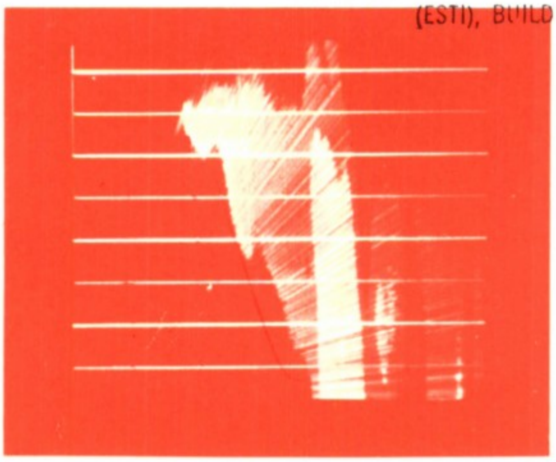
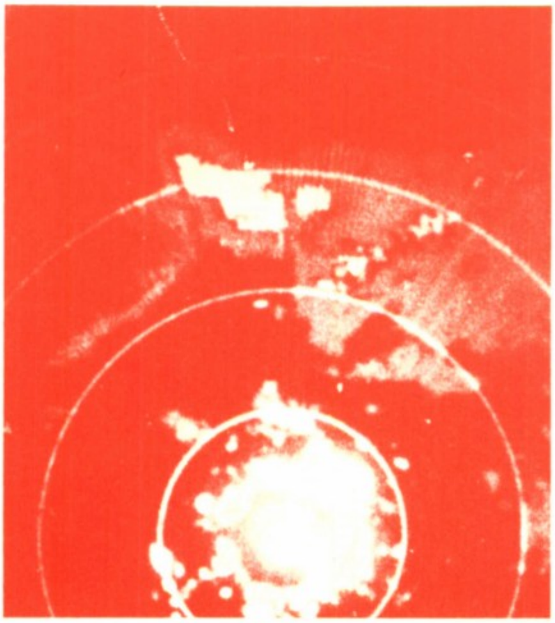


Frequency of Occurrence of Rain Attenuation of 10 DB or Greater at 10 GC

Weather Radar Research

Department of Meteorology

Massachusetts Institute of Technology



Final Report

Prepared for

Lincoln Laboratory

Under Purchase Order No. [redacted] CC-599

December 1966

ESLL

FREQUENCY OF OCCURRENCE OF RAIN ATTENUATION OF 10 DB OR GREATER AT 10 GC

Final Report, Phases 1 and 2
Lincoln Laboratory Purchase Order No. CC-599

Prepared for
Massachusetts Institute of Technology
Lincoln Laboratory

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Prepared by

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Massachusetts Institute of Technology

December 1966

ABSTRACT

An analysis of quantitative radar data supplemented by records of hourly precipitation amounts and excessive short duration rainfall at selected points was made to determine the frequency of occurrence of severe attenuation (defined here as 10 db or more) of 10 Gc radiation by rain at stations in central New England. The study was based on two years' data.

It was found that at an elevation of 5° above the horizon severe attenuation by intense thunderstorms may be expected for approximately 32 hours per year if all directions of propagation are involved. Along a particular azimuth it occurs for 5 hours per year. At an elevation angle of 10° the times are 14 and 3 hours respectively; at 20° they are $3\frac{1}{2}$ and 1 1/3 hours. Coarse resolution of the radar data precluded analysis at higher elevation angles.

Severe attenuation by heavy widespread rain is considerably more probable in southeastern New England, where approximately four hours per year at 5° elevation may be expected, than farther to the north and west. This type of storm does not cause as much as 10 db of attenuation at an elevation of 10° or more.

Techniques are suggested for applying the results to regions where rain gauge records but no quantitative radar data are available. Results of this preliminary analysis cannot be extended to higher radiation frequencies or smaller amounts of attenuation, because less intense storms whose statistics have not yet been thoroughly explored would be involved. An investigation of all types of New England storms, their intensities, their frequency of occurrence and the attenuation they would cause is in progress.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

TABLE OF CONTENTS

FREQUENCY OF OCCURRENCE OF RAIN ATTENUATION OF 10 db OR GREATER AT 10 Gc

I. INTRODUCTION

Adequate statistics concerning the amount and frequency of attenuation of microwaves by rain cannot be compiled on the basis of existing data. For such statistics, detailed and extensive knowledge of the distribution of precipitation in three dimensions is required. Because of the small-scale variability in precipitation intensity, however, the patterns cannot be depicted by ordinary networks of rain gauges; a combination of rain gauge records and quantitative radar observations is needed. Moreover, the records would have to cover many years and many geographical areas since storm structure may vary significantly with location, topography, season, and the general meteorological situation. Rain gauge records with varying degrees of resolution in time and coverage in space have been kept in many places for many years, but quantitative radar data have been taken only in a very few places and within the past several years.

Some studies have been made recently of the frequency of attenuation by rain for microwave relay links in certain areas in Japan by Ugai and Kaneda (1963), and Tokunagu and Tanaka (1964). In both of these studies, the rainfall information was provided primarily by gauges, but radar data were used to indicate typical spatial distributions of heavy precipitation for various types of storms. Because they were concerned with propagation paths very near the surface of the earth, the vertical structure of the storms was not considered. The USAF Climatic Center (1961) has issued a preliminary report which presents estimates of precipitation attenuation at 8 Kmc. The estimates are based on hourly rainfall records with no real information on the spatial distribution of the precipitation.

The Weather Radar Research project at M.I.T. has quantitative radar data for most storms since 1960. A study of typical patterns in New England storms in both horizontal and vertical, amounts of precipitation associated with them, and their relative frequency of occurrence is being made on the basis of three years' data, 1961-1963. Statistically this is a small sample, but rain gauge records are also being used, and these extend over longer periods so that the representativeness of the samples can be checked to some extent. When this study is completed it will serve as a basis for estimates of the amount of attenuation suffered by microwaves of various frequencies propagated at different elevation angles. A preliminary investigation which is restricted to a frequency of 10 Gc, to attenuation of 10 db or greater and to elevation angles of at least 5° above the horizon is presented in this report.

In addition to the estimates of the frequency of occurrence of severe attenuation, the report contains a discussion of the relations between radar reflectivity, rainfall rate and attenuation, and also a comparison of the information contained in radar and rain gauge records.

II. RELATIONSHIPS BETWEEN RAINFALL RATE, REFLECTIVITY AND ATTENUATION

Computations of radar reflectivity and attenuation of microwave radiation for rainfall of various intensities were first made by Ryde (1946); they were based on the theory of diffraction of a plane wave by a sphere and on empirical drop size distributions. Since that time, more extensive and accurate computations have been made and there have been many more measurements of drop size distributions in natural rain. These computations indicate that if the hydrometeors are small compared with the wavelength (Rayleigh scattering), the radar reflectivity is proportional to $Z \equiv \sum D_i^6$, where D_i is the diameter of an individual raindrop, or of the drop to which an ice or snow particle would melt, and the summation is taken over a unit volume. Several empirical relations between Z and the rainfall rate, R, have been deduced from drop size measurements for various types of rain, and differences between steady rain, showers, and thunderstorms have been recognized (Jones and Mueller, 1960). If all storms are to be grouped together, the relation $Z = 200\ R^{1.6}$ appears to be the best choice, where Z is in mm^6/m^3 and R in mm/hr. Comparisons have been made by Austin (1964) of rainfall rates recorded by a gauge and reflectivities of the atmosphere above the gauge measured by radar. They generally show agreement with the relation $Z_e = 200\ R^{1.6}$ well within a factor of two. Here Z_e is the effective value of the parameter Z as deduced from radar measurements rather than from drop samples. As long as the conditions for Rayleigh scattering are fulfilled, Z and Z_e should be the same.

Computations of attenuation of microwaves by rain indicate that at frequencies of 3 Gc or lower, attenuation is negligible, at 10 Gc it is computed to be $0.0074\ R^{1.31}$ db/km (Gunn and East, 1954). Comparisons of measured and computed attenuation along microwave links by both Ugai and Kaneda (1963) and Tokunagu and Tanaka (1964) showed excellent agreement. Austin (1963) has also made some measurements of attenuation of 10 Gc radiation by comparing maps of measured radar reflectivity at 3 and 10 Gc. She found significant attenuation to occur in three situations: (1) propagation through intense convective storms; (2) propagation through melting snow; and (3) propagation through many miles of moderate to heavy rain. Comparison of measured amounts of attenuation with the empirical values required estimates of the rainfall rate from the 3 Gc reflectivities as a preliminary step. Uncertainty of the Z-R relation and the fact that the intensity level maps were at 5 db intervals caused the comparisons to be rather crude, but within these limitations agreement was good.

On the basis of the computations and measurements just described, the following relations have been used for the present investigation. For rain, where R is in mm/hr,

$$Z_e \text{ at } 3 \text{ Gc } (mm^6/m^3) = 200\ R^{1.6}$$

$$\text{Attenuation (db/km) at } 10 \text{ Gc} = 0.0074\ R^{1.31}$$

For dry snow, the attenuation is negligible. For wet snow, both the reflectivity at 3 Gc and the attenuation at 10 Gc are approximately five times as great as for rain with the same precipitation rate. Wet snowflakes scatter and attenuate about the same as equivalent raindrops, but they fall more slowly; hence there are about five times as many particles per unit volume as in rain with the same precipitation rate.

In hailstorms, neither precipitation rate nor attenuation can be computed from radar data because there is no reliable Z-R relation. Hailstorms can be recognized, at least in New England, by the strong reflectivity at 3 Gc (Geotis, 1963). Since the hailstones are usually wet and are also accompanied by heavy rain, attenuation at 10 Gc is at least 10 db in any hailstorm in New England.

