THE FEASIBILITY OF A WEATHER RADAR NEAR FORT McMURRAY, ALBERTA

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ABSTRACT

The feasibility of a weather radar to map precipitation in the Alberta Oil Sands Environmental Research Program (AOSERP) study area near Fort McMurray, Alberta was investigated. Consultations with various groups and agencies associated with AOSERP revealed that representative precipitation data are of greatest importance to the Meteorology and Air Quality Technical Research Committee and the Hydrology Technical Research Committee. Typically, measurements are required of accumulated precipitation amounts accurate to 20 percent with spatial resolutions of four km^2. The present raingauge network may be unable to provide precipitation data with sufficient resolution and accuracy. On the other hand, careful study suggests that a radar calibrated with surface gauges may provide adequate estimates of surface precipitation.

Several problems must be carefully investigated before a useful weather radar system can be realized. Of prime consequence are radar design, melting layer effects, radar location and data management. Although capital and operating expenditures for a precipitation measurement radar system need to be closely examined, it has been shown elsewhere for areas greater than 3000 km^2 that a weather radar system is more economical for precipitation measurement than an equivalent raingauge network.

In summary, a weather radar (calibrated with precipitation gauges) can approach fulfilment of requirements for more accurate precipitation data within the AOSERP study area.

1. INTRODUCTION

Central to the impact of resource development within the Athabasca oil sands near Fort McMurray, Alberta are detailed considerations of the environment. Consequently, the Alberta Oil Sands Environmental Research Program (AOSERP), created early in 1975, provides information on solutions to environmental and social problems (AOSERP, 1976). It is anticipated that such information will provide a sound basis for government, industry and the public to manage the delicate balance among resource development, environmental protection and most importantly the quality of life.

Research required for future environmental decision making with respect to the Athabasca oil sands stems directly from eight Technical Research Committees (TRC) within AOSERP. Critical to environmental protection, the Meteorology and Air Quality TRC attempts to provide information for better land use planning and pollution control strategy. For example, measurements of precipitation in the vicinity of Fort McMurray are of prime importance for hydrologic studies and land reclamation research. More importantly, interactions between atmospheric pollutants and precipitation events are significant since deposition of pollutants on the surface often results from the pollutants being 'scavenged' by precipitation (see e.g. United States Atomic Energy Commission, 1970).

Until very recently in Canada, precipitation has usually been measured with standard equipment such as raingauges and snowgauges. In this regard, a climatological data acquisition system is planned for use in the AOSERP study area shown in Fig. 1. It is well-known, however, that measurements from widely-spaced gauges may not accurately represent all precipitation events. For example, intense storms 10 km across can pass undetected through a network of raingauges spaced 20 km apart. In order to adequately measure all precipitation, it has been suggested that weather radar be considered, since a weather radar can be used to map precipitation patterns over very large areas.

It is therefore the purpose of this study to investigate the scientific, technical and economic feasibility of a weather radar near Fort McMurray. Consultations among scientists, industrialists and the public, together with detailed

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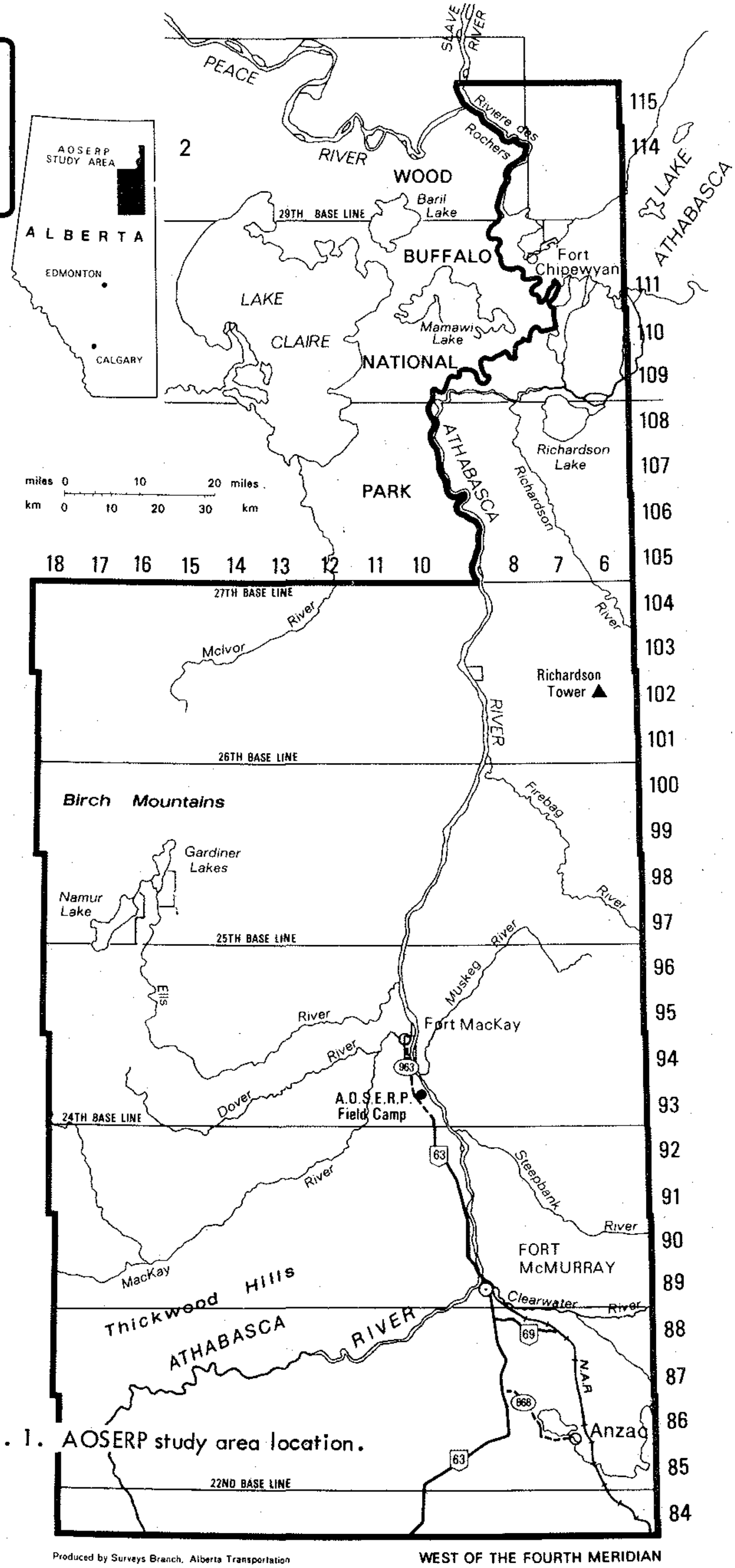

Fig. 1. AOSERP study area location.

investigations of the technical aspects of radar operation, suggest that the capabilities of gauge-calibrated weather radars are consistent with the requirements of those who desire precipitation measurements in the vicinity of Fort McMurray.

2. CONSULTATION WITH GROUPS INTERESTED IN PRECIPITATION MEASUREMENTS AND OTHER RADAR USES

2.1 PURPOSE OF CONSULTATIONS

Although weather radar is capable of mapping precipitation patterns, its ultimate feasibility depends upon demand for data from such a system. To determine the desirability of a weather radar system, various groups and agencies with interests in the AOSERP study area were consulted (see Appendix I). During the discussions consideration was given to types of continuing research and/or operations, and whether precipitation was an important concern. Future plans of the groups and agencies were also discussed. When information about precipitation was considered important, accuracy and resolution requirements were reviewed as well as the format and availability of the data. Of prime concern was whether or not the present or proposed raingauge system in the AOSERP study area is capable of providing all the necessary information. Requirements for capabilities of a weather radar system to provide additional precipitation data in space and time were discussed. With regard to radar site requirements in the AOSERP study area, specific geographic areas were determined where precipitation measurements were most desired.

2.2 GENERAL RESULTS

It is especially noteworthy that almost everyone interviewed expressed an interest in the use of radar to map precipitation patterns. However, beyond this general interest, the groups were classified into three categories. With a primary interest in precipitation data the first category contains those having requirements impossible to meet with a sparse raingauge network. The second category includes those who require good precipitation information but whose needs are not as critical. This category also includes those groups interested in using radar for purposes other than mapping precipitation. The last category, although not yet requiring precipitation data, wished to remain informed about the progress of using a weather radar in the AOSERP study area. Some were able to suggest other possible uses of the data.

2.3 GROUPS WITH A CRUCIAL REQUIREMENT FOR PRECIPITATION INFORMATION

After discussions with those who have a crucial need for precipitation data, it became apparent that there are two requirements. One is a need for information concerning precipitation rates and accumulated amounts of precipitation. The other is a need to understand the interaction between precipitation and air pollution.

The Hydrology Technical Research Committee attempts to analyze stream-flow and water quality in several catchment areas within the AOSERP study area and thereby develop mathematical models of catchment response. A major constraint is the quality of the input data since construction of the models requires information about the distribution of precipitation intensity and amount. Currently several streams in the area have hydrometric gauges but often there are no rain-gauges nearby. Many of the remaining streams are small, do not have hydrometric gauges, and the lack of roads precludes regular water quality sampling and flow measurement. Hydrologists therefore consider it advantageous to conduct 'real-time' (or "event-instigated") sampling programs. This requires information about the location, intensity, amount and extent of precipitation over the areas of interest, such as that available from a radar. The intensity information is important since light precipitation will tend to soak into the ground whereas heavy precipitation intensities result in the water running directly into the streams.

The Hydrology TRC estimated that the precipitation data from radar observations must have a spatial resolution of about 4 km^2, an intensity accuracy within at least a factor two, and daily accumulated amounts accurate to within 20 percent. The accuracy requirements are not as rigid for precipitation intensity information used in conducting real-time programs. The catchment areas of particular interest include the Birch Mountain, Muskeg Mountain and Thickwood Hills region.

The possibilities of a weather radar were enthusiastically received by the representatives of the Hydrology TRC. It was recognized that the format and availability of the radar data are problems of prime consequence for future consideration. Twelve hour maps of precipitation accumulation and mean precipitation rates are desirable shortly after precipitation events. Real-time information to plan event-instigated sampling programs is required much sooner than one day after precipitation over small catchments. These maps need not include radar-raingauge calibration information; however, radar data used in post event studies should include proper calibrations and therefore be more accurate. In addition, maps of accumulated precipitation and mean precipitation rates are desirable for periods shorter and longer than 12 hours. These and other data management concerns are discussed in Section 5. With regard to snow measurements for hydrologic studies, the primary requirement is a knowledge of the snow depth to within about 25 percent prior to run-off.

The other groups with a primary interest in precipitation data were those concerned with the interaction between precipitation and air pollution. This interest arises from the fact that scavenging by hydrometeors is one of the "most significant natural mechanisms for clearing the air" (Fuquay, 1970). However, this cleansing of the air results in bringing the pollutants to earth where their impact on plants, animals, etc. is important.

