NOTES AND RECOMMENDATIONS ON
McGILL SW5D WEATHER RADAR

W.M. Palmer 31 May 1965

Dr Hitschfeld

Rain on Radome

The thickness of the water layer on a radome may be estimated by equating the rate of flow of rain onto the radome to the rate of flow of the water film off the radome.

The flow of the water film is determined primarily by gravity and fluid viscous forces. Corrections due to the inertia of the raindrop, raindrops splashing off the radome, channelling, water in form of drops on radome (surface tension) may have to be made.

Gibble and Cohen show that the thickness of the water layer on the top hemisphere of the radome is constant for a steady rate of rainfall and is given by

$$d^3 = \frac{\eta rR}{\rho g}$$

where	d	=	thickness of water film	(cm)
	η	=	viscosity of water	($gm\ cm^{-1}\ sec^{-1}$)
	r	=	radius of radome	(cm)
	R	=	rate of rainfall	($cm\ sec^{-1}$)
	ρ	=	density of water	($gm\ cm^{-3}$)
	g	=	accel. due to gravity	($cm\ sec^{-2}$)

substituting $\eta = 1.0 \times 10^{-2}\ gm\ cm^{-1}\ sec^{-1}$

$r = 27.5\ ft = 27.5 \times 30.4\ cm$

$\rho = 1\ gm\ cm^{-3}$

$g = 980\ cm\ sec^{-2}$

and changing the units of d and R to mm and mm hr^{-1} gives

$$d\ (mm) = \frac{(R\ mm\ hr^{-1})^{1/3}}{14}$$

Table 1 summarizes the film thickness and 5.7 cm attenuation (2-way) for several different rates of rainfall.

The velocity profile within the film at latitude θ on the radome, a distance x from the radome is:

$$v = \frac{g \cos \theta}{\eta} \left(dx - \frac{x^2}{2}\right)$$

$$v_{mean} \text{ at the equator} = \frac{\rho g}{3\eta} d^2$$

$$v_{max} \text{ at the equator} = \frac{\rho g}{2\eta} d^2$$

The velocity profile is shown in Table 2.

Whilst the inertia of the raindrops due to their rate of fall in air will tend to reduce the film thickness and the attenuation (see Cohen letter), two-way attenuations of 3 to 5 db or more may be experienced when using a 55 foot diameter radome and 5.7 cm.

TABLE 1: WATER FILM THICKNESS ON 55' DIAM. RADOME AND 5.7 CM ATTENUATION

Rate of Rainfall	Film Thickness		Film Speed		Attenuation
			mean	max.	two-way
$mm\ hr^{-1}$	mm	thou	$m\ sec^{-1}$	$m\ sec^{-1}$	db
1	0.07	2.8	0.016	0.024	0.7
3	0.10	4.0	0.032	0.048	1.5
10	0.15	6.0	0.08	0.12	3
30	0.22	8.7	0.17	0.26	4
100	0.33	13	0.36	0.54	6
300	0.47	18.4	0.73	1.10	10

(After Blevis and based on Gibble rain model)

TABLE 2: VELOCITY PROFILE IN FILM

Distance from Radome (fraction of film thickness)	Relative Velocity (fraction of maximum)
0	0
0.2	0.35
0.4	0.65
0.6	0.85
0.8	0.96
1.0	1.00

Dr Hitschfeld.

WLP.

Estimates of Attenuation

I anticipate there may be some questions about my estimates of attenuation from rainfall data. My approach is somewhat different from the treatment of MW-32. Both methods use the idea that rainfall rates observed at a point in the path of a storm approximate those along a section through the storm. Both require a knowledge of the speed of the storm. However MW-32 integrates the rainfall rate in range whilst I have been interested in integrating the rainfall in time and considering total rainfalls at a point.

Attenuation at 5.7 cm is given approximately by:

$$\text{db} = \frac{\text{mm}}{\text{hr}} \times \frac{\text{n. miles}}{60} \qquad (1)$$

where the rate of rainfall in mm hr^{-1} is integrated a distance in n. miles along the beam to the target.

My alternative method of estimating the attenuation is:

$$\text{db} = \frac{\text{mm}}{60} \times \frac{\text{n. miles}}{\text{hr}}$$

$$= \frac{\text{mm}}{60} \times \text{knots} \qquad (2)$$

where the rate of rainfall is integrated over a period of time (the storm's duration) at a point in the path of the storm. The speed of the storm is measured in knots.

For example, if we consider a storm of 12.5 n. miles in depth moving at 25 knots it will have a duration of 1/2 hour. If the average rate of rainfall in the storm is 24 mm hr^{-1} the rainfall at a point will be 12 mm.

Equation (1) gives $\text{db} = \frac{24 \text{ mm hr}^{-1} \times 12.5 \text{ n. mi}}{60} = 5 \text{ db}$

Equation (2) gives $\text{db} = \frac{12 \text{ mm} \times 25 \text{ knots}}{60} = 5 \text{ db}$

In Equation (2) for a given total rainfall of 12 mm the attenuation varies as the storm speed:

Speed	Attenuation
12.5 knots	2.5 db
25	5.0
50	10.0

In Appendix 3 of my report I have computed the attenuation for a number of model storms having speeds of 25 knots.

It is important to make a distinction between attenuation all the way through the storm and attenuation to a point inside the storm. When radar is used to measure the rain in a storm it is necessary to integrate the contribution along a section through the storm. The contribution from the near edge will have little attenuation, the contribution from the far edge will be attenuated by most of the storm (See Table in Appendix 3).

I consider rainfalls in 24-hr periods because it frequently happens that most of this rain occurs in one storm of duration less than 4 hours. For example if 25 mm of rain fell in 24 hrs at a station, it is likely that more than 12 mm of this rain fell in less than 4 hrs. A storm travelling 25 knots will cover 100 n. miles in 4 hours. Hence the period for integrating the rainfall should usually be less than 4 hours to allow the whole storm, or storms, to be on the radar at one time. Storm durations are often less than 1 hour.

My studies of rain statistics (both automatic raingauge data and 24-hr rainfalls) and radar data (Fortin and facsimile) convinced me that storms of speed 25 knots and rainfall of 25 mm in less than 4 hours do occur in the Province of Quebec several times in a summer season. The attenuation all the way through these storms is $\frac{25 \times 25}{60}$ or over 10 db.

Dr Hitschfeld JUL - 6 1965

RECENT QUOTATIONS

		$M
Radome		
Essco - solid space frame	48 ft dia.	34
	55 ft dia.	42
Pedestals		
Antlab - Alberta type - O.K. 30 ft reflector in radome		31
Scientific Atlanta O.K. 32 ft reflector in radome		50
Radars and Transmitter/Receivers (S-Band)		
Decca		
1 2500 kw trans/rec		~ 110
2 750 kw (2.4 and 0.24 µsec) Radar		108
1 750 kw trans/rec		43
1 75 kw (0.1 µ) Marine Radar		~ 12
Marconi		
2250 kw trans/rec		83
Parametric receiver (4.5 db)		16
Mitsubishi		
1500 kw (Mt. Fuji) trans/rec		83
600 kw RC-31 Radar (including $30 M display)		127
Parametric receiver (3 db)		20
General Electric		
2000 kw (AN/FPS-6) trans/rec	1 only	145
	if many produced	80
Raytheon		
60 kw 0.05 µsec Transmitter		

C-Band Transmitters (for comparison with S-Band)

RCA	1000 kw	100
Canoga	1000 kw	~ 90

NOTES AND RECOMMENDATIONS

ON

McGILL SW5D WEATHER RADAR

31 May 1965

W.M. Palmer

Contents

McGILL SW5D WEATHER RADAR

1. <u>The Problem</u>

On 14 May 1962 McGill University applied to NRC for a $300,000 grant towards the cost of a high performance 10-cm weather radar with radome. The grant was awarded on 28 November 1963.

On 1 March 1965 the writer re-joined the Stormy Weather Group to make recommendations on the design, choice, procurement, siting and housing of the new SW5D radar.

Particular attention was to be paid to the quantitative measurement of rain and snow in the Province of Quebec and the Montreal area to make it possible to carry out programs of interest to the provincial and municipal governments.

The main requirements of a radar for research on the structure and motion of rain and snow storms are good sensitivity and high resolution with minimum distortions due to siting, range, attenuation, beamwidth, pulse length and fluctuating signals.

2. <u>The General Plan of this Study</u>

The choice of wavelength affects the design and economics of the entire radar system. Therefore we will start by making a choice between 5.7 cm or 10.7 cm. We know that for a given sensitivity and resolution it is possible to design a 5.7-cm radar which will cost some $50 M less than a 10.7-cm set. However we cannot recommend the 5.7 cm if attenuation at this wavelength will affect significantly the capability of the radar to make quantitative measurements of rainfall.

If, after careful assessment, we decide that the attenuation at 5.7 cm is excessive for our research purposes and operational programs, we will have to examine the performance of 10.7 cm with particular reference to the resolution of storms with a 1° beamwidth. At 10.7 cm it is not practical to obtain a beamwidth much narrower than 1° since for a 1° beam we must use a large, expensive antenna of about 30 ft in diameter.

The question then arises as to whether an antenna, radome, pedestal system costing about $100 M is in line with the cost of the radar itself and whether we end up with a balanced radar system. This leads us to examine the relative costs of the antenna and transmitter systems with a view to achieving the required combination of sensitivity and resolution at minimum cost.

The choice of some of the other major components of the radar system such as peak power, pulse length and receiver sensitivity can then be made on the basis of the sensitivity we require. A sensitivity of 0.10 to 0.15 mm/hr of rain at 100 nautical miles is the suggested requirement.

Having made decisions on the choice of the major components of the weather radar, it is then possible to consider some specialized techniques suggested by Dr. Marshall involving the use of two transmitters operating on slightly different wavelengths and the use of both a long and a short pulse length. The different wavelengths give independent signals, the long pulse gives good sensitivity, and the short pulse gives good resolution in the direction of the radar beam when studying cell structures in summer storms.

3. Attenuation at 5.7 cm

The question of attenuation at 5.7 cm is a difficult one because the standards of accuracy which we must set for ourselves, say, 5 db power loss or a factor of 2 in rainfall, are very close to the actual maximum attenuation values likely to be experienced in the Montreal area (MW-32).

The question of attenuation is also an important one, in the category of a $64,000 question, so that every effort should be made to arrive at the right decision. The present study

1) Examines recent values of the attenuation constant for 5.5 cm

2) Discusses the relationship between attenuation and amount of rainfall with particular emphasis on heavy storms.

3) Records data on the daily amount of rainfall at stations in the area within 150 nautical miles of Montreal.

Fig. 1 shows recent values of the attenuation constant for rain at 0°C as determined by Wexler and Atlas (1963) for 5.5-cm wavelengths together with those of Gunn and East (1954) for 18°C rain at 5.7 cm as reported in Fig. 1a of MW-32. The shapes of the two curves are slightly different but the values are essentially the same over the important* range of rates of rainfall from 2 to 200 mi hr^{-1}.

