USE OF RADAR IN METEOROLOGY

by

G.A. Clift

(CIMO Rapporteur on Meteorological Radars

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FOREWORD

At the seventh and eighth sessions of the WMO Commission for Instruments and Methods of Observation (CIMO) (Hamburg, 1977, and Mexico City, 1981) it was recognized that rapid advances were being made in weather radar technology. Whilst its use for storm detection and tracking was in no way diminished, increasing emphasis was being placed on measurement of precipitation for the benefit of hydrologists as well as meteorologists. The advent of small computers with rapid data-processing facilities was being followed by work to minimize the errors inherent in radar measurements.

CIMO was aware that Technical Note No. 78 (Use of ground-based radar in meteorology), published in 1966 and dealing at length with radar theory, was out of date in respect of radar applications. Technical Note No. 100 (Use of weather radar for aviation), published in 1970, whilst still relevant in many respects, was also lacking in information on the latest techniques.

It was agreed that a new Technical Note should be written and the CIMO Rapporteur on Meteorological Radars from 1973 to 1981, Mr. G. A. Clift (U.K.), was invited to undertake the task.

Since there is an abundance of documentation available on the research aspects of weather radar, much of it of a complex nature, this Technical Note is intended primarily as a straightforward guide to basic theory and to operational systems and their usage.

It is recognized that, due to the speed of new developments, an addendum will be needed within a few years.

I should like to take this opportunity of expressing the gratitude of WMO to Mr. G. A. Clift for the time and the effort he has devoted to preparing the text of this valuable publication.

G. O. P. OBASI
Secretary-General
SUMMARY

This Technical Note is intended to replace Technical Note No. 78, The use of ground-based radar in meteorology, which was published in 1966 and is now outdated. Some short sections of the former text have been used in this new version and new information is also provided in support of Technical Note No. 110, Use of weather radar for aviation, which was published in 1970.

For a full understanding of the potentialities of ground-based radar in meteorology it is necessary to have a clear grasp of what information the radar will supply and what its limitations are.

The vast majority of weather radars in use are still those providing observations for meteorological forecasting for aviation and for storm warnings. Many have been installed for 15 years or more; their data-processing facilities are either non-existent or very limited. Such radars are discussed in this Technical Note though they are no longer considered as the main thrust of weather radar activities.

The interest in the last decade has turned to the use of radar as a precipitation-measuring device. The term radar raingauge is sometimes used. It has become evident that conventional weather radar can form the basis of an extremely valuable meteorological and hydrological tool, despite shortcomings. In the early 1970s too much was expected from it; some early, limited experimental projects, of inestimable value in themselves, led to the belief that a radar system could measure precipitation with an accuracy unrivalled by any other means, which would permit fine decisions to be made in respect of flood warnings and water management. The findings often had limited applicability. Indeed, when the transfer from experimental to operational status took place, it became apparent that, whilst there is no better way to measure areal (as opposed to point) rainfall, the shortcomings had been underestimated.

However, it is now apparent that radar data with more limited accuracy can be invaluable and they can provide a vital input to flood warnings and to water management. Moreover, they permit subjective and objective forecasts of precipitation to be made, in terms both of quantity and of times of onset and cessation, and having a validity over the next few hours. For convective rain, a single radar may be adequate for such purposes, though for frontal rain a network of radars is highly desirable. These forecasts, which are proving to be more accurate than those derived from any other data, may be improved further if they are combined with data from satellites, particularly geostationary ones, and from conventional observations.

Despite the foregoing reservations about the accuracy of radar data, it is probable that, in the course of the next decade or two, the wide use of radar systems for precipitation measurement may lead to a steady improvement which will, in turn, lead to a further marked increase in the value of the data. In working towards this improvement in accuracy, a better knowledge of the reasons for inaccuracy can be a major step. This necessitates considerable research, particularly aimed at a more complete understanding of the nature of the atmosphere itself – for example, an understanding of low-level growth of precipitation or of evaporation.

This Technical Note is concerned primarily with the operational aspects of radar, but it includes references to research and chapters on the use of non-conventional systems. It covers basic theory in a limited way, referring the reader to more comprehensive textbooks; it discusses the types of radar available and the uses to which they can be put. It deals only briefly with data processing and transmission, as these are techniques not specific to radar data which are better discussed in detail elsewhere. The problems of errors and accuracies are considered and chapters are included on methods of operation and on the practical aspects of siting and maintenance. Aspects of costs and of cost-benefit considerations are mentioned, though the
latter are difficult to quantify and are often specific to particular locations. A chapter is devoted to Doppler radar, which is already close to attaining operational status.

Each chapter has been written so that it basically stands alone. Bibliographies are included at the end of each to cover references in the text, but the papers listed are by no means exhaustive. The literature now available is very considerable, though the majority is research-oriented. Of the textbooks, the most significant is by Battan (1973). Any reader who wishes to study the subject in depth is advised to refer to this book. For those concerned with radar engineering, an excellent textbook is that by Skolnik (1980). For a complete manual on radar meteorology, Sauvageot (1982) is also suggested.

About once every two years the American Meteorological Society holds Weather Radar Conferences at which many countries are represented. The papers are issued as preprints. Although a high proportion are concerned with research, the operational content of the papers has been increasing.

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La présente Note technique doit remplacer la Note technique N° 78 intitulée “The use of ground-based radar in meteorology” (Utilisation du radar au sol en météorologie), qui a été publiée en 1966 et est maintenant périmée. De courtes sections de l’ancien texte ont été utilisées dans cette nouvelle version, qui contient aussi de nouvelles informations complétant la Note technique N° 110 intitulée “Use of weather radar for aviation” (Utilisation du radar météorologique pour la navigation aérienne), qui a été publiée en 1970.

Pour pleinement comprendre quelles sont les potentialités du radar au sol pour la météorologie, il est nécessaire de savoir clairement quelles sont les informations qu’il fournit et ses limites.

La majeure partie des radars météorologiques utilisés actuellement sont encore ceux qui fournissent des observations destinées à la prévision météorologique pour la navigation aérienne et pour les avis de tempête. Un grand nombre ont été installés depuis quinze ans ou plus; ou bien ils ne sont pas équipés du tout pour le traitement des données ou bien cet équipement est très limité. Les radars de ce type sont décrits dans la présente Note technique bien qu’ils ne soient plus considérés comme l’instrument prépondérant pour les activités associées au radar météorologique.

Au cours de la dernière décennie, c’est l’utilisation du radar comme dispositif de mesure des précipitations qui a retenu l’intérêt. On utilise parfois le terme de pluviomètre-radar. Sur s’est rendu compte que le radar météorologique classique, malgré ses insuffisances, peut constituer la base d’un équipement météorologique et hydrologique extrêmement utile. Au début de la décennie 1970, on en attendait trop; quelques premiers projets expérimentaux limités, d’une inestimable valeur intrinsèque, ont conduit à penser qu’un système de radar pourrait servir à mesurer les précipitations avec une précision inégalée par tout autre moyen, ce qui permettrait de prendre des décisions judicieuses en matière d’avis de crues et de gestion des ressources en eau. Les résultats obtenus n’ont souvent pu conduire qu’à des applications limitées. En fait, en passant du stade expérimental à l’exploitation, on s’est rendu compte que, s’il s’agit bien là du meilleur moyen pour mesurer les précipitations dans une zone donnée (opposées aux précipitations ponctuelles), les insuffisances avaient été sous-estimées.

Il apparaît toutefois maintenant que les données de radar ayant une précision plus limitée peuvent revêtir une très grande valeur et présenter un intérêt primordial pour établir les avis de crues et gérer les ressources en eau. En outre, elles permettent de faire des prévisions subjectives et objectives des précipitations, tant en ce qui concerne la quantité que le moment où ces précipitations vont débuter puis cesser, la validité de ces prévisions s’étendant sur les quelques heures qui suivent. Pour les précipitations de convection, un seul radar peut suffire à cette fin, mais, pour les précipitations frontales, il est très souhaitable de disposer d’un réseau de radars. Ces prévisions, qui se révèlent plus précises que celles obtenues à partir d’autres données, peuvent être encore améliorées si on les combine à des données provenant de satellites – géostationnaires notamment – et à des données d’observation classiques.

Malgré les réserves qui précèdent concernant la précision des données de radar, il est probable que, au cours de la prochaine décennie ou des deux prochaines, une large utilisation des systèmes de radars pour mesurer les précipitations pourrait permettre de les améliorer régulièrement, ce qui, en fin de compte, conférerait une plus grande valeur encore à ces données. Pour tendre vers cette plus grande précision, il se peut que la démarche déterminante consiste à mieux connaître les raisons de l’imprécision. Ceci nécessite des recherches considérables visant notamment à comprendre plus complètement la nature de l’atmosphère elle-même et, par exemple, la faible augmentation des précipitations ou de l’évaporation.
La présente Note technique concerne essentiellement les aspects opérationnels du radar, mais elle se réfère aussi à des recherches et à des chapitres concernant l'utilisation des systèmes non classiques. La théorie fondamentale y est abordée de façon limitée, le lecteur étant prié de se reporter à des ouvrages plus complets; les types de radars disponibles et les possibilités d'utilisation qu'ils offrent sont également examinés. Le traitement et la transmission des données n'y sont que brièvement exposés, car il s'agit là de techniques qui ne concernent pas particulièrement les données de radar et sont étudiées à meilleur escient, de façon détaillée, dans d'autres textes. Les problèmes relatifs aux erreurs et à la précision sont examinés et certains chapitres sont consacrés aux méthodes d'exploitation et aux aspects pratiques concernant le choix de l'emplacement et la maintenance. Il y est question aussi du coût et de la rentabilité, bien que celle-ci soit difficile à évaluer et dépende souvent de certains sites. Un chapitre est consacré au radar Doppler qui en est déjà bientôt au stade de la mise en exploitation.

Chaque chapitre a été rédigé de telle sorte qu'il constitue une entité en soi et est complété, in fine, d'une bibliographie se rapportant aux références qui figurent dans le texte, mais les communications qui y sont citées ne la rendent en aucune façon exhaustive. La documentation maintenant disponible est très vaste, mais elle est en majeure partie destinée à la recherche. L'ouvrage le plus important est celui de Battan (1973)\(^1\). Il est conseillé à tout lecteur qui veut étudier la question de façon approfondie de se reporter à cet ouvrage. Pour ceux qui s'intéressent à l'ingénierie des radars, un excellent ouvrage est celui de Skolnik (1980)\(^2\). Il est également suggéré, si l'on cherche un manuel complet sur l'observation météorologique par radar, de consulter celui de Sauvageot (1982)\(^3\).

Environ tous les deux ans, l'American Meteorological Society organise des conférences sur les radars météorologiques auxquelles de nombreux pays sont représentés. Les communications paraissent sous forme de publications préliminaires. Une forte proportion concerne la recherche, mais le nombre de celles qui sont consacrées à l'exploitation augmente.

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РЕЗЮМЕ

Эта Техническая записка предназначена заменить Техническую записку № 78 «Использование наземного радиолокатора в метеорологии», которая была опубликована в 1966 г. и к настоящему времени устарела. Некоторые небольшие разделы предыдущего текста использованы в этом новом варианте, и, кроме того, дается новая информация в поддержку Технической записи № 110 «Использование метеорологического радиолокатора для авиации», которая была опубликована в 1970 г.

Для полного понимания потенциальных возможностей наземного радиолокатора в метеорологии необходимо иметь ясное представление о том, какую информацию будет давать радиолокатор и каковы его недостатки.

Большую часть используемых метеорологических радиолокаторов все еще составляют те, которые обеспечивают наблюдения, необходимые для подготовки метеорологических прогнозов для авиации и штормовых предупреждений. Многие из них работают в течение 15 лет и более; они либо вообще не имеют устройств для обработки данных, либо имеют лишь ограниченные. Такие радиолокаторы рассматриваются в этой Технической записи, хотя они больше не являются главной опорой в работе, связанной с использованием метеорологических радиолокаторов.

В последние десятилетие основной интерес проявляется к использованию радиолокатора как средства измерения осадков. Иногда используются термин радиолокационный дождемер. Стало очевидным, что обычный метеорологический радиолокатор, несмотря на его несовершенство, может служить основой для измерения важного метеорологических и гидрологических наблюдений. В начале 1970 гг. на радиолокаторах ждаль многие многочисленные экспериментальные проекты, имеющие неоспоримое содержание, заставляют поверить в то, что радиолокационная система может измерять осадки с точностью, недоступной каким-либо другим средствам, и это позволяет принять правильные решения в отношении предупреждений о паводках и системы мероприятий по межсезонному использованию воды. Результаты часто имели ограниченную применимость. Фактически при переходе от статуса экспериментального к статусу оперативного стало очевидным, что хотя и нет более совершенного пути измерения осадков, осредненных по площади (в противоположность осадкам на наблюдениях на одной станции), недостатки были недооценины.

Однако в настоящее время очевидно, что радиолокационные данные с более ограниченной точностью могут иметь неоспоримое значение и вносить ценный вклад в системы предупреждений о паводках и мероприятиях по рациональному использованию воды. Более того, они позволяют составлять субъективные и объективные прогнозы осадков как в отношении количества, так и сроков их начала и прекращения и при этом иметь срок действия в течение последующих нескольких часов. Для случаев непрерывных осадков таким образом может создаваться единичный радиолокатор, в то время как для фронтальных осадков крайне желательно иметь весь радиолокационных установок. Эти прогнозы, которые оказались более точными по сравнению с составленными на основании каких-либо других данных, могут быть еще более улучшены, если их дополнить данными со спутников, в особенности геостационарных, и данными обычных наблюдений.

Несмотря на упомянутые ограничения точности радиолокационных данных, весьма вероятно, что в течение следующих одного-двух десятилетий широкое использование радиолокационных систем для измерения осадков может привести к надежному улучшению, что, в свою очередь, приведет к дальнейшему заметному повышению ценности данных. В деятельности, направленной на повышение точности, основным шагом может быть более глубокое знание причин неточности. Это требует
значительной исследовательской работы, в основном направленной на более полное понимание природы самой атмосферы, например понимание процесса роста или испарения осадков в нижних слоях атмосферы.

В этой Технической записке рассматриваются в основном оперативные аспекты радиолокатора, но в ней делаются ссылки на исследования и главы, посвященные использованию нетрадиционных систем. В ней содержатся некоторые теоретические основы, отсылая читателя к более подробным учебникам; в ней рассматриваются типы имеющихся радиолокаторов и возможные пути их использования. В ней лишь кратко рассматриваются вопросы обработки и передачи данных, поскольку эти процессы не являются специфическими для радиолокационных данных и более подробно обсуждаются в других публикациях. Рассматриваются проблемы ошибок и точности, и имеются главы, посвященные методам работы и практическим аспектам их размещения и содержания. Упоминаются также аспекты стоимости и отношение затраты-выгода, хотя последние трудно определить количественно и они часто являются специфическими для конкретных местоположений. Одна глава посвящена дляоперовскому радиолокатору, который в настоящее время уже близок к оперативному статусу.

Каждая глава написана таким образом, чтобы она могла быть самостоятельной. В конце каждой главы приводится библиография, охватывающая ссылки, содержащиеся в тексте, однако перечисленные работы безусловно не являются исчерпывающими. В настоящее время имеется большой объем литературы, хотя большая часть ее имеет исследовательскую направленность. Что касается учебников, наиболее важным является учебник Баттана (1973 г.)\(^1\). Читателям, которые хотят изучить этот вопрос более подробно, рекомендуется обратиться к этой книге. Для тех, кто связан с радиолокационной техникой, прекрасным учебником является учебник Шкользника (1980 г.)\(^2\). В качестве исчерпывающего руководства по радиолокационной метеорологии предлагается также учебник Саважо (1982 г.)\(^3\).

Приблизительно раз в два года Американское метеорологическое общество проводит конференции по метеорологическим радиолокаторам, в которых принимают участие многие страны. Материалы издаются в виде рефератов. Хотя большая часть их посвящена исследовательской деятельности, процент оперативных вопросов в содержании статей увеличивается.

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La presente Nota Técnica tiene por objeto sustituir a la Nota Técnica N° 78 sobre “La utilización en meteorología de los radares terrestres”, que fue publicada en 1966 y que ahora ha quedado anticuada. Secciones del antiguo texto han sido utilizadas en esta nueva versión, a la par que se provee nueva información en respaldo de la Nota Técnica N° 110 “Utilización de radares meteorológicos para la aviación”, que fue publicada en 1970.

Para comprender plenamente el potencial del radar terrestre para la meteorología resulta necesario contar con una idea clara acerca de la información que el radar puede proveer y acerca de sus límites.

La amplia mayoría de radares meteorológicos en funcionamiento son aún aquellos que proporcionan observaciones para las previsiones meteorológicas para la aviación y los avisos de tormenta. Muchos fueron instalados hace 15 años o más; carecen de procesamiento de datos o solamente tienen unas instalaciones muy limitadas. De tales radares se habla en la presente Nota Técnica aunque ya no son considerados como de principal importancia en las actividades de los radares meteorológicos.

El interés se ha volcado en este último decenio sobre la utilización del radar en tanto que instrumento para medir las precipitaciones. A veces se utiliza el término radar pluviómetro. Resulta evidente que el radar meteorológico tradicional puede formar la base de un instrumento hidrológico valioso, a pesar de sus deficiencias. A principios de los años 70 se esperaba mucho del mismo; algunos primeros proyectos experimentales limitados, de inestimable valor en sí, condujeron a la creencia de que un sistema de radar podría medir las precipitaciones con una exactitud imposible de alcanzar por cualquier otro medio, lo que permitiría tomar excelentes decisiones en relación con la alerta de crecidas y la explotación de recursos hidráulicos. Los resultados tenían a menudo una aplicación limitada. Efectivamente, cuando tuvo lugar la transferencia del estatuto experimental al operacional, resultó manifiesto que, aunque no existe mejor manera de medir la precipitación zonal (por oposición en un punto), las deficiencias habían sido subestimadas.

No obstante, resulta ahora patente que los datos por radar con una exactitud más limitada pueden ser de inestimable valor y pueden proveer datos de entrada importantes para las alertas de crecidas y la explotación de recursos hidráulicos. Además, permiten realizar unas predicciones subjetivas y objetivas de la precipitación, tanto en términos cualitativos cuanto en los de las veces en que empieza y se para la misma, siendo además válidas durante las siguientes próximas horas. Para una lluvia convectiva puede ser adecuado un simple radar, aunque para una lluvia de frente sería sumamente deseable contar con una red de radares. Estas predicciones, que están demostrando ser más exactas que las proporcionadas por cualquier otro dato, pueden mejorarse aún más si se combinan con datos procedentes de satélites, particularmente de los geoestacionarios, y con las observaciones tradicionales.

A pesar de las precedentes reservas acerca de la exactitud de los datos por radar, resulta probable que, en el transcurso de los próximos 10 ó 20 años, la amplia utilización de sistemas de radares para medir las precipitaciones conduzca a un mejoramiento continuo que a su vez conducirá a un incremento más grande todavía del valor de los datos. En la búsqueda hacia el mejoramiento en la precisión, el mejor conocimiento de las razones de la inexactitud puede ser un paso importante. Esto necesita una investigación considerable, tendente especialmente a comprender de manera más completa, por ejemplo, la naturaleza de la propia atmósfera, así como la comprensión del bajo nivel de crecimiento de las precipitaciones o de la evaporación.
Esta Nota Técnica se preocupa principalmente de los aspectos operativos del radar, pero incluye referencias a la investigación y algunos capítulos sobre la utilización de los sistemas no tradicionales. Cubre la teoría básica de manera limitada y remite el lector a unos libros de texto más completos; señala los tipos de radares disponibles y la utilización que se puede hacer de los mismos. Trata sólo brevemente del proceso de transmisión de datos, ya que éstas son técnicas, no específicas a los datos por radar, que se explican mejor y de manera más detallada en otros lugares. Se examinan también los problemas de errores y exactitud, a la par que se incluyen unos capítulos sobre los métodos de funcionamiento y los aspectos prácticos del emplazamiento y de la conservación. Se mencionan asimismo los aspectos de los costos y de los costos-beneficios, aunque estos últimos son difíciles de cuantificar y a menudo son específicos a sitios particulares. Hay un capítulo que se dedica al radar Doppler, que dentro de poco va a alcanzar el estatuto de operativo.

Cada capítulo ha sido escrito de manera que fundamentalmente quede completo de por sí. Al final de cada uno se incluyen bibliografías que cubren las referencias que se hacen en el texto, aunque los documentos que se indican no son de manera alguna exhaustivos. Ahora existe un número muy considerable de obras, aunque la mayoría están orientadas hacia la investigación. De los libros de texto, el más significativo es el del Sr. Battan (1973)1. Se aconseja este libro a todo lector que desee estudiar a fondo este tema. Para aquellos interesados en la técnica del radar existe un excelente libro de texto escrito por el Sr. Skolnik (1980)2. Para contar con un manual completo de radares meteorológicos sugerimos también el libro del Sr. Sauvageot (1982)3.

Aproximadamente una vez cada dos años la American Meteorological Society celebra conferencias sobre radares meteorológicos, a la que asisten muchos países. Los documentos se publican como pretiradas. Aunque una elevada proporción de los documentos se ocupa de la investigación, cada vez aumenta más su contenido operativo.

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CHAPTER 1

INTRODUCTION

1.1 General remarks

Radar was first developed just prior to the World War of 1939–1945 as a means of detecting and tracking aircraft and ships. The war led to much rapid development in both ground-based and airborne radar, which became a vital factor in military activities. Since 1945 radar has additionally become an essential part of civil aviation traffic control. Its enormous value is so well known that it needs no further comment here.

The longer wavelengths originally used were mostly unaffected by meteorological conditions, but as these were shortened to 10 cm or less, it became apparent that reflections (or echoes) were occasionally obtained from meteorological targets with a consequent possible reduction in the maximum radar range. Sometimes transmission paths were also affected. In more recent times, radars for non-meteorological purposes have incorporated circuits to remove the worst effects of meteorological targets.

With the cessation of hostilities in 1945, meteorologists were able to acquire surplus radars, mostly using 10 cm or 3 cm wavelengths, to pursue their studies. They were aware of the potential of a new observational tool which could provide data not readily obtainable by any other means. Research workers in a number of countries carried out programmes of work aimed at understanding the phenomena of reflections from meteorological targets, converting the radar data into meteorological information and considering how radar systems could be used for routine operational purposes. (For a review of this work, see Kerr, 1951.) In the 1950s and 1960s, a number of countries began to use operationally fairly conventional radars, little different from aviation and marine radars, for the detection and tracking of thunderstorms and cyclones. (For examples, see Chapter 11 of Battan, 1973.) These were mostly sited at airfields or at storm-sensitive points. Warnings were issued to aircraft and, in some cases, to the local authorities and to the population. The information augmented other meteorological observations in the production of forecasts. Somewhat crude methods were devised for determining the intensity of the precipitation detected. Thus, the radars began to provide meteorological data, as opposed to information.

Meanwhile, the research workers were seeking to determine whether genuinely quantitative precipitation measurements could be made with sufficient accuracy to be of use to both meteorologists and hydrologists. This involved converting analogue values into digital values. Although this was possible with the earlier computers, the amount of data was so large, so much human effort was needed to put the data into digital form for assimilation, and the processing was so slow that it was possible to deal only with isolated events in an historical way. (See Austin and Richardson, 1952; Farnsworth and Mueller, 1953; Atlas et al., 1963.) Moreover, neither raw nor processed data could be transmitted to users, as suitable digital telecommunication techniques were not yet available.

Progress in the use of radar accelerated in the late 1960s with the advent of the small, fast computer. Real-time radar-derived precipitation data became possible (Wilk et al., 1967; Wilk and Kessler, 1970; Sirmans et al., 1970; and Chapter 7 of Battan, 1973). However, much work was still needed to determine the accuracy of the data and the means of improving it. This work is still continuing (see Chapter 5), but a number of countries have already proved to their own satisfaction the value of processed radar-derived data for flood-warning purposes in particular and for water management in general (see Chapter 7). Means of merging data from several radars into a composited format and of combining radar data with those from satellites and from more conventional meteorological instruments are being pursued. Techniques are being developed for short-range forecasting, up to several hours ahead, of precipitation amounts and of times of onset and cessation. Data either from a single radar or composited from several radars can be displayed on television-type screens, presented as hard copy or fed into computers for further processing in meteorological or
hydrological models. Data can also be printed out in the form of precipitation totals over catchment areas (see Chapter 4). Because it is digital, the information can be transmitted easily over large distances either for display as such or for further use. Whilst a great deal of work remains to be done, much of it concerning understanding the atmosphere, the promise of radar as a valuable operational tool over many decades to come is considerable.

1.2 Current scale of radar installations

It was estimated that in 1981 (Clift, 1981) there were between 600 and 650 weather radars in use by Meteorological Services throughout the world. Of these, there were about equal numbers of C-band (5 cm) and X-band (3 cm) – probably just over 200 of each. Of S-band (10 cm) there were somewhat fewer than 200, the remainder being made up of about 60 dual-wavelength radars, some of which were X-band/S-band and some K-band (0.86 cm)/X-band. These dual-wavelength radars are mostly used in the USSR or neighbouring countries. Whilst about 200 radar systems appeared to have some form of processing, either analogue or digital, beyond conventional PPI/RHI displays, less than 60 systems included automatic processing and the output of data, although this number is increasing quite rapidly.

Bibliography


CHAPTER 2

BASIC THEORY

2.1 General remarks

Unfamiliar terminology often handicaps the meteorologist in his understanding of the theory of the detection and measurement of precipitation by radar. While it is beyond the scope of this Technical Note to delve deeply into the principles of radar, a brief description will be helpful. (See Battan, 1973, and Skolnik, 1980, for detailed explanations.) Factors of importance in operational usage will be given greater emphasis in subsequent chapters.

In principle, radar is an echo-sounding device in which the range of a target is measured by the time taken for a small pulse of transmitted electromagnetic energy to travel to the target and back again after reflection. The azimuth (or bearing) and the elevation on which the target lies are determined by the direction in which the pulse of energy was transmitted in order to hit it. In reality, a train of pulses is transmitted, improving the response which is a measure of the mean power received. There are a number of factors limiting the range and other aspects of performance. These are discussed later. At this point it is sufficient to say that, in practice, meteorological targets are seldom visible to a radar at ranges beyond 300 km in temperate zones or above 400 km in tropical zones, whilst the intensity of precipitation falling upon the ground cannot be reasonably and regularly assessed with any pretence of accuracy at ranges much above 100 km in temperate countries, perhaps 150 km in tropical countries. The pulses referred to above are necessary in order to obtain a discrete, detectable echo with range discrimination. The pulse-length is a measure of the duration of this pulse and is usually expressed in microseconds, though it can be translated into distance by multiplying it by the speed of propagation of radio waves, $300 \times 10^8$ metres per second. The wavelength of the transmission (inversely proportional to the radio frequency) is normally in the range 3 to 10 (more specifically 3, 5.6 or 10 cm) or, exceptionally, 1.25 or 0.8 cm.

2.2 Antenna; definition of beamwidth; side-lobes

To launch the pulses into the atmosphere an antenna is required. In the case of a weather radar this usually consists of an antenna feed positioned at the focus, directing the energy at a parabolic reflector. In modern radars the shape of the rim is circular, but in many older sets it is wider in the horizontal than in the vertical, or vice versa. In all cases the purpose is to concentrate the radiated energy into a narrow beam. If the feed were a point source and the reflector circular, then the beam would be parallel-sided (or pencil-shaped) but this is neither practicable nor desirable, since only a very small volume of the atmosphere would be "illuminated". A slightly diverging beam is the desired result in practice. This has a maximum intensity along the axis perpendicular to the face of the reflector, and as the angle with this axis increases, the intensity falls off. The beamwidth, a measurement of some importance, is arbitrarily defined as the angle between those directions (either side of centre) in which the intensity of the beam is at least one-half of the maximum. The rate of decrease of intensity beyond the half-power points is very great, and for practical purposes the total energy is regarded as being transmitted between these half-power points or within the beamwidth as defined. However, the practical limitations of antenna design are such that, in addition to the main beam, there are small subsidiary beams known as side-lobes, which appear in decreasing strength, the greater the angle from the central axis (see Figures 1(a) and (b)). Although these account for, typically, only 5% of the total radiated power, they do produce unwanted echoes from close-range targets such as large buildings or perhaps from the ground, even when the antenna is elevated in order to avoid these permanent echoes falling within the main beam. Such side-lobe returns may prevent the measurement of precipitation within a few kilometres of the radar. If there are local heavy storms, side-lobe returns may be received from these and false impressions gained as to the distribution of the precipitation.
The same parabolic reflector and antenna feed as are used for transmitting are normally used for receiving the echo pulses. These pulses are channelled electronically into the receiver where, as their intensity may be as little as $10^{-17}$ times that of the outgoing pulses, they require considerable amplification before being fed either directly to a cathode-ray tube display or into a processing system (prior to display and/or print-out). (See Figure 3 in Chapter 3 for a simplified block diagram of a typical weather radar.)