The Meteorology and Air Quality TRC plans to develop a model which will predict the distribution of pollutants in the atmosphere to determine final pollution deposition fields. The problem is to determine the amount and type of material released into the atmosphere, where this material is deposited, and in what concentrations. The role of precipitation is important in this study since, as mentioned above, hydrometeors can scavenge material from the atmosphere and the rate of precipitation fall influences the collection efficiency. Therefore, maps of precipitation rates and accumulated amounts are desired for periods ranging from 10 minutes to perhaps one year. The spatial resolution suggested was about 4 km^2 with an error in the accumulated precipitation measurements less than about 20 percent. A general knowledge of precipitation patterns is also considered to be helpful in the interpretation of air quality measurements. For example, any deposition between the sources and monitoring sites may be influenced by the presence or absence of precipitation. In addition, interpolation of deposition patterns between monitoring sites might be improved with knowledge that precipitation was present in the area. It was recognized that a very dense raingauge system is necessary to provide the above information, especially in the case of rain showers. Information about snowfall is of use in a manner similar to rainfall data, the accuracy requirements being similar. However, it is recognized by the Committee that snow measurements by present techniques may not be as accurate as those for rain.

The Aquatic Fauna TRC is concerned with problems associated with contaminated precipitation. Assistance that can be provided by radar in tracking precipitation patterns to determine if precipitation originates or passes over pollution sources was fully considered. Should precipitation systems tend to track over a particular region, it is possible that deposition of pollutants over a long period of time may lead to contamination of the lakes and streams. This particular problem of pollutant deposition is also of concern to the Vegetation and the Terrestrial Fauna TRCs because of the possible impact upon plant and animal life.

There was interest shown by people, not associated with the AOSERP study area, in the applications of a weather radar based near Fort McMurray. Discussion with representatives of the Saskatchewan Research Council indicated a desire to determine the deposition of any pollutants downwind of the sources. Further, there was a need to obtain precipitation data in the area of Saskatchewan that would be covered by a weather radar.

2.4 GROUPS WITH A SECONDARY NEED FOR PRECIPITATION INFORMATION

Several of the agencies consulted stated that precipitation data presently available were usually adequate to suit their needs. However, most indicated that if weather radar data were available it would be used.

For example, the sections of both the Atmospheric Environment Service and the Alberta Forest Service responsible for forecasting suggested that real time radar data may be useful as a forecast aid if it showed the position, motion and intensity of precipitation systems. It is noteworthy that the literature describes how radar data can be used to determine areas of high forest fire risk (Krueger, 1968).

Representatives from industry commented on the possible application of radar data to determine the precipitation climatology of the oil sands region. There is a desire to obtain some estimate of the probability of unusual events such as very heavy rainfall. These data would be useful for industrial design, for example, in the construction of dikes and culverts.

The Terrestrial Fauna TRC indicated that information about rainfall and snow depth may be helpful in forecasting changes in wildlife populations. This committee and others asked about using a weather radar for tracking bird migrations. Weather radars have been used for this purpose with the most useful data coming from systems that do not use range correction circuitry. The ground clutter pattern near the radar site places a constraint on using the radar to track birds.

2.5 GROUPS WITHOUT IMMEDIATE REQUIREMENTS FOR PRECIPITATION DATA

Some representatives of industry, the public sector and the Human Environment TRC indicated that they did not require precipitation information at this time. Since they may eventually require these data, however, they all expressed a desire to be informed of the type of weather radar data available if a system is installed within the AOSERP study area.

2.6 SUMMARY

It is evident that precipitation is one of the more important meteorological parameters that must be measured for environmental studies within the AOSERP study area. The requirements range from real time knowledge of storm patterns to yearly summaries of precipitation events.

A weather radar system providing real time information about the location, motion and intensity of precipitating systems is useful to weather forecasters and to those planning research activities on an event-instigated basis. For later analysis, maps showing precipitation rates, accumulated amounts of precipitation and storm tracks can be incorporated into hydrologic studies and pollution research.

It was typically suggested that any system providing precipitation data must have a spatial resolution of about 4 km^2 and be able to measure accumulated amounts to within 20 percent and precipitation rates to within a factor two. The system may be required to provide data for analysis of precipitation parameters during periods as short as ten minutes to as long as one year.

Because many of those interviewed were not familiar with weather radars there were suggestions that data from such a system be in a form that would be readily understood. It was generally agreed that a weather radar added a new dimension to precipitation observations and that the present raingauge system was probably not sufficient by itself.

Given the requirements mentioned previously, the next sections will indicate whether the present raingauge system can fulfil these requirements.

3. RAINGAUGE AND RADAR MEASUREMENT OF PRECIPITATION

The requirements for precipitation measurement near Fort McMurray can be carried out in situ by raingauges (or snowgauges), and/or remotely by radar. The purpose of this section is to broadly outline the capabilities of raingauges and radar; more importantly, the capabilities of the existing precipitation measuring network in the AOSERP study area must be examined to determine any practicality of radar measurements whatsoever.

3.1 RAINGAUGES

Of all methods, raingauges probably provide the most accurate measure of rainfall at specific locations. However, it is well-known that rainfall varies considerably from point to point on the earth's surface. Such 'areal variability' implies that a network of raingauges is required to measure areal rainfall amounts. The accuracy of these areal precipitation measurements is then determined by the density of raingauges within the network[1].

The raingauge network within and surrounding the AOSERP study area is shown in Fig. 2. This map clearly shows that most of the gauges are located near the Athabasca River north of Fort McMurray. Because the spacing between raingauges is often greater than 30 km,it appears that required precipitation measurements resolved horizontally to 2 km (see Section 2) are virtually impossible. The locations of precipitation measuring equipment, together with the time resolutions of recorded data, are given in Table 1. Except for the tipping bucket raingauges and the raingauges at Namur Lake, Shell-Hartley, Lost Creek, Tar Lake and MacKay-Thickwood, the best time resolution in the recorded data is one hour. Since showers can often last less than one hour and are often smaller than the spacing between raingauges, it follows that the present raingauge network may not be able to produce accurate maps of accumulated precipitation or motions of some precipitation

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[1] The errors in measurement accuracy also depend upon other properties of the network and the precipitation being observed. A more complete treatment of the subject is given by Zawadzki (1975).

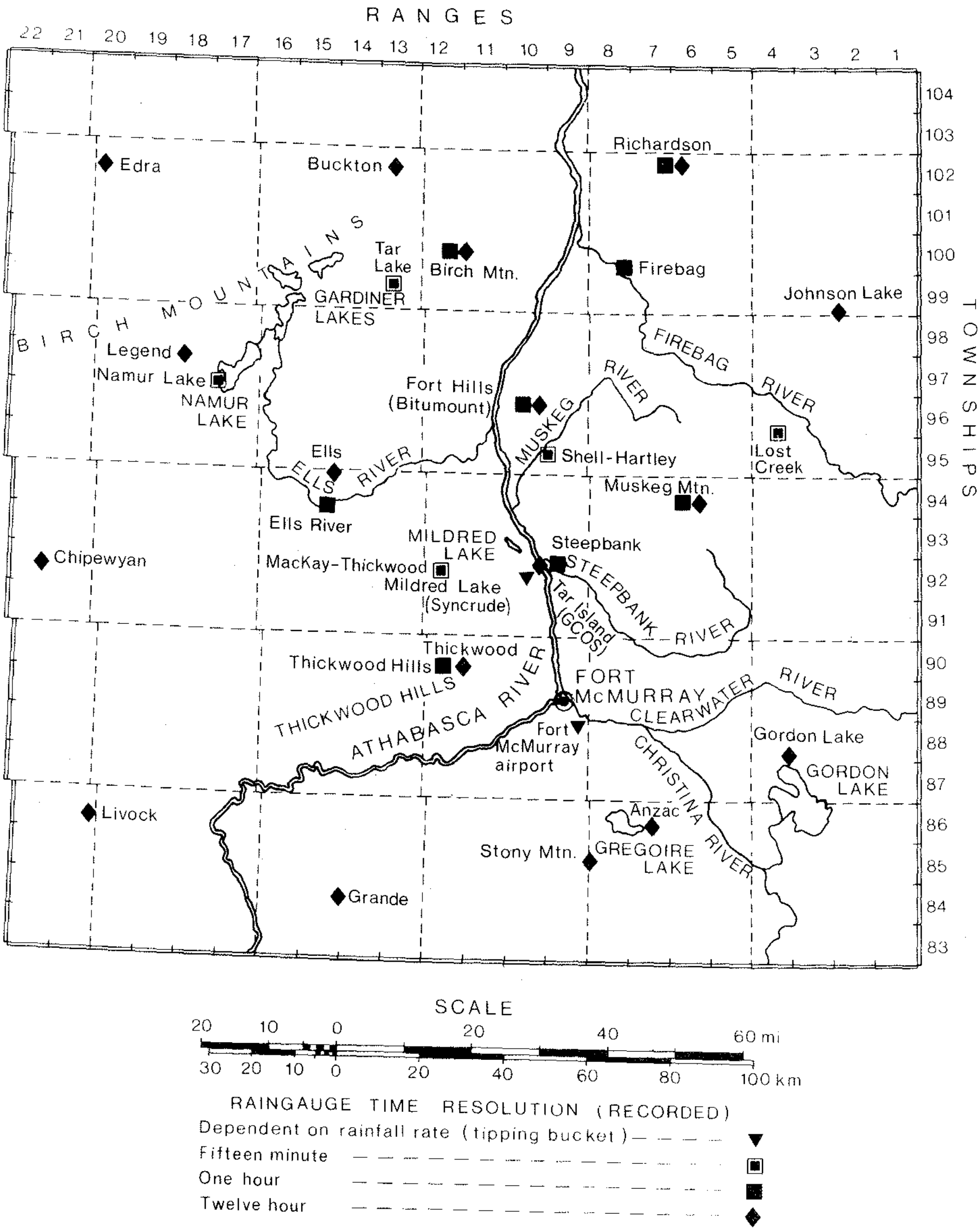

Fig. 2. Raingauge network within and surrounding the AOSERP study area.

Table 1. Location of raingauges in the vicinity of the Athabasca oil sands. The time resolution of data presently recorded is also given.