III. FREQUENCY OF OCCURRENCE OF SEVERE ATTENUATION IN NEW ENGLAND

A. Intensity of rain required to cause severe attenuation.

For this preliminary investigation, the term "severe attenuation" is used to indicate attenuation of at least 10 db. By considering only severe attenuation and elevation angles of 5° or greater, attenuation caused by moderate rain or melting snow has been largely eliminated and only severe convective storms and unusually heavy rain need be considered.

Basic data for the study are iso-echo contours of the averaged, range-normalized signal received by the SCR-615-B radar (f = 2.8 Gc, beam width = 3°). Contours are displayed on the PPI as described by Kodaira (1959) and photographed on 35 mm film. An example is in Fig. 1. At 10-minute intervals data are transcribed from the film to digital maps, which show average signal level in a grid of 5x5 mile squares. The intensity levels are at intervals of 5 db, which represent a factor of two in rainfall rate. Equivalent rainfall rates, R_e, of 1, 2, $4 \ldots 2^{n-1}$ mm/hr are assigned. Intense convective storms may occur either in squall lines or as scattered showers. Digital maps in Fig. 2 illustrate these patterns.

In Table 1 are values of attenuation in db/mile for 10 Gc radiation and the number of miles of precipitation required to attenuate 10 db for each rainfall category. It can be seen that if the horizontal dimensions of a shower are sufficiently small so that it is contained in one 5x5 mile square, only storms which reach category 7 in intensity would cause attenuation of 10 db or greater. In general, the intense portions of convective storms are not as large as the grid squares, and the probability that two or more storms of intensity category 6 (32 mm/hr) would line up to produce a total of 10 db attenuation for more than a few moments at a time is small. Therefore only

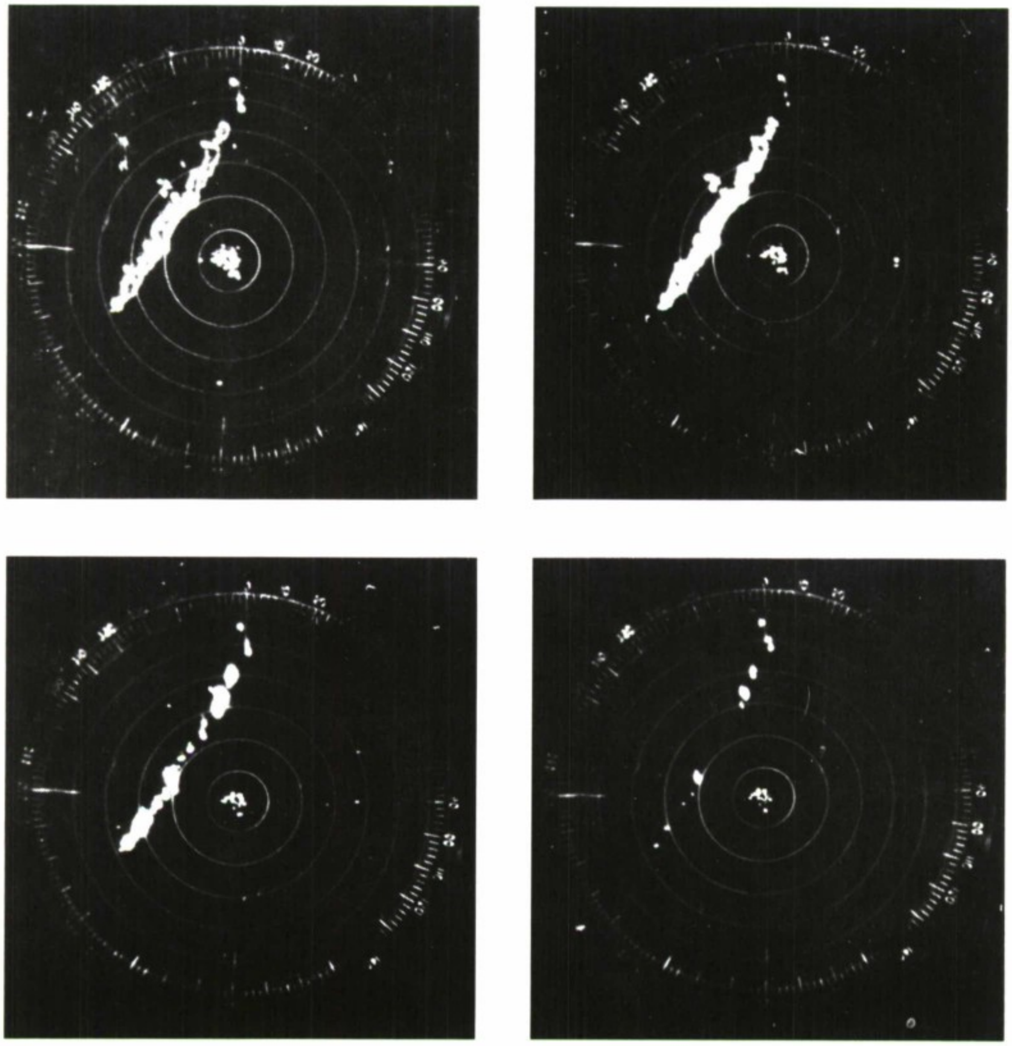
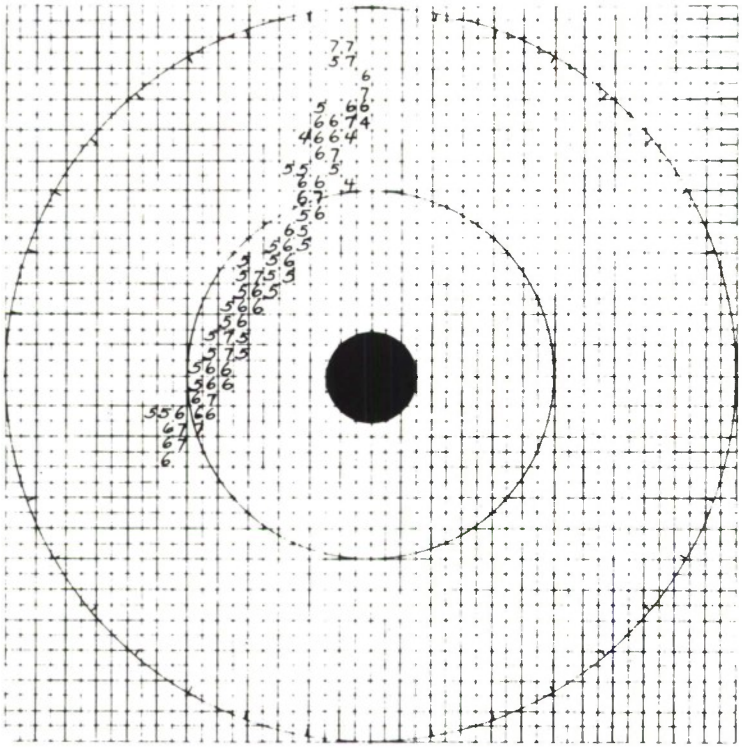


Fig. 1. Isoecho contours of a squall line observed with the SCR-615-B radar, 20 May 1963, 1525 EST. Range markers are at 20 mile intervals. Equivalent rainfall rates for thresholds of each level are 10, 20, 30, and 50 mm/hr.



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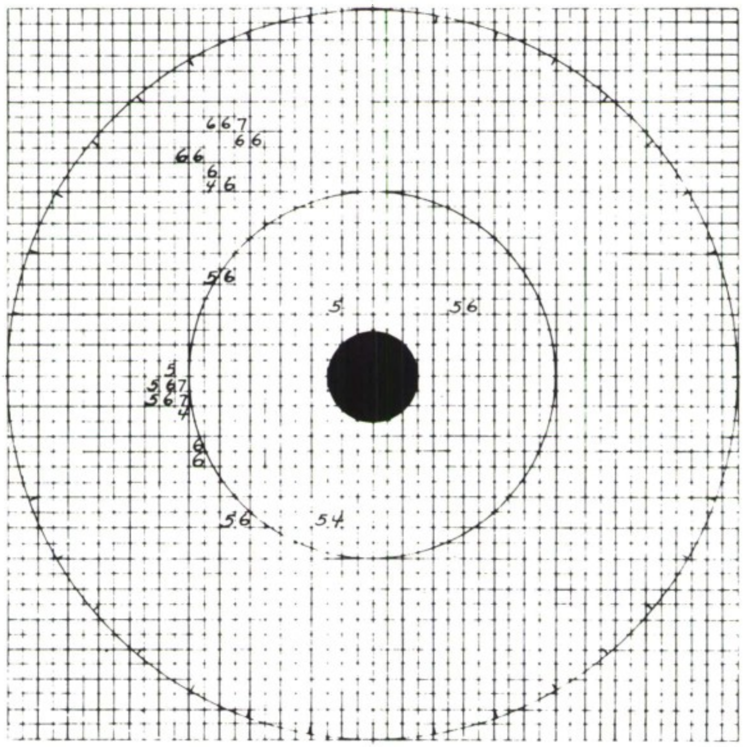

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Fig. 2. Digital maps of precipitation in a squall line and in scattered convective storms. Intensities were observed by the SCR-615-B radar and are displayed in a grid of 5 x 5 mile squares. Equivalent rainfall rates are 2^{n-1} mm/hr.

Table 1. Attenuation of 10 Gc radiation at various rainfall rates

Category	R_e (mm/hr)	Attenuation at 10 Gc: db/mile	Attenuation at 10 Gc: miles for 10 db
1	1	.012	830
2	2	.029	350
3	4	.071	140
4	8	.18	55
5	16	.44	23
6	32	1.1	9
7	64	2.7	4
8	128 (hail)	at least 5.0	2 or less
9	256 (hail)	at least 5.0	2 or less

Table 2. Distance to melting layer and transition interval for various elevation angles

Elevation Angle (degrees)	Distance to melting layer for indicated heights * (miles)						Transition (miles)	
	4-5	6-7	8-9	10-11	12-13	14-15	Actual	Rain Equivalent**
20	2.3	3.2	4.5	5.5	6.5	7.5	0.5	2.5
10	4.5	6.5	9	11	13	15	1	5
5	9	13	17	21	27	29	2	10
3	14	21	28	34	41	47	3	15
1	36	51	65	77	88		7	35

*Height of melting layer in thousands of feet.

