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USE OF WEATHER RADAR FOR AVIATION

(Report by a working group of the Commission for Instruments and Methods of Observation

prepared by

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## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreword</td>
<td>VII</td>
</tr>
<tr>
<td>Summary (English, French, Russian, Spanish)</td>
<td>IX</td>
</tr>
<tr>
<td>General — Aviation requirements for weather radar data</td>
<td>XIX</td>
</tr>
<tr>
<td>Introduction</td>
<td>XIX</td>
</tr>
<tr>
<td>General requirements</td>
<td>XIX</td>
</tr>
<tr>
<td>Performance criteria for ground-based and airborne weather radar</td>
<td>XIX</td>
</tr>
</tbody>
</table>

### Chapter 1 — Identification of phenomena dangerous for aviation

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Use of ground-based radars</td>
</tr>
<tr>
<td>1.1.1</td>
<td>Detection of hail</td>
</tr>
<tr>
<td>1.1.2</td>
<td>Echo intensity or reflectivity as an indicator of hail</td>
</tr>
<tr>
<td>1.1.2.1</td>
<td>For radar operating at a wavelength of 3 cm</td>
</tr>
<tr>
<td>1.1.2.2</td>
<td>For radar operating at a wavelength of 10 cm</td>
</tr>
<tr>
<td>1.1.3</td>
<td>Echo height as an indicator of hail</td>
</tr>
<tr>
<td>1.1.4</td>
<td>Summary</td>
</tr>
<tr>
<td>1.1.5</td>
<td>Association between turbulence and ground-based radar echoes from thunderstorms</td>
</tr>
<tr>
<td>1.1.5.1</td>
<td>Avoidance of thunderstorm turbulence</td>
</tr>
<tr>
<td>1.1.5.2</td>
<td>Turbulence intensity and radar echo characteristics</td>
</tr>
<tr>
<td>1.1.5.3</td>
<td>Turbulence in clear air in the vicinity of thunderstorms</td>
</tr>
<tr>
<td>1.1.5.4</td>
<td>Extension to other portions of the world</td>
</tr>
<tr>
<td>1.1.5.5</td>
<td>Summary</td>
</tr>
<tr>
<td>1.2</td>
<td>Use of airborne weather radar</td>
</tr>
<tr>
<td>1.2.1</td>
<td>Detection of hail</td>
</tr>
<tr>
<td>1.2.2</td>
<td>The avoidance of turbulence</td>
</tr>
</tbody>
</table>

| References | 12 |
| Annex — Thunderstorm flight policy and airborne weather radar | 14 |

### Chapter 2 — Measurement of the height of echoes

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Introduction</td>
</tr>
<tr>
<td>2.2</td>
<td>Operational procedure</td>
</tr>
<tr>
<td>2.3</td>
<td>Measurement of elevation angle</td>
</tr>
</tbody>
</table>

References
### CONTENTS

<table>
<thead>
<tr>
<th>Chapter 3</th>
<th>Interpretation of echoes for different types of radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>Antenna beam distortion — Correction of half a beamwidth</td>
</tr>
<tr>
<td>2.5</td>
<td>Threshold value of reflectivity</td>
</tr>
<tr>
<td>2.6</td>
<td>Range correction procedure</td>
</tr>
<tr>
<td>2.7</td>
<td>Range limitations for echo-top measurement</td>
</tr>
<tr>
<td>2.8</td>
<td>Error due to the variation of echo characteristics</td>
</tr>
<tr>
<td>2.9</td>
<td>Conclusion</td>
</tr>
<tr>
<td>References</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 4</th>
<th>Instrumental techniques — Processing and transmission of radar information</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Introductory remark</td>
</tr>
<tr>
<td>3.1.1</td>
<td>Attenuation of electromagnetic waves</td>
</tr>
<tr>
<td>3.1.1.1</td>
<td>Theory</td>
</tr>
<tr>
<td>3.1.1.2</td>
<td>General</td>
</tr>
<tr>
<td>3.1.1.3</td>
<td>Attenuation due to gases in the atmosphere</td>
</tr>
<tr>
<td>3.1.1.4</td>
<td>Attenuation due to liquid particles</td>
</tr>
<tr>
<td>3.1.1.5</td>
<td>Attenuation due to cloud</td>
</tr>
<tr>
<td>3.1.1.6</td>
<td>Attenuation due to rain</td>
</tr>
<tr>
<td>3.1.2</td>
<td>Practical consequences of attenuation</td>
</tr>
<tr>
<td>3.1.3</td>
<td>Correction of the attenuation</td>
</tr>
<tr>
<td>3.2</td>
<td>Errors associated with the beamwidth transmitted by the radar</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Beamwidth in the vertical plane</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Beamwidth in the horizontal plane</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Practical consequences concerning the choice of equipment</td>
</tr>
<tr>
<td>3.2.3.1</td>
<td>Ground radar</td>
</tr>
<tr>
<td>3.2.3.2</td>
<td>Airborne radar</td>
</tr>
<tr>
<td>References</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 4</th>
<th>Instrumental techniques — Processing and transmission of radar information</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>General aspects of the problem</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Improvement in the precision of relationships between radar information and meteorological phenomena</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Transmission of radar information</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Improving operational facilities for radar information</td>
</tr>
<tr>
<td>4.1.3.1</td>
<td>Equipment giving a temporary image</td>
</tr>
<tr>
<td>4.1.3.2</td>
<td>Devices providing permanent information</td>
</tr>
<tr>
<td>4.1.4</td>
<td>Examples of equipment for processing radar information</td>
</tr>
<tr>
<td>4.2</td>
<td>A radar echo-contouring system (U.S.A.)</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Basic principles of operation</td>
</tr>
<tr>
<td>4.2.2</td>
<td>VIP design</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Test and evaluation</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Automatic data processing</td>
</tr>
<tr>
<td>4.3</td>
<td>Transmission of radar information</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Experience of the Meteorological Service of the U.S.A.</td>
</tr>
<tr>
<td>4.3.1.1</td>
<td>Introduction</td>
</tr>
</tbody>
</table>
Chapter 5 — Transmission of radar information to aircraft in flight

5.1 General ................................................. 62
5.2 Example of practical methods for the transmission of radar information to aircraft in flight (Methods and procedures in use, or which have been tried, in the U.S.A.) ................................. 63
  5.2.1 Coded messages .................................. 63
  5.2.2 Direct pilot-to-forecast service ................. 63
  5.2.3 Broadcast of the PPI display using television techniques ............................................. 63
  5.2.4 Direct assistance to controllers ................. 64
5.3 Example of practical means for the transmission of radar information to aircraft in flight (Australian example) ......................................................... 64

Chapter 6 — New techniques

6.1 Introductory remark .................................. 65
  6.1.2 Possibilities in the use of radar with two wavelengths for meteorological purposes ...... 65
  6.2 Requisite characteristics of a weather radar with two wavelengths for the quantitative observation of cloud and precipitation ........................................ 69
  6.2.1 Determination of height of cloud base by radar ......................................................... 70
  6.2.2 Preliminary remarks ............................... 70
  6.2.2 Clouds considered as radar targets .......... 70

References ................................................. 72

NOTE: The terms of reference of the working group included inter alia the task of studying the use of data obtained by airborne radar for training aeronautical personnel. The amount of information which the group was able to acquire from qualified experts in the field was rather limited, so that the references in the text to this subject are not the result of such profound studies as for the other aspects of its work.
FOREWORD

During the fourth session of the WMO Commission for Instruments and Methods of Observation (CIMO) (Tokyo, 1965), the need was recognized for an overall study of the various uses of meteorological radar for aeronautical purposes. A working group was accordingly established to study all information useful for aeronautical purposes which could be obtained by ground-based or airborne radar. The terms of reference of the group specifically referred to problems relating to hail detection, turbulence in zones of precipitation, interpretation of echoes and the progress in instrumental techniques, including transmission of radar information to aircraft in flight. The working group was composed of Mr. H. Treussart (France) - (chairman), Mr. S. G. Bigler (U.S.A.), Mr. V. V. Kostarev (U.S.S.R.), Mr. K. Otani (Japan), who replaced Mr. T. Kume in 1967, Mr. W. B. Beckwith, representing CAeM, and Mr. R. Schwarz, representing ICAO.

At the fifth session of CIMO (Versailles, 1969), a report containing technical conclusions resulting from the studies made by the working group was presented for review. The Commission considered that the report contained much valuable material and recommended that the material annexed to the report should be published in the WMO Technical Note series. The present Technical Note thus represents the outcome of the work undertaken by this working group.

I should like to take this opportunity of expressing the gratitude of WMO to the members of the working group for the time and effort they have devoted in preparing the text of this valuable publication.

D. A. Davies
Secretary-General
SUMMARY

For safe operation of aircraft in all phases of flight including those of supersonic transport (SST) aircraft, there is undoubtedly a need for precise information on operationally significant weather. Weather radar, with its capability to display and present characteristic features of hazardous weather phenomena observed in the air as well as on the ground, is considered the most suitable equipment for this purpose. It has been urged at many WMO and ICAO meetings that the methods and procedures for the utilization of weather radar should be developed for aviation purposes. In the first section, this Note describes a general survey of what are the existing aviation requirements for weather radar, either ground-based or airborne, in connexion with performance criteria, range and accuracy.

Chapter 1 discusses the detection and identification of regions of hail and turbulence associated with thunderstorms, these being considered dangerous phenomena for aviation. It is shown through intensive surveys on hail detection that echo intensity, as an indicator of hail, observed using 10 cm wavelength radar exhibited a similar trend to that observed using 3 cm radar, but very little change in intensity with height. Several case studies of the probability of hail as a function of height are also illustrated for assessment of hail. As regards the problem of turbulence, considerable effort has been made to study the association between radar echo characteristics observed by ground-based radar and turbulence measured by instrumented aircraft. However, the summary indicates that there are no known methods for forecasting turbulence activity within a given thunderstorm. Brief mention is made of the use of airborne radar for detection of hail and the avoidance of turbulence by aircraft in flight.

Chapter 2 discusses the question of measuring the height of echoes observed by radar, which represents an index of storm activity. It is stressed that the maximum height of echo coming from relatively large precipitation particles should not be identified with the top of the cloud. Studies have revealed numerous errors due to factors such as elevation angle, antenna beam distortion and threshold value of reflectivity, etc. Although there is an urgent need for precise volume of air traffic, it is unfortunately not yet possible to adopt internationally accepted procedures owing to differences from one country to another in the ability to interpret radar observations.

Chapter 3 discusses interpretation of echoes for different types of radar. The data from weather radars depend not only on meteorological phenomena but also, to a great extent, on the characteristics of the radar. Each echo appearing on the radar screen should be interpreted, taking into account the individual characteristics of each set of equipment, this being particularly important when information on quantitative measurements is required. The study of attenuation of electromagnetic waves points out in a general way that the degree of attenuation due to various precipitation phenomena is negligible only at wavelengths of 10 cm or more, while at all other wavelengths no precise measurement can be made without a correction. If the beamwidth transmitted by radar is too wide, it also affects the interpretation of precipitation echoes considerably. Conclusions indicate that radar operating at a wavelength of 10 cm seems to be most likely to satisfy all the conditions for ground radar. For airborne radars, advantages and disadvantages of three wavelengths, Ku-, X- and C-bands, are discussed and the choice of wavelength is a matter for the user to decide.

Chapter 4 deals with the processing and transmission of radar information in great detail. Here, the broad concept expressed by the term "processing of radar information" is based on three operations to be applied to radar information, namely: improvement in the precision of relationship between radar information and
meteorological phenomena; transmission of radar information; and improvement of operational facilities. The processing and transmission facilities can be made available depending on what type of radar information is required—either for temporary or for permanent purposes. An example of equipment for processing radar information is illustrated under the title of a radar echo-contouring system developed by the U.S.A. In view of the great demand for transmission of the radar data by meteorologists at local forecast centres as well as by air traffic control personnel at airports, considerable attention has been given to this problem. In this connexion, the experience acquired by the U.S.A. using a remoting system designed for television display is described. The experience of Japan with a telephone facsimile system adopted for nation-wide transmission and a telephone-writer system for local air traffic operation is also outlined.

Transmission of radar information to aircraft in flight is also considered a subject important for aviation which is discussed in Chapter 5. Two types of transmitting operation have to be considered: the first is for the facilitation of aircraft approach, landing and take-off operations in the neighbourhood of the aerodrome, for which rapid transmission of precise data on echoes and frequent updating are required in view of the temporal and spatial variation of phenomena; the second is for the safeguarding of aircraft in flight and for flight planning, which does not require such great precision in locating and determining the intensity of the phenomena, hence the transmission is allowed for a longer period. Examples of practical methods used for these purposes by the U.S.A. and Australia are given in detail.

Chapter 6 discusses new techniques developed for radar observations. In recent years, an important study has been made in the U.S.S.R. with a view to improving measurements made by means of either two sets of radar using different wavelengths or a single set of equipment using two wavelengths. Based on the various experiments conducted in that country, this study opens up the possibilities of applying these comparatively new techniques to the quantitative measurement of cloud and precipitation. It also shows, on the other hand, that there still exist some difficulties in determining the height of cloud base by means of radar, even when the latter has two wavelengths.
RÉSUMÉ

Afin d’assurer la sécurité des aéronefs, y compris celle des aéronefs de transport supersoniques (TSS), au cours de toutes les phases de vol, il est évidemment nécessaire de disposer d’informations précises sur le temps significatif qui conditionne l’exploitation. Le radar météorologique, du fait qu’il est à même de donner aux équipages en vol et aux services au sol une représentation visuelle des caractéristiques essentielles des phénomènes météorologiques dangereux, apparaît comme l’équipement le mieux adapté pour fournir ces informations. A nombre de réunions de l’OMM et de l’OACI, il a été instamment recommandé d’adapter aux besoins de l’aviation les méthodes et procédés d’utilisation du radar météorologique. La présente Note débute par une étude générale des besoins actuels de l’aéronautique en matière de radar météorologique, du point de vue des critères de performance, de la portée et de la précision des radars au sol et des radars de bord.

Le chapitre 1 étudie la détection et l’identification des zones de grêle et de turbulence qui accompagnent les orages et qui présentent des risques pour l’aéronautique. A la suite de nombreuses études sur la détection de la grêle, il apparaît que l’intensité des échos observés sur un radar de 10 cm de longueur d’onde peut servir d’indice de la grêle au même titre que celle des échos observés sur un radar de 3 cm, à cette différence près qu’avec 10 cm de longueur d’onde l’intensité varie très peu en fonction de l’altitude. Plusieurs études pilotes concernant la probabilité de grêle en fonction de l’altitude sont également présentées en rapport avec le problème de l’estimation des risques de grêle. En ce qui concerne le problème de la turbulence, on a consacré beaucoup d’efforts à l’étude des rapports existant entre les caractéristiques des échos observés sur les radars au sol et la turbulence mesurée par des aéronefs équipés d’instruments appropriés. Toutefois, sur ce point, la Note conclut qu’il n’existe encore aucune méthode pour prévoir l’intensité de la turbulence à l’intérieur d’une cellule orageuse donnée. Il est brièvement fait mention de l’utilisation du radar de bord par les aéronefs en vol pour détecter les chutes de grêle et éviter les zones de turbulence.

Le chapitre 2 aborde le problème de la mesure de la hauteur des échos observés sur le radar en tant qu’indice de l’activité orageuse. On y souligne le fait qu’il ne faut pas confondre la hauteur maximale des échos renvoyés par de grosses particules précipitantes avec celle du sommet du nuage. Des études ont révélé les nombreuses erreurs qui peuvent résulter de divers facteurs : angle de site, déformation du faisceau radioélectrique de l’antenne et valeur du seuil de réflectivité, etc. Bien que l’intensité croissante du trafic aérien impose d’urgence de mesurer avec précision la hauteur maximale des échos, il n’est malheureusement pas encore possible d’adopter à cet égard des procédures uniformes à l’échelon international, en raison des différences constatées d’un pays à l’autre dans l’aptitude à interpréter les observations radar.

Le chapitre 3 traite de l’interprétation des échos observés sur différents modèles de radars. Les données fournies par les radars météorologiques dépendent non seulement des phénomènes météorologiques, mais aussi, dans une large mesure, des caractéristiques du radar. Chaque écho observé sur l’écran du radar doit être interprété en tenant compte des caractéristiques particulières de l’appareil, spécialement lorsqu’il s’agit d’effectuer des mesures quantitatives. L’étude de l’atténuation des ondes électromagnétiques révèle que, d’une manière générale, l’atténuation résultant des diverses formes de précipitations n’est négligeable qu’aux longueurs d’ondes égales ou supérieures à 10 cm, tandis qu’aux longueurs d’ondes inférieures il n’est pas possible d’effectuer de mesures précises sans procéder à des corrections. D’autre part, une largeur exagérée du faisceau électromagnétique émis par le radar complique énormément l’interprétation des échos renvoyés par les précipitations. La conclusion qui se dégage de tout cela est que la longueur d’onde de 10 cm semble la plus favorable pour qu’un radar au sol satis-
fasse à toutes les conditions requises. En ce qui concerne les radars de bord, la Note analyse les avantages et les inconvénients des trois bandes Ku-, X- et C- et conclut que c'est à l'usager qu'il appartient de choisir la longueur d'onde.

Le chapitre 4 établit à fond le traitement et la transmission de l'information radar. En l'occurrence, le terme général “traitement de l'information radar” englobe les trois opérations auxquelles cette information donne lieu, à savoir: amélioration de la corrélation entre les données radar et les phénomènes météorologiques; transmission des renseignements radar; et amélioration des moyens d'exploitation des renseignements radar. Le choix des moyens de traitement et de transmission de l'information radar dépend de la forme sous laquelle on veut consulter cette information: images fugitives ou documents permanents. Un système d'isocontour mis au point aux États-Unis est exposé à titre d'exemple d'équipement pour le traitement de l'information radar. Étant donné le besoin pressant d'informations radar pour les météorologues des centres de prévision locale et pour les agents du contrôle de la circulation aérienne sur les aérodromes, les auteurs de la Note ont été extrêmement attentifs au problème de la transmission de l'information radar. A ce sujet, il est fait état de l'expérience acquise aux États-Unis d'Amérique en ce qui concerne l'utilisation d'un système de transmission prévu pour permettre l'examen de l'image radar sur un écran de télévision. La Note rend également compte de l'expérience acquise au Japon avec un réseau national de transmission par fac-similé sur lignes téléphoniques et avec un système de téléautographe à usage local pour les besoins du contrôle de la circulation aérienne.

Le chapitre 5 traite d'un sujet qui revêt une grande importance pour l'aviation : la transmission de l'information radar aux aéronefs en vol. A cet égard, il faut considérer deux genres de transmissions. En premier lieu, celles qui visent à faciliter les manœuvres d'approche, d'atterrissage et de décollage des avions à proximité immédiate de l'aérodrome, auquel cas il est nécessaire de transmettre rapidement des données précises sur les échos relevés et de tenir ces renseignements à jour, à intervalles rapprochés, en raison des variations dans l'espace et dans le temps que subissent les phénomènes observés. En second lieu, les transmissions qui concernent la sécurité des aéronefs en vol et le planning de vol, auquel cas il n'est pas indispensable de localiser les phénomènes et d'en déterminer l'intensité avec une précision aussi poussée; de ce fait, ces transmissions peuvent avoir lieu beaucoup moins fréquemment. La Note fournit des exemples détaillés de méthodes pratiques utilisées à cet effet aux États-Unis et en Australie.

Le chapitre 6 examine de nouvelles méthodes d'observation par radar récemment mises au point. Ces dernières années, une importante étude a été effectuée en U.R.S.S. dans le dessein d'améliorer la qualité des mesures en utilisant deux radars fonctionnant sur des longueurs d'ondes différentes ou un seul radar comportant deux longueurs d'ondes. Se fondant sur les diverses expériences réalisées dans ce pays, l'étude expose les possibilités d'application de ces techniques relativement nouvelles à la mesure quantitative des nuages et des précipitations. D'autre part, elle révèle que la détermination de l'altitude de la base des nuages au moyen du radar, même lorsqu'il s'agit d'un radar à deux longueurs d'ondes, soulève encore certaines difficultés.
РЕЗЮМЕ

Для обеспечения безопасности операций самолетов во всех фазах полета, включая сверхзвуковые транспортные самолеты (СЗТС), несомненно, существует необходимость в точной информации об особых, с оперативной точки зрения, явлениях погоды. Метеорологический радиолокатор с его способностью давать изображения и представлять характерные особенности опасных метеорологических явлений, наблюдающихся с воздуха, а также с земли, считается наиболее подходящим средством для этой цели. На многих заседаниях ВМО и ИОГА выражались настоящие пожелания о том, чтобы были разработаны методы и процедуры использования метеорологических радиолокаторов для авиационных целей. В первом разделе настоящей записки дается общий обзор существующих авиационных требований к метеорологическому радиолокатору как наземному, так и переносному по воздуху, в отношении технических характеристик, дальности действия и точности.

