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Statistics of attenuation by rain of 13 GHz signals on earth-space paths in Canada

by
R.V. Webber, J.I. Strickland and J.J. Schlesak

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TABLE OF CONTENTS

1. INTRODUCTION 1

2. EXPERIMENT 1

3. CLIMATE 2

4. THEORY AND DATA REDUCTION 3

5. ATTENUATION DISTRIBUTIONS 7

   5.1 Monthly Attenuation Distributions 7

   5.2 Yearly Attenuation Distributions 7

   5.3 Average Monthly Attenuation Distributions 13

   5.4 Composite Annual Attenuation Distributions 20

   5.5 Attenuation at Fort Smith 20

6. WORST MONTH SATISTICS 22

   6.1 Average Worst Month Attenuation Distributions 22

   6.2 Worst Month Seasons 22

   6.3 Relations for Worst Month Statistics 25

7. DIURNAL STATISTICS 28

8. FADE DURATION STATISTICS 29

9. FADE RATE STATISTICS 34

   9.1 Selection and Processing of Data 34

   9.2 Maximum Fade Rate 34

   9.3 Fade Rate Distributions 34

   9.4 Dependence of Fade Rate on Attenuation Level 37

   9.5 Fade Rate Durations 37

10. DISCUSSION 41

   10.1 Attenuation 41

   10.2 Fade Rates 41

   10.3 Independence of Statistics at Different Stations 42

11. REFERENCES 43

1. INTRODUCTION

To accomodate the increased number of users of radio signals, communications systems are being designed more and more to operate at microwave frequencies that have hitherto been unused. A major difficulty with frequencies above 10 GHz is that they are attenuated by rain. To meet the reliability specifications of a satellite communication system that is to operate at these frequencies, a designer must be able to estimate the fractions of time in an average year, or in an average worst month, for which given attenuations will be exceeded on an earth-space path. These estimates are based on the measured attenuation statistics that are available from various locations around the world. Also, a knowledge of the fade rate statistics for these paths is necessary if the effect of the attenuation is to be overcome by up-link power control or site diversity arrangements.

This report presents attenuation statistics and fade rate statistics from six new locations, all in Canada, for 13 GHz signals on earth-space paths. These statistics are based on a total of 15.7 station-years of attenuation measurements with the operating times of the individual stations ranging from 1.68 years to 4.91 years. The operating time of 4.91 years is among the longest that have been reported for the monitoring by radiometer of a single earth-space path. The COST project in Europe, which has a total of 71 station-years of radiometer data, has reported operating times of 7.6 years for Stockholm, 7.4 years for Fucino and 6.2 years for Graz, all at 11.7 GHz [1]. Of those stations from outside of Europe that are in the CCIR data base [2] the one with the longest operating time is Clarksburg, USA with 4.0 years at 11.6 and 12.0 GHz.

Many of the statistics in this report have been published elsewhere[3,4] but in less detail than is given here.

2. EXPERIMENT

In 1972 radiometers were installed at seven locations across Canada to measure the statistics of rain attenuation at 13 GHz along the path from each station to a geostationary orbital position at 114 degrees west longitude. The construction, calibration and testing of the equipment has already been reported [5]. The locations were chosen to represent the Atlantic and the Pacific maritime climates and various continental climates; they are shown on the map in figure 1.

Figure 1. Map of Canada showing locations of radiometers.

The seven radiometers began operation in 1973, with the output being recorded every second on digital magnetic tape in 10-minute blocks. Recordings at Ottawa, Allan Park, Thunder Bay, Melville and Lake Cowichan continued into 1977 while those at Mill Village continued into 1979. Operations at

Fort Smith lasted about two years but provided no good attenuation data. All radiometers had periods of up to several months duration when, due to component failure, they were malfunctioning or were out of service. Table 1 lists latitude, longitude, some meteorological information and the operating times for each location as well as the elevation angle of each antenna beam [5,6,7].

TABLE 1

Characteristics of radiometer sites

Location	Long (deg W)	Lat (deg N)	Annual rain (cm)	Thunder storm-days	Jan mean daily max (deg C)	Jan mean daily (deg C)	El (deg)	Op time (years)
Mill Village, N. S.	64.5	44.5	130	10	+0.8	-3.9	20	4.91
Ottawa, Ont.	75.9	45.3	66	23	-6.4	-10.8	26	1.68
Allan Park, Ont.	80.9	44.2	76	24	-3.5	-7.3	29	1.72
Thunder Bay, Ont.	89.4	48.4	53	26	-9.4	-15.4	30	1.98
Melville, Sask.	102.8	50.9	28	20	-14.5	-19.8	31	2.52
Fort Smith, N. W. T.	111.9	59.9	22	12	-21.7	-26.8	22	-
Lake Cowichan, B. C.	124.1	48.8	197	3	+5.2	+2.6	33	2.93

3. CLIMATE

In choosing locations for the radiometers, an attempt was made to include, insofar as possible, climates representative of the major climatic areas of Canada. These range from the Atlantic and Pacific maritime climates to various continental regimes.

Mill Village is located near the Atlantic coast of Nova Scotia. Of all the radiometer locations, it has the second largest annual rainfall(Table 1) but has an average of only 10 thunderstorm days per year. It lies in the track of many of the storms which proceed up the east coast of North America. Rain occurs during all months of the year, and can last on and off for periods of many days.

Lake Cowichan experiences a Pacific maritime climate. It is located in a narrow valley on Vancouver Island off the Pacific coast of mainland Canada. The Coastal Range is located a short distance to the east on the mainland with mountains rising in excess of 2000 meters. There is very little heavy rain but a great deal of widespread drizzle, which falls mostly in the winter months and results in the largest annual rainfall of all the radiometer locations. The rain extends to only moderate heights above ground level and there are an average of only 3 thunderstorm days per year. July and August are dry months.

The remaining sites experience continental climates with cold winters and large annual variations in temperature ranging from maxima of $32-34°$ C to minima lower than $-40°$ C, at least at Thunder Bay and Melville.

Melville is located in south-eastern Saskatchewan, surrounded by prairie for many hundreds of kilometers. The land is only very slightly rolling, and contains no large bodies of water, particularly to the west. The annual accumulation of rain is 28 centimeters with an average of 20 thunderstorm days per year. The winters are very cold with virtually no rain. Summers are hot, and the rain tends to come in short, intense showers.

Although separated by approximately 1500 kilometers, the climates of Ottawa and Thunder Bay are similar. The average accumulations of rain are moderate and the number of thunderstorm days are 23 and 26, respectively. Even though Thunder Bay is on the shore of the largest and coldest of the Great Lakes, the dominant storm motion is from the woods and prairie to the west, and the effect of the lake is less than might be expected.

Allan Park, the most southerly location, lies to the leeward of Lake Huron at an altitude of more than 300 meters above the lake. Since Lake Huron is more than 100 kilometers wide, the air moving across the lake has ample opportunity to pick up moisture and deposit it on the high land. This area has an average of 24 thunderstorm days per year and the greatest annual accumulation of rain in the province of Ontario.

4. THEORY AND DATA REDUCTION

A radio signal at 13 GHz that travels along an earth-space path will be attenuated by any rain that may be on the path. For a radiometer with its beam pointed along that path, the measured antenna temperature T is related by radiation transfer theory to the attenuation A of the signal by

$$A = 10 \, log\left(\frac{T_m - T_{cs}}{T_m - T} \right) \qquad (1)$$

where T_{cs} is the measured antenna temperature when the sky is clear and T_m is the effective temperature of the rain.

Since rain occurs for only a small percentage of the time, the antenna temperature of the radiometer for most of the time is T_{cs}. To estimate an average value for T_{cs} the radiometer response when the antenna was pointed at a clear sky was compared with the response when the instrument was connected to a termination that was immersed in liquid nitrogen. A value of 90° K for T_{cs} gave the best overall consistency in the results.

In a separate experiment that was carried out at Ottawa a value for T_m was determined by comparing the attenuation calculated from radiometric measurements of sky noise temperature with that measured directly along the same path using the ATS-5 beacon at 15.3 GHz[5]. Over an entire season, the best agreement was obtained for an effective rain temperature of 272° K. This figure is regarded here as merely a curve fitting parameter and no significance is attached to its being 1 degree below the freezing point of water. With this method of determining T_m, attenuation caused by scattering is taken into account and need not be considered further.

The output of each radiometer used in this experiment was recorded according to an arbitrary scale which was linearly proportional to the antenna temperature. Therefore, equation (1) may be written

$$A = 10 \, log\left(\frac{R_m - R_{cs}}{R_m - R} \right) \qquad (2)$$

where R_m, R_{cs} and R are the points on the scale which correspond to the antenna temperatures T_m, T_{cs} and T, respectively.

Radiometer data with the lowest non-zero variance were assumed to represent clear sky temperatures. A record was identified as a clear sky event if the variance of its data was less than a pre-selected threshold.

The threshold was chosen as low as possible but large enough for there to be at least one clear sky event each day in at least 99 percent of the days. The value of R_{cs} was determined for each day by computing the mean of all the data in all clear sky events for that day. If there was no clear sky event in a given day the value of R_{cs} from the previous day was retained. The value of R_{cs} was used as one calibration point on the radiometer scale. A second calibration point R_{cal} was obtained by covering the antenna feed with microwave absorbing material at room temperature; the antenna temperature was then assumed to be 295° K. This calibration was normally done at intervals of 1 to about 10 days with a few occasions when the interval was longer than 10 days. Once at Mill Village there was a lapse of several months with no calibration; during that time the radiometer was quite stable and an extrapolated mean value was used for R_{cal}. The gain and the offset of each radiometer were adjusted so that R_{cal} and R_{cs} were separated by about half the dynamic range of the instrument.

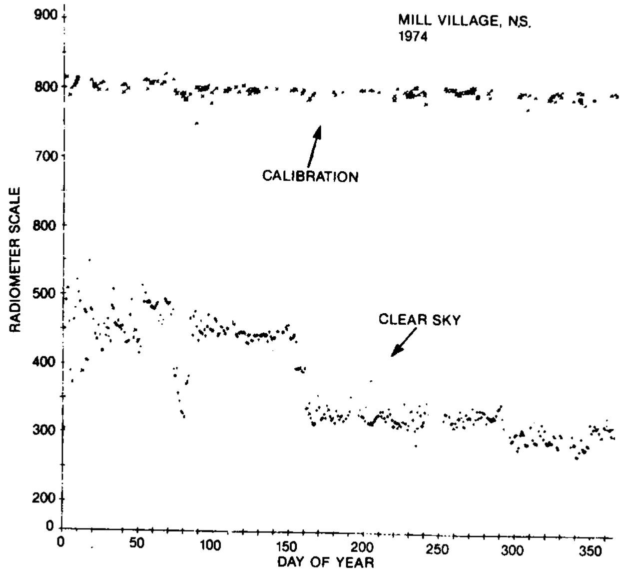


Figure 2. Clear sky values R_{cs} and calibration values R_{cal} for Mill Village 1974.

Figure 2 is a plot of R_{cs} and R_{cal} over the year 1974 for Mill Village. The plot for R_{cal} has a small negative slope and an rms deviation from the best fit straight line of 7 units on the ordinate scale or about 2.5 K. For about half the time the variability of R_{cs} was like that shown in the right half of figure 2. Much of this variation can be attributed to seasonal and daily changes in the temperature and humidity of the atmosphere. For the other half of the time, however, R_{cs} was more variable as in the left half of figure 2. These larger variations would be caused by small changes in the characteristics of the radiometer components that affect amplifier gain. At the higher end of the radiometer scale the reading is much less sensitive to these small changes than at the lower end and the observation that R_{cal} was much more stable than R_{cs} was not unexpected. Figure 2 also shows that R_{cs} and R_{cal} were independent of each other.

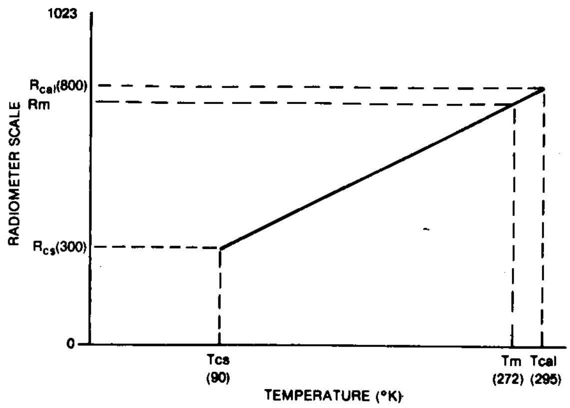


Figure 3. An illustration of the interpolation that was used to find R_m.

Figure 3 illustrates how T_{cs}, T_{cal} and T_m were used to obtain R_m by a linear interpolation between R_{cs} and R_{cal}. It may also be observed in figure 3 that the value obtained for R_m is much less sensitive to variations in R_{cs} than to variations in R_{cal}. The radiometer data were converted to attenuations by a table which was reset according to equation (2) whenever a new value was found for either R_{cal} or R_{cs}.

There were about 1.5 million 10-minute periods of data to be analysed. Of these, more than 98 percent were free of any rain attenuation and about 10,000 were calibration events. Routines were written to identify records that contained attenuation events and calibration events. The test for an attenuation event was based on the observation that attenuation caused by rain has a relatively high variance. If the variance of the radiometer data in a 10-minute record exceeded a specified threshold that record was identified as an attenuation event. This threshold was well above the threshold that was used to identify clear sky events but was low enough to ensure that all valid attenuation events were identified plus a few invalid ones. Attenuation events with any attenuation over 1.0 dB as well as calibration events were saved and were also plotted automatically; an inspection of these plots enabled bad records of either kind of event to be identified and later eliminated. An example of a calibration event is shown in figure 4 where the radiometer output is plotted as a function of time. For each day a summary record held the means and the variances of the data in each of the 144 ten-minute records.

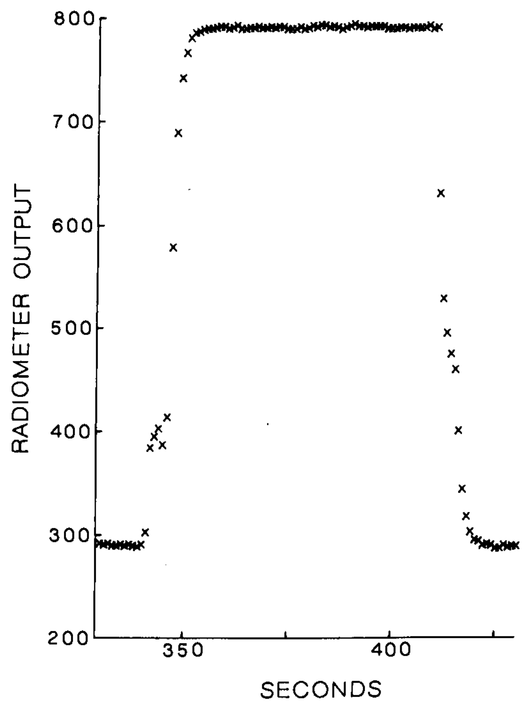


Figure 4. A plot of the radiometer output as a function of time for a calibration event.

The time that the radiometer was assumed to have been operating, the time base, includes every day for which a summary record was obtained, with any outage time subtracted. However, if for three weeks of recording time there were many spurious data but no valid ones, the radiometer was assumed to have gone out of order. Operating time after the end of the three-week period was not included unless the radiometer had been repaired. Although simple and easy to to apply, this method, no doubt, over-estimates the time base, so that in the results that follow, the fractions of time that attenuations are exceeded should be understood as minima rather than as exactly determined quantities. The time bases of the six radiometers are shown schematically in figure 5 and the net operating times are listed in Table 1. Of course, the statistics for Mill Village, since it had the longest operating time, will be the most reliable.

In the compilation of attenuation distributions, attenuation thresholds were chosen and a count was made of the number of seconds that each threshold was exceeded. The results of this count will be referred to as the "unnormalized distribution". In most cases the modifier "unnormalized" will be dropped when the number of seconds that a threshold was exceeded is converted to the fraction of operating time that the threshold was exceeded; when emphasis is needed the term "normalized distribution" will be used.

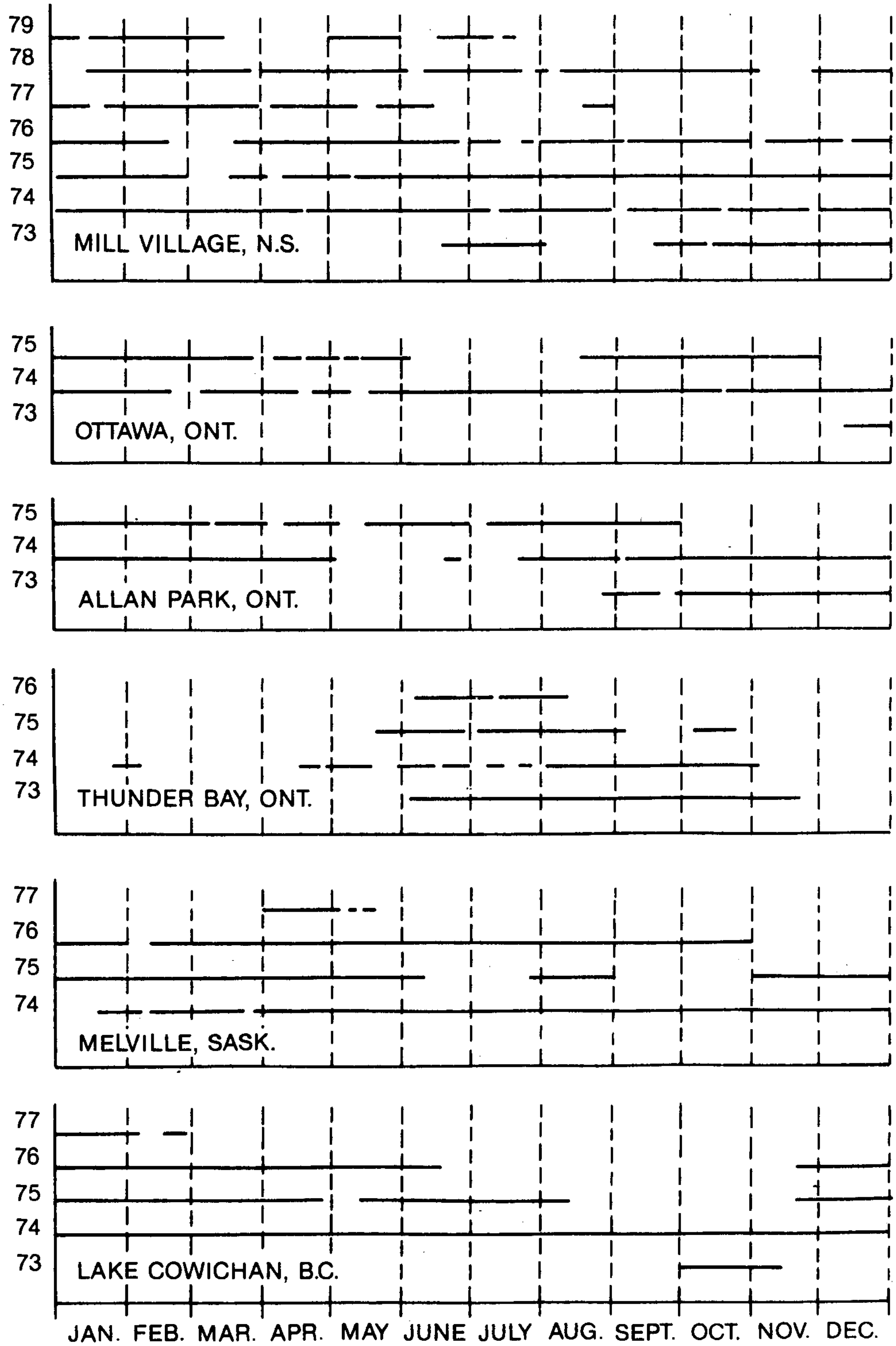


Figure 5. Time bases; horizontal lines represent times when the radiometers were operating.

