILLE-SPARTANBURG

SOUTH DAKOTA

abc ABERDEEN (1)
abc HURON
abc RAPID CITY
abc SIOUX FALLS

TENNESSEE

abc BRISTOL
abc CHATTANOOGA
abc KNOXVILLE
abc MEMPHIS
abc NASHVILLE
ac OAK RIDGE

TEXAS

abc ABILENE
abc AMARILLO
abc AUSTIN
abc BROWNSVILLE
abc CORPUS CHRISTI
abc DALLAS-FORT WORTH
ac DEL RIO
abc EL PASO
ac GALVESTON
abc HOUSTON
abc LUBBOCK
abc MIDLAND
abc PORT ARTHUR
abc SAN ANGELO
abc SAN ANTONIO
abc VICTORIA
abc WACO
abc WICHITA FALLS

UTAH

abc MILFORD
abc SALT LAKE CITY

VERMONT

abc BURLINGTON

abc LYNCHBURG
abc NORFOLK
abc RICHMOND
abc ROANOKE
ab WALLOPS ISLAND

WASHINGTON

abc OLYMPIA
abc QUILLAYUTE AIRPORT
abc SEATTLE-TACOMA AP
ac SEATTLE URBAN SITE
abc SPOKANE
abc STAMPEDE PASS
ac WALLA WALLA
abc YAKIMA

WEST INDIES

abc SAN JUAN P R

WEST VIRGINIA

abc BECKLEY
abc CHARLESTON
abc ELKINS
ab HUNTINGTON
ac PARKERSBURG

WISCONSIN

abc GREEN BAY
abc LA CROSSE
abc MADISON
abc MILWAUKEE

WYOMING

abc CASPER
abc CHEYENNE
abc LANDER
abc SHERIDAN

a Monthly summary issued   b Monthly summary includes available 3 hourly observations   c Annual Summary issued

SUBSCRIPTION: Price and ordering information available through; National Climatic Center, Federal Building Asheville, North Carolina 28801, ATTN: Publications.

(1) NWS Operations Terminated September 1, 1981. Publications Discontinued.
(2) NWS Operations Terminated September 4,1481. Publications Discontinued.
(3) NWS Operations Terminated November 1, 1981. Publications Discontinued
(4) NWS Operations Terminated January 1, 1982 Publications Discontinued.
(5) NWS Operations Terminated December 1, 1981. Publications Discontinued

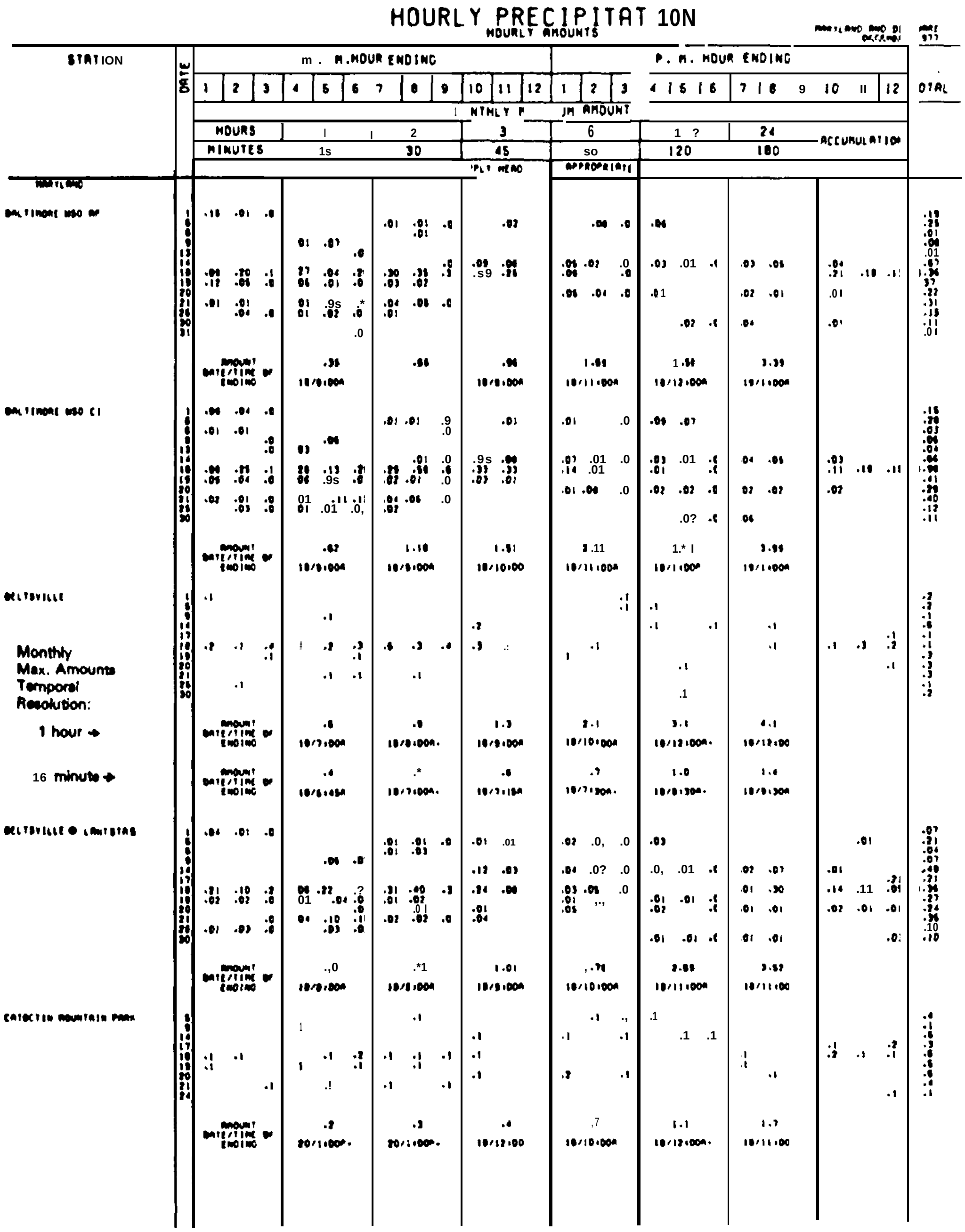
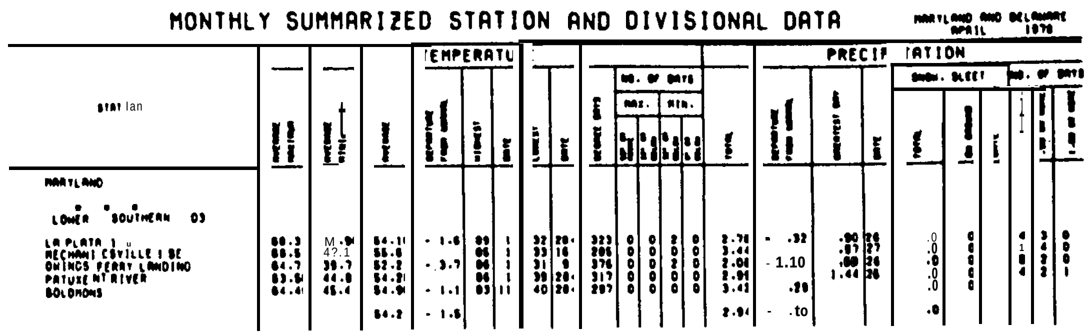