**Rain equivalent is distance in rain required to produce same attenuation as transition distance in wet snow.

thunderstorms of intensity 7 or higher were included in this study.

Consideration was also given to whether or not generally widespread rain is ever sufficiently intense to cause severe attenuation at elevation angles of 5° or greater. In widespread rain there is usually a layer of melting snow which the beam must traverse at some range, and attenuation is increased therein by a factor of approximately five. Table 2 gives the range at which the melting layer is encountered and the interval through which the center of the beam is in it for various elevation angles. In the last column is the number of miles of rain required to produce the same attenuation as the melting layer; it is assumed that the melting layer is 1000 ft thick. If rain of fairly uniform intensity were over the station and extended for a number of miles, then the total attenuation at any given elevation angle would be the product of the db/mile value in Table 1 times the sum of the distance to the melting layer plus the rain equivalent distance of the melting layer. For example, for category 4, 8 mm/hr, at an elevation angle of 5° and with the melting layer at 14,000-15,000 ft, the attenuation would be 0.18 db/mile x (29 + 10) miles $\approx$ 7 db. If the melting layer were lower or the elevation angle greater, the attenuation would be less. Therefore rain of 8 mm/hr or less could not cause as much as 10 db of attenuation at the elevation angles considered in this investigation. A rain area of 16 mm/hr could cause 10 db of attenuation at 5° elevation, but not at 10° or 20°.

Critical heights for thunderstorms may be estimated from Fig. 3 which shows the heights of propagation paths at various elevation angles as a function of range from the transmitting or receiving station.

B. Methods of analysis

Four stations, shown in Fig. 4, were chosen for investigation: Millstone Hill and Birch Hill Dam in Massachusetts; Concord, New Hampshire, and Woonsocket, Rhode Island. Millstone Hill was chosen because of the Lincoln Laboratory Facility there, the others because they are conveniently spread over the area observed by the radar, and they have hourly precipitation records which may be used for comparison with the radar measurements. At 5° elevation, storms must be roughly within a radius of 40 miles of the station to cause attenuation. Circles of this radius are drawn about each station. Also shown are the ground clutter and shadowed areas for the radar.

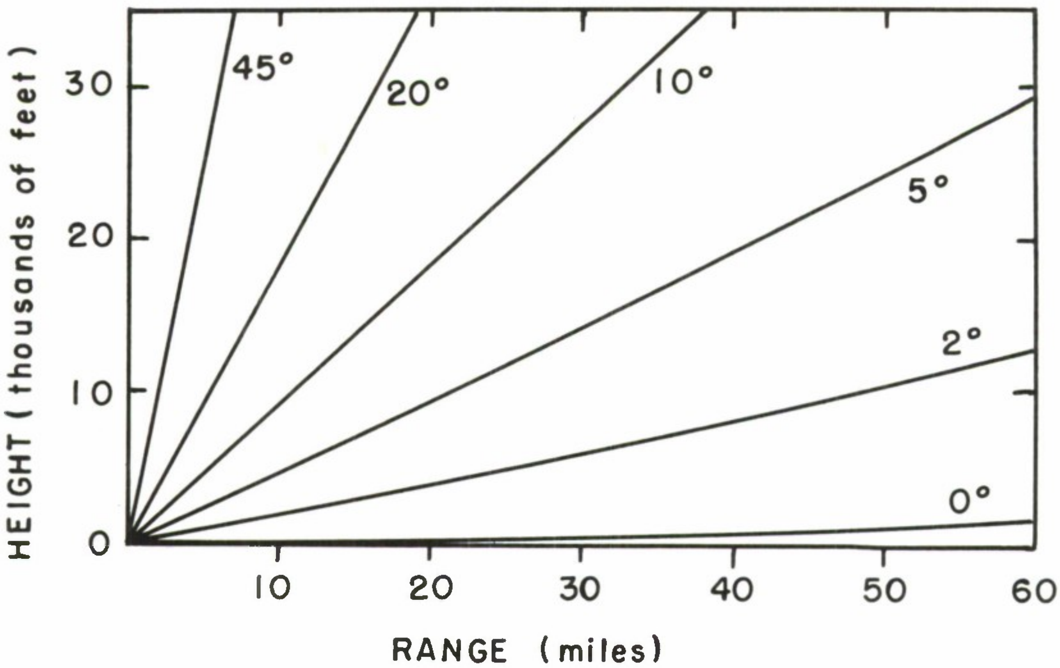

Fig. 3. Heights of propagation paths at various elevation angles as a function of range from the transmitting or receiving station.

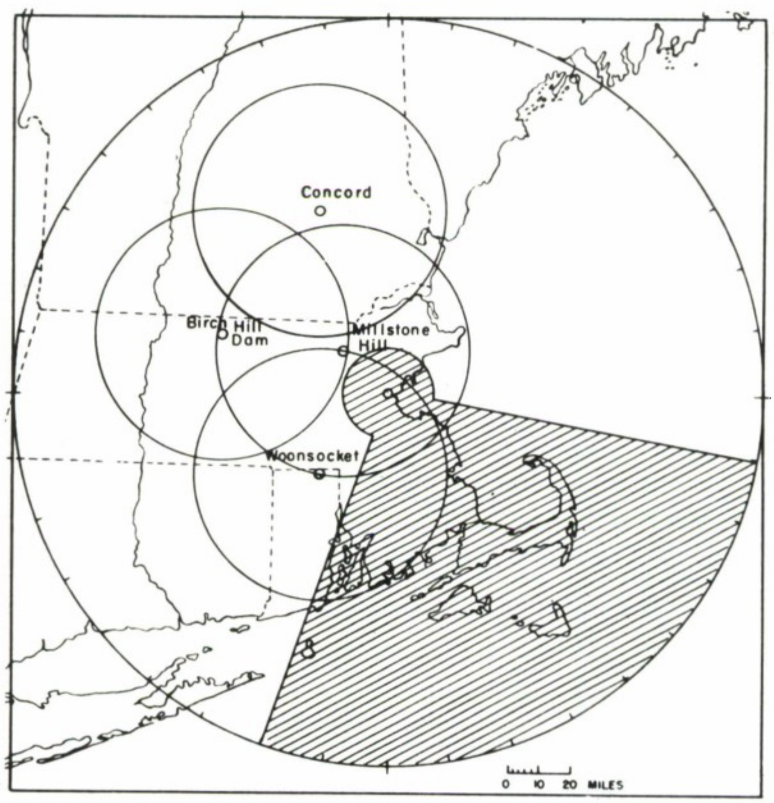

Fig. 4. Locations of four stations for which occurrence of severe attenuation was computed. Circles indicate approximate areas where intense convective storms would affect radiation propagated at an elevation of 5°.

For each station, the number of hours were counted when a storm of intensity category 7 or greater was near enough, in any direction, to cause severe attenuation for propagation paths with minimum elevation angles of 5°, 10° and 20°. Originally it was planned to consider 45° also, but this was not feasible because the distances involved (see Fig. 3) were so short that they could not be properly resolved into 5x5 mile squares. Also recorded were the number of hours when severely attenuating storms lay along four particular azimuths: (a) N-S, (b) NE-SW, (c) E-W, and (d) NW-SE; and the time when a severe storm was in the square over the station. In addition to the times actually counted, estimates were made for short periods, on the order of one-half to one hour, when the radar was being used for other observations but intense storms were in the area before and after the interruption. In 1961 the radar was not in operation for periods of several hours during four intense squall lines. For these periods and for eight occasions in 1961 and 1962 when there were isolated thunderstorms in the radar shadow or at times when the radar was not operating, estimates were also made based on rain gauge data and the few radar records which were available.

C. Assumptions concerning heights of convective storms.

The height to which severe attenuation occurs in thunderstorms cannot be readily ascertained, because if the hydrometeors are composed entirely of ice, attenuation is negligible even if the reflectivity is intense. Strong vertical motions in thunderstorms prevent development of ice crystals and subsequent melting at well-defined levels. Byers and Braham (1949) report that significant amounts of liquid water have frequently been observed in thunderstorms at 20,000 ft or higher even when the 0C isotherm is at a considerably lower level. Donaldson (1961) noted that strong thunderstorms observed at 10 Gc usually have maximum reflectivities at or above 20,000 ft. It is very