2.3 Equivalent echoing area

Although the word "reflections" is commonly used for return radar signals, electromagnetic waves, upon striking any object, are scattered in all directions. Thus, only a small portion of the power is directed back to the antenna. The amount depends on the size of the object and the material of which it consists. In
radar meteorology the object is a small particle of water or of ice, either spheroid or in snowflake form. To distinguish between the scattering capabilities of different particles it is convenient to define an equivalent echoing area $S$, which is the projected area of a perfectly reflecting sphere which would scatter towards the radar the same power as does the particle. The intensity of the back-scattered radiation at distance $r$ from the scattering particle is then proportional to $S/4\pi r^2$ and the back-scattering cross-section $\sigma$ is defined as $S/4\pi$ and represents the intensity at unit distance of the radiation back-scattered from the particle in the direction of the radar.

Although all particles in the beam scatter some energy back to the radar, the amount scattered back by a single particle is so minute as to be quite undetectable by the radar receiver. When the particles are large, however (e.g. the size of a raindrop) and a number of them lie within the beam and at the same range (strictly between ranges differing by not more than half a pulse-length - see section 2.7), the combined effect may be sufficient to give a detectable signal.

The requirements for the radar and the assemblage, or ensemble, of particles that are necessary in order that a detectable signal may be received and displayed (with or without digital processing) will be discussed in the following paragraphs.

2.4 The fundamental radar equation

A radar equation for the scattering of electromagnetic pulses by an extended target, such as an assemblage of airborne liquid particles, is commonly used. It is:

$$P_t = \frac{P_r h A_e}{8\pi r^2} F K \frac{\Sigma \sigma}{\Sigma \sigma}$$

where $P_t$ is the transmitted pulse power, $P_r$ is the average power in each echo pulse arriving at the radar receiver, $h$ is the pulse length, $A_e$ is the effective antenna aperture, $r$ is the range, $\sigma$ is the back-scattering cross-section of a single particle, the summation being over all the scattering particles in unit volume, $F$ is the fraction of the radar beam intercepted by the target and $K$ is an attenuation factor. The various factors appearing in this equation and related factors not occurring explicitly will be examined below.

The equation holds good provided that the wavelengths used are greater than 3 cm and the particles are no larger than 5 mm. It assumes what is known as the Rayleigh approximation for the back-scattering cross-section. If the wavelength is less than 3 cm, then what is known as the Mie theory applies and the equation takes a different form. Since the radars used for precipitation measurements are mostly of 3, 5.6 or 10 cm wavelength, and raindrops larger than 5 mm are rare, it will be assumed that the Rayleigh approximation is used unless otherwise stated. (For detailed reading on the subject, see Ryde, 1946; Gunn and East, 1954; Mic, 1908; and Chapter 4 of Battan, 1973.)

Generally, snowflakes, regardless of size, and small hailstones can be regarded as being within the Rayleigh approximation whereas larger hailstones cannot be.

2.5 The transmitted power ($P_t$) and pulse repetition frequency

In radar the power transmitted is in the form of bursts or pulses of high intensity but of short duration, the time interval between pulses being the period during which the equipment is in a state to receive the echo pulses returned from targets within the radar beam. Whilst the pulse is being transmitted, the receiver is rendered inoperative. Thus for a small, finite time no signals can be received. This corresponds to a range of something less than one km (dependent on pulse length - see paragraph 2.7) and is of no practical importance in conventional weather radars. The time interval between pulses must be such that signals from wanted targets within the radar beam have time to be detected at the receiver before the next pulse is transmitted. The frequency with which pulses are transmitted - the pulse repetition frequency (p.r.f.) - is therefore one of the factors governing the maximum range of detectable targets. The p.r.f. for a weather radar is usually between 250 and 300 pulses per second (p.p.s.). If 300 p.p.s. is used, the corresponding maximum range is 500 km. Since meteorological targets at or above this range will be below the radar horizon and will be seen only if anomalous propagation is taking place (see section 5.6), this maximum is ample.
CHAPTER 2

In equation (1), $P_t$ is the power transmitted in each pulse over the duration of the pulse and in most radars used for meteorological purposes it will be between 30 kW and 800 kW, the lower powers being at 3 cm wavelengths and the higher at 10 cm. The mean power radiated depends on pulse length and p.r.f. Thus, for a pulse duration of two microseconds, p.r.f. of 300 p.p.s. and peak power ($P_t$) of 600 kW, the mean power radiated is only 360 W. (Since it is the mean power which has to be considered, the radiation hazard to human beings is fairly small, even close to the radar.)

2.6 The received power ($P_r$) and receiver noise

There is a lower limit to the power level which can be detected by any radio or radar receiver. This is because every receiver generates random fluctuations within its own circuits. If the design is good, the level will be low but definite and measurable. This is effectively constant, but it is augmented by random signals from stray radiation which arrive at the antenna and are duly amplified. This combined noise forms a background against which the wanted signals must be detected and measured. Detectability decreases rapidly as the signal decreases to below the noise level but the cut-off is not sharp. For many practical purposes the noise level is taken as the minimum detectable signal (m.d.s.) level but other factors such as p.r.f., antenna rotation speed and signal characteristics also determine the absolute limit.

In modern receivers the m.d.s. is of the order of $10^{-14}$ W. This is sometimes expressed in terms of decibels below a milliwatt, typically $-106$ dBm. For a given radar in which $P_t$, $h$ and $A_e$ in equation (1) are constant, this minimum value of $P_r$ determines the minimum value of $\Sigma o$ which can be detected at a given range, $r$. (See footnote on page 11 for explanation of decibels.)

2.7 The pulse length ($h$)

It will be seen from equation (1) that the received power is directly proportional to the pulse length ($h$), so that as long a pulse length as is practicable appears desirable for meteorological work. Apart from the difficulty of maintaining a high power over a long period, however, the pulse length affects the discrimination in range. Targets separated by a distance of less than half a pulse length in range cannot be discriminated, since echoes received from the rear edge of the pulse as it passes targets at range $r$ will be received simultaneously with echoes from the leading edge of the pulse passing targets at range $r + \frac{h}{2}$. The decision on pulse length is therefore a compromise between obtaining the maximum received signal and the degree of resolution in range. Some radars have switchable pulse lengths, say, 0.5 microseconds for use at the lower ranges or when looking vertically, giving a resolution of 75 m, and three microseconds for use at longer ranges, giving a resolution of 450 m.

In practice, the trailing edge of the pulse is never vertical and straight; the range resolution is accordingly a little poorer. The most common pulse length is two microseconds.

2.8 Effective antenna aperture ($A_e$)

Equation (1) indicates that the signal received is directly proportional to $A_e$, so that, for meteorological purposes, the larger the antenna, the better. The limitations on size are mainly imposed by engineering considerations. A large reflector requires a larger pedestal and more powerful drive motors; such construction is inevitably much more expensive, though use of a radome (see section 3.6) reduces the mechanical complexity required.

The beamwidth of a circular parabolic reflector is approximately $1.2 \frac{\lambda}{d}$-radians where $\lambda$ is the wavelength and $d$ is the diameter. Thus for a $1^\circ$ beamwidth at 10 cm (to be precise, 10.7 cm), the required diameter is 7.3 m. This is the maximum practicable diameter used in weather-radar work and $1^\circ$ is the minimum beamwidth expected at any frequency (see section 2.10 and paragraph 4.5.4). This allows smaller reflectors at the shorter wavelengths, about 3.7 m at 5.6 cm and about 2.2 m at 3 cm. (What may appear to be the advantage of using a shorter wavelength and, thereby, requiring a smaller antenna is offset by the problem of attenuation discussed in section 2.14.)
For the purposes of equation (1), \( A_e \) may be regarded as proportional to the actual reflector diameter, the factor usually taken as \( \frac{A}{4} \), though Battan (1973) uses \( \frac{1}{2} \).

One of the significant features of beamwidth is that two targets separated by less than that beamwidth in angle cannot be separately distinguished by the radar. For example, if the beamwidth is 1°, two storms or intense parts of a single storm at a range of 180 km cannot be resolved if they are at the same range and closer together than about 3 km. As the range decreases, the separate targets may become defined; this can give the erroneous impression that a previously continuous echo belt has begun to split up into separate cells.

2.9 Effect of range (r)

Equation (1) demonstrates that the received signal power is inversely proportional to the square of the range of the target. This dependence is usually referred to as range attenuation; before assessment is made of the relative echoing power of two volumes in space, allowance must be made for this range factor.

The effect of range attenuation means that each range has its own minimum value of \( \Sigma \sigma \) (for use in equation (1)). Thus, as an echoing volume approaches the radar, smaller and smaller volumes can be detected. This could lead to an apparent increase in the size of the echo, even though greater resolution may be obtained (section 2.8), since the lower-intensity outer regions of the precipitation would be detected. It would be easy to make a false assumption that the area covered by precipitation was increasing if the reduced attenuation by range were not taken into account.

In all modern radars, range attenuation can be counteracted by the incorporation of a circuit, known variously as swept gain, range normalization or sensitivity time control, which adjusts the receiver amplification in step with range. In this way, a given target echo at, say, 100 km will appear the same at the receiver output as an equivalent target echo at, say, 10 km. There is a range limit to which this method is fully effective as, in order to deal with signals at extreme range, excessive and possibly less accurate attenuation is necessary at close range. Modern practice in radar data processing systems is to carry out the range normalization by software, either over the whole effective range or over the more distant part of the range, for example in excess of 100 km. This has the advantage of using digital techniques instead of an analogue circuit subject to drift. (There are now available sensitive receivers and swept gain circuits based on digital techniques, some of which are likely to be incorporated in weather radars.)

There is another effect of range: this is the path followed by an electromagnetic beam, which, because of the Earth's curvature, diverges from the Earth's surface under normal conditions of propagation. It results in, firstly, an area between the bottom of the beam and the Earth's surface in which neither detection nor measurement is possible, and secondly, in the beam passing through the melting layer (at whatever height it is, if above the ground) and thus complicating the calculations in the measurement of precipitation. These matters are discussed in greater detail in Chapter 5.

2.10 The fraction of the beam filled by scattering particles (\( F \))

The dimensions of the volume explored by a radar pulse are governed by the beamwidth and pulse length and by the range of that volume. As stated in section 2.2, modern weather radars have a conical beam. Older ones with a beamwidth much greater in one direction than in another are not used for precipitation measurement but only for detection and tracking. Though the principles apply equally to the latter type, only the conical beam is considered here. It has been indicated (in section 2.8) that 1° is the accepted optimum beamwidth. At a range of 100 km such a beam has a circular cross-section of radius about 1.75 km. Beamwidths of 2° are very common; at 100 km their cross-section radius is about 3.5 km. For equation (1) to hold good for quantitative measurement, the scattering particles should be uniformly distributed in size and number throughout the volume. This is never likely to be precisely the case, but it is apparent that the narrower the beam the more accurate is the assumption. On the other hand, the greater the range, the less likely it is that the beam will be filled and some empirical value may need to be given to \( F \) in order to make
equation (1) valid. (This is discussed further in paragraph 4.5.4.) One practical effect of the beam not being filled is that, even if range attenuation is corrected for, showers at longer ranges may appear to become more intense as they approach whereas, in fact, they are merely filling a greater proportion of the beam.

It will be noted that a narrow conical beam not only reduces the importance of factor $F$; it also increases the value of $A$, because of the size of antenna required to produce the beam.

2.11 The back-scattering cross-section of a single drop ($\sigma$) and of an assemblage of particles ($\Sigma\sigma$)

The back-scattering cross-section $\sigma$ (defined in section 2.3) of a spherical particle of diameter $D$ which is small compared with the wavelength $\lambda$ of the incident radiation is dependent principally upon the dielectric constant of the material of which the particle is composed and upon $\lambda$.

It is shown in Battan, 1973, that the back-scattering cross-section of a single particle

$$\sigma = \frac{\pi^5}{4} \left| K \right|^2 D \rho$$

where $K = (m^2 - 1)/(m^2 + 2)$ and $m$ is a complex refractive index. Thus, for the purpose of detecting and measuring precipitation by radar, $\sigma$ is proportional to $\frac{D^2}{\lambda^2}$. The relationship depends upon the assumption of the Rayleigh approximation. Thus, as explained in section 2.4, it applies when wavelengths of 3 cm or greater are used and when raindrops are less than about 5 mm in diameter or when the precipitation is in the form of snowflakes or small hailstones (which are often inseparable from large hailstones). The principal difference between water and snow is that the dielectric constant of the latter is considerably less, resulting in values of $\sigma$ only $1/5$ times that of water.

In the volume explored by the radar beam it is assumed that the particles can be regarded as being randomly distributed and the total radiation scattered back to the radar from the volume will be the sum of the individual contributions from the particles; the scattering will be incoherent.

Because of the random movements of the particles within the pulse volume, caused by turbulence and the differing fall speeds of different sizes, the signal received will have a rapidly fluctuating amplitude. Whether a conventional cathode-ray tube display is used or whether computer-processing takes place, received signals are averaged over a number of pulses (unintentionally in the first case, intentionally in the second). Then, the total back-scattering cross-section per unit volume, $\Sigma\sigma$, is equal to $284 \frac{\pi^6}{\lambda^4}$ for spherical drops or $55 \frac{\pi^6}{\lambda^4}$ for spherical ice particles. The summation is over all drops in unit volume.

In practice, the matter is more complex because particles in the atmosphere are frequently not spherical and may not be of a single composition. For example, ice crystals may exist as needles or plates or more complicated structures. Again, a hailstone may be in the first stage of melting, the core of ice being covered by a film of water; or a number of ice crystals may form a snowflake. Even large raindrops may depart appreciably from sphericity whilst falling, but for most rainfall when the proportion of large drops is extremely small, the effect of departure from sphericity is probably not appreciable. The lack of knowledge of the shapes and the distribution of the many forms which ice crystals and snowflakes take renders it impossible to make firm quantitative estimates of the echo to be expected from them, though, if the dimensions are small compared with wavelength, a rough guide can be obtained by considering the crystals to be spheres of the same mass.

It is possible to determine the shape of raindrops (and of other precipitation particles) by use of dual-polarized radars (Cherry et al., 1980). This is discussed further in section 4.10. The principal disadvantages of the method are that it is costly and has limited range.

An aspect of considerable interest and significance is the back-scattering cross-section of ice particles in the initial stages of melting when they have formed a wet film. It has been found that the dielectric properties of the outer film contribute most to the scattering by the particle. Thus there is a sudden increase in $\Sigma\sigma$, which is often enhanced even more because of differences in particle concentration near the $0^\circ$ isotherm caused by differences in the terminal velocity of snow and ice particles of the same mass and variations in
reflectivity due to the non-spherical shape of wet ice crystals. This leads to the bright band, the distinctive area of enhanced echo which can often be seen and recognized in displays, but which can cause difficulties in the processing of quantitative data. It is dealt with further in section 5.7.2.

It is clear from the foregoing that, provided a reasonable estimate can be made of drop-size distribution, a reasonable quantitative estimate of the received echo power from a volume of precipitation particles is possible, particularly if the particles are spherical. If the particles are ice crystals, snowflakes or melting ice, quantitative estimates are more difficult to achieve than if the precipitation is in the form of water drops.

### 2.12 The order of magnitude of \( \Sigma D^6 \) required for a detectable echo with typical radars

Equation (1) may now be rewritten, for targets comprising an assemblage of spherical water particles,

\[
\bar{P}_r = 284 \frac{\Sigma D^6}{k^4} \frac{P_t h A_e}{8\pi r^2} FK
\]

(2)

where the summation is over the whole range of drop sizes comprised in unit volume of the atmosphere.

For equipment operating on a wavelength of 10 cm, reasonable values of the radar parameters are:

- \( P_t = 10^{-14} \) for minimum detectable signal;
- \( P_t = 600 \) kW;
- \( h = 600 \) m;
- \( A_e = 6 \) m\(^2\) (equivalent to a circular reflector of diameter 4 m using a factor of about \( \frac{1}{2} \) between effective aerial aperture and true aerial aperture);
- \( F = 1 \) (equivalent to the whole beam at range \( r \) being filled with precipitation in which the distribution of drops of all sizes is random);
- \( K = 1 \) (assuming no attenuation other than that caused by range – approximately true for \( \lambda = 10 \) cm; see section 2.14);
- \( \lambda = 10 \) cm.

From equation (2), using metres,

\[
\Sigma D^6 = 4.1 \times 10^{-29} r^2 \text{ m}^6 \text{ m}^{-3}
\]

(3)

(The above assumed an antenna giving a 2° beamwidth instead of the preferred 1°.)

For the latter \( A_e \) becomes 25 and then

\[
\Sigma D^6 = 10^{-29} r^2 \text{ m}^6 \text{ m}^{-3}
\]

(4)

For equipment operating on a wavelength of 5.6 cm, reasonable values of the radar parameters are:

- \( P_t = 10^{-13} \) W for minimum detectable signal;
- \( P_t = 250 \) kW;
- \( h = 600 \) m;
- \( A_e = 6 \) m\(^2\);
- \( F = 1 \);
- \( K = 1 \) (assuming no attenuation other than that caused by range – only true for \( \lambda = 5.6 \) cm if there is no intervening precipitation; see paragraph 2.14);
- \( \lambda = 5.6 \) cm

Again, from equation (2),

\[
\Sigma D^6 = 8.7 \times 10^{-28} r^2 \text{ m}^6 \text{ m}^{-3}
\]

(5)

It must be emphasized that conventional radars, operating on 10, 5.6 or 3 cm wavelengths, detect only precipitation, or drops of precipitable size, not cloud particles. This can be demonstrated from the above equations. Clouds may have as many as 100 droplets per cm\(^3\) but only a small number of these will exceed a diameter of 20 \( \mu \)m, even in very well-developed convective clouds. If 20 \( \mu \)m is used in equation (3) it will be
found that 64 droplets per cm\(^3\) would be required to give a detectable signal from a range of 10 km, such a number being unknown. In equation (4), however, the number is reduced to the order of 16, which suggests that a 10 cm radar with a 1° beam may, very exceptionally, detect cloud droplets up to a range of a few kilometres.

On the other hand, if drops of precipitable size, for example 1 mm diameter, are present, it can be calculated from equation (3) that only one such droplet at a range of 10 km in every 240 m\(^3\) would be sufficient to give a detectable echo. Two such drops in every m\(^3\) would give a detectable echo at a range of 220 km. Since the fall speed in still air of drops of 1 mm diameter is about 4 m s\(^{-1}\), three such drops per m\(^3\) would give a rate of rainfall of only 0.02 mm h\(^{-1}\). The example shows that a 10 cm radar with the above characteristics would be a poor detector of clouds but a good detector of precipitation.

In fact, because rainfall is never composed of drops of uniform size, the above is theoretical only. In practice it is found that an empirical factor must be applied to the right-hand side of equation (2).

If the calculations made in respect of 10 cm wavelength are repeated for a comparable 5.6 radar, it will be found that there is a greater chance of the detection of cloud droplets at close range. If, then, cloud detection is needed, the shortest possible wavelength (e.g. 8 mm) should be used. On the other hand, as will be seen in section 2.14, the attenuation may then be so high that other severe limitations are imposed.

### 2.13 Drop-size distribution in rain; empirical formula relating echo intensity and rate of rainfall

It is well known that rainfall is never composed of drops all of one size. The drop-size distribution cannot be determined theoretically and, for the same rate of rainfall, may vary considerably from one rain event to another. Much work has been done in attempting to determine drop-size distributions in various rates of rainfall by a variety of techniques ranging from special counting gauges (for example, the Joss "distrometer" (Joss et al., 1970) to the use of coherent or Doppler radar and of specially instrumented aircraft. The results have been varied and are very valuable in a research sense. They have also contributed to the derivation of relationships between echo intensity and rainfall rate used operationally (see below). The great handicap is that, in all such methods, the volume of raindrops explored is very small compared with the volume of the atmosphere explored by conventional radar pulses.

Thus, since it is not practical operationally to measure \(\Sigma D^6\), that is, to measure the drop-size distribution at the ground and to convert this to a volume distribution by means of the fall speeds of different-sized drops, some other method is required to convert the received radar signals into rates of rainfall. The solution has been an empirical one, adopting a formula relating the average value of \(\Sigma D^6\) to the rate of rainfall \(R\). The form which is now conventionally accepted is:

\[
Z = a R^b
\]

where \(Z = \Sigma D^6\), \(D^6\) is measured in mm\(^6\) m\(^{-3}\) and \(R\) in mm h\(^{-1}\). \(Z\) is known as the radar reflectivity factor.

A large number of values of the constants \(a\) and \(b\) have been determined by different workers; the subject is discussed in more detail in Chapter 4.

### 2.14 The attenuation factor (\(K\))

The discussion so far has not taken account of \(K\), the attenuation factor. This is not to be confused with attenuation due to range (section 2.9). An electromagnetic wave traversing the atmosphere loses energy by absorption and scattering; it is the loss by these two mechanisms which leads to \(K\).

The only atmospheric gases which are of importance for attenuation by absorption are water vapour and oxygen, while attenuation by scattering from gaseous molecules is negligible. For wavelengths between 3 and 10 cm the attenuation due to the oxygen content of the atmosphere is reasonably constant; at sea-level
pressure it lies between 0.01 and 0.008 dB km⁻¹ (see footnote). This becomes significant when measuring precipitation at the longer ranges, being between 2 and 1.6 dB at 100 km (remembering that in radar applications two-way transmission must be considered). This would, in fact, be a very slight overestimate since, owing to the curvature of the Earth, the beam would traverse air at lower pressures as the range increased.

The attenuation due to water-vapour absorption depends, of course, on the water-vapour content of the air. It is quite negligible at 10 cm wavelength, being of the order of 0.0002 dB km⁻¹. However, it increases rapidly as the wavelength decreases; for a content of 7.5 g m⁻³ of water vapour at 1000 hPa pressure, it approaches the same value as for oxygen at 3 cm at 0.01 dB km⁻¹. Operational meteorological radars are mostly in the 3 to 10 cm range and those used for quantitative measurements are almost entirely at either 5.6 or 10 cm. If used for detection purposes the effects of absorption by atmospheric gases can be neglected. If a processing system is included, a correction factor can be applied.

Of greater importance is the attenuation by liquid and solid particles in the atmosphere. The attenuation is brought about by both scattering and absorption and is dependent on wavelength, \( \lambda \), the particle diameter, \( D \) (assumed to be spherical) and the dielectric constant. For clouds composed of water droplets the attenuation depends on water content and is virtually independent of drop size. For a water content of 1 g m⁻³, which is a high value for most clouds except small parts of convection clouds, the attenuation is nearly 0.1 dB km⁻¹ at 3 cm wavelengths and 0.01 dB km⁻¹ at 10 cm. For ice crystal clouds with a concentration of 1 g m⁻³ the comparable figures are about 0.004 dB km⁻¹ at 3 cm and 0.0008 dB km⁻¹ at 10 cm. Thus, even for very extensive cloud along the radar beam, in which the mean liquid water concentration is unlikely to exceed about 0.5 g m⁻³, the attenuation is not too significant at a wavelength of 10 cm, being only 0.5 dB or less over a path length of 100 km. However, it may approach 3 dB at 5.6 and 5 dB at 3 cm, thus indicating that under certain conditions neither 5.6 nor 3 cm is satisfactory for precipitation measurements.

The most serious problem arises with attenuation by precipitation. Assuming a mean drop-size distribution in rain as discussed in section 2.13 for back-scattering, average values for attenuation on different wavelengths at different rates of rainfall can be calculated. Table I gives figures in dB km⁻¹ for a range of rainfall rates at the commonly used wavelengths of 10, 5.6 and 3 cm and also for the more infrequently used 0.8 cm, whilst Figures 2(a) and (b) illustrate the effect graphically.

<table>
<thead>
<tr>
<th>Rate of rainfall (mm h⁻¹)</th>
<th>Wavelength (cm)</th>
<th>10</th>
<th>5.6</th>
<th>3</th>
<th>0.8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>1.0</td>
<td>5.0</td>
<td>10.0</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0003</td>
<td>0.002</td>
<td>0.006</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>0.0006</td>
<td>0.004</td>
<td>0.014</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>0.003</td>
<td>0.030</td>
<td>0.172</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>10.0</td>
<td>0.006</td>
<td>0.066</td>
<td>0.302</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.03</td>
<td>0.430</td>
<td>2.50</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.06</td>
<td>0.962</td>
<td>6.16</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>0.12</td>
<td>2.16</td>
<td>15.3</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>0.18</td>
<td>3.48</td>
<td>26.0</td>
<td>132</td>
<td></td>
</tr>
</tbody>
</table>

The decibel (dB) is a measure of relative power. If two powers \( P_1 \), \( P_2 \) differ from each other by \( N \) dB, then:

\[
\frac{P_1}{P_2} = 10^{N/10} \quad \text{or} \quad N = 10 \log_{10} \frac{P_1}{P_2}
\]

Thus, if a power \( P_1 \) is attenuated by 3 dB, it is reduced to half its value, and when attenuated by 10 dB, to one-tenth its value.
It is apparent that considerable reduction in received power can occur at the shorter wavelengths. Although this was realized at an early stage in radar meteorology, it did not prevent the common use of 3 cm radars. Many are still in use worldwide; they were mainly derivatives from navigational or control radars, and they were the cheapest form of weather radar available. (Generally speaking, the shorter the wavelength, the more compact the equipment and the lower the cost.) Because of the attenuation problem, 3 cm radars are seldom used for quantitative measurement, though there are some notable exceptions, particularly in northern Europe where rainfall intensities are generally lower than elsewhere.

The most effective wavelength for use in tropical or semi-tropical regions, where rainfall rates are high, is clearly 10 cm, with attenuation due to intervening precipitation (and cloud droplets) low and factor $K$ in equation (1) close to unity. The disadvantages are that the engineering is relatively heavy, installation problems are greater and, most important, a large antenna reflector is needed to obtain a narrow bandwidth (sections 2.8, 2.10).

During the 1970s, 5.6 cm radars became readily available. This compromise has proved attractive as it permits lighter engineering to achieve a narrow bandwidth and, in temperate regions, it is not generally subject to serious attenuation due to precipitation.
On the other hand, it is possible to use the attenuation in the atmosphere as a measure of the precipitation intensity. Although this is not a common method, it is sometimes used operationally, mostly in the USSR and some of its neighbouring countries. It is discussed in greater detail at section 4.8.

Bibliography


CHAPTER 3

OPERATIONAL RADAR EQUIPMENT

3.1 General remarks

This chapter contains a description of the equipment usually found in operational weather radar systems used for either detection and tracking purposes or for precipitation measurement by the conventional method of receiving echo signals. It includes descriptions of the types of display available for data which have not been digitally processed and general guidance is also given on the operational use of radars without processing systems. The additional equipment required for data processing and the methods of its use are discussed in Chapter 4.

The form of weather (or meteorological) radars has changed little over the years, though advances have been made in the sophistication of circuitry, which has resulted in improved stability and reliability. The radar is, in general, the same, whether its purpose is to detect and track or to measure. To the observer, outwardly, display systems of the Plan Position Indicator (PPI) or the Range Height Indicator (RHI) types have also changed little. On the other hand, in recent years there has been a move away from the conventional instantaneous and transitory, impermanent picture on a black and white cathode-ray tube, updated with each rotation of the antenna, towards the use of a delayed picture representing an integration of the data, possibly over a number of antenna rotations, the picture being refreshed and updated every few minutes and possibly stored for instant recall.

3.2 Typical radar equipment

The size of the radar depends to a considerable extent on the wavelength at which it transmits. As suggested in section 2.8, the size of the antenna system can become an engineering problem (and therefore expensive) at the longer wavelength of 10 cm. The only other wavelength-size-dependent areas are the transmitter/receiver, the waveguide between transmitter/receiver and antenna and the control circuits (which may have to be more substantial for 10 cm equipment in order to cope with the greater current required for antenna control motors).

The block diagram in Figure 3 is applicable to an operational meteorological radar of any of the wavelengths used - 10 cm, 5.6 cm, 3 cm and, occasionally, 0.8 cm - as the functions are identical. Information on the use of these wavelengths is given in the annex to this chapter. It is not the intention here to describe a radar system in full technical detail; rather a brief description is given for the benefit of those for whom the principles are new.