В главе 1 рассматривается вопрос об обнаружении и опознании районов выпадения града и районов турбулентности, связанных с грозами, которые считаются опасными явлениями для авиации. Путем обзора большого числа случаев обнаружения града показано, что интенсивность эха как индикатора града, наблюдаемого с помощью 10-см радиолокатора, обнаруживает тенденцию, аналогичную наблюдаемой при использовании 3-см радиолокатора, однако при очень небольшом изменении интенсивности с высотой. В качестве иллюстрации примеров оценки града приводится также исследование нескольких случаев вероятности града как функции высоты. Что касается проблемы турбулентности, то была проделана значительная работа по изучению взаимосвязи между характеристиками радарного эха, наблюдаемого с помощью наземного радиолокатора, и турбулентностью, измеряемой с помощью специально оборудованных самолетов. Однако результаты этой работы показывают, что известных методов прогнозирования турбулентной активности в пределах данной грозы не существует. Кратко излагается вопрос об использовании переносимого по воздуху радиолокатора с целью обнаружения града и избегания турбулентности самолетом в полете.

В главе 2 рассматривается вопрос об измерении наблюдаемой с помощью радиолокатора высоты эха, которая является указателем штормовой активности. Подчеркивается, что максимальная высота эха, "полу-
чаёмого от сравнительно больших частиц осадков, не должна отождествляться с вершиной облака. Исследования обнаружили многочисленные погрешности вследствие действия таких факторов, как угол возвышения, искажение луча антенны и величина порога отражаемости и т.д. Хотя и существует настоятельная необходимость в точных измерениях максимальной высоты эха в связи с возрастающей интенсивностью воздушного движения, к сожалению, пока еще невозможно принять в международном масштабе приемлемые процедуры ввиду различных возможностей разных стран в отношении интерпретации радиолокационных наблюдений.

В главе 3 рассматривается вопрос об интерпретации эха различных типов радиолокаторов. Данные метеорологических радиолокаторов зависят не только от метеорологических явлений, но также в значительной степени и от характеристик радиолокатора. Каждое эхо, возникающее на экране радиолокатора, должно интерпретироваться с учетом индивидуальных характеристик каждого комплекса оборудования, причем это имеет особое значение, когда требуется информация о количественных измерениях. Исследование затухания электромагнитных волн показывает в общих чертах, что степень затухания в зависимости от различных видов осадков является незначительной только при длине волны 10 см или более, в то время как на всех других длинах волн невозможно произвести точные измерения без внесения поправок. Если ширина луча, посылаемого радиолокатором, является слишком большой, то это также в значительной степени оказывается на интерпретации эха осадков. Выходы показывают, что радиолокатор, работающий на длине волны 10 см, по всей видимости, удовлетворяет всем условиям для наземного радиолокатора. Что касается радиолокатора, переносимого по воздуху, то рассматривается преимущества и недостатки трех длин волн – Kc, X и C, а решение вопроса о выборе длины волны должно приниматься потребителем.

В главе 4 весьма подробно излагается вопрос об обработке и передаче радиолокационной информации. Здесь в основе широкого понятия, выраженного термином "обработка радиолокационной информации", лежат три операции, применяемые в отношении радиолокационной информации, а именно: повышение точности взаимозависимости между радиолокационной информацией и метеорологическими явлениями, передача радиолокационной информации и усовершенствование оперативных средств. Средства обработки и передачи могут предоставляться, в зависимости
от требующегося типа радиолокационной информации, как для временных, так и для постоянных целей. Примером оборудования для обработки радиолокационной информации, приведенным в качестве иллюстрации, является "система профилирования радиолокационного эха, разработанная в США". Ввиду большого спроса на передачу радиолокационных данных со стороны meteorологов в местных прогнозистических центрах, а также со стороны персонала по контролю за воздушным движением в аэропортах этой проблеме уделяно большое внимание. В связи с этим описывается накопленный США опыт по использованию системы с дистанционным управлением, предназначенной для получения телевизионного изображения.

Кратко описывается также опыт Японии в использовании телефонной факсимильной системы, принятой для передачи радиолокационных данных в масштабе всей страны, и системы телефонной записи для движения местного воздушного транспорта.

Вопрос о передаче радиолокационной информации самолетам, находящимся в полете, также считается для авиации важным и рассматривается в главе 5. Существует два вида таких операций по передаче информации: первый предназначен для облегчения захода на посадку, посадки и взлета самолетов в окрестностях аэропорта, для чего требуется быстрая передача точных данных об эхе и частые уточнения ввиду изменений явлений во времени и пространстве; второй — для обеспечения безопасности самолетов в полете и планирования полета, для чего не требуется такой большой точности в определении местоположения и интенсивности явлений, в силу чего передача может осуществляться в течение более длительного периода. Приводятся подробные примеры практических методов, используемых для этих целей в США и Австралии.

В главе 6 рассматриваются разработанные новые методы радиолокационных наблюдений. В последние годы важное исследование было проведено в СССР с целью улучшения измерений, производимых либо с помощью двух радиолокационных установок с различной длиной волны, либо с помощью одной установки, использующей две различные длины волн. Данное исследование, в основе которого лежат различные эксперименты, проведенные в этой стране, открывает возможности применения этих сравнительно новых методов для количественного измерения облаков и осадков. Оно также показывает, с другой стороны, что еще существуют некоторые трудности в определении высоты нижней границы облаков с помощью радиолокатора, даже когда последний имеет две длины волны.
RESUMEN

Para poder garantizar, en todas y cada una de las fases del vuelo, el funcionamiento seguro de los aeronaves, incluidos los aviones supersónicos de transporte, no cabe duda que se requiere una información muy precisa en materia de tiempo significativo. El radar meteorológico, que puede brindar a las tripulaciones en vuelo y a las servicios de tierra una representación visual de las características fundamentales de los fenómenos meteorológicos peligrosos, es sin duda el equipo más adecuado para facilitar esa información. En muchas de las reuniones de la OMM y de la OACI se ha recomendado con insistencia que se adapten a las necesidades de la aviación los métodos y procedimientos que permitan utilizar el radar meteorológico. En la primera parte de la presente Nota Técnica se examinan las actuales necesidades de la aviación en materia de datos meteorológicos obtenidos por medio del radar desde el punto de vista del rendimiento, alcance y precisión de este último, ya se trate de instalaciones de radar terrestres o a bordo de aeronaves.

En el Capítulo 1 se examinan las formas y medios de detectar y localizar las zonas de granizo y de turbulencia, asociadas con las tormentas que se consideran peligrosas para la aviación. Se ha demostrado, mediante estudios muy detallados que se han llevado a cabo sobre la detección del granizo, que la intensidad de los ecos observados mediante un radar de 10 cm de longitud de onda puede servir como factor indicador del granizo, al igual que la de un radar de 3 cm, con la diferencia de que con 10 cm de longitud de onda la intensidad varía muy poco en función de la altura. Para determinar la probabilidad de que se produzca granizo en función de la altura, también se presentan varios casos típicos en relación con el problema de la evaluación del riesgo de granizo. En lo que respecta al problema de la turbulencia, se han llevado a cabo esfuerzos notables para estudiar la relación existente entre las características de los ecos de radar observados mediante instalaciones terrestres y la turbulencia medida con instrumentos instalados a bordo de aviones. No obstante, en la Nota se llega a la conclusión de que no existen métodos conocidos para prever la intensidad de la turbulencia dentro de un núcleo tormentoso determinado. Se menciona sucintamente el empleo de instalaciones de radar a bordo de aeronaves para detectar las precipitaciones de granizo y para que los aviones puedan evitar las zonas de turbulencia en vuelo.

En el Capítulo 2 se examina la cuestión de medir la altura de los ecos observados por radar, como factor representativo de la actividad tormentosa. Se hace hincapié en el hecho de que la altura máxima del eco procedente de partículas relativamente importantes de precipitaciones no debe identificarse con la cima de la nube. Los estudios que se han llevado a cabo han revelado infinidad de errores debidos a factores tales como el ángulo de elevación, la distorsión del haz radiocéltico de la antena y la concentración mínima de la reflectividad, etc. A pesar de que, debido al volumen creciente del tráfico aéreo, existe una necesidad urgente de medir de forma precisa la altura máxima de los ecos, desgraciadamente todavía no es posible adoptar procedimientos que sean aceptables a escala internacional, como consecuencia de las diferencias que existen de un país a otro en materia de conocimientos e interpretación de observaciones efectuadas por medio de radar.

En el Capítulo 3 se examinan las diversas interpretaciones de los ecos, para diferentes tipos de radar. Los datos obtenidos mediante los radares meteorológicos dependen no sólo de los fenómenos meteorológicos mismos, sino también, y en gran parte, de las características mismas del radar. Cada eco que aparece en la pantalla del radar se debe interpretar teniendo en cuenta las características particulares de cada aparato, especialmente cuando se trata de obtener información cuantitativa. El estudio de la atenuación de las ondas electromagnéticas indica, en términos generales, que el grado de atenuación debido a diversos fenómenos de precipitación es despreciable tan sólo cuando se trata de longitudes de onda iguales o superiores a 10 cm, mientras que para todas las longitudes de onda inferiores no se pueden efectuar medidas precisas sin las debidas correcciones. Por otro lado, si la anchura del haz transmitido por el
radar es excesiva, ello también afecta considerablemente la interpretación de los ecos relativos a la precipitación. Las conclusiones a que se llega indican que los radares que utilizan una longitud de onda de 10 cm parecen ser los que mejor satisfacen todas las condiciones del radar terrestre. En el caso de instalaciones de radar a bordo de aeronaves, se examinan las ventajas y desventajas de tres longitudes de onda, a saber: las bandas KU-, X- y C, y se indica que es el usuario quien debe decidir cuál es la longitud de onda que más le conviene.

El Capítulo 4 trata detalladamente de la preparación y transmisión de la información obtenida por medio del radar. Aquí, el amplio concepto que expresa el término “preparación de información obtenida por medio del radar” engloba tres operaciones a que da lugar la información del radar, a saber: mejora de la correlación existente entre la información procedente del radar y los fenómenos meteorológicos; transmisión de la información obtenida por medio del radar; y mejora de los medios prácticos de explotación de la información radar. Los medios necesarios para preparar la información y transmitirla dependen del tipo de información que se desea obtener: imágenes fugitivas o documentos permanentes. Bajo la denominación de sistema de delineación de contornos obtenidos por medio de ecos de radar, sistema concebido por los Estados Unidos, se ilustra un ejemplo del equipo necesario para preparar la información obtenida por medio del radar. En vista de la gran demanda que existe, por parte de los meteorólogos de los centros de predicción local así como del personal de control del tráfico aéreo de los aeropuertos en materia de transmisión de datos obtenidos por radar, este problema ha sido objeto de una atención muy particular. A este respecto, se describe la experiencia adquirida por los Estados Unidos en lo que se refiere a la utilización de un sistema de mando a distancia que permite examinar la imagen de la información radar por medio de una pantalla de televisión. También se da cuenta de la experiencia llevada a cabo por el Japón mediante un sistema telefónico de transmisiones de información por facsimil, y de un sistema de teleautógrafo telefónico utilizado para las operaciones de tráfico aéreo local.

La transmisión de información obtenida por medio de radar a las aeronaves en vuelo, que tan importante es para la aviación, es objeto de examen en el Capítulo 5. A este respecto, cabe considerar dos tipos de transmisión: el primero para facilitar las fases de aproximación, aterrizaje y despegue de los aviones en las cercanías de los aeródromos, en cuyo caso se requiere una transmisión rápida de datos precisos observados sobre los ecos y asimismo poner al día frecuentemente los mismos, debido a las variaciones, tanto en el tiempo como en el espacio, de los fenómenos observados; en segundo lugar, el tipo de transmisión necesaria para proteger las aeronaves en vuelo y para planificar este último, para el cual no es indispensable localizar y definir con tanta precisión la intensidad del fenómeno y, por ello, la transmisión se puede efectuar con menos frecuencia. Se dan ejemplos detallados de los métodos prácticos utilizados a este fin en los Estados Unidos y en Australia.

En el Capítulo 6 se examinan las nuevas técnicas de observación desarrolladas recientemente por medio del radar. En los últimos años, se ha realizado en la URSS un importante estudio con miras a mejorar la calidad de las medidas efectuadas por medio de dos radares que utilizan longitudes de onda diferentes, o bien mediante un solo radar que utiliza dos longitudes de onda distintas. Basándose en los diversos experimentos llevados a cabo en dicho país, este estudio ofrece la posibilidad de aplicar estas técnicas relativamente nuevas a la medida cuantitativa de las nubes y de las precipitaciones. Por otro lado, también demuestra que todavía existen algunas dificultades para determinar la altura de la base de las nubes por medio del radar, incluso cuando se utiliza un radar con dos longitudes de onda distintas.
GENERAL

AVIATION REQUIREMENTS FOR WEATHER RADAR DATA

Introduction

The importance of accurate observational data for the en-route as well as for the terminal phases of flight has been stressed by many ICAO and WMO (CAeM) meetings, the more recent of which were MFT/OPS/CAeM-III (1964), the 5th EUM Regional Air Navigation Meeting (1965), the 5th Air Navigation Conference/CAeM-IV (1967) and the first meeting of the SST Panel (1968). Most of these meetings have also urged greater efforts in developing methods and procedures for the utilization of weather radar for obtaining operationally significant weather information which, in effect, cannot be obtained economically or cannot be furnished as efficiently and as accurately by other means. The following is based in general on opinions expressed by these and other ICAO and WMO meetings; but details, particularly in connexion with performance criteria and range and accuracy requirements, should be regarded as views of individual members of the working group.

It will be appreciated that some of the requirements have not yet been implemented. Some of these requirements will probably never be met by means of conventional radars. Nevertheless, this study of the requirements, expressed in general terms, appears to serve a useful purpose, and in particular it may serve as a basis for an instrumental research programme.

General requirements

Where operationally significant weather information is furnished by radar, the general requirement, taking cost/benefit ratios into account, is usually for the display and presentation in the air and on the ground of radar data in such a way as to provide information on:

(a) The location, size (extent and height) of medium and large convective clouds and thunderstorms;
(b) The location, type and intensity of precipitation (hail, snow, rain);
(c) The location and intensity of turbulence (in cloud and CAT);
(d) The location of lightning (tentative, for SST);
(e) The location of ice crystal clouds (tentative, for SST);
(f) The location of gaps between clouds or of zones of weaker activity which, if wide enough, will allow a safe penetration.

Performance criteria for ground-based and airborne weather radar

(a) For local ground use

The requirement is for a visual display of significant echoes in the approach and climb-out area which, at major international aerodromes in areas where phenomena as outlined in paragraph 2 are relatively frequent, can be viewed by the pilot before take-off, or which can be transmitted to a pilot approaching to land, e.g. in the
form of landing reports. The same information is required by ATC units for approach and terminal control purposes and by meteorologists for the preparation of landing forecasts, SIGMET information, etc. The radar equipment employed for local use should have a variable horizontal range up to 200 nautical miles to accommodate approach and climb-out patterns of all types of aircraft, including the SST. It should have a vertical coverage of 18,000 metres (60,000 feet) to an accuracy of 300 metres (1,000 feet) and the capability of scanning vertically along a fixed azimuth. Intensity of precipitation should be proportional to the brightness of the echo, e.g. by means of a contouring system. When direct view of the scope is not feasible, a remote scope (radar repeater) is the preferred alternative, if possible with essential controls (range setting, gain, etc.) available at the site of the remoted screen. The second preference is for the more or less continuous transmission of radar data from a more distant radar installation to the aerodrome with not more than a minute or two delay between successive scope pictures.

(b) For en-route use

In order to make abrupt avoidance manoeuvres unnecessary, airborne weather radar equipment should be capable of providing information as outlined in paragraph 2 at ranges of 50 nautical miles for subsonic aircraft and 200 nautical miles for SST aircraft. The area of gaps between large convective clouds is important for safe navigation through stormy regions, and the equipment should define these areas with a discrimination of about two kilometres. Reliability, light weight, simplicity, and clear display are associated requirements.

Where en-route radar information is furnished by ground-based radar, it should, for relay to aircraft, provide essentially the same information as airborne weather radar with an indication of the position of the aircraft in relation to the echoes. If the ground-based weather radar data are for en-route surveillance and pre-flight briefing by meteorological offices, information should be at regular, frequent (e.g. half-hourly) intervals. The information, which can be in chart form combining data from several weather radars, should include the location, orientation, size (horizontal and vertical extent), intensity and direction of movement of severe convective storms, squall lines, and precipitation areas. The type of precipitation and an indication of the increase or decrease of activity should also be reported. Indications of CAT would be desirable. For SST operations, information on ice-crystal cloud and/or the presence of lightning may also be needed.
CHAPTER 1

IDENTIFICATION OF PHENOMENA DANGEROUS FOR AVIATION

We shall mainly examine the detection and identification of regions of hail and turbulence, these being of particular importance for aviation. We shall consider, successively, the use of ground radar and of airborne radar, going more deeply into the former, since it has been the subject of larger and more detailed studies than the latter.

1.1 Use of ground-based radars

1.1.1 Detection of hail

Radar is probably most useful to the forecaster when it is used to identify the anomalous or unexpected weather event, such as the thunderstorm embedded in a large area of light to moderate rain or the relatively small percentage of thunderstorms which produce severe local storms. A number of articles have been written on the features of echoes containing hail. These articles show important differences in echo characteristics which appear to be a function of latitude and climate.

In the U.S.A. and Canada two criteria are considered important in identification of hail, echo intensity or reflectivity, and echo height. Additional criteria have been considered in the U.S.S.R., where probability curves have been developed to aid in the identification of hail-bearing storms.

This document is concerned chiefly with operational techniques which have been found useful for identification of hail. Important theoretical discussions are omitted. The reader interested in full background information should first read the recent article by Atlas (1), for a general summary, and the referenced articles for more specific information.

1.1.2 Echo intensity or reflectivity as an indicator of hail

Measurements of echo intensity or reflectivity require carefully calibrated radars. Techniques in use by radar engineers for many years can be adapted to weather radars with much success. One such technique in use by the U.S. Weather Bureau has been discussed by Bigler and Brooks (2). Training of observers as well as electronics technicians is important before actual reflectivity measurements can be correctly made.

The radar reflectivity factor, $Z$, may be obtained from the standard radar storm equation:

$$Z = \frac{P_r R^2 C}{P_t}$$

where $P_r$ is the power returned to the radar from the scattering volume (in this case precipitation), $P_t$ the peak transmitted power of the radar, $R$ the range, and $C$ the radar constant which includes other operating parameters of the radar. When the scatterers are small compared with the wavelength and the dielectric constant is known, the radar reflectivity factor is proportional to a factor $Z = ND^6$, where $N$ is the number of scatterers per unit volume and $D$ their diameter. When $Z$ is obtained from measured reflectivity values rather than from observed
USE OF WEATHER RADAR FOR AVIATION

Drop diameters, it is denoted by $Z_e$. Additionally, the scattering particles are assumed to be raindrops and are small compared with the wavelength, hence Rayleigh scattering applies.

1.1.2.1 For radar operating at a wavelength of 3 cm

Donaldson (3) was the first to report on a large number of observations of hailstorms in the north-eastern U.S.A. Similar results have been reported for hailstorms in the central U.S.A. Figure 1 is a plot of the vertical profile of maximum reflectivity of storms of different intensity. The median profile for each storm classification shows that both the maximum reflectivity of the profile and its height increase with the severity of

Figure 1 - Median profiles of core $Z_e$ in 1957-58 New England thunderstorms, arranged in category of most severe weather. The 51 cases of hail include the 29 cases of large hail (diameter of 1/2 inch or larger) which are plotted separately. Also, the 11 tornado profiles are taken from the all-inclusive rain and hail categories (From Donaldson)
thunderstorm weather. The largest difference is between the median-core profiles of rain-thunderstorms and those of other categories, and for altitudes of 20,000 ft and above. Thus, hailstorms and tornado-producing thunderstorms are best identified by radar through the storm. This point is illustrated in Figure 2. Donaldson's curves for hail exceed the rain curves by an order of magnitude or more in $Z$ at all frequencies except the upper, or most intense, portions of the curves.

Borovikov et al. (5) have computed the probability of the occurrence of hail as a function of the height of the zone of maximum storm core reflectivity (Figure 3) curve (marked with an H). Their data indicate that the height of maximum reflectivity of hail-producing storms varies between 3 and 11 km, and that the probability of hail occurrence increases with increasing height above the ground.

Figure 2 - Frequency distribution of thunderstorm core $Z_p$ at altitude of 20,000 ft, arranged in category of most severe weather (From Donaldson)
Figure 3 – Probability of hail as a function of the height of maximum Ze (From Borovikov et al.)

The probability of hail has also been related to the temperature at the height of the reflectivity maximum. Figure 3 (curve marked with a T) shows that the reflectivity maximum occurs in the negative temperature regime, and that hail always occurs when the temperature at that level was colder than $-27^\circ C$.

It is important to mention that the radar used for these studies has a beamwidth of about 1° in both the horizontal and the vertical plane. It is likely that the results reported above could be applied to radars having a 2° beamwidth in both planes, but it is doubtful whether the same results would be found if the beamwidth in either the horizontal or the vertical plane exceeded this value by any significant amount.