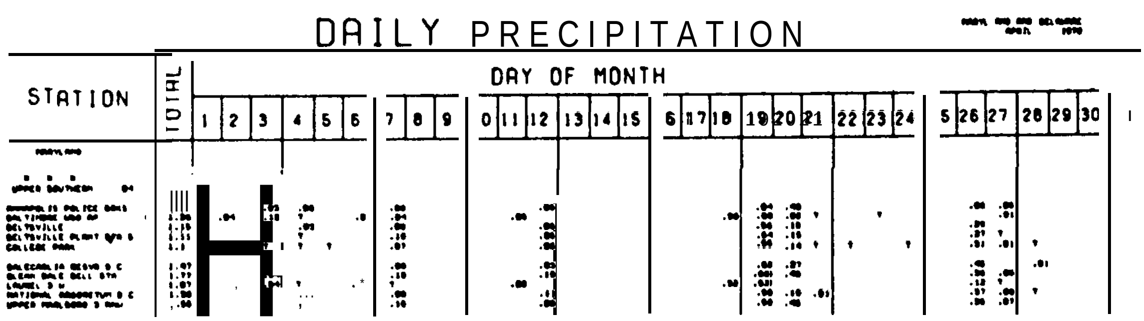
Figure 2.4-1. An Example of the Hourly Precipitation Data (HPD) Issued Monthly by State


MONTHLY SUMMARIZED STATION AND DIVISIONAL DATA

TEMPERATURE	PRECIPITATION

MARYLAND

LOWER SOUTHERN 03


DAILY PRECIPITATION

STATION	TOTAL	DAY OF MONTH
		1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

Figure 2.4-2. An Example of the Climatological Data Issued Monthly by State

ANNUAL CLIMATOLOGICAL DATA
METRIC UNITS

YEAR 1976

State and Station	Temperature – Averages – Daily maximum	Temperature – Averages – Daily minimum	Temperature – Averages – Annual	Temperature – Extremes – Highest	Date	Lowest	Date	Heating degree days	Cooling degree days	Precipitation – Total	Greatest in 24 hours	Date (s)	Snow – Total	Greatest in 24 hours	Date (s)	Relative humidity 1:00 a.m. EST	7:00 a.m. EST	1:00 p.m. EST	7:00 p.m. EST	Wind – Average speed	Resultant speed	Resultant direction	Fastest mile (1.6 kilometers) – Speed	Direction	Date	Average sky cover sunrise to sunset	Number of days – Sunrise to sunset – Clear, 0-0.3	Partly cloudy, 0.4-0.7	Cloudy, 0.8-1.0	Precipitation .25mm or more	Snow 25.4mm or more	Thunderstorms	Heavy fog	Max. temp. 32.2°C and above	Max. temp. 0°C and below	Min. temp. 0°C and below	Min. temp. -17.8°C and below
	°C	°C	°C	°C		°C		Base 18.3°C	Base 18.3°C		mm		mm	mm		%	%	%	%		m/s		m/s			Tenths											
MARYLAND																																					
BALTIMORE	10.[illegible]	7.1	12.8	34.4[illegible]	JUN 22	-15.0[illegible]	JAN 19	265[illegible]	69[illegible]	[illegible]	125	SEP 1-16	340	190	MAR 9	74	77	53	59	1.9	1.4	28	22.4	N4	MAR 13	[illegible]	128	87	151	102	2	35	19	27	11	108	

NORMAIS, MEANS AND EXTREMES

YEAR 1976

State and Station	Elevation Ground (Meters)	Temperature (°C) – Normal (1941-1970) – January – Daily Maximum	January – Daily Minimum	July – Daily Maximum	July – Daily Minimum	Annual	Extremes – Length (Yrs)	Record Highest	Record Lowest	Normal Heating Degree Days (1941-1970) – January	Seasonal	Precipitation (Millimeters) – Normal (1941-1970) – Wettest Month	Driest Month	Annual	Extremes – Wettest Month	Driest Month	Maximum in 24 Hours	Snow – Mean Total – January	Seasonal	Extreme – Maximum in 24 Hours	Relative Humidity (Percent) – January – 7:00 a.m. EST	1:00 p.m. EST	7:00 p.m. EST	July – 7:00 a.m. EST	1:00 p.m. EST	7:00 p.m. EST	Wind Speed (m.p.s.) – Mean Speed – January	July	Fastest Mile (1.6 Kilometers)	Sunshine (% of Possible) – January	July	Annual Mean Number of Days – Sunrise to Sunset – Clear	Partly Cloudy	Cloudy	Precipitation .25mm or More	Snow, Sleet, Hail 25.4mm or More	Thunderstorms	Heavy Fog	Temperature – Max ≥ 32.2°C	Min ≤ 0°C	Min ≤ -17.8°C
MARYLAND							81	42.[illegible]	-40.0							0	375																								
BALTIMORE INTL AP	49	5.5	-[illegible].9	30.4	19.2	12.[illegible]	26	38.9	-21.7	544	2627	107	71	1028	460	7	199	124	546	394	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4.4	3.0	35.[illegible]	[illegible]	[illegible]	106	109	150	112	7	29	29	31	100	•

MAXIMUM SHORT DURATION PRECIPITATION

YEAR 1976

[illegible]