It has already been stated (section 2.1) that a radar transmits a train of electromagnetic pulses. In order to obtain these short-duration, high-energy pulses, high voltage is required, typically between 12 and 20 kilovolts. Because of the short duration, e.g. one or two microseconds, the mean power is low but the safety precautions taken have to be those applicable to the voltages involved. A high voltage pulse is built up by a pulse-forming network, consisting of inductance and capacitance, which is part of a unit known as a modulator. A timing circuit, usually crystal-controlled, providing synchronization for the whole system, is necessary to fire the transmitter valve by means of a pulse transformer when the pulse has been built up. This timing circuit may, in some applications, be independent of the radar; this may be the case when the radar is used with a processing system or, alternatively, when two or more radars are in close proximity and might cause mutual interference if allowed to run independently.

The timing pulse, or trigger, subjects the transmitter valve, a magnetron, to a sudden very high-voltage pulse, normally negative. The magnetron immediately bursts into oscillation at a radio frequency determined almost entirely by its physical characteristics (but within the chosen wavelength band). This
oscillation is directed into a waveguide, which is a rectangular cross-section metal tube of either brass or copper (rarely, aluminium). The dimensions of the cross-section are determined by the wavelength. In the waveguide there will be a duplexer or circulator, a static electronically energized device which prevents the transmitter pulse from entering and damaging the receiver circuits but does not inhibit it from passing up to the antenna feed or horn. There it is directed at the reflector which projects an electromagnetic radiation beam into the atmosphere (see section 2.2).

The received pulses, on striking the reflector, are focused upon the aerial feed. They then travel down the waveguide to the duplexer which directs them to the receiver. These pulses are at the same radio frequency as the transmitted pulses, which is much too high for straightforward amplification (except, possibly, for one initial stage which is sometimes incorporated). They are therefore mixed with low-power oscillations of similar frequency from the local oscillator. The difference in frequency will be, typically, 30 MHz, which can be amplified without difficulty. (This procedure can be compared with that used in domestic television or radio receivers.) After various stages of amplification and detection, the received signals appear at the receiver output in the form of a varying d.c. voltage from 0 to, say, 2 volts, large echoes being represented by the higher values. This varying voltage, known as the video signal, is then applied to a cathode-ray tube display and/or fed into a processing system.

The receiver may possess a linear characteristic, in which case all signals will be amplified in such a way that all those above a certain voltage level reach saturation and thus cannot be compared in strength. For detection purposes this may be satisfactory, particularly as conventional black-and-white cathode-ray tubes are not very sensitive to signal levels. If the radar is to be used for precipitation measurement, a receiver with a logarithmic characteristic is usually provided. This is to ensure that all received precipitation signals can be amplified without reaching saturation; they can then be measured and compared in value. The range of signals which can be accommodated without saturating is known as the dynamic range; modern components have led to satisfactory improvement in this. (The range of signals received corresponding to a range of
mean precipitation rates to be measured from, say, 0.1 mm h\(^{-1}\) to 100 mm h\(^{-1}\) in temperate zones or to 200 mm h\(^{-1}\) in the tropics, a ratio of 1000:1 or 2000:1, is such that linear amplification is practicable only if a processor-controlled stepped attenuator is used.)

The receiver may also include range-normalization circuits, as discussed in section 2.9, unless the range attenuation correction is to be carried out in a processor.

The antenna is driven round in azimuth or up and down in elevation by motors controlled from the control rack. The usual arrangement is that one mode or the other can operate continuously whilst the other can be changed manually. The servo-mechanisms which determine the motor movement in the manual mode respond to the setting of dials or of mechanically operated digital displays. In some processor-oriented systems, when operating in the automatic mode, the servos are being continually stepped by the computer.

Positional data from the antenna system are obtained from synchro-mechanisms physically connected to the reflector support structure. These will be displayed at the control position either in dial form by repeater synchros or in digital form from analogue-to-digital (A to D) converters. They will also be linked into the display systems and/or into the processing system, if one exists, in order to relate the angular position of echoes to their range.

3.3 Display systems

In section 3.2 above it was said that the video output from the receiver, varying between 0 (ignoring noise level) and about 2 volts, is applied to the grid of a cathode-ray tube display. This voltage appears in a sequence directly related to the time taken from transmission to reception, i.e. to the range of the echo. The tube display can have a trace with origin at the centre running outwards to the circumference. If the trace is synchronized by the system trigger pulse, any return echoes will appear as a brightening of the tube at a point related to the range. In addition the trace can be calibrated by range markers from the centre outwards. By means of the synchro link from the antenna system referred to in section 3.2, if the antenna is being rotated in azimuth, the trace may be rotated in synchronism. In this way the echoes are displayed in their correct relative locations and the range markers appear as concentric rings. The locations can also be marked by the use of an auxiliary trace which may be moved up or down and from side to side. This can be connected to counters indicating the precise position of one end. With the aid of this marker trace, the movement in distance or direction of a significant echo may be determined over a chosen period of time.

The above describes the conventional PPI which has been used almost from the inception of radar and is likely to be used for some time to come (see Figure 4). It gives a bird's-eye view or projection on an almost horizontal plane of precipitation mostly at or near ground-level.

If the antenna is held at a fixed azimuth and is made to scan up and down, then the display may be turned into an RHI (Figure 5). The base line is moved to the lower part of the tube whilst the trace, anchored at the origin, one end of the base line, moves up and down in synchronism with the line of sight of the antenna. In this way echoes will again appear at the correct locations but now vertically as well as in range. Thus a vertical cross-section of one slice of the atmosphere is displayed. Range markers can again be available together with height lines and a marker trace. Corrections for the Earth's curvature can be applied, based on normal propagation. Either the Earth's surface may be curved downwards or the height lines may be curved upwards - usually the former.

Most manufacturers offer the alternative of separate PPI and RHI displays or one display which may be used for either function by the movement of a switch. The latter seems cost-effective as, without some form of memory, it is not possible to present both forms of picture at the same time.

There are three other, less common forms of display associated with non-processor radars. The first two are interesting as they illustrate the nature of the received signals. The A-scan display (Figure 6) sets time (equivalent to range) on a horizontal scale and displays the signals vertically in amplitude, up to a saturation level. When viewing such a display, it is immediately apparent that all returned signals fluctuate, but that those from precipitation, because of the random contributions from individual drops in the beam and their
relative motion, do so much more rapidly and produce less clearly-defined outlines. The form of the noise (section 2.6) is also demonstrated. This also fluctuates rapidly and it is not easy to determine the precise mean level. The A-scan is useful for test purposes; if a simulated signal is injected into the system, the output may be measured on it. For this purpose a gridded scale is usually provided. On the other hand, a standard cathode-ray oscilloscope may be used for the same purpose or, if accuracy is required, a sensitive output meter.

On some equipments a small portion of the A-scale can be expanded by delaying the start of the trace. This time-delay may be varied so that any echo may be selected and studied in greater detail. This form of display is known as an R-scan.

The third less common display is the Constant Altitude PPI (CAPPI) (Figure 7). This combines PPI with some of the advantages of RHI. To produce this the aerial goes through a cycle consisting of continuous rotation in azimuth with a step up in elevation after each rotation. Echoes from one constant altitude are portrayed (by suitable range gating) in successive contiguous circular rings on a PPI display. By the use of several displays, one for each desired altitude, a set of constant altitude maps is produced and a three-dimensional picture of the precipitation obtained. In modern systems, CAPPI displays are built up with the aid of a computer. The radar must have a narrow beamwidth to ensure that adequate resolution, particularly in height, is obtained.
3.4 General layout of equipment

A weather radar equipment consists basically of four units (see Figure 3):

(a) Antenna, including pedestal or mounting;
(b) Transmitter/receiver;
(c) Control rack;
(d) Display(s).

There are variations. Some systems have a separate microwave unit between the transmitter and the antenna; this will house the receiver and duplexer or circulator. Some manufacturers build the displays and control system into an operating console. Other systems have the operating controls (as opposed to the control circuitry) associated with separate display(s). The arrangements depend, at least in part, on the disposition of the equipment required by the user and also in part on technical limitations.
The antenna system, of course, must be mounted on a tower or on a building where a good radar horizon is obtainable. (This is discussed in Chapter 8.) The waveguide, carrying the power from transmitter to antenna and echo signals back from antenna to receiver, inserts a power loss in both directions which is dependent upon the length of waveguide (as well as being dependent upon the material used). It is sensible, therefore, to limit the distance between the transmitter/receiver and the antenna if possible. Fifteen metres is usually considered the maximum, though it is appropriate to mention that, provided the waveguide is in good condition, any loss caused should be constant and need not affect the accuracy of any measurements.

In some, mainly older and smaller radars, operating at 3 cm or less, the waveguide is kept very short by putting the final stage of the transmitter and the first stage of the receiver in a unit behind or under the antenna. It has the disadvantage that, unless a radome is used (see section 3.6), servicing is difficult in inclement weather.

The transmitter/receiver, usually the largest single unit inside the radar room, has its own controls, though it is possible to operate them remotely. In addition to the waveguide to the antenna, it is connected to the control rack and displays (and to the processor, if there is one) by cable. It is convenient to have all units close together, particularly for servicing purposes, but at a manned station there may be a separate operations room apart from the transmitter or radar room.

For one thing, the transmitter is invariably noisy; for another, it may be desirable to have the operators at some distance from the transmitter/receiver (which must be close to the antenna) – for instance, in a forecast office. It may be necessary, on an airfield for instance, to mount the radar antenna a considerable distance from the forecast office in order to gain a good horizon and avoid interference with other equipment. There is no technical problem in having the controls and the display at a distance of 1,000 metres or, perhaps, 1,500 metres. Direct cabling may be used; the length of such cables is limited by the inevitable losses which occur and, at some arbitrary point or points, it may be necessary to insert boosters. The cost of the cable and of laying it must also be considered. An alternative is to convert display and control data to digital format and to use a multiplex telephone-type line or radio link.

One disadvantage of separation of display and control from the radar is that an additional display is almost certainly required for the radar room for servicing purposes.
Radar equipment should not be expected to function satisfactorily in a poor environment. The requirements are more stringent if precipitation measurement is to be carried out and a processing system is included, in which case, in addition to dust-free surroundings, the temperature and humidity must be closely controlled.

If processing is undertaken at the radar site, the system immediately becomes more flexible, because digital outputs are available for data transmission over any distance.

3.5 Ancillary equipment

In most systems some items of ancillary equipment are necessary to ensure proper functioning. The chief ones are discussed below.

In section 3.4 reference was made to waveguide losses. In order to keep the waveguide in good condition it is necessary to keep it dry. Most radar systems therefore include a dehydrator which is connected into the waveguide. This pumps dry air into the guide and, in so doing, increases the air pressure in the waveguide very slightly. This process is particularly important when the radar is not operated continuously.

The system will require adequate power distribution arrangements. These, together with a good earthing circuit, will be important features in the equipment layout. The power required for a modern 10 cm radar with processor will probably be between 7 and 10 kVA, or a little less for shorter wavelengths.

To enable the stability of the equipment to be maintained, a constant mains voltage is necessary. To achieve this, an automatic voltage regulator is a necessity at many sites. Since the most likely time for the failure of a public power supply is in bad weather when the radar is most needed, a standby generator is usually a necessity. Unless the site is manned at such times, an automatic change-over system is required also. If there is a computer on site, there may also be a need for a “no-break” supply, with a battery-operated inverter system.

3.6 Radomes

Radomes are protective housings for the antennae of radars, satellite receiving stations and communication terminals. They are usually truncated spheres bolted to the platform on which the antennae stand. Some are made of rubberized material and are inflated to keep them at a pressure a little above ambient. The more common type now is of man-made fibre in triangular-shaped sections. The sections bolt together to form a self-supporting structure which is virtually spherical. In some cases the sections have aluminium strip edges and the structure is called a metal-space-frame radome. In others, the sections have edges reinforced with fibreglass and the structure is known as a dielectric-space-frame radome.

The real purpose of a radome is to protect the antenna from precipitation of all kinds, wind and pollutants. By so doing, it prevents deterioration of the antenna system and allows servicing to take place in all weather conditions. It also permits the use of antennae of lighter construction with, as a consequence, less powerful drive motors. Problems arising from uneven antenna rotation rates due to high or gusty winds are also overcome. There are, however, some disadvantages, particularly in measuring precipitation, as the radome material introduces attenuation which varies according to the wetness of the surface. Special coatings may be used to reduce the effect. The problem is discussed in more detail in the annex to Chapter 5.

The use of inflated rubber radomes is becoming less common because careful sealing is required and air interlocks are necessary to gain access so that pressure may be retained. This type of radome can be very stable in high winds. The space-frame radome needs no sealing other than is necessary to keep out snow and rain; slight leaks are of no importance and there is some merit in allowing a slight passage of freshening air through it. The radome should be of sufficient size to allow maintenance staff ease of access all round the antenna system.
3.7 Operational use of radars without processing systems

3.7.1 General

Since there are many radars in use which have no processing systems and installation of such radars is likely to continue for some years to come, some discussion on their operational use seems appropriate. There are no set rules; generally, operational practice is built up on experience of using a particular radar in a particular place, with the meteorologist using his knowledge to interpret the radar pictures or, alternatively, using the radar pictures to aid his interpretation of the meteorological situation as seen from the conventional data available to him. The following paragraphs can only be regarded as providing guidance, particularly in respect of avoiding some of the pitfalls. More comprehensive guidance can be obtained from the Weather Radar Manual, Part B which, although specific to the USA and now some years old, is still appropriate to most users.

3.7.2 Use of PPI

This conventional form of display of radar data is generally simple to operate. Apart from a brightness control there is a switch to select from three or four ranges, say, 50, 100, 200 and 400 km with range rings selectable at, say, 10 and 50 km intervals. A circular scale will allow azimuths to be read off, possibly with the aid of a revolving cursor. Incorporated in the circuitry will be a switchable bright trace line which can be rotated, moved in all directions and, sometimes, expanded. This can be used as a marker to determine the precise position of an echo and its movement in both range and direction over a selected period of time. It will be connected electrically to some form of range indicator, either a mechanical scale or a digital display.

The use of interscan techniques allows other information to be switched in, in particular the outlines of a country or region with significant towns or geographical features. This is of value to forecasters in locating the areas most likely to be affected by precipitation. In earlier forms of display a transparent overlay has to be used for the purpose.

Off-centring is a feature of most PPI displays. This allows closer study of a significant part of the picture by using a shorter scale – say, 50 km – and the area under observation to be brought to the centre of the cathode-ray tube.

It must be borne in mind that meteorological echoes move or change only slowly. There would therefore seem to be the possibility that they might be confused with permanent echoes. In practice, this seldom happens for, apart from the fact that an experienced observer will know where the permanent echoes are located, possibly even when anomalous propagation (see section 5.6) brings up some which are rarely seen, there is usually a difference in character between the signals received (and displayed) from solid buildings, mountains, etc. and those from precipitation.

Permanent echoes are more clearly defined whilst precipitation echoes tend to be fluffy in character. Nevertheless, the latter vary considerably in texture and pattern, often being related to the type of weather system producing them. Thus, it is quite simple to distinguish between frontal rain producing a continuous echo line moving steadily in one direction and convective rainfall producing a number of cells which grow and disappear with the movement of the weather system, being somewhat random. Observation of frontal rain permits much more accurate predictions to be made by a forecaster than observation of storms, though that in no way lessens the value of the latter which is much more vital in respect of aviation and often in respect of flood warnings.

It is important that the observer be aware of the limitations of the radar system, discussed previously in Chapter 2. The questions which should be asked include the following:
(a) Is it likely that the echo seen is the total echo, or is some of it being hidden by attenuation?
(b) Is attenuation due to nearby precipitation echoes hiding more distant precipitation?
(c) Could what appears to be an echo line really be a number of independent cells?
(d) Is the precipitation really increasing in area or in intensity as it comes nearer (or decreasing as it goes away), or is it filling more (or less) of the beam or being less (or more) attenuated?
(e) If there is a sharp increase in intensity at a certain range, is this due to bright-band-enhanced reflectivity?
(f) When precipitation intensity is high, could some of the echoes at close range be due to side-lobes?
(g) Is anomalous propagation causing permanent echoes at longer ranges to be confused with precipitation echoes?

In regions subject to tropical storms, the display should be studied carefully to determine whether any of the tell-tale signs associated with severe weather are present. It must be borne in mind that it is under such conditions that attenuation, particularly of the shorter wavelengths, is greatest and that therefore the patterns may not be immediately apparent. Hurricanes or cyclones should show spiral bands with an echo-free eye (Figures 8, 9). Tornadoes usually have a characteristic hook which protrudes from the main echo; the size and clear-cut definition of the hook are closely related to the width of the path of the tornado on the ground (Figure 10).

Figure 8 – Hurricane “Donna” on 6 September 1960 observed by means of an airborne 10.7 cm radar. Range markers are at intervals of 50 nautical miles (about 92 km). From Jordan, Schatzle and Cronise (1961) (Battan, 1973)

Figure 9 – PPI display of cyclone “David” showing the eye at about 80 km east of the radar. The bands of rain around it are associated with gale-force winds (French Meteorological Service)
If a severe storm echo has protruding fingers, usually on the upwind side, there is a strong probability of potentially damaging hailstones (Figure 11). The height to which precipitation extends is a useful guide to the severity of a storm; it is generally found that the higher the echo top, the greater the probability of hail. Often the echo extends into the stratosphere.
3.7.3 Use of RHI

If the heights of echoes are important, as, for instance, in the detection of severe storms likely to produce significant hail, then RHI is invaluable. The system, which may be incorporated into the PPI display with appropriate switching, will have similar facilities such as switchable range scales – for example 50, 100 and 200 km. (Beyond 200 km, RHI is of little practical value.) Range markers, appearing as vertical lines, will be provided, as will height lines at, say, 2.5 and 5 km. There may be two switchable height scales displayed – say, 12.5 km and 25 km. Earth’s curvature effects are usually allowed for; thus, the height lines or markers curve downwards away from the radar position. An interscan marker line may also be available.

In observing an RHI, most of the questions asked in PPI usage (section 3.7.2 above) should be repeated. If a bright band exists it will be more apparent (Figure 12), and the information from it will be rather more useful to the forecaster. One important feature in determining the height of the precipitation is that the width of the beam must not be overlooked. At a range of 50 km, for instance, a 1° beam covers a height in the atmosphere of about 1 km, or at a range of 100 km, 2 km. The echo will extend on the RHI, therefore, to 0.5 or 1 km above its real height. Further, if the echo being examined is of very high intensity and within, say, 50 km of the radar, then the effect of side-lobes will result in an extension of the echo to a much greater height, though, because of the lower power in these side-lobes the echo may appear suddenly to lose intensity or thickness at a fairly well-defined point (see Figure 13).

The best use of a conventional non-processing radar, particularly in storm-prone regions, is made by intelligent combination of PPI and RHI data. An experienced operator should be able to build up a good mental picture of the extent (in both the horizontal and vertical) and the severity of the precipitation which is being examined and, by noting changes which occur at intervals of, say, 15 minutes, should be able to predict (or assist the forecaster to predict) what further changes are likely.

![Figure 12](image_url)

Figure 12 – Well-defined bright band on the RHI of a 10 cm radar in Boston on 21 January 1959. The bright band was at a height of about 8 000 ft (2.4 km). Two dark height markers are at altitudes of 5 000 and 10 000 ft (1.52 and 3.05 km) and the heavy range mark is at 40 km. By courtesy of P. M. Austin, M.I.T. (Battan, 1973)
For storm-prone regions there is now a move towards Doppler systems which are able to give more definite warnings of hazardous conditions. These are discussed in Chapter 10.

3.7.4 Simple measurement of echo intensity

Precise measurement of precipitation requires a full processing system. The limitations in older radars due to receiver saturation and cathode-ray tube insensitivity inhibit the determination even of relative intensities by examination of the picture. However, some information can be obtained. The simplest method is to reduce the receiver gain manually and progressively so that higher and higher signal intensities are required to produce bright echoes on the tube. This can be valuable in determining the strongest parts of echoes displayed and hence the distribution of precipitation intensity throughout the echoing volume. This determination can be made more precise by the use of stepped sensitivity or calibrated attenuator. The received signals can be artificially attenuated by fixed known amounts. If required, though this is seldom done in practice, isopleths of signal intensity can be drawn and the values related empirically to precipitation intensity. It should be noted that, in using this or any other method of intensity determination, the errors discussed in Chapter 5 must be taken into consideration.

A developed form of stepped sensitivity is the iso-echo display. By arranging for signal intensity values to be divided into, say, six steps and for alternate steps to brighten or to black out the display, it is possible to indicate the isopleths on the tube. The picture will consist of alternate bright and dark patches from the outside of the echoing area towards that part giving the greatest signal intensity, generally (but not necessarily) towards the middle of the area. This method of contouring, which allows observers to see at a glance precipitation intensities in bands over the whole area, is used in airborne weather radars and is also found to be very useful in ground radars. (See Figure 14.)
Figure 14 – Isoecho contouring on a PPI from a 10 cm radar. Range markers at intervals of 20 nautical miles (37 km) (National Severe Storms Laboratory, Norman, Oklahoma)

Iso-echo displays are now available from part-processed data produced by the Digital Video Integrator and Processor (DVIP) discussed in Chapter 4.

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ANNEX

WAVELENGTHS IN OPERATIONAL USE

Although reference to operational wavelengths and the merits and disadvantages attached to each is made in different parts of this Technical Note, a summary may be useful.

1. 10 cm wavelength (S-band, 2700-2900 MHz) (see footnote)

This is the wavelength best suited to regions where heavy precipitation occurs and attenuation due to intervening precipitation might be a problem. It is therefore recommended particularly for tropical regions and in those areas where hurricanes, tornadoes and cyclones occur. Peak powers of the order of 650 kW are common in meteorological radars. Much higher values, up to 2 MW, are available in aviation and military radars and there is one weather radar in Japan, used specially for typhoon warning, with a peak power of 1.5 MW.

There is considerable manufacturing experience for 10 cm sets, but the increasing requirement for precipitation measurement has led to a need for narrow beamwidths. The size of reflector required for a given beamwidth is proportional to the wavelength. For a 1° beam at 10 cm a parabolic reflector of 7.3 m diameter is required. This is mechanically undesirable, though sometimes unavoidable; it is relatively expensive and requires quite large motors to drive it. A radome to house it would need to be about 10 m in diameter, and the total weight and wind stresses demand sturdy engineering in the supporting tower or building.

Overall, the demand for 10 cm radars is decreasing in non-tropical regions but many of the older equipments use this wavelength, usually with a 2° beam.

2. 5.6 cm wavelength (C-band, 5300-5700 MHz) (see footnote)

This wavelength was used a little during the 1939-1945 War in non-meteorological radars but fell mainly into disuse thereafter. In recent years it has been realized that it offers the best possible compromise for meteorological purposes and it is now used for most new radars installed in non-tropical regions. For a 1° beam the antenna required is about 3.7 m in diameter. Transmission at this wavelength has the ability to penetrate medium-intensity precipitation and when used with processing systems attenuation corrections can be incorporated in the program. Peak power outputs are usually of the order of 240 to 300 kW.

In some areas this wavelength is used for radio communication purposes, leading to a clash of interests which can usually be solved by choice of precise, well-separated frequencies.

3. 3 cm wavelength (X-band, 9300-10 000 MHz) (see footnote)

Radars operating on this wavelength have been very common in aviation (both ground-based and airborne) and in marine use. The majority of weather radars before 1970 were 3 cm, but these were used mostly for detection and tracking purposes. Few countries have been successful in using them for precipitation measurements; those that have are mostly in polar or near-polar climate zones. When the problem of attenuation by water droplets, even to the extent of the possible hiding of important weather features such as cyclones, was fully realized, the demand for 3 cm radars was much reduced.

NOTE: The figures for wavelengths tend to be used in a rather loose manner. They usually refer to a band rather than to a precise figure. For instance, "10 cm" can mean anything between 9.7 and 11.1 cm. The terms "S-band", "C-band", "X-band" and "K-band" are perhaps better, but these designations are liable to change.
These radars were attractive for the practical reasons that a 1° beam may be obtained with a reflector of only about 2 m diameter and that the antenna structure is easy to handle and relatively cheap.

Considering equation (2) in Chapter 2, it will be noted that the reduction in the $\lambda^4$ term will tend to increase the power of the received signal, but this is offset to a great extent by the decrease in transmitter power, usually 60 to 75 kW peak.

4. **0.8 cm wavelength (K-band, 37 500 MHz)** *(see footnote on previous page)*

This wavelength is not in wide operational use, though a number of dual-wavelength (3 cm/0.8 cm) radars are in operational use in the USSR and several other, mostly eastern European, countries. (See Chapter 11 for discussion on dual-wavelength operation.)

It will be noted from Table I (Chapter 2) that attenuation by water droplets at this wavelength is so great that the radiated energy can be rapidly and almost totally absorbed. As a result, the most commonly used method at 0.8 cm is to measure the attenuation against a monitored output rather than to use the received signal as a discrete measure of the precipitation echo.

Radars operating on this wavelength can be used to detect cloud, at least at short range (see section 2.12).
4.1 Introduction

The basic principles underlying the use of radar for the measurement of precipitation have been set out in Chapter 2. Operational radars and displays, together with their use, have been discussed in Chapter 3. Relatively simple means of determining precipitation intensity were described briefly. Such systems and such methods still represent the majority of radar systems in use and may do so for many years to come.

However, in the last few years the majority of new radar systems have included either full data-processing systems or, at least, equipment to digitize the analogue output from the radar receiver even though, in the latter case, the display may still be of the PPI or RHI type, albeit in colour. It is likely that most systems supplied to the Meteorological Services in the future will incorporate digital processing.

Whilst the possibilities of the digitization of radar data have been recognized for many years, it was not until small computers became available that, at an acceptable cost, these data could be processed and transmitted in virtual real time for immediate use in meteorological and hydrological forecasting.

Furthermore, the improvements in components which came with the solid-state revolution in electronics have made the basic radar a more reliable and accurate instrument which no longer requires constant attention from both operator and technician. Meteorologists and hydrologists were provided with a tool of considerable potential in precipitation forecasting, in flood warning and in water management. The uses of the processed data are considered in Chapter 7. The new systems are still able to provide the basic forms of data and displays to which many users are accustomed. (Some forms of digital processing or, perhaps more correctly, pre-processing are specifically for the purpose of providing ease of data transmission and greater flexibility within the familiar types of display.)

As data are converted into digits, they can be transmitted readily by conventional means over telephone lines, radio links or via geostationary satellites. Thus, it is possible not only to site the radar a great distance from the point or points at which the data are to be used, but also to transmit data to a central point for merging with those from other radars or with data from satellites or conventional ground observing stations.

The data, in digital form, can be displayed, using colours to represent different levels of intensity, on television receivers or other visual display media. They can be shown in an alphanumeric chart display or be printed out as instantaneous values or as integrated totals over predetermined sub-catchments in river basin areas. The integration periods may be selected and the totals used as an important input to computer flood-warning models, for instance.

It is very important to remember that, whereas a conventional raingauge, mounted at or near ground level, measures the precipitation at one point only, which is seldom truly representative of an area and often not even of another point a short distance away, a radar can provide a measure over a large area with acceptable accuracy. Under the very best conditions of siting, radar design and meteorological circumstances, this can be of the order of 30 000 km², though in practice the area is often somewhat smaller. A radar is capable of providing a great quantity of valuable and unrivalled data, particularly in conditions of scattered precipitation. For raingauges to compete would require a network of telemetered instruments, sited with a density neither practicable nor cost-effective.
This chapter deals with principles and methods of processing the data, but attention must be drawn to the problems of accurate measurement to be discussed in Chapter 5. Some of the hardware used in precipitation measurement is described briefly in the annex to this chapter, whilst a typical meteorological radar data processing system is shown in block diagram form in Figure 15.

4.2 Signal processing

4.2.1 General

It has been established in section 3.2 that the signals at the output of the radar receiver are in the form of a varying d.c. voltage and that the signal echoes which contribute to this voltage can be allocated their correct position on a plan view centred on the radar. Before the data can be processed, the signal echo voltages and the relevant angle information must be converted into digits. Then, in order that the signals should not remain a series of rapidly varying, transitory numbers, it is necessary to divide the area scanned by the radar into cells or "bins" of a suitable size and shape and to fill or refresh the bins constantly with the digitized received signals. Because of the noise-like character of the echoes from precipitation, it is also necessary to take a number of samples of independent, decorrelated measurements before arriving at a meaningful figure for the precipitation intensity within a bin (see later paragraphs). Once this has been achieved, the basic digital data are available for display or for further processing.

Although different methods have been developed both for reaching the stage described above and for the subsequent processing, there is a considerable degree of similarity between them, since the inputs are generally similar in form and the output requirements follow similar lines. The brief descriptions which follow are generalizations based on methods which have already been adopted by different workers in the field.