The lowest and the highest thresholds were always 1 dB and 10 dB, respectively, and between these limits thresholds were separated by the same increment; the increment, however, may change for different distributions.

5. ATTENUATION DISTRIBUTIONS

5.1 Monthly Attenuation Distributions

At any one station there were major differences from year to year in the attenuation distributions for a given calendar month. To illustrate these differences some of the monthly attenuation distributions from Mill Village and Melville will be discussed.

Figure 6 shows the attenuation distributions for Mill Village for each month of January in the years 1974-79. In these separate months of January the attenuation that was exceeded for 1×10^{-5} of the time ranged from 4 dB to more than 10 dB. An attenuation of 1 dB was exceeded for from 0.02 to 0.06 of the time. Figure 7 shows similar plots for the same station for the months of July 1973-79, with July 1977 missing. Among those months the fraction of the time that the attenuation exceeded 1 dB varied from 4×10^{-3} to nearly 0.03; these figures overlap the corresponding range for the months of January. In one month of July the attenuation that was exceeded for 1×10^{-5} of the time was less than 6 dB; in other months of July the attenuation was over 10 dB for up to 2×10^{-3} of the time.

At Melville in 1974 and 1976, as shown in figure 8, the month of January had a small amount of attenuation just above 1 dB, but January 1975 had none. In the same figure it is shown that the months of July 1974 and 1976 both had attenuation exceeding 10 dB, with the amount in 1974 being about four times the amount in 1976. There were no data for July 1975.

By comparing figure 8 with figures 6 and 7 it may be observed that for the Januarys the attenuation distributions for Melville are well below those for Mill Village, whereas for the Julys the two sets of curves overlap each other.

5.2 Yearly Attenuation Distributions

A yearly attenuation distribution was derived from all data that were available for each calendar year at each station. In this distribution each month is given equal weight regardless of how much of the month the equipment was down. (Later, in section 5.4 the composite annual attenuation distribution is presented. It is a best estimate of the average annual attenuation distribution for which down time is taken into account.) Again, this distribution will be illustrated with the curves for Mill Village and Melville.

The seven yearly attenuation distributions for the years 1973-79 at Mill Village are shown in figure 9. By comparing figure 9 with figures 6 and 7 it may be observed that, as would be expected, the differences among the yearly attenuation distributions are less than the differences among the attenuation distributions for either the month of January or the month of July.

Figure 10 shows the three yearly attenuation distributions for for the years 1974-76 at Melville. There are too few samples from that station to draw firm conclusions but, on comparing figures 8 and 10, it appears that the spread in the yearly attenuation distributions may be about the same as that in the distributions for the months of July.

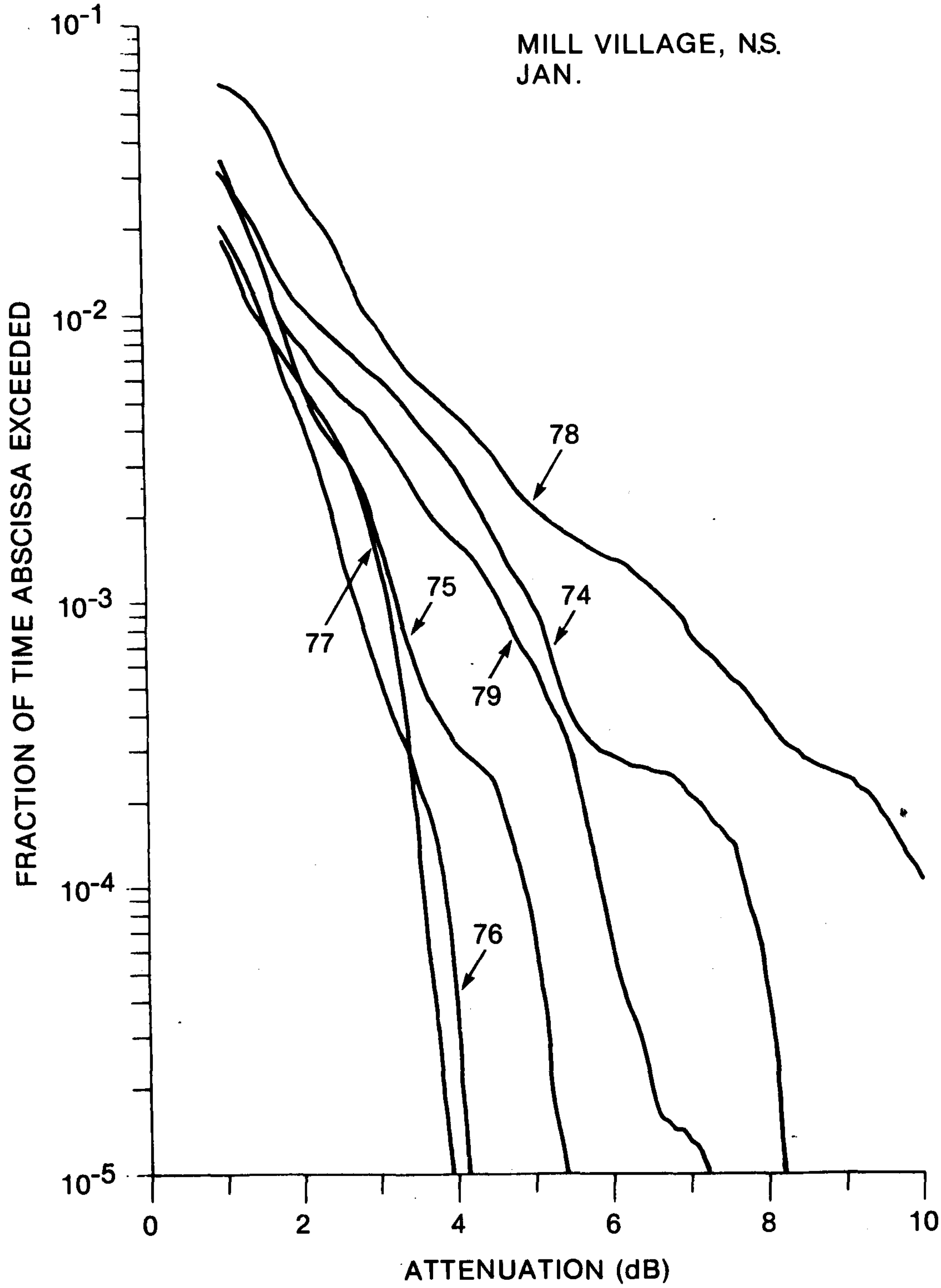


Figure 6. Monthly attenuation distributions for months of January at Mill Village.

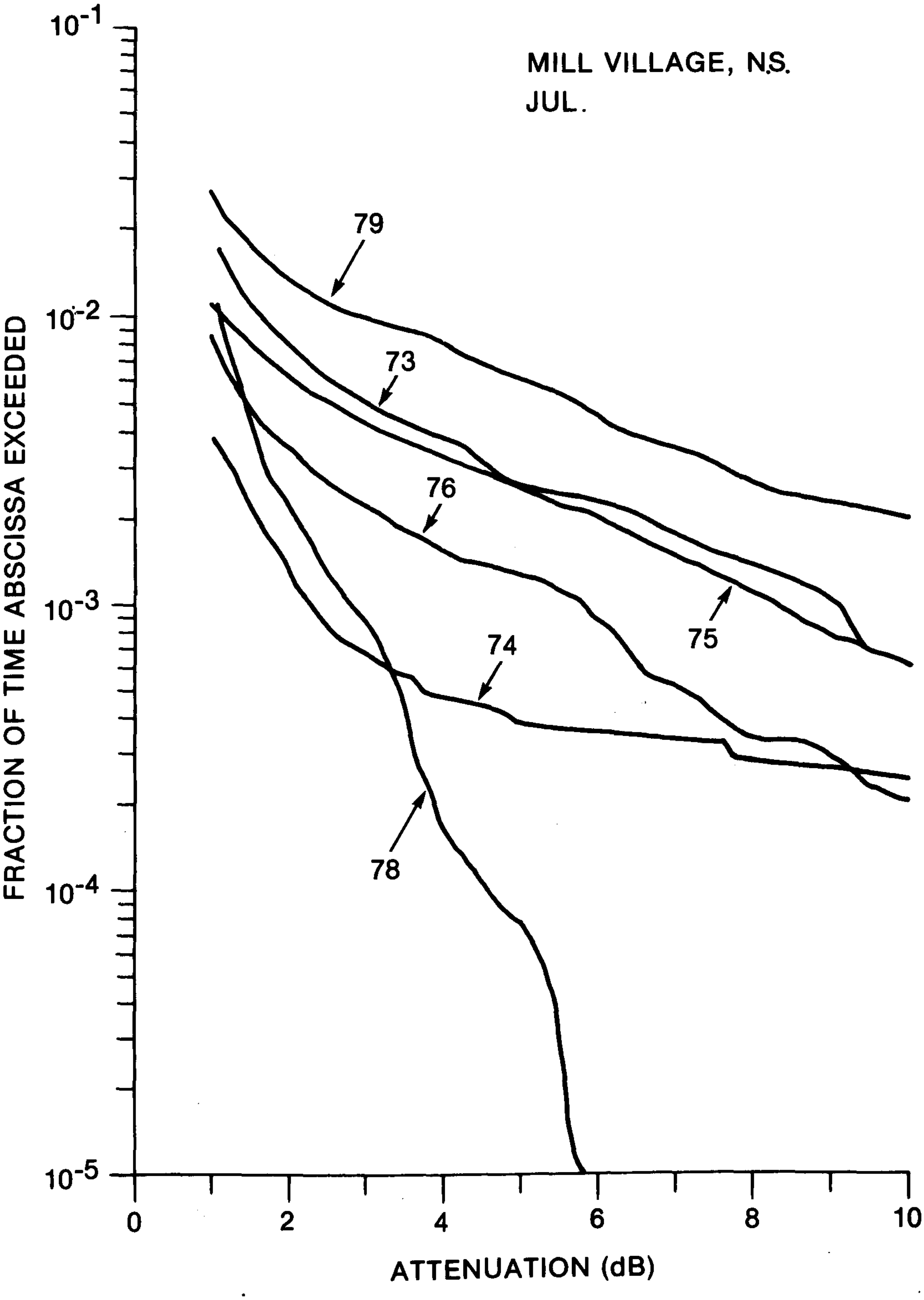


Figure 7. Monthly attenuation distributions for months of July at Mill Village.

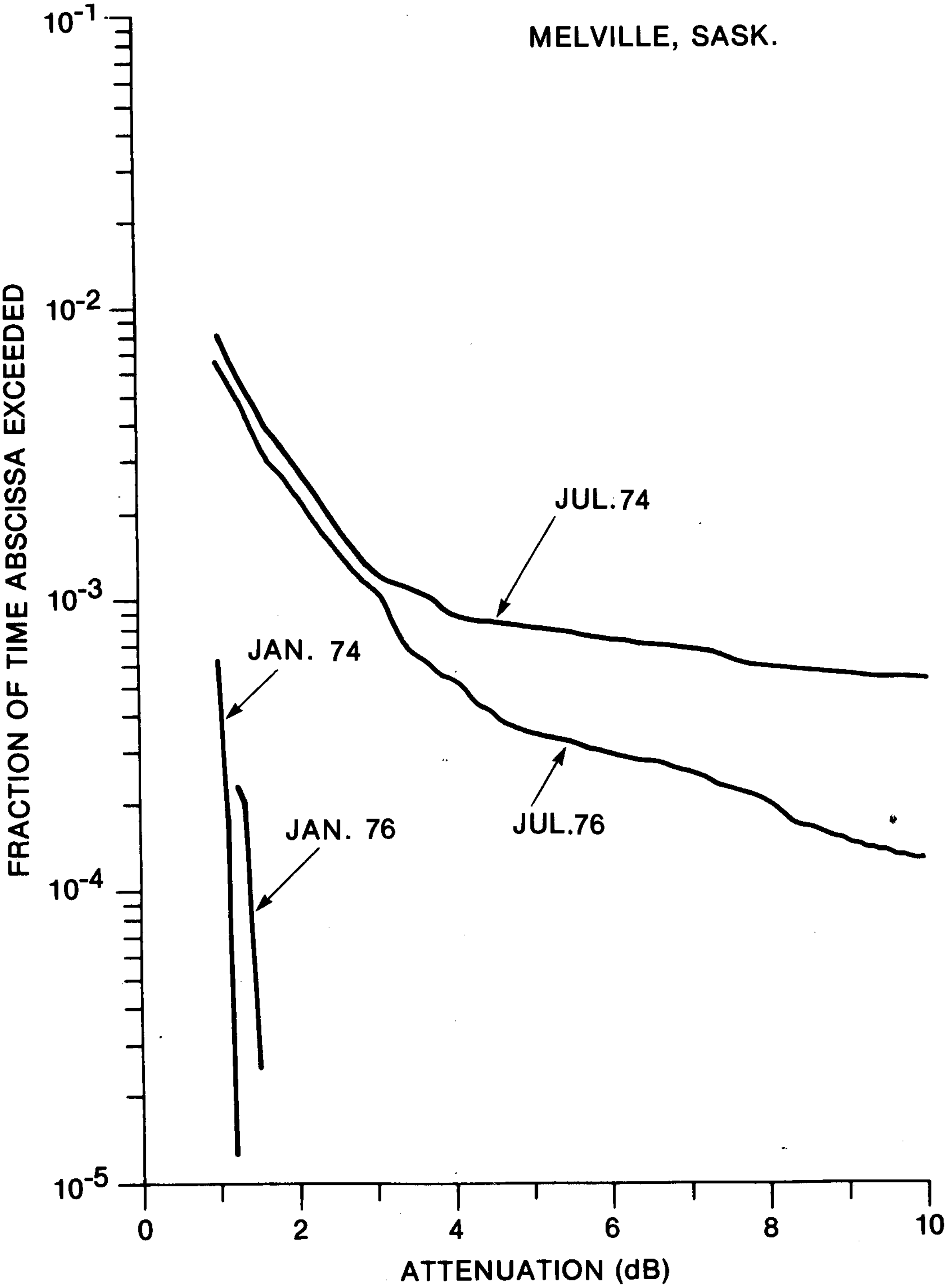


Figure 8. Monthly attenuation distributions for Melville.

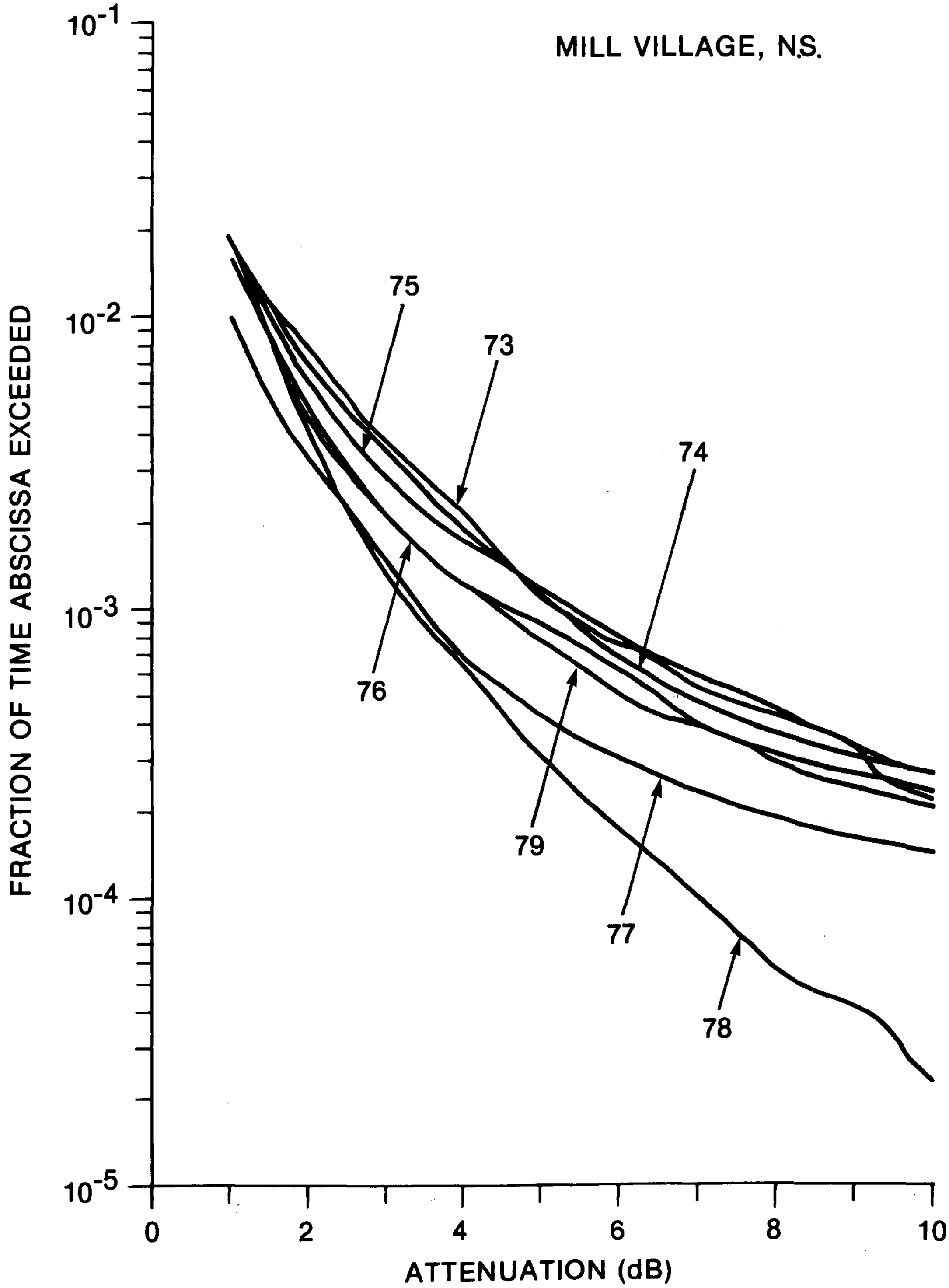


Figure 9. Yearly attenuation distributions for Mill Village.