For operational purposes, observations of the characteristics of the vertical profile are time-consuming, especially if the radar is not equipped with an RHI display. Measurements must be made manually, performing at least two functions (changing antenna elevation angle and adjusting the receiver sensitivity or attenuator controls), and would require one to two minutes per profile to make the measurements and relate them to other meteorological parameters, such as temperature at the top of the echo, elevation of the echo top to the tropopause, etc.

1.1.2.2 For radar operating at a wavelength of 10 cm

Measurements of thunderstorm core reflectivity using 10-cm wavelength radars do not exhibit a profile having a maximum aloft when hail is observed. Rather, the profile shows very little change with height up to about 20,000 ft, where it begins to decrease. The maximum reflectivity of hailstorms is very similar to that observed with 3-cm wavelength radars.

Geotis (6) has investigated 1-cm radar reflectivity at low levels as a hail indicator in the north-eastern U.S.A. and reports a remarkable correlation with hail occurrence when $Z_e = 5 \times 10^5 \text{ mm}^3/\text{m}^3$. 
Similarly, Ward, Wilk and Hermann (7) report that 85 per cent of the hailstorms in the central U.S.A. are identified by maximum $Z_e$ above $1 \times 10^5 \text{mm}^6/\text{m}^3$.

Well-calibrated ground-based radars could therefore be used effectively to identify those thunderstorms likely to contain hail. Since the duration of the hail is usually limited (there are important exceptions) constant monitoring of the radar displays is essential and, particularly for aviation, a rapid-response communication link is required to relay data from the radar observer through the traffic controller to the pilot in flight. The communication link is usually such that effective programmes for advising pilots are not really possible.

In all cases, the hail data have been obtained from networks of co-operative observers and the reports correlated with the observed radar echoes. In no instance has an investigation first examined all radar-echo reflectivity data to determine what percentage of all echoes having a reflectivity of a given value, such as $1 \times 10^5 \text{mm}^6/\text{m}^3$, contain hail. It should be noted that, in the absence of hail, $Z_e = 10^5 \text{mm}^6/\text{m}^3$ corresponds to a rainfall rate of about 2 in/h, a rate which is not infrequently observed.

Experience along the south coast of the U.S.A., where air mass characteristics are quite different from those in the central and north-eastern U.S.A., has shown that hail is rather infrequently observed, and that echoes having an intensity of about $1 \times 10^5 \text{mm}^6/\text{m}^3$ are generally associated with heavy rain. Thus, different criteria are required, but they have not yet been developed. For some applications, however, heavy rain may be as dangerous as hail.

Figure 4 - The probability of hail as a function of the maximum echo-top height (From Douglas, Borovikov et al.)
1.1.3 **Echo height as an indicator of hail**

While the typical ground-based weather radar is not ideally suited to careful monitoring of the heights of a number of radar echoes, useful echo-top measurements can usually be made easily and fairly accurately, provided the radar is equipped with a range-height display (RHi) and the radar beamwidth is fairly narrow in the vertical dimensions (certainly not more than 2°, and preferably 1° or less).

Typically, in a major thunderstorm the echo top rises sharply, remains at a high level for an extended period of time, then subsides. Associations between echo tops and occurrence of hail have been studied extensively. Figure 4 illustrates the probability of hail as a function of height for four relatively different climatic areas.

The hail probability appears to be better related to echo-top height than to echo-top temperatures. Penetration of the tropopause by the storm top enhances the probability of hail (3, 8); furthermore, the probability of large hail (one inch or more) only becomes significant when the echo tops reach heights in excess of 30,000 ft (above terrain).

1.1.4 **Summary**

The data presented above were developed for specific locations and, as the curves in the figures show, there are important differences in the significance of a given value of some of the parameters from location to location. Therefore, radar stations wishing to use techniques for assessing the probability of hail should initially use the data which originated in a similar climatic regime, with the intent to modify the curves on the basis of experience.

Data presented above indicate several parameters which have been found to be useful for assessing the probability that hail may occur at the ground. Measurements of a particular echo may show a high probability with another. It has been suggested by Borovikov et al. (5) that assessments of hail probability may be improved by considering a mean value of the sum of the percentages of all parameters.

1.1.5 **Association between turbulence and ground-based radar echoes from thunderstorms**

Considerable effort has been made in recent years to study the association between radar-echo characteristics observed by ground-based radar and turbulence measured by specially instrumented aircraft. While thunderstorm avoidance by aircraft is generally possible when radar is installed in the aircraft, the pilot must sometimes deliberately penetrate through precipitation in the hope of finding a region where hazardous weather conditions are least likely to be encountered. In addition, many smaller aircraft are not equipped with radar and the pilot must rely on whatever information is available by radio contact with ground stations and by visual observation from the cockpit. Therefore, flight assistance for the purpose of avoiding hazardous weather is often needed from ground-based radars.

There are many advantages, disadvantages, and special problems associated with using ground-based radar data for in-flight assistance. Usually, the location of the aircraft with respect to echoes is not precisely known and provision of headings and routes for the pilot to follow must be made very carefully, for a certain degree of responsibility is assumed when the pilot is directed to change course. Ground-based radars have a distinct advantage in that the equipment is located on a stable platform, and full attention may be given to operating the radar. Careful calibration of the performance of the ground-based radar is generally feasible but in many instances is not carried out.
1.1.5.1 Avoidance of thunderstorm turbulence

Circumnavigation at a distance at least fifteen miles from the edge of the visible cloud or radar echo continues to be the safest flight procedure. If penetration into a thunderstorm echo is necessary, then, at least statistically, the likelihood of encountering severe turbulence can be reduced.

Measurements of turbulence intensity have been made by instrumented aircraft during deliberate, controlled penetrations into thunderstorms in the central U.S.A. Generally, the thunderstorms were in the mature or decaying stage of their life cycle. Penetrations have usually been in the 23,000-ft to 40,000-ft altitude range, at a distance of 20 to 100 nautical miles from the radar.

The primary ground-based weather radar was the WSR-57, which operates on a wavelength of 10 cm. The radar was carefully calibrated to permit display of contours of echo intensity and calculation of radar reflectivity, \( Z_e \). The PPI displays were continuously photographed for later analysis. Aircraft location was continuously monitored by observation and photography of the PPI displays of a traffic control radar located adjacent to the weather radar. Decisions regarding the storm to be penetrated were made by a meteorologist and given to the air traffic controller who vectored the aircraft into the selected storm at the prescribed altitude.

1.1.5.2 Turbulence intensity and radar echo characteristics

Several studies (9, 10) have shown that the most severe turbulence tends to occur in the storms which contain the largest radar reflectivity values \( Z_e \). Figure 5 is a plot of the maximum derived gust velocity \(*\) measured

![Figure 5](image)

* Derived gust velocity is obtained from normal aircraft acceleration by scaling it to take account of the grosser effects of aircraft speed, height, weight, size, and shape. While providing a useful measure for relating experience on different aircraft, it gives no direct measure of the actual motion of the air. In accordance with usual practice, derived gust velocities are quoted in indicated rather than in true speed. In these data, 20 ft/sec derived gust velocity is equivalent to about 1 g incremental normal acceleration. Derived gust velocities are quoted in equivalent air speed \( EAS = \frac{TAS}{\sqrt{\frac{P}{P_0}}} \), where \( P \) is air density at flight altitude and \( P_0 \) refers to normal conditions at sea-level). The above definition of rough air agrees with that used by the National Aeronautics and Space Administration in the United States.
by the aircraft during penetration and the maximum radar reflectivity of the centre of the storm. Derived gust velocities rarely exceed 35 ft/sec (i.e. are rarely strong) in echoes having a maximum reflectivity less than $Z_e = 10^4 \text{mm}^3/\text{m}^3$.

A further refinement of these data (3) suggest that the probability of encountering large values of derived gust velocity appears to be higher in the 23,000-ft to 27,000-ft layer than in any of the higher altitudes (no penetrations were made below 23,000-ft).

Although the most severe turbulence encountered on a particular thunderstorm penetration may occur at the same location as the strongest portion of the echo along the aircraft track, or closest to the strongest portion of echo in the storm, there were many exceptions. Occasionally quite large gusts were measured just inside the edge of the visible cloud. On the occasions when this occurs, the edge of the visible cloud appears to be close to the edge of the radar echo.

Successive penetrations through the same part of the same storm often give widely different values of derived gust velocity. In general, therefore, relationships between storm turbulence and radar echo characteristics may be expected to be essentially statistical rather than deterministic in character.

Following studies conducted in the U.S.A. in the late 1940s, air carriers have instructed flight crews, when it is necessary to fly through precipitation areas, to choose routes through those portions of the airborne radar echoes having the weakest gradient of radar reflectivity along the flight path, as indicated by the iso-echo contouring feature. Analyses of the ground-based radar data have not revealed an association between reflectivity gradient along the flight path and turbulence measured by the aircraft (11, 13). It is important to note that, in all cases, the ground-based radars are located more than 20 miles from the echo at the time of penetration and that, owing to smoothing effects caused by the relatively wide beam ($2^\circ$), the observed gradient may be much more unrepresentative of the true conditions than the case with the airborne radars.

1.1.5.3 Turbulence in clear air in the vicinity of thunderstorms

A limited amount of data have been obtained during flights through clear air at altitudes between 40,000 ft and 45,000 ft in thunderstorm areas (12). These data show that, in approximately 2,200 nautical miles of flight, 40 patches of rough air were encountered, covering some 250 n. mi. of flight. In this rough air, derived gust velocities exceeding 10 ft/sec occurred on an average of once every three miles and 20 ft/sec (equivalent to about 1 g incremental normal acceleration) was exceeded once. Horizontal gusts produced fluctuations of indicated air speed which exceeded 10 ft/sec on the average of at least once every three miles of rough air, the largest fluctuation being 34 ft/sec. These patches of rough air may be potentially hazardous to an aircraft operating close to its ceiling.

Some ten per cent of the turbulence areas and five per cent of the most severe areas were located more than 10 n. mi. beyond the edge of the radar echoes. In flying above storm areas up to 5,000 ft above the general cloud level, an aircraft would certainly need to stay at least 15 n. mi. from the edge of an echo produced on a conventional airborne or ground radar to be sure of avoiding all but mild turbulence (12).

1.1.5.4 Extension to other portions of the world

The central U.S.A. is noted for its severe thunderstorms. Frequently, the thunderstorms form in an environment of atmospheric stratification marked by large values of moisture in the low levels, relative dryness in middle levels, and strong wind shear. This stratification of moisture permits excessive magnitudes of convective instability until rapid over-turning of air is triggered by a suitable disturbance. Atmospheres which are either very dry or very moist throughout tropospheric depths cannot harbour great convective instability. This greatly simplified picture permits a cautious generalization. In the tropics, when the atmosphere is moist and only slightly unstable through
a great depth, very strong radar echoes may occur in towering clouds without the extreme vertical velocity characteristics over the central U.S.A. Since atmospheric conditions in the tropics may sometimes develop the stratification similar to that mentioned above, then it is a matter of being sure of the general atmospheric conditions accompanying the storms.

Thunderstorm penetrations by instrumented aircraft have been carried out in England (14). Concurrent quantitative weather radar data are not available. Figure 6 shows that there is a higher probability of encountering a larger gust velocity in the central U.S.A. than in England. The penetrations in England covered the same range of altitudes as in the central U.S.A., and lower levels as well.
USE OF WEATHER RADAR FOR AVIATION

1.1.5.5 Summary

The preceding paragraphs outline various characteristics of radar echoes and their associations with turbulence. Throughout the text, reference is made to observed features of echoes. While forecasts of the degree of turbulence can be made in general terms, there are no known methods for forecasting changes within a given thunderstorm, therefore there are no techniques which can be applied to anticipate echo characteristics for more than a few minutes.

1.2 Use of airborne weather radar

1.2.1 Detection of hail

The problem of detecting the presence of hail in or near thunderstorms is a difficult one, even with the most sophisticated ground radars available today. With airborne radars, hail detection is even more difficult because of:

(a) Limitations in power supply and antenna size;
(b) Movement of the radar platform;
(c) Low reflectivity of even large hailstones which do not carry a water film at the higher flight altitudes.

Airborne radars have been utilized effectively, however, for avoiding damaging hail by recognizing certain echo shapes and following certain strict flight-operation procedures. One large airline in the U.S.A. has flown for 12 years without hail damage to its aircraft by following the avoidance procedures listed in paragraphs 4 and 8 of the annex.

Experience gained from early flight research with C-band airborne weather radar has shown that hail is often associated with "hooks", "fingers", or "scalloped" radar echoes (see Figure 7). This association was established during flights conducted in the U.S.A. below 20,000 ft. Confirmation has been obtained at higher flight levels, but to a lesser degree. To provide a greater assurance of avoiding hail encounters at these high flight levels, recommended separational distances between the precipitation cells and the aircraft have been increased (see annex, paragraph 4 A).

Large hailstones are frequently associated with fallout patterns downwind from the generating thunderstorms, and clear of the vertical walls of the generating thunderstorm. Safe flight policy dictates adequate separation distance and use of up-tilt of the antenna for detection of hail shafts falling from or near the anvil overhang.

The airborne weather radars employing X-band are likely to depict fewer of the hail-associated echo features described above because of the greater sensitivity and tendency to paint more of the peripheral areas of the thunderstorm cell which mask the echo protuberances. This can be partly compensated for by use of the contouring circuit.

1.2.2 The avoidance of turbulence

Studies made for establishing the association between thunderstorm echoes and turbulence with both airborne and ground radars have so far produced only statistical relationships. There are many variations in the turbulence patterns generated both within and outside thunderstorms.
Figure 7 — Echo configurations associated with some hailstorms (copied from photographs of airborne C-band weather radar scope)
Flight research and operational experience have shown, for example, that turbulence can be significant in the clear-air environment immediately outside the convective clouds. This same experience has also revealed that large thunderstorms can generate turbulence at distances up to 20 miles downstream by wake effect. The distinction between the convectively produced turbulence zones and those zones more characteristic of clear-air turbulence factors is not sharply defined.

Strong vertical motions are also sometimes found in the clear air for a few thousand feet above a growing convective cell. The uncertainty as to how far from a given thunderstorm cell the turbulence environment will extend requires a built-in tolerance for the safe conduct of flights.

The flight procedures which are outlined in the annex have for a number of years produced a good balance between safe flight conduct and a minimum of extensive detouring or flight diversions. This experience has been obtained in areas where severe thunderstorms, squall lines, large hail and tornadoes are a regular seasonal feature.

REFERENCES


* * *
THUNDERSTORM FLIGHT POLICY AND AIRBORNE WEATHER RADAR

1. Radar policy and requirements

A. Dispatch (flight control). Only aircraft with operative radar are dispatched under instrument flight rules or night visual flight rules when thunderstorms are expected along the route to be flown. If the radar is inoperative, but by careful route selection it is reasonably expected that thunderstorms can be avoided, then the flight can file IFR for traffic clearance purposes but it must plan to operate in day VFR conditions because of the inoperative radar.

B. En route. Only aircraft with operative radar are intentionally operated on routes where thunderstorms are more intense than weak or more numerous than widely scattered. Radar equipment on aircraft is intended as an aid in avoiding rather than penetrating thunderstorms. If feasible, an extensive deviation around the end of a squall line is in order, even though en-route fuelling and delay are experienced. When detours are impracticable due to trip length, extent of storm area or storms in the terminal area, the operational rules outlined below should apply.

C. Inoperative – in flight. In the event of en-route radar failure, the responsibility rests with the aircraft commander to determine whether a thunderstorm area can be traversed with safety and with reasonable comfort to passengers. He should monitor latest available weather reports and SIGMETS and consider any information regarding hazardous weather conditions provided by any approved source.

2. Radar terminology

A. Strong echo. Any echo which is indicated on the scope beyond 50 miles is normally considered a strong echo. A strong echo at shorter range will have a brilliance equivalent to the spot at the centre of the writing beam. In contour position a strong echo will have a well-defined jet-black core.

B. Weak echo. A weak echo is one which does not have a well-defined edge and is fuzzy throughout. No black holes appear in the echo in contour position. A weak echo will normally not be visible beyond 50 miles.

C. Moderate echo. A moderate echo is anything falling between the two classifications given above and is considered a transition stage.

D. Rainfall gradient. Rainfall gradient is the rate of change in rain intensity per unit distance. Steep rainfall gradient is generally associated with maximum turbulence and is a rapid change in rain intensity over a short horizontal distance and will be indicated by a sharp edge on the echo. At shorter ranges, in contour position, a steep rainfall gradient is indicated when the distance between no rain and the contour core is one mile or less. With a weak rainfall gradient this distance normally will be three miles or more.

3. Operation

(Radar tuned and operating normally.) When a flight encounters thunderstorm conditions it is desirable, when
feasible, that the area be circumnavigated. Early detours of storm areas are recommended, depending upon trip length and position of the storms.

4. **When early evasive action is not practicable, the following rules apply:**

   A. Avoid steep rainfall gradient areas of an echo by at least five miles (using 20-mile range). Increase this distance at higher altitudes whenever feasible, although steep rainfall gradients will be relatively fewer above 20,000 ft. Also increase this distance for echoes which are changing either size, shape or intensity rapidly or for echoes which have prominent scallops, hooks, fingers or other protrusions. Above 20,000 ft, avoid even weak echoes if possible. Recommended distance from weak echoes is five miles at 20,000 ft, 10 miles at 25,000 ft, 20 miles at 30,000 ft and above.

   B. Below 20,000 ft, weak echoes or areas of weak rainfall gradient may be flown through (or near) if judgment dictates this to be the most desirable procedure.

   C. When using the 20-mile range to circumnavigate storm cells, monitor the 50-mile range frequently to determine total extent of the area and to watch for additional developments.

   D. Maintain minimum vertical separation of 5,000 ft when flying above an echo.

5. **A navigable corridor with ample room will normally be found reasonably close.**

6. **When taking off in thunderstorm areas the radar set should be operated on the ground using upward antenna tilt to determine best possible climb-out path.**

7. **The radar is not to be used as a terrain-avoidance tool.** However, it may be used in terrain-mapping to establish the relative position of the aircraft to high terrain, large bodies of water and other easily distinguishable ground features.

8. **Tornadoes and hail.** Tornadoes and large hail, two products of the thunderstorm, constitute serious hazards to flying even though both are relatively infrequent. Radar offers the best means of avoidance. A majority of hail echoes show on the scope with characteristic fingers or hooks or scallops protruding from the main thunderstorm echo. Tornado identification is much less reliable, but it is known that certain major tornadoes produce a protrusion much like the shape of a figure six. Other tornadoes will leave no characteristic fingerprint identification. In either case, the most reliable evasive method is to avoid sharp-edged echoes by at least five miles.

9. **Cumulonimbus overhang.** Avoid flying under a cumulonimbus overhang whenever practicable. If such flight cannot be avoided, tilt the radar antenna full up occasionally, to guard against a fresh shaft of hail fall suddenly from the overhang.
CHAPTER 2
MEASUREMENT OF THE HEIGHT OF ECHOES

2.1 Introduction

It is a well-known fact that echoes given by radar equipment, most usually installed at meteorological stations (radar operating on a wavelength of 3.2 to 5.6 cm or 10.6 cm), come from relatively large particles usually falling as precipitation, and not from the extremely small particles constituting the visible part of a cloud. It is therefore essential not to identify the maximum heights of echoes with the tops of cloud. Unfortunately, certain users of radar information still do this.

The preceding remark should lead one to think that the heights of echoes would always give values lower than the heights of the tops of clouds. Unfortunately, for reasons which will be examined in more detail in the ensuing paragraphs, this is not always so. There are cases of echoes in thunderstorms with heights well above the corresponding heights of those observed from the visible parts of clouds. This, together with the fact that the difference between the maximum heights of an echo, measured simultaneously by two radars situated at different points, and probably having different characteristics, may exceed 2,000 m, has sometimes led users, and particularly aviation forecasters, to doubt the usefulness of weather radars and the validity of measurements made with them.

Due to the increasing volume of air traffic, however, the need for precise measurements of the maximum heights of echoes appears to be urgent and the requirements are becoming more and more exacting (for more accurate information, rapidly available, at any time, from any point on the area covered by the radar). It is essential that the meteorologist should know that such requirements are excessively exacting and frequently beyond the performance of weather radars at present in use.

Differences between the characteristics of radars, between observational procedures and procedures for corrections to the measurements lead to heterogeneous results. Unfortunately, although the adoption of internationally accepted procedures would be very desirable, it seems that, in practice, this is not possible for the moment, on account of varying degrees of development of radar observations from one country to another.

In view of the preceding remarks it would not appear to be possible to lay down strict rules for the measurement of the heights of tops of clouds.

We shall thus limit ourselves to an investigation into the difficulties in making such measurements and the restrictions to which they are subject.

2.2 Operational procedure

The change of the height of a convective echo top can be observed on an RHI scope in the vertical scan of a radar. However, the weather radar is usually operated in a horizontal search mode to obtain other important information such as distribution, intensity and tendency of the existing echo patterns. Besides, tops of several convective echoes can rather efficiently be observed on PPI simultaneously by tilting the antenna up and down. The significant echo-height data are usually selected by judicious sampling by the radar observer.
A typical procedure of measuring echo height on PPI is: (i) tilt up the antenna until the echo disappears; (ii) read out the elevation angle; (iii) subtract half a beamwidth; (iv) obtain the height using a range-height diagram as shown in Figure 8 which includes the effect of earth curvature.