Fig. 2 reproduces the data of Fig. 17 of MW-32 where actual amounts of rainfall are plotted against the apparent amounts as measured by 5.7-cm radar. In MW-32 it was suggested that the actual rainfalls all lie within a factor 1.7 (dotted line) of the observed or apparent rainfalls. However MW-12 on errors inherent in the radar measurement of rainfall shows that a small underestimate of radar performance will produce a very large over-estimate of rainfall. The errors increase exponentially with the attenuation. A study of the attenuation and rainfall in the model storms of MW-48 also indicates that the attenuation correction increases rapidly with amount of rainfall. The writer has also studied the attenuation and rainfall from actual and model storms† to confirm that the curved line shown in Fig. 2 is a more realistic upper limit for very heavy storms.

This upper limit has also been plotted on linear scales of rainfall to indicate the area or range of precipitation amounts which may occur for any given observed or apparent rainfall amount. For actual rainfalls of 25 to 50 mm there is a possibility that 5.7-cm radar measures less than half of the actual rain. Fig. 2 also shows the danger of a calibration error leading to very high estimates of rainfall. It is for this reason that attenuation

† see Appendix

* for attenuation

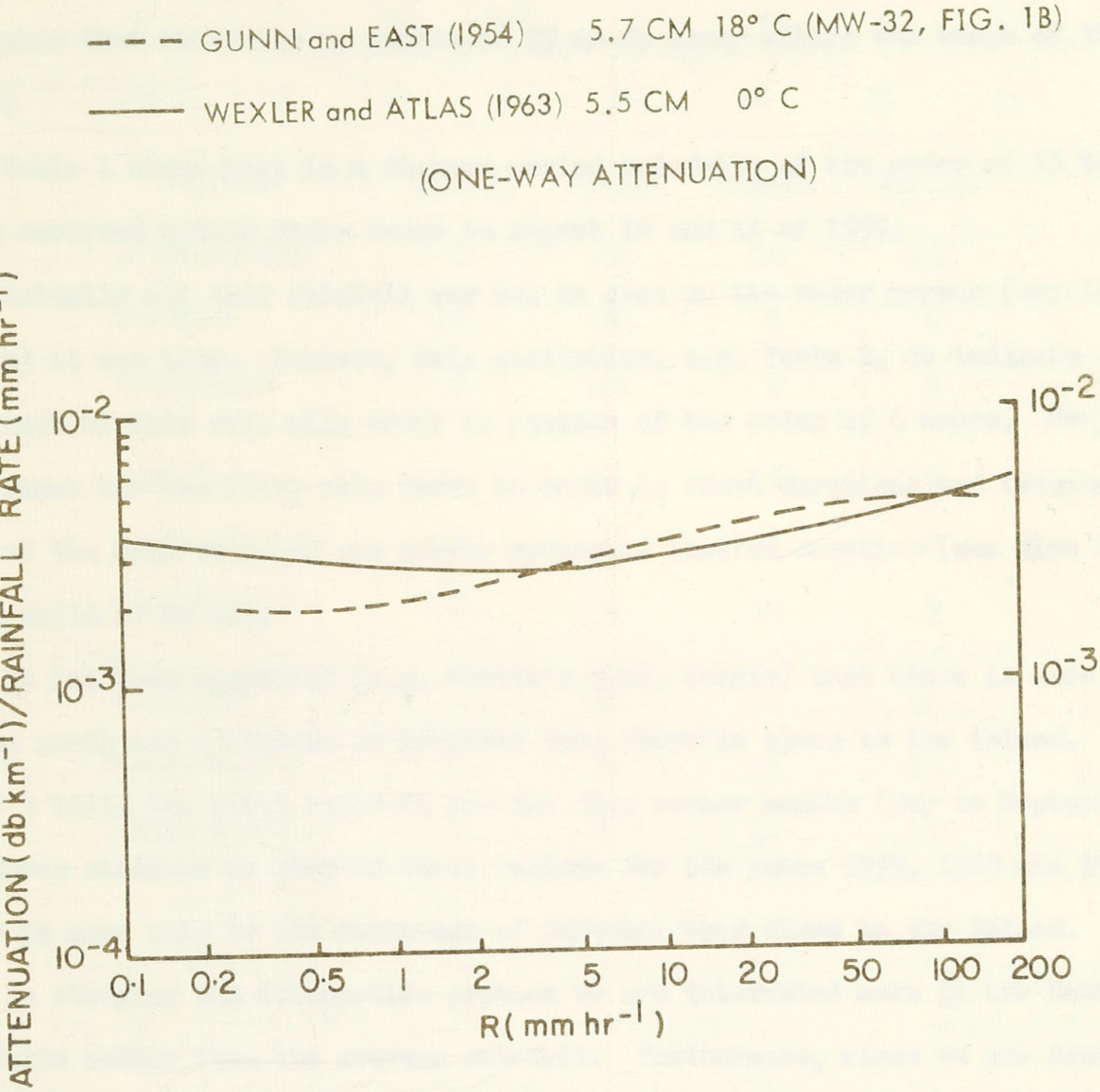


FIG. 1: ATTENUATION/RAINFALL-RATE VS RAINFALL-RATE

C BAND RADIATION AT 18° C AND 0° C

and attenuation corrections are described in the MW reports by phrases such as "insidious", "subtle", "not attractive", "troublesome", "unstable", "absurdly high rainfalls". However, to complete our argument against the use of 5.7-cm wavelength for quantitative radar measurements of rainfall we must show that rainfalls in excess of 25 mm do occur within the range of the radar.

Table 1 shows that in a 24-hour period rainfalls of the order of 25 to 50 mm occurred within radar range on August 10 and 15 of 1959.

Actually all this rainfall may not be seen on the radar screen (say 120 nmi radius) at one time. However, rain statistics, e.g. Table 2, do indicate that much of this rain will occur in periods of the order of 6 hours. MW-32 also shows how the heavy rain tends to occur in short durations and frequently most of the rain falls in one shower system of limited duration (see also the storm cells of MW-48).

It has been suggested (e.g. Fortin's M.Sc. thesis) that there is more rain to the north and northwest of Montreal than there is close to the island. Table 3 lists the total rainfall for the five summer months (May to September) for three stations in each of three regions for the years 1959, 1960 and 1961. There is more rain to the northwest of Montreal than close to the island.

In studying the attenuation problem we are interested more in the heaviest rainfalls rather than the average rainfall. Furthermore, since we are designing a radar with good sensitivity and resolution, we are interested in quantitative measurements of rainfall over a wide area corresponding to the effective coverage of the radar. This involves distances up to 240 n miles (twice the useful range) and storm echoes within range of the radar for periods from 4 to 24 hours. Hence to obtain some measure of the frequency of events of possible excessive attenuation, we examined the rainfall from about 100 stations

TABLE 1: DAILY RAINFALLS IN MILLIMETERS

(Nine Stations on 4 Days in August 1959)

Station	Aug 9	Aug 10	Aug 15	Aug 16
l'Assomption	8	26	10	14
Farnham	24	38	1	6
Huntingdon	6	49	2	6
Nominingue	5	26	15	6
Morin Heights	19	53	54	16
Shawbridge	22	24	40	9
Maniwaki	2	26	32	10
Mont Laurier	0	27	26	15
Ferme Neuve	1	28	44	13

TABLE 2: MAXIMUM RAINFALL IN DIFFERENT TIME PERIODS
(Mean of Heaviest Storms at McGill Observatory, May - Sept., 1963 and 1964)

	PERIOD (HOURS)						
	1/4	1/2	1	2	6	12	24
MAXIMUM RAINFALL (mm)	8	9	13	16	21	23	24

TABLE 3: SUMMER RAINFALL IN MILLIMETERS IN THREE REGIONS
(Average of 3 Stations - May to September)

	MONTREAL REGION	FURTHER NORTH	FURTHER NORTH AND WEST
	l'Assomption Farnham Huntingdon	Morin Heights Nominingue Shawinigan	Maniwaki Mont Laurier Ferme Neuve
1959	410	510	500
1960	320	380	450
1961	430	470	780

in southern Quebec (between Ottawa and Quebec City) and recorded in Table 4 the number of days in which at least 10 of these stations experienced more than one inch (25 mm) of rainfall on the same day. Extreme rainfalls fluctuate from year to year so ten years' results were averaged. Table 4 shows that on the average we can expect about 10 days of this heavy rain in each 5-month summer season.

There is a reasonable chance that most of these 10 days in the season will produce rain of attenuation greater than 5 db. Furthermore, studies of the heaviest rain are sometimes the most interesting. If the apparent radar rainfall is 20 mm, it is not really good enough to say the actual rainfall is somewhere between 20 mm and 50 mm (Fig. 2). We recommend the use of 10.7 cm to avoid the serious problem of attenuation at 5.7 cm.

4. Resolution with 1° Beam

We have chosen 10.7 cm for the wavelength. For good resolution we require a narrow beamwidth. At 10.7 cm we require a parabolic reflector of about 27-ft diameter to produce a 1° beam (3 db - one way or 6 db - two way). Actually we recommend using a 30-ft diameter reflector to give a 1° beam with side lobes depressed -48 db (2 way).

A recent study of the effect of finite beamwidth on resolution of storms was included in MW-48 so this section will be kept brief.

Table 5 gives the maximum displacement in nautical miles of storms having different gradients for various beamwidths. A beamwidth of 3 nmi displaces the edge of a storm of 10 db/nmi gradient a distance of 1 nmi.

Fig. 3 plots the maximum displacement against storm gradient for three beamwidths corresponding to 1 1/2°, 1°, and 1/2° beams at 115 nmi. It is preferable to use the 1° beam to the 1 1/2° beam, and the further step down to the 1/2° beam would be useful if we could have it (we can't at 10.7 cm).