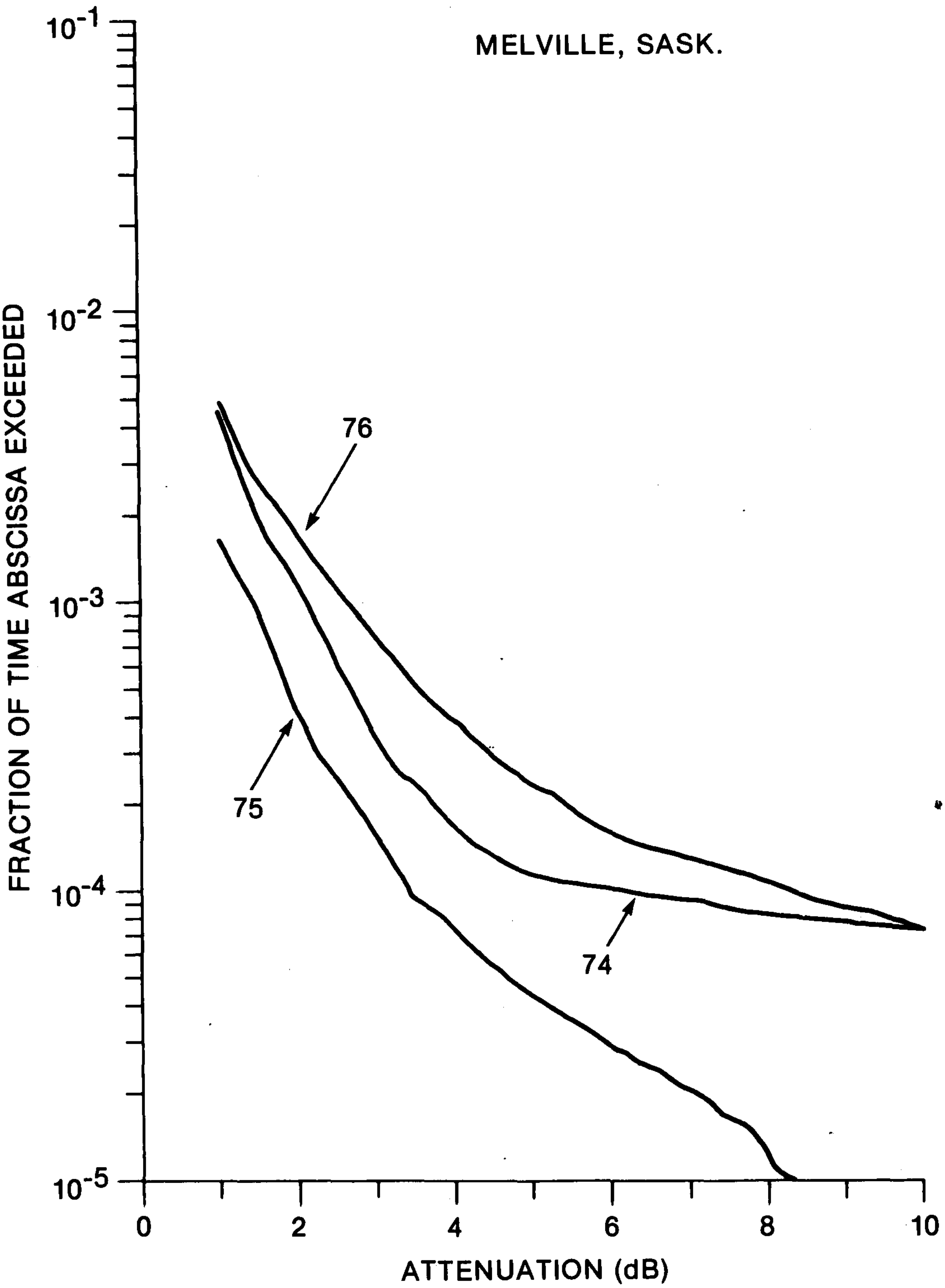


Figure 10. Yearly attenuation distributions for Melville.

From a comparision of figures 9 and 10 it appears also that there is more variability in the yearly attenuation distributions for Melville than in those for Mill Village.

5.3 Average Monthly Attenuation Distributions

The unnormalized attenuation distributions and the operating times for a given calendar month were summed over the years of the experiment. The normalized distribution that was derived from those sums is the "average attenuation distribution" for that month over those years.

Figure 11 shows the twelve average monthly attenuation distributions for Mill Village. On those curves the fraction of the time for which the attenuation exceeded 1 dB varies over the year by a factor of about three and the fraction of the time for which 10 dB was exceeded varies by a factor of over 50. Only for the month of April did the average attenuation fail to reach 10 dB for at least 1×10^{-5} of the time. However, an inspection of the several distributions of the month of April reveals that the attenuation exceeded 10 dB in April 1974, so there are examples of its exceeding 10 dB at Mill Village in every month of the year. The months of June to December, except for November, form a group which had higher fractions of time for which the attenuation exceeded all thresholds from about 4 dB to 10 dB.

The twelve average monthly attenuation distributions for Ottawa are shown in figure 12. Here the months in which the attenuation exceeded 10 dB are May to September and November while those in which the attenuation did not exceed 10 dB(for at least 1×10^{-5} of the time) are December to April and October. Clearly, the higher attenuations occur in the summer. Low attenuations occurred in the winter but only for a relatively small fraction of the time.

Eleven average monthly attenuation distributions for Allan Park are shown in figure 13. There is no curve for December since there was no attenuation above 1 dB in any December of the measurement period. July and August have the largest fraction of time for which the attenuation exceeded 10 dB while there was no attenuation that exceeded 4 dB for 1×10^{-5} of the time in November or January or, of course, in December.

The average monthly attenuation distributions for Thunder Bay are shown in figure 14. In the summer months, June, July, August and September, the attenuation exceeded 10 dB for larger fractions of the time than in any of the other months. There are no curves for December, January, February or March since there were almost no data for these months from this station.

The average monthly attenuation distributions for Melville are shown in figure 15. There was little or no attenuation in the five months October to February and almost all of the attenuation that exceeded 10 dB occurred in June, July and August. The latter months, along with May, account for most of the attenuation in excess of 1 dB.

For Lake Cowichan, as shown in figure 16, the average monthly attenuation distributions are quite different from those for the other stations. For the top curve in figure 16 the average monthly attenuation exceeded 1 dB for about 0.2 of the time which is about the same as that of the highest curves for the other stations. However, the attenuation did not exceed 4.4 dB (for at least 1×10^{-5} of the time) in any month. This is the only station where the attenuation did not reach 10 dB. The months with the most attenuation tended to be in the fall and the early winter, September to January, while those with the least attenuation were in the summer, June, July and August. August had no attenuation above 1 dB. However, as may be observed in figure 5, there are fewer years of data for the summer months than for the winter months so the average amount of attenuation time that was observed for each month may not represent the long-tem average as accurately for the summer months as for the winter months.

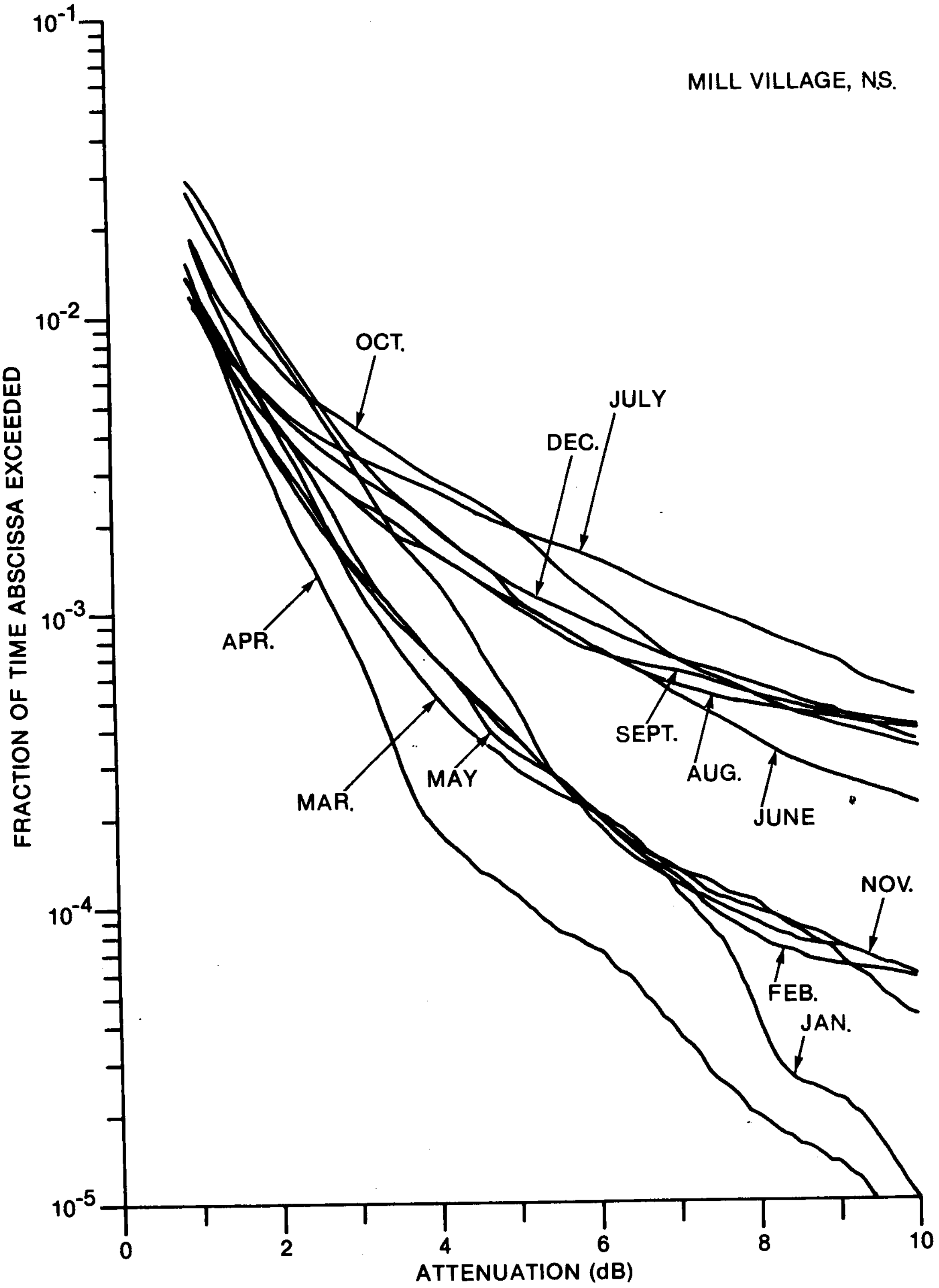


Figure 11. Average monthly attenuation distributions for Mill Village.

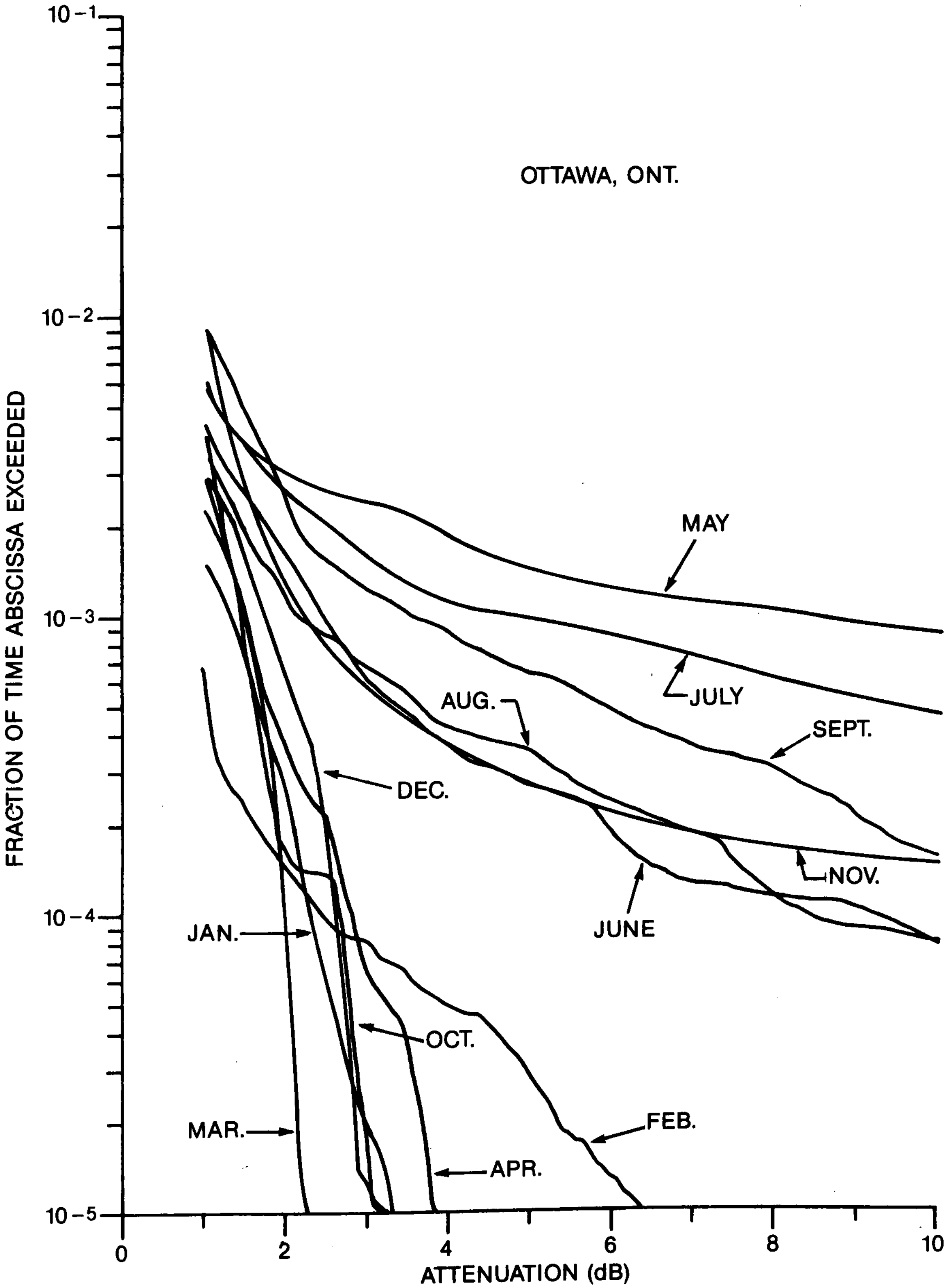


Figure 12. Average monthly attenuation distributions for Ottawa.

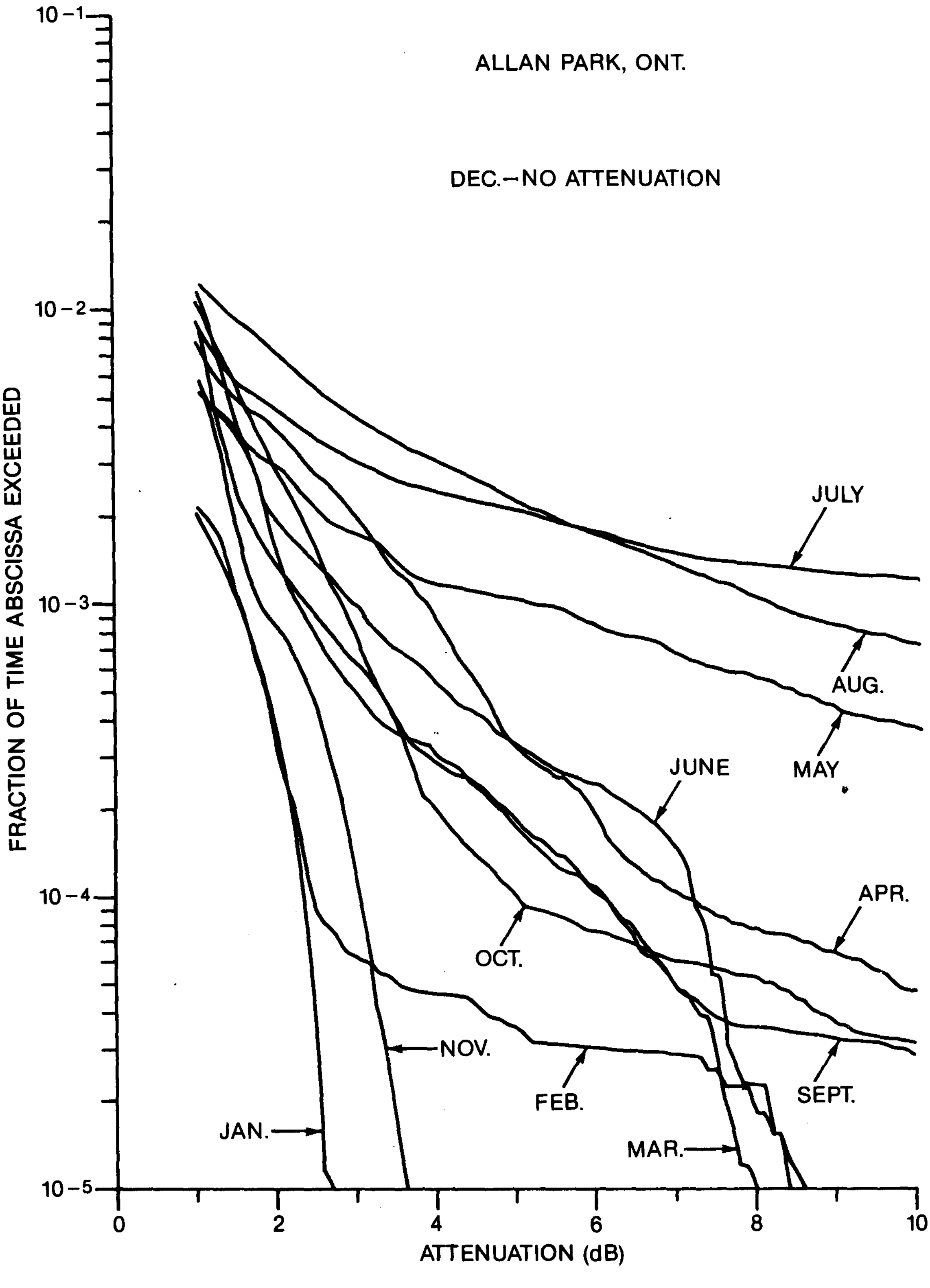


Figure 13. Average monthly attenuation distributions for Allan Park.