4.2.2 Data collection and sampling

The size of bin required for the initial data collection and sampling has a lower limit determined by the beamwidth and the pulse length. The achievable discrimination can, in fact, be no smaller than the beamwidth (since the power transmitted in any pulse effectively fills it) times half the pulse length (since this is the lower limit of range discrimination — see page 162 of Battan (1973)). In practice, the use of bins of this size would lead to an excess of data to be handled. In order to reduce the amount of data, a range cell may
be constructed from a number of range elements (see Figure 16); it can be shown that this averaging may lessen the effect of noise, and thus the signal-to-noise ratio is improved in proportion to the number of range elements added together. Typically, a range element will be 187.5 m (for a clock rate of 0.8 MHz) and four would be added together, making a bin 750 m \times 1°.

![Figure 16 - Construction of range cell and azimuth bracket.](image)

The antenna rotation rate of radars used for precipitation measurement is low, 6 r.p.m. at most, commonly 3 r.p.m., and in the British system about 1 r.p.m. There are several reasons for choice of rate. It can be partly dependent upon the method of data processing or, alternatively, the method of data processing is determined by the "standard" rate of rotation of the antenna. The former is true of the British system in which data are processed as they are received and the need to store raw data in polar co-ordinates is avoided (although there may be other reasons for storing polar data, e.g., for bright-band corrections (see section 5.7.2)). At 3 r.p.m. in the Swiss system, such data are put onto a computer disc before being fully processed. This means that there is a slight delay in the processed data becoming available but this is not significant. The combination of rotation rate and method of processing may leave gaps in data at long range. This can be counteracted by assuming values based on data in neighbouring bins, although there will inevitably be a loss of accuracy.

For calculation purposes, at the slow rotation rates used it is convenient to consider the antenna to be momentarily stationary. Since the time taken for a pulse to travel from the radar to a range of, say, 200 km \( \approx \frac{1}{4} \) millisecond – is short compared with the time taken for the antenna to move through a significant arc, this is an acceptable assumption. (At 6 r.p.m. the antenna will have moved only 0.024° in \( \frac{1}{4} \) millisecond.) The British system (Ball et al., 1976, 1979) then takes readings on the assumption that the beam pattern can be divided into a series of overlapping sectors of angular width equal to that of the beam moved on by 0.1° between successive readings. Figure 16 shows how a 1° sector can be divided into range elements combined to become range cells, the whole forming a polar range cell, the size of which determines the initial resolution.

An important feature of sampling is the necessity, in order to achieve the greatest accuracy, of using decorrelated measurements. In rain the reflected signal is the vector sum of the signals from each single drop within the pulse volume. The signal from a given pair of drops may add constructively if their distance from the radar differs by \( (2n + 1) \frac{\lambda}{4} \) (where \( n \) is an integer and \( \lambda \) the radar wavelength). Within a given pulse volume drops are moving continuously relative to one another so that the reflectivity of the whole is constantly changing. In practice the motions of the drops are such that the correlation between successive measurements (from successive pulses) becomes zero after about 3 to 15 milliseconds for meteorological radar wavelengths. The decorrelation time depends upon range (because this affects the width of the beam in space) and wind speed (which is proportional to the degree of atmospheric turbulence on which drop
sorting depends), hence by choice of sampling rate (and the number of signals averaged to form a sample) acceptably independent measurements can be made.

One advantage of a slow rotation rate such as 1 r.p.m. is that it allows sampling decorrelation times to be reduced (Ball et al., 1976), though this will affect clutter measurements as well as precipitation measurements and will make more difficult their removal by fluctuation spectra discrimination means (see section 4.5.2). A secondary advantage is that the shorter decorrelation times tend to counteract instability in the transmitter pulse and shortcomings in the receiver bandwidth.

A practical aspect affecting rotation rates is that many systems are required to provide height or volumetric data. A very slow rate of rotation would result in a considerable increase of the interval between availability of output data sets.

The number of polar range cells into which a complete circle can be divided is a compromise between having too many, which, as stated earlier, would result in too large quantities of data being available for ease of handling, and the loss of discrimination which occurs if they are too large. It should be noted that the farther from the radar, the larger the cells. This is of some importance when converting from polar to cartesian co-ordinates since the cartesian cells are the same size at all ranges, but the deterioration in discrimination in the process is matched by the deterioration in discrimination in the radar itself.

Averaging in range can be achieved by hardware in a unit similar to that described in the annex to this chapter called the Radar Signal Averaging Unit (RSAU), whilst the averaging in azimuth (in effect, averaging in time) can be achieved by software. Four range elements are averaged, though the number is adjustable from one to sixteen. The movement of the antenna and its tell-back positional change of 0.1° about every 15 milliseconds cause the RSAU to collect the receiver output data following the next available transmitter pulse. The RSAU, having averaged the selected number of range elements, transfers the averaged range cell resultant directly to the computer. The heavy overlapping of successive range cells ensures that adequate sampling is carried out during one sweep of the antenna. An important feature of this method with its slow antenna rotation rate is that it allows continuous real-time processing of the data using a standard mini-computer.

The size of cartesian cell used in the British system for a single radar is 5 km x 5 km for display purposes on an 84 x 84 grid based on a maximum range of 210 km. For sub-catchment data to 76 km, 2 km x 2 km squares are used. The original British system was developed to provide plan data only since, in the UK, such height information as may be required for meteorological forecasting and aviation advice can often be deduced from the information available (i.e. plan radar data together with other synoptic data). This means that ample time is available for real-time processing. In practice, time can be made available for range/height scanning without detracting significantly from the gathering of plan data; software is available for this. (The form of plan display is shown in Figure 17(a) for a single radar and in Figure 17(b) for a composite from four radars.)

In other systems higher rates of antenna rotation, e.g. 3 r.p.m., are used. In the method in use in Switzerland (Joss, 1978), single samples of range elements are taken during successive rotations. The same type of range element averaging takes place (as in the British system), the number of elements being commonly 8, whilst azimuth averaging is adjustable from one to 16 (or 32). In this method a sequence of data collection is followed by a period of calculation. Thus several minutes elapse before a complete polar cell is available, but this does not necessarily imply any reduction in the number of samples taken and the total data ultimately available.

The Swiss system (used elsewhere also) uses an initial spatial resolution of 1 km but reduces this to 2 km during processing. The fine resolution provides good statistical reliability and enables areas free from ground clutter to be more easily identified (see paragraph 4.5.2) – a matter of greater importance in mountainous countries.
Figure 17(a) — Photograph of a typical picture derived from a single radar in the UK network. The maximum range from the radar (at the centre of the picture) is 210 km. Each cell is 5 km x 5 km. Time is shown in the top left-hand corner, date and station number in the top right-hand corner. The scale of colours against intensities is in the bottom left-hand corner. (In later pictures a coloured square indicates whether the precipitation values have been adjusted with the aid of a small number of telemetered raingauge readings, the colour itself indicating the type of rainfall.) (British Crown copyright/RSRE photograph)

Figure 17(b) — Photograph of a typical composite picture derived from four radars in the U.K. network. The maximum range of each radar is 210 km, but where two radars overlap predetermined boundaries are used. Each cell is 5 km x 5 km. Time and date are shown in the bottom right-hand corner. The scale of colours on the left-hand side corresponds with the intensities in Figure 17(a), black representing zero. The area covered by the picture is 640 km x 640 km. The code on the right-hand side represents station numbers against which can be shown objectively determined rainfall types, in this instance frontal rainfall at stations 3 and 4 (the system was not implemented at stations 1 and 2 at the time) (British Crown copyright/RSRE photograph)
In this system the antenna carries out a spiral scan such that data are gathered to a height of 12 km within the effective range of the radar, in vertical cells 1 km in height. The displayed plan data in 2 km × 2 km cells can then be from any selected level (including ground) or the maximum values detected over a 430 × 400 km grid. In addition, east-west and north-south elevation slices are available showing the maximum values across the area in 2 × 1 km cells (see Figure 18.) This format is useful in providing information for aviation purposes, and the two vertical projections, together with the plan, can be shown on one colour-television screen. It represents a greater processing task but the main disadvantage is that it decreases temporal resolution.

![Figure 18](image)

Figure 18 — Three-dimensional display. This photograph of a display in the Swiss system shows the station name, time and date in the top right-hand corner and the scale of colours against intensities on the right-hand side. The main picture is a plan view of the area under observation; it can be selected to show precipitation intensities at any level (e.g. ground) or the maximum values regardless of height. The top part of the picture shows the maximum values in an east-west direction across the area and the bottom part the maximum values in a north-south direction. The area covered is 400 km × 430 km with plan display in 2 km × 2 km squares whilst the vertical sections are derived from 2 km × 2 km columns in 1 km steps to a height of 12 km (Swiss Meteorological Institute)

4.3 Calculation of precipitation intensities (Z-R relationship)

In section 2.13 there was discussion on drop-size distribution in rain leading to an empirical formula relating echo intensity and rate of rainfall, viz:

\[ Z = a R^b \]

where \( Z \) is known as the reflectivity factor and is \( \Sigma D^6 \), \( R \) is the rate of rainfall and \( a \) and \( b \) are constants. \( D^6 \) is usually measured in mm\(^6\) m\(^{-3}\) and \( R \) in mm h\(^{-1}\). The size of raindrops and their distribution in a given volume vary considerably (see Marshall and Palmer, 1948), both within one type of precipitation and, more so, from one type of precipitation to another. Thus, the “constants” \( a \) and \( b \) can vary considerably. Battan (1973) lists nearly 70 different relationships derived by different workers. Three typical ones are:

- For orographic rain and drizzle: \( Z = 31 R^{1.71} \)
- For stratiform rain: \( Z = 200 R^{1.6} \)
- For thunderstorm rain: \( Z = 486 R^{1.37} \)
Generally, the coefficient, $a$, increases and the exponent, $b$, decreases with increasing convective intensity (Wilson and Brandes, 1979).

The selection of the appropriate constants is the major problem in the measurement of precipitation. Unless users have particular knowledge of experience relating to their own region, it is common in temperate zones to use the relationship $Z = 200 R^b$ (or something close to it) for all types of rainfall, this representing a reasonable mean, though it is unlikely to be appropriate to rainfall causing flash floods.

It is conceivable that the constants could be adjusted to suit the type of rainfall, either automatically in accordance with the rainfall rates and the spread being measured, or by human intervention. No such idea has yet gained operational credence. The method of adjustment by interrogating a small number of telemetered raingauges, carefully sited and maintained, has been investigated for some time in research systems and more recently in operational systems. This takes account of errors and effects which are additional to those arising from incorrect selection of constants $a$ and $b$. Such techniques are likely to be incorporated in operational systems for many years to come. However, whilst generally allowing for variations in Z-R relationships and for problems arising from rainfall at very low levels in the atmosphere, they do not result in uniform performance in all synoptic situations. These problems are discussed in greater detail in Chapter 5.

4.4 Aspects of radar performance and electromagnetic radiation affecting precipitation measurements

4.4.1 Introduction

There are a number of features which affect the collection of satisfactory precipitation data. Some of these have been mentioned in Chapter 2 – for example, antenna aperture, range attenuation, attenuation due to scattering and absorption. Those for which variable corrections may have to be made in the light of conditions at the time of measuring are discussed in Chapter 5. Those for which action can be taken in radar design are dealt with here.

4.4.2 Dynamic range

This parameter was mentioned in section 3.2. It is a measure of the range of precipitation intensities which can be dealt with by the radio receiver without distortion of their relative values. If the dynamic range is too short, either light precipitation will not be detected at far ranges or heavy precipitation will be reduced in apparent value and potential flood conditions may not be observed.

It will be apparent that the value of the dynamic range required depends on the maximum instantaneous rates of precipitation or rainfall likely to be experienced in the region where the radar is sited. The fact that these vary considerably in different parts of the world is well known, but actual figures are hard to determine because of lack of suitable instrumentation. A rapid response raingauge is required, but such an instrument is rather complex and not suited to operational use.

Although instantaneous radar measurements may be smoothed by sampling (see section 4.2.2), it is still highly desirable to be able to detect the maximum values. It is believed that within a mean rate of, say, 128 mm h$^{-1}$ measured over a few minutes, there will be instantaneous values considerably in excess, possibly as high as 256 mm h$^{-1}$. Such figures would not be unknown in temperate zones. In the tropics, where mean rates in the order of 128 mm h$^{-1}$ are common, with mean rates of 256 mm h$^{-1}$ being experienced from time to time, it can be assumed that a figure of 512 mm h$^{-1}$ must be allowed for. An 80 dB receiver will handle mean precipitation rates between 0.1 mm h$^{-1}$ and 512 mm h$^{-1}$ and somewhat beyond the upper figure. Modern components and techniques make such a receiver possible, though users should be careful to ensure that the dynamic range is properly defined by the manufacturer and that it covers the whole receiver, not just part of it.

If the peak rates occur for a very short time only, or over a very small area, they may have only a marginal effect on precipitation totals. In a system in which the antenna rotation rate is slow, they may not even be detected by the radar, but this does not justify acceptance of too small a dynamic range.
4.4.3 Range attenuation

It was explained in section 2.9 how range attenuation is countered either by the adjustment of the receiver amplification in step with increasing range or by compensation in the computer in order that precipitation of equal intensity shall appear the same regardless of range. The correction curve applied should match the theoretical law to better than ±1 dB for all ranges at which measurements are made. Because it takes a finite time for the electronic circuits to settle after the transmitter fires and because there is usually some clutter close to the radar, it is seldom practicable to make meaningful measurements at ranges below about 5 km; swept gain does not therefore usually commence before 5 km. It does not usually continue beyond 200 km; sometimes less. Were it to go farther, or, more correctly, beyond the range where signals cease to have amplitude much above noise level, the hardware method would tend to reduce all signals to an amplitude difficult to handle and would therefore decrease the chances of consistent measurement. On the other hand, if the correction is programmed in software, these problems mostly disappear.

It will be noted that even the ±1 dB mentioned above is larger than is really desirable and may lead to appreciable errors in rainfall measurements. Unlike the figures for stability, however, swept gain errors should occur only at certain ranges and should be constant within the overall receiver stability figure.

4.5 Aspects of siting affecting precipitation measurement

4.5.1 Introduction

The difficulties of finding a perfect radar site are dealt with in Chapter 8. In practice, a site is almost invariably a compromise. The shortcomings which are likely to arise are discussed in the following paragraphs.

4.5.2 Permanent echoes

Permanent echoes are return signals from either natural or man-made objects (hills, buildings, towers, etc.). Within the variability that all radar signals possess, permanent echoes vary less rapidly under a given set of conditions. They are generally much larger than the echoes from precipitation and consequently tend to swamp them. The term ground clutter is often used to indicate the unwanted groups of signals received from a collection of permanent echoes.

It is possible to predict areas likely to be affected by permanent echoes (see section 8.3) but, once a site has been selected and the radar installed, such echoes can be removed only by complex circuitry which is not yet operationally available (see following section). In fact, the strength of the signals varies with the conditions such that, when wet, the amplitude is greater. Hence, it is not possible to subtract directly the signals measured when dry from the total returned signals when wet and thus determine the precipitation. At present, the method most used to remove these unwanted echoes is that of programming the computer to collect a clutter map when there is no precipitation; this can then be used to designate the locations where no viable measurements can be made. In the output from the computer these areas can be shown as having no signal returns, although it will be seen from the earlier part of this paragraph that, when wet, there may be some signal breakthrough. In uniform rain it is acceptable to interpolate over a small area of clutter in order to calculate rainfall totals.

Because of the rapidly changing nature of the echoing surfaces of precipitation drops, the fluctuation spectra of returned signals therefrom are different from those of signals from permanent echoes. This leads to the possibility of differentiating automatically between them. Work to this end was initiated in Japan (Aoyagi, 1978; Tatehira and Shimizu, 1980; Aoyagi and Kodaira, 1980) and is now being followed up elsewhere. The permanent echo signals recognized in this method can be subtracted from the total echo signals; whatever the degree of wetness, the residual signals represent the precipitation. A 60 dB rejection level has been claimed on occasions but a lower figure seems likely in operational systems. Should this prove to be, say, 20 dB, the method will be well justified. The same technique can be applied to differentiating between precipitation and sea-clutter (echoes due to the roughened surface of the sea). In this case, however,
the rejection level will be considerably lower because the variability of the echoes is much greater due to the effects of wind on the direction of movement and size of waves. However, should this be 10 dB or even less, it would still represent a worthwhile improvement.

Another method of removing permanent echoes is by using a Doppler radar (see Chapter 10). This can determine whether an echo is moving or is stationary and remove unwanted signals automatically by a processor. The system is, however, more expensive and is not yet in general operational use.

At most sites, however carefully selected, clutter is worst within fairly short range, perhaps up to 10 or 20 km. One method of minimizing the effect is to ignore data from the lowest elevation sweep (nominally with the bottom of the beam at 0°) up to a range of, say, 20 km, and to fill the gap with data from a higher elevation, say, 1.5°. This will be free of a good proportion of the clutter whilst, at 20 km, the beam will still be within 100 m of the Earth's surface. Some of the residual echoes, particularly those at very close range, will be due to side-lobes.

4.5.3 Screening

A further problem associated with siting is occultation, or screening, when the radar beam is intersected by an obstruction which will probably be seen as a permanent echo. Figure 19 demonstrates the effect. If the obstruction is very large, e.g. a mountain, there will be a dead area behind it and no precipitation will be observed. If, on the other hand, the screening is only partial, up to 60%, acceptable data can be obtained with the appropriate factor being applied. The precipitation which will be seen will probably not be close to ground level; the significance of this is discussed in section 5.5.

![Figure 19 - Illustration of the occurrence of screening and permanent echo (clutter) in a hilly region (Final Report, Dee Weather Radar, 1977)](image)

4.5.4 Beam-filling

The Z-R relationship in the equation in section 4.3 assumes that the radar beam is completely filled by precipitation scatterers. When this is not so – for example, in localized showers – the reflected energy will be less than the rate of precipitation would justify; as a result an underestimate will be made. As explained in section 2.10, at a range of 100 km, a 1° beam will cover an area in the atmosphere of 1.75 km in diameter. The need to have the beam filled is one of the major reasons for restricting the range to which measurements are made, and this, in turn, indicates the need for the beamwidth to be as narrow as is practicable. It is possible to improve the average accuracy from, say, 100 km onwards by using empirically derived correction factors based on the probability of beam-filling. Many systems make measurements to ranges in excess of 100 km even with beamwidths of 1.5° or 2°. Such measurements must be treated with reserve; their reliability will depend on the depth and type of the precipitation. These data can be very valuable for forecasting purposes, as opposed to measurement. (Note that the reservations on range due to the beam not being filled apply to a lesser degree to radars used for detection and tracking; in this case, any signal detected at maximum range, say, 400 km, however small it may seem in intensity, must represent in normal propagation conditions precipitation at a considerable height.)
4.6 Effective radar reflectivity factor, $Z_e$

The discussion on precipitation measurement so far has used the radar reflectivity factor, $Z$. It is only correct to do so if the scattering particles are very small compared with the radar wavelength and the back-scattering fulfills certain conditions. On the other hand, the radar beam often intersects ice crystals which are probably not spheroids, thus invalidating use of $Z$. Therefore a quantity known as effective radar reflectivity, $Z_e$, may be defined as the summation per unit volume of the sixth power of the diameters of spherical water drops in the Rayleigh scattering region which would back-scatter the same power as the measured reflectivity. In this way the reflectivity factor of scattering particles outside the Rayleigh region may be referred to. The methods of measurement and the units used are mostly the same as for $Z$, but for $Z_e$ the dBZ unit is often used representing reflectivity measured in decibels with respect to 1 mm m$^{-3}$ such that

$$\text{dBZ} = 10 \log_{10} \left( \frac{Z \text{ mm}^6 \text{ m}^{-3}}{1 \text{ mm}^6 \text{ m}^{-3}} \right)$$

Further discussion on $Z_e$ can be found in Chapter 4 et al. of Battan (1973), in Atlas et al. (1964) and in Browning (1978), the last-named drawing attention to its significance in the detection of hail.

4.7 Measurement of snow

In the previous paragraph it was pointed out that the radar equations are only valid if the precipitation particles are spheroid and small compared with the wavelength. The variability in size and shape of snowflakes suggests that radar measurement of falling snow is particularly difficult. Nevertheless, such measurement has been shown to be feasible using methods similar to those for rainfall. The measurement of snow falling on the ground presents difficulties due to the drifting which occurs and the resulting unevenness with which it lies. Thus, conventional rain gauges (including those which melt the snow) and weighing gauges are unreliable as sensors and a better, but not always practicable, method is a series of depth measurements over an area. Despite shortcomings, then, radar can be the most reliable means of measuring the water equivalent of snow, certainly in real time.

There has been less work done in this area than in measuring rainfall, but those projects carried out demonstrate quite clearly that the values to be given to the constant $a$, and, to a lesser extent, constant $b$ (in the equation $Z_e = aR^b$) depend upon the snow type. Imai (1960) gives for “dry” snow $Z_e = 540R^{2.0}$ and for “wet” snow $Z_e = 2100R^{2.1}$. Sekhon and Srivastava (1970) concluded that $Z_e = 1780R^{2.21}$ would give consistent results in most snowstorms. These values were used by Wilson (1975) with some success. Puhakka (1975) points out that the type of snowflake and the aggregation depend upon the temperature and suggests that coefficient $a$ could be adjusted accordingly with the highest values occurring when the surface temperature is increasing towards 0°C. His findings support those of Imai mentioned above.

Most of the findings have been based on a small number of snow-measurement projects in fairly flat terrain but a pattern has emerged, as implied above. One detailed case study (Collier and Larke, 1978) demonstrated that over hilly terrain radar measurements of snow depth or water equivalent are still meaningful.

The range to which snow measurements can be made is shorter than for rainfall measurements. This is due primarily to the fact that the growth and aggregation of snowflakes tend to take place at the lower levels, i.e. below the radar beam when Earth's curvature has taken effect.

The accuracy of snowfall measurement is discussed in section 5.10.

4.8 Precipitation measurement by attenuation

In section 2.14 it was stressed that electromagnetic radiation is attenuated by raindrops, particularly at the shorter wavelengths. As a result, when making measurements of precipitation by the now common reflectivity method, the longer wavelengths are recommended. However, it is possible to measure precipitation by measuring attenuation. Ryde (1947) and Wexler and Atlas (1963) point out that, at wavelengths near to 1 cm, the attenuation is related nearly linearly to the rainfall rate. In practice, the wavelength most used
has been 0.86 cm, though in some experiments 1.25 cm was employed. The method is to set up a number of targets (or receivers) at different points and to measure the signal strength on a dry day. In rain, the differences in signal strengths may be used to calculate the path-integrated rainfall (provided that the rain is not sufficiently heavy to prevent the reception of any signal). Gunn and East (1954) found that at 0.9 cm the relationship is \( K = 0.22 R \) and at 1.25 cm \( K = 0.12 R^{0.05} \), where \( K \) is the attenuation in dB km\(^{-1}\) one way (see Table I, Chapter 2) and \( R \) is the rainfall rate in mm h\(^{-1}\) at 18°C. (By extrapolation, at 0.86 cm, \( K = 0.23 R \).)

Temperature dependence is such that from 0 to 30°C the variations in attenuation for all intensities of rain do not exceed 15% of the value at 18°C.

This method, set out by Collis (1960), has not, by itself, become operationally acceptable. The practical problem of setting up reflectors, visible to the radar in different directions from it and stable in all conditions, is very considerable, particularly if there are to be a sufficient number to permit estimation of areal rainfall. However, attenuation methods have their place, as is indicated in the next section.

4.9 Dual-wavelength systems

A more sophisticated method of precipitation measurement is that of using two wavelengths simultaneously. In this way the measurements can be made from a combination of attenuation and reflectivity or by comparison of two levels of attenuation. This was suggested by Rogers and Wexler (1963), Abshaev (1968), Sulakvelidze and Dadali (1968) and Eccles and Mueller (1971). The USSR has turned this to operational use to some effect, combining either 0.8 and 3 cm wavelengths (Kostarev and Chernikov, 1968) or 3 and 10 cm wavelengths.

The calculations are simpler if, for both wavelengths, the beamwidth, pulse repetition frequency and power output are the same; in practice, this is difficult to achieve, so appropriate correlation has to be taken care of in the calculations.

This comparative method of measurement overcomes some of the problems of the variability in the \( Z/R \) relationship. Furthermore, it enables the liquid-water content to be calculated in addition to the rainfall rate, \( R \). If short wavelengths are used, then it becomes possible to detect clouds as well as to determine the water content, while Eccles (1978) demonstrates how, to determine precipitation rates liable to cause flash floods, an X-band/S-band (3 cm/10 cm) radar can be used operationally with greater accuracy than a single radar using reflectivity calculations. He argues the case for the implementation of such systems as an aid for accurate early flood forecasting, thus supporting the Soviet viewpoint.

There are, however, some disadvantages with dual-wavelength systems. Firstly, there is the practical one of increased cost and added complexity. Secondly, there are inevitable range limitations due to attenuation by absorption and scattering (see sections 2.14 and 5.4). If the precipitation is so heavy that, at the shorter wavelength, no returned signals are received, then the system can rely only on reflectivity measurements at the longer wavelength. It is apparent, therefore, that such radars are of greatest value in regions where precipitation intensities are not generally high, e.g. northern Europe. (Dual-wavelength radars can also be of value in determining the presence of hail, but this aspect of usage is still in the research stage (Eccles, 1975).)

4.10 Dual-polarization systems

The most common method of determining rainfall rate by radar is to measure the reflectivity and to use empirical relationships (which may be modified during processing – see Chapter 5). These relationships depend on the statistical distribution of drop sizes at the time of measurement; errors will be greater if either the volume under investigation or the time over which data are averaged is small. One method of overcoming this problem is to make use of the fact that large raindrops distort as they fall to become oblate spheroids with their axis of symmetry approximately vertical. The degree of oblateness increases with the size of the drops. Thus, the radar reflectivity factor measured using horizontal polarization will differ from that measured
using vertical polarization, and a method of determining the drop-size distribution presents itself. In addition to the drop-size distribution so determined, it is also possible to distinguish between raindrops and dry ice particles. The theory is described by Seliga and Bringi (1976) and later application of the technique by Cherry et al. (1980).

At present it is not possible to switch rapidly from one polarization to the other in a conventional radar. Special arrangements are required. Furthermore, the technique is effective only up to a range of about 40 km. At present it is therefore of greater value in research applications than it is operationally.

Bibliography


ANNEX

EQUIPMENT USED FOR PRECIPITATION MEASUREMENT

1. Digital Video Integrator and Processor (DVIP)

This device is basically a hard-wired processor which collects data from the radar and passes them to the main computer. It had, as its origin, the iso-echo system described in section 3.7.4, and can be described as an intensity contouring device which continuously averages logarithmic video signals from the radar receiver output in both range and azimuth. By using conventional exponential weighted digital integrator techniques, synchronized with the radar system, quantitative estimates of mean precipitation are obtained within the bins explained in section 4.2.1. These bins are, typically, 1 km by 1° out to the maximum usable range, usually between 200 and 400 km, and over 360°. The accuracy with which the device functions is dependent on the sampling within itself, but most of the errors will be introduced by the limitations of radar measurement dealt with in Chapter 5.

The DVIP may well contain range-normalization functions, making the need for special circuitry in the receiver for this purpose unnecessary. A stored correction curve will enable appropriate values to be subtracted from (or added to) each range bin.

Most DVIPs provide a contoured logarithmic output, of several intensity levels (say, six), which can be displayed on a conventional PPI in monochrome or on a color television, some simple intermediate processing being necessary for the latter.

It is possible to build into the DVIP other functions such as clutter rejection. It becomes a matter of choice whether this should be done at this stage or in the computer, if one exists.

The main output in a precipitation measuring system is, naturally, digital; a series of binary words correspond to each integrated video sample. These, together with angle data, also digitized, can be used for further processing for different purposes within a computer. However, the DVIP is basically a "stand-alone" unit, used to feed a display, often without further processing.

2. Radar Signal Averaging Unit (RSAU)

This unit performs some, but not all, of the functions of the DVIP. It takes in the same logarithmic video signals from the radar receiver, digitizing and sampling them at a rate of approximately once per radar pulse length. It consists essentially of an analogue-to-digital converter, a memory to which the averaged signal values are fed in discrete time elements (time being directly proportional to range), and control logic to ensure proper transfer of data on computer demand. Clock pulses are available to enable the radar signals to be sampled in the correct elements leading to range cells or bins of 750 m × 1°.

It will be noted that the RSAU is a less complex unit than the DVIP, as it performs fewer functions and has fewer outputs. Its product needs a greater degree of processing by computer.