FIG 2: COMPARISON OF ACTUAL RAINFALL AMOUNT WITH APPARENT AMOUNT MEASURED WITH 5.7 CM RADAR

(Ref. MW-32, Fig. 17)

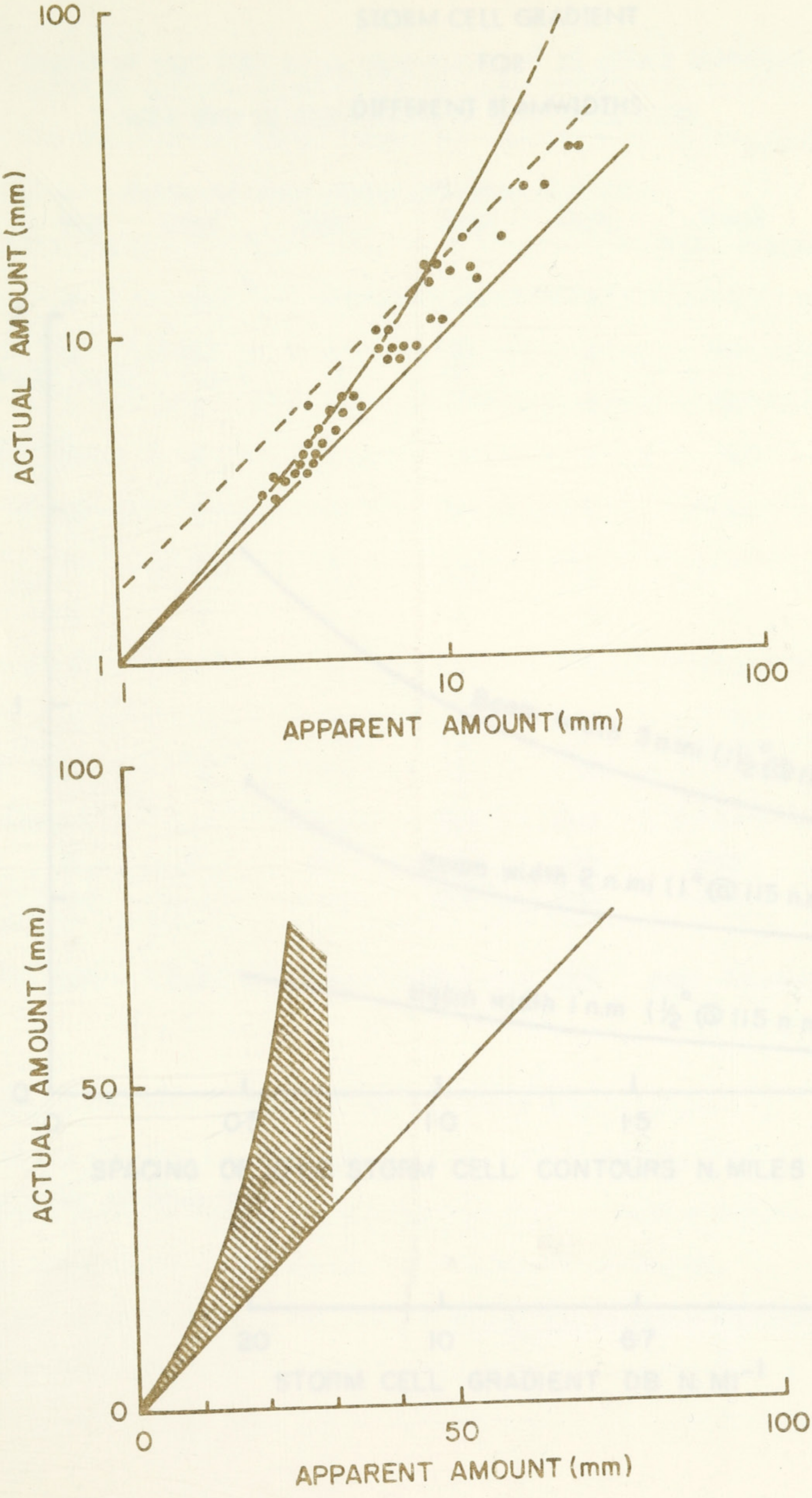


FIG. 3: MAXIMUM DISPLACEMENT OF EDGE OF STORM CELL

VS

STORM CELL GRADIENT

FOR

DIFFERENT BEAMWIDTHS

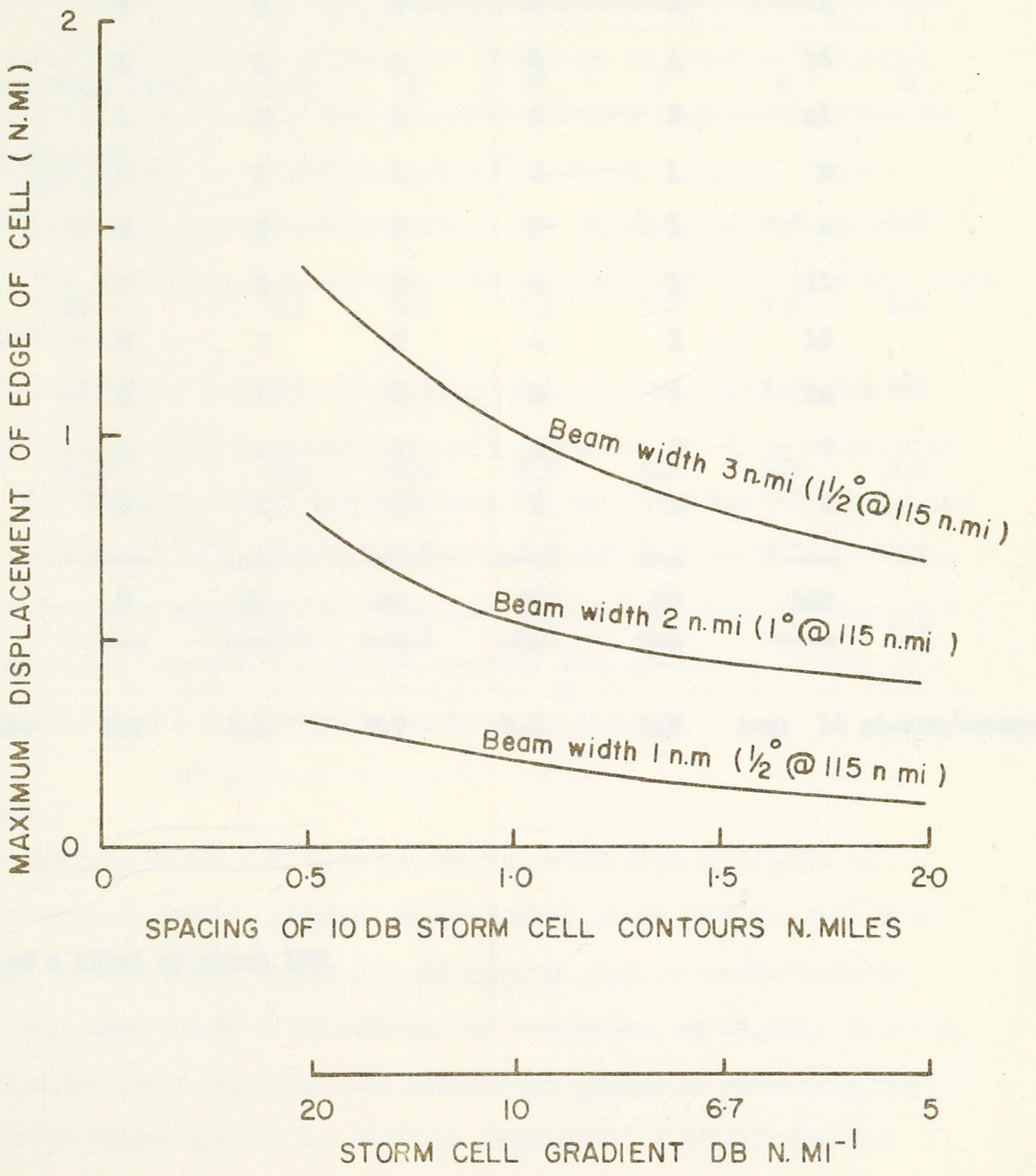


TABLE 4: NUMBER OF DAYS WITH 10 OR MORE STATIONS* IN QUEBEC REPORTING MORE THAN 25 MILLIMETERS OF RAIN IN 24 HOURS

	May	June	July	Aug.	Sept.	Total 5 Mo. Season
1964	0	0	2	2	0	4
1963	1	1	4	6	4	16
1962	1	2	4	2	2	11
1961	2	2	1	2	1	8
1960	2	3	2	0	1	8
1959	0	3	3	4	1	11
1958	0	3	5	4	3	15
1957	0	5	4	0	5	14
1956	1	1	2	4	1	9
1955	0	1	2	2	1	6
	7	21	29	26	19	102
Avg/mo.	0.7	2.1	2.9	2.6	1.9	Avg: 10 storms/season

*Out of a total of about 100.

TABLE 5: MAXIMUM DISPLACEMENT OF STORM CONTOURS

FOR

DIFFERENT BEAM WIDTHS AND STORM GRADIENTS

	MAXIMUM DISPLACEMENT (N. MILES)					
Beam Width (nmi)	0.5	1	2	3	4	8
Storm Gradient (db/mi)						
20	0.1	0.3	0.8	1.4	2.1	6.0
10	0.1	0.2	0.5	1.0	1.5	4.2
5	0.1	0.1	0.4	0.7	1.1	3.1
3.3	0.1	0.1	0.3	0.6	0.9	2.5
2.5	0.1	0.1	0.3	0.5	0.8	1.8
1.2	0.1	0.1	0.2	0.3	0.6	1.3

However, the step from the 1° to the $1/2^{\circ}$ beam does involve only small displacements of the order of 1/2 nmi at 115 nmi and distortions of this magnitude may not be excessive for some purposes. For better resolution it is necessary to use shorter ranges, as suggested on pages 19 and 20 of MW-37.

Given any storm profile it is useful to be able to sketch the echo profile. An idealized beam as shown in Fig. 4 makes this relatively simple. The more exact mathematical treatment of Donaldson (1965) may be required in special situations, but a good idea of the distortion existing in most storms can be obtained more quickly by approximate graphical methods. Figs. 5, 6 and 7 illustrate the echo profiles obtained from a few storms using 10.7 cm and a 1° beam. The distortion to be expected from attenuation at 5.7 cm is also shown for comparison.

For quantitative rainfall measurements by radar the distortion due to beamwidth of 1° is less troublesome than the distortion due to attenuation at 5.7 cm. The finite beamwidth simply spreads out the storm but still gives the correct total back-scattered power and total rainfall. It would be an advantage to have a beam narrower than 1° to give better definition of storm cells at 115 nmi range. However this is not possible with 10.7 cm so we will have to use shorter ranges when better resolution is required.

5. <u>Cost Study</u>

Our decision to use a 1° beam and 10.7 cm means that we require an expensive antenna, radome, pedestal system costing about $100 M. This is a larger and more expensive system than is normally used on weather radars. However, our requirements of sensitivity and resolution are higher. We shall now examine the costs of antenna and transmitter systems to check that the components we choose give us the required combination of sensitivity and resolution at minimum cost. Actually we don't have much choice concerning