In the use of RHI, the echo top can be read directly on the height scale. However, corrections for the half beamwidth and earth curvature effect are also necessary using the same diagram or any simple table.

2.3 Measurement of elevation angle

A small error in measuring the elevation angle exerts a great influence on the accuracy of the echo height in view of the long distance of the echo. The accuracy of measuring the elevation angle is usually considered to be about 0.5° overall, including mechanical, electrical and observational errors. This leads to errors in echo height of 1 km or more as shown in Table 1.

<table>
<thead>
<tr>
<th>Errors in elevation angle (°)</th>
<th>Distance (km)</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.3</td>
<td>0.5</td>
<td>1.0</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.4</td>
<td>0.9</td>
<td>1.7</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>0.9</td>
<td>1.7</td>
<td>3.5</td>
<td>5.2</td>
<td></td>
</tr>
</tbody>
</table>
A definite and feasible method for checking the accuracy of the elevation angle has not yet been found. In the U.S. radar manual, it is suggested that checking be performed in co-operation with aircraft operations, while in Japan measurements of the height of mountains with a fixed reflectivity level are recommended.

2.4 Antenna beam distortion — Correction of half a beamwidth

The energy transmitted from a radar forms an annular distribution which is defined by the antenna characteristics as shown in Figure 9. The beamwidth is used as an index of the antenna characteristics, the beam angle being defined as an angle where the power density becomes half that of the centre axis.

The subtraction of half a beamwidth mentioned in the paragraph on operational procedure is based on the assumption that only a small portion of the precipitation must extend into the beam to be detected. In heavy showers or thunderstorms, echo tops determined by the same method are generally higher than the actual cloud, since echoes do not disappear even outside the beamwidth owing to the high reflectivity of the storms. Conversely, in weak or medium precipitation at a distant range, subtraction of half a beamwidth sometimes underestimates the echo top. Saunders (1) reported that the radar echo tops exceed the actual cloud tops by an amount up to half the beamwidth without the correction.

Subtraction of half the beamwidth might be an expedient method. It does not necessarily give a better accuracy, since the apparent heights of echo tops depend on the vertical reflectivity profile within the storm. At any rate, the users of radar information should be aware of whether these corrections have been made or not. For instance, assuming that the beamwidth is 1.5°, and the elevation angle 3°, the approximate difference between the corrected and uncorrected heights will be 2,600 m at 200 km range, as can easily be seen in Figure 8.

Since the half beamwidth is proportional to $\lambda/d$, where $\lambda$ is the wavelength and $d$ is the antenna diameter, the value of beam correction will vary with the different types of radar.

![Configuration of antenna lobe](image)

![Angular distribution of energy](image)
2.5 Threshold value of reflectivity

As is easily understood from the typical observational procedure described above, the measured height of an echo top depends on the threshold value of reflectivity, generally the value of the minimum detectable signal (MDS) of radar. Strictly speaking, therefore, it is impossible to compare the value or echo height given by various radars unless all use the same threshold value or all have the same MDS.

Several papers (2, 3) have been presented on the discussion of accuracy of echo-top measurements. Donaldson (4) showed that, using data of the WSR-57 radar, the average error contributed by main lobe and side lobes increases with range and maximum storm reflectivity. Tatehira (5) calculated the received power as a function of elevation angle for rectangular targets of uniform reflectivity using the actual antenna pattern. He showed, for example, that, in a thunderstorm at 50 km range from a radar having reflectivity of 40 dB above MDS at the beam centre, the observed echo top is 2,800 m (3° of the elevation angle) higher than the actual height, even with the half-beam correction. In the same target having 15 dB of maximum reflectivity, the measured height with half-beamwidth correction coincides with the actual top.

While the conventional echo top is simply the maximum height of the minimum detectable echo, the difference in MDS between old-type radars and latest ones would amount to 10 dB or more.

Several proposals have been put forward that the threshold value of reflectivity should be determined for the measurement of the height of the echo top. Researchers in the U.S.S.R. have been using \( Z \) equivalent to 1 mm/h of rainfall as their standard for echo-height measurement. Donaldson (4) proposed \( Z = 1 \text{ mm}^3/m^3 \) as a worthy goal for the WSR-57 radar. This value corresponds to 0.036 mm/h of rainfall using the relation \( Z = 200R^{1.6} \), hence the difference of reflectivity level between these two proposals amounts to 26 dB.

The standardization of the threshold value would certainly result in a more constructive solution of the problem, while it would be difficult to realize in view of the great variety of radars.

2.6 Range correction procedure

There are different correction procedures for the range attenuation proportional to \( r^{-2} \), where \( r \) is the distance from radar. For instance, several radars in Japan have been equipped with iso-echo contouring devices which include range-corrected video circuits, while radars of the old type do not have any correction device. In the latest radars using the PIN modulator method, the range correction referring to a range of 180 km has been made in the microwave attenuator by suppressing the echo intensity at shorter distances, while in iso-echo contouring the range correction referring to 5 km should be made by increasing the video intensity at longer distance.

Among these different types of radar, the observed heights of the same echo top differ from each other, sometimes by up to 3,000 m, since the difference of the corrected reflectivity amounts to 20 and 30 dB at the distances of 50 and 150 km respectively.

It should be noted that heights observed by different radars may be compared only when the use of the same threshold value and the same correction procedure are assured.

**Anomalous propagation**

The range-height diagram used to determine the echo height assumes the normal curvature of the radar beam. In anomalous propagation, such as in an inversion layer, the observed echo height greatly exceeds the actual echo height. The radar installed on a high hill on the Sea of Japan coast often observes the mountain echoes in the southern area of Korea more than 400 km away on account of inversion over the Sea of Japan;
The apparent height of the mountain is about 10,000 m in this case. Also, in the U.S. radar manual, discrepancies of 30,000 ft in echo top as measured by two radars have been reported as an example of those effects such as increasing beamwidth and error in elevation angle with increasing distance and also anomalous propagation.

2.7 Range limitations for echo-top measurement

Measurements of echo height at long range are subject to serious errors due to several factors described in the previous paragraphs.

Moreover, a number of factors associated with errors in the intensity measurement also increase the errors in echo-top height. These include attenuation in intervening rain, difference in beam-filling factor, averaging problem of fluctuating signals, the unknown factor in the radar equation, and so on.

In view of these, it would be necessary and reasonable to specify the range limitation for echo-top measurement. Range limitation of approximately 200 km would be regarded as appropriate.

2.8 Error due to the variation of echo characteristics

Since the height of the convective echo increases rapidly during the developing stage, the reliability of the radar information on the echo top decreases drastically with time, and for this reason the data on echo height distributed must be renewed frequently.

In stratiform clouds, precipitation particles of sufficiently large size detectable by a weather radar may not be present in the upper portions of the clouds. In such precipitation, the echo top is a function of the range.

2.9 Conclusion

While the errors in measuring echo top can be numerous, as explained above, it should be emphasized that the height of echo top still remains important for aircraft operations because of its valuable index of storm activity.

It should also be added that very high accuracy can be obtained when a height is measured within the precipitation, such as bright bands and the core of maximum intensity in a convective cloud. Accurate measurement may also be obtained by pointing the antenna at the zenith to make the measurement directly overhead. In this case, the only error generally experienced is that caused by the finite length of the transmitted pulse.

REFERENCES


CHAPTER 3

INTERPRETATION OF ECHOES FOR DIFFERENT TYPES OF RADAR

Introductory remark

The data from weather radars do not only depend on meteorological phenomena. They depend also, to a great extent, on the characteristics of the radar. In fact, each echo should be interpreted, taking into account the individual characteristics of each set of equipment. This is particularly important in cases when quantitative information is required. In this chapter, we shall examine successively the consequences of phenomena associated with the attenuation of electromagnetic waves and errors which may be caused by a radar beam which is too wide.

3.1 Attenuation of electromagnetic waves

3.1.1 Theory

3.1.1.1 General

The radar equation gives the relationship between the characteristic parameters of a radar and those of the observed target. This equation does not take into account modifications which the electromagnetic wave undergoes on its path between the equipment and the target. In fact, the radar signal diminishes in intensity, depending on the properties of the medium traversed. The general term attenuation is defined as the resulting reduction in the strength returned to the radar. It is determined by the relationship:

\[ dP_r = -2aP_r \, dr \]  

where \( P_r \) is the strength received by the radar, \( dP_r \) is the decrease in this strength, \( a \) is the attenuation coefficient and \( dr \) is the differential increment in the distance along which the attenuation under consideration takes place. The factor 2 which appears in \( 1 \) takes account of the outward and return paths normally traversed by the radar wave.

Extending equation \( 1 \) to the space between the radar and a point at a distance \( r \) from it, we obtain the strength \( P_r \) received on the radar from the strength \( P_{r0} \) which would have been received with no attenuation:

\[ P_r = P_{r0} e^{-\int_0^r a \, dr} \]  

Giving the attenuation as a ratio of the two strengths and expressing this ratio in decibels, we finally obtain:

\[ A_r, \text{dB} = 10 \log \frac{P_r}{P_{r0}} = -2 \int_0^r k \, dr \]  

where \( A_r \) is the attenuation of the radar wave along a double path of length \( r \) (km) and \( k \) is the coefficient of attenuation per unit length (dB/km).
Equation (3) has the advantage of enabling the attenuation due to different causes, or occurring in parts of the path followed by the attenuated wave, to be taken into account by simple addition of the partial attenuations. In the particular case of a radar signal, there will usually be three sources of attenuation: gases in the atmosphere, cloud and precipitation. In order to obtain the total reduction in the strength returned to the radars, it is only necessary to add the effects of each.

3.1.1.2 Attenuation due to gases in the atmosphere

Attenuation due to gases in the atmosphere is essentially linked with absorption by water vapour and oxygen. These two problems have been investigated in detail by Van Vleck (1, 2) and for very high frequencies by Rosenblum (3). The effect of oxygen is usually considered small for all wavelengths over 1 cm. For wavelengths less than this, the attenuation due to oxygen increases rapidly (Figures 10 and 11).

![Figure 10 — Attenuation in dB/km due to oxygen and water vapour (7.5 g/m³) in air at a pressure of 760 mm of mercury and at a temperature of 20° C (Van Vleck)]

The attenuation varies appreciably with temperature and pressure: for wavelengths from 3 to 10 cm (those most frequently used in ground weather radars) it can be considered as being in the neighbourhood of 0.01 dB/km at a pressure of 760 cm of mercury and a temperature of 20° C. Research workers have frequently neglected this attenuation. If this is acceptable for targets at no great distance, the same is not true when the targets are at greater distances, and it is hoped to determine their characteristics quantitatively and accurately. For a target at 100 km the total attenuation is two decibels and to neglect this leads to an underestimation of the observed intensity of
rainfall of about 25 per cent. A correction for the attenuation due to oxygen can fairly easily be made by applying to the signal a correction term varying linearly with distance. However, this correction can only be approximate, for, strictly speaking, the term should take into account the variations of pressure and temperature in the space affected by the radar.

Table 2 gives the factor to be applied to the attenuation at 0°C and 76 cm of mercury, in order to obtain the attenuation at temperature $T$ and pressure $p$.

<table>
<thead>
<tr>
<th>$T$, °C</th>
<th>Factor $(p$ in atmospheres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>$1.00 \ p^2$</td>
</tr>
<tr>
<td>0</td>
<td>$1.19 \ p^2$</td>
</tr>
<tr>
<td>-20</td>
<td>$1.45 \ p^2$</td>
</tr>
<tr>
<td>-40</td>
<td>$1.78 \ p^2$</td>
</tr>
</tbody>
</table>
The attenuation due to water vapour is small for long wavelengths. It is practically negligible at $\lambda = 10$ cm; at $\lambda = 3$ cm it is even less, but for accurate measurements made in hot, humid countries, where the water vapour content of the air may be high, it is possible that we may have to take it into account. To fix ideas for a double path of 100 km in air at $20^\circ$ C containing 10 g water vapour per m$^3$, the attenuation which radiation of 3.2 cm undergoes is 1.4 dB (neglecting the variation of atmospheric pressure in the beam transmitted).

We know that the attenuation due to a particle is linked with the perpendicular cross-section of total absorption $Q_t$ of the latter and that $Q_t$ is equal to $Q_a + Q_s$ with $Q_a$ perpendicular cross-section of absorption and $Q_s$ perpendicular cross-section of diffusion.

In the case of spherical particles and when Rayleigh’s approximation is applicable, we have the following values for $Q_a$ and $Q_s$:

$$Q_a = \pi^2 I_m \left( -\frac{m^2 - 1}{m^2 + 2} \right) \frac{D^3}{\lambda}$$  \hspace{1cm} (4)

$$Q_s = \frac{2}{5} \pi^2 \left[ \frac{m^3 - 1}{m^3 + 2} \right] ^{\frac{3}{2}} \left( \frac{D^6}{\lambda^4} \right)$$  \hspace{1cm} (5)

where $m$ is a compound refractive index of the material constituting the particle, and $D =$ the diameter of the latter. The absorption due to a collection of particles will be the sum of the absorption due to each separate particle.

In particular, the absorption which a wave undergoes along a given path will be due to the sum of the effects of particles along this path. If we denote by $k$ the coefficient of attenuation per unit length, we can relate $k$ to $Q_t$ by adding the values of $Q_t$ corresponding to particles contained in the volume having unit cross-section and a length equal to the unit of length appearing in $k$. If we express $Q_t$ in square centimetres and the attenuation in decibels per kilometre, we have:

$$k (\text{dB} \cdot \text{km}^{-1}) = 0.4343 \Sigma Q_t = 0.4343(\Sigma Q_a + \Sigma Q_s)$$

If $a$ is very small, the only perpendicular cross-section $Q_a$ is significant, and we have:

$$k (\text{dB} \cdot \text{km}^{-1}) = 0.4343 \Sigma Q_a$$  \hspace{1cm} (6)

Substituting from (5) we finally obtain:

$$k (\text{dB} \cdot \text{km}^{-1}) = 0.4343 \pi^2 I_m (-K) \frac{\Sigma D^3}{\lambda}$$  \hspace{1cm} (7)

In this expression $\Sigma$ extends over unit volume and (-$K$) = $m^2 - 1$.

For short wavelengths (less than 2 cm) the attenuation due to water vapour varies rapidly; it reaches a maximum at about 1.3 cm, decreases to reach a minimum value at about 9 mm and then increases again, but for these short wavelengths the value of the attenuation cannot really be determined precisely.

Table 3 (Gunn and East – (4)) shows, for the wavelengths most frequently used in meteorology, the value in dB·km$^{-1}$ (single path) of the attenuation due to water vapour.
Table 3

\[ P = \text{pressure in atmospheres; } W = \text{water vapour content (gm}^{-3}) \]

<table>
<thead>
<tr>
<th>( T (^\circ C) )</th>
<th>( \lambda = 10 )</th>
<th>( \lambda = 5.7 )</th>
<th>( \lambda = 3.2 )</th>
<th>( \lambda = 0.9 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20(^\circ) C</td>
<td>( 0.07 \times 10^3 ) ( PW )</td>
<td>( 0.24 \times 10^3 ) ( PW )</td>
<td>( 0.7 \times 10^3 ) ( PW )</td>
<td>( 9.5 \times 10^3 ) ( PW )</td>
</tr>
<tr>
<td>0(^\circ) C</td>
<td>( 0.08 \times 10^3 ) ( PW )</td>
<td>( 0.27 \times 10^3 ) ( PW )</td>
<td>( 0.8 \times 10^3 ) ( PW )</td>
<td>( 10.4 \times 10^3 ) ( PW )</td>
</tr>
<tr>
<td>-20(^\circ) C</td>
<td>( 0.09 \times 10^3 ) ( PW )</td>
<td>( 0.30 \times 10^3 ) ( PW )</td>
<td>( 0.9 \times 10^3 ) ( PW )</td>
<td>( 11.4 \times 10^3 ) ( PW )</td>
</tr>
<tr>
<td>-40(^\circ) C</td>
<td>( 0.10 \times 10^3 ) ( PW )</td>
<td>( 0.34 \times 10^3 ) ( PW )</td>
<td>( 1.0 \times 10^3 ) ( PW )</td>
<td>( 12.6 \times 10^3 ) ( PW )</td>
</tr>
</tbody>
</table>

3.1.1.3 Attenuation due to liquid particles – General

The theory due to MIE enables the attenuation due to a particle to be determined in the same way as it enables the strength returned to the radar by such a particle to be determined. Unfortunately, the method leads to equations which are difficult to manipulate and can only be simplified if the diameter \( D \) of the particles is small compared with the wavelength of the radiation transmitted (Rayleigh’s approximation). The range in which Rayleigh’s approximation applies is much smaller than that which is tolerable in the case of the perpendicular of back diffusion.

Haddock (5), in calculating the ratio between the attenuation resulting from the theory due to MIE and that resulting from Rayleigh’s approximation, has shown that the particles in clouds satisfy the latter, whereas for raindrops, use of Rayleigh’s approximation leads to large errors for any wavelength less than 10 cm (Battan – (6)). To illustrate the point, for drops of 1 mm diameter, Rayleigh’s approximation is applicable for \( \lambda = 10 \) cm whereas for \( \lambda = 3 \) cm it gives a value only 1.7 times smaller than the value obtained by full application of the equations due to MIE. However, equation (7) is still interesting, for it shows the effect of temperature on attenuation. In fact, the imaginary part of \((-K)\) is not independent of temperature and consequently there are fluctuations in the attenuation due to temperature which cannot be neglected.

Table 4

<table>
<thead>
<tr>
<th>( T (^\circ C) )</th>
<th>( \lambda = 10 )</th>
<th>( \lambda = 3.2 )</th>
<th>( \lambda = 1.24 )</th>
<th>( \lambda = 0.62 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.00474</td>
<td>0.0188</td>
<td>0.047</td>
<td>0.0915</td>
</tr>
<tr>
<td>10</td>
<td>0.00688</td>
<td>0.0247</td>
<td>0.0615</td>
<td>0.1142</td>
</tr>
<tr>
<td>0</td>
<td>0.01102</td>
<td>0.0335</td>
<td>0.0807</td>
<td>0.1441</td>
</tr>
<tr>
<td>-8</td>
<td></td>
<td>0.1036</td>
<td>0.1713</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 gives \( I_m (-K) \) for various values of \( T \) and \( \lambda \). It can easily be seen that, for a difference of 20\(^\circ\), the attenuation varies from its initial value to a little over double, for \( \lambda = 10 \) cm, and from its initial value to a little less than double for \( \lambda = 3.2 \) cm. In the latter case, this result is only true if Rayleigh’s approximation applies. When it is necessary to fall back on the equation due to MIE, the result is quite different and, surprisingly, is reversed: the attenuation decreases when temperature decreases (about 40 per cent for a change from 18\(^\circ\) to 0\(^\circ\) C (Ryde (8) — see Figure 12).
3.1.1.4 Attenuation due to cloud

The droplets in clouds have a diameter which is sufficiently small for Rayleigh's approximation and consequently equation (7) to be applicable. Since, in this equation, the diameter of the drops occurs to the power of 3, the attenuation is independent of the dimensional spectrum of the droplets and it is convenient to express it as a function of the water content of the cloud. We obtain:

\[ k(\text{dB/km}) = 0.4343 \frac{5 \pi I_n (-K) M}{\lambda \rho} \]  

(8)

where \( M \) = water content in grammes per m\(^3\) and \( \rho \) = density of the liquid.

Table 5 gives, for three temperatures, the values of the attenuation in traversing a cloud mass.

<table>
<thead>
<tr>
<th>( T(\degree C) )</th>
<th>( \lambda \ 10 \text{ cm} ) ( M )</th>
<th>( \lambda \ 5.7 \text{ cm} ) ( M )</th>
<th>( \lambda \ 3.2 \text{ cm} ) ( M )</th>
<th>( \lambda \ 0.9 \text{ cm} ) ( M )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.39 \times 10^{-2}</td>
<td>1.36 \times 10^{-2}</td>
<td>4.83 \times 10^{-2}</td>
<td>64.7 \times 10^{-2}</td>
</tr>
<tr>
<td>10</td>
<td>0.56 \times 10^{-2}</td>
<td>1.96 \times 10^{-2}</td>
<td>6.30 \times 10^{-2}</td>
<td>68.1 \times 10^{-2}</td>
</tr>
<tr>
<td>0</td>
<td>0.90 \times 10^{-2}</td>
<td>2.72 \times 10^{-2}</td>
<td>8.58 \times 10^{-2}</td>
<td>99 \times 10^{-2}</td>
</tr>
</tbody>
</table>

Figure 12 – Relationship between the attenuation at 0\(\degree\) C and the attenuation at 18\(\degree\) C for different wavelengths (Ryde, 1946)

From the practical point of view it should be borne in mind that the values of the attenuation determined for rain or clouds are only approximate since they are usually found without taking temperature into account.
If we consider a cloud mass having a water content of 0.3 g/m³ and extending over 100 km we obtain at 20° (on the radar) an attenuation of 0.24 dB for \( \lambda = 10 \) cm and 2.7 dB for \( \lambda = 3.2 \) cm. This latter value is sufficient to show how deceptive would be any attempt at precise quantitative classification of echoes with a 3-cm radar without applying a correction for the attenuation due to dense cloud. Unfortunately, it is practically impossible to determine this correction since, for the most part, the cloud which makes the correction necessary escapes detection by the radar.