Figure 2.4-3.
An Example of the Annual Summary of Climatological Data

Figure 2.4-3. An Example of the Annual Summary of Climatological Data

LOCAL CLIMATOLOGICAL DATA

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
ENVIRONMENTAL DATA SERVICE

ASHEVILLE, NORTH CAROLINA
NATIONAL WEATHER SERVICE OFC
ASHEVILLE AIRPORT
AUGUST 1975

LATITUDE 35° 26' N LONGITUDE 82° 32' W ELEVATION (GROUND) 2140 FT. STANDARD TIME USED: EASTERN WBAN #03812

Date	Temperature °F Maximum	Minimum	Average	Departure from normal	Average dew point	Degree days base 65° Heating	Cooling	Weather types on dates of occurrence	Snow, ice pellets or ice on ground at 07AM in.	Precipitation Water equivalent in.	Snow, ice pellets in.	Avg. station pressure in. elev. 2170 feet m.s.l.	Wind Resultant direction	Resultant speed m.p.h.	Average speed m.p.h.	Fastest mile Speed m.p.h.	Fastest mile Direction	Sunshine Minutes	Percent of possible	Sky cover tenths Sunrise to sunset	Midnight to midnight	Date
1	83	63	73	-1	66	0	8	2 8	0	0	0	27.86	17	4.6	5.3	10	20	403	58	6	6	1
2	85	61	73	-1	65	0	8	23	0	T	0	27.87	10	2.7	5.6	10	13	612	73	4	5	2
3	88	62	75	1	66	0	10	2	0	0	0	27.81	16	4.0	6.2	13	18	634	76	5	5	3
4	86	63	75	1	68	0	10	2	0	0	0	27.80	17	6.2	7.3	16	23	500	61	6	6	4
5	84	65	75	1	68	0	10	23	0	.29	0	27.76	24	.5	5.8	16	31	318	38	7	7	5
6	75	64	70	-4	67	0	5	8	0	.35	0	27.71	32	2.8	5.2	13	35	0	0	10	10	6
7	75	63	68	-6	65	0	.	1 8	0	T	0	27.84	07	1.8	5.8	12	36	99	7	8	8	7
8	76	58	67	-7	62	0	a	2 8	0	0	0	28.01	18	3.9	4.3	9	15	109	13	9	8	8
9	81	57	69	-5	62	0	0	a 8	0	0	0	28.02	12	1.6	4.2	10	17	341	41	8	8	9
10	71	63	67	-7	66	0	2	2	0	.04	0	27.86	01	4.2	4.8	12	01	0	0	10	10	10
11	83	62	73	0	64	0	8	1	0	0	0	27.80	35	6.7	7.6	15	36	717	88	4	4	11
12	86	59	73	0	64	0	8	1 8	0	T	0	27.82	36	4.2	5.0	12	36	947	57	3	2	12
13	85	60	73	0	64	0	0	2 8	0	0	0	27.94	03	1.6	4.3	10	20	650	80	2	2	13
14	84	59	72	-1	66	0	7	23 8	0	.01	0	27.82	31	2.9	3.2	16	04	394	48	6	5	14
15	87	64	76	3	68	0	11	23 8	0	.10	0	27.88	22	.1	4.5	9	06	456	56	5	5	15
16	87	66	76	3	67	0	11	23 8	0	.31	0	27.87	04	1.8	8.3	16	31	488	60	6	6	16
17	86	63	75	2	68	0	10	23 8	0	.01	0	27.89	35	4.7	5.0	25	35	319	40	8	7	17
18	86	65	76	3	68	0	11	1 8	0	T	0	27.84	36	6.9	7.1	13	34	497	62	6	7	18
19	82	64	73	0	66	0	8	1 3 8	0	.09	0	27.88	32	1.4	6.6	12	24	318	40	7	7	19
20	83	64	74	1	67	0	8	2 8	0	.06	0	27.87	12	.5	4.9	8	13	406	51	4	5	20
21	84	64	74	2	67	0	8	2 8	0	0	0	28.04	10	3.7	5.2	12	18	479	58	3	3	21
22	87	63	75	3	67	0	10	a 8	0	0	0	28.02	02	3.3	5.9	14	34	502	63	5	5	22
23	88	63	76	4	69	0	11	2 8	0	T	0	28.00	34	4.6	5.6	10	34	593	79	3	5	23
24	88	65	77	5	68	0	12	23 8	0	.73	0	27.94	06	1.3	3.9	18	34	493	62	4	4	24
25	88*	63	76	4	67	0	11	2	0	0	0	27.90	34	4.0	6.0	9	35	719	90	3	3	25
26	88	63	75	3	66	0	10	2 8	0	0	0	27.96	34	5.1	5.9	12	33	546	68	4	5	26
27	87	65	76	5	66	0	11	1 3	0	.50	0	28.09	01	2.6	5.9	17	18	304	38	8	8	27
28	80	63	72	1	66	0	7	2	0	.13	0	28.06	13	2.1	6.2	12	18	286	36	8	8	28
29	80	61	71	0	63	0	6	2 8	0	0	0	27.97	18	4.4	4.9	10	13	393	50	6	6	29
30	83	57	70	-1	63	0	5	2	0	0	0	27.94	18	2.2	3.9	9	21	460	58	4	3	30
31	82	60	71	0	65	0	6	23	0	T	0	27.78	29	1.2	4.3	12	20	451	62	8	8	31
Sum	2588	1831				Total 0	Total 252			Total 3.83	Total 0	27.91	02	.7	5.2	23	35	Total 2019	For the month: 52	Sum 183	Sum 179	
Avg.	83.5	62.3	72.9	Dep. 0.1	Avg. 66	Dep. 0	Dep. 8			Dep. -0.87						Date: 17		Normal 3861		Avg. 5.9	Avg. 5.8	

Number of days				Season to date		Number of days		Greatest in 24 hours and dates			Greatest depth on ground of snow, ice pellets or ice and date
Maximum temp. ≥ 90°	≤ 32°	Minimum temp. ≤ 32°	≤ 0°	Total	Total	Precipitation ≥ .01 inch	12	Precipitation		Snow, ice pellets	
0	0	0	0	0	706	Snow, ice pellets ≥ 1.0 inch	0	1.32	16-17	0	
				Dep. 0	Dep. -50	Thunderstorms	10				
						Heavy fog	1				
						Clear 5 Partly cloudy 17 Cloudy 9					

HOURLY PRECIPITATION (WATER EQUIVALENT IN INCHES)

Date	A.M. hour ending at 1	2	3	4	5	6	7	8	9	10	11	12	P.M. hour ending at 1	2	3	4	5	6	7	8	9	10	11	12	Date
1																									1
2			.												1										2
3																									3
4																									4
5													T		.02	.02	TT	T		T	.1	11			5
6						.11	.0	1	T			T	T	.23	.8*	.09	T			T					6
7												T	T												7
8																									8
9																									9
10								T	1	.01	.01		T	T	.01	T	T								10
11																									11
12																T									12
13																									13
14														T						T	.0				14
15																	.01	.06		T					15
16																		.31							16
17															.15	.78	.01			T	T				17
18																				T					18
19									1	T				T	T	.09									19
20															.09										20
21																									21
22																									22
23																*									23
24																.43	.30								24
25																									25
26																									26
27														T	.02	33	TT	.02				.1	.2	T	27
28	.0															34	.06	.01							28
29																									29
30																									30
31																									31