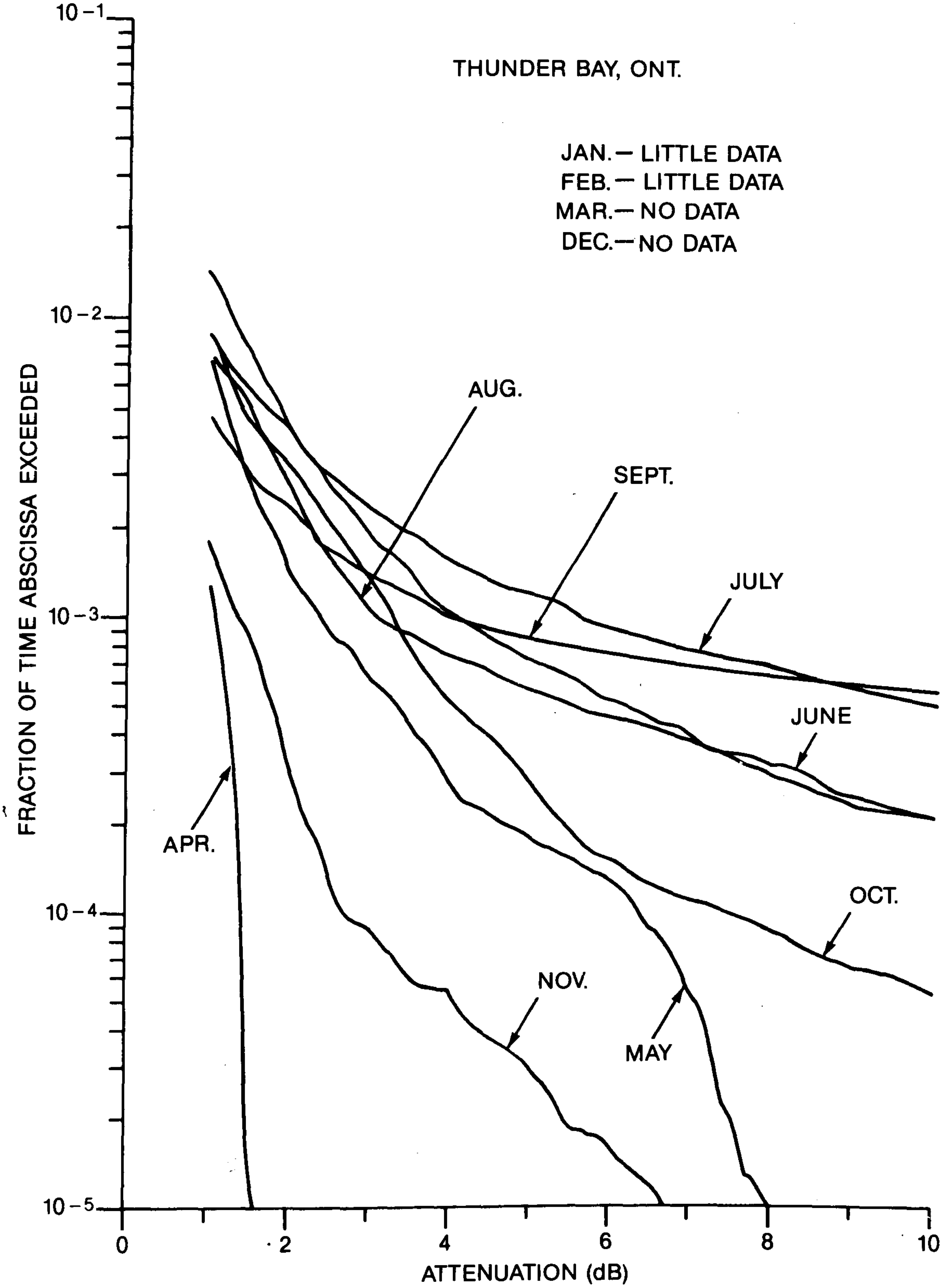


Figure 14. Average monthly attenuation distributions for Thunder Bay.

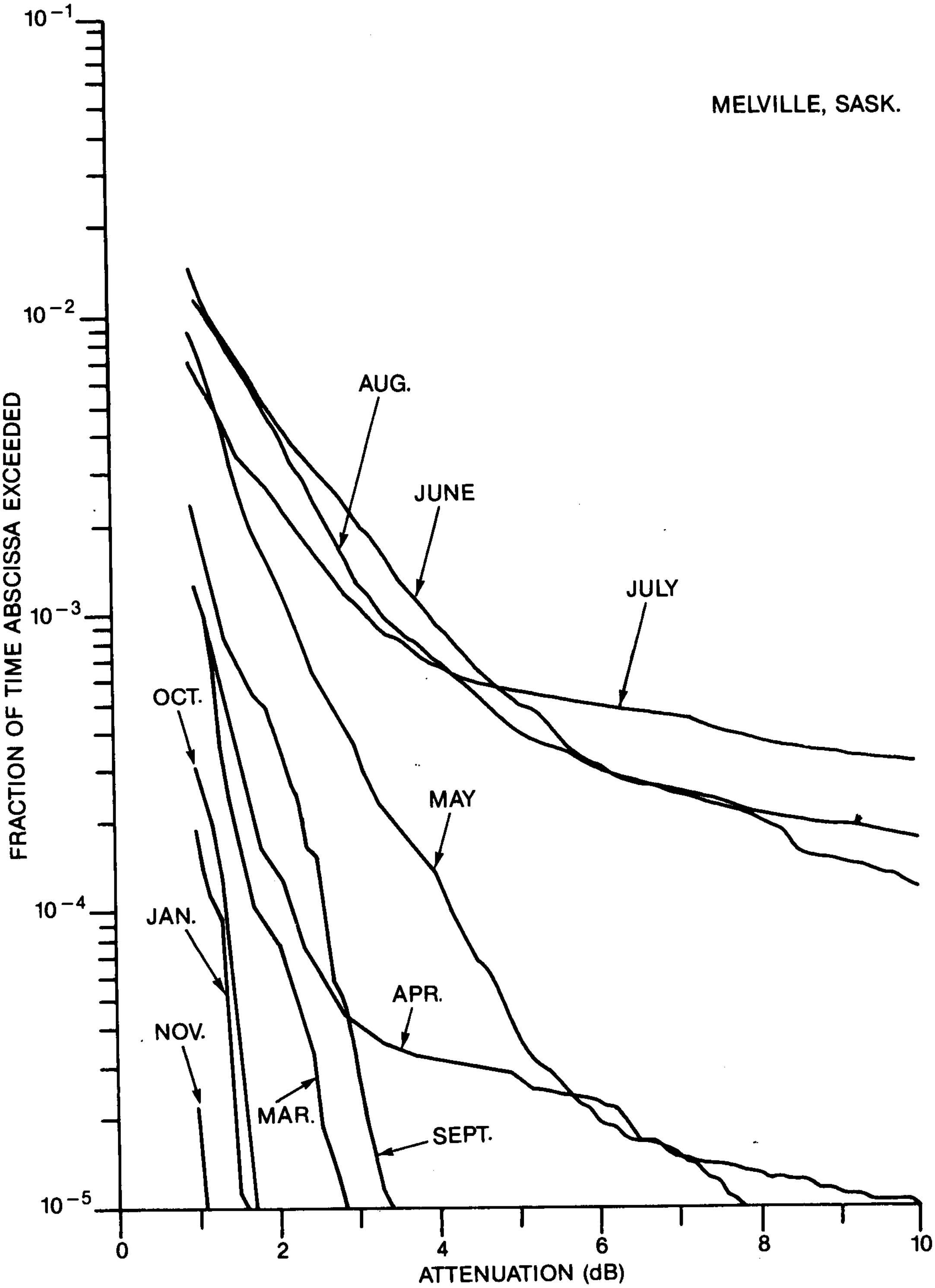


Figure 15. Average monthly attenuation distributions for Melville.

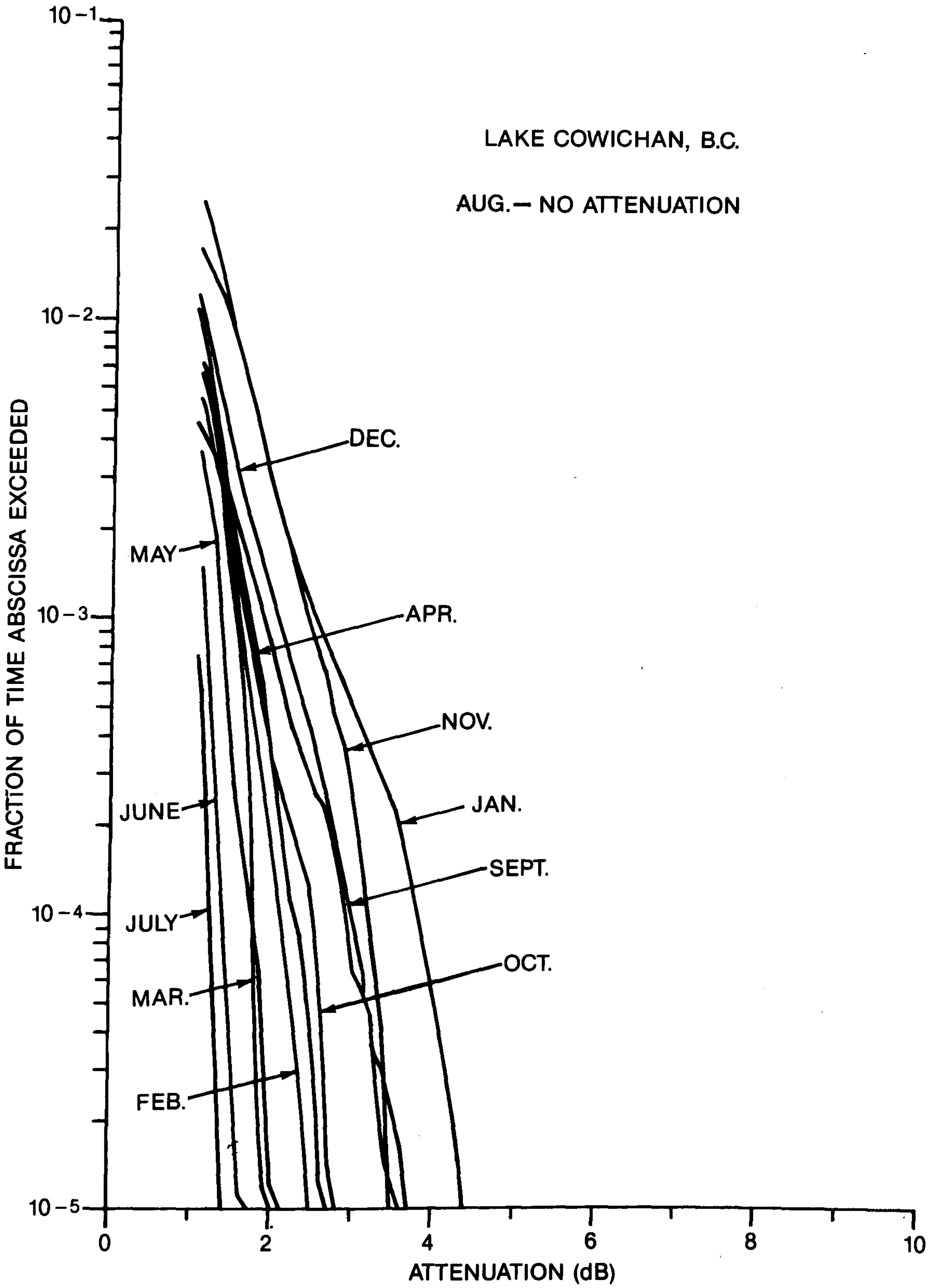


Figure 16. Average monthly attenuation distributions for Lake Cowichan.

5.4 Composite Annual Attenuation Distribution

From the average monthly attenuation distributions a composite annual attenuation distribution was constructed. The equation is

$$F_{ca} = \frac{\sum_{j=1}^{12} M_j F_j}{\sum_{j=1}^{12} M_j} \qquad (3)$$

where F_{ca} and F_j are the fractions of time that the same attenuation is exceeded on the composite annual attenuation distribution and on the average attenuation distribution for month j, respectively, and M_j is the number of days in month j ($M_2 = 28.25$). The six composite annual attenuation distributions are shown in figure 17 and the attenuations from those curves, that were exceeded for selected fractions of time, are listed in Table 2.

TABLE 2

Attenuation(dB) exceeded for selected fractions of time from composite annual attenuation distributions

	Fraction of time						
Location	1×10^{-2}	3×10^{-3}	1×10^{-3}	3×10^{-4}	1×10^{-4}	3×10^{-5}	1×10^{-5}
Mill Village, N. S.	1.4	2.7	4.7	8.2	>10	>10	>10
Ottawa, Ont.	<1	1.2	2.1	5.5	>10	>10	>10
Allan Park, Ont.	<1	1.7	3.3	7.5	>10	>10	>10
Thunder Bay, Ont.	<1	1.3	2.5	5.2	>10	>10	>10
Melville, Sask.	<1	1.2	2.1	3.4	5.9	>10	>10
Lake Cowichan, B. C.	<1	1.4	1.8	2.3	2.9	3.4	3.8

The composite annual attenuation distribution is the best estimate of the average yearly attenuation distribution that can be made from the data that were collected in this experiment. For the remainder of this report it will be referred to as the average yearly, or the average annual, attenuation distribution.

5.5 Attenuation at Fort Smith

Comparisons of the annual accumulations of rain, the number of thunderstorm days, maximum and minimum temperatures, etc., indicate that the statistics of precipitation attenuation at the one sub-arctic station, Fort Smith, would be more benign than those for the prairie climate at Melville, Saskatchewan. Unfortunately, the data from Fort Smith were too corrupt for analysis. During the summers, however, from the beginning of June to the end of August, there were events that appeared to be made up of attenuation with extraneous signals superimposed. Since the rest of the year was free of these events, it is likely that rain attenuation occurred at Fort Smith in the summer but not in the fall, winter or spring.

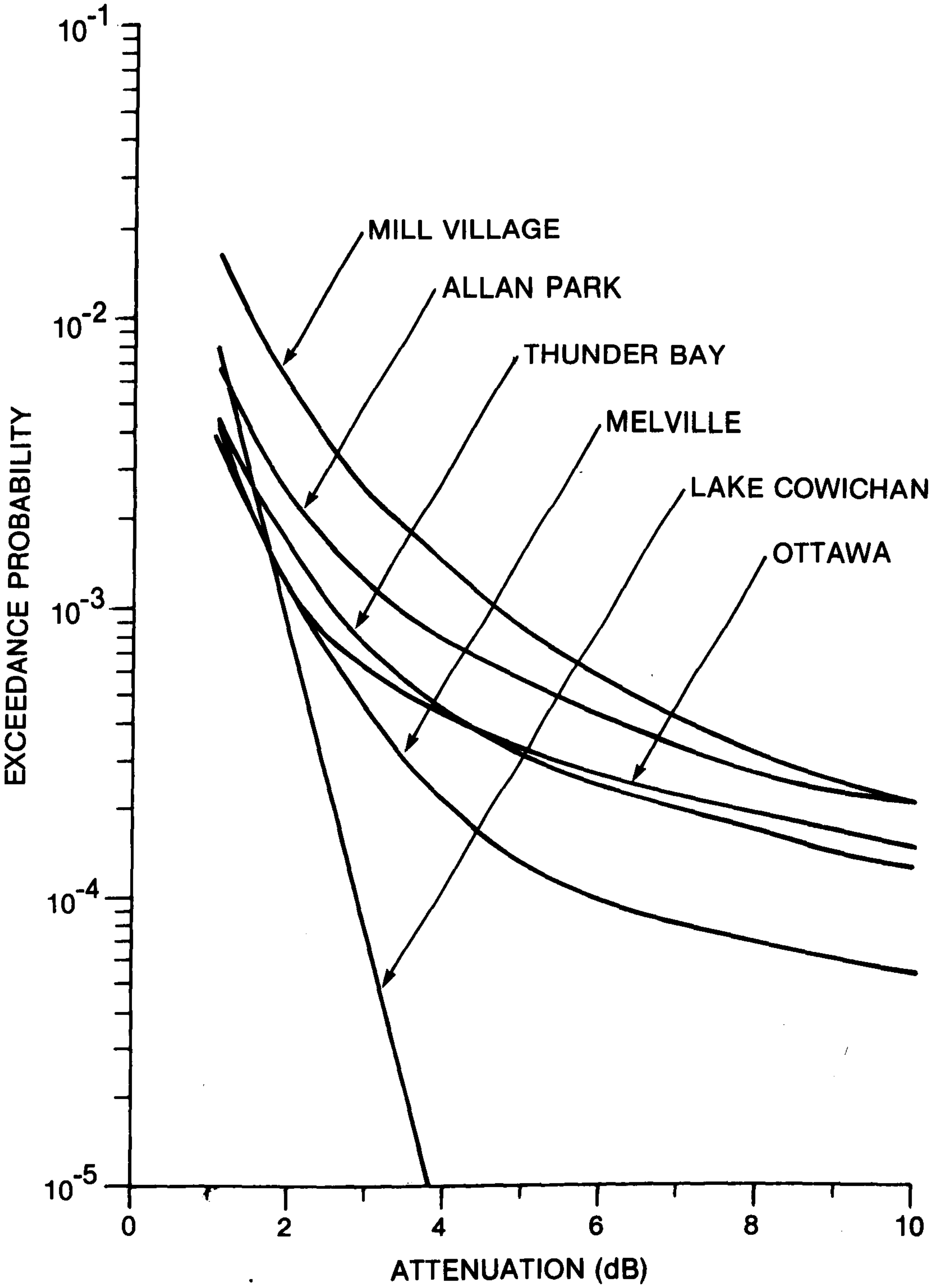


Figure 17. Composite annual attenuation distributions.