3. Scan converter

For convenience of analysis, the radar data are converted from the polar bin pattern to a cartesian square bin pattern. This makes every bin the same size, even though the resolution of the data within it will decrease with range from the radar. It is also easier to fit squares meaningfully to geographical areas and to river sub-catchments.
The polar-to-cartesian grid conversion is sometimes carried out within the computer, sometimes in a separate scan-converter unit. The process consists of setting up a grid of cells or bins of suitable size, squares of, say, 1, 2 or 5 km sides, and filling these with data from the previous stage (video processor or averaging unit), each polar bin being interrogated. It will be noted that close to the radar, several polar bins may be required to supply data to one cartesian cell, whereas at longer range one polar bin may cover part of several cartesian cells. Since the geometrical relationship between the two types of cell or bin is always the same, proper allocation and weighting can be determined to ensure meaningful representation of precipitation intensity values.

In certain circumstances it is advantageous to have the conversion carried out separately from the computer inasmuch as it reduces the data to a level which can be transmitted to a computing centre by telephone line or microwave radio link (though a high-quality service would be needed, possibly 9600 bits/second).

4. Radar computer interface

Depending on the overall design of the system, it may be necessary to have a special interface unit between the radar and the computer to ensure that all the necessary data and control signals are available for the correct operation of the program. The functions which it may be called upon to perform include the following:

(a) Conversion of angle data from the antenna to the digital form required, with digital display if not available elsewhere;
(b) Provision of interrupt control of the computer when the program has to respond to changes of antenna position;
(c) Control of antenna position if this is generated from the computer;
(d) Provision of clock facilities if not available elsewhere;
(e) Monitoring functions and test facilities to enable either the radar to be exercised without computer or the computer without the radar.

5. Computer

It is not proposed to discuss types of computer in this Technical Note. A manufacturer providing a complete system will incorporate a proprietary mini-computer of appropriate speed, with suitable functions and adequate storage to match his system design and the user's requirements. The speed will be critically dependent upon the data input rate, i.e. on the pulse repetition frequency and rate of rotation of the antenna (and upon the sampling rate required if there is no preprocessor such as a DVIP).

Any user designing his own system should be sufficiently competent technically to determine the significant parameters of the computer required. A skilled programmer will be needed to decide, for instance, the storage required, but such matters as what occurs in the event of a mains failure must be considered, particularly if the equipment has to operate at an unmanned station where program reloading may become a major task.

The functions which the computer must carry out will vary from system to system, but a selection of the following is likely, together with some not listed (the tasks are not in order):

(a) Averaging of input signals in azimuth (if not carried out previously);
(b) Averaging of input signals in range (if not carried out previously);
(c) Correction for range attenuation (if not carried out previously);
(d) Correction for screening (occultation) of the radar beam by intervening hills and obstacles;
(e) Elimination of ground clutter by comparison with a stored clutter map followed by interpolation to derive precipitation estimates in the cluttered areas; (or)
(f) Recognition of clutter signals by signal form differences and subtraction from precipitation signals in appropriate cells (see section 4.5.2);
MEASUREMENT OF PRECIPITATION

(g) Insertion of data from a scan at higher elevation into badly cluttered parts of the basic elevation scan (sometimes known as “pseudo-CAPPI”);

(h) Correction for attenuation through rain and atmospheric oxygen;

(i) Conversion from a large number of polar cells to a relatively small number of cartesian cells of appropriate size up to a selected range;

(j) Conversion of radar reflectivity factor $Z$ (or effective radar reflectivity factor $Z_e$) to rainfall rate $R$ using the relationship $Z = aR^b$ (with preselected values of constants $a$ and $b$);

(k) Adjustment of values of $R$ in accordance with readings of telemetered calibrating raingauges and to predetermined weighting plan (with modification of preselected values of constants $a$ and $b$ for discrete zones) (see section 5.8);

(l) Conversion of data to format for transmission;

(m) Writing to archive tape;

(n) Output of data for display and of calculated precipitation totals for selected sub-catchments if required;

(o) Control of radar antenna elevation and azimuth (if required);

(p) Various monitoring functions (some for program modification, some for transmission to control centre and some self-checking).

The peripherals for the computer will probably include a medium for data storage, such as a good-quality magnetic tape recorder, on which to archive all processed radar data in cartesian format, sub-catchment totals and certain monitoring data. Since the quantity of data will probably be such as to require tape-changing daily, it will be necessary at an unmanned site to transmit the data to a distant manned point for archiving. The same tape recorder may be used to load programs into the computer; thus, at an unmanned site a tape recorder of some kind will be necessary. It then becomes possible to use it for archiving in parallel with that at the distant point, building in a self-returning mechanism at the end of a tape with subsequent over-writing by new data. This means that, in the event of a breakdown in communications, data for one or two days may still be historically available. Alternatively or additionally, the processing equipment may include discs which allow greater flexibility. The program can be held on one and any changes simply made by insertion of another which has been pre-programmed. Increased storage capacity may also be available together with other facilities.

A necessity will be either a teletype (or similar keyboard device) with which to key in instructions to set the system into operation or to obtain special outputs for diagnostic purposes, or a visual display unit (VDU) in which messages can be stored and output on request. The teletype or VDU may also be used for obtaining print-outs of precipitation data or monitoring information.

6. Display units

For visual display of digital precipitation data, a colour television monitor or even a good-quality domestic television receiver can be used, but colour visual display units (VDUs) with flexible facilities are coming into favour. A number of colours (including black) are selected to represent bands of precipitation intensity. It is difficult to discriminate between more than sixteen, and eight are often considered sufficient. An example of the latter is:

<table>
<thead>
<tr>
<th>Intensity level</th>
<th>Intensity</th>
<th>Intensity code</th>
<th>Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$&lt; \frac{1}{8}$ mm h$^{-1}$</td>
<td>–</td>
<td>Black</td>
</tr>
<tr>
<td>1</td>
<td>$\frac{1}{8}$ – $1$ mm h$^{-1}$</td>
<td>L</td>
<td>Yellow</td>
</tr>
<tr>
<td>2</td>
<td>$1$ – $4$ mm h$^{-1}$</td>
<td>1</td>
<td>Green</td>
</tr>
<tr>
<td>3</td>
<td>$4$ – $8$ mm h$^{-1}$</td>
<td>4</td>
<td>Cyan</td>
</tr>
<tr>
<td>4</td>
<td>$8$ – $16$ mm h$^{-1}$</td>
<td>8</td>
<td>Blue</td>
</tr>
<tr>
<td>5</td>
<td>$16$ – $32$ mm h$^{-1}$</td>
<td>16</td>
<td>Violet</td>
</tr>
<tr>
<td>6</td>
<td>$32$ – $126$ mm h$^{-1}$</td>
<td>T</td>
<td>Red</td>
</tr>
<tr>
<td>7</td>
<td>$\geq 126$ mm h$^{-1}$</td>
<td>S</td>
<td>White</td>
</tr>
</tbody>
</table>
A typical picture is shown in Figure 17(a).

The range displayed will depend on the range to which data are computed or composited. For example, for a single radar site it may be $84 \times 84$ pixels of $5 \text{ km} \times 5 \text{ km}$, giving a picture $420 \text{ km} \times 420 \text{ km}$; for a composite of several radars it may be $128 \times 128$ pixels or $640 \text{ km} \times 640 \text{ km}$; for a combined radar-satellite display it may be $256 \times 256$ pixels or $1280 \text{ km} \times 1280 \text{ km}$.

The console which includes or controls the display will have facilities additional to those associated with the presentation of a colour picture of the types shown in Figures 17(a), 17(b) and 18. It is probable that some or all of the following features will be available, particularly if the circuits are microprocessor-based:

(a) Change of colour sequence or combination of intensity levels to show only three, such as "light", "moderate" and "heavy";
(b) Change of intensity scales displayed (see Table II), whilst retaining an acceptable compromise between accuracy and resolution;
(c) Geographical overlays (similar to those in Figures 17(a), 17(b) and 18) representing coastlines, national or district boundaries or sub-catchment boundaries, allowing visual location of precipitation;
(d) Recall of a number of recent pictures, enabling the observer to determine the track, speed and changing intensity of the precipitation, the latest picture automatically replacing the oldest in the store;
(e) Taping of a data sequence on an external recorder and playback of the tape (or of other tapes), allowing post-event analysis;
(f) A controllable marker or marker line, enabling an observer to track an area of precipitation of particular interest;
(g) Zoom facility, allowing a selected portion of the picture to be examined in greater detail.

<table>
<thead>
<tr>
<th>Level</th>
<th>A - Scale for normal precipitation rates</th>
<th>B - Scale for fairly heavy to heavy precipitation rates</th>
<th>C - Scale for very heavy to exceptionally heavy precipitation rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>dBZ</td>
<td>$R$ (mm h$^{-1}$)</td>
<td>dBZ</td>
<td>$R$ (mm h$^{-1}$)</td>
</tr>
<tr>
<td>1</td>
<td>&lt;23</td>
<td>&lt;1</td>
<td>&lt;40</td>
</tr>
<tr>
<td>2</td>
<td>28</td>
<td>1-2</td>
<td>42</td>
</tr>
<tr>
<td>3</td>
<td>33</td>
<td>2-4</td>
<td>44</td>
</tr>
<tr>
<td>4</td>
<td>35.5</td>
<td>4-6</td>
<td>46</td>
</tr>
<tr>
<td>5</td>
<td>38</td>
<td>6-9</td>
<td>48</td>
</tr>
<tr>
<td>6</td>
<td>40</td>
<td>9-12</td>
<td>50</td>
</tr>
<tr>
<td>7</td>
<td>42</td>
<td>12-15</td>
<td>52</td>
</tr>
<tr>
<td>8</td>
<td>&gt;42</td>
<td>&gt;15</td>
<td>&gt;52</td>
</tr>
</tbody>
</table>

NOTE: If, for example, in Scale C the value of 265 mm h$^{-1}$ appeared insufficient, it would be possible to re-scale the levels so that No. 1 becomes <64, No. 7 becomes 265-353 and No. 8 becomes >353. Such an adjustment would be particularly justified in the case of heavy hail.

The above facilities would be applicable when the display is remote from the radar and the processor; if it is at the radar site, it may be possible to replay pictures direct from the main archive and to change the cell size from, say, $4 \text{ km} \times 4 \text{ km}$ to $10 \text{ km} \times 10 \text{ km}$.

The advantages of colour displays providing an immediately available representation of precipitation intensities in a pseudo-geographical pattern or at various height levels are too self-evident to require further discussion. Such displays can also provide ready evidence of unwanted facets of radar data, for example of the existence of a bright band (Figure 25).
CHAPTER 5

ACCURACY OF RADAR MEASUREMENTS OF PRECIPITATION

5.1 Introduction

In the preceding chapters, mention has been made of the various parameters of the radar itself with reference to desirable design features. The methods of measuring precipitation and some of the difficulties have been discussed. This chapter summarizes the errors which may arise in attempting to obtain accurate precipitation measurements and points towards ways in which they may be reduced.

It is advisable to offer an explanation as to what is meant in the text by “error” and “accuracy”. The WMO Guide to Meteorological Instrument and Observing Practices, fourth edition, section 1.7.1, states:

In physical measurement, accuracy is defined as the closeness with which an observation of a quantity, or the mean of a series of observations, is considered to approach the unknown true value of the quantity. To achieve accuracy in measurement, instruments should have and maintain a calibration under given conditions to within the desired accuracy; the errors under other conditions should be known and be constant in time within required limits.

An error of observation is the departure of a measured quantity from its true value. Such an error is, in general, partly "systematic" and partly "random" or "accidental". A systematic error, whether instrumental or due to the personal equation of the observer, can usually be found experimentally and allowed for. The random errors present in a measurement can be reduced in magnitude by repeating an observation of an unchanging quantity and determining the mean of the n values.

In meteorological measurements, the problem of errors of measured values, whether individual or mean values, is complicated by the fact that the measured quantities are not themselves constant, but are subject to change on various time-scales. Experiment can usually discriminate between random errors of measurement and short-period fluctuations of the measured quantity. It is, however, more difficult to distinguish a long-period change of systematic error from a genuine secular trend of the measured quantity.

Such concepts can be applied to precipitation-measuring radar; the errors, although covering a number of facets, can all be categorized, and some action, though not always totally successfully, can be taken to counteract or minimize them.

The categories of the sources of error are as follows:

(a) Those due to shortcomings in the radar system and in the processing of data;
(b) Those arising from a variety of geographical and geometric features;
(c) Those due to uncertainties in physical properties.

In brief, those under (a) should not be of major importance provided that a radar is of modern design and well-maintained and the computer program is written to reduce errors to an insignificant level; those under (b) are generally identifiable and understood, are fairly constant and can be corrected for in the program. On the other hand, those under (c) pose a considerable problem. They include the major difficulty of determining the precise \( Z-R \) relationship, the effects of orographic rain and associated vertical gradient, low-level enhancement or evaporation and bright-band enhancement.

5.2 Radar system errors

5.2.1 Introduction

Certain aspects of radar performance have been dealt with in earlier chapters. Dynamic range (sections 3.2, 4.4.2) is important for accuracy of measurement. Range attenuation (section 2.9) should be taken care of in either the receiver design or the computer program. Radome attenuation (section 3.6) may be a problem under certain circumstances and is discussed in greater detail in the annex to this chapter.
5.2.2 Stability

A modern transmitter should be able to maintain its output to within ±0.5 dB (after an initial warming-up period). Older ones may be only slightly less stable — say, ±0.25 dB. Greater uncertainty exists in the receiver; even with modern technology and the maintenance of ambient temperature within a few degrees, the stability may be no better than ±1 dB. Dependent upon the rainfall rate, this may represent an appreciable error in precipitation measurement. (Table III shows the effect of such errors, shown as a percentage of rainfall against dBZ — see also section 4.6.)

Table III

Illustration of errors in precipitation measurement

Assuming that \( Z = 200 R^{1.6} \):

<table>
<thead>
<tr>
<th>Reflectivity error (dBZ)</th>
<th>Equivalent error in R (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>7.5</td>
</tr>
<tr>
<td>1.0</td>
<td>16.0</td>
</tr>
<tr>
<td>2.0</td>
<td>33.0</td>
</tr>
<tr>
<td>3.0</td>
<td>53.0</td>
</tr>
<tr>
<td>4.0</td>
<td>77.0</td>
</tr>
<tr>
<td>5.0</td>
<td>105.0</td>
</tr>
</tbody>
</table>

Stability is of greater significance than accuracy of radar parameters since all precipitation measurements are subjected to processing corrections and adjustments which can take account of such inaccuracies. Any form of drift or instability is more difficult both to detect and to correct for. Whilst it is possible to monitor transmitter output and receiver performance continuously and to input the data to the processor, the instruments used are not necessarily more stable than those which they are checking, particularly in the case of the transmitter.

5.3 Processing errors

It is inevitable that some errors should be introduced in the processing of data. All sampling techniques allow for certain errors, mostly small, whilst the need for processing in near real time means that some approximations may be made. Such errors depend upon the particular methods used, but it is unlikely that they would amount to more than a small percentage of the overall errors in any operational system.

5.4 Attenuation

Attenuation due to causes other than increasing range was discussed at length in section 2.14. It will be recalled that it was caused by the absorption of electromagnetic energy by water vapour and oxygen and by both scattering and absorption by liquid and solid particles in the atmosphere. The effect of oxygen is more or less constant for any given range and a fixed correction curve can be applied to the computation. The effect of water vapour is very dependent on wavelength; at 10 cm it is negligible, at 5.6 cm it is small, but at 3 cm it is significant. The amount of water vapour in the atmosphere is, of course, variable and applying a correction is not simple. This suggests that the longer wavelengths should be used when carrying out quantitative measurements. However, the major attenuation effect is due to the precipitation particles. Reference to section 2.14 and Table I shows that, in fairly heavy precipitation such as that found in temperate regions (say, 50 mm h\(^{-1}\) or more), it is not possible to use 3 cm, as the attenuation may be so complete that other heavy precipitation at a distance where it would normally be detected may not even be seen. Nevertheless, some good results have been obtained with 3 cm radars in polar climates, where heavy precipitation is less common (Jatila and Puhakka, 1973; Puhakka, 1978).

In temperate regions 5.6 cm is usually very satisfactory; although corrections may be necessary, they are not difficult to implement. They can be based on an assessment of intervening precipitation gained from the radar itself. In tropical regions and in other areas where high-intensity precipitation occurs it is advisable to use 10 cm, since 5.6 cm then suffers from the same defects as those of 3 cm referred to above. Even at 10 cm, corrections should be made in the heaviest rainfall.
One practical effect of the need to avoid attenuation as much as possible and, therefore, to use a longer wavelength is that a larger reflector, with consequent higher cost, is necessary.

5.5 Earth's curvature effects and low-level precipitation development

In space an electromagnetic beam travels in a straight line. In the Earth's atmosphere, however, there are vertical variations in pressure, temperature and humidity. The gradients cause refraction of the beam. The radar meteorologist is generally concerned with a beam projected at an elevation at or close to 0°. In this case, under what can be termed "normal conditions", the beam behaves over the range in which we are interested as though on the circumference of a circle with a radius 4/3 times that of the Earth. It will be seen from Figure 20 that, at a range of 100 km, with the bottom of the beam set at 0°, nothing can be seen by the radar below 600 m; at a range of 200 km, nothing can be seen below 2 300 m. It will be realized at once that this has a limiting effect on the maximum usable range, although for detection purposes in the tropics a much greater range is possible than elsewhere due to the high vertical development which takes place.

The effects of this divergence between the beam and the Earth's surface on estimates of precipitation intensities at the surface are as follows:

(a) Low-level precipitation may be missed altogether;
(b) Low-level precipitation enhancement may take place, unseen by the radar, leading to underestimations;
(c) Low-level evaporation may occur, thus leading the radar to overestimate;
(d) Because radar measurements may be made at considerable height above the ground, the precipitation may actually fall in an area some distance from that indicated by the radar (this is particularly true in snow);
(e) The beam will reach the melting layer earlier than it would have done otherwise.
Figure 21 – Cross-sections along the line AA-BB (Figure 22) for (a) a case of low-level rainfall enhancement at a medium wind speed, and (b) a case of little enhancement at a high wind speed. Dotted lines show the height of the radar beams (Collier et al., 1983) (British Crown copyright)
The problems arising from (e) are dealt with in section 5.7.2. The others, (a) to (d), result in some of the most serious errors in radar precipitation calculations. They can, to an increasing extent, be corrected for by raingauge comparisons (section 5.8) but the consistency of such corrections has yet to be established under all conditions. It may be that a greater understanding of the atmosphere is required and that knowledge of local meteorological effects would be an asset, both in writing a program for a particular area and in interpreting the data. It points to the possible need for human intervention before data are transmitted to all users (see section 5.11).

Work in the field covering (a) to (d) above resulted in an interesting and significant study (Collier et al., 1983). Two specific instances demonstrate the effect of orography upon radar measurements. Although all sites will be different and the precise effects variable, even on different azimuths at one site, the examples given are worthy of attention and may act as a useful guide to what might occur elsewhere.

Figures 21(a) and 21(b) show the cross-section of the direction from which the wind was blowing on the days in question—the same direction in each case. The radar is at BB. Due partly to the terrain, partly to the divergence of the radar beam from the ground and partly to clutter at ranges less than 24 km (requiring use of the next beam elevation above nominal 0° to in-fill), there can be no possibility of the radar measuring precipitation anywhere below 600 m. Orographic rain on the slopes unseen by the radar seems highly probable. With the aid of raingauge readings the pattern in Figure 21(a) was deduced confirming the rainfall which is probably typical. The 900 m wind speed was known to be 29 kn. However, Figure 21(b) shows a very different picture. The circumstances are precisely the same, except that the 900 m wind speed has increased to 55 kn. The orographic effect has almost disappeared and the rainfall rates, again determined with the aid of gauges, are markedly lower than would have been deduced from the example in Figure 21(a).
Figure 22 shows the position of the line AA-BB and the high ground which commences 25 km from AA and rises to levels in the order of 1000 m. Collier et al. (1983) deduce that, when the wind speed exceeds a certain figure, the high land to the windward causes a "rain shadow" which overcomes the effect of orography.

This significant study indicates the variable features which may be encountered in radar measurement and the need to understand the properties of each radar site.

5.6 Anomalous propagation

The previous paragraph referred to normal propagation conditions. Consideration has to be given to abnormal conditions. Sharp temperature inversions or conditions of strong hydrolapse change the refraction of the beam, leading to what is known as anomalous propagation. This occurs quite frequently, particularly in the tropics. The beam can be effectively ducted along the Earth's surface or reflected from it (Figure 23). This leads to many more ground echoes being received, with consequent difficulty in measuring precipitation in the areas concerned. Figure 24, which shows plan displays from the same radar (near Paris) on two different occasions when there was no significant precipitation, demonstrates the effect well. The existence of anomalous propagation is usually obvious to a human observer, but not to a computer. Work initiated by Japan on clutter suppression (section 4.5.2) may prove to be valuable inasmuch as the method recognizes clutter as it exists at the time of measurement rather than by comparison with a stored map obtained earlier under other conditions.

![Figure 23 - Anomalous propagation; reflection of the radar beam from the Earth's surface](image)

It will be apparent that anomalous propagation can lead to a shortening of achievable ranges due to a combination of more obstructions and absorption of the energy by those obstructions. On some occasions range is lost because the beam is refracted into the ground rather than along the surface.

There are some circumstances under which range can be extended undesirably. If there is a good horizon (for example, over a desert or the sea), a distant large target such as a range of mountains may appear on a display one time-base later, i.e. the signal echo is received after the next trigger pulse has fired the transmitter. Depending on the pulse recurrence frequency (p.r.f.), the target could be over 1000 km away. Again, this effect will be apparent to an observer but not to a computer.

It is unusual, but not unknown, for anomalous propagation to have the opposite effect from that described above. In this the beam is refracted less than is normal and it travels over the top of normally observed permanent echoes.
Figure 24 - Echoes due to anomalous propagation from a radar near Paris. Both pictures were taken when no precipitation was present. The left-hand picture shows the PPI under normal propagation conditions; the right-hand picture shows the effect of the beam being trapped near the Earth’s surface, resulting in echoes from distances up to 400 km, including the French and English coasts and the Jura Mountains (French Meteorological Service).
The height of the inversion/hydrolapse above the radar is important. Anomalous propagation is most likely when it is within a few hundred feet of the radar height. It becomes more unlikely with higher inversions and rarely occurs when the inversion is more than about 1200 m above the radar. It will not occur when the radar beam is above the inversion/hydrolapse. On most occasions when anomalous propagation is observed, it will be limited to certain regions and at times may occur only in a narrow sector from one radar.

5.7 Errors due to uncertainties in physical properties

The errors under this heading are equally as important as those referred to in the previous paragraph, though the relative importance varies from place to place.

5.7.1 Z-R relationship

In section 4.3 the relationship between reflectivity factor \( Z \) and rate of rainfall \( R \) was discussed with particular reference to the values assigned to the constants \( a \) and \( b \). \( (Z = aR^b, \text{where } Z = \Sigma D^6, D \text{ being the drop-size diameter}. ) \) The errors which can arise from selection of the wrong constants are considerable, assigned values varying from \( Z = 31 R^{1.71} \) in orographic rain to \( Z = 486 R^{1.37} \) in thunderstorms. (There must be a possibility that the small value of \( a = 31 \) in the first relationship is due to the radar seeing only a small proportion of the precipitation.) For snow, a relationship of \( Z = 2000 R^{2.0} \) is often quoted.

It is apparent that, by a totally wrong choice, the rate of rainfall could be incorrectly assessed by a factor of 10 or more. Use of the compromise relationship appropriate to stratiform rain, \( Z = 200 R^{1.6} \), reduces that possibility considerably. In most operational systems 200 and 1.6 (or figures close to them) are adopted for \( a \) and \( b \).

Although future work in understanding the atmosphere may lead to more direct methods of assessing the constants, the present standard method of adjustment of \( a \) and \( b \) is by comparison of radar readings with a number of telemetering raingauges. This is discussed in section 5.8.

5.7.2 Bright band

Previous discussion on the Z-R relationship has indicated the marked differences in reflectivity factor between different types of rain and between rain and snow (or solid precipitation). The highest reflectivity factors are associated with wet snow. As solid precipitation particles fall through the 0°C level and begin to melt, they acquire a wholly wet surface. The radar then sees enhanced echoes known as the bright band. The increase in reflectivity can be at least 50%, sometimes considerably more. This, then, is a further source of error and one which is difficult to allow for.

Firstly, the bright band needs to be recognized; it is not always immediately apparent, though it is usually much more easily seen on a colour range-height display (see Figure 25) than on a colour plan display. However, on the latter it can often be detected as a ring of apparently higher-intensity precipitation centred on the radar. As the belt of rain moves over the area the bright band usually remains more or less stationary. If the rain is of showery nature, it may not be apparent.

The extent to which it will affect measurement depends on the proportion of the beam filled by melting particles (as opposed to either ice having a dry surface or water drops); at the longer ranges this proportion is likely to be relatively small.

Ways of correcting for the errors arising have been considered, but some are little more than cosmetic. Comparison with raingauges (see section 5.8) will be helpful, but a more promising method currently being developed is the comparison of precipitation fields, in space, at different angles of elevation; this can indicate the precise position and depth of the bright band. A mean bright-band profile can then be used to correct the measurements. It seems likely that whatever method is eventually used, a large amount of computer space will be required to carry out the recognition and correction procedures.
5.8 Use of raingauges for comparison and adjustment

It has been emphasized previously in the text that radar and raingauges make different measurements, the one over an area, the other at specific locations. Mention has also been made of the use of gauges for comparison purposes; it is generally accepted by radar meteorologists that, if the best possible radar-derived data are to be obtained, some form of comparison with data from gauges is essential. The aim is to minimize the errors arising from the Z-R relationship (section 5.7.1) but it also enables corrections to be made for unseen low-level enhancement or evaporation (section 5.5) and for wind effects. It also helps to correct for inaccuracies within the radar itself, though it is highly desirable that these be corrected at source.

There are considerable problems, firstly in obtaining genuine radar/gauge comparisons, and secondly in knowing how best to make use of them in order to improve the quality of the precipitation data in real time. The development of the techniques is being continually evolved. An excellent review has been prepared by Wilson and Brandes (1979).

Ideally, as suggested in section 4.3, the constants $a$ and $b$ would be automatically adjusted by the program in accordance with the measured rate of rainfall and other data, particularly from raingauges, available to the computer. This entails machine recognition of the rain type. Work to this end is now being undertaken, with some encouraging results, but it is probably necessary for a greater understanding of the physical properties of the atmosphere to be acquired before total success is achieved.

It has been established by observation and measurement that the rain type may be ill-defined or that two types may exist either together or in different areas of the radar's field of coverage. For instance, a large area of stratiform rain may have within it an important cell of orographic rain. Moreover, quite large radar
reflectivity gradients exist in both showers and widespread rain (Harrold, 1973; Mueller, 1977). Any technique based on an examination of reflectivity gradients is likely to require comprehensive diagnostic software which might not be compatible with operation in a real-time environment.

The number of gauge sites required for real-time comparison is uncertain. The figure depends upon the topography of the region and the rain types encountered. All the sites should be in representative areas, at differing ranges and well-separated azimuths but, most important, in the sub-catchments of particular interest to the users of the data. In practice, the number is likely to be between five and fifteen.

The gauges need to be well maintained; tipping-bucket gauges, the type necessary if digital data are to be obtained easily, are often mechanically unreliable and, like raingauges of all types, are susceptible to the ingress of leaves, sand, etc. For these reasons, if only a small number of sites are available, it is preferable that there should be three gauges at each so that faulty ones may be detected.

If a larger number of sites are used, then single gauges are more acceptable, particularly if it is possible to determine objectively when any one site is not functioning correctly. No rules for this can be formulated; they depend on local circumstances and local knowledge.

Gauges should be such that the resolution is no worse than 0.2 mm h\(^{-1}\) in temperate regions. Anything higher will degrade the value of the comparison, though in torrential rain the rate of tip may lead to other inaccuracies.

When gauge data have been received at the radar site and found acceptable, the problem remains as to how they should be used. It is unlikely that a mean, taken from either a small or a large number of sites, can be applied to the whole of the area under radar surveillance; it would be rare for the same reflectivity factor to be applicable everywhere. Moreover, other circumstances, e.g. orography, may affect the differences between gauge and radar readings in particular areas, but not always to the same extent. Thus, it is necessary to determine which sectors or areas should use factors derived from each gauge site or from a combination of certain gauges, appropriately weighted. In fact, an analysis for any particular radar site can lead to a field of adjustment factors suited to a given set of conditions. The techniques of deriving the field will depend on the number of gauges used (Collier et al., 1983).