LOCATION*		PRESENT TIME RESOLUTION IN RECORDED DATA	RAINGAUGE TYPE	AGENCY
Name	Section-Township-Range			
Birch Mtn.	24-100-12	1 hour	weighing	Meteorology and Air Quality TRC (AOSERP)
Ells River	3- 94-15	"		
Firebag	1-100- 8	"		
Fort Hills(Bitumount)	27- 96-10	"		
Lost Creek	2- 96- 4	15 min		
MacKay-Thickwood	8- 92-12	"		
Mildred Lake (Syncrude)	16- 92-10	-	tipping bucket	
Muskeg Mtn.	9- 94- 6	1 hour	weighing	
Namur Lake	7- 97-17	15 min		
Richardson	26-102- 7	1 hour		
Shell-Hartley	25- 95-10	15 min		
Steepbank	20- 92- 9	1 hour		
Stony Mtn.	19- 85- 8	PROPOSED		
Tar Lake	19- 99-13	15 min		
Thickwood Hills	11- 90-12	1 hour	weighing	
Tar Island(GCOS)	24- 92-10	12 hours	accumulating	Great Canadian Oil Sands
Anzac	9- 86- 7			-
Birch Mtn.	24-100-12			Alberta Forest Service
Bitumount	27- 96-10			
Buckton	20-102-13			
Chipewyan	14- 92-22			
Edra	17-102-20			
Ells	35- 94-15			
Gordon Lake	12- 88- 4			
Grande	24- 84-15			
Johnson Lake	7- 99- 2			
Legend	29- 97-18			
Livock	13- 86-21			
Muskeg Mtn.	9- 94- 6			
Richardson	31-102- 6			
Stony Mtn.	7- 85- 8			
Thickwood	11- 90-12			
Fort McMurray Airport	36- 88- 9	-	tipping tucket	Atmospheric Environment Service

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* All locations are west of the Fourth Meridian.

generating systems (see Section 2). A more detailed description of the accuracy of raingauge networks in relation to radar measurements is given in Section 4 of this investigation.

3.2 RADAR MEASUREMENTS

The shortcomings of measuring precipitation with raingauges are almost completely overcome using weather radar. Briefly, electromagnetic energy transmitted from a radar set along a narrow beam is scattered by precipitation located some distance away. Energy scattered by precipitation back toward the radar is intercepted by the radar antenna and detected by a sensitive receiver. Data derived from the radar receiver are related directly to the physical properties of the precipitation observed. For example, large raindrops backscatter more energy to the receiver than smaller raindrops. In general terms, the difference between the energy transmitted and that received by the radar is related to the rate at which the detected precipitation falls to the surface, and the distance of the precipitation from the radar. Consequently, surface measurements are used to derive relationships between rainfall (or snowfall) rate and the corresponding radar measurements. The spatial and temporal stability of such calibration relationships then determines the accuracy of further radar-derived precipitation measurements made elsewhere[1].

The quantitative nature of weather radar makes it particularly attractive for use in the vicinity of Fort McMurray simply because it allows precipitation measurements to be carried out remotely; a seemingly simple solution to the difficult problem of installing a dense network of raingauges where access is possible only at considerable expense. Moreover, within 100 km distance from a radar, the spatial resolution which decreases with range and is limited by the size of the radar antenna, can easily be within 2 km, a requirement outlined in Section 2 above. The temporal resolution in the determination of instantaneous precipitation rates depends upon the time interval between sequential observations immediately above a specified surface location. This time interval depends upon the movement

[1] A more detailed discussion of radar methods, including calibration, is given in Appendix II.

of the radar antenna and can be as small as a few seconds, but for hydrological use can be greater than 30 seconds.

It is evident that quantitative radar observations in the vicinity of Fort McMurray can complement the existing raingauge network in that:

1. Radar can be used to interpolate between raingauges; precipitation otherwise undetected by a sparse raingauge network would be detected.

2. Precipitation systems can be followed with time (see Section 2) since instantaneous maps of precipitation rate from a circular region of radius perhaps exceeding 100 km are available every few seconds from a radar.

From the above discussion it is clear that radar qualifies as an instrument to provide quantitative areal measurements of precipitation rate and accumulated amounts of precipitation. Radar also fulfils the spatial and temporal resolution requirements of precipitation related studies to be conducted in conjunction with AOSERP. It remains to determine whether it is logistically possible to install and operate a weather radar in the vicinity of Fort McMurray, and whether quantitative radar measurements are sufficiently accurate for the requirements of the AOSERP studies. These considerations are treated in more detail in the next sections.

4. IMPORTANT ASPECTS OF THE FEASIBILITY

One of the most important aspects of the feasibility study was to determine the accuracy of precipitation measurement by radar. Consequently, a bibliography was compiled from all relevant available literature (emphasis was given to work conducted during the last 10 years) on radar as a tool for precipitation measurement. This bibliography is presented in Appendix III together with sources for the various articles. Information of prime importance to understand precipitation mapping by radar, together with those articles related to snow measurement, are distinguished from the more comprehensive list. Although not referred to directly, many following comments on the accuracy of precipitation measurement by radar were derived from the articles listed in the bibliography.

4.1 ACCURACY

The shortcomings of raingauges described previously, especially their inability to provide areal estimates of precipitation, are somewhat overcome by radar techniques. Radar measurements also suffer from uncertainties and understanding the accuracy of such quantitative precipitation measurements can sometimes be a bewildering affair. However, the complexity of the problem cannot be overlooked.

Signals received by radar after scattering from precipitation are interpreted in terms of rainfall amount, as described in Appendix II. Fundamental limitations of radar techniques and the variable nature of precipitation lead to uncertainties in the interpretation of radar signals. Some of the causes (perhaps not all!) of errors in radar estimation of rainfall or snowfall are listed in Table 2. Notwithstanding these difficulties, it is shown for example by Wilson (1970) that the radar accuracy of precipitation estimation can be improved if the radar is calibrated against raingauges, an excitement shared by Lowing et al. (1975, p. 6) who indicate "The raingauge alternative to radar estimation of rainfall is comparatively inaccurate for areal estimation of rainfall".

In recent years there have been significant advances in calibration and data analysis procedures. These steps facilitate more precise comments on the accuracy of precipitation measurement by radar. Therefore, it is considered expedient to dwell upon the ability of a radar-raingauge system to quantitatively measure precipitation, raingauges being used to calibrate the radar.

Table 2. Some sources of error in the measurement of rainfall or snowfall which result from the precipitation disposition itself, or which are inherent in radar techniques.

- Frequency of radar data collection
- Errors in electronic radar calibration
- Anomalous propagation
- Attenuation of the radar beam
- Errors due to radar averaging of precipitation
- Non-uniform filling of the radar beam
- Radar beam intercepts the melting level
- Presence of hail or other hydrometeors
- Variations in distributions with size of raindrops
- Variations in snow crystal type
- Vertical air motions which affect fall-speed of raindrops
- Evaporation or growth of precipitation below the radar beam

To assess the accuracy of radar precipitation measurements an exact standard is required that is considered to represent, for example, the amount of rainfall over some specified area. Because raingauge networks are usually structured with less than an infinite density of raingauges, such networks cannot represent areal rainfall exactly. It is also recognized that point measurements by gauges themselves are subject to errors. However, some studies have considered the rainfall measured from a relatively dense network (1 gauge per 7 km^2, Wilson, 1970; 1 gauge per 3 km^2, Woodley et al., 1975) to be a measure of actual average rainfall. Other studies (Harrold et al., 1974; Collier et al., 1975) have used the radar echo intensity pattern to interpolate between gauges within a dense network to obtain an 'optimum' field. In all the above cases the difference between calibrated radar measurements and the 'actual' or 'optimum' measurements is considered as a measure of accuracy.

The philosophy in precipitation measurement by radar is to utilize a radar calibrated against some number of surface measuring precipitation gauges, the number of calibration gauges being less than that required to obtain 'actual' or 'optimum' measurements referred to above. With a few calibration gauges the areal rainfall is determined using the radar to provide the spatial precipitation distribution and the gauges to specify the precipitation magnitude (Wilson, 1976). The precipitation rate measured by radar is determined by comparison of radar and surface precipitation measurements to establish an appropriate Z-R relationship (see Appendix II). Such Z-R relationships are then applied to radar measurements elsewhere (where there are no raingauges) and therefore used to improve areal precipitation measurements.

To determine quantitative areal precipitation measurements with radar, either a climatological Z-R relationship is used[1], or a Z-R relation is derived using a raingauge in the vicinity of the precipitation being observed. Although useful in general, the 'climatological' relationship clearly cannot apply to specific precipitation events, and is therefore limited in its spatial and temporal stability. Examples of the use of the climatological relationships are cited by Wilson (1970) and Brandes (1975). Calibration relationships derived closer in space and time to the precipitation being observed were used by Harrold et al. (1974) and Collier et al. (1975). Regardless of the calibration relationship, however, it is recognized (Wilson 1976) that the utility of calibration factors decreases with increasing distance from surface located calibration gauges. Rainfall over an area is therefore better estimated using a scattered distribution of gauges (rather than one) to specify the precipitation magnitude in adjustment of spatial precipitation distributions measured by radar. Although the accuracy of total rainfall obtained by radar-raingauge systems is improved by increasing the calibration gauge density, other parameters are even more important in understanding the accuracy of a radar calibrated with raingauges. In fact, the chance of each individual calibration gauge being rained upon is extremely important in the design of a calibration gauge network needed to support operational adjustment of radar rainfall estimates (Smith and Dixon, 1976).

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[1] $Z = 200\ R^{1.6}$ is a typical 'climatological' Z-R relationship (Marshall and Palmer, 1948).

Each raingauge calibration site can be composed of one raingauge (Wilson, 1970) or a cluster of gauges (Woodley et al., 1975; Collier et al., 1975). The adjustment of the radar pattern using calibration sites can then proceed in several different manners. Within a specified area precipitation from one or more calibration sites can be compared to radar measurements taken over the sites. Such comparisons can be combined to give an average adjustment factor (Woodley et al., 1975; Harrold et al., 1974) to be applied to radar measurements at other locations. Alternatively, radar measurements can be adjusted using calibration sites by weighing the radar measurements according to their inverse distance from the calibration site. In this manner, single adjustments can be obtained for small individual regions called sub-catchment areas (Collier et al., 1975). Similar to the weighted adjustments are field adjustment factors described by Brandes (1975). Field adjustments, although they require a network of gauges as calibration sites, are considered to be better than average adjustments. The field adjustments ensure that the derived radar-raingauge precipitation field closely fits the actual gauge measurements, but at the same time the radar observed detail between gauges is retained. Although it is common to adjust radar rainfall estimates by simply multiplying by an adjustment factor, it is now recognized that such procedures sometimes give unsatisfactory results (Cain and Smith, 1976). Clearly, progress is still being made towards using radar to determine areal rainfall amounts.

Once a radar-raingauge calibration Z-R relationship is obtained by one of the adjustment methods mentioned above, it is used in conjunction with other spatial precipitation measurements determined by radar to obtain the gauge adjusted radar determination of areal rainfall. The amount of precipitation accumulated for various periods of time over specified areas, derived from gauge adjusted radar measurements, are then compared with the accumulated amount of precipitation obtained from 'actual' or 'optimum' measurements. A summary comparison of the average error in gauge adjusted radar estimates for various experiments is given in Table 3. In this table, the average error in accumulated precipitation is defined by

$$|R_{a,o} - R_e| / R_{a,o}$$

$R_{a,o}$ = 'actual' or 'optimum' rainfall

R_e = gauge adjusted radar estimate

Table 3. Comparison among experiments of the average error in gauge adjusted radar estimates.