6. WORST MONTH STATISTICS

6.1 Average Worst Month Attenuation Distributions

The average worst-month attenuation distribution, which conforms to the CCIR definition [8], was found for each year for each station. The mean of the several worst calender month distributions for a given station gave the average worst-month distribution for that station.

The attenuation distributions for the average worst months over the total experimental periods are shown in figure 18. In these calculations only those months were included for which the radiometer operated for at least 75% of the time. Because of the many gaps in the data (figure 5) it is possible that those curves deviate significantly from the ones that would have been obtained if the recording had been uninterrupted.

Also, the worst months of the first and the last years of each station were included although those years were only partial years. The attenuations that were exceeded, according to figure 18, in an average worst month for selected fractions of time are listed in Table 3.

TABLE 3

Attenuation(dB) exceeded for selected fractions of time from worst month attenuation distributions

	Fraction of time						
Location	1×10^{-2}	3×10^{-3}	1×10^{-3}	3×10^{-4}	1×10^{-4}	3×10^{-5}	1×10^{-5}
Mill Village, N. S.	2.0	4.4	7.3	>10	>10	>10	>10
Ottawa, Ont.	1.1	2.2	8.5	>10	>10	>10	>10
Allan Park, Ont.	1.2	3.1	9.9	>10	>10	>10	>10
Thunder Bay, Ont.	1.5	2.8	7.4	>10	>10	>10	>10
Melville, Sask.	1.6	2.7	4.2	>10	>10	>10	>10
Lake Cowichan, B. C.	1.5	2.1	2.8	3.4	3.8	4.2	4.4

6.2 Worst Month Seasons

Table 4 lists the worst months for each station. No worst month is given if the radiometer did not operate for more than 75% of any month of the year. There are several examples which illustrate that the worst month at one attenuation may differ from that at another.

The seasons of worst-month occurrence at the different stations are given in Table 5. Because of the small number of years for which data were obtained, the limits of the worst month seasons are only tentative. It is clear, however, that worst months do not occur in the winter at the inland stations whereas they do occur in the winter at both the east coast and the west coast stations. The longest worst-month season was at Mill Village—nine months. The other maritime station, Lake Cowichan, had a much shorter season of only three months. The worst-month season listed for Ottawa is the least certain. The recording time for that station spanned two years but for one of those years there were no data for most of June, all of July and most of August. The worst-month seasons for the other three inland stations include the summer months; the one for Allan Park extends into the early fall and the one for Melville into the late spring.

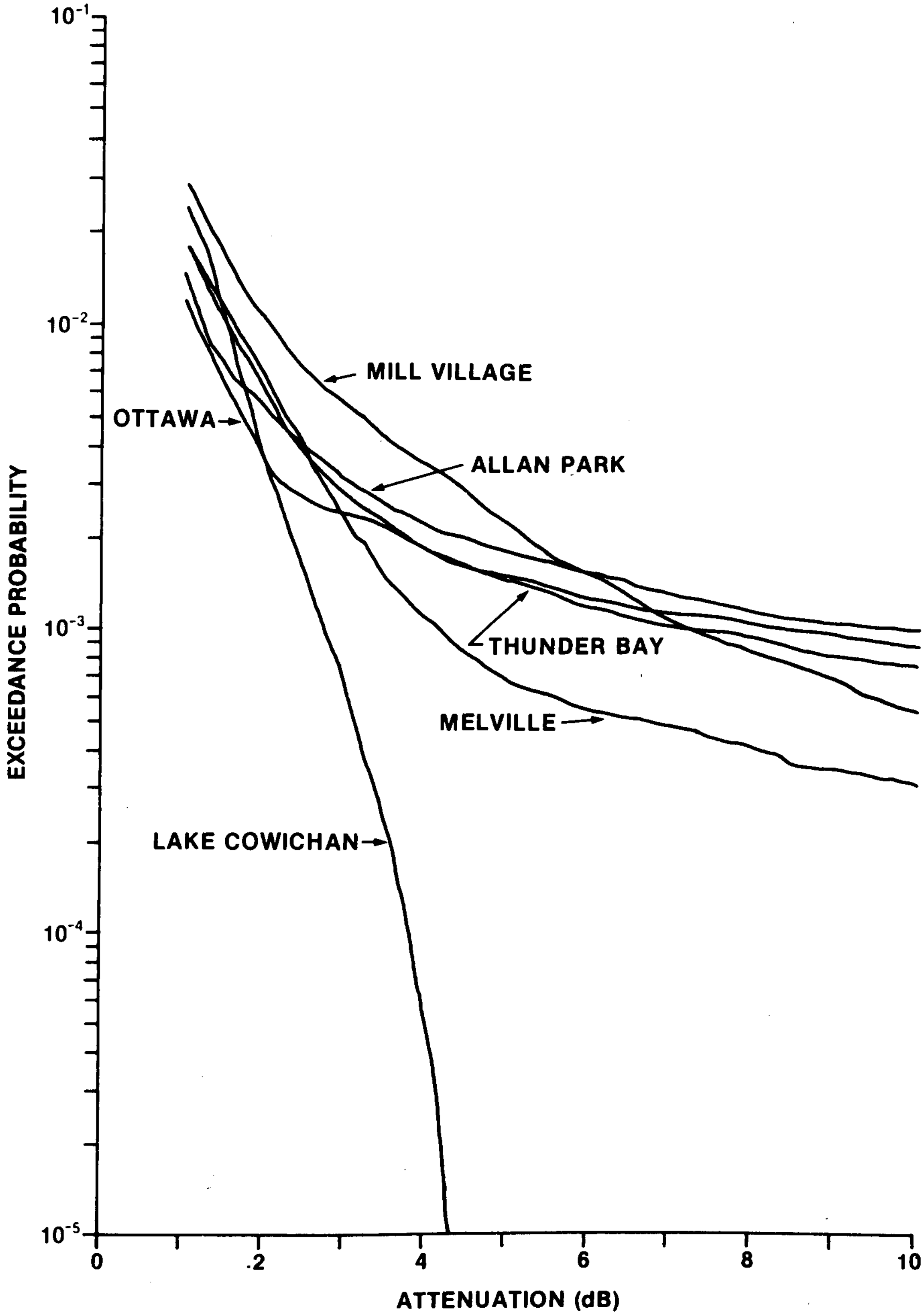


Figure 18. Average worst month attenuation distributions.

TABLE 4

Worst attenuation months

Location		'73	'74	'75	'76	'77	'78	'79
Mill Village, N. S.	4 dB	Jul.	Dec.	Oct.	Oct.	Feb.	Aug.	Jan.
	6 dB	"	Aug.	Dec.	"	"	Sep.	Jun.
	8 dB	"	"	"	"	"	"	"
	10 dB	"	"	"	"	-	"	"
Ottawa, Ont.	4 dB	-	May	May	-	-		
	6 dB	-	"	"	-	-		
	8 dB	-	"	"	-	-		
	10 dB	-	"	"	-	-		
Allan Park, Ont.	4 dB	Oct.	Aug.	Aug.	-	-		
	6 dB	"	"	Jul.	-	-		
	8 dB	"	"	"	-	-		
	10 dB	"	"	"	-	-		
Thunder Bay, Ont.	4 dB	Sep.	Aug.	Jun.	Jun.	-		
	6 dB	"	"	"	"	-		
	8 dB	"	"	Jul.	Jul.	-		
	10 dB	"	"	"	Jun.	-		
Melville, Sask.	4 dB	-	Jul.	Aug.	Jun.	-		
	6 dB	-	"	"	Aug.	-		
	8 dB	-	"	"	"	-		
	10 dB	-	"	May	"	-		
Lake Cowichan, B. C.	2 dB	-	Nov.	Dec.	Jan.	Jan.		
	3 dB	-	"	"	"	"		

TABLE 5

Worst Month Seasons

Mill Village, N. S.	June to February
Ottawa, Ont.	May to August(?)
Allan Park, Ont.	July to October
Thunder Bay, Ont.	June to September
Melville, Sask.	May to August
Lake Cowichan, B. C.	November to January

6.3 Relations for Worst Month Statistics

System planning often requires the specification of the percentage of time $P_{awm}(\%)$ of exceeding a given attenuation in the average worst month. It is useful to be able to convert $P_{awm}(\%)$ to the more generally available annual statistic $P_y(\%)$, the percent probability of exceeding the given attenuation in an average year. For this purpose the CCIR[9] uses the equation

$$P_y(\%) = a(P_{awm}(\%))^b \tag{4}$$

where a and b are constants. Also in use by the CCIR[8] is a rearrangement of equation (6),

$$Q = c(P_y)^{-d} \tag{5}$$

where Q is the ratio of the average worst month exceedance probability P_{awm} to the mean annual exceedance probability P_y where both exceedances are at the same attenuation, and c and d are constants.

To determine the values of the constants in equations (4) and (5), P_{awm} and P_y were found for integral values of attenuation from 2 to 10 dB (for Lake Cowichan only for 2 and 3 dB). P_{awm} was then plotted as a function of P_y on logarithmic axes as in figure 19. From the slope and the intercept of the straight lines, which were obtained by linear regression fits, the values of a and b were computed and from them the values of c and d were derived; these values are listed in Table 6 for each radiometer location.

TABLE 6

Constants for equations (4) and (5)

Location	a	b	c	d
Mill Village, N. S.	0.49	1.11	1.19	0.101
Ottawa,Ont.	0.46	1.41	0.46	0.290
Allan Park, Ont.	0.63	1.45	0.33	0.312
Thunder Bay, Ont.	0.34	1.26	0.92	0.205
Melville, Sask.	0.19	1.03	4.42	0.026
Lake Cowichan, B. C.	0.23	1.25	1.30	0.201
All stations	0.39	1.24	0.87	0.196
CCIR	0.29	1.15	1.64	0.130

In figure 20 all of the points for all of the stations are plotted together. From the parameters of the solid line, which was also obtained by a linear regression fit, "all station" values for the four constants were found. The "all station" values for the four constants as well as the values used by the CCIR in 1982[8,9] are also listed in Table 6. The dashed line in figure 20 was drawn with the use of the CCIR constants; in view of the scatter of the points the two lines show good agreement. However, from a comparison of figures 19 and 20, it is clear that for any one station it is better to use the constants for that station than to use either the "all station" constants or those recommended by the CCIR.

By definition, the value of Q must be between 1 and 12. A value of 1 means that the exceedance time is uniformly distributed over all of the months of the year, a larger value, say 5, that 5/12 of that time is in the worst month, and a value of 12 that the attenuation occurred only in one month.

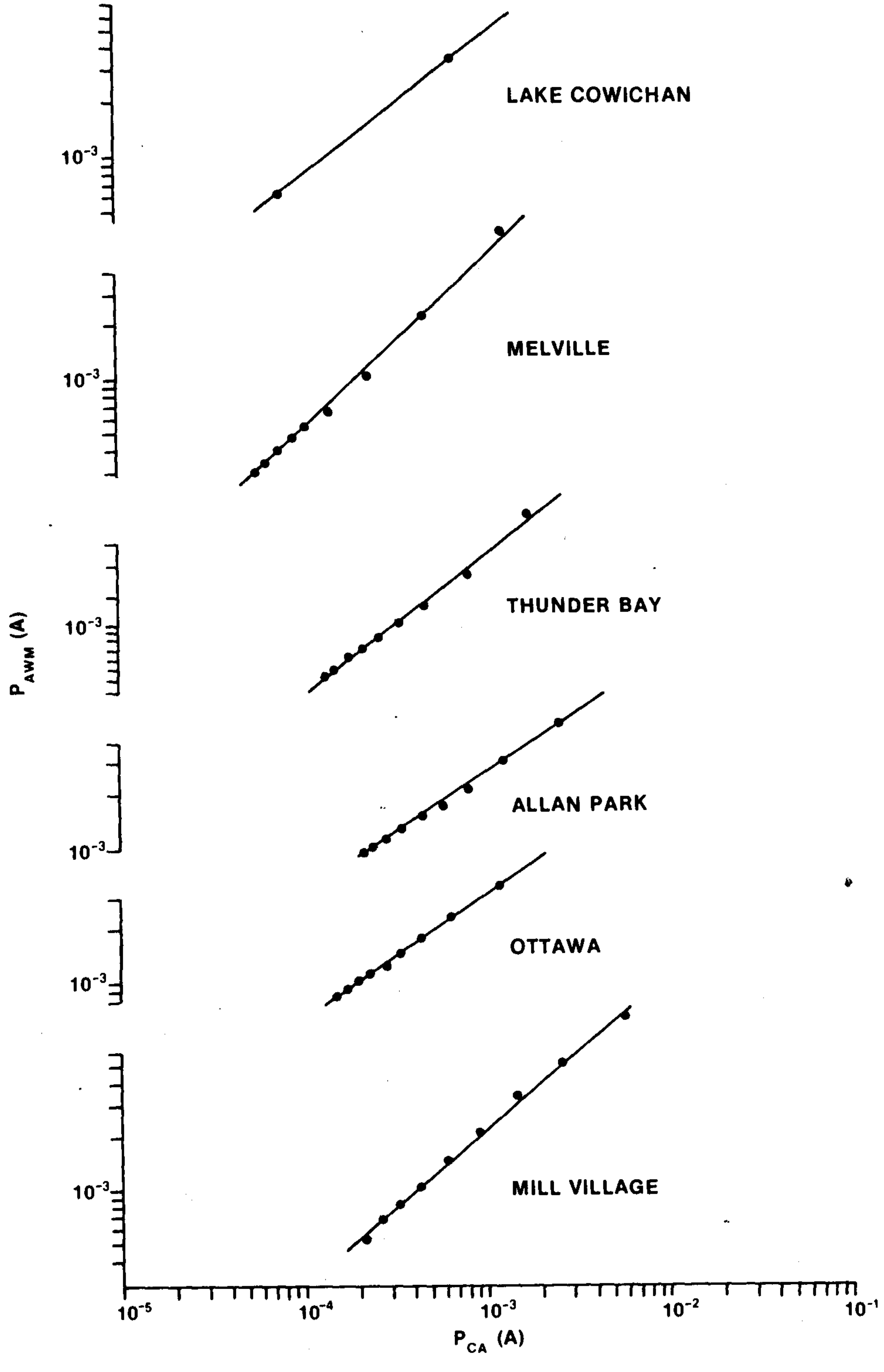


Figure 19. Average worst month attenuation probability plotted as a function of composite annual attenuation probability. The ordinate scale is the same as the abscissa scale; plots have been displaced vertically to avoid overlap.

If Q is small, the exceedance time that is not in the worst month must be distributed over several months, but if Q is large, that exceedance time may be distributed over only a few months.

For each station the values of Q are plotted as a function of attenuation in figure 21. For Thunder Bay and Ottawa, Q is about 3 at an attenuation of 1 dB and it rises almost linearly to a value of about 6 at 10 dB; this implies that at 1 dB about 25%, and at 10 dB about 50%, of the exceedance time is in the worst month. The Allan Park curve is about 1 unit below, but is parallel to, those for Thunder Bay and Ottawa; the percentage of the exceedance time that is in the worst month at 1 dB and at 10 dB are, therefore, about 17% and 33%, respectively. For Melville the value of Q is between 5 and 6 when the attenuation is above 1.3 dB; this means that, for those attenuations, 40% to 50% of the exceedance time is in the worst month. Below 1.3 dB the percentage is below 40%.

Of all the stations Mill Village has the lowest values for Q. It rises from 1.7 at 1 dB to about 2.7 at 8 to 10 dB; this corresponds to 14% to 22% of the exceedance time being in the worst month. It follows that for all attenuations at Mill Village the exceedance time that is not in the worst month must be distributed over a larger number of months than at the other stations. This is consistent with the observation that Mill Village has the longest worst-month season.

The greatest range of the values of Q was found in the Lake Cowichan data. At attenuations of 1 dB and 4.2 dB the values of Q are 3 and 12, respectively, and the percentages of the exceedance times that are in the worst months are 25% and 100%, respectively.

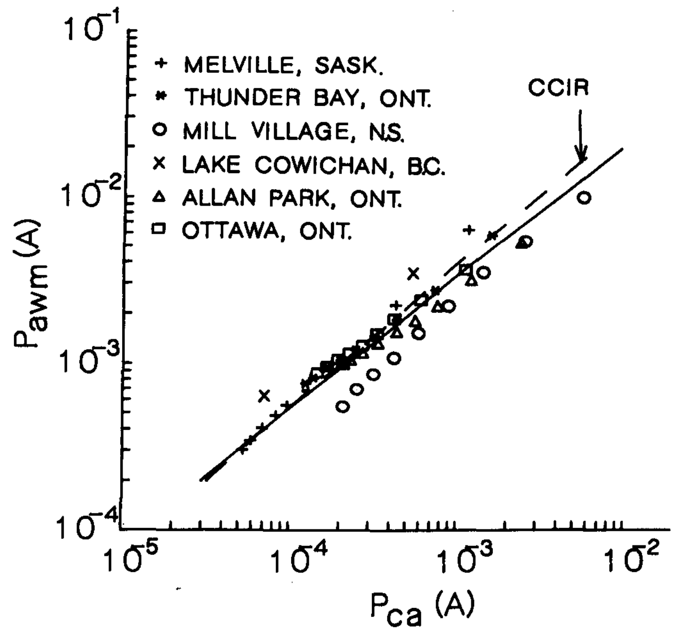


Figure 20. Average worst month attenuation probability plotted as a function of composite annual attenuation probability; all stations.