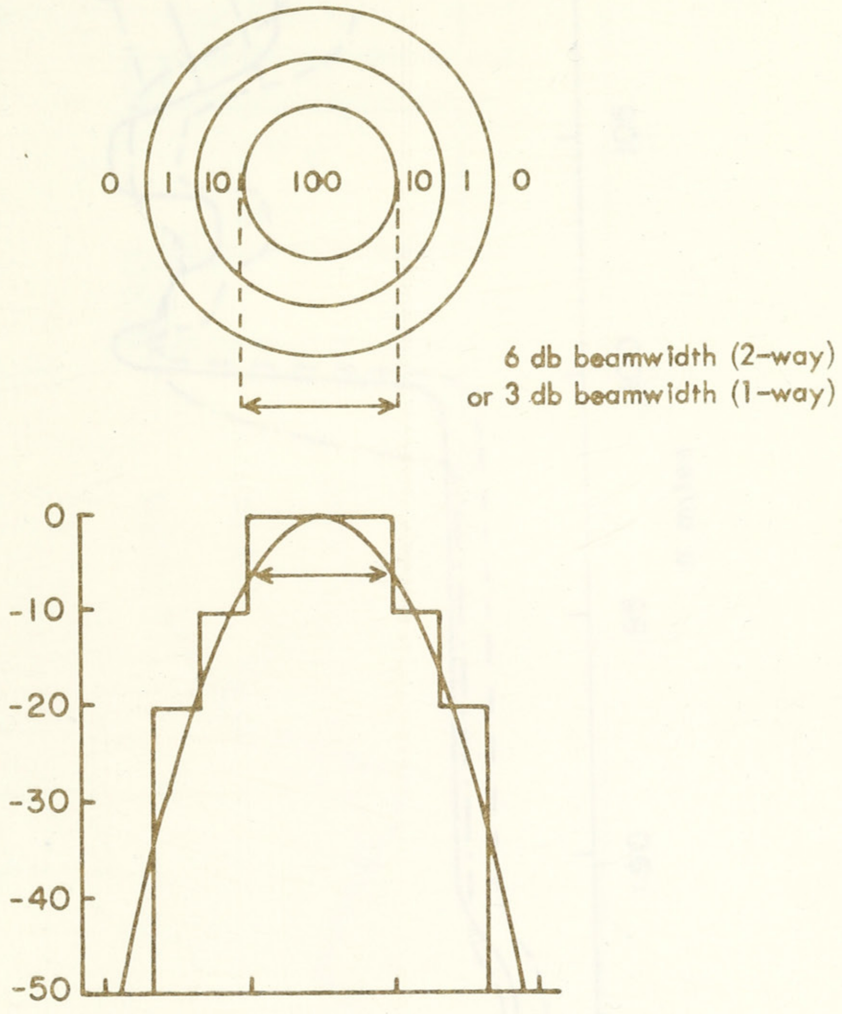


FIG. 4: IDEALIZED RADAR BEAM

FIG. 5: STORM AND ECHO PROFILES WITH 10 CM AND 5 CM RADARS

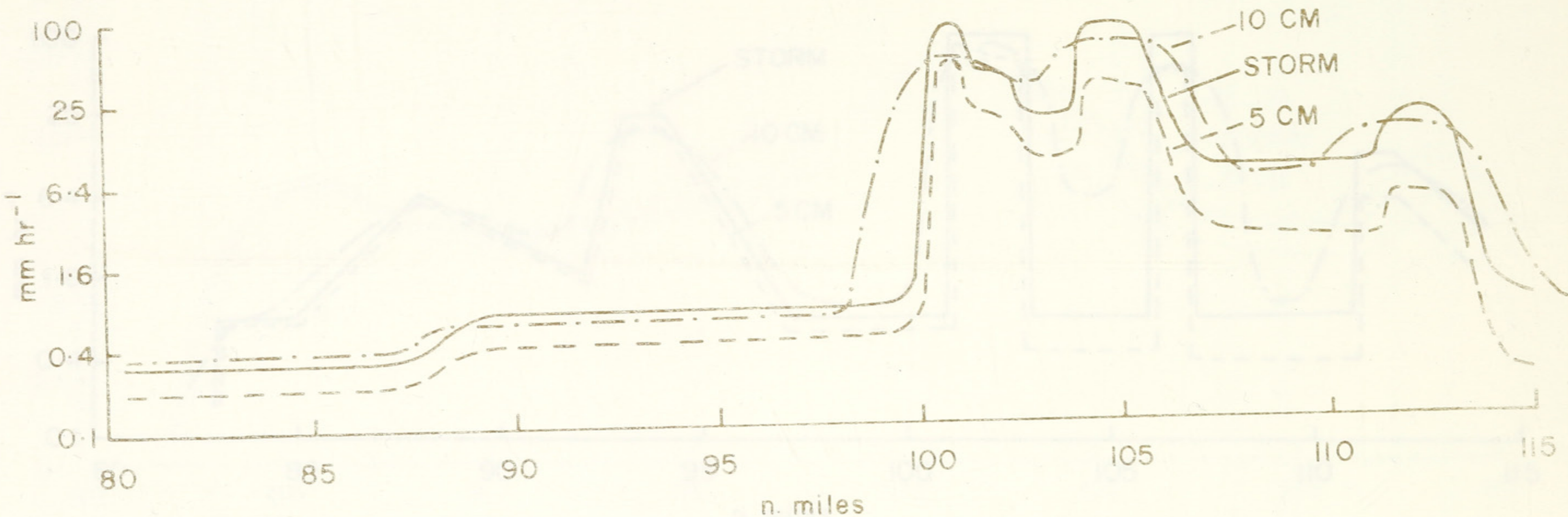


FIG. 6: STORM AND ECHO PROFILES WITH 10 CM AND 5 CM RADARS

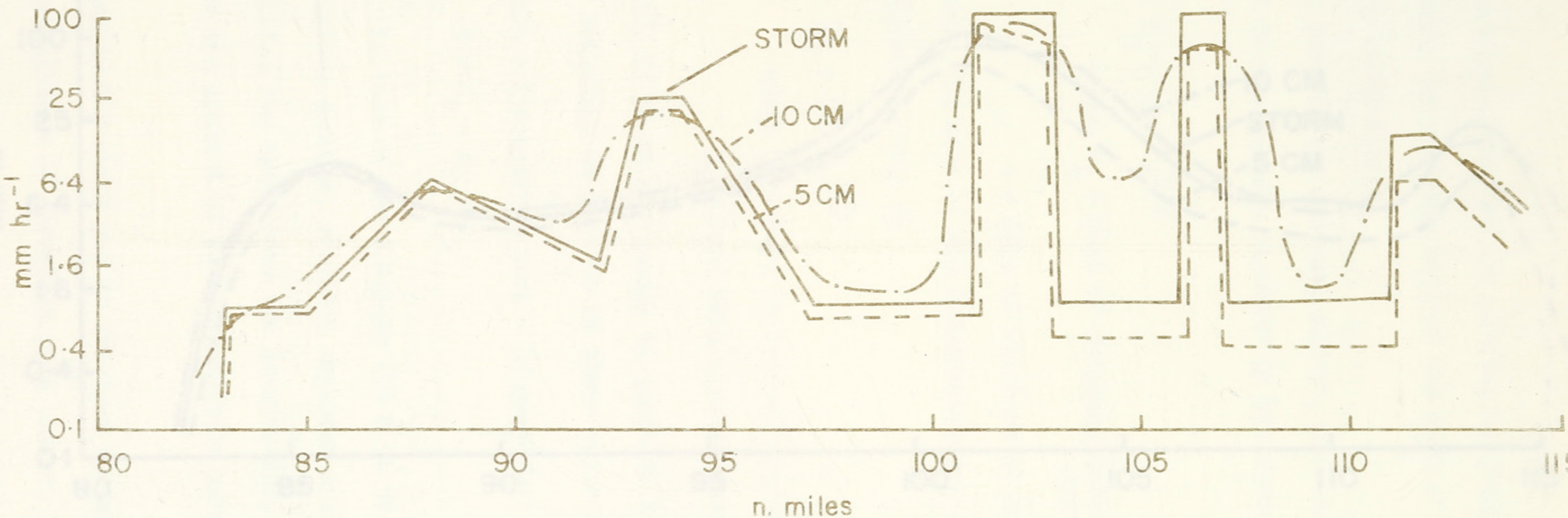
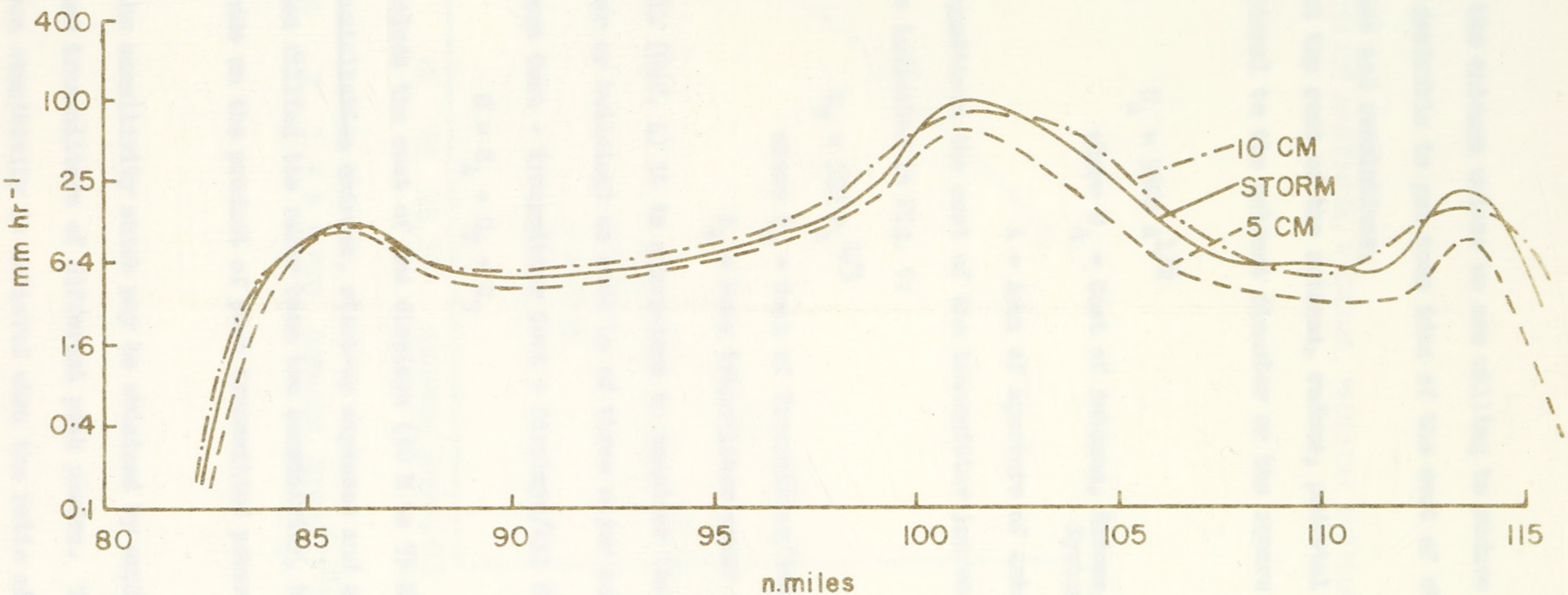


FIG. 7: STORM AND ECHO PROFILES WITH 10 AND 5 CM RADARS



the size and cost of the antenna unless we are willing to reduce the resolution. However it is desirable to get some idea of the cost of obtaining different sensitivities and resolutions.

Fig. 8 shows that the cost of the antenna, radome, pedestal system is approximately proportional to the antenna diameter or the square root of its area:

$$C_A = 3800\, A^{1/2}$$

where C_A = Cost of Antenna, Radome, Pedestal System in \$,

A = Area of aperture of antenna in ft^2.

For 10.7 cm transmitters the cost of the transmitter increases with peak power roughly as indicated in Fig. 9:

$$C_T = 550\, P_t^{2/3}$$

where C_T = Cost of Transmitter/Receiver in \$,

P_t = Peak transmitter power in kw.

Following Skolnik (Ref. 4) it is convenient to consider the cost of the radar (excluding tower or building) as made up of three major components:

Radar Cost = Antenna Cost + Transmitter Cost + Displays/All Other Costs

$$C = C_A + C_T + C_3$$

The costs C_3 include the cost of the displays (50 M to 75 M) and miscellaneous equipment, installation charges, start-up expenses and contingencies.

For precipitation filling the radar beam the sensitivity, based on the radar equation, depends on the product of peak transmitted power and antenna area or $P_t A$.