Data Source	Experiment [Reference]						
	Wilson ['70]	Brandes ['75]	Woodley ['75]	Wilson ['75]	Harrold ['74]	Collier ['75]	Wilson ['75]
	Oklahoma Thdrstms	Oklahoma Thdrstms	Florida Showers	Great Lakes Summer	Wales Rain	Wales Rain	Great Lakes Winter
Area Size (km^2)	3500	4000	570	170	500	700	855
Time Interval	storm	storm	24 hr	24 hr	1 hr	3 hr	24 hr
Radar Range (km)	37-95	37-95	65-140	95-112	12-48	12-48	18-64
Collection Frequency (per hr)	6-12	12	12	6	60	60	6
Calibration Gauge Density ($1/km^2$)	1/1100	1/900	1/3250	1/275	1/700	1/700	1/800
Adjustment Procedure*	A	F	A	F	A	W	F
Average Error (%)	28	13	~20	24	14	9	15

* A - average adjustment, F - field adjustment and W - weighted adjustment.

It is apparent from this table that the average error in accumulated amounts for the various conditions indicated is between 9 and 28 percent.

Fig. 3 shows the mean absolute percentage difference (modulus of average error) between radar estimates of accumulated rainfall using one calibration site and 'optimum' estimates (Collier, 1975). The accuracy so-indicated is given in terms of the time during which the accumulated amounts were measured, and the area over which the measurements were taken. The curves presented were derived using a new radar calibration determined each hour. For a specified area and increasing periods of time, the error decreases mostly because meteorological factors which influence the accuracy of each calibration event tend to cancel out with time. Instead, if the calibration relationship was determined over a 6-12 hour period, and used to determine radar adjusted rainfall measurements over that period, the error could be greater than that given in Fig. 3. This is because precipitation events which occur during the longer period (e.g. 6-12 hours) could cause bias in the type of rainfall which fell into the calibration gauge. For example, over a long time period, much of the rain which fell into a calibration gauge may have been due to a small convective storm lasting a short time, while most of the rainfall over the area of interest may have been due to widespread rain. Because convective and widespread rains may produce different calibration adjustments to be applied to the radar measurements, it is clear in this case that the convective adjustments may not be appropriate for much of the area of interest. Therefore, the applicability of a single raingauge-radar calibration decreases with time. These comments regarding radar calibration using gauges which accumulate over long time periods are especially relevant for precipitation measurement in those regions of the AOSERP study area where the time resolution in the recorded data is often worse than one hour as indicated in Table 1.

It is shown in Fig. 3 for a fixed time period of integration that the error in measurement of accumulated rainfall decreases with increasing area. For small areas wind drift appears to degrade the accuracy (Harrold et al., 1974). This occurs because errors due to the representativeness[1] of the calibration gauge tend to cancel out with

[1] In the context here the representativeness of calibration raingauges refers to their ability to represent distributions with drop size and the corresponding calibration Z-R relationship over extended areas.

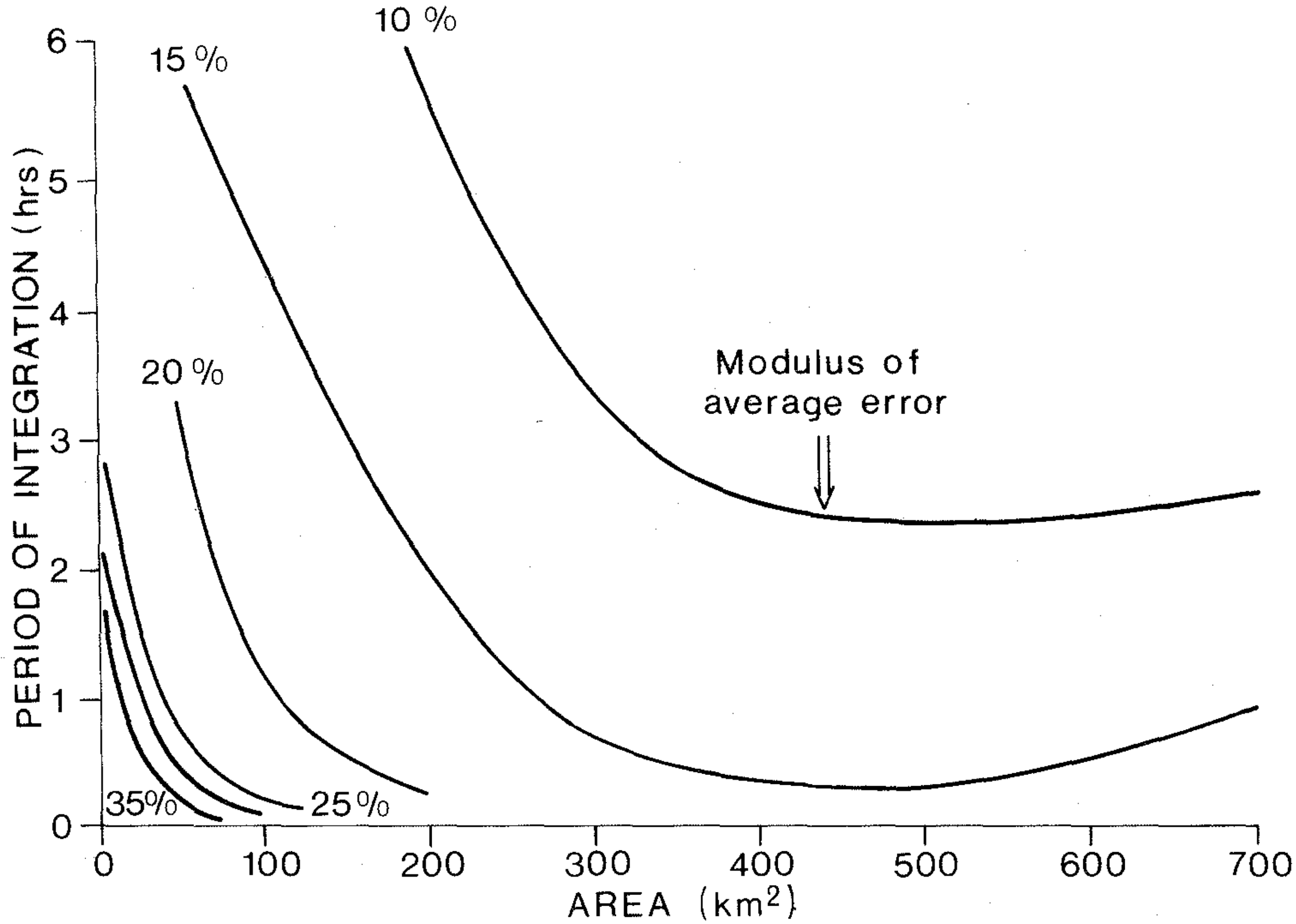

Fig. 3. Mean absolute percentage difference (modulus of average error) between radar estimates and optimum estimates of accumulated rainfall (after Collier, 1975).

increasing area; further increasing the area causes greater errors because the calibration raingauge is no longer representative of the larger area. That the calibration gauges lose their representativeness with range was mentioned by Wilson (1970).

Fig. 3 can be used to determine the accuracy in the measurement of average rainfall rates, which can be considered as the amount of accumulated precipitation divided by the time interval during which the precipitation was collected. Depending upon the accuracy of the calibration Z-R relationship, it appears from Fig. 3 that for areas less than 50 km^2 and time intervals less than 10 min, say, the accuracy in measurement of precipitation rate is worse than 35 percent. Average rates calculated over large areas or using data collected over longer periods of time can be expected, on the basis of data presented in Fig. 3, to be somewhat more accurate. Instantaneous radar measurements of precipitation may be less accurate. Based upon the variability of climatological Z-R relationships, Stout and Mueller (1968) indicate for any one measurement of Z, that the rainfall rate will be between 0.66 and 1.52 times the true rate, 68 percent of the time. They also indicate that uncertainty in the radar measurement of Z after electronic calibration is about the same as that introduced by uncertainties in the Z-R relationship. Instantaneous rainfall rates therefore, using a climatological relationship, could deviate from the true rate by as much as factors 0.2 - 0.5 or 2 - 5. Such is the case for instantaneous radar rainfall rate measurements in the vicinity of Fort McMurray since a climatological Z-R relationship has not been established for this region. Some improvement however might be expected using a Z-R relationship derived from radar-raingauge comparisons made closer in space and time to the precipitation being measured.

The accuracies indicated in Fig. 3 are generally better than those obtained in other experiments. This is also evidenced by referring to Table 3 where smaller average errors are reported by Harrold et al. (1974) and Collier et al. (1975). It is suggested by Collier (1975) that the prime reason for the smaller errors may be because the maximum range from the radar was smaller than in some other studies, and that the 'actual' rainfall was more accurately known. Fig. 4a shows the performance of a radar-raingauge system as a function of range taken from Collier (1975). Although it is not clear how these results were obtained, it appears that the accuracy

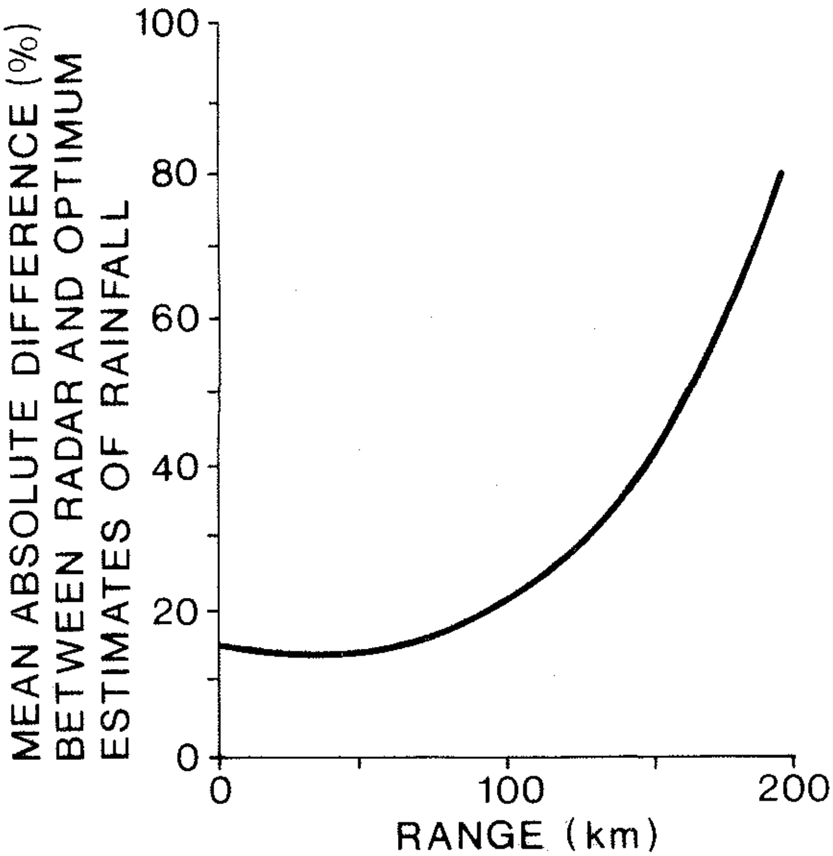

Fig. 4a. Accuracy of calibrated radar precipitation measurements as a function of range (after Collier, 1975).