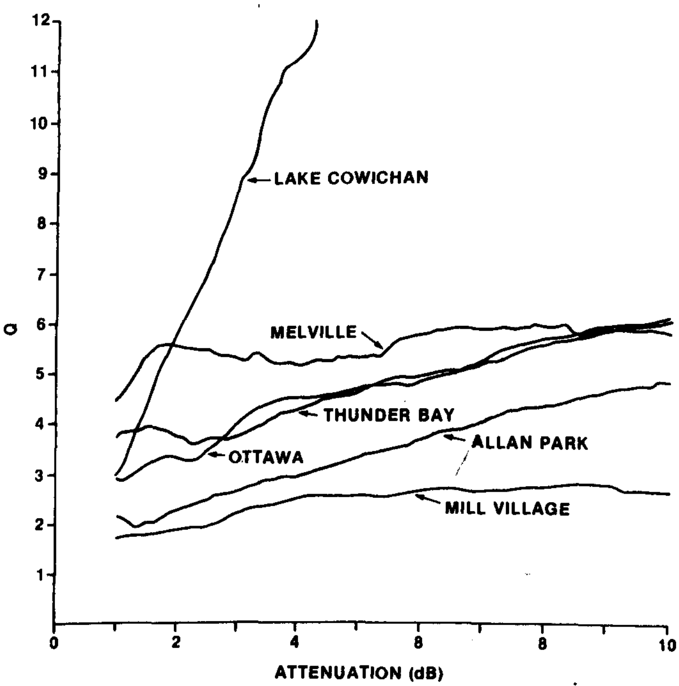


Figure 21. Q plotted as a function of attenuation.

By plotting Q as a function of annual attenuation probability a curve is obtained that is useful in converting worst month statistics to average annual statistics[8]. Figure 22 is a plot of this relationship for the six sites. The curves for Thunder Bay and Ottawa merge over part of their length as do the curves for Mill Village and Allan Park. Otherwise the six curves are quite separate and cannot be represented by a single relation.

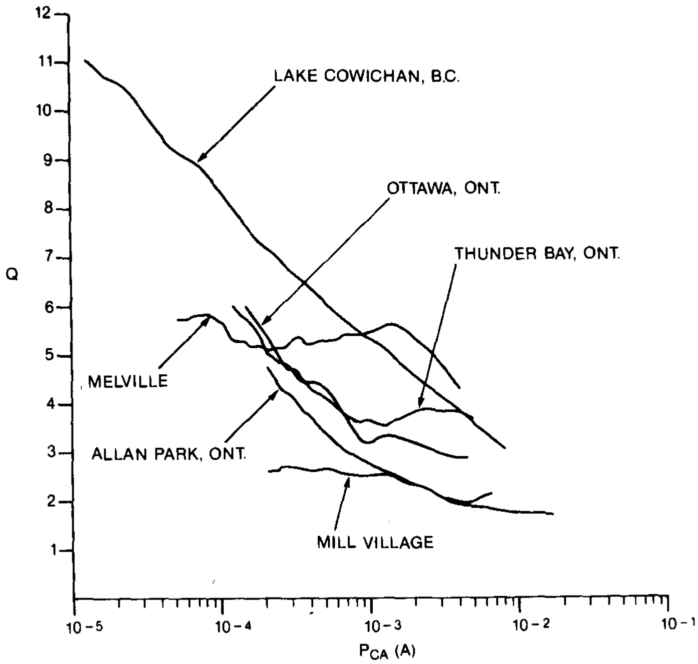


Figure 22. Q plotted as a function of composite annual attenuation probability.

7. DIURNAL STATISTICS

The day was divided into four six-hour periods and separate distributions were compiled for the attenuations which occurred in each of those periods. For a sorting of the attenuation into these diurnal periods to be statistically meaningful the number of fades that are sorted must be much greater than the number of diurnal periods. Table 7 shows the number of fades for 3, 6 and 10 dB thresholds that occurred at each site during the whole of the experimental period. These numbers are large enough for reliable sorting into four diurnal periods, with some reservation about the 10-dB statistics for Melville.

TABLE 7

Location	Total number of fades			Equiv. operating time(years)
	3 dB	6 dB	10 dB	
Mill Village, N. S.	1155	332	154	5.1
Ottawa, Ont.	94	54	34	1.7
Allan Park, Ont.	210	84	32	1.8
Thunder Bay, Ont.	306	151	90	2.1
Melville, Sask.	142	26	11	2.6
Lake Cowichan, B. C.	59	-	-	2.7

The percentage of the total exceedance time that fell in each of the four diurnal periods is shown diagramatically in figures 23 and 24 for thresholds of 3 dB and 10 dB, respectively. For the 3 dB threshold(figure 23) the attenuation in each period at Mill Village varied by only about 5%. At Ottawa 80% of the attenuation occurred between noon and midnight and at Allan Park about 60% occurred during the night hours, between 1800 hours and 0600 hours. At Thunder Bay the attenuation was much lower than average in the morning, between 0600 hours and 1200 hours, and at Melville it was lower than average during the afternoon, between 1200 hours and 1800 hours. At Lake Cowichan, which had the most striking pattern of all, over 70% of the attenuation occurred in the afternoon, between 1200 hours and 1800 hours.

For the 10-dB threshold(figure 24) the diagrams for four of the stations show the same general patterns as do the 3-dB diagrams, but here the patterns are more pronounced. At Mill Village the attenuation is more uniformly distributed throughout the day and at Ottawa a larger percentage(95%) of the attenuation occurred between noon and midnight. At Thunder Bay the percentage of the attenuation that occurred between 0600 hours and 1200 hours was decreased to about 2%, and at Melville the percentage that occurred between 1200 hours and 1800 hours was decreased to about the same value. At Allan Park the pattern for the 10-dB threshold is rather different from the one for the 3-dB threshold. For the 10-dB threshold the percentage attenuation that occurred between 1800 hours and 2400 hours was lower, while the percentage that occurred between 0600 hours and 1200 hours was higher, so that about 69% of the attenuation, instead of about 50%, occurred in the first half of the day.

8. FADE DURATION STATISTICS

Fade durations were measured at integral attenuation thresholds from 2 dB to 10 dB and those of 15 or more seconds were sorted into 17 duration bins. The bin for the longest fades was for fades of 150 minutes and over, otherwise the bins had about the same width on a logarithmic scale.

To compare the frequency of

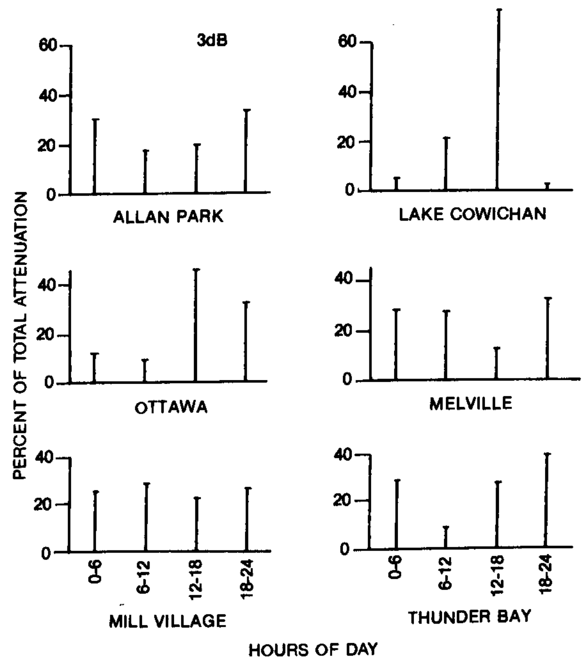


Figure 23. Percentages of time that the attenuation exceeded 3 dB in four diurnal periods; local time.

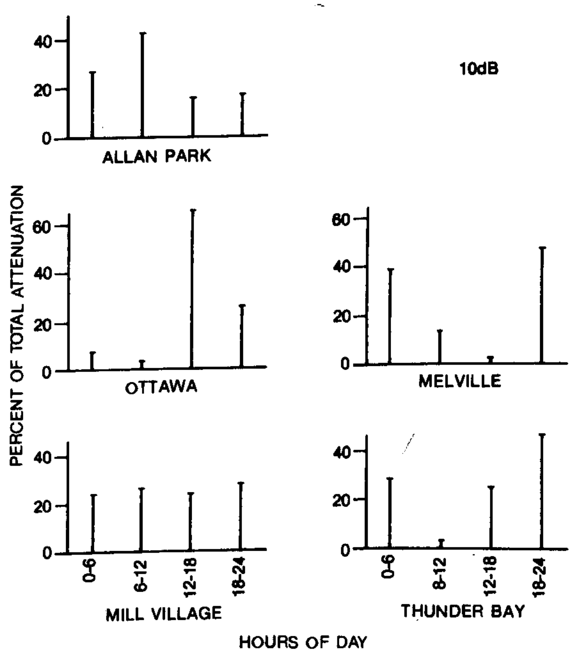


Figure 24. Percentages of time that the attenuation exceeded 10 dB in four diurnal periods; local time.

occurrence of fades at the different stations, the number of fades per year was estimated for each station. However, since neither the time when the radiometers were operating nor the frequency of occurrence of fades were uniformly distributed throughout the year, the use, in this estimation, of the actual time that the radiometers were in operation would not give equal weight to all times of the year. For example, as may be noted in figure 5, the result for Thunder Bay would be too heavily weighted toward the summer months. To decrease this bias an "equivalent" operating time was used; it was estimated for each station by assigning a weight from 0 to 1 to each gap in the operating time and subtracting the product of the length of the gap and its weight from the time between the beginning and the end of the entire recording period. For the four inland stations, where attenuation ocurred mostly in the summer with little or none in the winter, summer gaps were given a weight of 1 while winter gaps were given a weight of 0. For spring and fall months the weight varied between 0 and 1. For the two maritime stations a weight of 1 was used for all seasons. The assigning of a weight to a gap was partly intuitive and the frequencies of occurrence of fades that were arrived at are only "ball park" figures. However, the uncertainties in these figures would not be reduced significantly by a more elaborate procedure. The "equivalent" number of operating years for each station are listed in Table 7.

The fade duration distributions for 3, 6, and 10 dB, when these attenuations occurred, are shown for the six stations in figures 25 to 27. In each of these figures the curves for the various levels form, roughly, arcs of concentric circles, with the curves for the lower attenuations, which had the most fades, being smoother than those for the higher attenuations.

As is shown in figure 25, Mill Village had the most fades per year at 3 dB and Lake Cowichan had the fewest. Thunder Bay and Allan Park had about equal numbers, and Ottawa and Melville had about equal numbers. At an attenuation of 6 dB (figure 26), the Mill Village curve is still the highest but it is only a little above the curves for Thunder Bay, Allan Park and Ottawa. Except for the longest fades, the Melville curve is well below those for the other stations. At 10 dB (figure 27) the curve for Melville is much the lowest while those for the other four stations are not clearly separated. The times exceeded by the longest fades, which are not clear in figures 25 to 27, are listed in Table 8 for several attenuation thresholds. The longest fades at 2 dB are 3 to 10 times as long as the longest fades at 10 dB. Of all the stations Mill Village had the longest fades at 2, 3 and 4 dB while Lake Cowichan had the shortest fades at 2 and 3 dB.

TABLE 8

Minutes exceeded by the longest fades

	Attenuation(dB)					
Location	2	3	4	6	8	10
Mill Village, N.S.	150	150	150	30	20	15
Ottawa, Ont.	50	50	20	20	20	20
Allan Park, Ont.	70	70	50	30	20	20
Thunder Bay, Ont.	50	30	20	15	15	15
Melville, Sask.	70	30	20	20	15	15
Lake Cowichan, B. C.	50	20	3	-	-	-

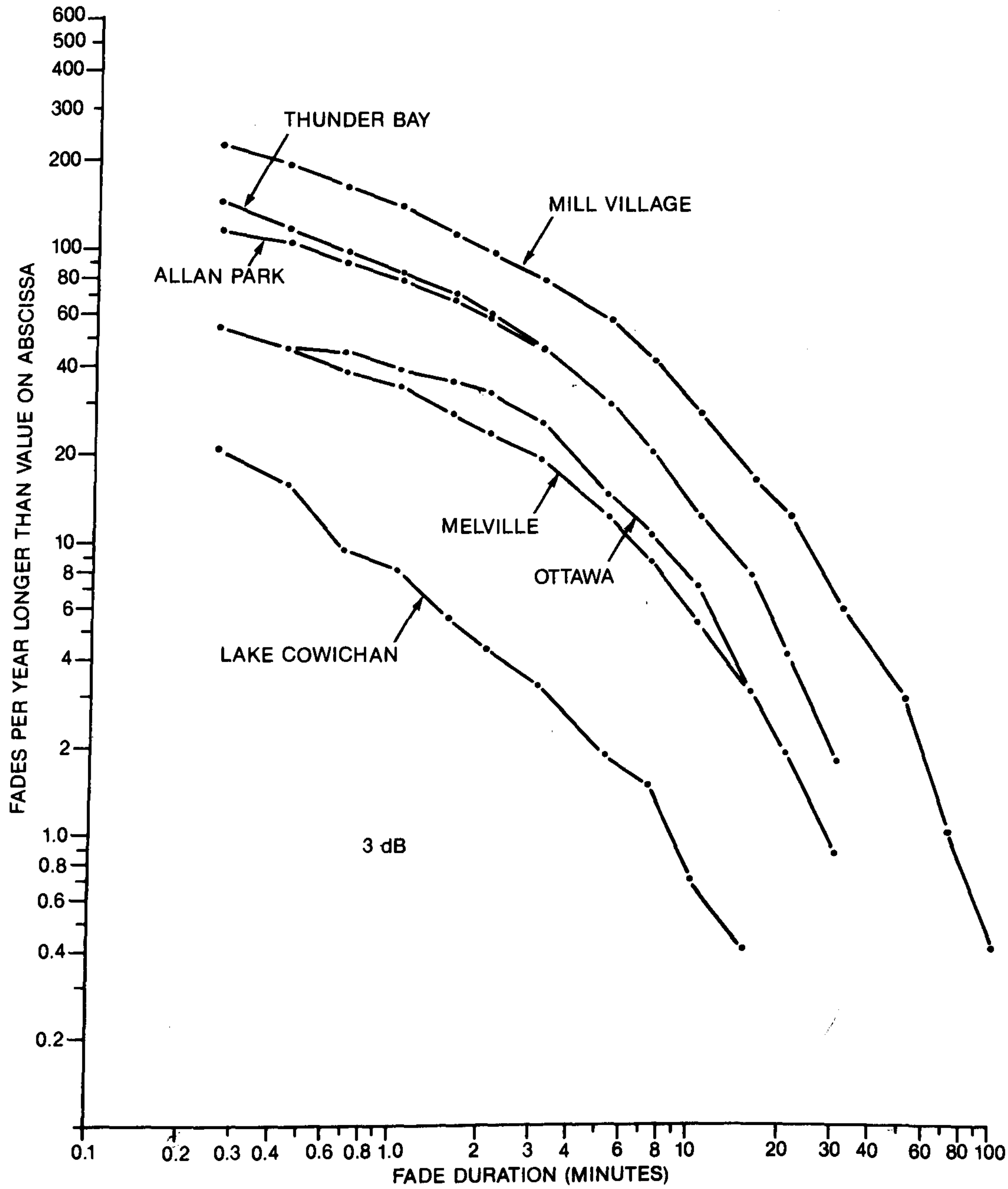


Figure 25. Distributions of 3 dB fades.

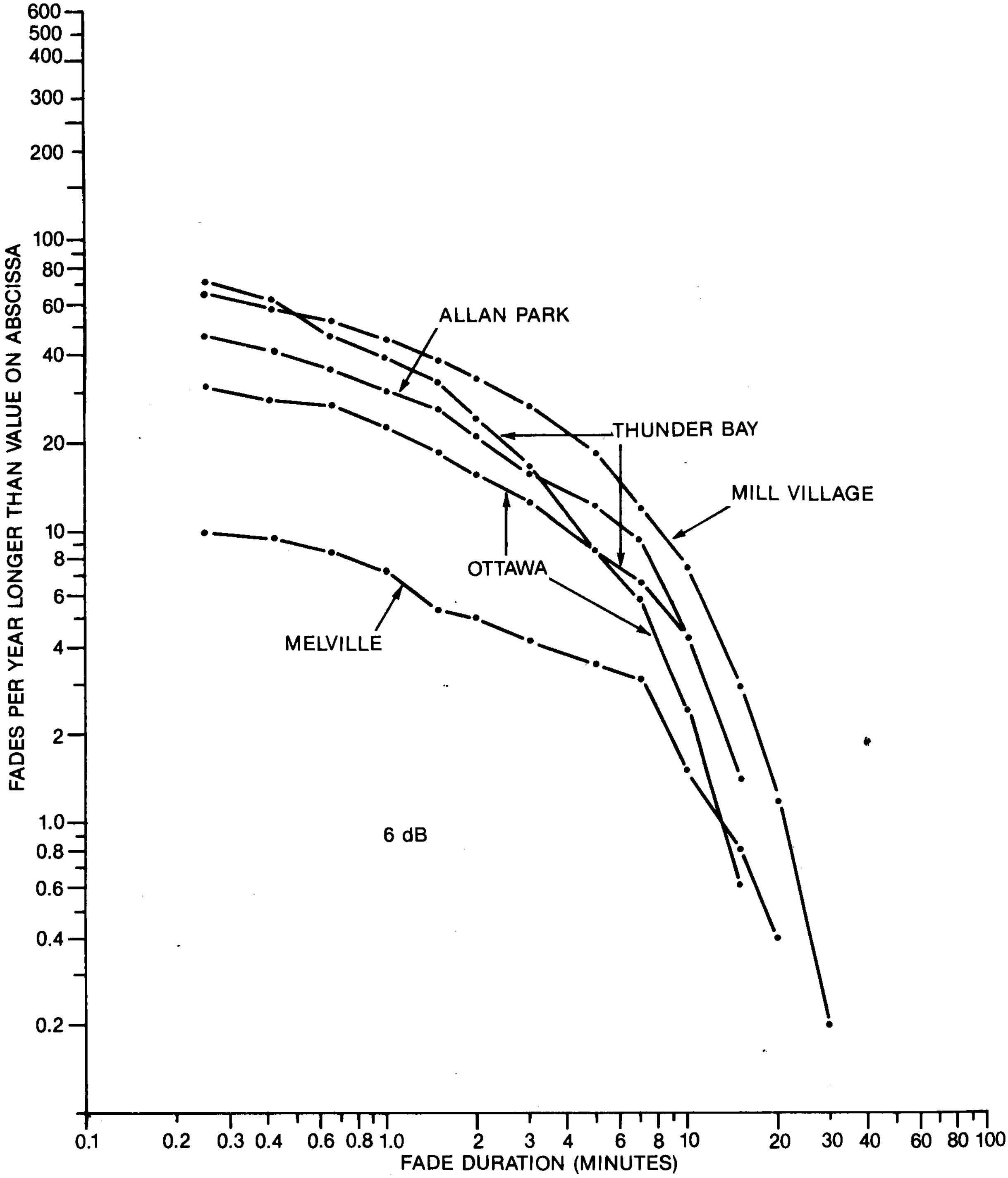


Figure 26. Distributions of 6 dB fades.