SUMMARY BY HOURS

Hour (local time)	Sky cover (tenths)	Station pressure in.	Temperature Air °F	Dew pt. °F	Relative humidity %	Wind speed m.p.h.	Resultant wind Direction	Speed m.p.h.
01	5	27.9[illegible]	65	65	99	3.0	06	.6
04	6	27.9[illegible]	64	64	100	3.4	35	1.9
07	6	27.9[illegible]	64	64	100	4.1	34	2.5
10	6	27.9[illegible]	70	68	76	6.4	36	3.3
13	6	27.9[illegible]	71	67	63	7.6	05	1.4
16	7	27.9[illegible]	72	67	60	7.6	17	2.4
19	7	27.9[illegible]	69	67	62	5.9	12	.4
22	6	27.9[illegible]	67	66	82	5.7	13	.8

[illegible footnotes]

I certify that this is an official publication of the National Oceanic and Atmospheric Administration, and is compiled from records on file at the National Climatic Center, Asheville, North Carolina, 28801.

DIRECTOR, NATIONAL CLIMATIC CENTER

USCOMM - NOAA - ASHEVILLE 08/18/75

ASHEVILLE, NORTH CAROLINA

Figure 2.4-4. An Example of the Local Climatological Data for Asheville, NC precipitation data. Note that the same information is available on the Hourly Precipitation Data records but that the type of rainfall event is not noted in the latter.

Finally the National Climatic Center prepares a Storm Summary on a monthly basis. This information is of little value to system engineers since it emphasizes the damage done by the storm rather than the meteorological parameters of the storm. For example, the most severe rain event in Asheville, NC, in 1975 occurred on August 24; however, this event is not indicated in the Storm Summary because it apparently caused no significant damage.

2.4.1.2 Rain Gauges. If more information is desired regarding higher rain rates associated with thunderstorms it can be obtained for most first-order Weather Service Office (defined as those offices manned by Weather Service personnel) sites. These sites generally have both tipping bucket and universal weighing gauge precipitation monitors. The tipping bucket gauges generally accumulate the number of 0.01 inch precipitation events in a day which is utilized to collaborate with the accumulation in the other gauges. However, some tipping bucket gauges employ a readout strip chart (triple register chart of operations recorder register) similar to that shown in Figure 2.4-5. By estimating the time between tips the rain rate may be estimated. The location of those stations having triple register charts was not available from the National Climatic Center.

The universal weighing gauge is also capable of providing rain rate information and is the main instrument utilized to provide the 5-minute to 1 hour precipitation data. This measurement is accomplished by reading directly from the 24-hour strip chart on the gauge. An example of one of these strip charts is shown in Figure 2.4-6. These charts are available dating back about 10 years from the National Climatic Center for 25 cents per chart. By measuring the slope of the line, the rain rate to at least 5 minute resolution may be obtained and even l-minute rain rates may be inferred from

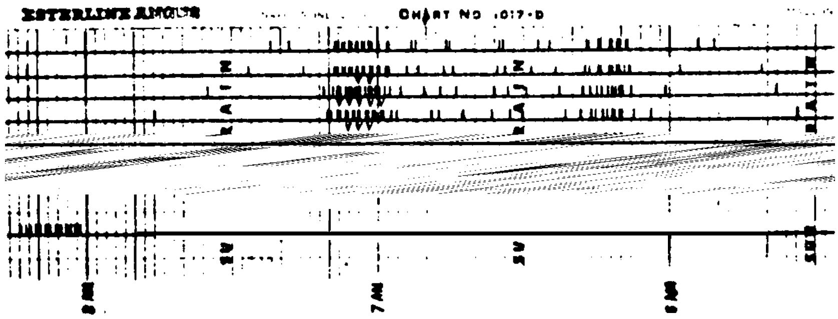


Figure 2.4-5. Example of Operations Recorder Record (from N.W.S. Field Measurements Handbook, No. 1, PG B7-9)

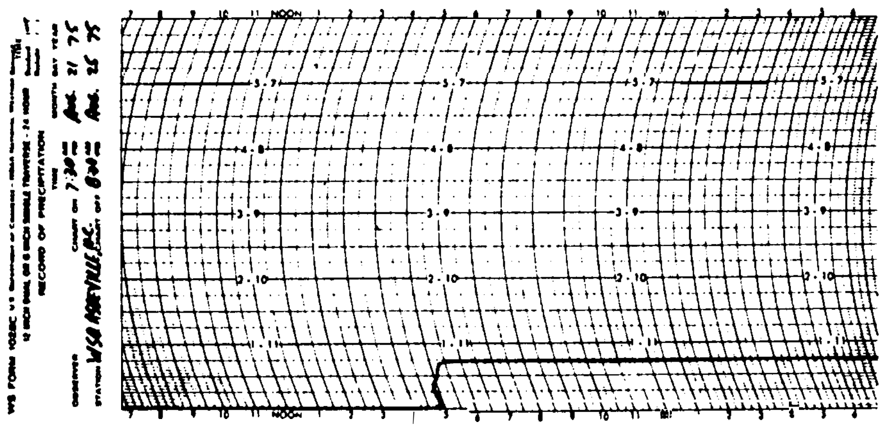


Figure 2.4-6. An Example of a Universal Weighing Gauge Strip Chart

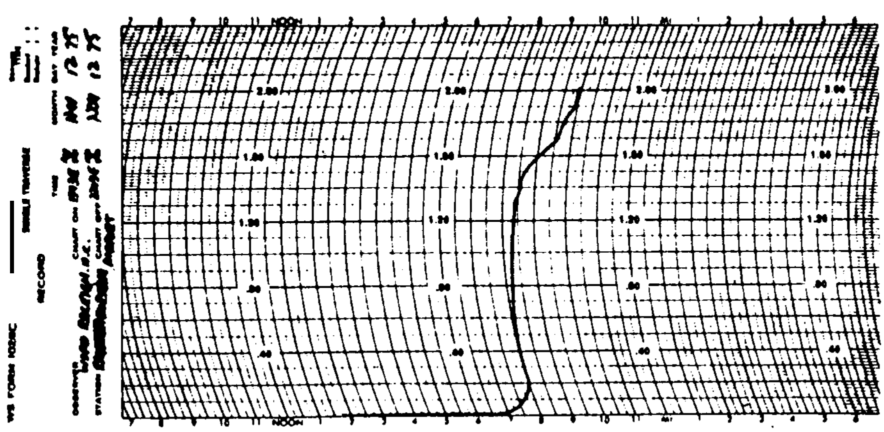


Figure 2.4-7. An Example of an Intense Rain Event

some charts. It appears that these charts are the best source of information for a short duration rate data.