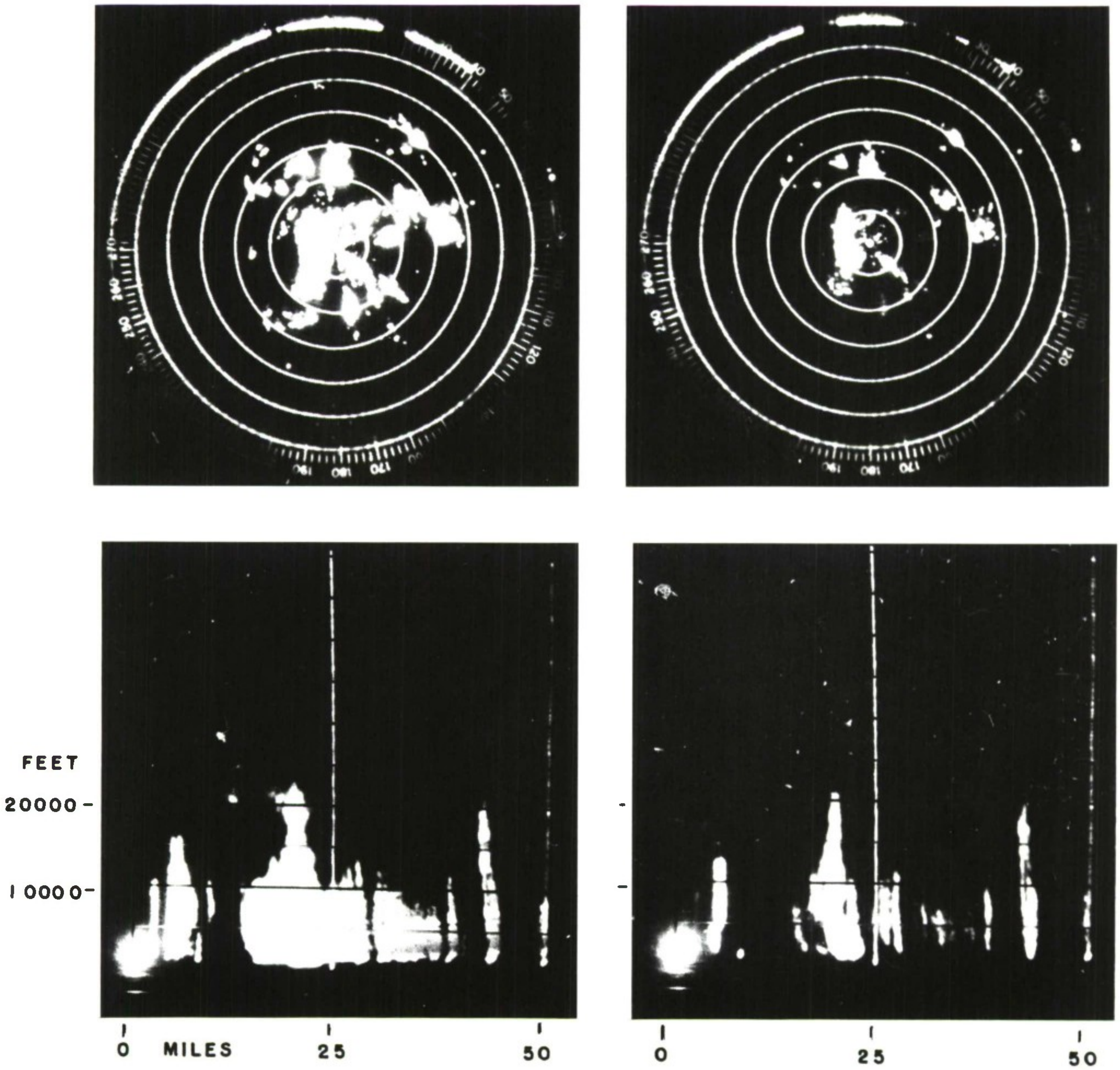

Fig. 5. Example of rain cells which are small in horizontal dimension, observed by AN/CPS-9 radar on 27 December 1964. Intensity levels 3 and 4 are shown. Range markers on PPI are at 20-mile intervals.

likely that the maximum reflectivity occurs just at the level where attenuation ceases to deplete the signal significantly. On the basis of these observations, it has been assumed that thunderstorms without hail (category 7, R_e = 64 mm/hr) cause attenuation up to 20,000 ft, and that above that level the hydrometeors are composed entirely of ice. Moderate hailstorms (category 8) and severe hailstorms (category 9) are assumed to attenuate to 25,000 ft and 30,000 ft respectively. These assumptions are believed to be reasonable even if somewhat arbitrary. Experiments to provide further information on this question are described in section V.

D. Assumptions concerning heavy widespread rain.

Even in widespread precipitation heavy rain occurs in relatively small areas, 30 miles or less in dimension (Nason, 1965). These areas are generally composed of many small intense cells which extend vertically to 10,000 or 15,000 ft. An example is in Fig. 5. Unfortunately, neither of the radars at the Laboratory for Earth Sciences can adequately depict the structure and intensity of these cells. The 3 Gc radar has poor resolution and the 10 Gc radiation is attenuated by the rain. Further, there is evidence that the heavy rain in these cells is composed of relatively small drops, so that the rainfall rate is underestimated even by the unattenuated radar. It has, therefore, been necessary to base estimates of severe attenuation by widespread rain on the rain gauge data. If any gauge within 20 miles of the station reported as much as 0.5 inches in a single hour it was assumed to represent an area of rain whose intensity is at least 16 mm/hr and whose dimensions are sufficient to cause 10 db of attenuation at an elevation of 5^{o}, provided the melting layer is at least 12,000 ft high.

In a recent study, Tweedy (1965) found that areas of heaviest rain are often associated with a low-level jet and move very rapidly, sometimes at

60 knots or even faster. Under these circumstances, an area of 16 mm/hr which is 30 miles in dimension could move over a gauge in a half-hour or less and deposit only 0.3 inch of rain. Moderate rain during the rest of the hour would be expected to raise the amount to 0.4 inch. It seems probable, therefore, that severe attenuation also occurs when hourly amounts between 0.4 and 0.5 inch are recorded within 20 miles of the station. Therefore these cases were also included in the results in Tables 3 and 4.

E. Results.

Results of the analysis are in Tables 3-5. There appears to be no significant difference in the results for the four stations nor for the different azimuths. Values obtained when times for both years, all stations and all azimuths are averaged are in Tables 6-7 and in Fig. 6. If the probability of occurrence of thunderstorms is the same for all points in the area, and if all storms are assumed to attenuate up to the same height, then the frequency of occurrence of severe attenuation would be expected to vary as $1/\tan^2 \alpha$, where α is the elevation angle. Along a particular azimuth it should vary as $1/\tan \alpha$. It can be seen from Fig. 6 that the observed variation with α agrees with these functions, except at high elevation angles where the breadth of the storms (assumed to be 5 miles) causes the curves to flatten to a constant value for $\alpha > 60^\circ$.

It is believed that any errors in the values presented are likely to be underestimates rather than overestimates. On the days when thunderstorms were observed by the radar, some intense ones on the far sides of stations 1 and 2 may have been underestimated and omitted from the count because at long ranges the intense core of the storm may not fill the radar beam. For stations 3 and 4, intense storms in the ground clutter or the radar shadow would fail to be observed. This underestimate could be as great as 30% for Woonsocket which is very close to the shadow, but probably does not exceed 15% for the other stations.

For periods when thunderstorms occurred but the radar was not in operation, times were included only when the rain gauge data indicated an intense storm in the vicinity of the station. Intense storms, however, sometimes move between the gauges missing them entirely, so that in this case, also, an underestimate is probable.

With regard to the widespread rainstorms, the uncertainty is quite large. All of the storms involved would undoubtedly cause strong attenuation at 10 Gc, but without a detailed analysis of the individual rain gauge records it cannot be ascertained whether it would actually exceed 10 db at an elevation angle of 5°.

The values in Tables 3-5 and Fig. 6 may be considered as the minimum times when severe attenuation would occur. It may be inferred from characteristics of the various types of storms considered that if smaller amounts of attenuation or lower elevation angles were considered the times would increase very sharply.

It is recognized that two years' data is a rather small sample. Originally 1963 was also included, but was subsequently discarded as being unrepresentative both because intense convective storms were relatively infrequent in New England during that summer and because the 3 Gc radar was being used for several types of measurements and the PPI records sometimes lacked continuity. Representativeness of 1961 and 1962 is discussed in the following section.

Table 3. Hours in 1961 when severe attenuation would have occurred in any direction and at selected azimuths for various elevation angles.

	Elevation angle:	5°		10°		20°		Over Station
	Azimuth	A	S	A	S	A	S	
		Thunderstorms						
1. Concord N. H.	N-S	26.3	5.3	5.7	2.2	2.3	0.5	0.5
	NE-SW		2.3		1.5		0.8	
	E-W		2.0		1.2		0.8	
	NW-SE		3.5		2.3		1.2	
		Widespread rain						
	N-S	2.0	0.5					
	NE-SW							
	E-W							
	NW-SE		0.5					
		Thunderstorms						
2. Birch Hill Dam Mass.	N-S	32.0	3.5	11.7	1.7	2.3	0.8	0.7
	NE-SW		3.7		1.5		1.0	
	E-W		4.5		2.5		0.7	
	NW-SE		3.2		2.2		1.0	
		Widespread rain						
	N-S	2.0	1.0					
	NE-SW		1.0					
	E-W							
	NW-SE							
		Thunderstorms						
3. Millstone Hill Mass.	N-S	41.3	8.5	19.7	4.5	3.7	1.7	0.7
	NE-SW		7.0		4.7		2.0	
	E-W		7.0		5.2		1.2	
	NW-SE		4.3		2.8		1.7	
		Widespread rain						
	N-S	3.7	1.3					
	NE-SW		2.3					
	E-W							
	NW-SE		0.7					
		Thunderstorms						
4. Woonsocket R.I.	N-S	35.5	5.2	13.2	2.3	3.2	0.7	0.2
	NE-SW		3.8		2.3		0.7	
	E-W		4.7		2.8		0.7	
	NW-SE		3.7		2.5		1.0	
		Widespread rain						
	N-S	5.8	2.2					
	NE-SW		2.0					
	E-W		2.0					
	NW-SE		1.3					

A: any direction
S: selected azimuth

Table 4. Hours in 1962 when severe attenuation would have occurred in any direction and at selected azimuths for various elevation angles.