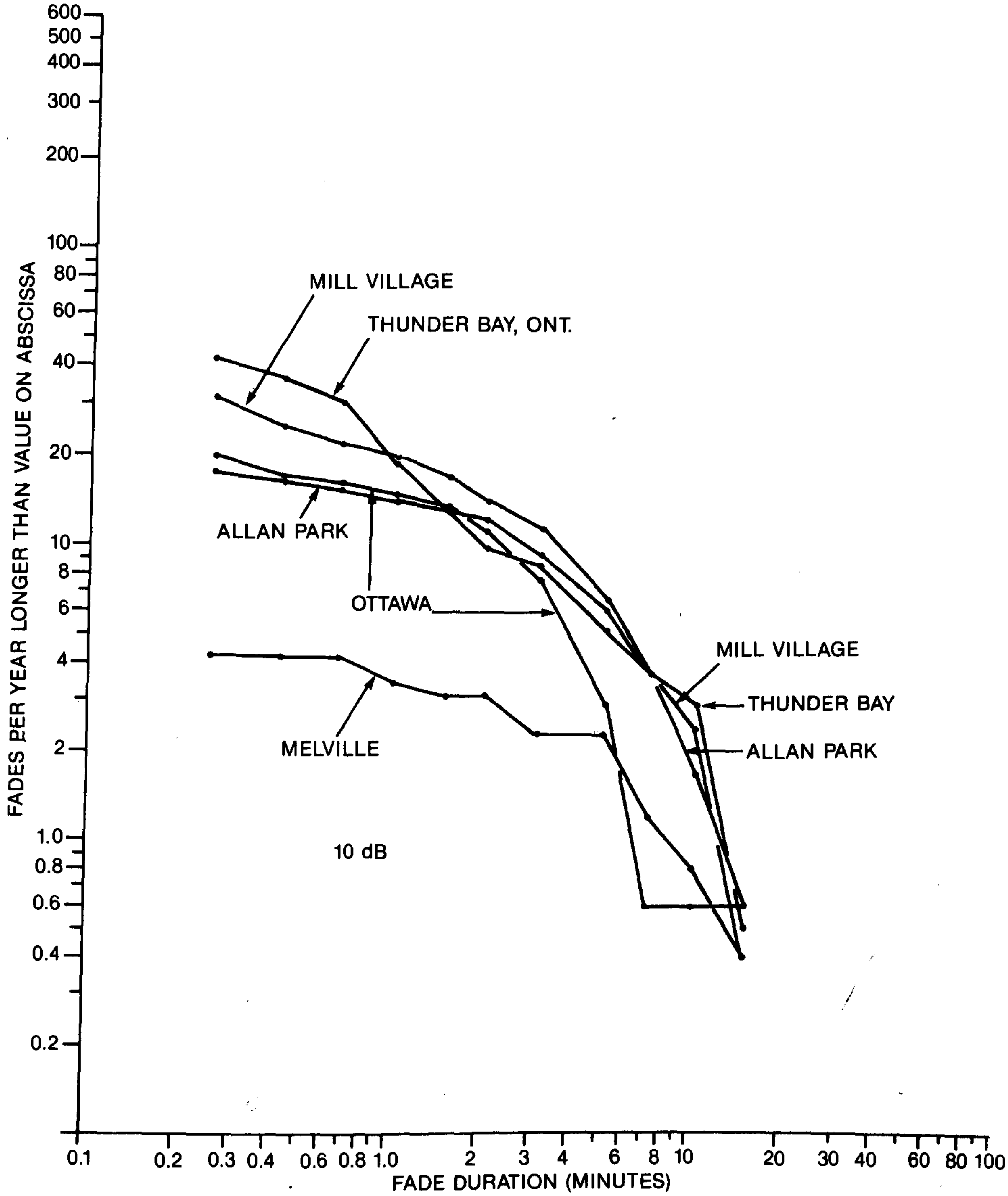


Figure 27. Distributions of 10 dB fades.

9. FADE RATE STATISTICS

9.1 Selection and Processing of Data

The restrictions on the data that could be used were more stringent for computing fade rates than for compiling attenuation distributions. To ensure that only good data were used a plot of attenuation as a function of time was scanned for each ten-minute data block on a CRT display. A total of 15 station-years of data was used in the fade rate analysis.

In figure 28A the top curve is a plot of the raw radiometer data for a 320-second period while the bottom curve is the attenuation that was derived from that data (attenuations of 10 dB or greater are not plotted). These curves show scatter which was due, at least in part, to equipment noise and which is representative of the scatter that was present in much of the data. In figures 28B and 28C the individual points are shown for expanded portions of the curves of figure 28A. The top curves in both of these figures show about the same scatter in the raw data while the bottom curves show more scatter for attenuations in the 8-10 dB range than for those in the 4-5 dB range. This is because a given change in the radiometer output, e.g. a change to the next higher or the next lower digit, results in a greater change in the attenuation value when the attenuation is high than when it is low. It is clear from those plots that a fade rate that was calculated for a 1-second interval, i.e. from two successive points, may have little relation to the longer-term fade rate. To get statistics on the longer-term fade rates, which is the object of this study, straight line regression fits were made to 10 seconds of data (eleven points) at a time. The fade rate, given by the slope of the straight line, was assigned to the middle of the ten-second period and to the mean attenuation for that period. Five examples of straight line fits are shown in the lower plots of figures 28B and 28C. These fits introduce some error, mostly in the highest fade rates; for example, a high fade rate that lasted for only three or four seconds would be assigned a value which was lower than its true value. Also, for the calculations to produce a single occurrence of a high fade rate, that fade rate must have been maintained, on average, for at least 10 seconds.

Since accurate radiometer measurements are limited to attenuations of 10 dB or less, only attenuations which were less than 10 dB were used to compute fade rates. The upper limit on the mean attenuation for the 10-second period of a straight line fit depended on the fade rate and was, for example, 8.0 dB and 9.0 dB for fade rates of 0.4 dB per second and 0.2 dB per second, respectively. Fade rates were computed for every second of an attenuation event.

No consistent differences between the statistics for the positive and the negative fade rates were found so only those for the absolute fade rates are reported here.

9.2 Maximum Fade Rate

The highest fade rate that was found was 0.42 dB per second; it was obtained from the Mill Village data for an attenuation of 7.8 dB.

9.3 Fade Rate Distributions

Fade rate distributions are shown in figure 29 for attenuations that are greater than or equal to the threshold values of 1, 3, 5 and 7 dB (for Melville the lowest threshold was 2 dB instead of 1 dB). In this figure the range of the ordinate is from about 1 second per year to about 2.5 hours per year, and the total operating time that was used for fade rate statistics is given in years for each station. The curves are approximately straight lines.

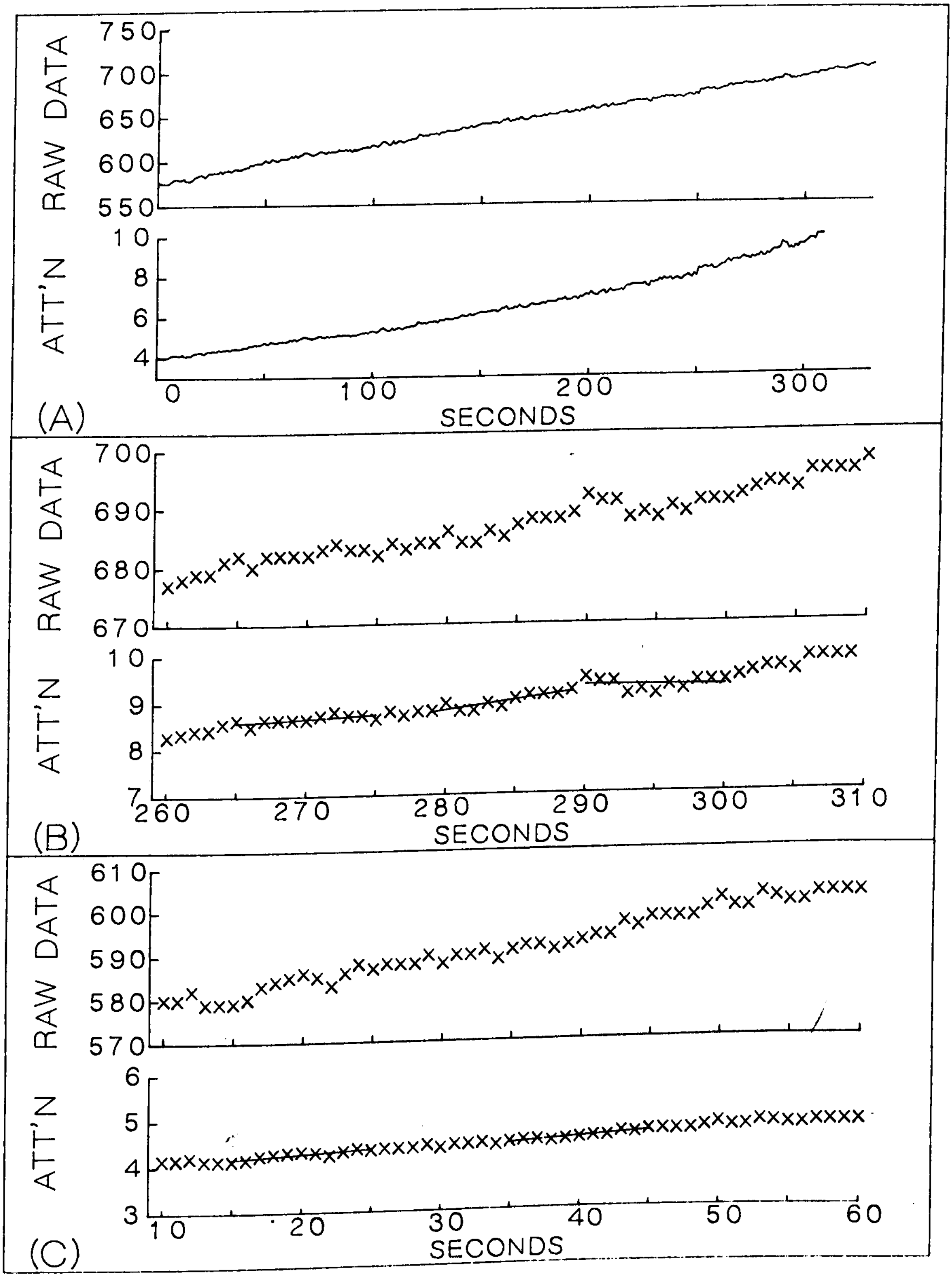


Figure 28. Examples of raw radiometer data and the corresponding attenuations and of regression fits to determine fade rates.

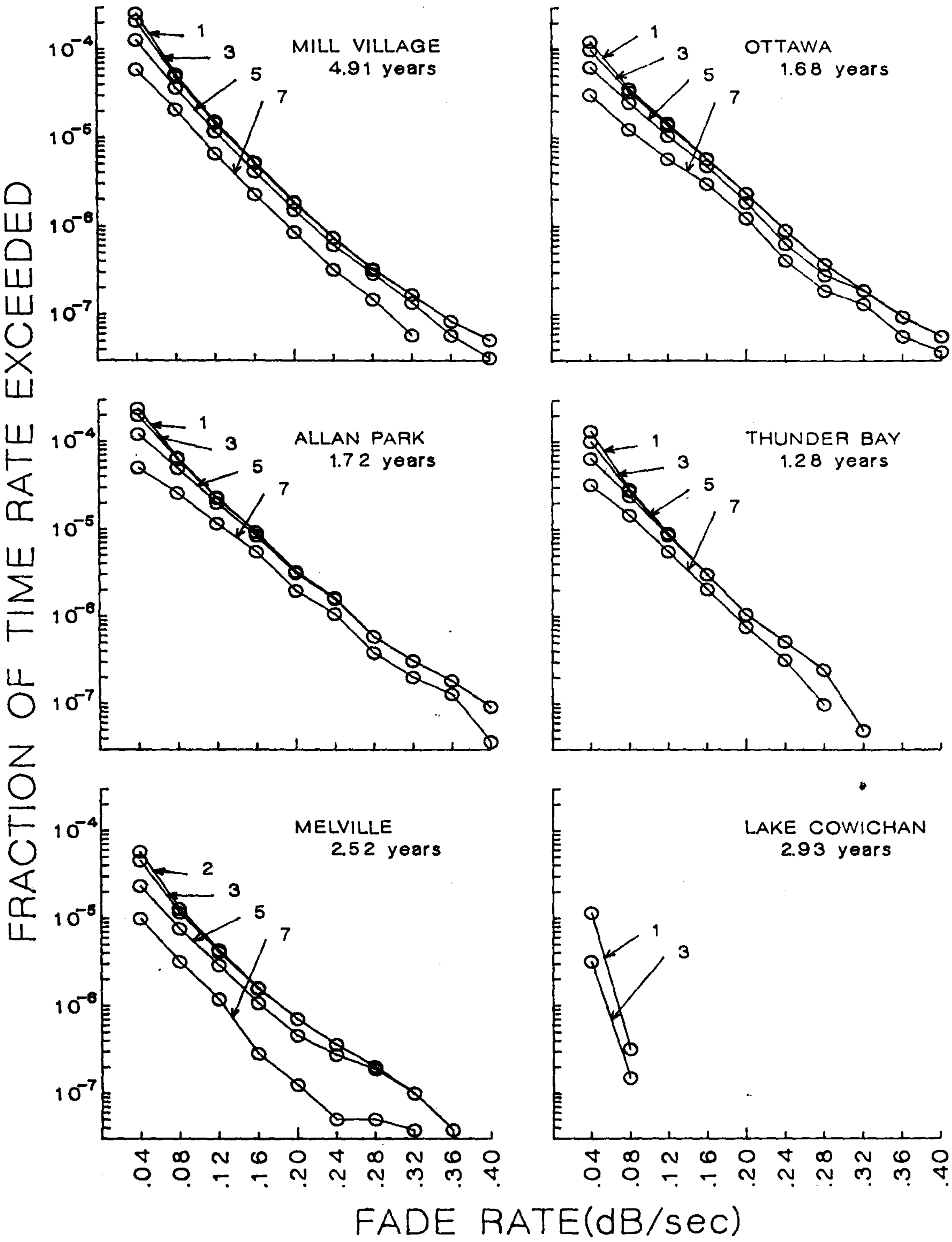


Figure 29. Fade rate distributions for attenuations exceeding thresholds of 1, 3, 5 and 7 dB(2, 3, 5 and 7 dB for Melville.)

For the lowest attenuation threshold of 1 dB, the fraction of time that the fade rate exceeded 0.04 dB per second varied from 3×10^{-4}(2.5 hours per year) at Mill Village to 1×10^{-5}(five minutes per year) at Lake Cowichan. Three stations had fade rates that exceeded 0.40 dB per second; the highest fraction of time for which that fade rate was exceeded occurred at Mill Village and was about 5×10^{-8} (two seconds per year; taking into account the 10 seconds that is required for a regression fit this becomes, in this case, 9 seconds per year). At Lake Cowichan the fade rate exceeded 0.08 dB per second for only about 3×10^{-6} of the time and did not reach 0.12 dB per second at all. Also, in figure 29 the curves for the attenuation thresholds of 1, 3 and 5 dB merge at the highest fade rates. The explanation is that most of the highest fade rates occurred at attenuations above 5 dB so the fractions of time that these fade rates were exceeded is about the same for all attenuation thresholds of 5 dB or less.

9.4 Dependence of Fade Rate on Attenuation Level

Figures 30 and 31 show how the occurrence of high fade rates is related to the attenuation level. In those figures the abscissa is divided into 0.2 dB attenuation intervals and each point that is plotted refers to one interval only. In figure 30 the ordinate represents the fraction of time, for each attenuation interval, that the fade rate exceeded the indicated thresholds. The curves in that figure show that as the attenuation increases there is a rapid increase in the fraction of time that the fade rate is high. For example, in the attenuation range 7 to 9 dB the fade rate exceeded 0.16 and 0.08 dB per second for up to 10% of the time at Ottawa and for up to 40% of the time at Allan Park, respectively. The ordinate in figure 31 represents the number of seconds per year, for each attenuation interval, that the fade rate exceeded the same thresholds. The curves in that figure show a clear tendency at Mill Village, Ottawa, Allan Park and Thunder Bay for the higher fade rates to occur only at times of high attenuation. This tendency was not observed in the Melville data, however, and there were too few high fade rates at Lake Cowichan to justify any conclusions on this point. Exceedence times for fade rates of 0.04 dB per second or less were several times those for a fade rate of 0.08 dB per second. There was no tendency for these lower fade rates to be limited to any particular attenuation levels.