The last automated rain gauge utilized by the U.S. Weather Service is the Fischer-Porter gauge. This unit is a weighing gauge which punches a paper strip chart in a binary "coded decimal (BCD) format every 15 minutes. The gauge may be set to record every 5 minutes, but that resolution is generally not utilized by the Weather Service. The gauge records to only the nearest 0.1 inch.

2.4.1.3 Estimating Rain Rate From Gauge Records. An example of how intense rain rates may be estimated is now given. The dates of the highest rain rate events are found in the CD, Annual Summary. Note that from Figure 2.4-3 the most intense rain rates (0.38 inches in 5 minutes) at the Asheville, NC, WSO occurred on August 24, ending at 1658 Eastern Standard Time. This occurred during a thunderstorm (see Figure 2.4-4) but it was not the most rain in a 24-hour period, which occurred on August 17. The amount of precipitation between 1500 and 1700 EST on August 17 is noted in the LCD in Figure 2.4-4. This process is utilized to determine the list of dates for the high rain rate events. Copies of the rain gauge charts for these dates are then obtained from National Climatic Center. For the August 24 event, the most accurate data appears directly on the gauge readout shown in Figure 2.4-6. By estimating the slope of the cumulative data, the rain rate just before 4 PM was more than 4.56 inch/hr (116 mm/hr) for the first several minutes. Interpolation yields a rate approaching 150 mm/hr for 2 minutes. Another example of a cloud burst is shown in Figure 2.4-7. Herein rain rates approaching 300 mm/hr (12 inches/hr) occurred at 8 PM and contributed to the airline crash at this airport at that time. Clearly the attenuation at a ground station would be significant for this severe 2 minute event (0.00038% of a year).

Bodtmann and Ruthroff (1974) have demonstrated a technique of estimating rain rate distributions directly from these rain gauge charts with l-minute resolution. Since computing derivatives from these charts is notoriously inaccurate, considerable processing is necessary to get accurate results, especially at high rain rates. Figure **2.4-8** is an example of a Dallas, TX rain event cumulative and rain rate (l-minute integration) distribution. Clearly the method is powerful and readily adaptable to field measurements made using a commercial weighing gauge.

2.4.2 Canadian Sources

The Atmospheric Environment Office* prepares several documents containing rain and snow precipitation data. These documents** are:

. Monthly Record - Western Canada - Part 1
- Provinces of British Columbia, Alberta, Saskatchewan and Manitoba
- $23.40 foreign per year
- $ 2.40 foreign per issue

. Monthly Record - Northern Canada - Part 2
- Territories of Yukon and Northwest
- $14.90 foreign per year
- S 1.50 foreign per issue

. Monthly Record - Eastern Canada - Part 3
- Provinces of Ontario, Quebec, Nova Scotia and New Brunswick
- $23.40 foreign per year
- $ 2.40 foreign per issue

• Canadian Weather Review
- published monthly
- covers about 250 surface stations throughout Canada
- $8.40 foreign per year
- $.85 foreign per issue
- available about one month following the date of recording

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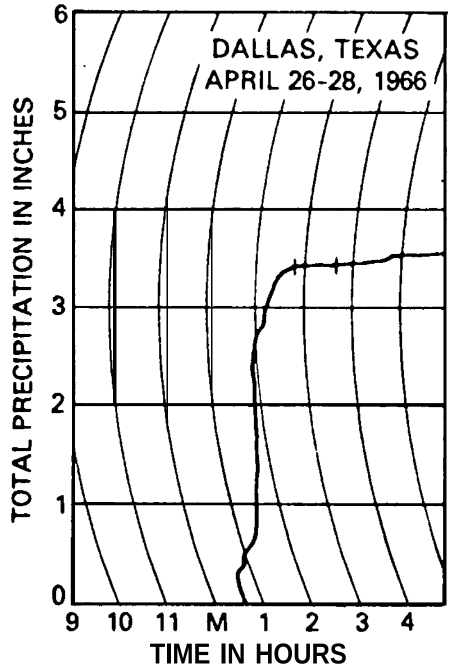
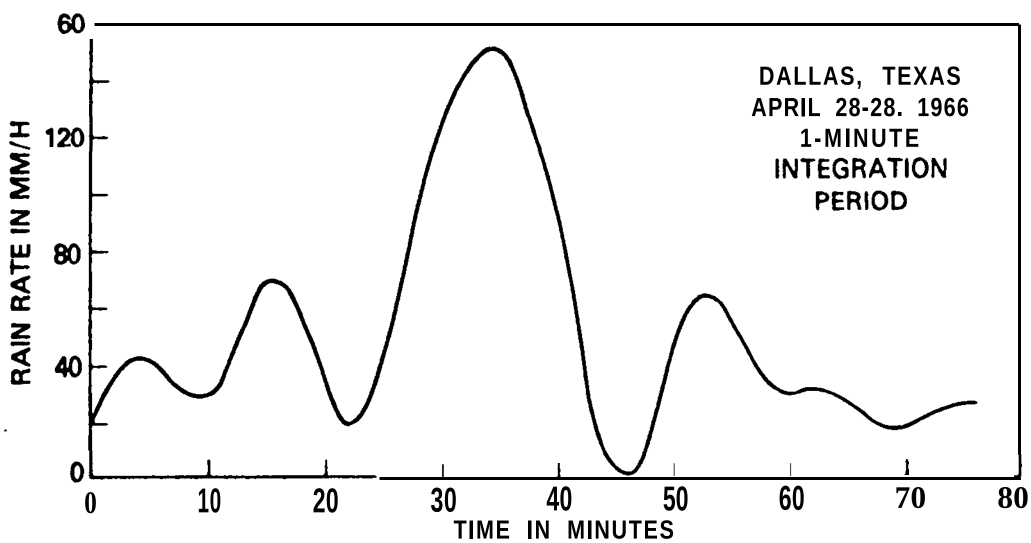
* Head Office, 4905 Dufferin Street, Downsview, Ontario M3H 5T4, Canada

** Available from: Supply and Services Canada, Publishing Centre, Hull, Quebec, KDA 0S9, Canada. Make checks payable to Receiver General for Canada. Canadians should request domestic price schedule.



a) **National Weather Service Weighing Gauge Chart**



b) **Rain Rates vs.** Time Computed From Weighing Gauge Data

Figure 2.4-8. An Example of Generation of Rain Rate Data From a Weighing Gauge Chart

The data in the Monthly Records (available about four months following recording) is of most importance to the earth space path engineer. As shown in Figure 2.4-9, the rainfall, snowfall and total precipitation are given for each day of the month. The Monthly Summary table indicates the number of thunderstorms, etc., and the recording rain gauge data for selected cities is given. These are the maximum amounts for the duration periods indicated on the date of occurrence. In addition, the number of hourly periods with rainfall accumulations between 0.01-0.09, 0.1-0.19, etc., inches is noted. These data are obtained from tipping bucket rain gauges measuring in increments of 0.01 inches.