The adjustment factors, or "assessment factors", as they are termed, consist of straightforward multiplication factors. (Some workers use radar/gauge (R/G); others use gauge/radar (G/R).) These are applied directly to the processed radar measurements. Thus, although the original purpose of the radar/gauge comparison was to determine the best fit values of \(a\) and \(b\) (in \(Z = aR^b\)), in practice it is not necessary to adjust these in the computer program. By direct adjustment of the calculated intensities the other causes of error mentioned earlier in this chapter (unseen enhancement or evaporation, wind effects and radar hardware inaccuracies) are also accounted for.

In a real-time system, the gauges should be interrogated frequently, say every 15 minutes, as assessment factors can vary rapidly with time. The factors can then be recalculated on a past-hour basis and then applied to the radar data until the next interrogation. Considerable care is needed in their application; unless they are recognized as viable in any given set of circumstances, they may cause the rainfall data to be less accurate than if no factor were applied at all. This is most likely to occur during convective rain and localized showers. It can also occur when rates are small and a correspondingly small difference in measured intensity can represent a large percentage difference.

5.9 Accuracy of rainfall measurements

There is now a considerable amount of literature on radar/gauge comparisons. For detailed reading, the following are recommended: Zawadzki (1975), Wilson (1976), Cain and Smith (1976), Wilson and Brandes (1979) and Collier et al. (1983). The last-named is particularly relevant as its findings are based on an operational system.
As part of a long-term assessment, radar-derived precipitation data should be compared historically with those obtained from any well-sited and trustworthy gauges read hourly or daily within the area covered by the radar. This may show up deficiencies in the radar data over certain areas; conversely, it may demonstrate that a particular gauge is unreliable. It may help to determine the best sites for the gauges required for real-time assessment.

It is generally found that when a radar/gauge comparison is carried out, the differences increase as the range increases. Thus, adjustment factors are applied at greater ranges with less confidence in their validity. Nevertheless, and despite the limitations put on ranges to which precipitation measurements should normally be made (depending on the site and upon the radar, up to 100 km in temperate zones, up to 150 km in the tropics), it is possible to obtain relatively accurate data in small areas above the normally accepted maximum range by provision of a further telemetered comparison gauge in the area of interest. It is necessary for the radar to have a good field of view in the appropriate direction. Below the maximum range also, the quality of data may be improved in a small area by the same procedure. It seems likely that data for such special interests should be processed separately from the radar system.

The user understandably asks what the accuracy of radar-derived rainfall data really is. This is a difficult question to answer. As there are so many variables, it is doubtful whether one figure to cover all circumstances can ever be given. First of all the accuracy of raingauge measurements for use as a standard is uncertain, and areal data based upon raingauges alone is even less certain. The only reasonable standard for areal measurement is the “optimum field” (Harrold et al., 1974) derived from data from a large number of gauges with the radar interpolating between them.

Most accuracy claims so far made have been based on limited experimental projects rather than on operational systems running routinely over long periods in all conditions. With these limitations in mind it is possible to quote from the Dee Weather Radar Project Report (1977), as follows:

(i) If a radar/raingauge calibration is carried out at the end of each hour, then the radar estimates of hourly rainfall over subcatchments (~50 km²) differ from the optimum estimates (i.e. the estimates given by a dense network of raingauges modified by the radar pattern between gauges) by about 15% within 15 km of the calibration gauge, and about 20% at a distance of 20 km;
(ii) Raingauge densities of between about one gauge per 30 km² and one gauge per 200 km², dependent on the type of rain, would be needed to obtain hourly estimates of subcatchment rainfall of the same accuracy as the radar;
(iii) The accuracy increases as the period of summation is increased. Six-hourly estimates are on average 5% more accurate than three-hour estimates;
(iv) The accuracy is greater, the larger the area of measurement about the calibration site, up to an area of about 500 km², beyond which the calibration becomes unrepresentative. Accuracy decreases markedly over small areas to the extent that point estimates of hourly rainfall differ from the gauge by about 37%.

It should be noted that these findings were based on occasions when there was no bright band present. It is believed that when there is a bright band, the “errors” are increased on average by a factor of 1.5.

![Figure 26 - Mean error (without regard to sign) in the measurement of areal rainfall, using a radar calibrated against a single raingauge, plotted as a function of the area and period of integration (Collier, 1977)](image-url)
Figure 26 shows how the accuracy of the radar estimates of rainfall increase as both the averaging period and the averaging area increase. For areas in excess of about 450 km², however, the accuracy begins to drop again because the calibration gauges becomes unrepresentative of the larger area.

Wilson and Brandes (1979) show examples of radar areal estimates of rainfall utilizing gauges for calibration. These are shown in Table IV, whilst a comparison of standard error of point radar rainfall measurements for two occasions is shown in Figure 27.

### Table IV

Radar areal estimates of rainfall utilizing gauges for calibration (Wilson and Brandes, 1979)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Location</th>
<th>Rain type</th>
<th>Radar size (km²)</th>
<th>Z-R relation</th>
<th>Number of cases</th>
<th>Radar observation frequency (min)</th>
<th>Radar range (km)</th>
<th>Area size (km²)</th>
<th>Duration</th>
<th>Adjustment type and calibrating gauge density (km²/gauge)</th>
<th>Error before and after (%)</th>
<th>Percent error using adjustment gauges only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wilson (1970)</td>
<td>Oklahoma Thundershowers</td>
<td>10/2</td>
<td>K_R²(b)</td>
<td>23</td>
<td>5-10</td>
<td>35-100 3500 Storm</td>
<td>A(3500)</td>
<td>51 (35)</td>
<td>60</td>
<td>A(3500)</td>
<td>(30)</td>
<td>31</td>
</tr>
<tr>
<td>Brandes (1975)</td>
<td>Oklahoma Thundershowers</td>
<td>10/2</td>
<td>200R²(b)</td>
<td>9</td>
<td>5</td>
<td>45-100 3000 Storm</td>
<td>V(1000)</td>
<td>52 (13)</td>
<td>21</td>
<td>V(1000)</td>
<td>(14)</td>
<td>24</td>
</tr>
<tr>
<td>Woodley et al. (1974)</td>
<td>Florida Showers</td>
<td>10/2</td>
<td>300R²(b)</td>
<td>39</td>
<td>5</td>
<td>85-115 570 24 h</td>
<td>A(1600)</td>
<td>43 (30)</td>
<td>58</td>
<td>A(1600)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Harold et al. (1974)</td>
<td>England Showers</td>
<td>10/2</td>
<td>200R²(b)</td>
<td>27</td>
<td>1</td>
<td>12-48 50-100 1h</td>
<td>V(1600)</td>
<td>48 (46)</td>
<td>48</td>
<td>V(1600)</td>
<td>(15)</td>
<td>21</td>
</tr>
<tr>
<td>Wilson (1975a)</td>
<td>New York Showers</td>
<td>10/2</td>
<td>200R²(b)</td>
<td>41</td>
<td>1</td>
<td>95-112 170 24 h</td>
<td>A(1500)</td>
<td>49 (22)</td>
<td>22</td>
<td>A(1500)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Collier et al. (1975)</td>
<td>England Showers</td>
<td>10/1</td>
<td>200R²(b)</td>
<td>13</td>
<td>1</td>
<td>12-48 700 3 h</td>
<td>V(230)</td>
<td>7 (7)</td>
<td>7</td>
<td>V(230)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Jalka and Puhakka (1972a,b)</td>
<td>Finland Showers</td>
<td>3/1.8</td>
<td>200R²(b)</td>
<td>6</td>
<td>5</td>
<td>18-28 180 300 Storm</td>
<td>A(1800)</td>
<td>43 (23)</td>
<td>63</td>
<td>A(1800)</td>
<td>(18)</td>
<td>-</td>
</tr>
<tr>
<td>Huffman and Towery (1978)</td>
<td>Illinois Showers</td>
<td>10/1</td>
<td>300R²(b)</td>
<td>67 (b)</td>
<td>3</td>
<td>20-100 5300 0.5 h</td>
<td>V(150)</td>
<td>55 (27)</td>
<td>32</td>
<td>V(150)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes:
- (a) A: average adjustment; V: variable spatial adjustment.
- (b) Radar estimates adjusted to remove average bias for the total experiment.
- (c) Density of rain gage clusters is approximately 8 gages/pers cluster.
- (d) Density of rain areal estimates uses approximately 2 gages per cluster.
- (e) Error when observed drop size distribution used is 98%.
- (f) Number of 30 min periods in storm.

Figure 27 – Standard error of point radar rainfall measurements (total storm accumulation) versus the distance of the measurement from the calibrating gauge for two thunderstorm dates. The solid horizontal lines indicate the standard error for each storm after utilizing the mean radar bias (G/R) for calibration. The radar data were collected with the NSSL WSR-57 (10 cm). For example, on 6 June 1974 the standard error in the radar-estimated rainfall at a point 20 km from the nearest calibration gauge is 30% if the radar is adjusted only by that single gauge and 39% if adjusted by the average G/R ratio from all calibration gauges (Wilson and Brandes, 1979).
Browning (1978) states that:

It is interesting to compare the accuracy of radar with that achievable with rain gauge networks of different densities. The full curves in Figure 28* represent the accuracy of hourly rainfall totals over subcatchments that can be achieved with a calibrated radar located within 50 km of the area of interest. The dotted curves represent the accuracy achieved with networks of rain gauges in the absence of radar. For both sets of curves the accuracy is plotted as a function of rain gauge density. The accuracy of the rain gauge networks depends critically on the nature of the rain, as shown by the large differences in the four dotted curves. The radar measurements, on the other hand, were nearly independent of rainfall type. It can be seen, for example, that the radar system calibrated using two rain gauges over the 1000 km² experimental area had the same accuracy as a rain gauge network of nine gauges per 1000 km² in the presence of typical widespread rain. In showery situations, the same radar system had an accuracy comparable with a rain gauge network with density of about 50 gauges per 1000 km². The above results apply when the radar beam does not intersect the melting level; Figure 28* shows that when it does, the mean error of the radar estimates increases from 20 to 30%, again assuming two calibrating gauges per 1000 km². Although the main assessment of accuracy in the DWRP** was carried out over a limited azimuth sector with an area of only 1000 km², the area covered quantitatively by such a radar is more than an order of magnitude greater. If accurate measurements of rainfall are required over large areas it becomes increasingly impractical to use rain gauges alone, especially when the gauges have to be telemetered to provide data in real time. It has been estimated (Water Resources Board, 1973) that, if an accuracy of 25% is required, the cost-effectiveness of a calibrated radar system exceeds that of a telemetering rain gauge network, provided measurements are required over an area larger than 3000 km².

Each user may have different views on the degree of accuracy which he requires from areal rainfall measurements. (This is discussed further in Chapter 7.) Some readers may be discouraged by the large number of error sources set out in this chapter. If so, it must be re-emphasized that radar is capable of making real-time measurements over a wide area which are not available from any other source. Moreover, it can be said with certainty that the accuracy of radar-derived measurements, whilst still needing improvement, is such that both meteorological and hydrological forecasters can gain much from them. Real-time flash-flood warnings can be given with a high degree of success, particularly when made in conjunction with data from other sources. Further, although desirable consistency has not yet been proved, there are definite signs that adequate streamflow forecasting is possible.

It must be stressed that, for each individual system, it is necessary to carry out careful operational assessments which may later reflect into overall assessments of the accuracy of radar.

![Figure 28](image_url)

Figure 28 - Mean error of the hourly rainfall totals in subcatchments of average area 60 m², as determined from radar measurements in various kinds of rainfall conditions, plotted as a function of the number density of calibrating rain gauge sites (full curves). Also shown for comparison is the mean error of the hourly subcatchment totals as determined from a network of rain gauges in the absence of radar, again plotted as a function of the number density of rain gauge sites (dotted curves). The set of four dotted curves represents the measurement errors for the rain gauge network in the presence of (1) extremely isolated showers, (2) typical showers, (3) typical widespread rain and (4) extremely uniform rain. For all curves the mean error is defined as the mean value of the difference between the estimated rainfall and the optimum estimate (defined in the text) without regard to sign (After Collier, 1977) (Browning, 1978)

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* In this text (renumbered)
** Dee Weather Radar Project
5.10 Accuracy of snow and hail measurements

Many of the problems which arise in rainfall measurement apply equally in snow and hail measurement. In section 4.7 the Z-R relationships appropriate to snow were quoted; it was indicated that there is no known satisfactory method of measuring snow depth over an area or its equivalent water volume. (Generally, it is assumed that 10 mm in depth of snow is equivalent to 1 mm of water.) It is not possible, therefore, to claim any great accuracy for radar snow measurements. After such comparisons as have been attempted (Jatila, 1973; Puhakka, 1975; Wilson, 1975), the broad conclusion was reached that, within a range of 40 km, about 68% of radar-derived snowfall amounts fell in the interval -24% to +32% of the amounts measured by gauges. These measurements were carried out in fairly flat terrain. Collier and Larke (1978) carried out an assessment in hilly terrain and, using a large number of depth measurements for comparison, found mean differences of 13% regardless of sign. However, until data are available from an operational system, little can be said on this subject.

Hail presents other problems. Because of the size and shape of hailstones, hail does not conform to the assumptions involved with the use of the radar equation (equation (1), Chapter 2), which applies only when drops are relatively small and approximately spherical. However, hail occurrences are generally short-lived and hail often falls on a narrow front. Because of this it may well not fill the radar beam and its intensity will be very much underestimated. Because of its short-lived nature it may have little effect on flooding, but the real importance of hail in many countries is the damage it is likely to inflict on crops. This is discussed in Chapter 11.

5.11 Conclusion

Unless radar-derived data, and the corrections used to obtain them, are properly understood, there is a risk that, although accuracy may be satisfactory for most of the time, on a few occasions it will be so poor that credibility is destroyed. Meanwhile, work being carried out by radar meteorologists in several parts of the world leads to optimism in expecting accuracy of measurement to improve over the next decade. Indeed, some of the examples quoted in this chapter may be considered as already out of date.

Nevertheless, it may be that accuracies will never be as good as meteorologists and hydrologists would like, but they are already better than can be obtained from any source other than a raingauge at one point only. Satellites, both now and in the foreseeable future, are not able to measure precipitation though they give some indication of where it is taking place and whether it is light, moderate or heavy.

In addition to the improvements in the objective assessment of precipitation intensities, with the increasing ability of the computer to recognize rainfall types and the presence of a bright band, for instance, there is some thought being given to methods of human intervention. A significant development in this direction is a system known as FRONTIERS (Forecasting Rain Optimized using New Techniques of Interactively Enhanced Radar and Satellite) (Browning, 1979). In this system, digital data from a network of radars and a geostationary satellite are composited on a video display. An experienced forecaster can modify the picture, in effect adjusting values, as he sees fit and in accordance with his knowledge of the meteorological situation derived from all possible sources. Basic data will not be affected.

Bibliography


The practical merits of radomes are set out in section 3.6. Unfortunately, certain disadvantages are also involved.

The space-frame type has a physical effect on the transmitted beam and side-lobes. Some perturbation occurs, measurable in respect of the latter but not significant in respect of the main beam. With a properly designed structure, the effects are sensibly constant and do not affect precipitation measurement; they can therefore be ignored.

More important is the fact that, whatever the material or structure, some attenuation or loss of electromagnetic energy takes place. This is either absorbed in the structure or reflected by it. A figure of not more than 0.5 dB for transmission in each direction is usually quoted (i.e. 0.5 dB for the transmission path plus 0.5 dB for the receiving path). The material chosen nowadays is such that the wavelength of the radar has no significant effect, though in earlier space-frame models it was necessary to match material to wavelength.

If the attenuation figure (of, say, 0.5 dB) remained constant under all conditions, there would be no difficulty in making permanent corrections in the computer program. Unfortunately, when the radome is wet, the attenuation increases markedly since the water film adds to the absorption or reflection effects of the structure. The figure is not known with any certainty. It depends on several factors, the size of the structure, its material, cleanliness, hydrophobic characteristic, the thickness of the water film and the nature of the rivulets upon it. The water is also frequency-sensitive. In any particular installation, the size, material and radar frequency are constants; they affect the total attenuation but not its variability. To reduce the latter, it is recommended that regular cleaning (say, annually, depending on the degree of pollution in the area) and the application of a suitable hydrophobic compound should be undertaken.

One secondary advantage of a hydrophobic surface is that the material does not then absorb water and the recovery time after precipitation has ceased is very much faster. Rubber materials are generally more absorbent than man-made fibres and tend to be less satisfactory as regards both total attenuation and recovery time.

There is a divergence of views as to the seriousness of the attenuation problem. Work carried out has produced different results and therefore more evidence is required. Amongst the uncertainties are the knowledge of the thickness of the water film on any part of the radome. Wilson (1978) believes that the film reaches a maximum thickness regardless of an increase in the rate of rainfall upon it, but this is not borne out by most results. Some workers have pointed out that the viscosity of water increases with a fall in temperature; thus, the attenuation will be greater in cold weather than in hot. A further unwelcome effect could occur if the water on a hydrophobic surface ran down in rivulets in an unchanging pattern. This would form a grating which could distort the beam.

A number of estimates of the attenuation for rainfall rates of, say, 40 mm h⁻¹ appear to differ widely, but it is not known what differences existed in radome characteristics. Wilson (1978) found that 1 dB was appropriate whilst Kodaira and others quote 4 dB or more.

It seems desirable that a careful review should be made of this not insignificant feature of precipitation measurement, but the variability of rainfall and of other weather conditions, particularly wind speed and direction, militate against consistent and satisfactory results being obtained. Nevertheless, the aim should be for work to be carried out with the eventual incorporation of running corrections in the precipitation data processing program.
It will be apparent that radome attenuation is likely to be considerably more serious in tropical regions, where rainfall rates are significantly higher. On the other hand, in temperate and polar regions, ice and snow accretion can occur, almost without limit, with consequently greater attenuation. To combat this, heating inside the radome is necessary, but calculations show that considerable power, perhaps in excess of 20 kW, depending upon the size, may be required to prevent all risk of icing, even in the UK.

In addition to the divergent views on the quantitative effect of precipitation on radomes there are also differing opinions on the quantitative effect of precipitation on antenna systems not protected by radomes. It is reasonable to assume that there will be some loss, depending not only on the surface of the reflector but perhaps rather more on the water on the horn or feed which directs the energy at the reflector. One radome manufacturer claims that such attenuation is greater and less controllable than that resulting from a space-frame radome.
6.1 Introduction

The transmission and exchange of meteorological data have led to the development of complex and comprehensive systems of the transfer of such data both nationally and internationally. Without such facilities, real-time observations would have little purpose. This is equally true of radar data, unprocessed or processed. It is not appropriate to this Technical Note to provide technical details of data-transmission systems. However, a short chapter on the alternatives available and their limitations is considered useful.

6.2 Analog data links

Until the advent of digitization of radar data, transmission of pictures was severely limited. In some cases the requirement still exists to have a PPI/RHI display separated from the radar, but by a relatively short distance; a radar of this kind exists for detection purposes only and does not have a digital output. An airfield installation is the most likely circumstance. The cables for such a purpose will be of high quality with low loss characteristic. Nevertheless, beyond a distance of about 1500 m picture quality will fall off and a true representation of the original will not be obtained. It is possible to insert amplifiers at intervals along the cable to boost the signal but the procedure becomes so expensive that the alternative of digitizing the output and using simpler transmission circuits becomes more attractive, both as regards cost and technically. In fact, some modern radar systems include digitizing circuits as a standard option, whether the radar is required for precipitation measurements or not.

6.3 Digital data links

Once the data are converted to digital form they can be transmitted over virtually any distance without loss of quality; it may be advisable to incorporate error-checking circuits or to include redundant data, although these matters can be taken care of, at least as well, by software in the computer. The quality of the transmission circuits required depends directly on the data transmission rate to be used. Over short distances where the user's own cables can be installed (such as across an airfield), it is possible to link the radar system output directly to the line with, perhaps, the simplest of interfaces. If the data are to be transmitted over long distances, however, then a more complex interface unit, a modem (from "modulator-demodulator"), is required. There will be identical modems at each end of the link. They vary in type according to the rate of data transmission required and must therefore be selected to meet the user's needs.

The rate of picture transfer depends upon the amount of information within that picture, but in broad terms it can be said that it is possible to send a grid of 100 x 100 pixels with eight intensity levels, using a modem operating at 600 or 1200 bits/second, in about 3 or 1½ minutes respectively. Since the frequency of picture refresh is likely to be once every 10 or 15 minutes, the picture transmission time is usually of no great technical significance except in regions where rapid runoff of rainfall (which can cause immediate flooding) demands higher frequency of picture refresh. On the other hand, to an observer awaiting a new picture, three minutes is much too long. In most parts of the world, speech-quality telephone lines can carry data at 1200 bits/second.

* Since confusion often exists, the following definitions of data transmission terms are offered:
  
  **Baud:** the number of times per second that the signal on the transmission line changes. It is not synonymous with bits/second and not necessarily numerically equal to it. For example, if bits are coded in pairs, the baud rate is half the bit rate.
  
  **Bit:** short for binary digit; the unit of information in the binary code represented by "0" or "1".
  
  **Bit rate:** expressed in bits/second, the rate at which data enter or leave a terminal, processor, modem, etc. Not necessarily equal to baud but often is at rates less than 1200 bits/second.
  
  **Byte:** a sequence of binary digits usually operated on as a unit; frequently consists of eight bits representing one alpha-numeric character.
To transmit fine-resolution data at high speed (greater than 1 200 bits/second) with, perhaps, at least twenty times the number of intensity levels, it is necessary to use a different rate. This will probably be via a 2 400 bits/second modem. These data will not be displayed visually but will be subjected to further processing. The link required will be of better quality than those normally used for speech and will consequently be more expensive. Although much higher rates are likely to be available soon, the highest rate now generally available in the world over such links is 9 600 bits/second, but that can be divided into several multiplexed rates of, say, 2 400 bits/second or less. (Such high rates are not possible with direct cable links between radar system and display.)

6.4 Transmission media

There are basically three transmission media for digital data over a distance: telephone line, radio (usually microwave) link and satellite.

The first, telephone line, is the most commonly used medium in developed countries, particularly in the more populated areas where comprehensive telephone systems already exist. Lines are usually rented from the national telecommunications authority, which makes different quality links available. There is also the option of private wire connections or the public switched network. If regular data refresh is required, then the former are essential; they are more reliable and probably cheaper. If only occasional data refresh is required, then the latter may be adequate, and it will be cheaper. The big disadvantages with telephone lines are that the user has no control over the service and the most likely time for failure (due to local flooding or power failures) is in severe weather when it is most essential to transmit data. Lines of doubtful quality should, in any case, be avoided.

Radio links, unless part of a national telecommunications network, are under the control of the user. They can contain circuits with the same data rates as telephone lines and, with modern equipment, can have a very high reliability. For a relatively low increase in cost further data channels may be added. The disadvantages are that the choice of system is dependent upon the terrain. At the shorter wavelengths which are used, there must be direct line of sight between the transmitting antenna and the receiving antenna; otherwise, repeater stations are necessary, with resulting increase in the capital cost (which may already be considerable, particularly if it is necessary to install stations in rather inaccessible places or to put equipment on high towers in order to obtain line of sight).

Satellites can be used as data links provided that suitable ground stations are available. Data-collection platforms (DCPs), which are relatively cheap, are especially suitable for remote places (or in places which, if not strictly remote, do not have telephone or radio facilities). For small amounts of data at fixed intervals and not in real time, it is usual to receive the information via a master receiving station and then by normal communication means. However, radar data are usually required in real time; therefore a ground receiving station at the user's radar control or display centre is necessary. This will be much more expensive than the DCP but the total cost of such a system will probably be less than that of a radio link with repeaters. The unknown factor is uncertainty about what satellites will be available in the future and how they will be funded.

It is apparent that cheap, single-channel DCPs could be ideal for bringing data from remote calibrating raingauges to the radar site, provided that there is a cheap local ground receiving station to complement them. This task could also be carried out by meteor scatter systems, which use ionized meteor trails to reflect or re-radiate VHF radio signals from one point to another. Such systems are not, however, appropriate to streams of radar data, mainly because a variable transmission "wait time" is necessary, sometimes in excess of 100 seconds, and the quantity of data would be too great for one burst of transmission.
CHAPTER 7

USE OF RADAR-DERIVED PRECIPITATION DATA; COST/BENEFITS

7.1 Introduction

The greater part of this Technical Note deals with the theory and practice of radar systems used for the detection and tracking of storms and for the measurement of precipitation intensity. In section 1.1 it was said that a number of countries have already proved to their own satisfaction that radar-derived data are of value, although, naturally, those countries and others are constantly seeking to confirm their views, to improve the quality and accuracy of data and to make greater use of them. Techniques are being developed for short-range forecasting of precipitation amounts up to several hours ahead, and of the times of onset and cessation. In the first part of this chapter, potential users of radar-derived precipitation data and their requirements are considered. In the second part, cost/benefit considerations are discussed.

Throughout the chapter it is recognized that it is impossible to be precise about users' requirements, since these will vary from one country to another. Thus, any figures quoted can be regarded only as guidelines to be adjusted to individual circumstances and needs.

It is an over-simplification to think of a radar system merely as a replacement for a network of raingauges providing similar information. It can provide areal data in virtual real time to a greater level of accuracy than any other practical source, but, in addition, it can provide data of broader meteorological and hydrological character. The purpose of this chapter, in the context of the Technical Note as a whole, is to encourage users and potential users to derive the greatest possible value from the data available.

7.2 Benefits of radar data

Radar have been used operationally for many years for storm warning purposes, both at airports and in those places where violent storms are likely to threaten life and property. The greatest value in the latter role has been in countries affected by severe storms — for example, the southern United States, Japan and India. It is not possible to put a monetary value on the early warnings which radar can provide; the aim is to maximize the response of the people to protect their property and themselves as best they can. In the aviation field it is possible to assess the value of an aircraft lost, but, despite the efforts of insurance companies, no true value can be put on human lives.

Turning to the potential benefits of precipitation-measuring radars, these may be summarized as follows:

(a) One radar with a digital processing system is able to provide quantitative measurements of surface precipitation intensity over a wide area, provided it is well sited.

(b) A network of radars with overlapping areas of coverage can provide data over a very large area, thus enabling precipitation patterns to be seen in a synoptic-scale context and enabling meaningful short-term forecasts to be made. Each radar system is able to process large quantities of data and to transmit them economically and in virtual real time to a central site, where they can be integrated with data from a number of other radars in the network to give a composite picture.

(c) Either single-site data or composited data can be disseminated promptly in simple user-oriented format to any number of users who may display them on a relatively low-cost receiver, store them for instant recall or record them for future use. The interval between updating may be adjusted, within reason, to suit the users' needs, from a few minutes to a much longer period. Integrated rainfall (and snowfall) for selected periods over designated catchments or sub-catchments may be made available for print-out at a user's terminal or for further processing.
(d) Single-site data may be obtained in the form of vertical sections of the atmosphere as well as in plan form. Thus, a three-dimensional picture may be made available for the purpose of advising aircraft as to the areas to be avoided and to provide meteorologists with additional knowledge of the structure of the precipitation system.

The improved forecasting obtainable from radar-derived precipitation data is of particular value to authorities responsible for urban areas where the runoff from roofs and roads is so rapid that flood warnings are not possible once rain has fallen. Consultation between meteorologist and hydrologist on a developing situation can lead to significant improvements in the service provided to those concerned.

In addition to the benefits set out above, a network of radars can provide a composited picture of precipitation which can be combined with data from a meteorological satellite (preferably geostationary) to give a larger picture over wide areas including tracts of sea and unpopulated land. The radar data can thus assist in the interpretation of the satellite data.

### 7.3 Potential users and usage

In a report on user requirements for a proposed radar network in western Europe, Newsome (1981) suggests that users may be separated into two categories, primary and secondary. A primary user is defined as one who takes the output directly from the radar system; a secondary user is defined as one who takes processed data or information from a primary user.

The major primary users in most parts of the world, seeking regular and reliable information on actual or forecast precipitation in particular areas, will probably be:

(a) National Meteorological Services;
(b) Hydrological Services or water authorities, including resource-management and water-supply and treatment authorities.

The Meteorological Services, using the data in association with meteorological data from other sources, will provide general forecasts for the public and more specific ones for commercial customers. The Hydrological Services may require precipitation data to provide forecasts of water required for irrigation, or for reservoir and river regulation purposes. They would certainly use such data for providing warnings of imminent flooding. The precise requirements of these primary users may also be subdivided into “area” and “local”.