3.1.1.5 Attenuation due to rain

Rayleigh's approximation cannot be applied to wavelengths of less than 10 cm and it is essential to take into account the spectrum of the distribution of the diameters of the droplets in the precipitation. As a result of various investigations, particularly those by Ryde (7), it has been found possible to relate the attenuation, expressed in decibels per kilometre, directly to the intensity of rainfall. Thus at 18° C we obtain the following attenuations (dB.km⁻¹):

<table>
<thead>
<tr>
<th>( \lambda = 10 ) cm</th>
<th>( \lambda = 5.7 ) cm</th>
<th>( \lambda = 3.2 ) cm</th>
<th>( \lambda = 1.8 ) cm</th>
<th>( \lambda = 0.9 ) cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0003R^{1.00}</td>
<td>0.0022R^{1.17}</td>
<td>0.0074R^{1.31}</td>
<td>0.045R^{1.14}</td>
<td>0.22R^{1.00}</td>
</tr>
</tbody>
</table>

\( R \) = intensity of rainfall in mm/h

It is to be noted that the attenuation is a linear function of \( R \) for the wavelengths 10 cm and 0.9 cm only which, in particular, explains how it is possible to make measurements of the intensity of rainfall by measuring the attenuation which a 0.9-cm beam undergoes in passing through precipitation (Godard (8)).

Using the data of Table 6 it is possible to calculate the attenuation as a function of \( R \). Table 7 gives this in dB per kilometre for the wavelength most frequently used in meteorology.

<table>
<thead>
<tr>
<th>Intensity of rainfall ( R ) (mm/h)</th>
<th>Attenuation due to rain (dB/km) (single path)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wavelength ( \lambda )</td>
</tr>
<tr>
<td></td>
<td>0.9 cm</td>
</tr>
<tr>
<td>0.5</td>
<td>0.11</td>
</tr>
<tr>
<td>1</td>
<td>0.22</td>
</tr>
<tr>
<td>5</td>
<td>1.1</td>
</tr>
<tr>
<td>10</td>
<td>2.2</td>
</tr>
<tr>
<td>50</td>
<td>11</td>
</tr>
<tr>
<td>100</td>
<td>22</td>
</tr>
<tr>
<td>200</td>
<td>44</td>
</tr>
</tbody>
</table>
This table shows particularly well the distinct difference between the attenuation at 3 cm and that at 10 cm. It appears that the latter is practically always negligible, whereas for 3 cm the attenuation leads to large errors as soon as the rainfall intensity exceeds a few millimetres per hour. To illustrate this it will be noticed that a rainfall of 5 mm/h with 3 cm gives an attenuation identical with that with 10 cm passing through precipitation falling at the rate of 200 mm/h.

It will also be noticed that there is a very appreciable decrease in the attenuation in passing from a wavelength of 3.2 cm to a wavelength of 5.7 cm that it is advantageous to use the latter wavelength for airborne radars when the airframe of the aircraft permits the use of a sufficiently large antenna.

3.1.1.6 Attenuation due to solid particles

Because of the dielectric properties of ice, the problem of attenuation due to solid particles is more complex than that of attenuation due to water droplets. It involves both the properties of absorption and diffusion of the particle. In the special case of snow, values of the attenuation, limited to the case of Rayleigh’s approximation, have been calculated. We obtain:

Table 8

<table>
<thead>
<tr>
<th>T = 0° C</th>
<th>λ = 10 cm</th>
<th>λ = 5.7 cm</th>
<th>λ = 3.2 cm</th>
<th>λ = 1.8 cm*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.035x10^{-5} R^{1.6}</td>
<td>0.033x10^{-5} R^{1.6}</td>
<td>3.3x10^{-5} R^{1.6}</td>
<td>33.2x10^{-5} R^{1.6}</td>
</tr>
</tbody>
</table>

* (Rayleigh's approximation not valid)

It can easily be ascertained, by comparing Tables 8 and 6, that the attenuation is much less severe in dry snow than it is in rain, which means that measurements made on snowfall by means of radar operating on the X-band (3.2 cm) are acceptable.

Very little information is available on the problem of the attenuation associated with hail. We may, however, quote the work of Ryde (7) on the subject. If we consider the intensity, \( R \), of precipitation to be defined, in this special case, as the amount of water per hour (expressed in mm/h) from the melted hail, the value for the attenuation, between \( \lambda = 1 \) cm and \( \lambda = 10 \) cm, is given by:

\[
\text{Attenuation (dB/km)} = AR
\]

where \( A \) is as found from Table 9.

Table 9

<table>
<thead>
<tr>
<th>Diameter of hailstones (cm)</th>
<th>( \lambda = 1 ) cm</th>
<th>( \lambda = 3 ) cm</th>
<th>( \lambda = 10 ) cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
</tr>
<tr>
<td>0.25</td>
<td>( 2.7 \times 10^{-2} )</td>
<td>( 3.7 \times 10^{-6} )</td>
<td>( 2.2 \times 10^{-5} )</td>
</tr>
<tr>
<td>0.5</td>
<td>( 1.1 \times 10^{-1} )</td>
<td>( 1.5 \times 10^{-3} )</td>
<td>( 2.7 \times 10^{-5} )</td>
</tr>
<tr>
<td>1.0</td>
<td>( 7.3 \times 10^{-2} )</td>
<td>( 8.6 \times 10^{-3} )</td>
<td>( 7.5 \times 10^{-5} )</td>
</tr>
<tr>
<td>1.5</td>
<td>( 2.8 \times 10^{-2} )</td>
<td>( 1.7 \times 10^{-2} )</td>
<td>( 1.8 \times 10^{-4} )</td>
</tr>
<tr>
<td>2.0</td>
<td>( 1.0 \times 10^{-2} )</td>
<td>( 1.7 \times 10^{-2} )</td>
<td>( 3.6 \times 10^{-4} )</td>
</tr>
</tbody>
</table>
Here again it appears that the attenuation increases very appreciably when $\lambda$ changes from 10 to 3 cm.

The effect of temperature on this attenuation is not negligible. Ryde (7) has shown that the attenuation decreases when $T$ is negative. For hailstones with diameter 0.3 cm at a temperature of $-40^\circ$ C, it is necessary to apply a factor 0.3 for $\lambda = 10$ cm, and a factor 0.86 for $\lambda = 3$ cm, to the values contained in Table 9.

For hailstones of diameter 0.3 cm, the ratio of the attenuation due to rain to that due to hail (with the same intensity in the two cases), is 0.1 for $\lambda = 1$ cm, 0.01 for $\lambda = 3$ cm and 0.08 for $\lambda = 10$ cm. This ratio has a minimum value of $\lambda = 3$ cm.

### 3.1.2 Practical consequences of attenuation

The first practical consequence of phenomena associated with attenuation is clearly a reduction in the limits of the range in which the equipment can be used. We shall touch only briefly on this aspect of the problem as it has been adequately dealt with elsewhere (WMO Technical Note No. 78, 1966) and Table 9 is sufficient to show the degrees of “penetration” of the various wavelengths used for weather radars. We shall, however, emphasize the very limited possibilities of waves in the bands measured in millimetres, where detection through precipitation of moderate intensity extending over several kilometres is practically ruled out.

At the longer wavelengths of 5.7 cm and 3.2 cm, the attenuation is less severe and the limits of detection of the phenomena, even at a fairly great distance, can be regarded as acceptable at temperate latitudes, where heavy precipitation is usually limited to small or moderate areas. However, the limits are not acceptable in tropical and equatorial regions, where a wavelength of 10 cm should be given preference wherever possible.

The second consequence is linked with the fact that the energy reaching the radar from the precipitation depends not only on the nature of the latter, but also on the magnitude of phenomena associated with attenuation along the double path traversed by the radar wave; it is quite clear that, if these are large, any determination of the intensity, $R$, of precipitation, using a value for the energy reaching the radar which has not been corrected, will be erroneous.

Table 10 gives the width of the rain area giving rise to an attenuation of 4.8 dB, as a function of $\lambda$ and the intensity of rainfall, i.e. dividing by 2 the value of the intensity of precipitation, determined from the relationship $Z = 200R^{1.6}$.

<table>
<thead>
<tr>
<th>$R$ mm/h</th>
<th>$\lambda = 10$ cm</th>
<th>$\lambda = 5.7$ cm</th>
<th>$\lambda = 3.2$ cm</th>
<th>$\lambda = 0.9$ cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>$16 \times 10^3$</td>
<td>$2.4 \times 10^3$</td>
<td>800</td>
<td>21.8</td>
</tr>
<tr>
<td>1.0</td>
<td>$8 \times 10^3$</td>
<td>$1.2 \times 10^3$</td>
<td>343</td>
<td>10.9</td>
</tr>
<tr>
<td>5.0</td>
<td>$1.6 \times 10^3$</td>
<td>$1.6 \times 10^2$</td>
<td>40</td>
<td>2.18</td>
</tr>
<tr>
<td>10</td>
<td>800</td>
<td>72.7</td>
<td>16</td>
<td>1.09</td>
</tr>
<tr>
<td>50</td>
<td>160</td>
<td>11.1</td>
<td>1.9</td>
<td>0.22</td>
</tr>
<tr>
<td>100</td>
<td>80</td>
<td>4.5</td>
<td>0.78</td>
<td>0.11</td>
</tr>
<tr>
<td>200</td>
<td>40</td>
<td>2.1</td>
<td>0.31</td>
<td>0.05</td>
</tr>
</tbody>
</table>
This table shows that a shower of moderate intensity and dimensions is sufficient to give rise, with 3 cm, to an error, from the single to double path, in the intensity of rainfall, if no correction for attenuation is applied. On the other hand, with 10 cm, the attenuation will only be appreciable in the case of exceptional showers, both as regards intensity and dimensions. Figure 13 gives, for wavelengths of 10 cm, 5.7 cm, 3.2 cm and 1 cm, the width of precipitation reducing the intensity of the precipitation to half its real value.

One of the problems frequently facing users of weather radars is that of determining the severity of phenomena associated with a shower of limited horizontal extent. A good example of this type of problem is that which a meteorologist providing services for aviation has to face up to. Most frequently he is required to specify whether a phenomena corresponding to an echo observed on the radar is, or is not, dangerous for aviation. Usually a decision is taken, based on the maximum value of the intensity of the echo appearing on the radar. It is therefore essential to know to what extent this value is modified by attenuation.

The problem is extremely complex, for it raises doubts concerning the structure itself of the observed showers. This, in view of the multiplicity of forms which the showers may assume, would mean that a very large number of cases should be examined. We may, however, limit the arguments to two simple cases, for which extremely simple theoretical profiles will be assumed. In the first, a rectangular profile will be assumed for the shower, i.e. an instantaneous start and end of the shower, with no variation in the intensity of the precipitation over the whole of its area. In the second, the profile will be supposed to be triangular, i.e. the start and end of the shower take place with a linear variation in the intensity of the precipitation.

In both cases, we suppose that the showers are of rain only, and in giving the final result the intensities of echoes are reduced to intensities of rainfall, using the equation $Z = 200 R^{1.6}$. It is to be noted, however, that, for the wavelength of 0.9 cm and sometimes even for the wavelength of 3.2 cm, this practice is open to some criticism due to the fact, already mentioned, that with high intensities of rainfall, Rayleigh's approximation is not applicable for these wavelengths. The determination of the apparent profiles of showers of the first type follows directly by using the coefficient of attenuation appropriate to each intensity of rainfall. Figures 14 and 15 give, for the wavelengths most frequently used in meteorology, the apparent profiles for intensities of 10 and 100 millimetres per hour, which can be considered as representative of moderate showers and very heavy showers, respectively. For the
Figure 14 — Modification of the profile of homogeneous precipitation of intensity 10 mm/h. (1) It is assumed that the precipitation is in accordance with the equation $Z = 200 R^{1.5}$; (2) the pulse rise time of the radar has been neglected.

Figure 15 — Modification of the profile of homogeneous precipitation of intensity 100 mm/h. (1) It is assumed that the precipitation is in accordance with the equation $Z = 200 R^{1.5}$; (2) the pulse rise time of the radar has been neglected.
first assumed intensity, it can be readily seen that a radar operating on 0.9 cm gives rise to a distortion of the profile which is quite unacceptable. This distortion is practically negligible for wavelengths of 10 and 5.7 cm and is still tolerable for a wavelength of 3.2 cm, if the shower is not too extensive.

On the other hand, in the case of an intensity of 100 mm/h, only a wavelength of 10 cm gives satisfactory results over the whole extent of the observed phenomenon. For the three other wavelengths, the results are really only representative of the edge of the shower nearest to the radars. If we classify showers according to the maximum intensity returned to the radar, the phenomenon observed may, however, be classified as violent since, in this particular case, the part of the echo nearest to the radar gives the true value of this maximum intensity. It should, however, be noted that this result is only approximate since, in the curves of Figure 15, the duration of the pulse transmitted by the radar and the attenuation which occurs in the time interval corresponding to the duration of this pulse have not been taken into account. In fact, when the pulse just penetrates into the area of precipitation, the energy associated with its rear edge is not affected by attenuation but the same is not true of the energy associated with the leading edge.

It is really only permissible to neglect this phenomenon due to severe attenuation if we assume that the pulse emitted by the radar is short. To fix our ideas, on the assumption of homogeneous precipitation falling at 100 mm/h and a radar operating on a wavelength of 0.9 cm and with a pulse of two microseconds, the maximum signal appearing in Figure 15 would undergo an attenuation of one decibel.

In the case of a triangular theoretical profile, the problem of the determination is slightly more complex. We can, however, find a relationship which gives a value for the attenuation as a function of the distance traversed (Treussart (9)) and, from this, calculate for each point the intensity of precipitation which could be observed on the radar (assuming, as before, $Z = 200 R^{1.6}$).

Figures 16 and 17 show the observed profiles for the four usual wavelengths when the variations in the intensity of the precipitation are respectively five and ten millimetres per hour per kilometre. In each of the figures, the value of the minimum intensity which can be detected by the radars is also shown, it being supposed that, at the

![Figure 16 - Modification of the profile of a shower 20 km wide in which the intensity, $R$, of precipitation varies by 10 mm/h km ($R_m$ minimum intensity which can be detected)]
Figure 17 - Modification of the profile of a shower 20 km wide in which the intensity, \( R \), of precipitation varies by 5 mm/h km (\( R_m \), minimum intensity which can be detected)
distance of observation, this intensity is 1 mm/h. It will be readily understood, from an examination of the curves, how dangerous it could be to make any estimate of the hazard to aviation of such phenomena, using echoes from radars operating on wavelengths of 0.9 or 3.2 cm.

In the particular case of the latter wavelength and precipitation varying by 10 mm/h km, it is quite likely that a consideration of the echo would lead an inexperienced observer to advise a pilot to enter the area of rainfall, the latter having a maximum intensity hardly exceeding 25 mm/h. In actual fact, a pilot doing so would not have passed through the region of maximum intensity (forecast to be at 4 km) when his aircraft is at a position 5.5 km inside the area of precipitation. He would then be flying in a dangerous region where the true value of the intensity of precipitation is twice that determined by means of the radar.

From the point of view of measurement of precipitation, if we consider that the area between each profile in Figures 16 and 17 and the straight horizontal line representing the minimum intensity of precipitation, which can be detected by the radars in use, is representative of the amount of rain which would be measured along the axis of the radar, without any correction for attenuation, then all the advantages of using long wavelengths for observing showers, even those of moderate dimensions, will be readily understood.

Figure 18 (a) and (b) - Isocontours of one and the same area of precipitation, by means of: (a) a 10-cm radar; (b) a 3-cm radar (after P. Austin)
The considerable distortion of echoes resulting from attenuation has been demonstrated experimentally, in particular, by Austin (10), who carried out observations in one and the same area of precipitation using a 10-cm radar and a 3.2-cm radar.

Figure 18 (a) and (b) gives a representation of a region with showers, determined by Austin, using information given by the two sets of equipment. There are more showers above 100 mm/h on the 10-cm picture than showers above 40 mm/h on the 3-cm picture.

A statistical analysis of the consequences of attenuation has been carried out in the region of Montreal by Hamilton and Marshall (11); one of the conclusions was that the rainfall amounts due to heavy falls (maximum intensity, over 40 mm per hour) in one season gave a total of 473 mm. These same falls, measured at a distance of 48 km by radars operating on wavelengths of 3.2 and 5.7 cm, would have had their totals reduced to 144 and 349 mm, respectively.

All these studies go to show that it is necessary to exercise great care in using information derived from equipment using a wavelength which is too short. They show, in particular, how essential it is for the users of such radars to be fully aware of the underestimation of the intensity of phenomena, which might result from a direct use of the echoes appearing on the radar screens.

3.1.3 Correction of the attenuation

The preceding paragraphs show that, in a general way, the attenuation is only negligible at wavelengths of 10 cm or more. At all other wavelengths, no precise measurement can be made without a correction being made to the power returned to the radar. In the majority of cases, this operation reduces to a simple interpretation of the echoes by the radar operator. We shall not dwell on this method, which is greatly lacking in precision and the subjective nature of which is only too evident.

We know that attenuation depends on phenomena observed by the radar (rain), but also on phenomena which the equipment does not take into account or only partly takes into account (cloud, temperature). It thus appears that a rigorous correction to the attenuation should be based both on the radar data to be corrected and on information which is not derived from the radar. In fact, the attempts at correction which have been carried out in practice have, so far, used radar information only and so can only lead to values which have not been adequately corrected.

Hitchfeld and Bordan (12) have carried out an exhaustive critical examination of possible methods of correcting errors due to attenuation. They have shown that such corrections necessitated a rigorous calibration of the radar. They have calculated that an error of less than one decibel on the radar could lead to an infinite value for the intensity of the precipitation.

Several research workers have, however, suggested methods or equipment for making corrections to the attenuation. For example, Kodaira (13) has designed an electronic device which makes the correction automatically. This unit can only be used, however, in cases when the attenuation is moderate (a value of 6 dB is usually considered to be the upper limit). Wein (14) has also suggested the use of an electronic unit correcting the attenuation of signals from a 3.2-cm radar; he has shown that the quality of performance depends not only on the precision of the calibration of the radar but also on the granulometric spectrum of the precipitation. The latter directly influences the relationship between the backward diffusion of the precipitation and the attenuation due to it. In conclusion, he doubts whether this device could ever be made fully automatic and is of the opinion that, in normal operation, the operator should make an adjustment, based on his estimation of the meteorological conditions, at least every 30 minutes.
3.2 Errors associated with the beamwidth transmitted by the radar

The various relationships giving the power returned to a radar by precipitation of a given intensity imply that all the energy transmitted by the equipment has affected the precipitation. For this, it is therefore necessary to intercept completely the beam transmitted by the radar. We shall examine separately the consequences implied by this condition, in the vertical and horizontal planes.

3.2.1 Beamwidth in the vertical plane

This problem is related to that of the measurement of the height of echoes, set out in the preceding chapter, so the question will only be considered rather briefly here.

The formation of precipitation at high altitudes being limited, it appears that the radar beam will be completely intercepted at relatively large distances only if its width in the vertical plane is small. At 100 kilomètres, precipitation with a vertical development of 3,000 m only represents a thickness of about 2,400 metres, situated above the radar horizon (allowing for a correction for the curvature of the earth, under normal conditions of propagation).

Such precipitation can only completely affect radar beams having a width in the vertical plane, equal to or less than 2°. Table 11 (based on the equation \( \theta = \frac{70\lambda}{d} \), where \( \theta \) is the beamwidth in degrees and \( d \) the dimension of the antenna in the plane containing \( \theta \)) gives the width \( \theta \) in degrees of the beam transmitted by the radar, as a function of the dimension \( d \) of the antenna and of the wavelength.

<table>
<thead>
<tr>
<th>( \lambda ) cm</th>
<th>( d = ) dimensions (in metres) of the antenna of the radar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>3.2</td>
<td>.22</td>
</tr>
<tr>
<td>5.7</td>
<td>4.0</td>
</tr>
<tr>
<td>10.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

We can easily see that for the longest wavelengths it is necessary to provide antennae of large dimensions in order to obtain small beamwidths.

In practice, economic considerations lead meteorologists to adopt a compromise. In the case of a radar of wavelength 10 cm, an angle of aperture of the beam of about 2° seems to be a reasonable solution if the range, for quantitative measurement, is limited to a radius of 100 km.
3.2.2 Beamwidth in the horizontal plane

In the pertinent literature much more space has been devoted to the beamwidth in the vertical plane than to the width in the horizontal plane. This, in a general way, has led to an underestimation of the importance of having good definition on the radar screen in the horizontal plane also. In fact, the great variability of the observed phenomenon in the horizontal plane may lead to errors which are perhaps even greater than those occurring in the vertical plane, even when the condition of total interception is fulfilled.