The tipping bucket rain gauge data is available for many more Canadian locations. The charts from these gauges are available upon request from the Climatological Recording Services Branch of the Head Office in Downsview, Ontario, at a nominal charge.

2.4.3 Worldwide Sources

Many countries prepare meteorological data similar to the U.S. and Canada. Many of these are on file at the National Weather Service Library, Room 816, Gramax Bldg., 13th Street, Silver Spring, MD. One document, the Monthly Climatic Data for the World, does list the number of days per month a station receives more than 1 mm of rain and the total rainfall per month. The data is coarse and can only provide a general indication of the precipitation climate. An example is shown in Figure 2.4-10. This document was discontinued with the December 1980 issue, but back issues are available for $4.20 per monthly copy from the National Climatic Center.

2.5 ESTIMATION OF RAIN RATE

The rain rate measurement is an inexact process because of the discrete nature of rainfall. Obviously, because rain falls as raindrops, the rain rate is computed by measuring the rain accumulation per given" a` -a for a known period of time at a point. The shortest period of time reported by the U.S. and Canadian

TABLE/TABLEAU 2

PRECIPITATION

MARCH 1977 MARS

STATION		TOTAL	% OF NORMAL / % DE LA NORMALE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	●●●
ONTARIO ONTARIO																																			
OTTAWA BRITANNIA	R/P	[illegible]					2.3	1.0							1.0	[illegible]	2.0	1.0													7.4	1.3	1.8		
	S/N	[illegible]			T																		0.5	0.3	[illegible]										
	P	[illegible]			T		2.3	1.0							1.5	[illegible]	2.0	1.0					0.5	0.3	[illegible]						7.4	1.3	1.8		
OTTAWA CDA	R/P	[illegible]	[illegible]				2.8	1.3							[illegible]	17.0	5.1	3.0						0.3							6.4	0.3	1.0		
	S/N	[illegible]	[illegible]	T	T		T	0.3	T	T										T			1.0	0.5	[illegible]	0.5									●
N	P	[illegible]	[illegible]	T	T		2.8	1.5	T	T					[illegible]	17.0	5.1	3.0		T			1.0	0.8	[illegible]	0.8					6.4	0.3	1.0		
OTTAWA INT'L A	R/P	[illegible]	[illegible]				0.4	0.4							T	[illegible]	12.5	T	1.0					0.2							[illegible]	1.4	1.4		
	S/N	[illegible]	77	T	T		0.5	1.2	T	T										T			1.1	T	[illegible]	2.0									●
N	P	[illegible]	[illegible]	T	T		0.9	1.4	T	T					T	[illegible]	12.5	T	1.0	T			1.1	0.2	[illegible]	2.7					[illegible]	1.4	1.4		
OTTAWA NRC	R/P	[illegible]	[illegible]				11.7									[illegible]	4.1	2.5	0.3												10.2		[illegible]		
	S/N	[illegible]	[illegible]					T		T													0.3		[illegible]										●
	P	[illegible]	[illegible]				11.7	T		T						[illegible]	4.1	2.5	0.3				0.3		[illegible]						10.2		[illegible]		

[illegible]

MARCH 1977 MARS

RECORDING RAIN GAUGE DATA/DONNEES DES PLUVIOGRAPHES

TABLE/TABLEAU 7

STATION	MAXIMUM AMOUNTA (.01 inch) HAUTEUR MAXIMUM (en .01 de pouce) FOR DURATION INDICATED - WITH DATES OF OCCURENCE POUR LES DUREES MENTIONEES ET DATES																HOURLY RAINFALL CHUTE DE PLUIE HORAIRE No. of occurrences in ● — per storm					
	5 min.		10 min.		15 min.		30 min		60 min		120 min		6 hr.		12 hr.							
	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	AMOUNT VALEUR	DATE	.01–.09	.10–.19	.20–.49	.50–.99	1.00–1.99	2.00 or more ou plus
ONTARIO ONTARIO																						
OTTAWA INT'L A	04	30	05	04	08	13	13	13	19	04	32	13	78	13	111	13	46	11				
SAULT STE MARIE A	04	12	05	12	08	12	15	12	27	12	35	12	71	12	77	12	43	6	3			
SIMCOE	06	04	11	12	15	12	25	12	32	12	49	12	103	12	129	12	40	6	2			
SIOUX LOOKOUT A ●	02	27	03	27	04	27	08	27	13	27	13	27	14	27	14	27	3					
SUDBURY A ●	M		M		M		M		M		M		M		M		M	M				

RCH 1977 MARS

MONTHLY SUMMARY

STATION	NUMBER OF DAYS WITH / NOMBRE DE JOURS AVEC										
	TEMPERATURES ≤ 0.0°C	THUNDERSTORMS ORAGES	RAIN OR DRIZZLE PLUIE OU BRUINE	FREEZING PRECIPITATION PRECIPITATIONS SE CONGELANT	HAIL GRELE	SNOW NEIGE	MEASURABLE PRECIPITATION PRECIPITATION MESURABLE	FOG BROUILLARD	SMOKE OR HAZE FUMEE OU BRUME SECHE	DUST OR BLOWING SAND POUSSIERE OU SABLE CHASSE ELEVEE	BLOWING SNOW CHASSE NEIGE ELEVEE
TARIO											
NORTH BAY A	24	1	6	1		7	12	5	1		
OTTAWA INT'L A	22	1	9	1		5	12	11	8		1
PETAWAWA A	27	1	8	1		4	10	5	4		
PETERBOROUGH A	28	2	8	1		5	12	2	6		1
PICKLE LAKE	31		3	3		10	12	3			1