The major secondary users will probably be:

(a) Local government authorities, particularly in towns and cities;
(b) Electricity supply undertakings, particularly those using hydro-electric power generation;
(c) Civil aviation authorities concerned with the effects of precipitation on airport and aircraft operations;
(d) Road-transport organizations concerned about short- and longer-term effects of precipitation on roads and hence the movement of heavy vehicles;
(e) Rail- and sea-transport undertakings where certain types and intensities of precipitation can cause problems for traffic movement.

Other secondary users will probably include:

(f) Industrial interests, particularly those whose operations are carried out in the open, e.g. the construction industry;
(g) Agriculture, including horticulture and forestry, particularly at certain times of year;
(h) Recreational and amenity pursuits, particularly activities such as sailing, ski-ing, mountaineering, etc.
In some countries some users listed above as secondary may become primary users, whilst precise data requirements will vary under different weather conditions. The latter may be categorized as normal (i.e. when intensities and duration of precipitation do not cause the user significant problems) or abnormal (when intensities and/or durations of precipitation cause the user significant problems and may cause him to take precautions to minimize the adverse effects of such events).

In normal conditions in temperate zones, the following information may be required:

(a) For the meteorologist: general information on precipitation to supplement his information on the area, speed and direction of movement of weather systems;
(b) For the hydrologist: general information on precipitation to assure himself that reservoirs and rivers within his area of interest are being, or will be, topped up.

In abnormal conditions in temperate zones, the following may be required:

(a) For the meteorologist: detailed information on precipitation so that not only can he judge the area, speed and direction of movement of weather systems, but also issue appropriate warnings to secondary users;
(b) For the hydrologist: detailed information on precipitation so that he may ensure that all control of water functions is activated, that staff for special duty are called out for flood alerts and that local authorities, police, fire brigades, etc. are warned.

In normal conditions in dry regions, there will probably be no detectable precipitation.

In abnormal conditions in dry areas, the following may be required:

(a) For the meteorologist: warnings of storms which may be sufficiently violent to affect aircraft on landing or take-off and shipping at sea or in harbours;
(b) For the hydrologist: detailed information on the quantity of precipitation and the area covered by it in order to ensure that the maximum possible amount is being collected for storage and irrigation.

In tropical areas, normal conditions are likely to be rainy for part of the year and dry for the remainder.

In the wet season, the following may be required:

(a) For the meteorologist: detailed information on precipitation as a major input to his information on the area, speed and direction of movement of weather systems and as a major aid to the issuing of warnings to local authorities and the general public;
(b) For the hydrologist: detailed information on precipitation to enable him to take what, in such areas, may be routine action to ensure that heavy rain causes as little disturbance as possible and that freshwater sources do not become polluted because of overloaded drains and sewers.

In the dry season (in tropical areas), there may be no detectable precipitation whatsoever. On the other hand, in certain areas there may be the same requirements as in abnormal conditions in dry areas.

Tables V, VI(a) and VI(b) demonstrate an approach made in western Europe, a temperate zone, towards setting out an Information Conceptual Dissemination Diagram and agreed user requirements for both normal and abnormal weather conditions. Comparable tables in other regions may contain markedly different details.

As part of the growing emphasis being attached to water management in general, particular interest is being shown in the need to maintain reservoirs at the optimum level for hydro-electric generation. This entails knowledge of sub-catchment precipitation, drain-off time and river flow rates. The part which radar can play in this is discussed by Larsen (1977).

Amongst the advantages, not previously discussed, of the real-time information which radar-derived data can provide are the possibility of warnings for motorways and to airport operators of heavy rainfall leading to possible aquaplaning (Sagbom, 1979); such warnings can be given automatically.
It is also possible to predict the likelihood of hail with greater certainty (Waldvogel, 1981) though this is achieved more readily with Doppler radar.

Lightning gives echoes on radar displays, more particularly at wavelengths of 10 cm and greater. Such echoes may be transitory and therefore difficult to capture, but sufficiently apparent to provide a basis for warnings. The greatest use of radar lightning detection has been in studying storm structure (Rust and Doviak, 1982). Again, lightning detection is more readily associated with Doppler radar. Another aspect is work being undertaken leading to the use of radar data to predict the probability of lightning, both spatially and temporally.

There is also some evidence that gale-force winds can be predicted (Bond et al., 1981).

The advantages of a network of radars over a single radar, with the compositing of data to form a single picture, can be demonstrated in countries or regions with a wide geographical area of interest. The movement of precipitation systems can be tracked across large distances whilst the risk of any one radar not being able to see the full scope of the precipitation and thus being misleading is eliminated. Moreover, in a well-planned network, the failure of one radar can be offset by the coverage from neighbouring radars.

In view of the digital nature of the data and of the availability of modern communication systems, the establishment of international networks could be practicable (Clift, 1981; Newsome and Clift, 1983). Data from across national boundaries may be of use for general forecasting purposes. Moreover, when rivers and catchment areas cross national boundaries, data can be used for calculating streamflow.

It is in the hydrological use of precipitation radars that many recent projects have been carried out (the Dee Project Report, 1977; Gorrie and Kouwen, 1977; Barge et al., 1979; Humphries and Barge, 1979; Collier et al., 1980; Hall and Barday, 1980; Vogel, 1981).
### Table VI(a) User requirements (normal weather conditions)

<table>
<thead>
<tr>
<th>Authority</th>
<th>Meteorological</th>
<th>Hydrological</th>
<th>Agriculture</th>
<th>Transport</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recipient</td>
<td>Central (principal) office</td>
<td>Subsidiary (local) office</td>
<td>River basin ops. centre</td>
<td>Urban sewer operations</td>
<td>Hydro- electric power generation</td>
</tr>
<tr>
<td>1. Area of interest</td>
<td>National</td>
<td>Regional</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>2. Areal resolution (km²)</td>
<td>50</td>
<td>2</td>
<td>50</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>3. Precipitation reporting</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>12h</td>
</tr>
<tr>
<td>3.1 Frequency of reporting</td>
<td>1h</td>
<td>1h</td>
<td>6h</td>
<td>6h</td>
<td>6h</td>
</tr>
<tr>
<td>3.2 Period over which precipitation is totalled</td>
<td></td>
<td></td>
<td>Integrated totals over period between reports</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3 Resolution of reported precipitation</td>
<td>6 (selected from 127)</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>3</td>
</tr>
<tr>
<td>(a) Number of levels of intensity (mm h⁻¹)</td>
<td>0 – 25.0</td>
<td>0 – 25.0</td>
<td>0 – 25.0</td>
<td>0 – 25.0</td>
<td>0 – 25.0 in increments of 8.0 mm</td>
</tr>
<tr>
<td>(b) Scale (mm totalled)</td>
<td>Incrments depend on selection of levels</td>
<td>in 2 mm increments</td>
<td>in 2 mm increments</td>
<td>in 2 mm increments</td>
<td></td>
</tr>
<tr>
<td>4. Precipitation forecasting</td>
<td>1h</td>
<td>1h</td>
<td>6h</td>
<td>6h</td>
<td>6h</td>
</tr>
<tr>
<td>4.1 Frequency of forecast message</td>
<td>1h</td>
<td>1h</td>
<td>6h</td>
<td>6h</td>
<td>6h</td>
</tr>
<tr>
<td>4.2 Forecast period ahead</td>
<td>36h</td>
<td>6h</td>
<td>72h</td>
<td>24h</td>
<td>36h</td>
</tr>
<tr>
<td>4.3 Time resolution of forecast message</td>
<td>1st 6h</td>
<td>1h</td>
<td>6h</td>
<td>6h</td>
<td>6h</td>
</tr>
</tbody>
</table>

### Table VI(b) User requirements (abnormal weather conditions)

<table>
<thead>
<tr>
<th>Authority</th>
<th>Meteorological</th>
<th>Hydrological</th>
<th>Agriculture</th>
<th>Transport</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recipient</td>
<td>Central (principal) office</td>
<td>Subsidiary (local) office</td>
<td>River basin ops. centre</td>
<td>Urban sewer operations</td>
<td>Hydro- electric power generation</td>
</tr>
<tr>
<td>1. Area of interest</td>
<td>National</td>
<td>Regional</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>2. Areal resolution (km²)</td>
<td>50</td>
<td>2</td>
<td>50</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>3. Precipitation reporting</td>
<td>5min</td>
<td>5min</td>
<td>5min</td>
<td>5min</td>
<td>30min</td>
</tr>
<tr>
<td>3.1 Frequency of reporting</td>
<td>1h</td>
<td>5min</td>
<td>15min</td>
<td>15min</td>
<td>30min</td>
</tr>
<tr>
<td>3.2 Period over which precipitation is totalled</td>
<td></td>
<td></td>
<td>Integrated totals over period between reports</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3 Resolution of reported precipitation</td>
<td>6 (selected from 127)</td>
<td>127</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>(a) Number of levels of intensity (mm h⁻¹)</td>
<td>0 – 25.0</td>
<td>0 – 25.0</td>
<td>0 – 25.0</td>
<td>0 – 25.0 in increments of 3.0 mm</td>
<td></td>
</tr>
<tr>
<td>(b) Scale (mm totalled)</td>
<td>Incrments depend on selection of levels</td>
<td>in 1 mm increments</td>
<td>in 1 mm increments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Precipitation forecasting</td>
<td>1h</td>
<td>15min</td>
<td>15min</td>
<td>15min</td>
<td>30min</td>
</tr>
<tr>
<td>4.1 Frequency of forecast message</td>
<td>1h</td>
<td>15min</td>
<td>15min</td>
<td>15min</td>
<td>30min</td>
</tr>
<tr>
<td>4.2 Forecast period ahead</td>
<td>3h</td>
<td>3h</td>
<td>1h</td>
<td>24h</td>
<td>3h</td>
</tr>
<tr>
<td>4.3 Time resolution of forecast message</td>
<td>1st 6h</td>
<td>1h</td>
<td>5min</td>
<td>15min</td>
<td>15min</td>
</tr>
<tr>
<td>4.4 Remainder 6h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.4 Cost/benefits

It is difficult to quantify with any accuracy the cost/benefits of meteorological services as a whole in terms applicable to all countries and all users, though Mason (1966) attempted it for the UK. It is no easier to quantify the value of radar systems as part of those services. This paragraph can, therefore, only give generalized indications and is intended only to stimulate more detailed considerations in individual countries.

As would be expected, the cost of a system depends directly on the size, complexity and purpose for which it is required. Thus, if a 3 cm radar, to be used for general observation purposes only, with no processing facilities and with a conventional black and white PPI/RHI, costs $Y, then the addition of a simple processor and colour display might cost a further $\frac{1}{2}Y$. However, a 3 cm radar would be of little use for precipitation measurements in most parts of the world. Then, the 5.6 cm radar needed for that purpose in temperate zones would cost between $1\frac{1}{2}Y$ and $2Y$, with a comprehensive processing system adding between $\frac{1}{2}Y$ and $Y$ (assuming standard equipment is purchased, with standard software packages modified for local needs). A 10 cm radar needed in tropical zones would cost between $2Y$ and $3Y$, with the processing system adding between $\frac{1}{2}Y$ and $Y$ (as for 5.6 cm). To these figures for 5.6 or 10 cm systems should be added between $\frac{1}{4}Y$ and $\frac{1}{2}Y$ for spare parts and test equipment, depending upon the maintenance policy of the user. Over and above this are the costs of civil works and installation; these are very dependent upon the site and may add a further $Y$ or $2Y$. (Costs of telecommunication facilities would be additional.) Thus, the cost of a total installation of standard equipment for precipitation measurement would probably be in the order of $4Y$ to $6Y$. Any requirement calling for the development of new equipment or software could add a further $2Y$ or more.

It is always undesirable to add a processing system to an old radar which does not possess the necessary quality to feed it with reliable data. If the system is to be purchased in two stages, therefore, it is important to ensure that the radar will be viable for the foreseeable future.

Costs of maintenance and operation depend upon the policy and methods adopted but will normally be in the order of $\frac{1}{4}Y$ to $\frac{1}{2}Y$ per annum.

Turning to benefits, a tropical cyclone can do material damage costing several millions of dollars. Early warning from radar may lead to the saving of only a small percentage, but this can easily exceed the cost of the system (say, US $800000) by a large factor. This ignores the incalculable human life aspect. The saving of one aircraft may offset the cost of several radar installations.

A study carried out as part of the Dee Weather Radar Project in 1973 compared the costs of implementing a radar network and a raingauge network to give comparable coverage. It came down heavily in favour of radar.

An attempt to calculate the potential benefits of a radar network was made in the UK (Bussell et al., 1978), but any such attempt must tend to be subjective and unproven. Bussell’s figures, based on a network of ten radars with a life of twelve years, showed the total annual cost of ownership to be nearly US $2000000. The annual benefits suggested from a combination of real-time radar data and improved short-period forecasts of precipitation included the following:

- Flood warnings: US $6000000
- Agriculture and horticulture: US $10000000
- Construction industry advice: US $20000000
- Transport warnings: US $3600000

No figure was included for the improvement of water management, but the overall cost/benefit ratio was calculated as 1 : 20.

A more recent and extremely detailed study of the benefits of flood warnings has been carried out in the UK (National Water Council/Meteorological Office, 1983). The report, as yet unpublished, divides the
country into areas and estimates the benefit attributable in each, firstly, using radar data alone and, secondly, using a combination of radar data and satellite data with forecaster intervention (FRONTIERS, see section 5.11). The totals arrived at were US $1,800,000 for the former and US $4,500,000 for the latter. These figures are probably the most accurate yet derived but it must be remembered that they apply to one particular country only.

A mathematical radar system synthesis was carried out by Kowecki (1978) in an attempt to evaluate the benefits; this does not attempt to put figures into the model.

A valuable paper dealing with user requirements and economic values of short-range weather forecasts and current weather information (towards which radar data are only one input) has been written by Murphy and Brown (1981). This comprehensive analysis includes a summary of published figures.

To ensure realistic consideration, the cost of ownership of a system should be taken into account. This is the total cost over the expected life of the equipment, including initial capital outlay and all running expenses. This concept is also relevant to the placing of contracts for new equipment, since a low capital outlay sometimes results in heavy maintenance costs.

7.5 Conclusion

In a proper determination of cost/benefits of any data-producing system (not necessarily radar), it is important to be precise about the user requirements. These are often unclear; there is confusion between what a user needs and what he can be given. On the other hand, there is a tendency to ascribe figures for benefits based on assumptions rather than proof.

Notwithstanding the above, there is growing evidence of the value of radar-derived precipitation data, despite their imperfections, provided that these data are disseminated to users and acted upon rapidly. It may be necessary for each country, with its different requirements and different problems, to carry out its own assessment. To do this requires an objective detailed study based on operational experience of a soundly based system.

Bibliography


CHAPTER 8

SITING OF WEATHER RADARS

8.1 Introduction

The finding of a suitable site for a weather radar invariably presents problems even when the equipment is to be used only as a meteorological aid in the detection and tracking of storms. These problems increase when the purpose of the equipment is to measure precipitation. For the first purpose the user will wish to obtain information from as great a range as possible; this will necessitate operating at a low angle of elevation with a good field of view throughout 360° in azimuth, although for shorter-range information an angle of elevation of up to, say, 2° may be used.

For the second purpose, measurement of precipitation intensity and areal rainfall, siting problems are related more closely to the incidence of permanent echoes and obstructions as well as to the maximum range achievable. Furthermore, the need to avoid, as far as possible, intersection of the beam with the melting layer emphasizes that the radar should be operated at the lowest possible angle of elevation, usually with the bottom edge of the beam at or near 0°. This adds importance to the provision of a radar antenna with a narrow beamwidth, preferably no greater than 1° whatever the wavelength of the radar transmitter.

8.2 Practical considerations

There are no firm rules for site selection and a perfect site is virtually unknown; compromise is almost inevitable.

The main aspects to be taken into account are:

(a) Horizon;
(b) Permanent echoes (and possible sea clutter);
(c) Maximum range required;
(d) Intersection with melting layer;
(e) Low-level precipitation (areas where this is most likely to occur);
(f) Sub-catchment coverage;
(g) Availability of suitable facilities, e.g. electric power, roads, building;
(h) Permissible separation between (i) radar antenna and transmitter/receiver, and (ii) transmitter/receiver and control and display units;
(i) Possible interference with, or from, other electronic systems in the vicinity;
(j) Whether the site is to be manned or unmanned.

8.3 Horizon, permanent echoes, maximum range, melting layer and low-level precipitation

The task of selection to cover aspects (a) to (e) in section 8.2 usually means careful examination, firstly by use of maps which give clear contours and heights, and secondly by visiting the potential sites. There is, unfortunately, no satisfactory practical procedure for carrying out a site trial. A mobile radar can be of some help, but its characteristics, particularly antenna size, are unlikely to be the same as those of the equipment eventually to be installed. Moreover, the height of the antenna above ground is often critical. For these reasons the pattern of permanent echoes from the mobile radar may be different from that from the fixed radar eventually installed.

The cost of works services and of radar installation depends very much on the site; as an average figure it is likely to be in the order of US $120 000 (without the building of roads). It is apparent that a wrong choice can be a very expensive mistake.
SITING OF WEATHER RADARS

The requirement for a good horizon is self-apparent. It is therefore often assumed that the highest point possible is desirable, e.g. on the top of a tall building or hill. Sometimes such a site is unavoidable as it is the only way to avoid obstructions but unfortunately, it is likely to increase the permanent echoes (or ground clutter) from hills and man-made objects (buildings, towers, etc.), not only because more will be visible to the main beam but also because the side-lobes (containing a small proportion of the transmitted electromagnetic energy), which are present with any radar antenna (see section 2.2), will produce echoes from buildings etc. on the lower slopes of the hill or in the valleys below the radar. On the other hand, a high site with a horizon below 0° ensures the best possible long-range performance. If the radar is to be used for cyclone warning or the data are to be used primarily for forecasting, this is particularly important. The increase in clutter may be offset by infilling (see section 4.5.2). It is desirable however to avoid a hill or mountain where lines of other hills or mountains occupy a significant part of the middle distance.

It is usual to look for a site from which the elevation of the horizon and of obstructions is as near as possible to 0° throughout 360° in azimuth, or at least in the sector of greatest interest. A site with elevations more than 0.2° below the horizontal, particularly in urban areas where tall or large buildings produce return echoes, may lead to an unacceptable amount of local clutter, though setting the antenna height so that a line of closely knit trees or buildings act as a shield may be a practical solution. On the other hand, a site with elevations greater than 0.3° above the horizontal may lead to too much obstruction, too much missing of low-level precipitation data and too frequent intersection of the melting layer.

It is possible to avoid a great deal of local clutter by operating at a higher elevation, but this severely limits the maximum usable range for all purposes and particularly for precipitation measurement. If the electronic suppression system (section 4.5.2) is successful, then the presence of clutter becomes less important. Most echoes from fixed objects can also be removed if the radar has Doppler facilities (see section 10.3.3).

It must be remembered in seeking a site that, although qualitative data can, in theory, be obtained from ranges up to 400 km or more, under normal propagation conditions the effect of the Earth's curvature (section 5.5) is such that at that range the precipitation must be at a height of at least 9.5 km (above site level) to be seen. A more practical maximum range outside the tropics is 200 to 250 km, where the height of the bottom of the beam, if set at 0°, is between 2.25 and 3.75 km (above site level).

If the radar is to be sited to measure precipitation, the maximum practical range for acceptably accurate data depends not only on the horizon and the Earth's curvature but also on the beamwidth and the height of the melting layer. With a 1° beamwidth and a horizon at 0°, it should be possible to achieve 100 km on most occasions in temperate regions and perhaps 125 to 150 km in the tropics provided that appropriate corrections are made in the software.

The study on the ground at the potential site should include a theodolite check. This demands good visibility; care should be taken to ensure that no significant feature is missed. The more distant, less visible features may be filled in from the maps later. A series of photographs taken from a known level surface (e.g. a theodolite stand) can be a useful back-up. Finally, a plan chart can be plotted showing all features of importance and expected areas of ground clutter; isolines for the lowest levels which will be visible to the radar at selected elevations can be superimposed.

Useful assistance can be obtained from a computer. Programs have been developed in connection with plotting ordnance survey maps. These can be extended to predict radar horizons and ground clutter in great detail but it is essential that the maps be digitized with a fine resolution, say ≤ 0.5 km, particularly in the area of the potential site. A point to be watched is that such programs do not usually show the effect of local trees and buildings on the radar horizon. For this reason, amongst others, there is no option but to visit the site on a clear day, even though a computer may be able to give a better overall clutter diagram. These matters are not well documented but Bolton and Tam (1974) and Moores and Harrold (1975) provide useful reading.
CHAPTER 8

The ideal weather radar site would be a low saucer with the antenna looking just over the rim. Since this is unlikely to be achievable, consideration could be given to making an artificial rim, at least in the direction in which most problems are expected. On suitable ground this can be done by building a fence of wire-netting of suitable mesh at a distance from the radar antenna in excess of the Rayleigh distance. (The Rayleigh distance is that at which the beam has become fully formed; it is calculated from the formula $\frac{\lambda}{D^2}$, where $D$ is the diameter of the reflector and $\lambda$ the wavelength. For a 5.6 cm radar with a 1° beamwidth this would be about 110 m; for a 10 cm radar with a 1° beamwidth it would be about 225 m or with a 2° beamwidth about 60 m.) Such a fence may be aesthetically unacceptable in many places and expensive to install. A line of closely knit trees may serve the same purpose but these would require cropping from time to time.

8.4 Sub-catchment coverage

If the radar is required for precipitation measurement for hydrological purposes, it will be necessary to site it to give adequate coverage of the designated sub-catchments (aspect (f) in section 8.2). Compromise will again be necessary. Clearly, the aim must be to operate the radar at an elevation setting such that precipitation can be measured as close to the ground as possible without finding that the higher land is giving extensive clutter. It is preferable for the radar to have a clear field of view up the valleys rather than across the tops of ridges, but this depends to a great extent on the width of valleys. If the sub-catchments consist of wide valleys amongst gently sloping uplands, then clutter may be no problem. On the other hand, if they are narrow with steep sides – a more likely circumstance in flood-prone areas – then it may not be possible to measure low-level precipitation; assumptions will have to be made from higher-level data. In general, it is preferable to site the radar on the edge of the sub-catchments of interest rather than in the middle but range and other limitations often preclude this.

8.5 Practical aspects of site selection

The practical aspects cover (g) to (h) in section 8.2. A weather radar solely for detection and tracking is usually found on or near to an airfield or a meteorological forecasting office. This probably means that all the civil works facilities are available and that it becomes a minimum-cost installation unless it is necessary to mount the antenna on a very high tower in order to gain a reasonable horizon.

In many cases the antenna is on the roof of an airport building with the main equipment in a room immediately below the roof, this often being close to the forecast office. Thus, the main displays can be in that office together with control if required. In other cases, with control remaining in or near the forecast office, the antenna is mounted on a small building or tower sufficiently far from the main airport complex to avoid the need for height whilst still retaining an acceptable horizon. This has the disadvantage that long cables may be necessary between the radar site and the forecast office. These, and the cost of trenching, will be expensive. Moreover, above about 1500 m, because of cable losses, it may be necessary to fit boosters in the line to keep up the levels of the signals. It may therefore be cheaper to digitize all data and to use a multiplex telephone-type circuit or even a microwave radio link.

If it is intended that the radar should be manned, then these matters may lose their importance, because the system will be controlled by dedicated operators. Either some simple method will be in use whereby the data-reduced information in message form will be transmitted to the forecaster or a single cable carrying only signal and angle voltages will be needed to supply a second display.

A further advantage of being a long way from the main airport complex is that there is less likelihood of interference with or from other airfield electronic equipment. Such interference on the weather radar display often appears as spokes of echo. To a human observer, watching a conventional PPI or RHI display, it will be immediately apparent and recognizable, but a computer will include it in its calculations and produce erroneous data which may well not be recognizable to an observer of a colour display.
A suitable site will often be one where masts or towers already exist. These need not be a major restriction. In general, provided that the obstruction does not subtend an angle more than half that of the radar beamwidth, it will have no noticeable effect on received signals looked at on conventional PPI or RHI displays, but corrections may be necessary in a computer program.

The separation between the antenna and the transmitter-receiver has no absolute limit. However, the waveguide used to transfer the electromagnetic power from one to the other is not only expensive, but it introduces an electrical loss dependent upon material. This is typically 0.13 dB m$^{-1}$ at 3 cm, 0.06 dB m$^{-1}$ at 5.6 cm and 0.03 dB m$^{-1}$ at 10 cm wavelengths, the figures being for one direction only. Manufacturers usually recommend the waveguide run to be limited to 15 metres with an absolute limit of 30 metres.

Lastly, particular attention should be paid to comprehensive lightning protection. A lightning strike can cause considerable damage to a radar system either directly on the antenna or building or even on cross-site cables. Digital circuits in the computer and other parts of the system can be damaged by relatively low-level transients and should be separately protected.

8.6 Manned/unmanned site

The choice of radar site may depend quite markedly upon whether it will be manned or unmanned. The former will require that there is ready access at all times and that staff can live close by. These factors may heavily restrict the choice. On the other hand, an unmanned site provides wide scope for selecting a point from which the best possible coverage can be obtained. As long as occasional access, perhaps by a four-wheel drive vehicle, or even helicopter, is possible and all the necessary facilities are on site for electrical power and maintenance, then even the remotest sites become viable. The probabilities in respect of equipment performance are discussed in Chapter 9.

Bibliography


CHAPTER 9

MAINTENANCE

9.1 Introduction

The importance of good maintenance is not always clearly understood. It is true to say that equipment performance is sometimes criticized unfairly when the real problem has been lack of suitable technical staff or lack of adequate training. In addition, documentation provided by manufacturers may be unsatisfactory, equipment may be inadequately designed for good serviceability and its component parts may not be readily accessible for servicing purposes. In many Meteorological Services, a weather radar, particularly if it includes a processing system, is likely to be the most complex and expensive equipment for which it is responsible. It is essential therefore that all steps necessary for its proper maintenance be considered beforehand.

Radar systems used for detection and tracking purposes, i.e. to provide data of a mainly qualitative nature, will still provide information when performing below the optimum level, though it is dangerous to let the performance fall too far. On the other hand, when the radar is used for precipitation measurement, performance levels must be checked frequently and maintained to a very high standard.

Performance depends on the environment in which the equipment has to work. The temperature and humidity conditions are important, while sand and salt can be causes of trouble. Manufacturers will advise on the conditions acceptable to their equipment; generally an office-type environment is satisfactory for most of the internal parts of the system, though a computer may require closer control. An antenna is usually designed to operate in the open air, but, as stated in section 3.6, there are distinct advantages in the use of a radome.

9.2 Routine maintenance

The manufacturer should advise, in his documentation, on the routine maintenance tasks to be carried out. These are somewhat less with modern systems, a high proportion consisting of checking voltages and currents for which suitable meters and switches should be provided. If these tasks are done regularly and a record is kept, early warnings may be gained of incipient change in performance or failure. Work of a mechanical nature will consist mainly of cleaning sliprings and greasing motors in the antenna system, a task probably required about twice per year, and of adjusting the functional parts of the teletype (or similar electro-mechanical device), a task the frequency of which depends on the amount of usage and the age of the device. A computer should require little attention - generally, two to four times per year, mainly for cleaning and the running of diagnostic routines.

One important aspect is the checking of receiver performance. The necessary frequency is a matter to be determined by experience and circumstances; after the installation of the radar, weekly checks are recommended, the period being extended when stability and accuracy are established as within the specified limits, say, ±1 dB. This period should not be less frequent than monthly unless a sophisticated self-monitoring system is incorporated.

The time spent on routine maintenance of a complete system is probably about three to four man-hours, assuming that any necessary test equipment is available on site and is in working order. In order to achieve the availability discussed in section 9.4, a new system in continuous use should not need maintenance more frequently than every two or three weeks. It may even be possible to extend this further.
9.3 Mean time between failures; mean time to repair

It is possible for a manufacturer to calculate the mean time between failures (MTBF) from the design data for the individual parts. This is now a well-established practice. Performance of any equipment of the nature of radar tends to be variable initially. Random or design faults may occur within the first few months of installation. Thereafter, the system will settle down and should behave in accordance with the predictions made for it for a period of a number of years, after which the MTBF will almost imperceptibly begin to rise. Eventually, a decision has to be taken by the owner as to when the cost of repair or the time out of action justifies purchase of new equipment or complete refurbishing. As a rough guide, a weather radar system in constant use should have a useful life of at least 10 years and may work satisfactorily for more than 15 years.

A modern solid-state standard system in a proper environment should be able to achieve an MTBF of at least 1,000 hours (or six weeks) once the system has settled. In this context, it is worth noting that such good results are not likely to be readily achieved if the system includes non-standard or laboratory-built items or if the computer uses non-proven basic programs. Purchasers are strongly advised to enquire into the record of similar equipment already in use and to give some weight to proven records as well as to accessibility of all major parts.