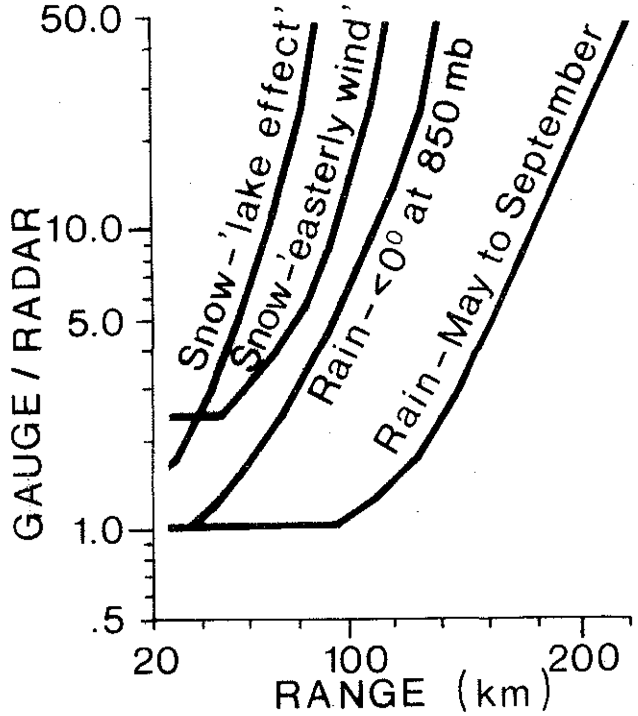

Fig. 4b. Accuracy of radar measurements for various precipitation conditions as a function of range (after Wilson, 1976).

remains relatively constant with increasing range until about 100 km. The accuracy then begins to diminish quite rapidly with range.

Shown in Fig. 4b are accuracies when temperatures at 850 mb (about 1.5 km above sea level) are below freezing. It is apparent that at a fixed range (60 km, say) rainfall is measured less accurately when the atmosphere is cooler. This is in agreement with studies conducted in Wales (see e.g. Harrold et al., 1974) which indicate that radar measurements of rainfall, made when the radar beam intersects the melting level, agree less perfectly with 'actual' or 'optimum' measurements of rainfall. Such results are especially relevant for precipitation measurements in Alberta, Canada since the climate is substantially cooler than that of Wales.

Fig. 4b also shows the ability of radars to measure snowfall. In broad agreement with earlier results reported by Carlson and Marshall (1972), it is evident that snowfall is somewhat more difficult to measure than rainfall[1]. The accuracy of snowfall measurement also diminishes much more rapidly with range than for measurement of rainfall.

4.2 SUMMARY OF ACCURACIES - RELEVANCE TO FORT McMURRAY REGION

Based upon the foregoing discussion it is possible to generalize the accuracy estimates. Such generalizations substantially agree with Wilson (1976) who suggests that radar precipitation estimates to within 10 to 20 percent can be obtained for the following approximate conditions:

area $\geq$ 100 km^2

integration time interval $\geq$ 3 hrs

radar range 50 - 100 km

calibration gauge density $\geq$ 1 per 3000 km^2

[2] collection frequency $\geq$ 6 per hour

precipitation amounts $\geq$ 1 mm hr^{-1}

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[1] Conventional measurements of snowfall at the surface are sometimes inaccurate; such inaccuracies cannot be overlooked since they degrade any adjustments made to radar measurements of snowfall. However, accurately calibrated weather radars can provide improved estimates of surface snowfall.

[2] If the radar collects data less frequently, important rainfall changes may pass undetected by the radar.

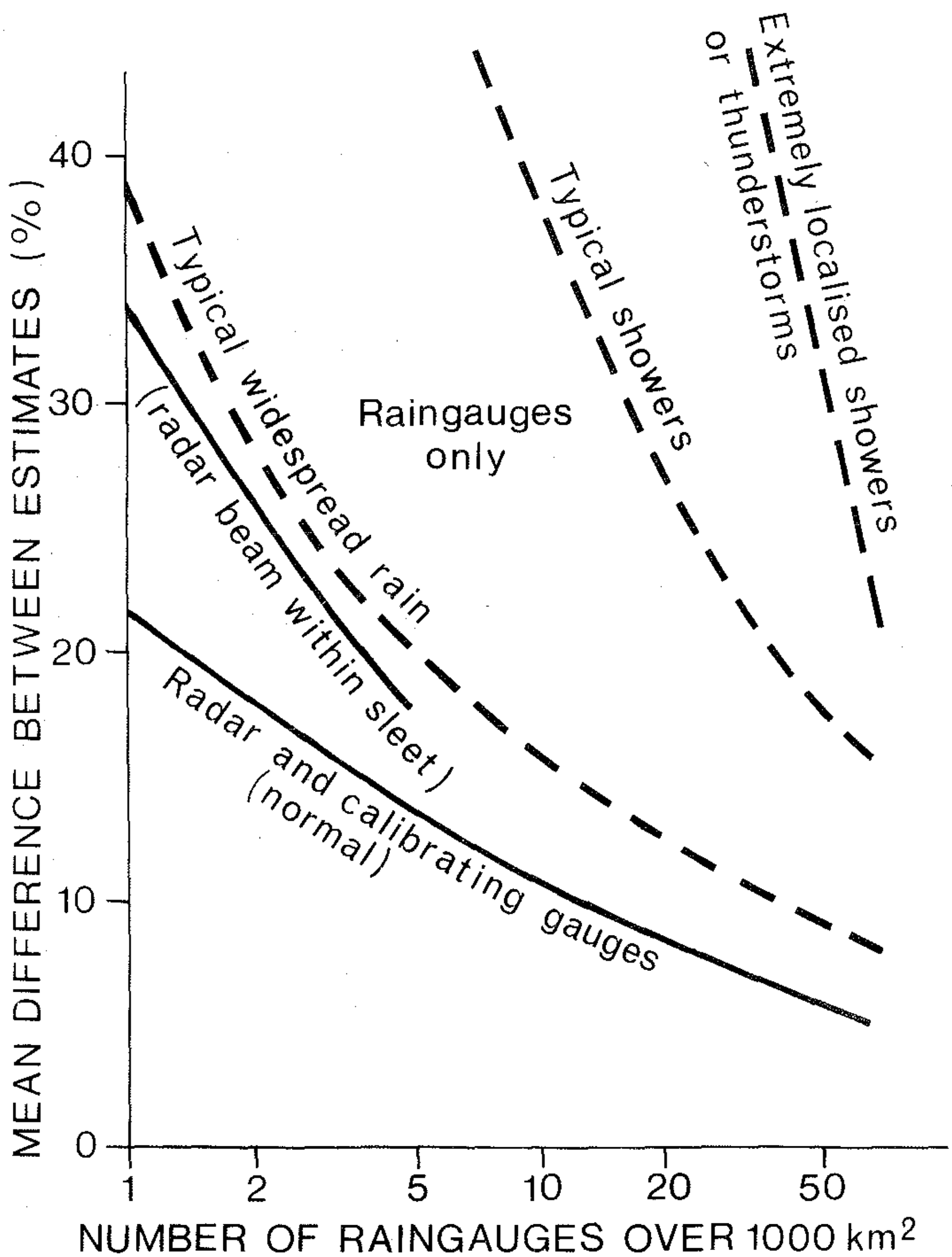
Smaller errors are likely for radar ranges closer than 50 km, collection frequencies >12 per hour, new calibration Z-R relationships at least every 3 hours, and for the melting level to be located entirely above the radar beam.

It is important to emphasize that results obtained in other parts of the world are not necessarily applicable in Alberta. With this proviso, it is expedient to compare the accuracy of a radar-raingauge system to raingauges alone, especially in the context of its applicability to Alberta.

The mean difference between estimates and 'optimum' or 'actual' rainfall, appropriate for Wales, as a function of raingauge numbers is illustrated in Fig. 5 taken from Collier (1975). This diagram indicates the accuracy of radar estimates for gauge calibration sites distributed over 1000 km^2. The accuracy of raingauges without radar is also shown. It is evident for this 1000 km^2 area that the accuracy which can be obtained using a radar and more than one calibration gauge site is usually within 20 percent. The radar-raingauge system is particularly superior over raingauges for shower rainfall measurements. In typical showers, a radar system calibrated using two raingauge sites gives the same accuracy as a raingauge network of about 50 gauges over 1000 km^2.

In an attempt to apply the results of Fig. 5 to the Fort McMurray region, Fig. 6 was drawn as a first estimate of the expected accuracy of precipitation measurements using a radar and existing raingauges. For the purposes here, the radar was assumed to be located at the Fort McMurray airport; distances 100 km from Fort McMurray are indicated on Fig. 6. Each raingauge with recorded data having a time resolution of one hour or better was treated as a calibration site. According to Fig. 5, precipitation within an area of 1000 km^2 in the vicinity of the calibration site can be measured to within about 20 percent. Therefore, those circular areas of 1000 km^2 within 100 km range and centered over each raingauges are shown on Fig. 6 to depict the total area within which precipitation may be measured to within 20 percent. Circular areas which overlap imply a gauge density greater than 1 per 1000 km^2 and therefore an accuracy better than 20 percent.

Extreme caution must be exercised in the use of Fig. 6 since the data



Mean percentage difference between optimum estimates of hourly rainfall and radar estimates calibrated using various numbers of calibrated sites.

Mean percentage difference between optimum estimates of hourly rainfall and estimates using various numbers of raingauges without radar.

Fig. 5. Difference between estimates of hourly rainfall related to raingauge density (see text for explanation; after Collier, 1975).