Fig. 10 shows the sensitivity which may be obtained by employing antennas of different sizes and transmitters of different peak powers. The minimum cost line, for a given sensitivity is achieved when the ratio of antenna cost/

FIG. 8: COST OF ANTENNA, RADOME, PEDESTAL SYSTEM

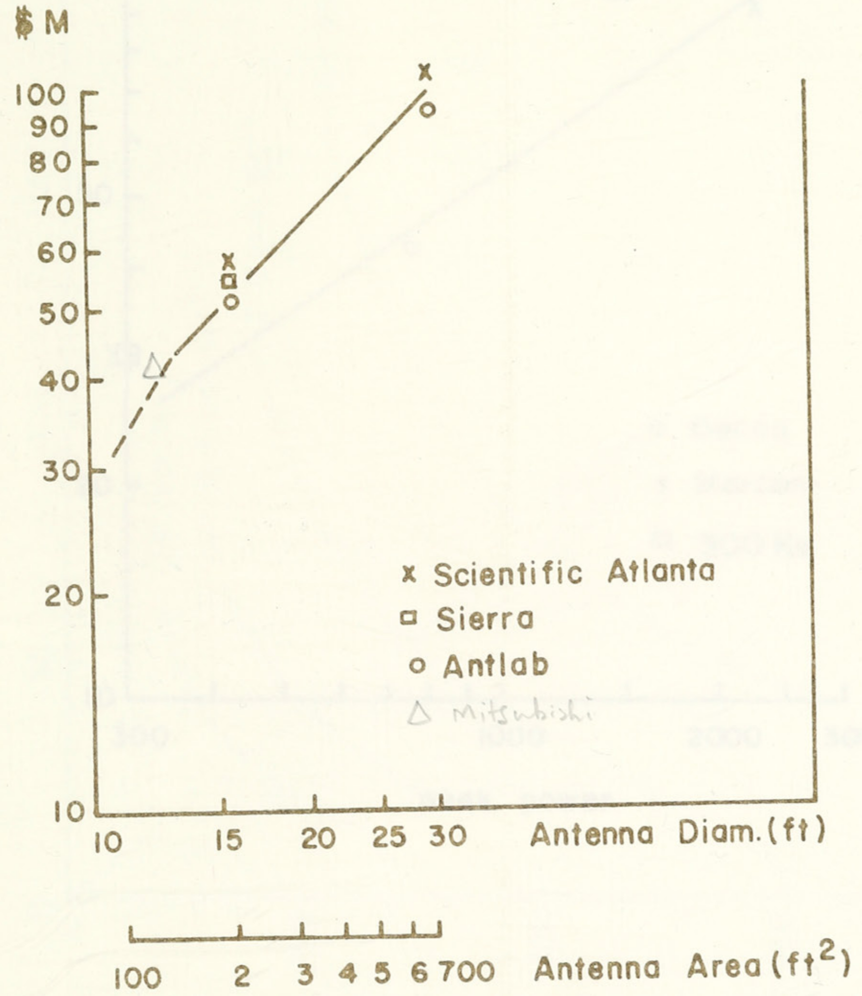


FIG. 9: TRANSMITTER/RECEIVER SYSTEM COST

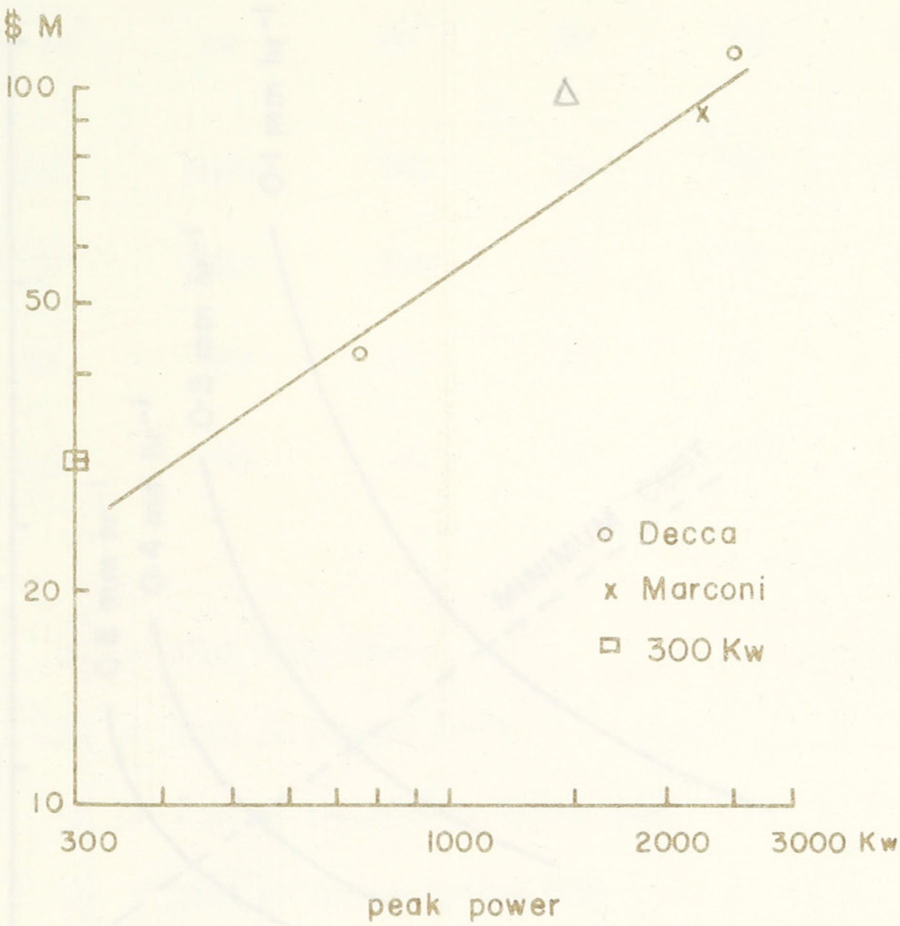


FIG. 10: MINIMUM DETECTABLE RATE OF RAINFALL AT 100 N. MILES FOR DIFFERENT TRANSMITTER AND ANTENNA COSTS

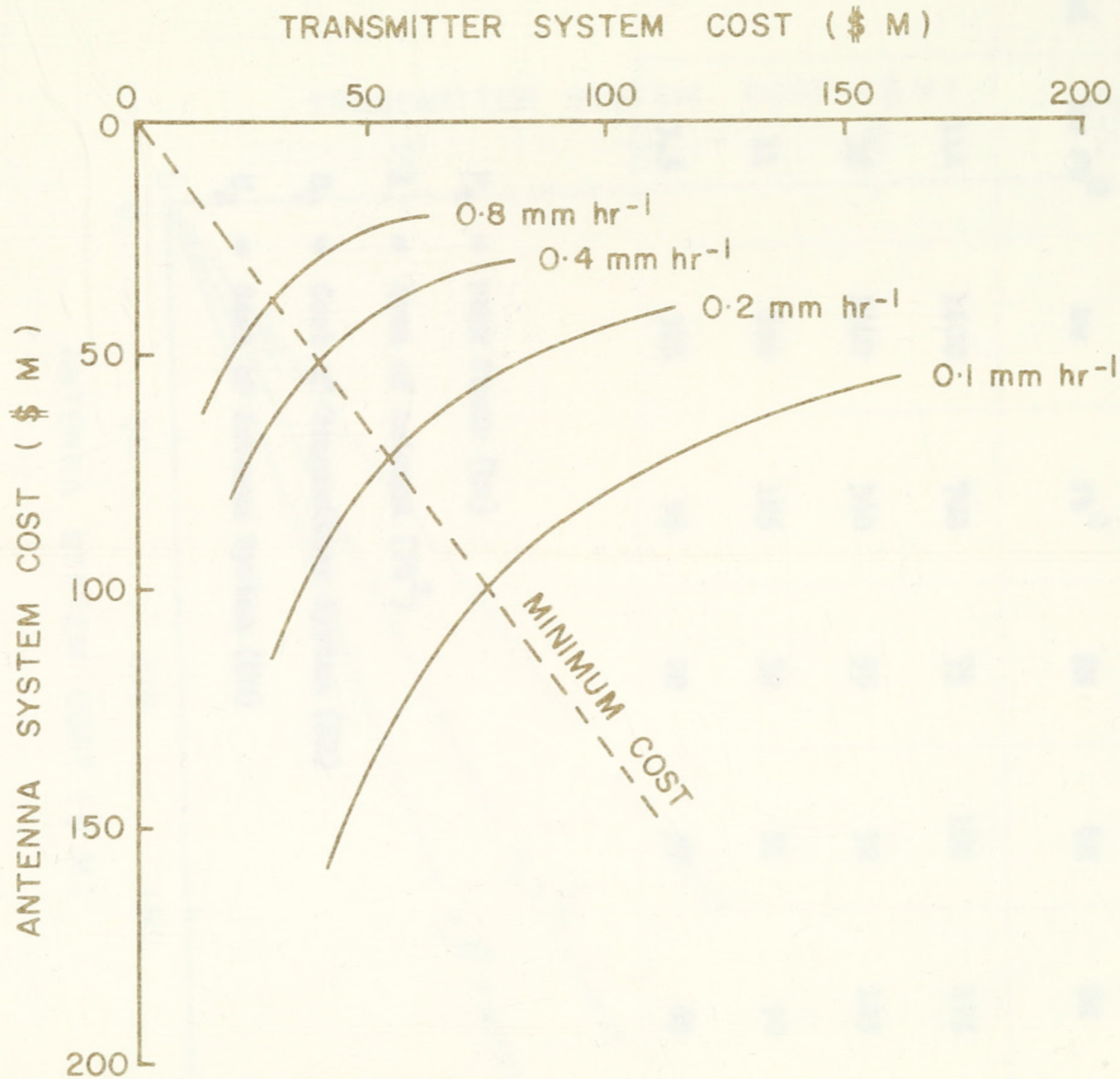


TABLE 6: MINIMUM COSTS FOR DIFFERENT SENSITIVITIES

R min 100 nmi	P_tA kw ft^2	P_t kw	A ft^2	C_T \$M	C_A \$M	$C = C_T + C_A$ \$M
0.1	112	1600	700	75	100	175
0.2	35	1000	360	55	72	125
0.4	11	600	185	39	51	90
0.8	3.5	375	95	28	37	65

P_t = Peak Power (kw)

A = Area of Antenna (ft^2)

C_T = Cost of Transmitter System (\$M)

C_A = Cost of Antenna System (\$M)

FIG. 11: RELATIVE TRANSMITTER COST TO ANTENNA COST FOR MAXIMIZING SENSITIVITY-RESOLUTION FUNCTIONS $P_t A$, $P_t A^{3/2}$ AND $P_t A^2$