9.5 Fade Rate Durations

Distributions of fade rate durations, i.e. the times for which fade rate thresholds were exceeded continuously, are shown in figure 32. When computing fade rate durations account was taken of the fact that if the fade rate obtained by a single computation exceeded a certain threshold, then that threshold must have been exceeded for at least 10 seconds. For this reason an estimate from figure 32 of the time that the higher fade rate thresholds were exceeded may be more than the same estimate that is read from figure 29. At Mill Village there were 900 events per year when the fade rate continuously exceeded 0.04 dB per second for 10 or more seconds. Twice per year the same threshold was continuously exceeded for 80 or more seconds. By contrast, once per year the fade rate continuously exceeded 0.36 dB per second for 10 or more seconds and 0.2 times per year for 15 seconds; the latter example corresponds to one such event in the entire operating period of 4.91 years. Of course, a fade rate duration of less than 10 seconds could not be detected. The two curves for Lake Cowichan are much steeper than those for the same thresholds at any of the other stations.

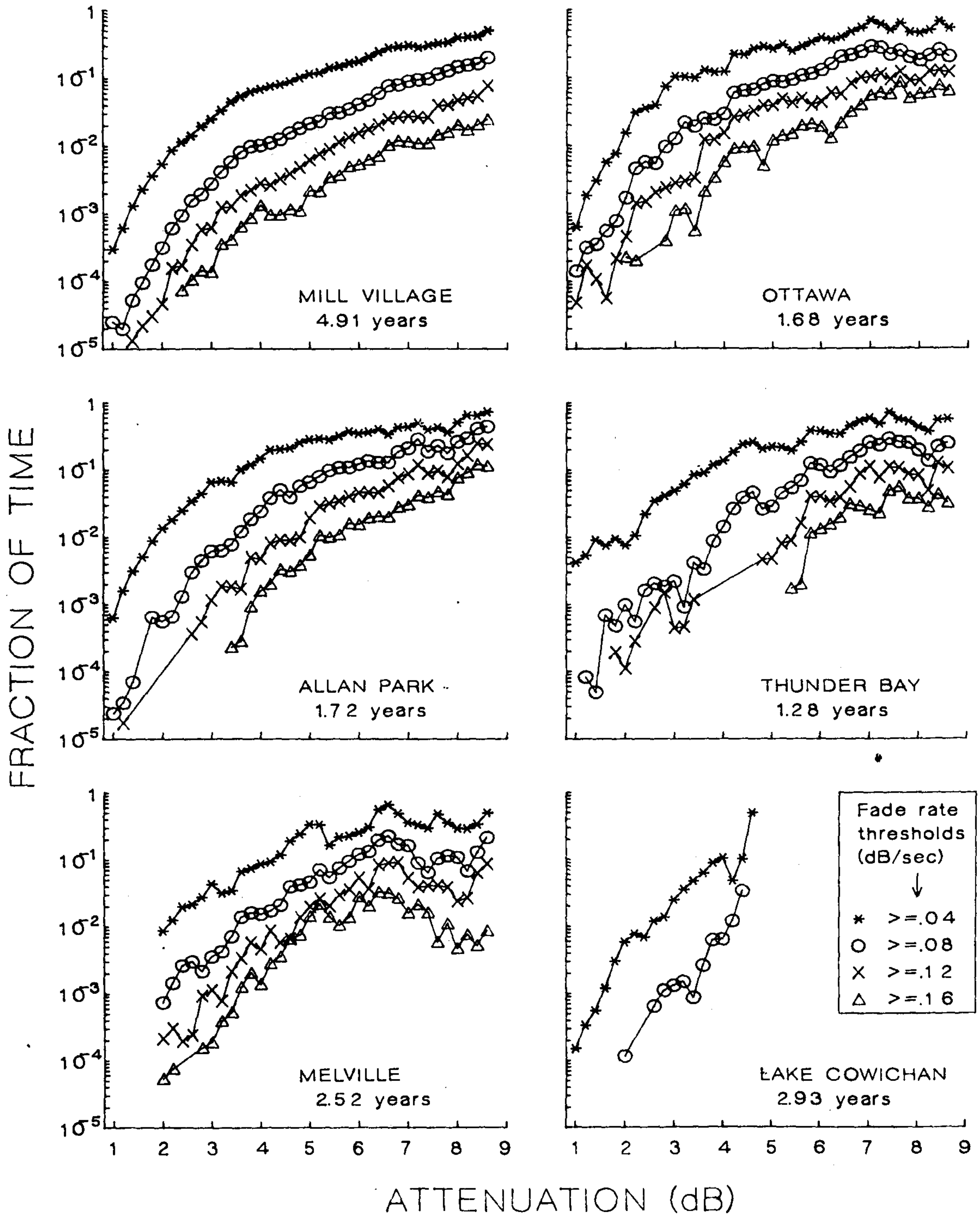


Figure 30. Fraction of time that fade rate exceeded 0.04,0.08,0.12 and 0.16 dB per second in 0.2 dB attenuation intervals.

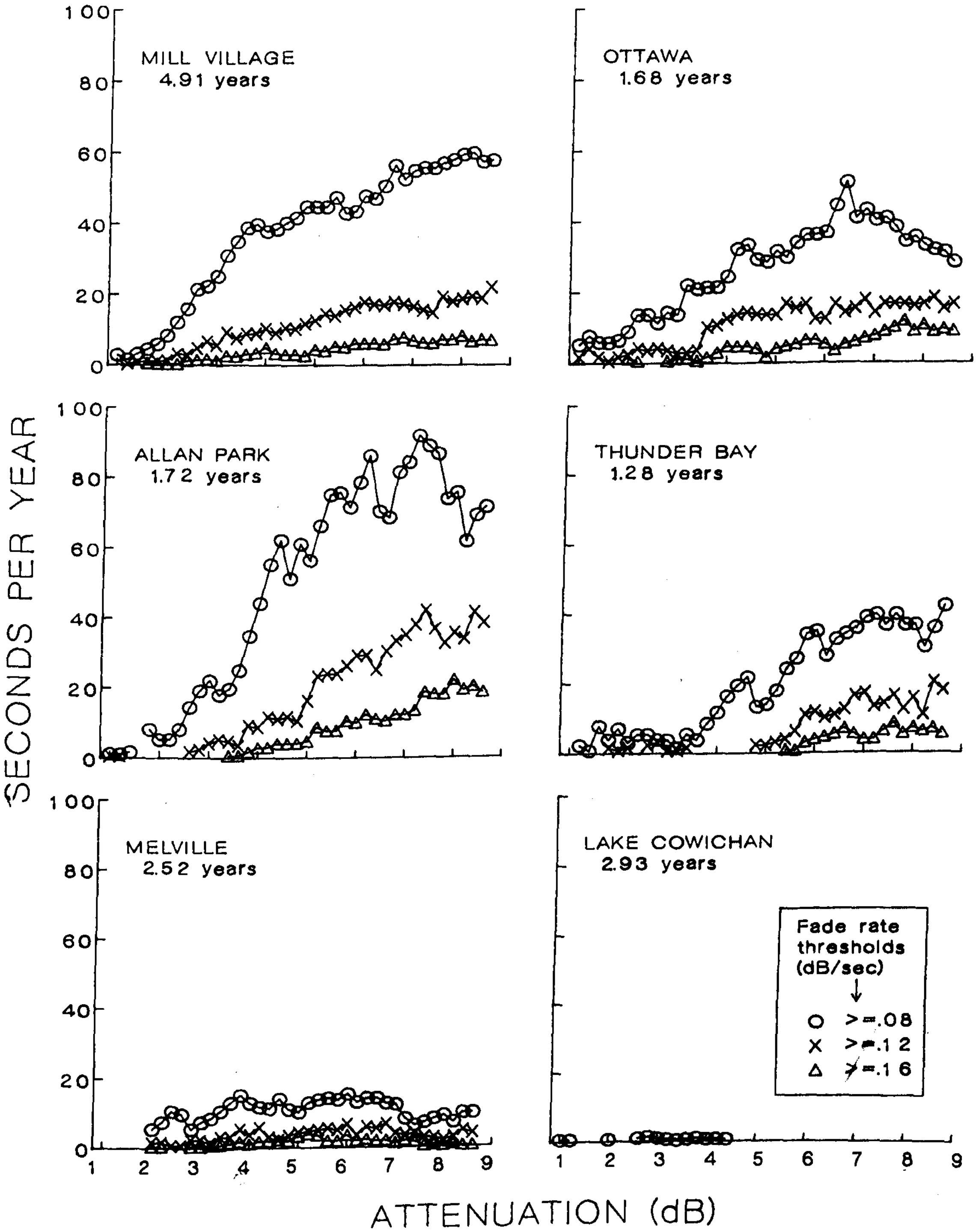
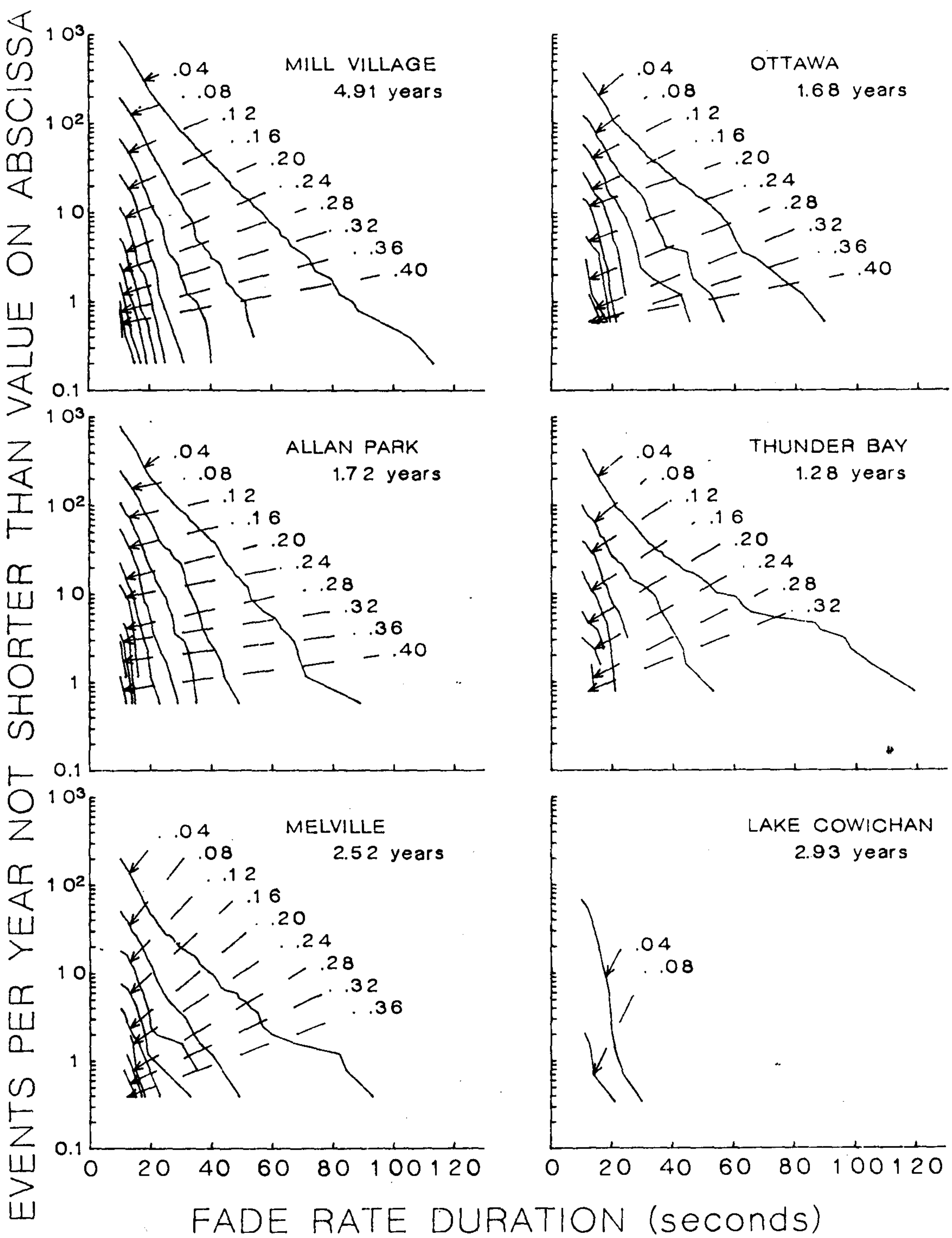


Figure 31. Average number of seconds per year that fade rate exceeded 0.08, 0.12 and 0.16 dB per second in 0.2 dB attenuation intervals.



Fibure 32. Fade rate duration distributions for the fade rate thresholds shown.

10. DISCUSSION

10.1 Attenuation

Although there are about five years of data for Mill Village, the year to year differences in both the monthly attenuation distributions and in the yearly attenuation distributions show that this is not long enough to obtain stable long-term statistics. To get stable statistics it appears that 10 to 20 or more years of data would be required as is the case for rainfall statistics[10].

From the statistics reported here, a general observation that can be made is that there was little or no attenuation at any station when the temperature at ground level was well below freezing. Table 1 lists the mean daily temperatures and the mean daily maximum temperatures for each station for the month of January. The temperatures in January are chosen to represent the winter temperatures since it is the coldest month of the year for five of the stations. The exception is Mill Village where the mean daily temperature for the coldest month, February, is about one-half degree below that of January.

The three inland stations for which winter data were obtained have January mean daily maximum temperatures that are well below freezing. Their January mean daily temperatures are, of course, even lower. At these stations in January the temperature would seldom rise to the melting point of ice and most, if not all, of the precipitation would be snow. Since snow is a poor absorber of radio signal energy, there would be little or no attenuation at these stations during January. The two stations that have appreciable amounts of attenuation in the winter, Mill Village and Lake Cowichan, have January mean daily maximum temperatures which are above freezing, +0.8° C and +5.2° C, respectively. For Lake Cowichan the mean daily temperature is also above freezing, at +2.6° C, but for Mill Village it is below, at −3.9° C. At these temperatures most, if not all, of the precipitation in January would be rain at Lake Cowichan and much of it would be rain at Mill Village. This explains how those two stations could have worst attenuation months in the winter whereas at the other stations all worst months were in the spring, summer or fall.

The two maritime stations, Mill Village and Lake Cowichan, both show extremes in attenuation behaviour but not always in the same respect. Lake Cowichan has an average amount of attenuation at 1 dB but, of all the stations, it has the least amount above 2 dB and it is the only one to have none above 4.4 dB. It also had the fewest fades at 3 dB(Table 7) and the shortest fades at 3 and 4 dB(Table 8). This is not unexpected since most of Lake Cowichan's high annual accumulation of rain falls as drizzle at low rain rates with very little falling at high rain rates—a characteristic that is unique among these stations. By contrast, Mill Village, which has the second highest annual rainfall(Table 1), had the most attenuation in the range 1 to 10 dB(figure 17), the most fades at 3, 6 and 10 dB(Table 7) and the longest fades in the range 2 to 8 dB(Table 8). This, too, is consistent with the year-round occurrence of rain at Mill Village with frequent storms that are accompanied by high rain rates.

10.2 Fade Rates

For attenuations below ten dB the fade rates found here for 13 GHz are consistent with the results of Lin et. al.[11], Matricianni [12], Dintelmann [13] and Nackoney [14], who reported fade rates of up to 0.23 dB per second at 19.6 GHz, 0.22 dB per second at 11.6 GHz, 0.5 dB per second at 11 GHz and 0.38 dB per second at 11.7 GHz, respectively. Also, the results for Mill Village, Ottawa, Allan Park and Thunder Bay, but not those for Melville, are in agreement with the observations of Lin [11] and Matricciani [12] that high fade rates are more likely to occur at higher attenuations than at lower ones.

10.3 Independence of statistics at Different Stations.

There are a number of other observations that show that the statistics for each station are largely independent of those for the other stations.

First, an inspection of the monthly attenuation distributions reveals that there were at least eight instances when the amount of attenuation during a 1-month period was much lower at one station than was average for that month at that station and that the occurrence of one of these events at one station was not related to the amount of attenuation that occurred at the other stations during that same month. These periods corresponded, no doubt, to periods when there was little or no rain.

Second, for the five stations not including Lake Cowichan the exceedance time from the composite annual attenuation distributions (figure 17) varied by a factor of five to ten for all attenuations. The highest exceedance times are for the Atlantic station, Mill Village. Of the other four stations, Ottawa and Thunder Bay lie closest together but all are quite separate from one another. Lake Cowichan, the Pacific station, has a very different distribution. It has the second highest amount of attenuation at 1 dB, but the lowest amount above 2 dB, and none at all above about 4.4 dB.

Third, among the diurnal statistics no two stations have similar distributions of the attenuation throughout the day (figure 24). Again, the two maritime stations represent the extremes in that the attenuation is most uniformly distributed throughout the day at Mill Village and is most concentrated in one six-hour period of the day at Lake Cowichan. Also, the patterns for the four inland stations are distinctly different from one another.

Fourth, in the plot of Q as a function of attenuation (figure 21) the curves for Ottawa and Thunder Bay lie close together, but the others are well separated from one another.

Fifth, at the five stations that had fade rates exceeding 0.2 dB per second, which does not include Lake Cowichan, the fade rate exceedance for that threshold, i.e., the fraction of operating time for which the fade rate exceeded that threshold, varies by a factor of about five. For the same five stations the corresponding exceedances for a threshold of 0.04 dB per second also varied by a factor of five but if Lake Cowichan is included this factor becomes twenty-five. The highest fade rate exceedances were at Allan Park for thresholds of 0.08 dB per second or above and were shared by Allan Park and Mill Village for a threshold of 0.04 dB per second. The lowest were at Lake Cowichan.

Sixth, for the inland stations the length of the longest fades varied at all attenuation levels by a factor of about two (Table 8). In the attenuation range 2 to 4 dB these fades were about three times as long at Mill Village as at the inland stations while in the range 6 to 10 dB their lengths were about the same. For an attenuation of 2 dB at Lake Cowichan, the lengths of these fades were about the same as at the inland stations but for 3 and 4 dB they were much shorter.

It is clear, therefore, that no single factor dominates the attenuation statistics all across Canada. In particular, the differences among the attenuation statistics cannot be attributed to differences in latitude for the latitudes of the different sites are within seven degrees of each other. Also, there are no uniquely maritime statistics since in many cases the differences between the statistics for the two maritime stations are greater than for any other pair of stations. Nor is there any correlation between the statistics and the distance from the nearest ocean to the site where the data were recorded. These results lead clearly to the conclusion that for microwave signals on earth-space paths both attenuation statistics and fade rate statistics are influenced primarily by geographical and climatic conditions that are relatively local to the ground station.

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