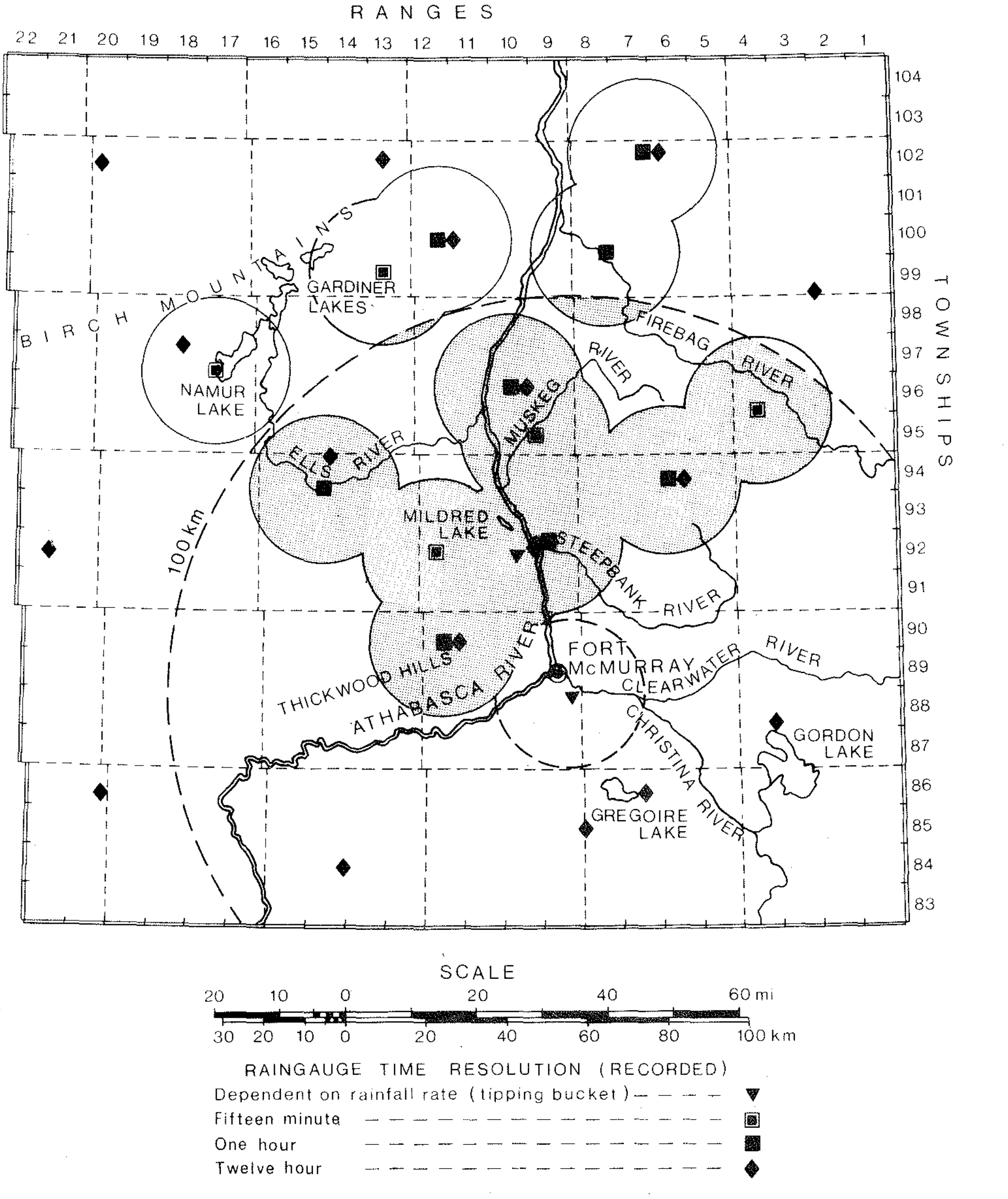


Fig. 6. Regions where accuracy of precipitation measurements with weather radar and raingauges in the vicinity of Fort McMurray may be within 20 percent. Circular areas are 1000 km^2. Radar range of 100 km is also shown (see text for further explanation).

used to derive the diagram were obtained in Wales, and intercontinental transfer of such results may be questionable. Furthermore, attempts to interpolate between the gauges to adjust the radar measurements are not considered. It is also assumed of course that the calibration sites (if rained upon) are representative of the 1000 km^2 circular area. The accuracy possible using a radar in conjunction with the raingauges illustrated in Fig. 6 can be clearly understood (despite uncertainties mentioned above) with reference to Fig. 5. For each of the circular areas, to measure showery precipitation with similar accuracy, about 20 - 50 raingauges would be required.

In summary, this section shows the advantage of a gauge calibrated radar system for measuring areal precipitation amounts. The next section considers other important aspects such as the logistics of installing and operating such a system, calibration, costs, siting considerations and data handling.

5. FUTURE CONSIDERATIONS

This section outlines various aspects which might be considered if a weather radar system is to be installed in the vicinity of Fort McMurray. It is not intended to discuss every detail, but suggested that the points mentioned here serve as guidelines for future plans.

5.1 RADAR AND DATA ACQUISITION SYSTEMS

The experience of the authors supports the view that whenever possible, electronic equipment items should be bought off the shelf rather than 'in house' design and manufacture of items. The major equipment includes the radar, test and calibration facilities, the data acquisition system, playback and display facilities, and data processing facilities.

Appendix IV details a standard weather radar with which the authors are entirely familiar. A radar with a wavelength of 5 cm is considered to be most attractive for use in the AOSERP study area, recognizing that very intense precipitation events may present attenuation problems. If future studies of convective storms are planned, then a radar with 10 cm wavelength should be considered. The cost of the radar system shown in Appendix IV complete with radome, an antenna control that permits CAPPIs[1] and a digital data recording system is $100,000. However, to avoid excessive ground clutter, to improve resolution and to avoid intercepting the melting level, a 1° beamwidth is necessary which requires a 3.6 meter antenna for the 5 cm wavelength. The additional cost to meet the 1° beamwidth specifications would be between 20,000 - $50,000.

One of the difficulties in measuring snow with radar is that the dielectric constant of ice is less than water; snow is therefore more difficult than rain to detect. To help overcome this problem it is suggested that the radar system be capable of different pulse durations. Increasing the pulse duration during snow storms causes more energy to be transmitted, thereby increasing the probability of detecting light precipitation. It is now possible to record radar data in digital form on

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[1] Constant Altitude Plan Position Indicator.

computer compatible magnetic tape without the aid of a computer. This requires averaging of data to be performed by electronic circuits. This averaging is necessary to reduce the uncertainty in reflectivity measurements because of statistical fluctuations in the received signal (see e.g. Marshall and Hitschfeld, 1953). Typical averaging is over 1 km in range and 1° in azimuth, depending upon the pulse duration, pulse repetition frequency, beamwidth, and rotation rate of the antenna.

By recording the radar data in digital form on magnetic tape it is possible to conduct many different types of analyses. However, this capability requires a considerable amount of data management.

5.2 DATA MANAGEMENT AND RADAR CALIBRATION

As mentioned in Section 2 one of the requirements of any precipitation measurement system is that the data be readily accessible and in a form nearly anyone can comprehend. If a weather radar system with a digital data recording facility is to be established in the vicinity of Fort McMurray, the attention to be given to data management cannot be overemphasized. The information recorded on the computer compatible magnetic tapes is in the form of numbers (e.g. binary numbers), which mean nothing to someone who wants a rainfall rate. The data must therefore go through several steps before they are in a useful format.

The first step is to apply all the necessary calibrations. These include the electrical calibrations which determine how much average received power each digital number represents, and the raingauge calibrations which provide a Z-R relationship. It is important that the electrical calibration take into account radome loss. The attenuation of the radome will of course increase if it becomes coated with water or ice. To determine the Z-R relationship, consideration must be given to the various methods mentioned in Section 4. For example, should raingauge calibrations be combined to yield one average Z-R relationship for a particular region at a particular time? Consideration of raingauge calibration sites is required, for example, whether each site should consist of a cluster of raingauges or just one gauge (see Section 4). Further, the integration times used for the radar-raingauge comparisons must be considered. It is recognized that a data file (e.g. new magnetic tape) should be created and contain only relevant meteorological events with ground clutter, electronic noise, anomalous propagation, etc. removed. One facility to carry this out is described by Ramsden, et al. (1976), in which an interactive computer graphics program permits those with little radar or computer experience to examine digital radar data and extract records of interest.

The final step involves production of computer programs to allow anyone access of clean calibrated data. It is then possible to produce maps, tables, etc. of precipitation rates, accumulated precipitation amounts or storm tracks for any time interval desired, and for any location within the area of radar coverage. The programs so-developed should be reasonably easy to use on various computers to allow widest possible access of the data.

In summary, to facilitate the use of weather radar data by those not familiar with radars or computers, the data should be preprocessed to provide clean calibrated data perhaps in the form of rainfall rates. Standard programs can also be made available to permit output of the data in the form of contour maps or other useful formats. Because of the need for data to plan real-time event-instigated activities, some form of output must be made available more quickly.

5.3 OTHER COST CONSIDERATIONS

In addition to the radar and data processing system, other capital costs must be considered. These include a tower for the antenna and pedestal assembly, a building to house the system, power, land, test equipment, spare components, and display facilities. Consideration should be given to a display that will permit the examination of the digital data on a daily basis to determine whether the system performed well and whether the recorded data quality is acceptable. For example, excessive electronic noise and missing data can be readily detected and the problem rectified before too much data are lost.

Once the radar and data acquisition systems are installed the major operational expenses are spare parts for maintenance in addition to personnel for operations, electronic calibrations, and maintenance of the system on a 24 hour basis. A team of three or four technicians could be responsible for the radar and data acquisition system as well as preliminary data analysis.

5.4 LOGISTICS

As mentioned previously, thought must be given to the problem of data management and especially to determination of appropriate Z-R relationships. Associated with the determination of the Z-R relationships is the affect of the melting level on the observations (see Harrold and Kitchingham, 1975). This is a serious concern in Alberta during spring and fall when the melting level is usually close to the ground.

The selection of a site for the radar also requires careful consideration. There are two aspects to consider; ground clutter and radar range to important regions where precipitation measurements are required. The radar should be placed to minimize the amount of permanent echo and possible blocking of the beam. It is possible to analyze the topography and determine the ground clutter patterns for various radar sites (Moores and Harrold, 1975). Usually ground clutter limits the minimum useable range to about 20 km. Accuracy constraints (see Section 4) limit the best measurement range to about 100 km. A cursory survey of the AOSERP study area indicated that the region was not extremely hilly and that a site near the Fort McMurray airport may be acceptable. This location may allow good radar coverage along the Athabasca River and over catchment areas on either side. The sites of GCOS, Syncrude, and the AOSERP camp at Mildred Lake would also be within the region of best measurement. The raingauges situated at these locations would be useful for determining the Z-R relationships. In addition, access to a radar site close to Fort McMurray is not difficult.

One last consideration is whether or not a computer should be at the radar site to facilitate data reduction and quick production of precipitation maps. If a computer is not located at the radar site then another playback system is necessary to monitor the quality of the digital data. This may involve digital to analog conversion of the data to permit its display.

This section indicates many aspects of a weather radar system to be considered in order to obtain useable data. Indeed, particular radar-raingauge calibration procedures, management of data, and development of data output programs are of prime importance. However, techniques developed in Alberta and elsewhere can be applied to these problems of operating a radar near Fort McMurray. Furthermore, even though the initial capital cost of a radar system is fairly large, a weather radar is more economical than raingauges for measuring precipitation over catchment areas greater than 3000 km^2 (Taylor, 1975; Collier et al., 1975).

6. CONCLUSIONS

The feasibility of a weather radar to map precipitation in the vicinity of Fort McMurray was investigated with regard to a) requirements for precipitation data and b) the technical possibility of radar providing the data. Various groups and agencies with an interest in the AOSERP study area were consulted to determine their requirements for precipitation information, especially the type of information provided by a weather radar. The discussions revealed groups which could be placed into three requirement categories. There were those with a primary need for accurate precipitation data, those with a secondary need but a desire to use such data if available, and those without an immediate need for such data. Two groups ranked above all others in their acute need for accurate precipitation data. The Meteorology and Air Quality Technical Research Committee of the Alberta Oil Sands Environmental Research Program requires precipitation data to determine the interaction between precipitation and air pollution. The Hydrology Technical Research Committee requires precipitation data to study catchment response to precipitation events. It was further determined that there is a requirement for detailed and accurate observations of precipitation rates, accumulated precipitation amounts and paths of precipitating systems. Typically, spatial resolutions of four km^2 and measurements of accumulated amounts of precipitation accurate to 20 percent are needed.