	Elevation angle:	5°		10°		20°		Over Station
	Azimuth	A	S	A	S	A	S	
		Thunderstorms						
1. Concord N. H.	N-S	38.7	9.8	17.2	5.0	4.3	1.7	0.2
	NE-SW		5.5		2.8		1.7	
	E-W		6.8		4.2		1.7	
	NW-SE		8.2		4.2		1.2	
		Widespread rain						
	N-S	1.0						
	NE-SW							
	E-W		0.5					
	NW-SE							
		Thunderstorms						
2. Birch Hill Dam Mass.	N-S	28.8	6.3	13.5	4.2	3.8	1.8	0.7
	NE-SW		4.0		2.5		0.7	
	E-W		7.2		4.0		1.3	
	NW-SE		6.2		5.2		2.8	
		Widespread rain						
		0						
		Thunderstorms						
3. Millstone Hill Mass.	N-S	30.3	4.3	18.2	3.0	5.0	1.7	0.3
	NE-SW		6.7		4.5		1.8	
	E-W		8.3		6.3		2.0	
	NW-SE		6.3		3.2		1.7	
		Widespread rain						
	N-S	2.0	2.0					
	NE-SW							
	E-W							
	NW-SE							
		Thunderstorms						
4. Woonsocket R. I.	N-S	21.0	2.2	8.2	1.8	3.0	0.8	0.5
	NE-SW		2.3		2.7		1.2	
	E-W		3.8		2.7		1.3	
	NW-SE		3.2		3.2		1.5	
		Widespread rain						
	N-S	3.0	1.0					
	NE-SW							
	E-W		0.5					
	NW-SE		0.5					

A: any direction
S: selected azimuth

Table 5. Per cents of the times of severe attenuation by thunderstorms which were calculated from radar and rain gauge records respectively.

Elevation angle	Station	Counted from radar maps		Interpolated from radar maps		Estimated from rain gauge data	
		1961	1962	1961	1962	1961	1962
5^{o}	Concord, N.H.	57	94	5	5	38	1
	Birch Hill	62	90	4	3	34	6
	Millstone Hill	74	90	4	3	21	8
	Woonsocket	80	82	5	0	15	18
10^{o}	Concord	60	96	9	4	30	0
	Birch Hill	47	94	4	2	49	4
	Millstone Hill	87	91	4	4	9	5
	Woonsocket	82	79	8	0	10	21
20^{o}	Concord	35	95	0	5	65	0
	Birch Hill	29	100	0	0	71	0
	Millstone Hill	95	100	5	0	0	0
	Woonsocket	68	77	5	0	27	23
Over station	Concord	0	100	0	0	100	0
	Birch Hill	0	50	0	0	100	50
	Millstone Hill	100	100	0	0	0	0
	Woonsocket	0	100	0	0	100	0

Table 6. Average number of hours and days per year of severe attenuation by thunderstorms for various elevation angles.

Elevation angle	Hours		Days	
	Any direction	Particular azimuth	Any direction	Particular azimuth.
5^{o}	31.7	5.1	18	10
10^{o}	14.0	3.2	13	8
20^{o}	3.5	1.3	7	5
Over station	0.4		3	

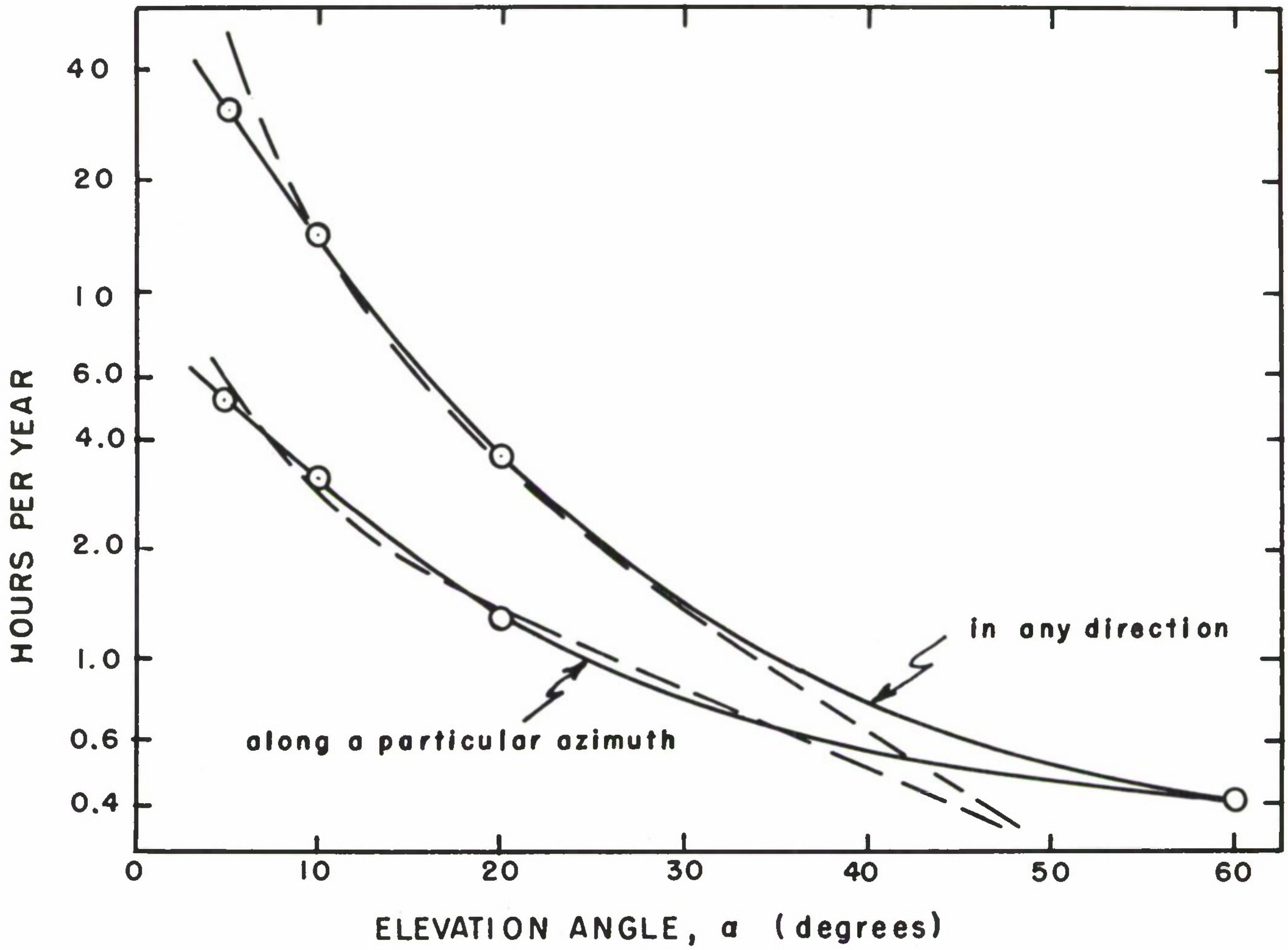

Fig. 6. Number of hours per year of severe attenuation (10 db or more) of 10 Gc radiation by intense thunderstorms for stations in central New England. Solid lines are deduced from radar and rain gauge data for 1961 and 1962. Dashed lines show relative variation of $1/\tan\alpha$ and $1/\tan^2\alpha$.

Table 7. Ratios of total time of severe attenuation to time when intense storms are over station.

Elevation angle	Over station	Particular azimuth	Any direction
5°	1	15	80
10°	1	8	35
20°	1	3	9

IV. COMPARISON OF RADAR AND RAIN GAUGE RECORDS OF INTENSE RAINFALL

Radar records of precipitation patterns are available at only a few locations, but rain gauge data have been kept at numerous places and the records often extend over many years. A comparison of radar and rain gauge data should help in assessing the usefulness of the latter for making estimates of attenuation. Since heavy rain is usually of short duration, two types of rain gauge records have been considered, excessive short duration rainfall and hourly precipitation amounts.

Excessive short duration rainfall, defined in Table 8, is reported monthly and annually by the U.S. Weather Bureau in the National Summaries of Climatological Data. The criterion of 0.3 inch in 10 minutes is very close to that applied to the radar data, for which it was assumed that an equivalent rainfall rate of roughly 2 inches/hour in a 5x5 mile grid square would cause severe attenuation for a period of 10 minutes. Excessive short duration rainfall is recorded for the following ten stations in New England, but only three, designated by asterisks, are within the area involved in the attenuation survey: Bridgeport, New Haven and Hartford in Connecticut; Boston*, Nantucket and Pittsfield in Massachusetts; Providence*, Rhode Island; Burlington, Vermont; Concord*, New Hampshire; and Portland, Maine. Table 9 presents a summary of the reports of excessive short duration rainfall at these stations during 1961 and 1962, with special emphasis on the occasions when it was caused by thunderstorms. It appears that the probability of occurrence of intense thunderstorms is about the same over the entire area, in agreement with the results obtained from the radar. The average number of occurrences of excessive short duration rainfall from thunderstorms is somewhat lower than the average number of times

Table 8. Amount of precipitation required in various time intervals to be termed excessive short duration rainfall

Interval (minutes)	Precipitation (inches)	Interval	Precipitation
5	.25	60	.80
10	.30	80	1.00
15	.35	100	1.20
20	.40	120	1.40
30	.50	150	1.70
45	.65	180	2.00

the radar showed an intense convective storm in the square over one of the stations.

A comparison was also made with the Hourly Precipitation Data, published monthly by the U.S. Weather Bureau. Figure 7 shows the New England stations which report hourly precipitation amounts. In Fig. 8 are the distributions of hourly amounts recorded respectively at the stations themselves and at any gauge within 40 miles any time during a day when severe attenuation by thunderstorms occurred. Percentages in Fig. 8a are for 113 cases; Millstone Hill, for which there are no rainfall records, is not included. For Fig. 8b all four stations are involved and there are 146 cases. The average number of recording rain gauges in the 40-mile circles is 14, the values ranging from 10 in the area surrounding Concord to 17 around Birch Hill Dam.