Figure 2.4-9. Examples of the Canadian Monthly Record Precipitation Data

SURFACE DATF OCTOBER 1977

STATION	LATITUDE	LONGITUDE	ELEVATION	NUMBER OF DAYS OF OBSNS.	PRESSURE MEAN STATION	PRESSURE MEAN SEA LEVEL	TEMPERATURE MEAN	TEMPERATURE DEPARTURE	VAPOR PRESSURE MEAN	VAPOR PRESSURE DEPARTURE	PRECIPITATION NO. OF DAYS ≥ 1 MM.	PRECIPITATION TOTAL	PRECIPITATION DEPARTURE	SUNSHINE PERCENTAGE OF LONG-TERM AVERAGE
	° '	° '	METERS		MB	MB	°C	°C	MB	MB		MM	MM	%
CANADA-EASTERN														
ALERT	82 30 N	62 20 W	63	31	1003.7	1012.2	-18.9	. 0.9	1.1	-0.1	4	9	- 7	
EUREKA	80 00 N	es 66 W	10	31	100FJ. S	1009.9	-21.0	. 0.5	l .2	.0.1	1	4	- 3	
RESOLUTE	74 43 N	94 59 W	67	31	998.0	1006.9	-14.3	. 0.3	2.1	.0.2	6	22	. 6	106
CL1OC	70 27 N	68 33 H	6	31	1002.1	1005.4	- 7.s	- 1.2	3.2	-0.3	11	55	. 21	
HALL BEACH	68 47 N	81 ls W	8	31	1004.9	1005.8	- 9.4	. 1.6	3.0	+0.2	9	27	+ 4	
BAKER LAKE	64 18 N	96 00 W	13	31	1007.0	1008.6	- 5.1	● 2.4	4.0	.0, s	10	57	. 37	
CORAL HARBOUR	64 12 N	83 22 W	64	31	999.0	1OO-J.3	- 5.8	● 2.2	3.9	● 0.4	16	46	. 17	
FROBISHER BAY	63 4S N	60 33 W	34	31	1002.3	1006.7	- 3.8	. 0.9	4.0	.0.2	13	52	. 18	97
CHuR CHILL	SO 45 N	94 04 W	29	31	100s. s	1009.1	2.5	: 3.6	5.7	.0.6	6	23	. ls	142
INOUCDJOUAC	6S 27 N	78 07 N	6	31	1008.1	1008.7	1.7	: 2.1	6.3	.0.7	14	71	. 22	131
FORT CHIMO	58 06 N	68 '2s W	37	31	1004.4	1009.1	0.1	● 0.4	5.4	.0.2	12	4s	. 9	
TROUT LAKE	53 SO N	89 S2 N	220	31	987.0	1014.2	4.9	. 3.1	6.2	-0.1	5	47	- 6	
NITCHEQUON	53 12 N	70 S4 W	S36	31	948.7	1014.0	0.9	: 0.3	5.,7	0.0	13	64	- 16	
MOOSONEE	S1 16 N	80 39 W	10	31	1013.4	1014.7	5.3	1.4	6.8	-0.4	6	58	- 15	173
ARMSTRONG	SO 17 N	88 54 H	323	31			4.1	. 1.0			5	34	- 2s	147
KAPUSKASJNG	49 25 N	82 28 N	227	31	998.4	1016.S	4.3	- 0.3	6.S	-0.6	9	69	- 3	
IX RRLO1ON	49 42 N	86 S7 N	331											
SEPT-ILES	60 13 N	6S 16 N	6S	31	1006.6	1013.4	4.0	. 0.9	6.s	-0.2	14	157	. 74	107
GOOSE	S3 19 N	60 2S N	49	31	1005.2	1011.3	3.2	0.0	5.9	-0.1	10	78	. 1s	102
NORTH BAY	46 2? N	79 26 N	371	31	972.4	1017.4	5.4	- 1.2	7.2	-1.0	9	62	- 22	128
MANIWAKI	46 2S N	75 so W	170	31	995.8	1016.7	5.8	- 1.1	7.2	-0.9	9	63	- 5	106
TORONTO/MALTON INT AP	43 41 N	79 S8 N	173	31	996.2	1017.3	8.0	- 1.5	8.5	-1.1	6	69	● 10	
MONTREAL/DORVAL INT AP	4S 28 N	73 46 W	36	31	1011.6	1016.0	7.6	- 1.4	8.5	-0.4	11	113	. 3s	
BAGOTVILLE	40 20 N	71 00 N	159	31	99S.6	101s.2	5.6	- 0.1	6.7	-0.6	10	61	- 2	
CHATHAM	47 01 N	6S 27 N	34	31	1009.6	1013.7	7.2	- 0.2	8.1	-0.2	16	257	+174	87
STEPHENVILLE	40 S2 N	so 33 W	26	31	1009.6	1012.8	7.6	. 0.6	8.4	0.0	17	183	. 84	
GANDE R I NT AP	48 57 N	69 34 W	151	31	993.8	1012.4	6.3	0.0	6.1	.0.1	14	127	● 26	90
SHEARWATER	44 38 N	63 30 W	51	31	1008.7	1015.0	9.8	: 0.2	10.2	0.0	13	142	. 33	108
SYDNEY	46 10 N	so 03 W	62	31	1006.8	1014.4	8.7	0,4	8.7	-1.1	13	130	. ls	70
SHELBURNE	4S 43 N	SS IS N	30											
SABLE ISLAND	43 6S N	60 01 N	4	31	1015.4	1015.9	11.7	. 0.1	11.7	0.0	14	122	. 12	70
ST. JOHN'S (TORBAY)	47 37 N	52 4s W	141											
ST PIERRE AND MIQUELON														
ST PIERRE	46 46 N	S6 10 44		31	1013.9	1014. s	9.1	● 0.2	9.8	.0.4	13	87	- so	112
UNITEDSTATES-NORTHEAST														
INTERNATIONAL FALLS	48 34 N	93 23 N		31	97s .0	1016.7	6.3	- 0.1				20	- 23	
DULUTH	46 SO N	92 11 W		31	976.4	1017.3	6.0	- 0.6				81	. 23	104
ST. CLOUD	45 35 N	94 11 W		31	979.0	10 17.6	1.0	- 0.9						
SAULT STE. MARIE	46 28 N	84 2? W		31	993.0	1016.8	7.1	- 0.8	8.1	0.0	8	47	- 25	81
BURLINGTON	44 28 N	73 09 W		31	1001.8	1016.6	8.1	- 1.2	8.2		10	126	. 58	88
CARIBOU	46 52 N	68 01 W		31	991 .s		6.4	- 0.2				1 3s	. 51	
DES MOINES	41 32 N	93 39 W		31	986.8	1018.0	11.3	. 1.1	9.4	-0.2	10	130	. 7s	82
COLUMBIA	38 49 N	92 13 W		31	990. 1	1018.5	13.1	- 1.3				112	• 26	85
CHICAGO	41 47 N	87 4s W		31	99S.6	1018.3	11.0	- 2.0	8.9	-0.8	9	42	- 24	76
ST. LOUIS	38 4S N	90 23 W		31	998.3	1018.9	13.1	- 2.0	11. s	.0.7	7	96	. 2s	94
DAYTON	39 S4 N	84 13 W		31	985.8	1018.6	11.0	- 2.1	8.6		9	98	. 49	76
COLUMBUS	40 00 N	82 63 W		31	986. S	1018.5	13.1	- 1.3	8.3	-1.9	9	6S	. 17	85
BUFFALO	42 S6 N	78 44 W		31	989.3	1017. S	9.0	- 1.1	9.1	0.0	9	66	- 10	91
NEW YORK LA GUARDIA	40 46 N	73 54 W		31	100s.4	1016.9	12.7	- 1.8	11.1	-0.3	2	148	. 73	
BOSTON	42 22 N	71 02 W		31	1011.4	1016. o	12.9	- 0.1	11.2	.0.6	2	118	. 41	85
BLUE HILL OBS	42 13 N	71 07 W		31	992. 1	101s..2	10.7	- 1.1	10.6	.0.6	12	163	. 71	89
CHATHAM	41 40 N	69 SO W												
MQSRINC1ON DULLES	38 57 N	77 27 W												
WASHINGTON NATIONAL	38 51 N	77 02 W		31	1013.5	1017.8	15.0	- 0.4	11.0	-0.7	7	136	. 68	84