Based on the results of investigations reported in the literature, the present raingauge network will not provide precipitation data with the resolution and accuracy required. However, recent investigations show, for showery precipitation at a radar range less than 100 km, that a radar and one calibration raingauge per 1000 km^2 will measure accumulated rainfall amounts with an accuracy to about 20 percent. The same measurement accuracy can be met with a raingauge network having 50 gauges per 1000 km^2. Therefore, the requirements for precipitation observations within the AOSERP study area can be more closely met if the raingauge density is increased considerably, or if a weather radar is used in conjunction with the present raingauge network. Compared to measurement of rainfall, the capability of radar to measure snowfall deteriorates somewhat more rapidly with radar range.

Before a weather radar system can provide useful information, careful consideration must be given to several problems. Most importantly, data management must be investigated so that the basic radar data can be translated into a form that is readily understood. Other concerns such as calibration methods, the effect of the melting level and location of the radar require careful attention.

Radars can now be kept in a van or trailer. This may be particularly attractive for AOSERP, since it appears that precipitation data acquisition is of prime concern for a limited number of years, at which time the radar may be transported elsewhere. In addition to expenditures for a shelter, tower, etc. the initial capital investment in a weather radar and digital data acquisition system is about 120,000 - $150,000. Analysis of this initial investment, compared to corresponding capital and operating costs for an equivalent gauge network, is well beyond the scope of this study. However, for areas greater than 3000 km^2 it has been found elsewhere (Taylor, 1975; Collier et al., 1975) that a weather radar system is more economical than an equivalent raingauge network. This may well apply to the AOSERP study area where road access is very limited.

In conclusion, it was found that a weather radar (calibrated with precipitation gauges) can approach fulfilment of requirements for more precise precipitation data within the AOSERP study area.

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APPENDIX I

SPECIALISTS CONSULTED TO HELP DETERMINE FEASIBILITY OF WEATHER RADAR MEASUREMENTS IN CONJUNCTION WITH AOSERP

A. Alberta Oil Sands Environmental Research Program (AOSERP):

R.P. Angle	- Committee Member Meteorology and Air Quality Technical Research Committee (TRC) - Meteorologist, Pollution Control Division Air Quality Control Branch Alberta Environment
M. Bik	- Committee Member Aquatic Fauna TRC - Senior Environmental Adviser Syncrude Canada Ltd.
F. Burbidge	- Co-chairman Meteorology and Air Quality TRC - Superintendent, Scientific Services Atmospheric Environment Service Environment Canada
W.L. Cary	- Committee Member Meteorology and Air Quality TRC - Coordinator, Environmental Conservation Great Canadian Oil Sands Ltd. (GCOS)
M. Falk	- Program Coordinator Alberta Oil Sands Environmental Research Program
A. Fedkenheuer	- Projects Leader Vegetation TRC

C.R. Froelich	- Projects Leader Hydrology TRC
R. Gerard	- Committee Member Hydrology TRC - Research Officer Transportation and Surface Water Engineering Alberta Research Council
D. Golding	- Committee Member Hydrology TRC - Research Scientist, Forest Hydrology Northern Forest Research Center Canadian Forestry Service
D.A. Hackbarth	- Committee Member Hydrogeology TRC - Research Officer Groundwater Division Alberta Research Council
B.M. Kasinska-Banas	- Projects Leader Human Environment TRC
G.A. Kemp	- Projects Leader Terrestrial Fauna TRC
A. Mann	- Projects Leader Meteorology and Air Quality TRC

F. McDougall	- Chairman Vegetation TRC - Director of Forestry Alberta Forest Service Alberta Energy and Natural Resources
M. Spitzer	- Committee Member Hydrology TRC - Engineer, Hydrometric Surveys Water Surveys Environment Canada
E. Stashko	- Committee Member Meteorology and Air Quality TRC - Head, Weather Section Alberta Forest Service Alberta Energy and Natural Resources
P.W. Summers	- Chairman Meteorology and Air Quality TRC - Chief, Atmospheric Dispersion Division Atmospheric Environment Service Environment Canada
T. Turner	- Projects Manager Meteorology and Air Quality TRC - Research Meteorologist Atmospheric Environment Service Environment Canada

H. Veldhuissen	- Committee Member Meteorology and Air Quality TRC - Head, Air Pollution Control Section Environmental Control Branch Environmental Protection Service Environment Canada
R.R. Wallace	- Chairman and Projects Leader Aquatic Fauna TRC

B. Others:

D.A. Birdsall	- Director of Western Region Environmental Research Associates LGL Ltd.
R. Charlton	- Associate Professor Meteorology Division Department of Geography University of Alberta
J. Davidson	- Assistant Mayor Town of Fort McMurray
D.J. Dewar	- Western Regional Administrator Air Transport Canada
R. Gorby	- Staff Process Engineer Mining and Extracting Section Tar Sands Department Shell Canada Resources Ltd.
B. Janz	- Meteorologist, Scientific Services Atmospheric Environment Service Environment Canada

R.F. Klemm	- Research Officer Chemistry Division Alberta Research Council
G. Legg	- Western Regional Director Atmospheric Environment Service Environment Canada
J. Maybank	- Head, Physics Division Saskatchewan Research Council
R. Mustapha	- Branch Head Technical Services Division Flow Forecasting Branch Alberta Environment
W.J. Richardson	- Vice-President, Research Environmental Research Associates LGL Ltd.
S. Shewchuk	- Atmospheric Physicist Saskatchewan Research Council
D. Stringer	- Engineer, Drilling Department Petrofina Ltd.

APPENDIX II

THE MEASUREMENT OF RAINFALL BY RADAR

INTRODUCTION

This section briefly outlines principles behind the measurement of rainfall by radar. A more detailed account can be found in Battan (1973).

RADAR DETECTION OF PRECIPITATION

A radar periodically (e.g. 300 times per second) transmits from an antenna a pulse of microwave radiation, the duration of the pulse being typically a few microseconds, the peak power transmitted usually several hundred kilowatts and the frequency in the gigahertz range. When this pulse of microwave energy intercepts precipitation, some of the energy is scattered back to the antenna where it is detected and processed; resulting data can be displayed on a cathode ray tube indicator or possibly stored on computer compatible magnetic tape. The time between transmission of the pulse and reception of the backscattered radiation determines the range of the precipitation from the radar, while the antenna position determines the azimuth and elevation of the precipitation with respect to the radar site. The magnitude of the received power is a measure of the precipitation intensity.

For spherical particles, small compared to the wavelength of the transmitted radiation (Rayleigh scattering), the average received power from a unit volume can be represented as

$$\overline{P}_r = \frac{C\,|K|^2}{r^2} \sum_{\substack{\text{unit}\\ \text{vol}}} D_i^6 \tag{1}$$

where C is a constant representing radar dependent parameters, $|K|^2$ is the dielectric constant, r is the range from the radar to the particles, and D_i is the particle diameter. Equation (1) can be written as

$$\overline{P}_r = \frac{C\,|K|^2}{r^2} Z \tag{2}$$

where Z is the reflectivity factor. For an assumed dielectric constant when the conditions for Rayleigh scattering are not fulfilled, Z can be replaced by Z_e, the equivalent radar reflectivity factor. Since Z is the sum over a unit volume of the sixth power of the particle diameters, it is usually expressed as millimeters to the sixth power per cubic meter ($mm^6 m^{-3}$).

RATE OF PRECIPITATION

The rate of precipitation (R) is defined as the flux of water volume reaching the ground per unit time. The precipitation intercepted by the radar beam can also be interpreted in terms of flux. A single drop contributes to the precipitation rate according to the relation

$$\Delta R_i \ \alpha \frac{\pi}{6} D_i^3 w_i \tag{3}$$

where w_i is the fall speed of a raindrop with diameter D_i. The precipitation rate from a unit volume is just

$$R = \sum_{\substack{\text{unit}\\ \text{vol}}} \Delta R_i = \frac{\pi}{6} \sum_{\substack{\text{unit}\\ \text{vol}}} D_i^3 w_i \tag{4}$$

Terminal fall speeds of water drops have been measured and found to be a function of the drop diameter (du Toit, 1967). Very small drops ($D < 80\ \mu$) fall according to Stoke's law with a terminal speed proportional to the square of their diameters. For drops with very large diameters ($D > 4.5$ mm) the terminal fall speed is nearly independent of diameter. Therefore, the contribution to the precipitation rate for very small and large drops is as follows:

$$\Delta R_i \ \alpha\ D_i^5 \ \text{ for } \ D_i < 80\ \mu \tag{5}$$

and

$$\Delta R_i \ \alpha\ D_i^3 \ \text{ for } \ D_i > 4.5 \text{ mm} \tag{6}$$

THE Z-R RELATIONSHIP

It has been shown that both the precipitation rate (R) and the reflectivity factor (Z) are related to the diameter of precipitation particles. It is therefore possible to relate the precipitation rate to measurements of the reflectivity factor. From equations (1) and (2) it is apparent that the contribution to the reflectivity factor from drops in any one diameter interval is

$$\Delta Z_i \;\alpha\; D_i^6 \tag{7}$$

For very large drops equation (6) shows that $\Delta R_i \;\alpha\; D_i^3$ so that $\Delta Z_i \;\alpha\; (\Delta R_i)^2$. Therefore, if all the drops in a unit volume are very large

$$Z = \Sigma\, \Delta Z_i \;\alpha\; \Sigma\, (\Delta R_i)^2 < (\Sigma\, \Delta R_i)^2 = R^2 \tag{8}$$

Similarly for a unit volume containing only very small drops, equations (5) and (7) show that

$$Z = \Sigma\, \Delta Z_i \;\alpha\; \Sigma\, (\Delta R_i)^{1.2} < (\Sigma\, \Delta R_i)^{1.2} = R^{1.2} \tag{9}$$

Consequently, the reflectivity can be related to the precipitation rate by an expression of the form

$$Z = AR^b \tag{10}$$

where, based on the arguments above, $1.2 < b < 2$. The actual values of A and b depend upon the distribution of the raindrops with size.

CALIBRATION OF THE RADAR

Marshall and Palmer (1948) measured the distribution of raindrops with size for stratiform rain and found an exponential relation between the drop diameter and the number of drops per unit volume. They found a Z-R relationship to be

$$Z = 200R^{1.6} \tag{11}$$

(note the exponent lies within the limits determined above). It is well known that the distribution of raindrops with size varies with time, geographical location and meteorological conditions, so that equation (11) cannot generally be used to determine precipitation rates from radar measurements. Therefore, it is necessary to determine the appropriate Z-R relation by measuring raindrop sizes or measuring R with a raingauge and comparing to values of radar measurements of Z. The latter method is most common but there are limitations that must be considered (see sec. 4). By combining equations (2) and (10) it is possible to relate the average received power to the precipitation rate

$$\overline{P}_r = \frac{CAR^b}{r^2} \tag{12}$$

where C now includes the dielectric constant as well as the radar parameters. Rearranging equation (12) gives

$$R = \left(\frac{r^2 \overline{P}_r}{CA}\right)^{1/b} \tag{13}$$

The calibration problem is to determine A and b by comparing raingauge measurements of R with radar measurements of Z. As an example, the parameters A or b can be determined by comparing rain accumulations at a particular gauge with $\Sigma \overline{P}_r^{\,1/b}$ over that gauge for intervals of 1 hr. The values of $\overline{P}_r$ used in the summation would be mean values of the average received power for some appropriate area (say 2 km^2) above the gauge. If there are several raingauges within the area of radar coverage then the calibration can be determined for appropriate areas around each gauge. Once the calibration is complete, other measurements of Z can be interpreted in terms of areal rainfall rates and amounts.