In only 40 per cent of the cases was an hourly amount as large as 0.4 inch recorded within 40 miles of the station while the station itself recorded 0.4 inch or more in only 13 per cent of the cases. The latter percentage represents an average of twice a year at each of the three stations, in agreement with the average number of occurrences of excessive short duration rainfall from thunder-

Table 9. Summary of reports of excessive short duration rain in New England for 1961 and 1962

			1961	1962
1.	Number of days recorded anywhere		27	18
2.	Type of storm: Thunderstorms		23	14
	Widespread rain		4	4
3.	Number of thunderstorm days when n stations recorded	n = 1	17	10
		2	4	3
		3	2	
		4		
		5		1
4.	Days when Boston, Providence or Concord recorded (thunderstorms only)		6	4
	Days when n stations recorded	n = 1	5	3
		2	1	1

5. Average number of thunderstorm occasions per year

All stations	2.6
Boston, Providence and Concord	2.0

Table 10. Comparison of number of reports of excessive short duration rainfall and hourly amounts $\geq$ 0.5 inch for 1961-1962 with 5 and 10-year averages.

Station	Reports per year of excessive short duration rainfall			Number of hours per year when precipitation exceeded 0.5 inch				
	1961 - 1962			1961 - 1962			5 and 10 yr averages	
	Total	Thunderstorms	Widespread rain	Total	Thunderstorms	Widespread rain	Total	No. of years averaged
Hartford	3.5	3.5	0	3.0	2.0	1.0	4.5	5
Boston	4.5	3.0	1.5	3.5	2.0	1.5	5.5	10
Providence	2.5	1.5	1.0	3.5	0.5	3.0	4.0	10
Portland	2.5	1.5	1.0	3.5	0.5	3.0	4.0	10
Burlington	4.0	4.0	0	2.5	2.5	0	3.0	5

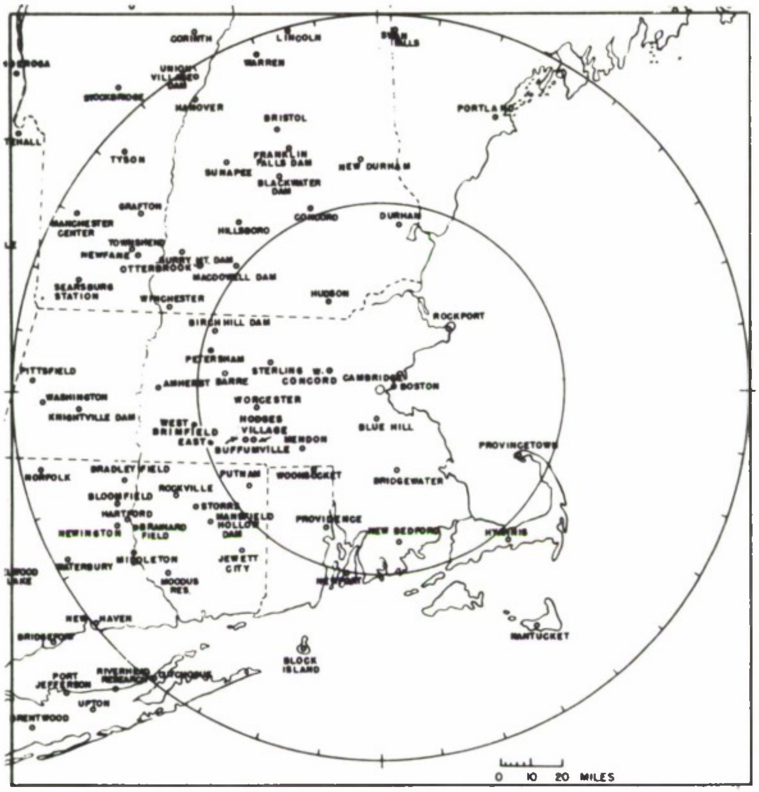

Fig. 7. Location of New England stations which report hourly precipitation amounts.

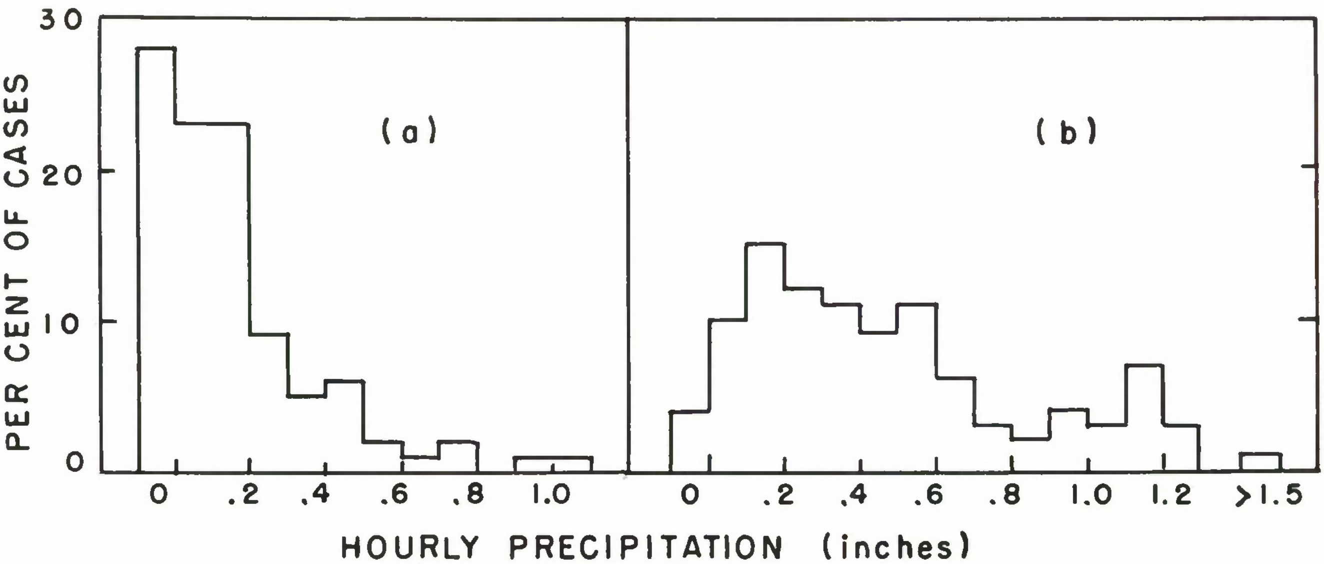

Fig. 8. Distributions of maximum hourly precipitation amounts recorded on days in 1961 and 1962 when 3 Gc radiation propagated at 5° elevation from selected stations would have suffered severe attenuation; (a) recorded at the station itself, 106 cases; (b) recorded at any gauge within 40 miles of the station, 146 cases.

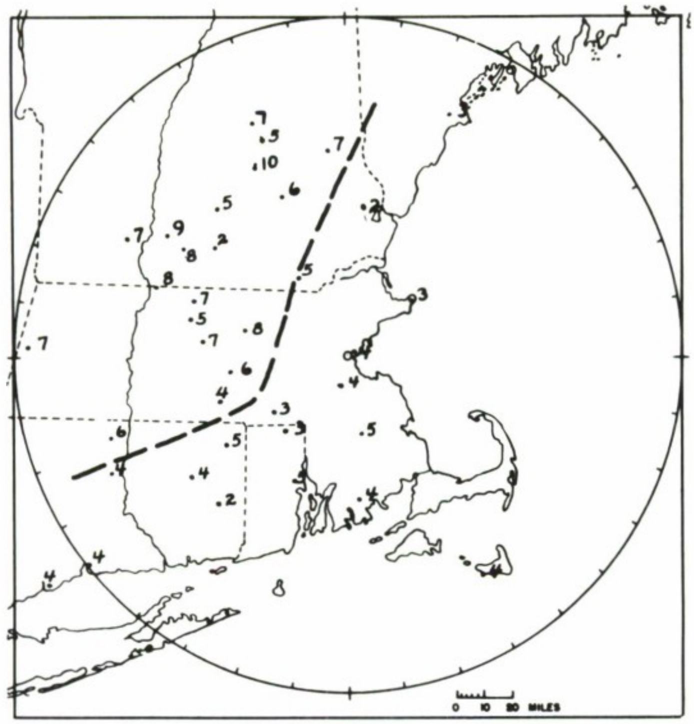

Fig. 9. Number of times during 1961 and 1962 that hourly rainfall amounts of 0.4 inch or more were recorded at the indicated stations during thunderstorm situations.

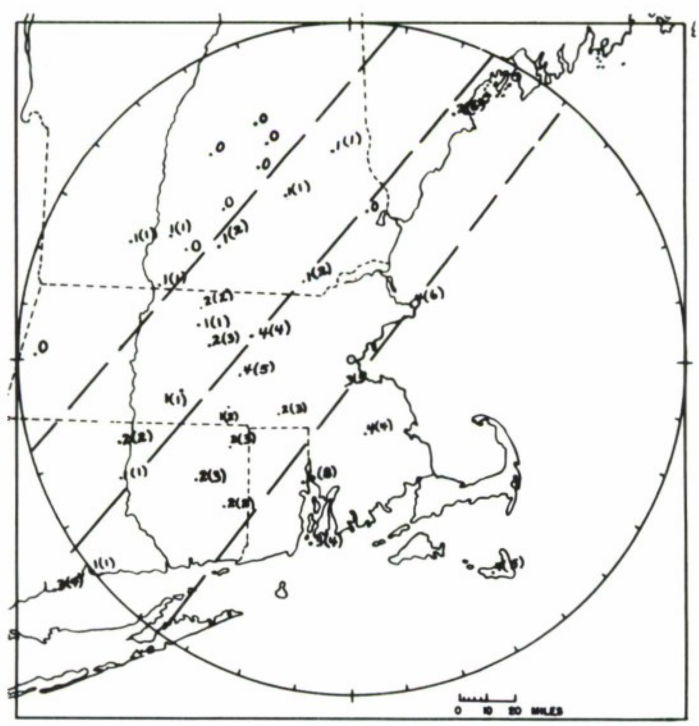

Fig. 10. Number of days and number of hours (in parentheses) during 1961 and 1962 that hourly rainfall amounts of 0.5 inch or more were recorded at the indicated stations during widespread raihstorms.

storms and slightly fewer than the number of occurrences of a category 7 storm in a particular square. The value of 0.4 inch in one hour was selected as a criterion for determining whether an intense thunderstorm passed over a particular point for two reasons. On occasions when excessive short duration rainfall is reported, the 60-minute amounts are nearly always at least 0.4 inch; on the radar maps a grid square containing rain of category 7, which alone would deposit 0.3 inch of rain in the 10 minutes it requires to pass over a point, is usually surrounded by several squares of lower intensity rain. Figure 9 shows the number of times during 1961 and 1962 that 0.4 inch of rain or more in one hour fell from thunderstorms at the various stations in the area under consideration. The frequency of occurrence appears to be slightly greater in the northwestern portion than in the southeastern, separated by the dashed line.