Harrold (15) has examined in detail the errors which could be caused by using various beamwidths in measurements made of a small-dimension shower and within which the rainfall intensity decreases from the centre towards the perimeter. He has shown that the use of a wide beam led to an underestimation of the intensity of precipitation at the centre of the shower and, conversely, to an overestimation at the periphery. In the case of the rainfall under consideration, the beams at the distance of the shower having widths of 2.4 km and 4.9 km reduce the true intensity of the precipitation from over 100 to 90 and 70 mm/h respectively (Figure 19). The mean intensity for the shower is, however, less affected than the maximum intensity. In the most unfavourable case (4.9-km beam) it is subject to an error of no more than 17 per cent.

In conclusion, it would also appear to be desirable that the beam transmitted by the radar should have a limited aperture in the horizontal plane. In practice it seems reasonable to use a circular antenna giving the same angle in all planes.

Figure 19 — Apparent intensity of rain through a shower observed with beamwidths of 2.4 and 4.9 km.
- - - - true intensity;
- --- - - observed intensity with 2.4-km beam;
- + - + observed intensity with 4.9-km beam.
3.2.3 Practical consequences concerning the choice of equipment

3.2.3.1 Ground radar

From the foregoing remarks, it appears that quantitative measurements necessitate the use of radar having a narrow transmission beam in all planes and using a wavelength which is subject to little or no attenuation. These two conditions are contradictory and the final choice can only result from a compromise. A wavelength of 10 cm seems to be the most likely to satisfy reasonably all the conditions. For this reason it should be given preference whenever precise, quantitative measurements are required.

3.2.3.2 Airborne radar

The choice of the proper wavelength for airborne weather radars is a matter for the user to decide, depending upon the corollary purposes for which the radar will be used. There is also a limiting factor of space available on a specific aircraft for installation of the radar antenna. Tabulated below is a comparison of characteristics attributable to radars of each of three wavelengths commonly in use today:

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>K_u-band</th>
<th>X-band</th>
<th>C-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.85 cm</td>
<td>3.3 cm</td>
<td>5.5 cm</td>
</tr>
<tr>
<td>Typical antenna size (diameter)</td>
<td>20 cm</td>
<td>45 cm</td>
<td>60 cm or larger</td>
</tr>
<tr>
<td>Typical beamwidth</td>
<td>2.5°</td>
<td>3.5°</td>
<td>5°</td>
</tr>
<tr>
<td>Attenuation characteristics</td>
<td>0.22 dB/km per mm/h</td>
<td>0.014 dB/km per mm/h</td>
<td>0.004 dB/km per mm/h</td>
</tr>
</tbody>
</table>

**K_u-band**

*Advantages*

1. Can be used on smaller aircraft with limited radome spaces.
2. Displays echoes from light precipitation.
3. Can detect most cumuliform clouds and ice crystals.

*Disadvantages*

1. Signal attenuates severely in more than light precipitation.
2. Cannot be employed for corridor navigation if light rain or cumulus clouds are present.
3. Cannot detect the true characteristics of the storm and determine the danger zones.

**X-band**

1. Echo characteristics from thunderstorm cells are sharp but tend to attenuate.
2. Has good range capability.
3. Can be used for avoiding most turbulence and hail, except in severe thunderstorms and in tropical rains.

1. Signal attenuates in moderate and in heavy rain.
2. During flights near heavy thunderstorms echo pattern may give false information of the most dangerous zones (versimilitude).
3. Tends to display echoes of cells of no significance in turbulence and hail detection.
CHAPTER 3

Advantages

4. Has good ground-mapping characteristics for navigation except when flying above intense rain zones.

Disadvantages

1. Echoes are not as sharp as in radars of lower wavelength.

C-band

1. Attenuation of signal is negligible and reliable radar picture of turbulence and hail is possible in practically all cases.

2. Minimum of obscuration of important cells by lighter precipitation.

3. Penetration of cloud mass of line storm development can be made safely with minimum of detouring.

4. Has good range capabilities.

REFERENCES


CHAPTER 4
INSTRUMENTAL TECHNIQUES – PROCESSING AND TRANSMISSION OF RADAR INFORMATION

4.1 General aspects of the problem

We designate by the general term “processing of radar information” all those operations which are applied to information obtained by the use of radar, with a view to:

- Determining relationship with meteorological phenomena;
- Facilitating transmission of the information;
- Improving operational facilities.

In the case of conventional radars involving pulses, the radar information reduces to the signal given with known or unknown amplitude. The meteorological phenomenon which is most frequently observed is precipitation, this being identified by position and possibly intensity.

There is no need to dwell on the problems raised in connexion with determining the position of the phenomena being observed; these are known and are not specifically meteorological problems. On the other hand, we shall lay more stress on determining the intensity of the phenomena.

4.1.1 Improvement in the precision of relationships between radar information and meteorological phenomena

How many investigations, both theoretical and empirical, have been carried out with a view to relating the amplitude of signals from weather radars to the intensity of precipitation? Without entering into details, we may say that these investigations have led to relationships of the form

\[ Z = AR^b \]

where \( Z \) = radar reflectivity of the observed phenomenon,
\( R \) = intensity of precipitation,
\( A \) and \( b \) = numerical coefficients, which are functions of the nature of the precipitation (rain, snow or hail); these vary from author to author and even from one occasion of precipitation to another.

Limiting our attention to the simplest case of rain, we may use the mean relationship:

\[ Z = 200 R^{1.6}, \]

\( Z \) being a quantity which may be given directly by the radar; it thus appears to be possible to determine the intensity of precipitation, using only information from a weather radar. In actual fact, the problem is not as simple as the \( Z/R \) relationships, already referred to, would lead one to suppose. These relationships are in fact only valid when mean values for the parameter \( Z \) are available. Unfortunately, the strength of radar signals on which \( Z \) depends is subject to fluctuations due to the random distribution of particles giving rise to diffusion within the radar beam. It is therefore essential to determine the mean value of \( Z \), before any operational use is made of the signal, whenever it is intended to make quantitative use of the radar.

This problem has been studied by many authors, among whom may be mentioned: Marshall, Hitzfeld and Wallace. They have shown that, in order to obtain precise meteorological measurements by means of radar,
it is essential to integrate a number of stochastically independent signals (independent in the sense used in the theory of probability). In a general way we assume that integration of about a hundred independent signals reduces fluctuations in the signals to an acceptable level.

For a very long time, difficulties in carrying out such an integration meant that the procedure was not adopted; due to the advent of new electronic devices and, in particular, to the widespread use of transistors and, more recently, integrated circuits, it has been possible to find a relatively simple solution to this important problem. We may quote, as an example, the unit developed by Lhermitte of the National Severe Storm Laboratory in the U.S.A. In such equipment, in order to obtain a sufficient number of independent samples, all the radar signals affecting a given range of distance are integrated. This range is usually limited to a value of about one kilometre. However, the number of samples integrated in this way is still inadequate and it is essential to continue integration for several radar transmissions. In order to keep the angular dimension for each such radar reading sufficiently small, it is essential to reduce the speed of rotation of the antenna. To fix our ideas, the equipment devised by Lhermitte operates with a speed of rotation of three degrees/second which gives a speed of repetition of PPI images of one image every two minutes.

It is to be noted that the integration accomplished in this way is inevitably accompanied by a deterioration in the definition of the radar images, the elementary area over which it takes place being appreciably larger than the "radar point" which can be observed on a conventional screen. Integration of the signal, by eliminating fluctuations, makes it possible to obtain a precise quantitative value for the signal. This is what is usually done: at the output of the unit we obtain a parameter which can easily be related to a meteorological phenomenon. In practice, such an operation may lead to the radar screen giving an image in which several lines of equal intensity of the radar signal appear simultaneously.

4.1.2 Transmission of radar information

The problem of the transmission of the radar image is essentially linked with the fact that radar information gives rise to extremely short signals, the dispatch of which necessitates the use of circuits of large bandwidth. The transmission of a pulse of duration \( \gamma \), for example, necessitates the use of a link, of which the pass band, expressed in Hertz, is of the order of \( \frac{1.2}{\gamma} \) (\( \gamma \) being expressed in seconds). For example, a radar using pulses with a duration of two microseconds necessitates the use of a transmission line having a bandwidth of the order of 600 KHz. From the practical point of view, obtaining such lines leads to the adoption either of costly coaxial lines, or of Hertzian beams, the cost of which is usually prohibitive.

For several years, users of radar have considered the possibility of transmitting the information derived from their equipment by telephone lines. The problem to be solved is essentially a problem of compressing the band, the width usually available on a telephone line being limited to about 2 KHz. Several procedures for transmission can be conceived. The simplest, but certainly not the most economical, is based on storing in the memory unit the information collected by the radar during one complete rotation of the antenna; the data so stored are then transmitted at a lower frequency compatible with the bandwidth of the telephone link. Without entering into the details of such a system, one may nevertheless say that the degree of complexity of the system depends essentially on the quantity of information which it is desired to transmit. If we allow for the fact that the speed of transmission is determined by the width of the band of the telephone line, the quantity of information also determines the time for the dispatch of an entire radar image. The meteorologist is thus led to seek a compromise between the desire for detailed information and the necessity to update it at frequent intervals. It is generally accepted that a transmission time of about two minutes is compatible with the requirements of normal operation.

The transmission time being fixed, it is up to the meteorologist to choose the type of image to be transmitted. This may be either an image at a single level, i.e. not taking into account the intensity of radar signals, or an image
at several levels. Obtaining an image of the latter type necessitates, for each “point” of the radar image, the transmission of a larger quantity of information which will naturally depend on the number of levels to be transmitted. Here again, the meteorologist has to seek the best compromise between an image with good definition and an image giving a large number of levels. A definition giving a “point” radar having a dimension of the order of a kilomètre and a number of levels limited to four seems to be compatible both with the possibilities of modern technology and the most usual requirements of meteorologists.

Storage of the total information contained in a radar image unfortunately requires fairly complex equipment which, of necessity, is costly. That is why this solution is not always adopted. It is, in fact, possible to have simpler equipment for the transmission of information in real time. In such systems, the information stored by the radar is supplied at a speed which is slow enough for transmission to take place as it becomes available. If, for example, we consider a unit with an integrating device analogous to that mentioned in the preceding paragraph, and giving a complete image every two minutes, it is possible to provide a reading system for the information, operating at a sufficiently low speed for it to be transmitted directly by telephone line. We shall see in the next paragraph, however, that this device, which is particularly attractive, is less flexible in its use than the storage unit. In particular, it does not enable full use to be made of the information retrieval devices which modern technology has made available to meteorologists.

As in the case of equipment where information is stored, units operating in real time make it possible for images at one or several levels to be transmitted. In the first case, the relatively limited amount of information to be transmitted makes it possible to increase the speed of rotation of the antenna of the radar and this, in certain cases, may be an advantage. A solution which is related to those above consists of transmitting successively images at a single level which can be varied from image to image. This system leads to the most simple arrangements but, from the point of view of retrieval of the image, has a certain number of disadvantages; in particular, whenever an overall examination of the meteorological situation is required, it is essential to provide supplementary visual equipment giving an image of sufficiently long duration. This constraint limits the use of the simplest visual equipment and so detracts from the value of the method.

4.1.3 Improving operational facilities for radar information

In this section we shall mainly consider equipment intended to complete the processing of radar information. We can make a distinction between two large categories of equipment: those giving a temporary image and those giving permanent information susceptible to be archived.

4.1.3.1 Equipment giving a temporary image

These sets of equipment comprise mainly those based on the use of cathode-ray tubes. These may be either conventional radar tubes, or long-persistence tubes or television tubes. The simplest procedure is to use conventional radar tubes, similar to those used for screens currently in operation. In fact, when such a solution is adopted, the operating station for radar information differs very little, from the point of view of equipment, from an ordinary radar station.

In practice, adoption of this procedure necessitates storing all the information as it is received at the operating centre. In fact, the cathode-ray tubes of radar screens do not have adequate retentive powers for operation to be possible at the speed of dissemination of information necessitated by the small bandwidth of a telephone line. If we consider the case, previously mentioned, of the transmission of an image being completed in two minutes, it appears that elements transmitted at the beginning of the period would cease to be visible even before the whole image reaches the operating station and at no time would the meteorologist have an overall picture of the situation. When the whole of the information has been stored, it is sufficient to read this rapidly, in order for the operator to be under working conditions similar to those which he would hold, were he at a conventional radar station.
This solution also has the advantage, when the meteorologist can accept a fairly low rate of renewal of the image (transmission of one image in a quarter of an hour, for example), that it does not cause the telephone line to be immobilized for the whole period of operation of the radar. This is an advantage which cannot be disregarded when the processing of the radar information is carried out on a line which is used for other transmissions, as is frequently the case with meteorological stations of moderate importance.

When the transmission of several levels of the radar signal is carried out as a sequence, a radar screen without storage can be more easily used, owing to the relatively short transmission time of an image at a single level. With such a solution, however, the meteorologist has only incomplete information at his disposal at any given moment. If he requires more detailed information he would have to look at the images corresponding to the different levels as they are transmitted. This necessarily results in the operator having to spend more time in front of the visual equipment which, when one considers how busy meteorologists are at stations, is a great disadvantage and may rule out adoption of the system.

The use of screens with cathode-ray tubes with storage or giving long persistence of the image alleviates this disadvantage. As a first approximation, we may consider that these devices are comparable with conventional screens with exceptionally high retentive power which may exceed several minutes. Operation is then much more convenient.

In spite of the progress which has been made in recent years in the manufacture of storage tubes, equipments comprising such tubes remain very expensive. In other respects, from the point of view of meteorological operation, they have a certain number of disadvantages: they are usually of limited dimensions, usually about ten centimetres, and only in exceptional cases do they exceed 20 centimetres. Another difficulty associated with the operation of these tubes lies in their low dynamics. In order to be able to cause several values of the amplitude of radar signals to appear simultaneously, it is in fact necessary to use the variations of the luminance of the screen as a function of the amplitude of the signals.

These variations are unfortunately limited by saturation phenomena, and it proves to be difficult to obtain good definition on these screens for a large number of different levels. In current operation, it seems reasonable to limit the number of levels to a maximum of four in the case of equipment which is not adjusted at frequent intervals.

The use of television tubes in the field of processing radar information is no technical novelty; they are already in current use by many operating services (air navigation for example). The main difficulty raised by their use is the necessity to provide for a change in the system of co-ordinates. The original radar image is, in fact, given in polar co-ordinates, while the television image is in Cartesian co-ordinates. This conversion necessitates storage of the set of information and the use of logical circuits to find a point in Cartesian co-ordinates corresponding to each point in polar co-ordinates. Without going into the details of such a device, we can say that the design is complex and, in spite of the recent progress made in the field of storage, the cost remains generally high.

The conversion unit can be placed before or after one transmission system. When processing of radar information is necessary locally, or when it is intended to transmit information to several operational centres, it is preferable to make the change in co-ordinates before transmission. On the other hand, when only one centre is involved, it is preferable to make the conversion at the level of the operations room, since the use of a television tube, due to its low persistence, necessitates complete storage of the information.

From the point of view of facility of operation, the television tube is very attractive. It enables images of large dimensions to be obtained and the images have a luminance which is sufficient for operation under normal lighting conditions of the surroundings. The dynamics of the tube, without being exceptional, are greater than those of a storage tube, and the tube enables a sufficient number of levels for all the usual uses of weather radar to be made to appear simultaneously. From the economic point of view, the use, as a screen of equipment in widespread use, is extremely advantageous. At low cost, it enables the number of operational positions in one and the same operational centre to be increased. Before leaving devices depending on television techniques, something must be
said about the possibilities of colour television. Although this has not yet been used by meteorologists, it seems likely that in the comparatively near future it may be possible to obtain polychromatic pictures of areas of precipitation, the various intensities of which would be identified by different colours and shades. Such a technique would very appreciably facilitate the operation of radar pictures, and it is surprising that apparently no efforts in this direction have as yet been made in any country.

4.1.3.2 Devices providing permanent information

In this section, we shall examine equipment leading to recording of the information. We shall distinguish between units giving a visual record, i.e. a true retrieval of the radar picture, and those which merely store the information without the possibility of using it immediately and directly. The latter are used mainly for documents intended for the archives or for use a posteriori with the aid of more elaborate devices, such as computers, for example.

We shall not devote much space to this latter category of equipment. It includes mainly magnetic recorders and units using paper-tapes. We shall mention, however, the possibilities of combining magnetic recording and visual devices in which storage is necessary. When such devices are available, it is in fact sufficient to record the signals received by telephone line and then to read these at a speed which is compatible with the persistence of the visual system used to obtain an operational picture. Thus we can obtain, relatively easily, an economic unit giving both visual and archival information. In the devices giving directly a permanent radar picture, we must distinguish between two large categories, depending on whether the picture which is obtained is given in numerical form or not.

Amongst the equipments giving a radar picture in non-numerical form, particular reference should be made to facsimile equipments. Their interest lies in the fact that they depend on units which have been widely used experimentally for other purposes. Unfortunately, they have the disadvantage of providing a rather slow retrieval of the picture which places their performance as regards speed right on the limits of what is acceptable. In particular, if the time of transmission of the information by telephone line is added to the time of recording, it is to be feared that the delay between the time of the radar observation and the time when the information can be used may be too great.

It should be noted, however, that the recent development of coded facsimile equipment, by giving a transmission of variable duration, a function of the number of echoes appearing on the radar screen, should make it possible to reduce appreciably the mean time required to obtain recordings. While awaiting the widespread utilization of such equipment and to reduce the time of transmission of a facsimile picture to an acceptable value with conventional equipment, it would be preferable, whenever possible, to carry out the conversion of co-ordinates to the level of the radar rather than to that of the receiving station. In this way we can superimpose the time of transmission and the time of retrieval of the image and finally obtain a time which is compatible with present operational requirements. In the case of an image by facsimile, the various degrees of intensity of the radar signal are due to the density of recording. The amplitude of the radar signal is greater or less according to the darker or lighter tone of the recording. However, the characteristics of the picture must be used with discretion and it is reasonable to keep the number of levels recorded to a low value. Here again, the number to be selected varies appreciably with operational conditions and in particular with the availability of staff. If it is possible to make a certain number of tunings both at the radar station and at the operational station, the number of levels can be increased. If such a régime is not acceptable, it would seem to be reasonable to limit the number of levels to four. The appearance in recent years of facsimile equipment depending on photographic processes should lead to an improvement in this field.

One definite advantage of the facsimile system is that it is possible for an operational centre to disseminate to the various interested services a printed document which can be immediately interpreted and, possibly, adapted for a specific purpose. In particular, it would appear to be possible, for aviation purposes, to use levels enabling dangerous regions to be shown and also regions where there are no hazards for aviation.
In this respect, it is as well to mention that such use of radar information is only of value in so far as the information which is disseminated can be up-dated sufficiently rapidly. In practice, this imposes restrictions, except when equipment with a sufficient degree of automation can be used. In this connexion it seems that, due to the progress which has been made in recent years with devices depending on photographic processes, these have an advantage over equipment using ordinary paper. Finally, it is as well to mention that operation by means of facsimile with frequent dissemination of recordings leads to a financial burden which should not be underestimated.

Very similar to the foregoing equipment, from the point of view of operation, is equipment giving a recording of the radar image on paper, but not converted to Cartesian co-ordinates. The main disadvantage of such equipment is bound up with the fact that it is necessary to manufacture it specially for the use for which it is intended. For this reason devices of this kind are rarely used. We may, however, quote certain facsimile equipment designed in the U.S.A. using polar co-ordinates. It seems, however, that these are isolated instances and it would appear that it is not proposed to produce them industrially, at least for the time being.

In connexion with this type of operation, we may also mention a device which was developed in France a few years ago, even though it has not been used at the reception end. It enables recording of six levels of intensity in less than one minute. This is effected by the recording of a variable number of lines depending on the intensity of the observed phenomenon. Several years of operation of this device have shown that it has the following disadvantages:

- Rather poor radial definition of the image (one thirtieth of the total scale);
- Flimsy paper, which is inconvenient to handle (metallic paper with recording by sparking);
- A certain degree of training is necessary for operation.

It is probable that a certain number of the foregoing weaknesses could be partly overcome fairly easily, and that this type of equipment could, by virtue of its relative simplicity, constitute a useful local recording device.

It is with units giving an image showing, numerically, the intensity of the observed phenomenon that the most advanced method for the processing of radar information is achieved. In such equipment, recording takes place by means of a device which may either be an ordinary typewriter, a teleprinter or, more usually, a high-speed printing device similar to those used as ancillary equipment with computers. Work on this subject has originated mainly in the U.S.A. and it is impossible to approach the question without mentioning the STRADAP equipment, developed by the Cambridge Research Laboratory, and the equipment devised by the Massachusetts Institute of Technology and, more recently, by the National Severe Storms Laboratory.

Equipment showing numerical results has the advantage of conserving the main geometrical characteristics of the radar image, through the intermediary of a grid representation. The distortions which occur are essentially associated with the degree of definition, which is often only moderate and which is limited by the dimensions of the characters identifying each radar point. These may take various forms (figures, letters symbols) but for obvious reasons of convenience usually only figures are used. As a result, determination of the intensity of phenomena is limited to a scale with ten levels which is quite adequate for most operational purposes.