The latter aspect will have an important effect on mean time to repair (MTTR). Unless a major mechanical fault has occurred, it should be possible in a well-designed system to have completed the repair within two to three hours of reaching the site. This assumes, of course, that a complete range of spare circuit boards and sub-systems is immediately available, together with adequate tools and test equipment.

For a continuously functioning system, it may be necessary to replace mechanical parts, such as antenna drive motors, every two or three years. This may entail the interruption of operation for two or three days. If the system is being used in a country where continuous usage is not needed, it may be advisable to carry out such tasks during dry spells.

Experience shows that MTBF tends to deteriorate if the system is not in continuous use, i.e., if it is properly measured in terms of running hours, but not to the extent of justifying continuous use when long, dry spells occur. (It is advisable to carry out a comprehensive check of the system some time before the anticipated end of a dry spell and to ensure that it is has settled correctly before precipitation is expected.)

9.4 Availability

It has become fashionable to use the term “availability” in respect of any electronically based system. This is measured in terms of the time for which the system can produce data (in the case of weather radar, whether or not precipitation is present). There are, of course, occasions when routine maintenance will take the system out of action. As seen from the previous paragraph, these should normally be short, perhaps an hour or two. It is certainly possible in most countries to arrange for routine maintenance which is likely to disable the system to be carried out at times of no precipitation. There is now evidence that a radar alone should provide at least 96% availability even including maintenance time and at least 98% excluding it. Computer systems should achieve similar figures. Causes of non-availability leading to much poorer overall system availability are all too often in the support functions, e.g., power supplies and telecommunication systems taking data to the users. (The figures quoted above assume that technical staff can reach the site within two or three hours of the occurrence of a failure.)

9.5 Monitoring

At a manned site, daily checks may be carried out in a routine which may not even need technical expertise if the equipment is suitably designed. If the system is not under constant surveillance, even though staff are on site, then some form of automatic monitoring is desirable. At its simplest this may consist of discernible warnings which indicate whether the radar or the computer (or some other subdivision) has failed.
If the site is unmanned, such a warning system has added value, for signals may be transmitted, possibly interspersed with radar data, which not only warn the maintenance staff at a control centre of failure but also indicate which part of the system requires attention. Such signals can also be used to indicate such things as failure of air-conditioning or shortage of diesel fuel.

A more complex form of monitoring is finding favour with unmanned operational electronic systems in the widest context. This allows a technician to check on performance in some detail, perhaps up to 30 functions in a complete weather radar system. By this means, which consists basically of a number of small sensors implanted in the system, with a small processor, a teletype device and a telephone line, it is possible to carry out a comprehensive check without visiting the site. This can lead to the recognition of incipient faults or can give the technician information on the fault after it has occurred. Such a monitoring system may also be used to perform certain operating functions remotely, such as switching on or off and carrying out adjustments. The system can be arranged to carry out its checks automatically at set intervals and to print out the results.

If the radar system is basically reliable and does not need much attention, the simpler monitoring method of indicating fault areas to responsible technical staff at a distant point is usually adequate. It is inexpensive and can be provided for less than US $10,000 (plus telecommunication costs). To be fully effective it should include a circuit for detecting when the EHT supply to the magnetron has failed and for re-applying it automatically, since EHT "trips" for no specific reason are not uncommon in radar systems. Safety aspects must be included, limiting the number of EHT re-set attempts in case a genuine fault has occurred and protecting technicians.

The more complex monitoring system described above may cost US $40,000 (plus telecommunications). This may not be considered as justified in meteorological radar systems, particularly as it adds to the complexity and the need for maintenance of additional equipment.

It is apparent that the reliability of any monitoring system must be considerably better than that of the equipment which it is monitoring, perhaps by a factor of 10.

One form of monitoring which is particularly useful in connection with precipitation measurements is that which carries out a running check on transmitter output and receiver performance (which can, of course, be included in the more comprehensive monitoring system outlined in the previous paragraphs). By tapping into the waveguide at appropriate points close to the transmitter/receiver, it is possible (a) to measure the power being transmitted to the antenna and (b) to feed into the receiver a known signal during the quiescent period of the system. The monitor outputs can be recorded or transmitted to the user as actual values or can generate alarm signals when outside set limits. It is also possible to feed the values to the computer for use in modifying the data, though this does not yet appear to have been done operationally. (Overall system checks which require the setting up of a transponder or signal generator some distance from the antenna are generally impracticable on a permanent basis.)

9.6 Maintenance policy

The formulation of maintenance policy depends on the human and technical resources available. As explained in section 9.1, it is essential to maintain a radar system well in order to obtain viable data. Manufacturers usually offer training courses as part of a procurement package, but to benefit from such courses, staff must have a good understanding of electronics beforehand. If there is a processing system, it may also be necessary for the staff to understand computers and programming. However, in view of the expertise involved, it is advisable to employ a specialist firm for the total maintenance of the computer and peripherals or, if such is not available locally, then to employ the manufacturer or his agent to carry out an overhaul annually before weather-sensitive periods or every few months.
At a manned site it is usual to employ the same technical staff for both operation and maintenance. This entails some training in radar meteorology as well as in electronic techniques. It may mean that staff are under-employed but that they must be available at all times. On the other hand, an unmanned site requires technical staff who need have no great knowledge of radar meteorology, who are free to perform other technical duties but who should be available for the radar system at short notice when they are needed. The effort required to maintain a complete, continuously running, modern radar system with processor is that provided by between half and one fully trained man. This may be higher for the first few months but should then settle to a low level for seven to ten years, depending on the environment and on the skill of the technical staff. Within this span, there will be periods of greater activity for major replacements of mechanical parts. After the span of years maintenance will become increasingly time-consuming and costly until it is no longer viable and replacement is necessary. (Note that, despite the relatively small effort that should be required to maintain a radar system, it is necessary to have at least five men to ensure that a full maintenance roster can be operated. Further, for safety reasons, it is advisable that two men always be on site together if any work other than simple checks is to be carried out.)
CHAPTER 10

DOPPLER RADAR

10.1 Introduction

The radars discussed so far in this Technical Note have been non-coherent. This means that, pulse-to-pulse, the transmitter frequency is not totally stable, though stable enough to be recognized by the radar receiver which examines the pulse amplitude on return rather than its frequency. Such radars are able to detect changes in intensity of precipitation echoes and their relativity in size and location. It is possible to estimate their relative motion and, from that, the speed of movement of a target.

In order to measure the absolute speed of movement (or velocity) of a raindrop and its direction of movement instantaneously, it is necessary to use a radar with a very precise transmitter frequency and a receiver system sensitive to the changes of frequency induced by a moving target, even though in the case of meteorological targets these changes may be small. This type of radar is sometimes referred to as a coherent radar but more frequently as a Doppler radar since it uses the well-known Doppler effect. An outline only of both the theory and the operational aspects is given here.

10.2 Basic theory

The theory of operation of a Doppler radar system is explained in Battan (1973) and, in greater detail, in Skolnik (1980), whilst Doviak et al. (1979) discuss the theory in relation to meteorological targets.

If \( f \) is the Doppler shift frequency, \( V \) the radial velocity (with respect to the radar) of the target (sometimes known as the Doppler velocity) and \( \lambda \) the radar wavelength, then
\[
2\pi f = \frac{V}{\lambda}.
\]

This applies to any form of electromagnetic transmission, but, as explained in section 2.1, in order to obtain the precise location of targets it is necessary to transmit pulses rather than continuous waves. Thus, a pulsed Doppler radar measures the change of frequency from pulse to pulse. It actually measures the difference in phase \( \phi \) between successive pulses, yielding \( \Delta \phi / \Delta t \) and hence \( f \), the Doppler shift frequency. In order to measure \( f \), it is necessary to obtain measurements of \( \phi \) at a frequency of at least \( 2f \). The maximum value of \( f \) which can be detected is given by \( f_{\text{max}} = \frac{c}{2\lambda} \). This corresponds to a maximum Doppler velocity, \( V_{\text{max}} = \frac{c}{2\lambda} \). It is then apparent that if it is desired to measure high velocities unambiguously, the longer wavelengths together with high p.r.f.s are required (e.g. 10 cm and 8000 pulses per second would give \( V_{\text{max}} = 200 \text{ m s}^{-1} \)).

If a target moves at a speed such that the distance travelled between successive pulses exceeds one wavelength (i.e. the change of phase exceeds \( 2\pi \)) the values derived for \( f \) and \( V \) are ambiguous. The radar parameters must be set to avoid this.

Since \( f_{\text{max}} \) and \( V_{\text{max}} \) are both proportional to the p.r.f., which determines the maximum unambiguous range of a pulsed radar \( (r_{\text{max}} = \frac{c}{2 \text{ p.r.f.}} \), where \( c \) is the speed of propagation of an electromagnetic wave), it can be seen that
\[
\begin{align*}
   f_{\text{max}} &= \frac{1}{4} \frac{c}{f_{\text{max}}} \\
   \text{and} \quad V_{\text{max}} &= \lambda / 8 \frac{c}{r_{\text{max}}}
\end{align*}
\]

Thus, a 10 cm radar in determining a \( V_{\text{max}} \) of 200 m s\(^{-1} \) would have a maximum unambiguous range of 18.7 km. It is apparent that, in a conventional Doppler system, it is necessary to accept a compromise between \( V_{\text{max}} \) and \( r_{\text{max}} \).
In an effort to overcome the severe range restriction of Doppler radars, a number of different methods have been considered. One is to have two separate p.r.fs within one radar (Sirmans et al., 1976). Another is to assume spatial continuity in order to overcome ambiguity, though such assumption may be dangerous in the conditions when data are most required. There is also the possibility of radars with selectable p.r.fs. Nutten et al. (1979) mention a C-band radar which will allow $V_{\text{max}}$ of 40, 20 or 10 m s$^{-1}$, corresponding to $R_{\text{max}}$ of 51, 102 and 204 km.

When the radar is looking at a volume in space containing a great many drops of differing size and velocity, it will be detecting a spectrum of Doppler shift frequencies. The received signal will contain information about the back-scattering cross-sections of the drops and their radial velocities. The back-scattered power may be extracted from this. It is a function of Doppler shift frequency and is called the Doppler spectrum.

In practice, it is necessary to obtain the spectrum for discrete ranges; this is done either by keeping the antenna still and moving the range gate out in discrete steps, the time for which it remains at each range being known as the "dwell time," or by having a series of range gates at fixed ranges. If they are fixed, it is then possible to rotate the antenna if desired.

The spread of the Doppler spectrum will be determined by a number of factors, including the following:

(a) The spread of the fall velocities of the particles in the volume (this will be directly related to the drop-size distribution);
(b) The amount of turbulence in the volume (small raindrops and snowflakes will be affected much more than large drops and hail);
(c) The air motion across the beam.

It is possible to obtain a considerable amount of information from the Doppler spectrum, in particular the mean velocity and the velocity variance.

The major limitation of a single Doppler radar, apart from the problems of unambiguous range and velocity, is that the radial velocity component of targets from one point only can be obtained.

To obtain a complete picture of that part of the atmosphere under investigation, two or even three Doppler systems are required. Much of the research work has been carried out with multiple systems. (See, for instance, Wilson et al., 1980.) Three radars are necessary to determine three components of velocity, though the three components of wind, which are connected by the mass continuity equation, can be deduced from two radars suitably spaced apart.

It must be borne in mind that ice crystals and water drops, the scatterers which are used as tracers, fall through the air at speeds dependent upon their size. Their fall or terminal velocity may be estimated from their radar reflectivity and used if necessary as a correction in calculating wind speeds. However, the best accuracy will be achieved when the scatterers are moving at the same velocity and in the same direction as the air around them.

10.3 Operational aspects

10.3.1 Introduction

Doppler radars have been used for research purposes for many years, both singly and, more recently, in multiple networks consisting usually of two or three radars. They have played a considerable part in the investigation of the atmosphere and are considered by some radar meteorologists to be indispensable in the study of the dynamics of air masses, particularly of convective clouds. However, problems of interpretation of data still exist and it is only in very recent years that serious consideration has been given to their use as operational systems. In certain parts of the world, particularly those subject to violent weather, they are now regarded as a highly desirable form of radar. They are inherently more complex and more expensive than conventional radars, and they require greater processing power and more maintenance effort. Despite this,
predictions are being made that they will be in wide use in certain parts of the world by the end of the next decade and in the USA radars with Doppler capability will form a large national network. Amongst many interesting papers, those of Serafin and Lhermitte (1980), Wilson et al., (1981) and Rust and Doviak (1982) indicate the likely future use of Doppler radars. A series of papers dealing with operational aspects appear in the Bulletin of the American Meteorological Society for October 1980.

10.3.2 Methods of operation

Displays specifically for operational use with Doppler radars have not yet been fully developed, though a number of laboratory models exist. The most common versions are the velocity-azimuth display (VAD) and the plan-shear indicator (PSI). In general, most displays present either vertical or horizontal data against azimuth, usually in colour but sometimes in alphanumeric or pseudo-graphical form. It is an advantage if displays are available side-by-side, showing reflectivity and Doppler velocity (Figure 29). For detailed discussion on the subject, the reader is referred to Gray et al. (1975), Burgess et al. (1976), Brown and Borgogno (1980), Moninger and Nelson (1980) and Wilson et al. (1980).

In practical applications, for the measurement of profiles of wind velocity when particle fall velocities are likely to be small (e.g. in widespread precipitation), it is necessary to scan at a fairly low angle of elevation. A VAD can be used, the horizontal wind-speed being easily read off as the maximum value shown. To determine change of wind (speed or direction) with height, a series of PPI-type scans are carried out at increasing altitude. It is possible to see from a VAD the direction of the wind as well as the speed at any given elevation and thence to build a picture from the ground upwards. (A number of practical applications of Doppler radar are discussed by Browning, 1978.)

10.3.3 Applications

Doppler radar has two distinct primary uses. The first, mainly for general forecasting purposes, lies in its ability to provide data which may reveal signatures useful for the advanced warning of such phenomena as tornadoes and severe storms; moreover, it can provide more information on their intensity and structure than any other practical means. The second use is its ability to measure wind shear. The most useful system is one which, in addition, can measure precipitation intensities in a conventional way as well as providing Doppler data. One important advantage of such a dual system is that it is possible to determine with some degree of accuracy the position and extent of permanent echoes (which are, by definition, stationary) from the Doppler channel. This information can then be used in an attempt to ensure that only precipitation data are measured by the non-Doppler channel. As with any other system of clutter removal, the method is unlikely to be totally successful since, under some transmission and weather conditions, permanent echoes can appear to move and, conversely, precipitation is sometimes effectively stationary.

It must be remembered that a Doppler radar can normally provide data only if there are particles in the atmosphere to act as scatterers, usually precipitation but occasionally insects or birds. However, under certain circumstances a sufficiently powerful radar will detect inhomogeneities of refractive index, thus giving some indication of clear-air turbulence or wind shear. It would be dangerous to assume that the absence of such indication meant that turbulence did not exist. This inevitably reduces its operational value.

To obtain echoes from refractive inhomogeneities and for the purpose of measuring precipitation intensity to the greatest possible ranges (cf. conventional non-Doppler radar) or studying the structure of severe storms, the longer wavelengths are necessary, preferably 10 cm.

For operational applications these techniques are currently being developed. However, the large number of radars which would be required for a network and the difficulty of combining data from multiple radars in real time is likely to lead to slow introduction operationally. The determination of the three-dimensional kinematic structure of precipitating systems remains a research exercise.

Wilson et al. (1980) recommend that, in regions where severe storms occur, Doppler radars should be of 10 cm wavelength with beamwidth of 1° and that automatic procedures for removing velocity and range ambiguities should be incorporated.
Figure 29 - Doppler radar colour displays during a coastal storm at Ocean Shores, Washington. Pictures are for the time 13:16 PST on 4 March 1979; they are PPIs at an elevation angle of 7° and the slant range marks are at 10 km intervals. (a) Radar reflectivity factor showing a bright band (melting level) at a height of about 2.2 km (slant range 17 km); (b) Doppler velocity display showing wind variations with height (Wilson et al., 1981).
10.3.4 Airport applications

Real concern with low-level wind shear exists at airports. Strauch (1979) notes that a wind-shear warning system should be able to detect wind shears along approach and departure paths and provide warnings of dangerous winds that may propagate into these paths. It must have all-weather capability. Dangerous wind-shear regions may be only a few kilometres in size, so measurement of wind profiles at only one point at an airport does not provide sufficient information. However, measurement of the vertical profiles of the horizontal wind and its temporal change provides valuable information in many meteorological conditions.

In principle, the installation of a Doppler radar to look along the approach and departure paths of aircraft seems fairly straightforward. It is advisable to keep the system simple initially. The problems which have to be dealt with include:

(a) Ground clutter, which is unavoidable at low level and which cannot be entirely removed by MTI (moving target indication) methods without the risk of removing some wind information also (cf. section 10.3.3);
(b) The relationship between particle speed and wind, which approximates to 1:1 in widespread precipitation but is much less certain in convective conditions;
(c) The radar height resolution, which may be insufficient to detect the precise characteristics of the wind profile. (There are limitations to the speed of antenna movement in terms of dwell time for sampling purposes and to the minimum time for data processing.)

For the limited purposes of measuring wind shear at or near an airfield it can be assumed that the slant range to which measurements are required will be sufficiently low to avoid any difficulty caused by range ambiguity. This allows higher values of \( V_{\max} \). Moreover, as attenuation due to water droplets is unlikely to be a problem, 5.6 or even 3 cm radars are acceptable.

Amongst other possible uses of Doppler radar in airfield operations there are:

(a) The measurement of changes in headwind speed which affect landings in particular;
(b) The detection of turbulence, set up by large jet aircraft, which affects following aircraft (in some conditions it would be difficult to separate this from turbulence due to natural phenomena);
(c) The detection of gust fronts and “downbursts”. The former are associated with air rapidly descending from the base of a cumulonimbus cloud and spreading out horizontally within several hundred metres of the ground (Wilson et al., 1980). This air often moves in a very different direction from the established flow. A downburst is a surface wind in excess of 17 m s\(^{-1}\) caused by small-scale downdraughts from the base of cumulonimbus cloud (Fujita, 1978). Both of these hazards are readily detectable on a Doppler colour display.

10.4 Conclusion

A major problem with Doppler radar is that it can produce data in several different forms and in large quantities. Thus, it is difficult to determine what type of display is best, though generally for a non-specialist operator it should convey factual, straightforward information only. If the radar is multi-functional, then several single-purpose displays may be preferable. If a multiple radar system is in use, then single-purpose displays or representations may present composited information (Figure 30).

It is apparent that, if the correct form of display is chosen, Doppler radar allows the reproduction in pictorial form of a clear overall view of a storm, with periodic updating. Such a complex display will, of course, be expensive.

Data processing for a single-purpose Doppler radar, e.g. determining wind shear only, or even for a dual radar wind-shear system, does not present too much difficulty. However, for a multi-task radar, the processing requirements increase very sharply. For a multiple, multi-task radar system the requirements are indeed massive.
As has been suggested in section 10.3.1, the display and processing difficulties and uncertainties have so far restricted the operational use of Doppler radar despite its potential. When considered together with the costs involved, it seems likely that operational Doppler installations will for the present be limited to those countries which experience violent conditions most frequently and which have the financial and technical resources to provide and maintain such systems.

Ostensibly, one of the most valuable and urgent applications could be the detection and measurement of wind shear for airport operations (section 10.3.4). Relatively simple, single low-powered 5.6 or 3 cm Doppler radars might satisfy this requirement provided that scatterers are present. Although such radars may be developed within the next few years, wind-shear measurements may also be made by acoustic radars or by lasers which may prove more cost-effective.

Two or more radars are necessary to obtain the three-dimensional data which may be of far greater value to some users, but, in relation to cost, others may consider that a single, complex radar system with Doppler facility is preferable. This is able to provide a much wider range of data, including wind-shear information, precipitation intensity, location of fronts, detection of gust fronts, downbursts, tornadoes, hurricane winds and clear-air turbulence. It may be possible to give only 20 minutes' warning of the approach of tornados, but this can be sufficient justification for such a complex (and expensive) system.

Mention should be made briefly of a further possibility with Doppler radar. Rust and Doviak (1982) discuss lightning studies using radar and suggest that this is a promising new area of research.

**Bibliography**


CHAPTER 11

SPECIALIZED USES OF RADAR

11.1 Introduction

The previous chapters in this Technical Note have dealt with operational radar equipment and systems or, in the case of the chapter on Doppler radar, with equipment which is expected to become operational in due course. Leading up to operational systems there has been an enormous amount of research and development effort; this will continue into the future. Many of the projects are documented in the proceedings or preprints of the Conferences on Radar Meteorology organized by the American Meteorological Society.

There remain a small number of specialized or limited uses of weather radar, some of which may eventually lead to new operational systems or practices. This final chapter deals with some of these. Their inclusion indicates the flexibility of radar as a meteorological observing instrument of which increasing use may be made in the future.

11.2 Hail

Recently there has been increasing interest in the possibility of detection and measurement of hail, although the need has existed for many years. Primarily because of damage caused to crops, precipitation-enhancement projects or hail-suppression projects have been undertaken in such countries as the USA, Canada, the USSR and Switzerland, and in the last few years, in Spain (Atmospheric Technology No. 4, 1973; Krauss, 1979; Sulakvelidze et al., 1974; Federer et al., 1979; Waldvogel, 1981; WMO, 1976-1981). The aim is to prevent the build-up of ice crystals into hailstones of dangerous size. The method is to seed the clouds whilst the hailstones are still small and thus to encourage them to turn into water drops. Seeding, with silver iodide crystals, either by firing rockets or by dropping from aircraft, is costly; it is therefore essential to observe, track and measure potentially dangerous hailstorms with some accuracy. To achieve this a radar can be a valuable tool, though there are problems in measuring large-diameter hailstones on account of their high spatial and temporal variability. The results of experiments carried out by a number of workers are not uniform. One of the main difficulties is that an echo from precipitation can be so large that there is no sure way of knowing what proportion is due to hail or whether hail is being detected at all. Waldvogel et al. (1979) demonstrate that a large proportion of cells might meet the criteria for seeding but would not produce hail on the ground.

Measurements have been carried out with single-wavelength radars, dual wavelength radars, dual or circular polarization radars and Doppler radars. S-band (10 cm) radars are virtually essential for a single-wavelength radar because of the severe attenuation which affects shorter wavelengths. Considerably more work is needed to establish usable techniques, but in Switzerland there has been some success in the comparison of S-band radar measurement with hail-pad data. (Hail-pads consist of foam rubber plates covered with thin aluminium foil; they measure the kinetic energy of the hailstones which strike them.) At ranges up to 40 km, kinetic energies derived from the two methods of measurement have been compared for nearly 200 hail-pads.

The conclusions arrived at from a number of experiments carried out by several countries have been listed by Waldvogel (1981) as follows:

(a) Hail detection
   (i) Hail cells can be detected at a very early stage in their development even with a simple X-band radar.
(ii) If the height of the 45 dBZ contour is more than 1.4 km above the 0°C level, the cell is a “hail cell”. (45 dBZ means that $45 = 10 \log Z$, where $Z$ is defined as the radar reflectivity factor in the empirical equation $Z = a R^b$, $R$ being rainfall, $a$ and $b$ constants, and $Z$ is equal to $\Sigma D^6$ where $D$ is the drop diameter.)

(iii) About 50% of the detected hail cells never produce hail on the ground. This corresponds to a waste of about 30% of seeding material or a false alarm time of about 30%.

(iv) Different simple hail criteria from different places in the world look very similar.

(b) Hail measurement

(i) Heavy hailfalls can be measured with a simple 10 cm radar.

(ii) A generally valid relationship between the flux of the kinetic energy ($\dot{E}$) of the hailstones and the radar reflectivity ($Z$) exists. ($\dot{E} = 5 \times 10^{-6} \times Z^{0.84}$.)

(iii) The ensemble of hailstones during a heavy rainfall can be treated as Rayleigh scatterers.

(iv) Radar reflectivities due to rain or hail can be “separated” with a simple solution for time-and/or area-integrated quantities of large hailfalls.

(v) The agreement between hail-pad and radar-data-derived hailfall parameters is ±30% for large hailfalls. The correlation coefficient between the kinetic energies at the hail-pad sites and their corresponding radar values varies from 0.6 to 0.8 as long as heavy hailfalls with at least 20 non-zero data points are considered.

(vi) Medium and light hailfalls are more complicated; the main problems are the separation of rain from hail reflections and the representativeness of the hail-pad measurements (for example, Waldvogel, 1981; Waldvogel et al., 1979, 1980; Srivastava and Jameson, 1977; Dye and Martner, 1978).

11.3 Vertically Integrated Liquid (VIL)

A new radar analysis tool considered in recent years allows the observer to integrate echo intensities over the depth of a thunderstorm. This is known as Vertically Integrated Liquid (VIL) (Greene and Clark, 1972). It is now believed to be of greater significance in the prediction of severe weather than just the lowest level (or zero-tilt) areal precipitation field (McCann, 1978) and is being specified in the operational requirements of some users.

The method of operation is to sweep the storm vertically, determine the Video Integrator and Processor (VIP) levels at a number of heights, feed these into a computer for conversion to reflectivity, then integrate the resulting values to determine VIL.

To obtain accurate figures it is necessary to scan vertically to give intervals in the order of, say, 2 km. However, the antenna must be programmed to avoid the overlap which will falsify the results. Further, depending upon the beamwidth, the resolution may be poor at ranges beyond about 50 km. In practice, problems arise because there are likely to be several azimuths at which the radar is required to measure VIL. This will be time-consuming and will lead to a large quantity of data being made available for processing. This quantity is not beyond the capability of a modern processor but it is necessary during storm situations to continue to process all possible data. In view of the rapid growth and decay of storms it is essential to scan and to process the data frequently, at least once every five minutes, say.

It is apparent that, in the regions where VIL may be of most value, storms will be most intense and S-band radars are therefore highly desirable in order to avoid attenuation.
11.4 Detection of dust-storms

In some regions there is a requirement to detect dust-storms and, if possible, to measure the quantity of dust and size of particles within them. In view of the damage and discomfort which they can cause, forecasts of dust-storms can be extremely valuable. No research in depth appears to have been taken in the use of radar for this purpose, but there are a number of recorded instances of detection.

Dust-storms occur where the surface layer of soil is very dry and finely divided. Thus, the most likely occurrence is of very small particles being picked up by the wind and carried away. Such particles are the most difficult to detect by radar in the same way as very small water droplets are difficult. Zakharov (1965) estimates that, in moderate or strong winds, particles up to 30 μm in diameter may be carried for more than 1500 km, those between 100 and 600 μm for several kilometres and that those greater than 1000 μm or 1 mm would only be lifted and displaced for a short distance. The strength of wind necessary to lift dust particles depends on the nature of the soil.

Fedorov and Stepanenko (1978) assume that dust particles can be regarded as having reflectivity calculable in the same terms as precipitation particles. On this basis, an X-band (3 cm) radar will detect dust particles of effective scattering cross-section per unit volume of $10^{-13}$ cm to ranges of 120 km. Such sizes are rare; it seems more likely that ranges of 20 to 30 km would be the maximum for most particle sizes.

As with precipitation, shorter-wavelength radars, 1.25 or 0.8 cm, will more readily detect smaller particles but will lack the penetration, whereas 5.6 and 10 cm will detect only the larger particles.

Dust particles can, of course, act as the scatterers which are normally necessary for detection of wind shear by Doppler radar. Since the range required is usually quite short, the particles can be quite small.

Dust particles are normally dry, almost by definition; on the rare occasions when they are wet their reflectivity will be increased considerably.

11.5 Detection of cloud

It was shown in section 2.12 that conventional weather radars can measure only precipitation or drops of precipitable size. As a result, they are of no value in cloud detection except in convective cloud, which contains drops of appreciable size, say, greater than 20 μm. Nevertheless, from equation (2)* in Chapter 2 it will be seen that, as the wavelength is decreased, the ability to detect small drops or particles is increased. Thus, lightweight radars operating at, say, 0.8 cm are able to detect cloud provided that it contains a sufficient number of particles. On the other hand, some special research radars with very large antennae, high powers and, perhaps, long pulse-lengths, operating at much longer wavelengths, will also detect cloud.

Outside the research field, the two functions which cloud-detection radars could fulfill are probably to determine (a) cloud height and (b) visibility. However, these two requirements can be met more adequately and more cheaply by laser systems or, possibly, acoustic radar.

Bibliography


* $P_r = 284 \frac{\mu D^n}{\lambda^4} \frac{P_r h A_t}{8\pi^2 F K}$