The inadequacy of point measurements for determining frequency of occurrence and/or distribution of thunderstorms is apparent. The radar showed that intense thunderstorms were within approximately 40 miles of any station on an average of 18 days a year, but the average number of reports of excessive short duration rainfall or more than 0.4 inch of rain in an hour from thunderstorms at any station was only twice a year. In Table 7, average ratios are given between the times the intense rain is over the station and the times it is along any particular azimuth or near enough in any direction to cause severe attenuation at the various elevation angles. It is recognized that the ratios in Table 7 are only rough indications both because the sample of two years' data is small and because the areas defined as "over the station" and "along an azimuth" are dependent upon the quantization of the intensity maps into 5x5 mile squares. Further, the ratios which apply in New England may not be appropriate for other regions. In the absence of other information, however, they provide some sort of basis for a guess concerning the probability of attenuation by thunderstorms in locations for which there are records of short duration rainfall, but no quantitative radar information.

Comparison of radar and rain gauge records for heavy rain in widespread storms was discussed in the previous section. It was concluded that hourly rainfall amounts of 0.5 inch or more recorded over the station itself or within 20 miles would almost certainly cause severe attenuation at 5° elevation for a period of about an hour, and that values between 0.4 inch and 0.5 inch probably represent rapidly moving areas of intense rain which would cause severe attenuation for about one-half hour. In Fig. 10 are the numbers of days and hours in 1961 and 1962 when hourly amounts of 0.5 inch or more were reported during widespread rainstorms. The dashed lines separate the entire area into regions according to the frequency of occurrence.

The representativeness of the years 1961-1962 was investigated by comparing the occasions of excessive short duration rainfall in those years with 5 and 10-year averages of the number of hours when precipitation amounts of 0.5 inch or greater were recorded. The latter are in the Decennial and Five Year Summaries of Hourly Observations published by the U.S. Weather Bureau (1962); the ten-year averages cover 1951-1960 and the five-year ones 1956-1960. Comparisons are in Table 10 and indicate that 1961-1962 is a satisfactorily representative sample.

If estimates of the occurrence of severe attenuation for locations where there are no radar data are to be based on rain gauge records only, it is suggested that analysis of heavy widespread rainstorms be similar to that used in this study, and that the ratios in Table 7 be applied to thunderstorms. Either a report of excessive short duration rainfall or an hourly amount in excess of 0.4 inch would be assumed to indicate rain of sufficient intensity to attenuate severely. It is important that the two types of heavy rain be considered separately because of significant differences in structure and behavior.

V. VARIATION OF ATTENUATION WITH HEIGHT IN INTENSE CONVECTIVE STORMS

One of the problems encountered in calculating attenuation in convective storms is uncertainty concerning the composition of hydrometeors in the upper portions. In the study described in Section III of this report it was assumed that in thunderstorms where the equivalent rainfall rate is between 50 and 100 mm/hr, liquid water particles exist up to a height of 20,000 ft in sufficient numbers to cause severe attenuation; in more intense storms liquid water particles were presumed to occur at even higher levels. The evidence on which these assumptions were based is somewhat indirect, and during the summer of 1964 an experiment was conducted to make a more direct investigation of this question.

Presentations of reflectivity distribution in the vertical were displayed and photographed simultaneously on the 3 Gc and 10 Gc radars. Comparison of the patterns showed the levels at which the apparent reflectivity at 10 Gc decreases relative to that at 3 Gc as the beams penetrate into the storms. Such a dropping off indicates attenuation, and the amount of attenuation can be measured by the extent of relative signal reduction. It is necessary to measure a progressive decrease in relative signal intensity rather than simply a difference in absolute value of the indicated reflectivities. The latter might result from attenuation by storms in front of the one under observation, from non-Rayleigh scattering at the higher frequency, or from the difference in beam widths of the two radars. In general, the broader beam tends to smooth out details of storm structure. An effect which is of particular interest is observed when the center of the beam is near the top of the storm; in this case regions of stronger reflectivity at somewhat lower levels would still be within the broad beam and the signal intensity would be greater than that measured with a narrower beam at the same elevation angle.

Measurements were made on 12 days in 37 storms. These included almost all occasions when storms with equivalent Z (Z_e) of 10^5 mm^6/m^3 or greater were within 50 miles of the radar station. Data were relatively sparse because of the unusual dryness of the summer. On the basis of storm structure and attenuation characteristics, they could be divided into three groups as summarized in Table 11.

Storms in Group A had tall well-defined cells; on the radars the tops appeared between 40,000 and 50,000 ft, and the most intense cores from the surface to 20,000 or 30,000 ft. An example is the storm in Fig. 11, observed on 1 July 1964. A quantitative analysis of the attenuation could be made for the 13 storms in this group, but because of the poor resolution of the 3 Gc radar, the variation of attenuation with height could not be determined with precision. The profiles through this storm, in Fig. 12, are typical of storms in Group A. At 3000 ft in this intense storm the two-way attenuation at 10 Gc is a little over 30 db, and is in good agreement with the computed value. At 10,000 ft the attenuation is still severe. At 20,000 ft, where attenuation is negligible but both beams are still in the intense portion of the storm, the two radars indicate the same reflectivity. At 30,000 ft the 3 Gc radar consistently measures a higher reflectivity because of the pronounced beam width effect near the top of the storm. In all of the storms in Group A there

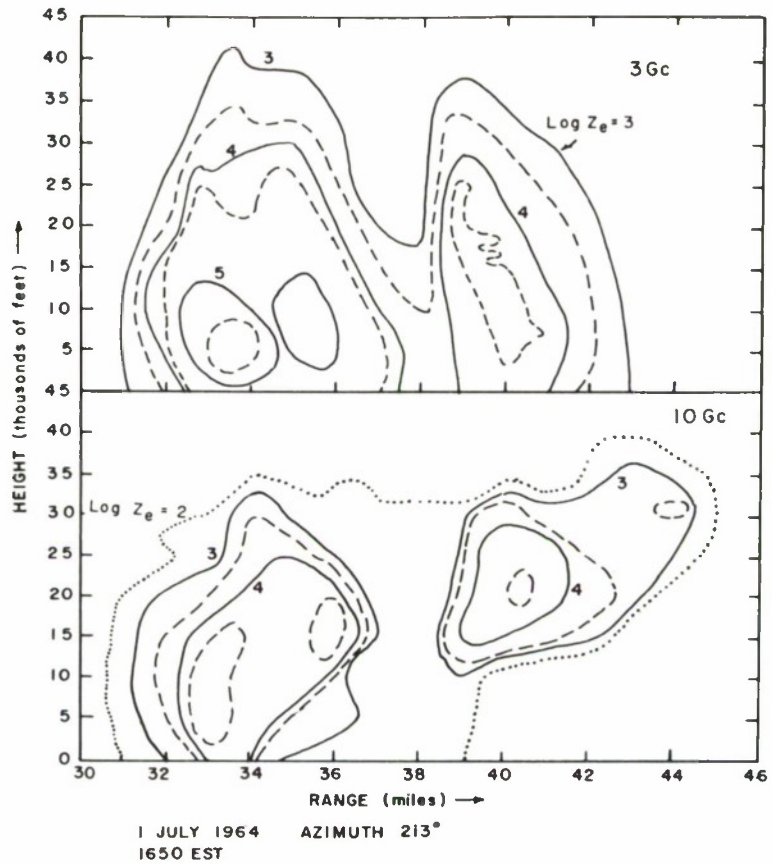

Fig. 11. Reflectivity contours in a tall well-defined thunderstorm, as depicted at 3 Gc with a 3^{0} beam width and at 10 Gc with a 1^{o} beam width. Observations were made on 1 July 1964, 1650 EST, azimuth 213^{o}.

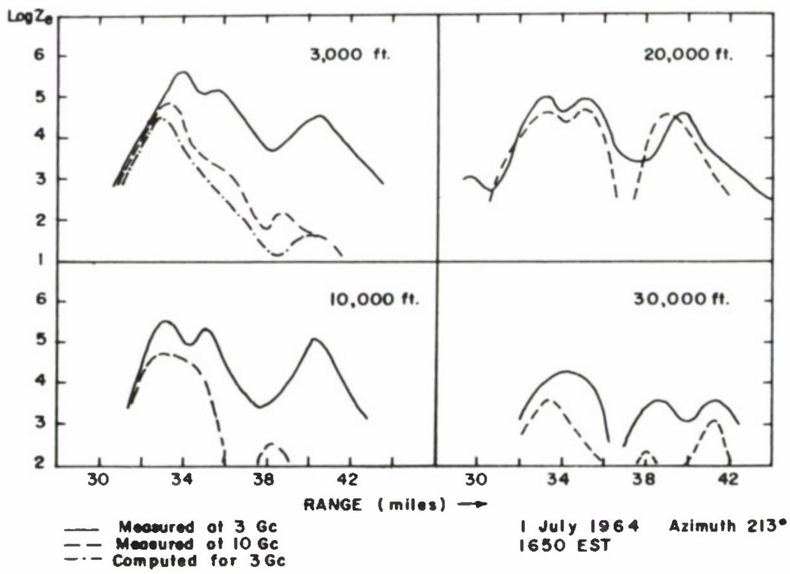

Fig. 12. Indicated reflectivities at 3 Gc and 10 Gc as a function of range along several propagation paths through the storm shown in Fig. 11.