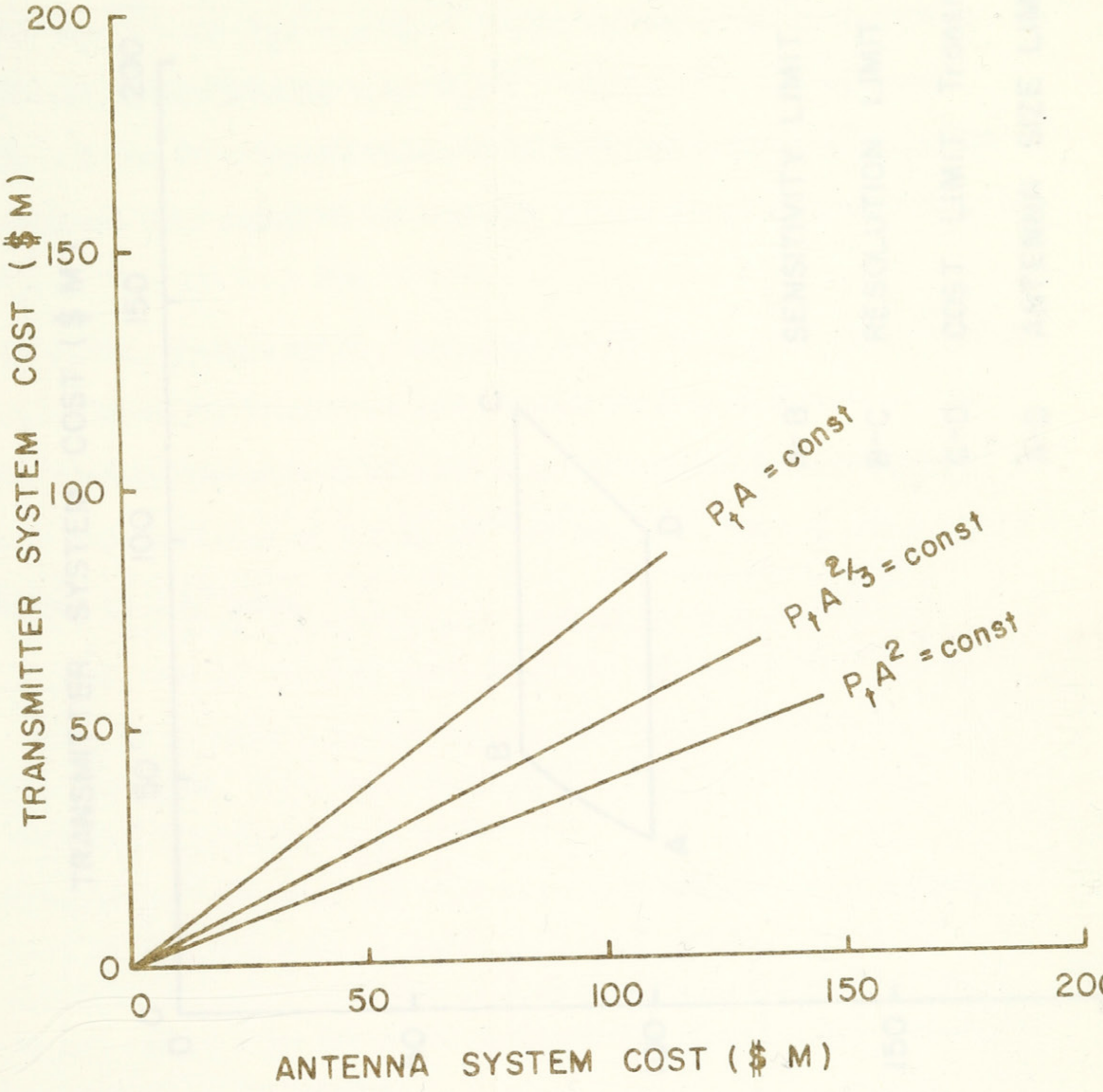
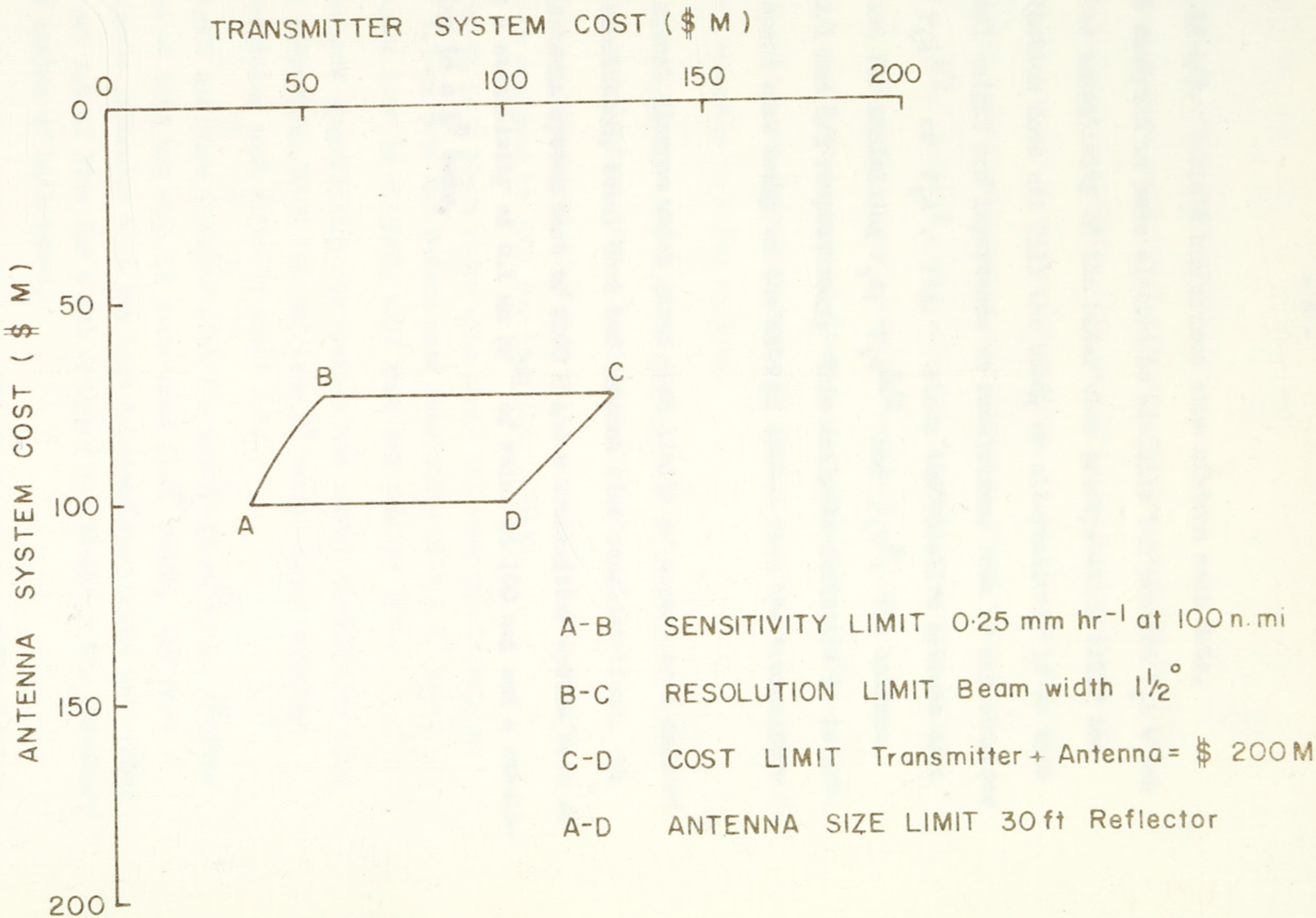


FIG. 12: COST LIMITS FOR TRANSMITTER AND ANTENNA SYSTEMS



transmitter cost is 4/3. Table 6 summarizes some minimum cost data.

In the above analysis we have elected to maximize the product $P_t A$ which is a measure of the sensitivity of the radar when precipitation fills the beam. If precipitation does not fill the beam, or alternatively if we wish to place additional weight and importance on resolution, then we may consider products such as $P_t A^{3/2}$ or $P_t A^2$. Fig. shows the relative antenna cost to transmitter cost for maximizing $P_t A$, $P_t A^{3/2}$ and $P_t A^2$. The optimum ratios are 4/3, 2/1 and 8/3 respectively. This analysis indicates it is not unreasonable to spend more money on the antenna system than the transmitter system.

Fig. 11 is a cost diagram which gives cost limits or a cost area defined by sensitivity, resolution, total cost and antenna size considerations. We might choose an antenna system cost of $100 M and a transmitter system cost of $75 M and obtain a sensitivity of 0.1 mm hr^{-1} of rain, at 100 nmi and a resolution corresponding to a 1^o beam.

6. Sensitivity and Weather Radar Parameters

Having chosen the wavelength (10.7 cm), the antenna size (30 ft), and made a rough cost analysis indicating that we might wish to spend $100 M on the antenna system and $75 M on the transmitter, it is time to look more closely at the actual specifications and sensitivities of existing and possible weather radars. Table 7 gives data for 7 existing weather radars and Table 8 similar information for 7 possible weather radars.

We have followed a form of presentation suggested by Gunn (1961). Since the Stormy Weather Group are very familiar with this type of data (e.g. MW-48), we shall limit our comments to a few remarks.

CPS-9 - We are aiming to copy the sensitivity and resolution of this radar and eliminate the attenuation problem.

Curtis Wright and Mitsubishi RC-4B are "all-purpose" 5.7-cm weather radars designed to sell for less than $200 M.

Mitsubishi RC-31 is a 10-cm radar with about the same sensitivity as the 5.7-cm sets but rather poor resolution with a 2° beam. Antenna cost is slightly more than transmitter cost.

WSR-57 - designed specifically for weather has better sensitivity than the Mitsubishi RC-31 but the same 2° beam. Again antenna/transmitter cost ratio is about 1.1.

Alberta FPS-502 has been included with its new 22-ft antenna. Resolution of this set will be quite good (1.2° beam). Our cost analysis indicates that the high antenna/transmitter cost ratio is not out of line for a set designed for studying the structure and motion of hailstorms.

Mitsubishi high power weather radar on Mt. Fuji uses our CAPPI display. The design of this radar may have been influenced by its location, 12,400 ft above sea level, the high winds, and its specialized use for detecting typhoons. (We have an interesting booklet on Mitsubishi Weather Radars.)