The main weakness of numerical recording lies in the relatively slow printing of the data. This varies considerably from one system to another. With ordinary typewriters and teleprinters, the time which is necessary to obtain a complete PPI image is too great and is incompatible with many applications. In particular they do not enable aviation to be operated on a rational basis. On the other hand, it appears that suitable printing times can be obtained using the high-speed printing devices for computers. Unfortunately these are expensive and it is doubtful whether their use could be extended to a large number of stations.

Numerical recording is of the greatest interest whenever time is not the essential factor. In particular, it appears that it would be advantageous to use this system whenever it is proposed to operate the radar for climatological purposes without the aid of a computer.
4.1.4 Examples of equipment for processing radar information

In the course of this brief examination of the question, there appear to be many possibilities and the choice is often embarrassing. Each of the possible solutions has advantages and disadvantages; some of these solutions are satisfactory for certain purposes, but are less satisfactory for others. For reasons dictated by economy, which are easily understood, the meteorologist cannot adopt the best solution for each purpose. We are up against the inevitable problem of a compromise.

The documents mentioned in this section provide examples of solutions to the problem. They contain descriptions of equipment in current use in various countries (U.S.A., Japan) and describe the experience acquired by those using such equipment, particularly in the field of the transmission of radar images.

4.2 A radar echo-contouring system (U.S.A.)

Research in recent years has shown radar echo intensity to be an important parameter for interpretation of weather echo data. Measurement systems in use by research groups have been difficult to use in weather offices. Generally, research groups have designed their data acquisition efforts to include radarscope photography to permit careful analyses days or months after the event. Weather office operations, however, require equipment systems which are easy to use and can be operated by observers or forecasters.

The ESSA Weather Bureau has designed an echo-contouring system for use in weather offices. The device is termed the Video Integrator and Processor or VIP.

The device:
(i) Provides signal intensity information in contoured form for PPI and RHI display;
(ii) Integrates the weather signal to smooth the pulse-to-pulse variation in echo amplitude;
(iii) Displays a full set of contours with each rotation of the antenna;
(iv) Indicates the maximum observed contour during each rotation of the antenna;
(v) Provides up to six selectable contours.

4.2.1 Basic principles of operation

The amplitude of a return signal from a precipitation target fluctuates in a random manner (see earlier discussion on signal fluctuations), giving rise to the problem of interpretation. A mean value for the fluctuating amplitude is the desired value that allows the radar meteorologist to infer rainfall rates. The statistical method used to improve the accuracy of the estimate of a mean value from randomly fluctuating values is simply a method of averaging. For a given volume in space this averaging technique is utilized by the VIP to improve the mean value estimate of precipitation intensity. The VIP combines averaging in range with averaging in azimuth or elevation.

Range averaging is performed electronically by integrating the incoming video signal over the range of interest for any given radar pulse. The resulting signal is proportional to:

\[ P_r \approx \int_{r_1}^{r_2} e \, dr \]
where $P_r$ is the average received signal, $e$ is the amplitude of the instantaneous return echo and $r_1$ and $r_2$ are the
beginning and ending ranges respectively.

The second averaging technique is integration of the returned signal on a pulse-to-pulse basis, or simply integration in azimuth or elevation. For a given volume in space, averaging in azimuth or elevation is accomplished by electronically averaging the signal amplitude for a number of pulses. This type of averaging is given by:

$$\frac{1}{n} \sum_{n} e$$

where $n$ is the number of pulses averaged.

The VIP utilizes both the range and azimuth (elevation) averaging methods.

The accuracy of the VIP's resulting estimate of a mean value for the intensity of the return echo from a given precipitation volume is a function of the effective sample size and the fluctuating characteristics of the echo. The design for the WSR-57 radar scanning at a rate of 3 rpm and with averaging over an interval of one nautical mile gives the accuracy of the VIP as plus or minus 1.48 dB.

The VIP averaging principle can be used on any radar but the accuracy depends on the PRF, pulse length, antenna scan rate and the desired range resolution. Assuming that the antenna beamwidth defines the azimuth resolution, the following equations can be used to calculate the accuracy of averaging:

$$n_1 = \frac{\text{radar pulses}}{\text{beamwidth}} = \frac{(\text{beamwidth}) \text{ PRF}}{\text{antenna scan speed}}$$

$$n_2 = \frac{\text{effective range samples}}{\text{range increment}} = \frac{\text{range resolution}}{\text{pulse length}}$$

giving an effective statistical sample size $n_e = n_1 n_2$.

The accuracy can be shown, at the 95 per cent confidence limits, to

$$\pm 1.96 \left( \frac{5.57 \text{ dB}}{n_e} \right)$$

The equations indicate that pulse length, PRF and the antenna scanning rate have an important bearing on the accuracy of the contours. Weather radars should therefore have provision for normal use of pulse lengths of the

![Figure 20 - Video Integrator and Processor](image_url)
order of $1 \mu$ sec, and antenna rotation speeds of 2-4 per minute, depending upon the desired accuracy of the contours. The averaging interval in range must be kept relatively small to minimize smoothing of small areas of strong signals and subsequent loss of important data. A cursory examination of the size of hail areas within thunderstorms has shown that frequently the hail area in an echo may be 1-2 km in diameter, therefore the increment of range over which averaging is performed should be kept to 1-2 km to reduce the probability that a hail area may not be observed. Further details of the averaging technique and accuracy may be found in references (1) and (2).

4.2.2 VIP design

The VIP is designed to display echo contours for ranges between 10 and 125 nautical miles. Figure 20 is a simplified functional block diagram. The video signal from the logarithmic receiver is amplified and integrated and subsequently coupled to six operational amplifiers operating as level sensors. The output is fed through the normal video circuits. Correction of signal amplitude as a function of range (the $\frac{1}{r^2}$ factor in the radar equation) is performed in the radar receiver system. The range correction circuit, usually designated as STC, must be correctly calibrated.

In addition to the appearance of the contours on the PPI and RHI displays (Figures 21 and 22), the console operator is provided with visual indication (summary lights) of all signal levels present during each rotation of the radar antenna. A level selector feature allows the console operator to select a particular level for display. In this mode of VIP operation the selected contour is displayed at full video brightness.

Ground clutter is essentially eliminated by blanking all signals between 0 and 10 miles range. When necessary, the blanking range can be extended to 15 miles or more.

4.2.3 Test and evaluation

Numerous tests have been conducted on the VIP (3). Analysis of the WSR-57 and VIP operating as a system pointed out the following assumptions that must be valid for maintenance of the accuracy of the echo contours: (a) The response characteristics of the radar receiving system must not change excessively with time; (b) the inverse square law range correction provided by the sensitivity time control (STC) circuitry provides the desired range compensation, provided it is properly calibrated. Overall system accuracy (radar and VIP) is of the order of 4-5 dB.

4.2.4 Automatic data processing

The VIP output is in the form of a fixed voltage for each contour level. Conversion of this signal output to digital form suitable for automatic computer processing has already been accomplished (4); a great deal of work is necessary, however, before such processing can be done in weather stations. Communication systems, computer processing time, and dissemination of analysed products requires a considerable investment of money. The technology is available.

4.3 Transmission of radar information

4.3.1 Experience of the Meteorological Service of the U.S.A.
4.3.1.1 Introduction

Communication of radar data has been a serious problem since weather echoes were first observed in the early 1940s. A large portion of the radar intelligence cannot be retrieved for transmission to remote locations. Although numerous codes and word messages have been devised and used, none can be considered as a satisfactory means for relaying radar data.

Until recent years, the cost of provision of displays in offices more than about one kilometre from the radar has been prohibitive and only a very few long-distance remoting links have been established.

The World Meteorological Organization Technical Note No. 78, “Use of ground-based radar in meteorology” (pages 30-33), contains a summary of various types of radar remoting equipment. The U.S. ESSA Weather Bureau has purchased a number of units of the equipment described as Type IIC entitled “scan-converted slow scan”. The following sections describe this equipment. A detailed description may be found in reference (5).

The design criteria for this remoting equipment included the following:

(i) Cost must be less than that of weather radar;
(ii) Provision must be made for remoting of the Plan Position Indicator display;
(iii) There must be a method for insertion of echo interpretive material such as height, intensity and movement;
(iv) Display at the remote terminal must be in a lighted room;
(v) The signal must be transmitted over 3-kHz telephone lines or by radio;
(vi) Display at the remote terminal must be close to real time;
(vii) The system must be capable of simultaneously serving a number of different locations;
(viii) Remoting distance should be at least 500 miles.

Figure 23 – Remoting system information flow
Although originally designed for television display at the remote location, facsimile recorders have also been designed to serve as the receiving unit. The facsimile offers the advantage of a paper copy which can be used to study the past history of observed echo patterns and low-cost receiving equipment.

Figure 23 is an information-flow diagram of the remoting system. Of greatest importance to meteorologists is the provision for entry of hand-written interpretive data by use of the data-insertion device.

4.3.1.2 Equipment description

4.3.1.2.1 Transmitter unit

The transmitter consists of a PPI repeater display, data-insertion device, television camera and suitable modulator unit. The TV camera utilizes a tube having a relatively long storage to permit continuous read-out at the slow-scanning rate in rectilinear co-ordinates. The resultant narrow-band video (0-2,000 Hertz) is mixed with line- and frame-synchronizing pulses and then modulated onto a 2,400-Hz carrier. Using a 7.5-Hz line rate in a progressive scan, it takes 100 seconds to scan one complete PPI picture. After passing through a low-pass filter, the lower sideband plus carrier (vestigial transmission) is then transmitted on a nominal 3-KHz telephone line to the receiver sites. The total bandwidth required by the modulation envelope using the above technique is 400 Hz to 2,800 Hz.

4.3.1.2.2 On-line monitor

This unit contains a seven-inch direct-view storage tube to permit viewing of the PPI and hand-written data as transmitted over the telephone lines. The display is very useful in the weather office since echoes may be viewed with respect to geographic features such as rivers and coast-lines and the political boundaries, which are included in the data-insertion device. Images may be stored up to 15 minutes when transmission of video data is interrupted. Interruptions may occur when the radar antenna is scanning in the RHI mode or in manual PPI sector scanning.

4.3.1.2.3 Receiver

In the receiver, the video signal is recovered using demodulation techniques. The line and frame synchronization are separated and reconstituted from the demodulated video signal. The resolution requirement is 125 range rings per radius or 500 TV lines.

Display of the video data may be in one of three modes:

(a) The receiver may consist of an on-line monitor;

(b) A closed-circuit television camera may view an on-line monitor display. Standard television monitors may then be attached to the camera to permit simultaneous viewing in a number of separate rooms in a building;

(c) An 11-in. facsimile recorder may be modified to record the data.

No other electronic equipment is needed at the receiving location. Provision must be made to include a date-time indication in each frame of the recorded data. To reduce facsimile paper consumption, a timer may be used to limit operation of the recorder.
Figure 24 — Remoting outlets from Galveston radar

Figure 25
4.3.1.3 Operation

The original concept of using leased private telephone lines of facsimile quality has proven to be quite satisfactory. Data may be transmitted continuously to a large number of users. Figure 24 illustrates the locations of receiving equipment in the Houston-Galveston (Texas) area.

A second option has also proven to be satisfactory. Dial telephone calls may be used instead of leased lines. To use this arrangement, a device must be installed between the transmitter and receiver and the line. In the U.S.A. the device is called a Model 602C Dataphone and is obtained on a rental arrangement with the telephone company. Figure 25 illustrates a recording made 2,000 miles away from the transmitter. The major problem found in this arrangement is the quality of the telephone line system. If voices or other noises are heard on the line, the remote display is badly cluttered and may be unusable.

4.3.1.4 Maintenance burden

The equipment design utilizes solid-state concepts wherever possible. Experience after a cumulative total of approximately six years shows that the transmitter and receiver each require approximately 0.25 man-years per year. The cost of replacement parts is a few hundred US dollars per year plus approximately one direct-view storage tube for each on-line monitor and receiver, at a cost of about US $1,600 each.

4.3.2 Experience of the Meteorological Service of Japan

4.3.2.1 History and background

The weather radar network in Japan has been developed in the past fifteen years, and is now almost completed, covering the whole country with sixteen radars. In the first stage of the development, the main applications of radar were the tracking of typhoons and severe storms.

Recently, the requirements for timely and detailed radar information have increased considerably, reflecting the rapid development of industry, electricity plants and transportation.

Owing to the high-density population and the locality of severe weather in the mountainous islands, each of over fifty local forecast centres in every prefecture is responsible for the dissemination of warnings and advisory messages for the public in its own prefecture.

Meanwhile, the forecasters in the international airport and the area control centre require radar data transmission in the real-time mode, while a number of small domestic airports require the timely transmission of limited radar data, although less frequently.

Since a radar must conform to the various above-mentioned requirements of the different users simultaneously, a compromise would be inevitable from the economical standpoint.

4.3.2.2 Reasons for adoption of telephone facsimile

A number of remoting systems have been used for trials such as repeater scope and microwave relay, photographic facsimile and UHF or VHF wave, IT and microwave, slow-scan videcon camera and microwave, telephone facsimile and telephone writer.
The telephone facsimile system was finally found to be the most suitable means for radar data transmission on a nation-wide scale because:

(i) Radar data can be transmitted simultaneously to ten or more stations;
(ii) Radar sketches including echo interpretive remarks can be sent without reduction of original size;
(iii) Cost of the equipment is not expensive (less than 15 per cent of that of radar);
(iv) Equipment is easily available, simple and stable;
(v) The signal can be transmitted over 3-KHz telephone line, and dial telephone call is permitted;
(vi) Paper copies can be made from a semi-transparent receiving paper for distribution;
(vii) Original paper can be used with the same scale as that of the weather charts at the forecaster’s desk;
(viii) Additional use of the slow-scan converting system may be feasible over the same telephone line in the future.

4.3.2.2.1 Description of the equipment

A number of different kinds of facsimile have been mass-produced. The main specifications of the equipment selected for radar data transmission are as follows:

**Transmitter**

<table>
<thead>
<tr>
<th>Equipment size</th>
<th>770 × 335 × 420 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective picture size</td>
<td>275 × 420 mm</td>
</tr>
<tr>
<td>Drum diameter</td>
<td>92 mm</td>
</tr>
<tr>
<td>Scanning line density</td>
<td>3 lines / mm</td>
</tr>
<tr>
<td>Transmission time</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Drum speed</td>
<td>125 rpm</td>
</tr>
<tr>
<td>Power consumption</td>
<td>100 VA</td>
</tr>
</tbody>
</table>

The effective size of the picture is sufficient to send a radar sketch of full size. Transmission time can be reduced by changing the line density.

**Receiver**

<table>
<thead>
<tr>
<th>Equipment size</th>
<th>480 × 420 × 545 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective picture size</td>
<td>Same as transmitter</td>
</tr>
<tr>
<td>Recording system</td>
<td>Discharge disruptive system</td>
</tr>
<tr>
<td>Minimum input level</td>
<td>-30 dB</td>
</tr>
<tr>
<td>Allowable input level fluctuation</td>
<td>-10 to 25 dB</td>
</tr>
<tr>
<td>Power consumption</td>
<td>200 VA</td>
</tr>
</tbody>
</table>

**Impulse sender and operating panel**

Radar data can be transmitted simultaneously to a large number of users with this device.

The cost of the equipment is less than 20,000 US dollars; that of the receiver only is 4,000 US dollars.

4.3.2.2.2 Information flow over telephone line

Radar data are sent to the forecast centres and the airports by commercial telephone-line link as shown in the flow chart of Figure 26. Leased line should be used partly from weather stations to telephone offices in the same town. However, the distance of the leased line is quite short compared with the dial call line. The frequency of busy lines is less than one per cent. The charge of the dial telephone line is on the next page.
4.3.2.2.3 Operation

In accordance with the standard procedure for radar observations in Japan, the observed radar data are finally expressed in a detailed sketch on transparent tetron film paper overlaid on the PPI scope. Map, range and azimuth marks, stations and contours of radar shadow are printed on the film paper. A unified scale is used for the radar map and the sectional weather map throughout all stations.

Reflectivity of the echo pattern is expressed in two or three shades with coloured pencils using the iso-echo contouring device or reducing receiver gain. The intensity and height of the significant echoes, the movement, tendency and the other necessary annotations are also given on the film paper. RHI sketches can be drawn in the corner of the paper, if necessary.

Simplified sketches in black pencil are prepared by making a copy of the original sketch to serve for the telefacsimile transmission. In future plans, the sketched copy will be used in a data centre for microcopy or printing (see Figure 27).

The received facsimile paper as shown in Figure 28 has the same size as the sectional weather chart and is easily understandable, without ground clutter. It can be overlaid on the local weather chart at the tracing desk for the convenience of forecasters' use. At the airport the sketch copy can be used for briefing and reproduced for distribution.

4.3.2.3 Telephone writer

4.3.2.3.1 Introduction

The telephone writer has been successfully used for radar sketch transmission over leased telephone lines from a radar station to a nearby local airport for domestic lines in Japan.
Figure 27 – Simplified sketch for facsimile transmission
Figure 28
Urgent need for radar data is not often experienced in an airport having only several flights a day. However, timely transmissions of radar sketches of the limited area surrounding the airport are quite helpful for safe landing or take-off and for making decisions of whether to hold or to go to an alternative airport.

4.3.2.3.2 Equipment description

The telephone writer is originally produced for transmission of the written message over a wire, telephone or radio circuit.

Principles of the equipment are shown in Figure 29. The position of a writing pen in X-Y co-ordinates on the transmitter is converted to the voice signal by frequency modulation, in two separated frequency regions. The receiver pen writes the same figures, following the movement of the transmitter pen.

Principal specifications

Available writing area  . . 127 X 89 m
Weight: transmitter . . 6 kg
receiver . . 11 kg
Power: transmitter . . 10 watts
receiver . . 15 watts
Frequency . . . . 1,310-1,490 and 2,060-2,340 cps.

4.3.2.3.3 Operation

The echo pattern is drawn on a film overlay on which map and range marks are printed, by overlaying the film on the PPI scope or on radar sketches. Radar data are sent to the receiving stations by following the echo contours on the film with a transmitter pen and writing the necessary annotations such as height, intensity and movement of echoes.

At the receiving station, sufficient information on weather can be obtained by superimposing the same overlay as that used for transmission on the received echo pattern.
The sketched area can be chosen 30 to 200 km in length, depending on weather situations. Transmission time is only three minutes even with the most complicated echo pattern.

4.3.2.3.4 Remarks

Experience at the local airport shows that a transmission frequency of approximately eighty per month is enough to satisfy the needs of air traffic operations for radar data.

Information sent by this method is also satisfactory and especially helpful in the case of thunderstorms, low visibility in snow showers and strong cross-winds with frontal passage.

The merits of this remoting system are:

(i) The equipment is easily available, simple and stable;
(ii) The cost of the equipment is less than 600 US dollars and that of expendables is quite low;
(iii) Supplementary comments and requests can be exchanged by voice over the same leased line;
(iv) Paper copies are easily obtained for distribution and study of past weather.

REFERENCES


CHAPTER 5

TRANSMISSION OF RADAR INFORMATION TO AIRCRAFT IN FLIGHT

5.1 General

One of the most important problems which the radar-meteorologist has to face up to is the transmission of radar information. Unfortunately, the problem is complex, due to the temporal and spatial variability of echoes. In the particular case of providing safeguards for aircraft, the problem is more complex, due to the necessity for quasi-immediate dissemination of the data. The limitations imposed by the present means and procedures for air-ground communications mean that the requirement is inadequately met.

In a general way, the problem of the transmission of radar data should be considered both from the standpoint of the maximum acceptable time of transmission and the frequency of the transmissions. The time of transmission depends essentially on the characteristics of the means of transmission which is used and on the preliminary processing operations to which the raw data, given by the radar, are subjected (e.g. integration of video signals, conversion of co-ordinates). The frequency of transmission should be determined, taking into account the spatial and temporal variations of echoes which depend on the precision in determining the position of echoes which is necessary for any given purpose.

In the case of aviation, two types of use have to be considered:

Use in the neighbourhood of an aerodrome with a view to facilitating approach, landing and take-off operations;

Use on a larger scale, in order to safeguard aircraft in flight and for flight planning.

5.1.1 The first type of operation requires very precise data and, in consequence, taking into account the variability of observed phenomena, leads to the adoption of rapid transmission and frequent up-dating of these data. The minimum time allowed by techniques for distribution of data would be the ideal solution. However, for financial reasons, this solution is not always practicable and a compromise must be reached. The latter generally prompts the adoption, for the picture transmission, of some display using a telephone line, the pass band of which prescribes a minimum transmission time for a given resolution. Such a display can be regarded as giving the possibility of transmitting a whole PPI or RHI picture with sufficient precision in less than two minutes.

The WBRR equipment used by the U.S. Weather Bureau gives an excellent example of this feasibility (transmission time for a PPI picture: 90 seconds; see paragraph 4.3.1).