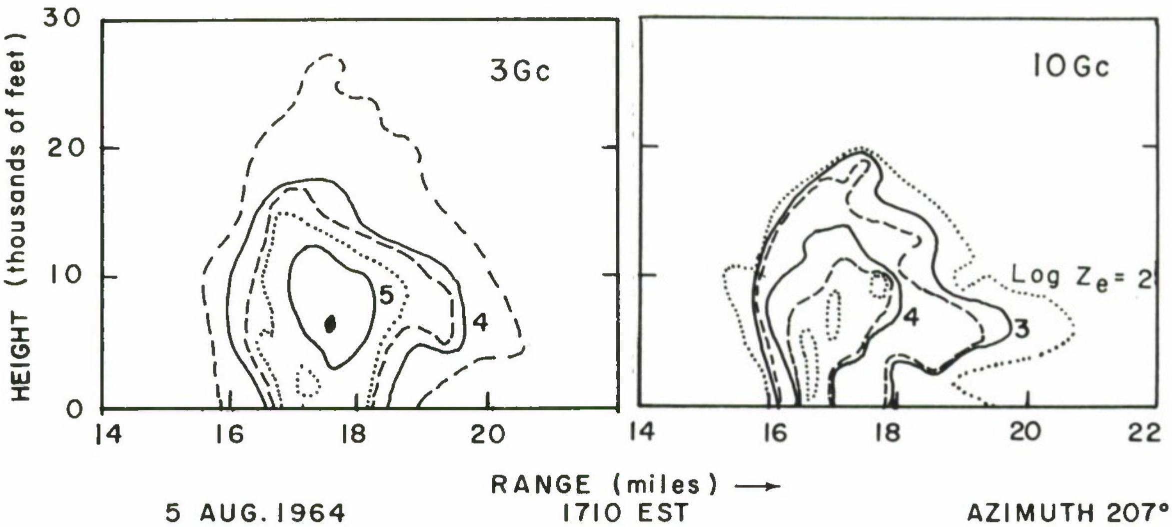

Fig. 13. Reflectivity contours in a thunderstorm of small dimensions as depicted at 3 Gc with a 3° beam width and at 10 Gc with a 1° beam width. Observations were made on 5 August 1964, 1710 EST, azimuth 207°.

Table 11. Grouping and characteristics of the intense convective storms which were analyzed for attenuation. All were in 1964.

Date	Number of Storms	log Z_e (max)
Group A: Tall well-defined cells		
June 10	1	5.0
June 20	1	6.0
July 1	4	6.3
July 3	2	5.9
July 6	5	6.7
Group B: Not tall, small intense cores up to ~10,000 ft		
June 8	3	5.8
July 7	2	5.0
August 5	4	5.2
Group C: Tall, with very complex cell structure		
May 19	6	5.3
June 10	2	5.0

was strong attenuation up to 15,000 ft and, with two exceptions, none at 20,000 ft or higher. The two exceptions were the most intense storms which were measured ($Z_e > 10^6$) and in them attenuation continued up to 25,000 and 30,000 ft respectively.

Storms in the Group B were intense but not tall. Cores of highest reflectivity were small in horizontal dimensions and extended vertically only to about 10,000 ft; storm tops on the radar were around 20,000 ft. An example of a Group B storm is in Fig. 13. Quantitative analysis of attenuation in these storms was not feasible because discrepancies caused by differences in beam width were so pronounced. At all levels the 10 Gc radar indicated lower reflectivities than were observed at 3 Gc. Below 10,000 ft there is significant attenuation, while in the vicinity of 10,000 ft and above it, the beam width effect causes the 3 Gc radar to measure higher reflectivity. Indications of significant attenuation below 10,000 ft were not only the lower reflectivities at 10 Gc but also the appearance of the strongest echoes very near to the front (the side nearest the radar) of the storm with the rear portions extremely weak at low levels. The "stepped" effect in Fig. 13 b is also a common indication of attenuation. When there are several small intense cores, the only apparent portions of the farther ones are tops which extend above the cells in front. These small intense cores were not resolved on the 3 Gc radar.

In the third group were six storms on two days (19 May and 10 June) whose major characteristic was complexity of structure. The storms were tall but contained numerous small intense cores with maximum values of log Z_e between 5.0 and 5.3. There were clear indications of significant attenuation below 20,000 ft, but it could not be evaluated quantitatively. The complex pattern was badly distorted by attenuation at 10 Gc and smoothed by the broad beam of the 3 Gc radar, so that it was not even possible to clearly identify corresponding cells on the two displays.

On two days the AN/CPS-9 data were doubtful because of a poor magnetron spectrum. These data were omitted from the study.

In the investigation concerning frequency of severe attenuation, it was assumed that when storms are sufficiently intense so that the average Z_e value in a 5x5 mile square is at least $10^{5.0}$ mm^6/m^3, attenuation continues unabated up to height of 20,000 ft. From this study, it appears that a height two or three thousand feet lower might have been more realistic. This would reduce the calculated frequency of severe attenuation by about 20%. It is doubtful that any storms of the Group B type, which are definitely lower, were included in the attenuation study, because their intense portions are so small the recorded reflectivity in 5x5 mile squares would have been lower.

VI. CONCLUSION

An analysis of quantitative radar data supplemented by records of hourly precipitation amounts and excessive short duration rainfall at selected points was made to determine the frequency of occurrence of severe attenuation (defined here as 10 db or more) of 10 Gc radiation by rain at several selected stations in central New England. The study was based on two years' data, 1961 and 1962.

Attenuation of this severity is most often caused by intense thunderstorms. It was found that for propagation paths of 5^o above the horizon severe attenuation by thunderstorms would have occurred for an average of 32 hours per year if all directions were involved, for 5 hours per year if propagation were restricted to a single azimuth. The frequency of occurrence when no direction is specified is expected to be roughly proportional to the inverse square of tan α where α is the elevation angle; along a particular azimuth the frequency would vary inversely as tan α. Results for 10° and 20° elevation were in good agreement with the expected variation, being 13 and $3\frac{1}{2}$ hours per year respectively when no azimuth is specified and 3 and 1 1/3 hours in any particular direction. The radar data were reduced to digital maps in a grid of 5x5 mile squares, and the resolution was too coarse to permit analysis for higher elevation angles. No consistent differences were found from station to station or at different azimuths. The results of this preliminary analysis cannot be extended to higher radiation frequencies or smaller amounts of attenuation because these would involve less intense storms whose statistics have not yet been explored. An investigation including all types of New England storms, their intensities, and their frequency of occurrence is in process.

Attenuation of 10 db or more at 10 Gc may occasionally be caused by very heavy rain (at least 0.5 inch/hr) in widespread storms, but only at elevation angles of 5° or less. Storms of this type primarily affect the southeastern portion of New England where they may cause severe attenuation for a total of two to four hours on two or three days each year. Their frequency decreases sharply to the north and west, so that in the northwestern portions of the area considered they caused severe attenuation either not at all or only for a very brief period. Because of the infrequency of these storms, statistics based on a two-year sample are not very satisfactory. At lower elevation angles, the times when heavy widespread rain causes severe attenuation would increase sharply.

Comparison was made of the frequency of occurrence of one-half inch or more of rain in any single hour during the two sample years with five and ten-year averages compiled by the U.S. Weather Bureau for selected stations.

Agreement was good enough to indicate that the sample years are satisfactorily representative.

Ratios were found between the frequency of occurrence of an intense thunderstorm directly over the station, one anywhere in the area near enough to cause attenuation, and of one along a particular azimuth. It was suggested that these ratios be used to estimate the frequency of occurrence of severe attenuation by thunderstorms for regions where rain gauge records but no quantitative radar data are available. For severe attenuation by heavy widespread rain the climatology of each region would have to be considered individually.

There is no satisfactory means of assessing the accuracy of the results obtained in this analysis. It is noted, however, that most of the uncertainties involved tend to cause an underestimate rather than an overestimate. Therefore the given values probably represent the minimum number of hours of severe attenuation which might be expected.

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13. ABSTRACT

An analysis of quantitative radar data supplemented by records of hourly precipitation amounts and excessive short duration rainfall at selected points was made to determine the frequency of occurrence of severe attenuation (defined here as 10 db or more) of 10 Gc radiation by rain at stations in central New England. The study was based on two years' data.

It was found that at an elevation of 5° above the horizon severe attenuation by intense thunderstorms may be expected for approximately 32 hours per year if all directions of propagation are involved. Along a particular azimuth it occurs for 5 hours per year. At an elevation angle of 10° the times are 14 and 3 hours respectively; at 20° they are 3-1/2 and 1-1/3 hours. Coarse resolution of the radar data precluded analysis at higher elevation angles. Severe attenuation by heavy widespread rain is considerably more probable in southeastern New England, where approximately 4 hours per year at 5° elevation may be expected, than farther to the north and west. This type of storm does not cause as much as 10 db of attenuation at an elevation of 10° or more.

Techniques are suggested for applying the results to regions where rain gauge records but no quantitative radar data are available. Results of this preliminary analysis cannot be extended to higher radiation frequencies or smaller amounts of attenuation, because less intense storms whose statistics have not yet been thoroughly explored would be involved. An investigation of all types of New England storms, their intensities, their frequency of occurrence and the attenuation they would cause is in progress.

14. KEY WORDS

rain attenuation
weather radar research
rainfall rate
radar reflectivity
rain gauge records