Figure 2.4-10. An. Example of the Monthly Climatic Data for . the World

Weather Services is five minutes. Assuming the rain rate is uniform for that period of time, the computed point rain rate and the "instantaneous" point rain rate are equal. However, the question arises as to how the apparent rain rate varies as the integration (computing) time is varied. This effect has been addressed experimentally by experimenters at the Bell Telephone Laboratories.

At Holmdel, NJ, measurements (Bodtmann and Ruthroff-1974) of the apparent rain rate versus the gauge integration period over a 2-year period have yielded the results in Figure 2.5-1. These results extend from 1.5 seconds to 2 minutes and are normalized to a one-minute integration time. Unfortunately, the measurement do not extend to a 5-minute integration time which would be *very* convenient for comparison of the Lin model with other rain models which employ a one-minute integration period (see Chapter 3). The variation between a 2-minute and a 5-minute integration time is expected to be significant for high rain rates. However, Figure 2.5-1 clearly shows that for rain rates below 50 mm/h the error due to the integration time is small. This effect arises because the low rain rate events tend to be spatially and temporally uniform, while the rain rates between 50 and 120 mm/h are dominated by spatially and temporally nonuniform convective rains.

Only the most severe cells create rain rates above 120 mm/h and these are highly variable. Therefore, a significant peak rain rate two or three times as high as the one-minute average can occur for one second during the one-minute period. As an example, a typical rain rate versus time profile comparing the one-minute and ten-second integration times is shown in Figure 2.5-2 (Bodtmann and Ruthroff-1974) .

The impact of varying integration times can be significant for both the measurement of cumulative rain rate statistics (related to cumulative attenuation statistics) and rain rate duration measurements (related to attenuation fade duration). Lin (1978) has experimentally determined the effect of the integration time on cumulative statistics. The results for Palmetto, GA are shown in

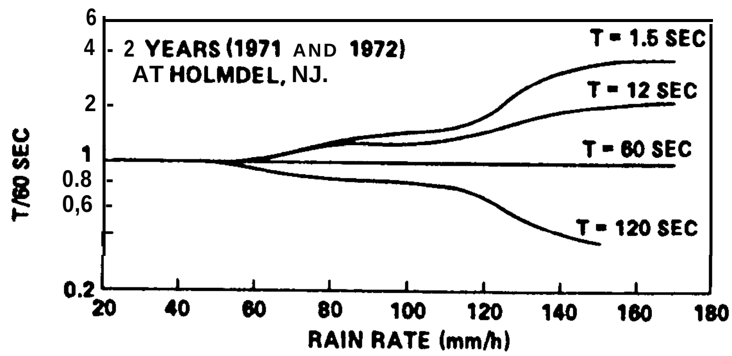


Figure 2.5-1. Rain Rate Distribution Versus Gauge Integration Time

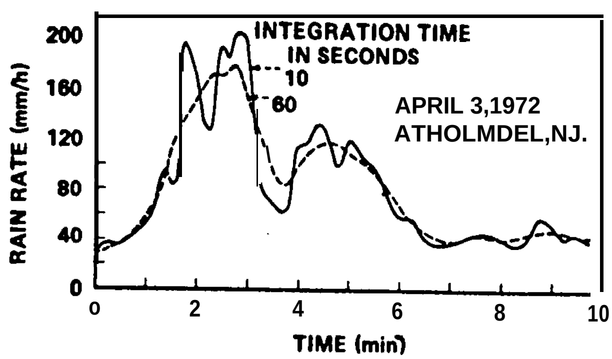


Figure 2.5-2. Integrating Rain Gauge Results for Two Integration Times

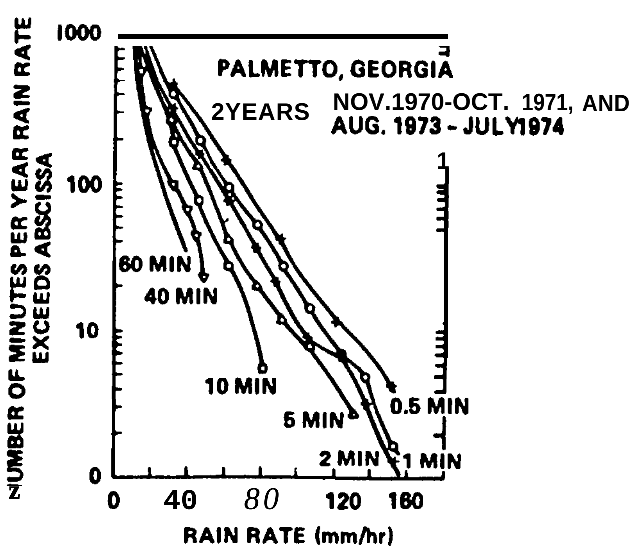


Figure 2.5-3. Cumulative Rain Rate Statistics Versus Integration Period

Figure 2.5-3. Clearly the difference between a l-minute and 30-second integration time is significant. Similar results for rain rate duration statistics are not available.

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