TABLE 7: SPECIFICATIONS OF 7 WEATHER RADARS

		GPS-9		CURTISS WRIGHT		MITSUBISHI RC-4B		MITSUBISHI RC-31		WSR-57		ALBERTA FPS-502		MITSUBISHI MT. FUJI	
			db		db*		db		db		db		db		db
Wavelength	(cm)	3.2	0	5.7	-10	5.7	-10	10.7	-21	10	-21	10.7	-21	10.7	-21
Antenna Diam.	(ft)	7.8	0	8.0	0	10	2	13	5	12	4	22	9	16	6
Peak Power	(kw)	250	0	350	1	300	1	600	4	500	3	500	3	1500	8
Pulse Length	(μs)	5	0	2	- 6	1	-11	2	- 6	4	- 1	1.75	- 7	35	- 2
Pulse Recur. Freq.	(sec^{-1})	186		324		220		220		200		480		310	
Noise Level	(db)	12	0	12	0	11	1	11	1	7	5	11	1	6	6
			0		-15		-17		-17		-10		-15		- 3
Sensitivity	mm hr^{-1} @ 100 nmi	0.1		0.9		1.0		1.0		0.4		0.9		0.15	
Resolution	degrees beamwidth	1.0		1.7		1.4		2.0		2.0		1.2		1.7	
Antenna Cost / Transmitter Cost		$\frac{25}{50}$ = 0.5		$\frac{25}{40}$ = 0.6		$\frac{35}{35}$ = 1.0		$\frac{45}{40}$ = 1.1		$\frac{40}{35}$ = 1.1		$\frac{75}{35}$ = 2.1		$\frac{60}{70}$ = 0.9	
Approx. Total Cost ($M)		200		175		175		225		250		250		275	

*db are relative to CPS-9

TABLE 8: SPECIFICATIONS OF POSSIBLE WEATHER RADARS

		EAST 1953	db	GUNN 1961	db	RCA 1°	db	RCA 1/2°	db	DECCA 750	db	DECCA 2500	db	MARCONI	db
Wavelength	(cm)	5.7	-10	5.7	-10	5.7	-10	5.7	-10	10.7	-21	10.7	-21	10.7	-21
Antenna Diam.	(ft)	2.7 x 10.7	- 2	12.0	4	15	6	30	11	30	11	30	11	30	11
Peak Power	(kw)	10.0	- 4	250	0	1000	6	1000	6	750	5	2500	10	2250	9.5
Pulse Length	(μs)	1	-11	3	- 3	4	- 1	4	- 1	3	- 3	5	0	4	- 1
Pulse Recur. Freq.	(sec^{-1})	∠ 500		270		250		250		275		250		250	
Noise Level	(db)	14	- 2 -29	7	5 - 4	9	3 4	9	3 9	6	6 - 2	9	3 3	9	3 1
Sensitivity	$mm\ hr^{-1}$ @ 100 nmi	5.5		0.18		0.06		0.03		0.13		0.07		0.09	
Resolution	degrees beamwidth	4° x 1°		1.2		1.0		0.5		1.0		1.0		1.0	
Antenna Cost / Transmitter Cost		$\frac{25}{20}$ = 1.2		$\frac{40}{35}$ = 1.1		$\frac{50}{90}$ = 0.6		$\frac{100}{90}$ = 1.1		$\frac{100}{50}$ = 2.0		$\frac{100}{100}$ = 1.0		$\frac{100}{90}$ = 1.1	
Approx. Total Cost	($M)	125		175		250		300		250		325		300	

Looking at the specifications of 7 possible radars in Table 8, we note that the Decca 750 has a good combination of sensitivity and resolution and no attenuation. This set would have performance characteristics rather similar to the radar suggested by Gunn (1961) except for the wavelength. The Decca 750 has a high antenna/transmitter cost ratio similar to our Alberta set. It is not unreasonable for a high-resolution radar. We could use two 750 kw Decca transmitters without producing an unbalanced system. Increasing the peak power from a Decca 750 kw to a Decca 2500 kw does not appear to be too attractive since we gain 5 db in peak power but lose about 3 db in noise level or receiver sensitivity since the 2500-kw system is not now available with a travelling wave tube in the receiver front end. A Marconi set is a possible alternative to a Decca.

7. Siting the Radar

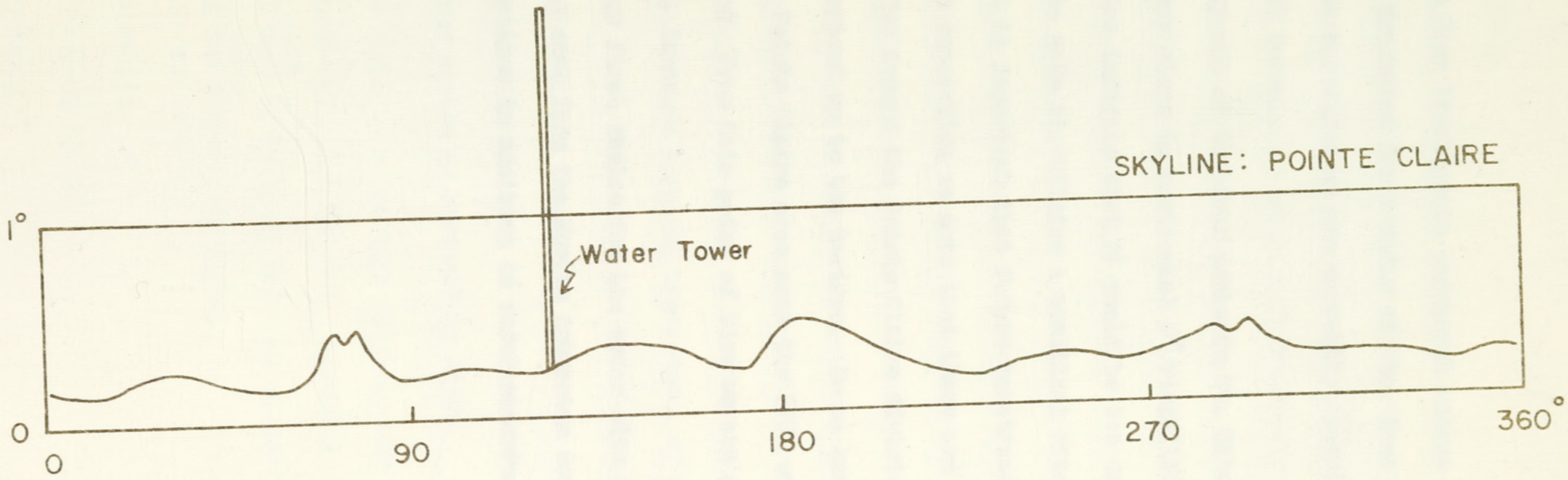
Three locations were considered: Ste. Anne de Bellevue Arboretum, Pointe Claire Pulp and Paper Research Institute Building, and the top of Mt. St. Hilaire.

Skylines, Fig. 13, from Ste. Anne de Bellevue and Pointe Claire were obtained by analyses of maps and observations on the sites. In order to clear the trees at these sites, it is necessary to place the antenna on a tower or building at least 60 ft high. When this is done the skylines are fairly good with little above $1/2^{\circ}$. Two peaks in the Lake of Two Mountains area do extend above $1/2^{\circ}$ when viewed from Ste. Anne. Their height (0.6° and 0.7°) and extent (6 and 8 degrees) are not likely to cause excessive screening. The water tower situated 0.4 miles from the PPRI building has an elevation angle of about 2° and subtends an angle of 1.2° in azimuth.

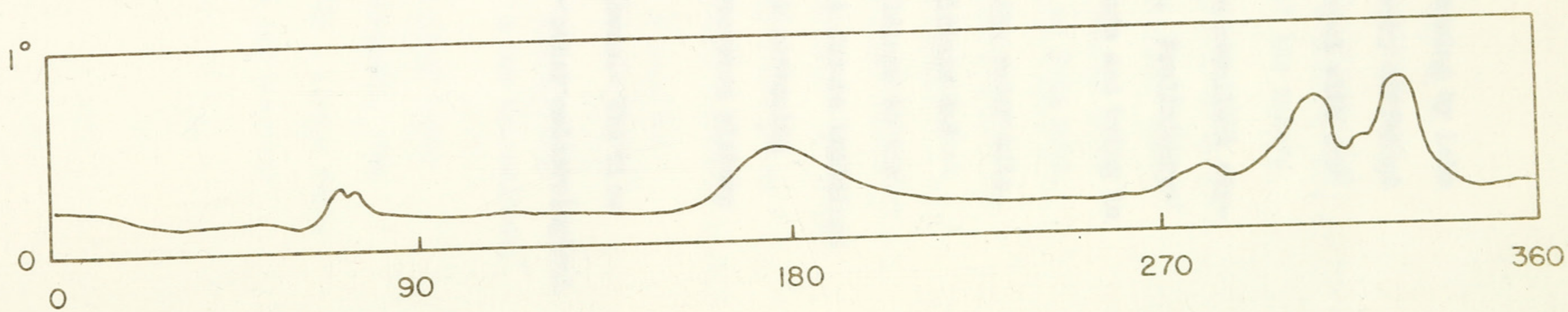
Our experience with the CPS-9 (1° beam) situated at Dorval Airport indicates that the Lakeshore is a good radar site as far as the skyline and

FIG. 13: SKYLINES FOR RADARS AT POINTE CLAIRE AND STE. ANNE DE BELLEVUE

SKYLINE: POINTE CLAIRE



SKYLINE: STE. ANNE DE B.



freedom from troublesome permanent echoes are concerned. Screening by Lake of Two Mountains for a radar at Ste. Anne de Bellevue is not very different from the screening we are currently experiencing from Mount Royal with our radar at Dorval.

Any one of the four peaks on Mt. Hilaire would provide an excellent sky-line very close to horizontal 0° visibility in all directions. Preliminary enquiries indicate that it would be too expensive to build roads and bring in power to make St. Hilaire a practical site for the radar.

It is important that future construction will not spoil the radar site. In this connection we note that there are quite a few new buildings and factories around the Pointe Claire district. Several new buildings to the north extend up to the horizon. Do we have any guarantee that future buildings in the Pointe Claire area near the PPRI will not cause a major screening problem? From this point of view we are much safer on the arboretum plateau at Ste. Annes.

Our first choice for the radar site is Ste. Anne de Bellevue. The view looking east from the Morgan Arboretum would be excellent for other meteorological observations in addition to radar measurements.

8. **Reliability**

It is important that the radar set operates continuously without any attention. Since we are emphasizing quantitative measurements of snow and rainfall we require minimum fluctuations in the calibration of the radar. We are going to considerable expense to obtain good radar coverage with freedom from distortion due to attenuation on the beam width. Continuity of operation is of equal importance.

The design of 10-cm radars is further advanced than 5-cm or 3-cm sets. Extensive experience has been gained over many years with medium to high power S-band radars, and equipment manufacturers such as Decca claim that their 750 kw S-band sets may be operated unattended and require little maintenance. The 2 megawatt transmitters are relatively new and less is known about their performance and reliability. The relatively small gain in sensitivity which may be achieved by using a 2 megawatt transmitter may be off-set by more frequent break-downs or calibration errors.

For some programs continuous 24-hr operation is essential. In these situations there is a major advantage in having two transmitters to maintain operations in the event of a failure of either transmitter. A two transmitter/receiver system is produced by Decca.

9. Recommendations

1. Since heavy rain storms attenuate 5.7 cm as much as 5 to 10 db, it is recommended 10.7 cm be used.

2. A 30 ft diameter solid surface paraboloid reflector should be used to give a 1° beam with side lobes depressed below -46 db.

3. The question of using a radome is still under discussion. Little or no cost saving is achieved by not using a radome. Heavy rain on the radome can cause attenuation of the order of 5 db at S-Band. Use of a radome would reduce risk of down-time and allow a check on an automated CAPPI system capable of operating continuously in all weathers and all localities.

4. The purchase of one 750 kw Decca S-Band Transmitter of pulse length 2.4 or 3 microseconds is recommended. A Decca receiver with logarithmic amplifier and travelling wave tube and noise level 6 db is also recommended. Since we expect to use a second transmitter of low peak power and very short pulse length, we should consider purchasing the Decca S-Band frequency diversity unit.