5.1.2 The second type of use does not require such great precision in the localization and in the determination of the intensity of the phenomena; thus the transmitted information remains valid for a longer period, which fixes the frequency of data renewal to be adopted. Hence a longer time for data transmission can be satisfactory for this type of operation. In practice, this allows the use of semi-automatic procedures such as the transmission by medium-speed facsimile of the picture obtained from the radar scope when the shape of the echoes is reproduced on a transparent paper (see paragraph 4.3.2.1).
5.2 Example of practical methods for the transmission of radar information to aircraft in flight (Methods and procedures in use, or which have been tried, in the U.S.A.)

Although most large passenger-carrying aircraft are equipped with weather radar, many smaller aircraft are not. Usually pilots of the smaller craft avoid areas of thunderstorms, but occasionally situations develop in which a pilot may need assistance in order to avoid unintentional flight into convective storms. Additionally, the radar-equipped aircraft occasionally need assistance. Several methods of transmitting weather-radar data to pilots have been tested in the U.S.A. with varying degrees of success. It is important to understand that ground personnel do not assume responsibility for direct instructions to pilots to fly on specific courses (vectoring); rather, the methods described below have attempted to give the pilot data on the location of thunderstorms so that he may make a decision on the specific route to be flown.

5.2.1 Coded messages

The standard U.S. radar report which may be relayed by radio gives a general word-numeral summary of the location of areas, lines or cells and the relative location in azimuth and range from the ground-based radar. These messages may be used to describe the general echo pattern, intensity, height, and movement, but generally the information is not sufficiently detailed to permit selection of routes through an area of echoes. These radar reports are prepared hourly when precipitation echoes are observed and may be broadcast with the general weather data, or on special request from a pilot.

5.2.2 Direct pilot-to-forecast service

Experiments with this method have been conducted under two different arrangements.

In the first instance, the forecasters were located in the weather forecast centre. When pilots wanted weather information, they contacted the forecaster on an assigned radio frequency. Information on general weather conditions, such as observed terminal weather, was transmitted as requested. In addition, a PPI repeater display from the nearby weather radar was used by the forecaster to advise the pilot of the specific location of echoes along the specified flight path.

In the second instance, the forecasters were located in the traffic control facility. Repeater scopes from nearby weather radars and the traffic control radars in the centre were used by the forecaster for relay of information, once again on radio frequencies used solely by the forecaster. Although both systems were effective, neither have been implemented in the U.S.A.

5.2.3 Broadcast of the PPI display using television techniques

Arrangements were made in the north-eastern U.S.A. for temporary utilization of a UHF television channel for continuous broadcast of a traffic control radar display. A small portable television receiver was installed in the cockpit for the pilot’s use. All data included in the PPI display, i.e. aircraft targets, weather, video-map, were displayed to the pilot. The system was tested for several months but abandoned because it was found that the pilot had a great deal of difficulty in identifying his aircraft target and following it across the PPI display. Precipitation echoes would frequently obscure the aircraft target and the pilot could not locate himself with sufficient accuracy to allow use of the display for planning the flight. The experiment was subsequently abandoned.
5.2.4 Direct assistance to controllers

Recently, weather radar personnel have been assigned to three Air Route Traffic Control Centres (ARTCC) in the western U.S.A. for the purpose of extracting weather echo data from the traffic control radars. The weather echo data are then disseminated from the centre by facsimile and teletypewriter messages.

The weather staff also assists the traffic controller in the interpretation of the weather echoes, for use during radio contacts with pilots. In turn, the controllers are frequently requested to obtain pilot reports in specified areas to aid in interpretation of the radar data and to supplement weather observations obtained from other sources.

5.3 Example of practical means for the transmission of radar information to aircraft in flight (Australian example)

Since 1963, very considerable efforts have been made in Australia with a view to keeping aircraft in flight informed of the position and nature of zones of turbulence.

Without entering into details of the organization which has been set up for the purpose (project JACMAS (for Joint Approach Control Meteorological Service)) we shall show how information based on weather radar data is made available for both pilots and air traffic controllers. Instructions to keep clear based on this information are mandatory in the stacking area and within a radius of 10 nautical miles from the aerodrome. Elsewhere, these instructions are advisory only. For the principal air routes, the characteristics of zones of turbulence are recorded on an endless magnetic tape and broadcast on radio wavelengths for air traffic control.

Details of this very interesting experiment can be found in a document presented by P. A. Barclay at the Conference on Weather Radars at Montreal, 1968 (Proceedings of the 13th Radar Meteorology Conference, PP. 439-441).
CHAPTER 6

NEW TECHNIQUES

Introductory remark

In recent years, important studies have been made with a view to improving measurements made by means of radar using either two sets of equipment having different wavelengths or a single set of equipment using two wavelengths. The most important work in this field has been undertaken in the U.S.S.R.

This chapter sets out, through the various experiments conducted in that country, the various possibilities of this comparatively new technique. It also shows, in the second part, the difficulties we come up against when we try to determine height of cloud base by means of radar, even when the latter has two wavelengths.

6.1 Possibilities in the use of radar with two wavelengths for meteorological purposes

The amplitude of echoes given by precipitation and cloud on radars using a single wavelength provides us with rapid information on the position, area, displacement and development of centres of thundery activity and showers. The spectrum of fluctuations in the amplitude of radar signals can also provide information on air movements in zones in which there are cloud droplets or droplets falling as precipitation. Due to the special nature of the relationship between the amplitudes of the echoes and the dimensions of the diffusing droplets (sixth power of the diameter), however, determination of the intensity of precipitation or of the water content of cloud by radar with a single wavelength still remains very imprecise.

We know, in fact, that, since the distribution of the dimensions of the raindrops can vary appreciably from one instance of precipitation to another, the relationship between the intensity of precipitation, \( R \), and the reflectivity, \( Z \), is not constant. Thus the coefficients in the general relationship \( Z = AR^b \) vary over wide limits for different occasions of rainfall, \( A \) lying between 60 and 800 and \( b \) between 1.1 and 1.9. The error due to this variability in the \( Z/R \) relationship, may, in extreme cases, amount to several hundred per cent. The decrease in the wavelength of the radar gives rise to other sources of error, the principal of which are the inadequacy of Rayleigh's approximation and modification of the amplitude of echoes due to phenomena associated with attenuation. An improvement in the measurements of the intensity of precipitation and the water content of clouds can be obtained by using the relationship which exists between the latter two quantities and the attenuation. Unfortunately, it is practically impossible to determine the attenuation with a radar with a single wavelength. Methods of measurement based on the use of calibrated targets can only be used for research work and the introduction of an assumption of a constant reflectivity over the whole path of the radar wave considerably reduces the value of such measurements.

On the other hand, we can, relatively simply, make a precise determination of the attenuation of the radar waves in cloud or in precipitation, using a radar with two wavelengths. Even though, in the present state of the technique, this measurement is only possible in zones of limited dimensions, the information obtained enables the meteorological information given by the radar to be improved upon and usefully extended. Using a radar with two wavelengths we can, in fact, obtain information which can be used to:

- Determine the water content of clouds formed of liquid droplets;
- Improve the \( Z/R \) relationship;
Determine the parameters of Marshall’s law of distribution \( N(D) = N_0 \sigma^D \);
Estimate the nature of the droplets in clouds and show up probable regions of icing.

We shall look into the principles of the measurements of attenuation in cloud or precipitation, based on a comparison, along the entire length of the radar path, of the amplitude of echoes given by two wavelengths having different coefficients of attenuation.

Let us suppose that, in the construction of the radar, the following conditions are fulfilled:

The same axes and the same radiation diagrams for the antennae for the two wavelengths;
The same impulse width and the same frequency;
Integration of the amplitude of the signals received on the two wavelengths (fluctuations eliminated).

The path for measurement is shown in Figure 30. It is situated in the zone ab, giving a radar echo for the two wavelengths. The signals are integrated to eliminate fluctuations. The radar with a long wavelength is little affected by attenuation, but the same does not apply to the radar with a short wavelength. Figure 31 shows the variation of the mean signal strength as a function of distance for the two wavelengths under consideration. Let \( P_{1m} \) be the strength of the echo given by the long wavelength at the beginning of the path; \( P_{2m} \) that at the end of the path; \( Z_{1m} \) and \( Z_{2m} \) the corresponding reflectivities; \( Z_{1a} \) and \( Z_{2a} \) the values obtained with the shortest wavelength; \( R(r) \) the distribution of the intensity of precipitation along the path; and \( \Delta l \) the length of the path ab. The strength returned by precipitation from point a for the longest wavelength may be written in the form:

\[
P_{1m} = C_1 \frac{Z_{1m}}{r^2} \cdot 10^{-0.2K_1} \int_0^r R(r) \, dr
\]

where \( C_1 \) is a constant determined by the characteristics of the “long wavelength” channel of the radar, \( K_1 \) is the attenuation coefficient for long waves, and \( r_a \) the distance between point a and the radar.
1. Mean distribution of the radar echo over the path (long-wave)
2. Mean distribution of the radar echo over the path (short-wave)

Figure 31

Under the same conditions, the strength received at the end of the path is:

$$P_{2n} = C_1 \frac{Z_{2n}}{r_b^2} 10^{-0.2K_n} \int_0^{r_b} R(r) \, dr$$  \hspace{1cm} (11)

In the same way, if $r_b$ is the distance between $b$ and the radar, the strength of echoes received at the beginning and at the end of the path for the shortest wavelength is:

$$P_{1n} = C_2 \frac{Z_{1n}}{r_b^2} 10^{-0.2K_n} \int_0^{r_b} R(r) \, dr$$  \hspace{1cm} (12)

$$P_{2a} = C_2 \frac{Z_{2a}}{r_b^2} 10^{-0.2K_n} \int_0^{r_b} R(r) \, dr$$  \hspace{1cm} (13)

From equations (10), (11), (12) and (13) we obtain $b$, the mean relative attenuation for propagation in rain along the path $ab$. Calculations and experimental data due to Godard (1) have shown that for a wavelength of 0.86 cm, the attenuation in precipitation is directly proportional to its intensity. If this is used, the result is that we obtain for the mean attenuation and the mean intensity of precipitation expressions which are extremely simple:

$$b = 5 \left( \log \frac{P_{1n} P_{2a}}{P_{2n} P_{1a}} - \log \frac{Z_{1n} Z_{2a}}{Z_{2n} Z_{1a}} \right)$$  \hspace{1cm} (14)

$$R = \frac{5 \left( \log \frac{P_{1n} P_{2a}}{P_{2n} P_{1a}} - \log \frac{Z_{1n} Z_{2a}}{Z_{2n} Z_{1a}} \right) \Delta l}{(K_2 - K_1)}$$  \hspace{1cm} (15)
In clouds where the droplets are small compared with the wavelength and for which Rayleigh's approximation applies, \( Z_{in} = Z_{1a} \) and \( Z_{2n} = Z_{2a} \), and equation (15) can be simplified to:

\[
\frac{5 \log \frac{P_{1n}}{P_{2n}}}{P_{2a} P_{1a}} \frac{P_{2n}}{P_{1n}} \sim R = \frac{A}{\lambda(I(K_2 - K_1))}
\]

(16)

It will be seen that in equations (15) and (16) there are no terms which are a function of the characteristics of the radar or of the distance. Consequently, measurements can be made without calibrating the equipment and without applying a correction for distance. Since these latter operations give rise to errors, the accuracy of the final result is improved by eliminating them.

By making measurements of the attenuation and of the reflectivity along various portions of the path, with different values for the amplitude of the echo, we obtain a number of pairs of values for the intensity of rainfall and the reflectivity, for the long wavelength. If we have at least two pairs of corresponding values for \( Z_n \) and \( R_n \), we can calculate the coefficients in the equation \( Z = AR^b \).

In this way we obtain the following values for the exponent \( b \):

\[
b = \log \frac{Z_1 - \log Z_2}{\log R_1 - \log R_2}
\]

(17)

and for the coefficient \( A \):

\[
A = \frac{Z_1}{R_1} = \frac{Z_2}{R_2}
\]

(18)

Although these coefficients are determined from data for a limited part of the echo, the method can be extended to other centres of precipitation lying within the limits of the range of the radar. It is known that in the case of rain falling from a homogeneous air mass, the relationship between the intensity of rainfall and the reflectivity remains constant over a period of a few hours; consequently it is sufficient to carry out the procedure for the determination of the values of \( A \) and \( b \), 10 and 12 times within 24 hours. Pairs of corresponding values (reflectivity - intensity of precipitation) can also be used for the determination of the parameters of the distribution function of the diameters of rain droplets. According to Marshall this function is:

\[
N(D) = N_0 e^{\lambda D}
\]

where \( N_0 \) is the concentration of droplets of dimension "zero" determined by extrapolation, \( \lambda \) a parameter of dimension \( 1/D \), and \( D \) the diameter of the droplets.

It can be shown that, if \( A \) and \( b \) are known, \( N_0 \) and \( \lambda \) can be expressed as a function of the reflectivity of precipitation, as follows:

\[
N_0 = 1.26 \times 10^8 A^{-\frac{2.8}{b}} Z^{-\frac{2.8-1.8b}{b}}
\]

(19)

\[
\lambda = 31.6 A^{-\frac{0.4}{b}} Z^\frac{0.4(1-b)}{b}
\]

(20)

When it is necessary to know the concentration of droplets of a given dimension as a function of the reflectivity, for example, in order to detect regions which would be dangerous for flights by supersonic aircraft, this can be done by means of diagrams prepared in advance. As an example, we give a table showing the number of droplets per cubic metre, with diameters lying between 2 mm and 2.5 mm as a function of the reflectivity, using two different equations.

(a) Mean relationship for all rainfall: \( Z = 200 R^{1.6} \).

(b) Relationship \( Z = 400 R^{1.2} \), an equation which is typical for thundery showers.
We can easily see that there is a considerable variation in the concentration of large droplets when the $Z/R$ relationship is changed.

The attenuation of electromagnetic waves in the millimetre band, when propagated through cloud, diminishes sharply when the droplets crystallize, while the reflectivity varies but little. Consequently, zones of supercooled droplets in clouds formed of crystals will show up as zones of greater attenuation. A comparison of the PPI images obtained with the two wavelengths of the radar enable an estimate to be made of the nature of the droplets in the cloud.

### 6.1.2 Requisite characteristics of a weather radar with two wavelengths for the quantitative observation of cloud and precipitation

6.1.2.1 In order to make a valid comparison of echoes obtained from the two wavelengths, it is essential that the volumes contributing to the formation of the echo should be the same. This requires that, for the two wavelengths, the beam should have the same axis and same width and that pulses should have the same amplitude and same frequency.

6.1.2.2 The spectrum of fluctuations of the amplitude of the echo associated with relative movements of the particles causing diffusion varies considerably with the wavelength. Consequently, in order to avoid errors in measurements, it is necessary to integrate the signals over a sufficiently long period corresponding to reception of 1,500 to 2,000 pulses.

This number may also vary depending on the equipment or, more precisely, on the wavelength and on the frequency. In fact, the period of integration is chosen taking into account the coefficient of autocorrelation of the signal in such a way as to obtain an integration over a comparable set of values or equal to 100 statistically independent samples.

6.1.2.3 Formula (15) also shows the possibility of errors associated with variations in the granulometric spectrum of the elements giving rise to diffusion and with differences between the true law of diffusion and Rayleigh's approximation.

In a general way, the relative value of the error decreases as the length of the path increases. In practice, this length is determined by the capabilities of the radar on the shortest wavelength. In order to improve the accuracy of the results, this should therefore be increased to the maximum. It would probably be most rational to increase the sensitivity of the receiver, using integrating assemblies which, for pulses of a periodic nature, would give an
appreciable improvement in the signal-noise ratio. It is to be noted that the use of such circuits also goes to improve the quality of the measurements.

Measurement of absorption, using a radar with two wavelengths, can be made automatic. Applying equation (14), all that is necessary is to insert two systems of automatic control of the amplification in the reception circuits of the radar. The first control is to maintain the signal given by the longest wavelength, at the end of the path, at a constant level. The second control, inserted in the "short-wave" channel, is to ensure equality of the signals received at the beginning of the path on the two wavelengths.

Due to the action of these devices for automatic amplification control, the signal received on the "short-wave" channel at the end of the path is a function of the absorption to be measured. By amplifying this signal by means of a logarithmic amplifier, a continuous recording can be obtained. This has been done at the Central Aerological Observatory of the U.S.S.R. where the accuracy of measurements of rainfall intensity, obtained by determining the relative absorption sustained by the two wavelengths of the same radar, has been checked.

Thus, measurements made with a radar with two wavelengths, a modernized type MRL-1, have shown that errors are not large. The accuracy obtained corresponds to that of a raingauge network where the distance between each instrument is approximately 0.25 km.

6.2 Determination of height of cloud base by radar

6.2.1 Preliminary remarks

Information relating to water content, the nature (ice or water) and heights of base and top of clouds and intermediate layers is of considerable importance for service to aviation.

Most frequently, the most important of these is height of cloud base; in the case of the lowest clouds, this height determines landing conditions for aircraft.

This concept of height of cloud base is not based on a precise official definition and the results of measurements depend on the methods of observation, on the equipment and on the conditions under which observations are made.

It is probably most convenient to consider the height of cloud base as the height at which the pilot of an aircraft loses sight of the horizon, since the introduction of oblique or vertical visibility increases the importance of the effect of time of day and the effect of the nature of the next lowest layer. We shall examine the possibility of using radar for obtaining these data relating to clouds.

6.2.2 Clouds considered as radar targets

Clouds, as targets capable of producing radar echoes, and the possibilities of measurement of their characteristics by radar, have been studied in detail by Atlas and other research workers (5, 6). These authors have used radar for various purposes and the experimental data obtained show that it is possible to measure, at a distance, the main characteristics of clouds to a sufficient degree of accuracy for many practical purposes.

The observations have been supposed to have been made by means of a radar with a single wavelength and the reflectivity of the cloud has been supposed to have been determined from the strength of the radar echo.
With a view to determining the limits of accuracy of the measurements which can be made, observations of clouds have been made simultaneously by means of an aircraft equipped as an airborne laboratory and having a radar operating on a wavelength of 3 cm, at the Central Aerological Observatory of the Hydrometeorological Service of the U.S.S.R. Rather unexpectedly, the strength of radar signals from clouds has been found to be much greater than data from aircraft on the concentration and dimensions of the particles causing diffusion would lead one to expect. In addition, in many cases, a zone of echoes below the cloud, and sometimes extending to the surface, has been found.

The difference between the value for the strength of an echo as found by radar and the value determined from data from aircraft quite often exceeds 10 decibels. This difference cannot be explained by errors of measurement. In the zone below the cloud which, as regards intensity of echo, did not differ from the region inside the cloud, the observations by aircraft did not show any differences in visibility. The cause of disagreement between the data so obtained has been made evident since IRC equipment constructed by Nevzorov has been in operation. This equipment enables large zones within the cloud to be explored (9).

Analysis of the data obtained by means of the new equipment has shown the existence in the cloud of particles with large diameters. The concentration of these is low and their presence cannot be detected by ordinary methods. These particles which give rise to the main component of the radar echo given by the cloud are also the cause of the echo in the intermediate layers and below the cloud. These larger particles have practically no effect on either the visibility or the water content. Data obtained during the first experiments have often been confirmed in recent years by measurements from aircraft. The process of formation of the large particles, however, remains obscure. It is possible that they may form spontaneously.

No connexion has been found between the distribution of cloud droplets of normal dimensions and the concentration of large droplets, the temporal and spatial variation of the latter being chaotic. Data now available show, however, that the presence of large droplets in cloud is the rule rather than the exception.

The presence of large droplets in cloud, giving rise to the main component of the radar signal, while of no importance for visibility or water content, makes it impossible to determine these using the reflectivity given by a radar with one wavelength. Neither can there be any question of determining the height of the cloud base, for this is not marked by any discontinuity in the radar echo.

It is to be noted that, even in the few cases of clouds and fog not containing large droplets, the outlook for using radar with a single wavelength for the estimation of water content in the zone under observation is not at all favourable. In such clouds the reflectivity depends on their heterogeneous nature, the latter being associated with turbulence, which, as regards scale, is comparable with the wavelength of the radar. This has been demonstrated in the report by Nato and Atlas presented at the 12th Conference on Radar Meteorology.

There remains the possibility of using for the required measurements the relationship between attenuation of waves in the millimetre band and the water content of cloud. This attenuation can be determined by radar, working on two suitable wavelengths, e.g. 0.86 and 3.2 cm (see paragraph 6.1).

It should be added, however, that such measurements necessitate a very high degree of general sensitivity of the channel in the centimetre band and can only give accurate values of cloud base when the water content of the cloud is high.

We therefore reach the conclusion that in the present state of weather radar techniques, their use for measuring cloud base for the purposes of service to aviation cannot be recommended. It is probable that, with a lower expenditure, better results may obtained by the use of an optical device, lidar for example.
REFERENCES


No. 10  The forecasting from weather data of potato blight and other plant diseases and pests. P. M. Austin Bourke.

No. 11  The standardization of the measurement of evaporation as a climatic factor. G. W. Robertson.


No. 17  Notes on the problems of cargo ventilation. W. F. McDonald (reprinted 1968).

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