APPENDIX III

BIBLIOGRAPHY AND SOURCES

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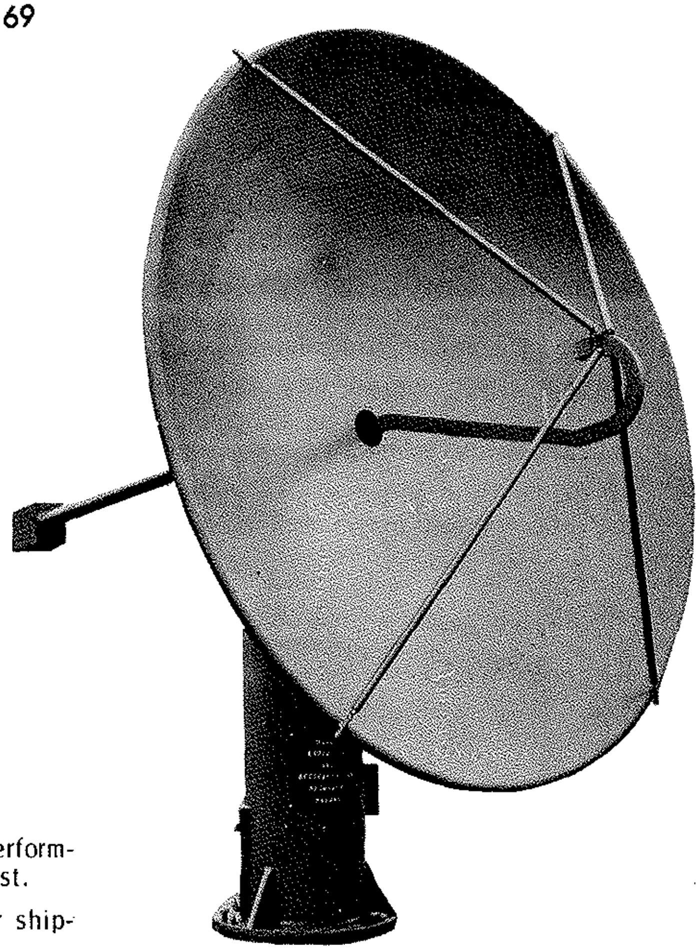
APPENDIX IV

(Following Pages)

A TYPICAL WEATHER RADAR SYSTEM

WSR-74 WEATHER RADARS



The advanced techniques and low cost production methods pioneered by Enterprise in their WR-100-5 series was the forerunner of WSR-74. By incorporating the improved features required by National Weather Service, Enterprise was successful in winning the contracts for WSR-74 radars in both S band (10cm) and C band (5cm).

WSR-74 is the "State-Of-The-Art" radar for installation throughout the United States. It is now available to the meteorological community of the world for precise observation of weather phenomenon associated with precipitation.

The specifications describe a radar with outstanding performance, maximum reliability, simple installation and low cost.

Variations of WSR-74 are available for fixed, mobile or shipboard installation.

ANTENNA & RADOME

To achieve high reliability and lowest antenna installation cost, the WSR-74 antenna is generally used with a molded fiberglass radome. In addition to protecting the antenna from the elements, the radome reduces wind and ice loading, allowing for a light weight pedestal structure. This reduces the loads on the drive system and the supporting tower, increasing reliability and lowering total cost. The drive system uses permanently lubricated gears which eliminate failure due to neglected pedestal lubrication. The light weight antenna system can be installed by simple, low cost rigging techniques.

AZM* DESIGN

Reliability begins with a design using, to the maximum extent possible, integrated circuits and solid state components. Long-life coaxial Magnetrons are used.

All components and circuit elements are easily accessible for inspection and test. Color coded test points and adjustments allow rapid alignment and fault location.

These design features justify the slogan, *AZM**.

**APPROACHING ZERO MAINTENANCE*

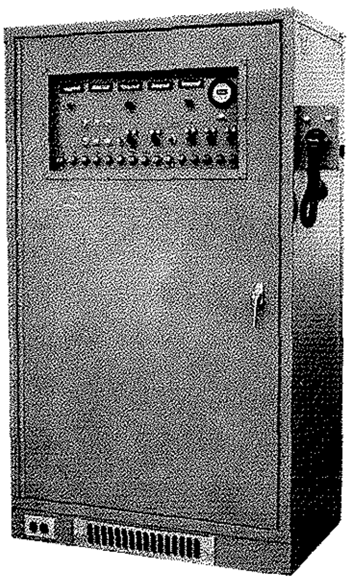
DIGITAL VIDEO INTEGRATOR & PROCESSOR (DVIP)

The DVIP processes the radar data to provide, either in digital or analog format, six preset rainfall rate ranges over a dynamic range of 63 DB received signal strength.

It allows maximum flexibility in the handling of radar data for operator observation as well as for storage and computer manipulation for operational and research uses.

The analog DVIP outputs drive the PPI and RHI displays so that three intensity levels are alternately presented, indicating six precipitation levels. Colored lamps for each level give a "quick look" capability. Selector switches allow specific levels to be selected for display.

The digital DVIP output may be stored on magnetic tape for future analysis or processed in real time for operational use in such missions as hail suppression or precipitation enhancement.



TRANSMITTER -RECEIVER

The long-life coaxial Magnetron and the completely enclosed, oil bath, modulator assures reliable transmitter operation. Operating frequency is easily set by a calibrated tuning knob. All high voltage parts are enclosed and interlocked. A bi-directional coupler is provided for power and VSWR measurement.

The receiver system is a super-hetrodyne, direct coupled system with logarithmic response. Linear outputs can be supplied. Automatic frequency controls (AFC) prevent receiver drift. Manually controlled attenuators are provided for calibration. A parametric amplifier is available for the WSR-74-S.

All transmitter-receiver component parts are located so that they may be replaced within 20 minutes.

CONTROL CONSOLE

Extensive human engineering studies have developed a console of maximum effectiveness and convenience.

Plan Position Indicator, Range Height Indicator, "A" indicator and DVIP indications are provided.

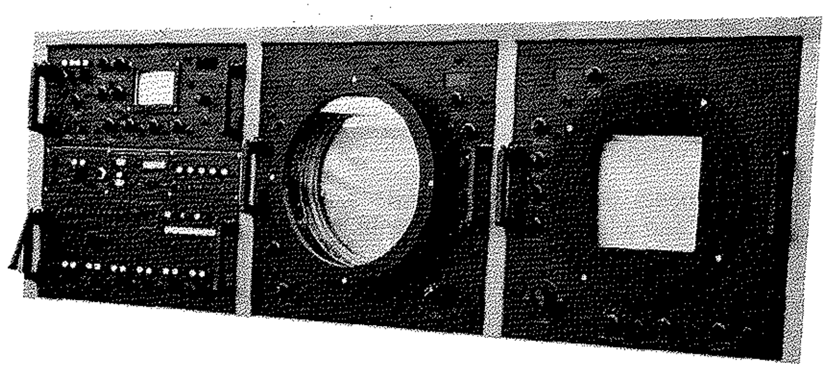
Digital readouts of range, elevation, azimuth and time make for easy data recording.

The PPI can be equipped with a reflection plotter or with illuminated map overlays.

The RHI is corrected for earth curvature. Elevation scan from -2° to +60° is controlled from the RHI unit.

An electronic range strobe is provided on all displays.

All units extend on ball bearings slides for ease of inspection and maintenance.



WSR-74 WEATHER RADARS

SYSTEM SPECIFICATIONS

WSR-74-S S BAND	PARAMETER	WSR-74-C C BAND
2700-2900 MHZ	OPERATING FREQUENCY	5600-5650 MH
500 KW	PEAK POWER	250 KW
1 OR 4 MICROSEC	PULSE WIDTH	3 MICROSEC
545 OR 162 PPS	REPETITION RATE	259 PPS
	RECEIVER NOISE FIGURE	
9 DB MAX	NORMAL	9 DB MAX
6 DB MAX	WITH PARAMP	
-104 DBM	MINIMUM DISCERNABLE SIGNAL	-104 DBM
12 FEET	ANTENNA DIAMETER	8 FEET
38 DB	ANTENNA GAIN	40 DB
2.0°	ANTENNA BEAMWIDTH	1.5°
18 FEET	RADOME DIAMETER	12 FEET
0.25 DB	RADOME INSERTION LOSS	0.5 DB
2500 W	POWER CONSUMPTION	2500 W
120 OR 230V 3 PHASE 50 OR 60HZ ± 2HZ	INPUT POWER	120 OR 230V 1 PHASE 50 OR 60HZ ± 2HZ
A, PPI, RHI	DISPLAYS	A, PPI, RHI
6	DVIP LEVELS	6
COAXIAL	MAGNETRON TYPE	COAXIAL

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1		AOSERP First Annual Report, 1975
2	AF 4.1.1	Walleye and Goldeye Fisheries Investigations in the Peace-Athabasca Delta--1975
3	HE 1.1.1	Structure of a Traditional Baseline Data System
4	VE 2.2	Preliminary Vegetation Survey of the AOSERP Study Area
5	HY 3.1	Evaluation of Wastewaters from an Oil Sands Extraction Plant
6		Housing for the North--Stackwall System Construction Report
7	AF 3.1.1	Synopsis of the Physical and Biological Limnology and Fishery Programs within the Alberta Oil Sands Area
8	AF 1.2.1	Impact of Saline Waters upon Freshwater Biota (A Literature Review and Bibliography)
9	ME 3.3	Preliminary Investigation into the Magnitude of Fog Occurrence and Associated Problems in the Oil Sands Area
10	HE 2.1	Development of a Research Design Related to Archaeological Studies in the Athabasca Oil Sands Area (at print)
11	AF 2.2.1	Life Cycles of Some Common Aquatic Insects of the Athabasca River
12	ME 1.7	Very High Resolution Meteorological Satellite Study of Oil Sands Weather, A Feasibility Study
13	ME 2.3.1	Plume Dispersion Measurements from an Oil Sands Extraction Plant
14	HE 2.4	Athabasca Oil Sands Historical Research Project (3 volumes)(at print)
15	ME 3.4	Climatology of Low Level Air Trajectories in the Alberta Oil Sands Area
16	ME 1.6	The Feasibility of a Weather Radar near Fort McMurray, Alberta

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For information regarding any of these publications
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