5. Antenna azimuth rotation of 6 rpm is recommended to achieve a complete scanning cycle in a period of 3 minutes.

6. The best site for the radar is Ste. Anne de Bellevue on the plateau near the Morgan Arboretum.

7. The antenna on top of the building should be high enough to clear trees 70 ft high. A 60 ft high building with an elevator is recommended. The elevator will cost $20,000. Laboratory space costs about $25 a square foot. Total cost of building with two storeys of laboratory space and elevator is of the order of $100,000.

10. Procurement and Cost

Information on the cost of various components of radar systems from different suppliers is available in the McGill files.

It seemed desirable to narrow the field of enquiry. Accordingly attention was paid to choosing the wavelength and antenna size. Once the decision has been made to use 10.7 cm and a 30-ft antenna, the problem of procurement is much simplified.

The total cost of the radar set, excluding the cost of the building, will be less than $300 M. Provided we choose one 750 kw transmitter/receiver the cost will be close to $250 M. It is recommended that we get the long delivery items on order as soon as possible. Suggested suppliers and alternate suppliers for the major components are listed below together with a cost estimate quoted in C$ for the equipment delivered to the site. We expect to receive additional quotations in the next few weeks but no major changes in cost are expected.

Radar Component	Suggested Supplier	Alternate Supplier	Cost Estimate ($M Can.)
Antenna	R.F. Systems	Antenna Systems	22
Radome	~~Toronto (?)~~ ESSCO	War Assets	35 (#34 for 48', #42 for 55')
Pedestal	Antlab	Scientific Atlanta	35
Transmitter/Receiver	Decca	Marconi	43
Other Radar Parts Spares Installation	Decca		25
Display and Records			65
Contingencies			25
Radar without building			250
Add Building			80
Elevator			20
Total Cost			$350

11. References

1. Atlas, D. "Advances in Radar Meteorology", reprinted from Advances in Geophysics, Vol. 10, Academic Press Inc., New York, 1964.

2. Battan, L.J. "Radar Meteorology", University of Chicago Press, Chicago, 1957.

3. Hiser, H.W. "Radar Meteorology", 1963, Third Edition, University of Miami (may be revised and updated and published by Louisiana State University Press).

4. Skolnik, M.I. "Introduction to Radar Systems", McGraw-Hill Book Co. Inc., 1962.

5. Mitsubishi Weather Radars.

6. McGill Stormy Weather Reports MW 1 to 38.

7. Proceedings of Weather Radar Conferences, 1 to 11.

8. "The Use of Radar in Weather Forecasting with Particular Reference to Radar Set AN/CPS-9", Air Weather Service Technical Report AWSTR 105-97, Dept. of the U.S. Air Force, 1952.

9. "Lectures on Weather Radar", Houghton, Marshall, Ligda, Austin and Fleisher, Massachusetts Institute of Technology, Cambridge, Mass., 1957.

10. Donaldson (1965) on Resolution and beamwidth.

APPENDIX 1: PULP AND PAPER RESEARCH INSTITUTE AT POINTE CLAIRE, P.Q.

PPRI is a tripartite enterprise with Government, Pulp and Paper Industries and McGill University. The Government provided the building, McGill contributes to the post-graduate training programme and the industries supply the budget money in proportion to their tonnage of products shipped for sale. Consolidated Paper Corporation Ltd. give in addition $150,000 annually to PPRI. They specialize in development and rely on PPRI for long term fundamental work.

Sections are the main subdivisions of PPRI organization. Each one is under the responsibility of a chairman. They are identified as Woodlands, Wood and Fibres, Process, Engineering and Technical Services. According to the number of active projects a section can be split into divisions. Normally, a division includes 6 to 8 people. Technical Services employ the largest number of people and have the highest technician to scientist ratio.

Details of the size and cost of the PPRI Laboratories are given below:

Erection	1957.
Design	Wing structure for unrestricted expansion.
Stories	3 wings at 2; 1 wing at 1, All crawl-space below ground level for utility services.
Area	70,000 sq. ft.
Erection Cost	$2,250,000, $32/sq. ft.
Additional Equipment	$500,000.
Architect	Dobush and Stewart.
Consulting Engineer	Jas. A. Kearns, 4465 Sherbrooke St. West.
Personnel - At Pointe Claire	125 2 to 1 ratio of technicians to scientists
Still at McGill	65
Total	190
Annual Budget	$2,000,000.

Floor plans of the PPRI building were obtained.

APPENDIX 2: NOTES ON ELEVATOR

The sites at both Ste. Anne de Bellevue (Macdonald College) and Pointe Claire (Pulp and Paper Research Institute) require a building about 60 ft high so that the antenna mounted on top of the building will not be shielded by trees and local buildings. A tower or building of 60 ft requires an elevator for personnel and equipment. An out-door ladder would not be safe and extremely inconvenient.

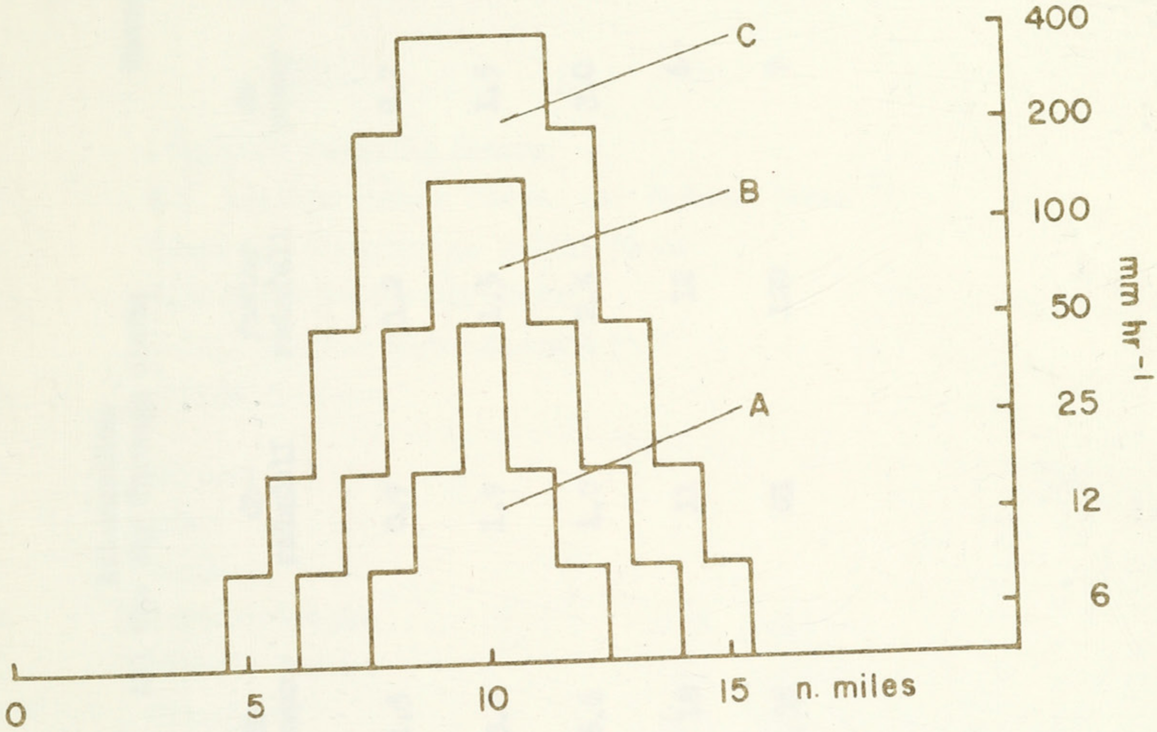
Our requirements were discussed with Mr. Robert Leslie of Otis Elevator Co. Ltd. He suggested that they could build a 2000-lb capacity 4-storey elevator for $17,000. Typical size and operating conditions are summarized below:

Load:	2000 lbs
Speed:	100 ft/min
Platform:	6'4" x 4'5"
Effective Area:	6'0" x 3'8"
Door:	7'0" high - 3'0" wide
Motor:	7 H.P., 3 phase, 208 v or 575 v
Stops:	4 storeys
Operation:	Single Automatic Push Button Inching feature (not self-levelling)
Cost:	$17 M approx. (Probably between $15 M and $20 M)
Extra Load:	4000 lb capacity - add $3 M
Self Levelling:	Add $1.5 M.

We would not anticipate any special problems with this elevator except the location and shielding of the elevator motors would have to be considered carefully to be compatible with the radar equipment on the top floor.

APPENDIX 3: MODEL STORMS

(cf MW-48, Figs. 12a, 27)



APPENDIX 3: TABLE SHOWING ATTENUATION AND RADAR RAINFALL FOR MODEL STORMS

Model Storm	Speed	Actual Rainfall	Attenuation All the Way Through Storm			Measurement of Total Rain in the Storm			
	knots	mm	db power	db rainfall	factor rainfall	db power	db rainfall	factor rainfall	radar rainfall
A	25	4	1.5	0.9	1.2	0.7	0.4	1.1	3.6
A^1	25	8	3.2	1.9	1.5	1.5	0.9	1.2	6.5
B	25	16	6.6	4.0	2.5	3.0	1.8	1.5	11
B^1	25	40	18	11	12	6	3.6	2.3	17
C	25	70	35	21	120	9	5.4	3.5	20

APPENDIX 4.

McGill Files on New Weather Radar

Important information on the McGill Weather Radar Concept, Siting Problems, Procurement Data from several companies, Description of Radar Components etc. etc. was filed, over a period of years, in Room 203 of the Macdonald Physics Building. These data are relevant to the present design, siting and procurement problem and were studied by the writer. Additions have been made to these files but the original information in each file was not removed or re-filed under another heading. The files were numbered in the following order:

No.	Title		
1	Available Existing Radars		
2	U.S. Weather Bureau Specs. for Weather Radar		
3	Notes and Thoughts on McGill Radar		
4	More Notes on Weather Radar		
5	McGill Weather Radar Concept SW5D		
6	Siting Problems		
7	Marconi		
8	RCA		
9	Decca		
10	Curtiss-Wright	12 B	Raytheon
11	Alberta Radar	12 C	Cossor
12 A	Mitsubishi	12 D	Gen. Elect.
13	Spun Dishes and Antennas		
14	Pedestal and Antenna Mounts		
15	Magnetrons		
16	Transmitter-Receivers (see also Company Files); Cost of Components		
17	Building		
18	Elevator		
19	Road (St. Hilaire)		
20	Financing (NRC + Prov of Que)		
21	Crown Assets		

APPENDIX 4

McGill Files on New Weather Radar

Important information on the McGill Weather Radar Concept, Siting Problems, Procurement Data from several companies, Description of Radar Components etc. etc. was filed, over a period of years, in Room 209 of the Macdonald Physics Building. These data are relevant to the present design, siting and procurement problem and were studied by the writer. Additions have been made to these files but the original information in each file was not removed or re-filed under another heading. The files were numbered in the following order:

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7	Marconi
8	RCA
9	Decca
10	Curtiss-Wright
11	Alberta Radar
12 A	Mitsubishi
12 B	Raytheon
12 C	Cossor
12 D	Gen. Elect.
13	Spun Dishes and Antennas
14	Pedestal and Antenna Mounts
15	Magnetrons
16	Transmitter-Receivers (see Company Files) also Cost of Components
17	Building
18	Elevator
19	Road (St. Hilaire)
20	Financing (NRC + Prov of Que)
21	Crown Assets