INSTRUMENTS AND OBSERVING METHODS

REPORT No. 8

METEOROLOGICAL RADARS

REPORT ON METEOROLOGICAL RADARS

by

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INTRODUCTION

The Terms of Reference found in Resolution 11 (CIMO-VII) will have been met to the best of my ability with the completion of this Report as CIMO Rapporteur on Meteorological Radars, except that

a. I have been unable, due to lack of time, to complete the preparation of the new WMO Technical Note

and

b. I have had no contact with the Working Group on Precipitation and Evaporation.

My earlier report in CIMO-VII/Doc.30, the first on ground-based weather radar for many years, set out the many developments which had taken place over a relatively long period. This report is inevitably shorter. Firstly, it has not been considered necessary to cover the same ground on basic aspects. Secondly, although there has been rapidly expanding activity over the last four years in many parts of the work and the expansion seems likely to continue in the foreseeable future—the main thrust, as far as equipment is concerned, has been in consolidation of ideas rather than in innovation. Nevertheless, some interesting and promising developments have taken place.

This report provides the technical background to my final report to the Commission which will appear in the CIMO-VIII/Doc. series shortly, and should be used by delegates to the eighth session of CIMO for their preparation on this subject.
1. THE STATUS OF CONVENTIONAL METEOROLOGICAL RADAR AS AN INSTRUMENT

The most significant feature of the period of this Report has been the growing realisation in many countries that conventional weather radar can be an extremely valuable meteorological and hydrological tool, despite shortcomings. Indeed, it is interesting to note changing attitudes towards weather radar. In the early 1970s, too much was expected from it; it was believed that it could measure precipitation not only with an accuracy unrivalled by any other means but also with an accuracy to permit fine decisions being made in flood warnings and water management. The findings from some limited experimental projects were taken to be applicable in a wider context. Unfortunately, as frequently occurs, the transfer from experimental to operational status emphasised that the shortcomings had been underestimated.

As a result, practising meteorologists and hydrologists have begun to look more closely at what radar, either on its own or with other "sensors," particularly satellites, can provide. It is now seen that "semi-quantitative" radar data are invaluable; that, providing the limitations are understood, they can be a vital input to flood warnings and to water management. Moreover, they permit subjective and objective forecasts to be made of precipitation over the next few hours (up to six or more) which can be more accurate than those made using any other data.

At the same time, the requirement to improve accuracy has not been forsaken. The better understanding of the reasons for inaccuracy is a major step towards correcting for them, but it seems likely that a long period of research and development may be necessary before truly quantitative measurements can be made—whatever the word "quantitative" can be taken to mean. Indeed, there are some circumstances—the mountains of Switzerland spring readily to mind—where it may never be possible to measure above the peaks what will actually fall on the ground below. On the other hand, some of the problems may be partially resolved by a growing understanding of the nature of the atmosphere itself and of the causes and effects of, say, low level growth or evaporation.

The original convention that the prime value of weather radar is to provide warnings of storms to aviation still applies in many countries. The methods of use of a Plan Positive Indicator (PPI) or Range-Height Indicator (RHI) in a forecast or briefing office are well-established and will not be discussed in this Report. Equally, the observation and tracking of tropical storms and cyclones with conventional radars is a well-established routine in the most vulnerable countries; there is little new on which to comment, except in respect of Doppler radars (see para 15).

One development of value in aviation forecasting is the availability of a three-dimensional colour display which represents the maximum levels of precipitation in that part of the atmosphere being scanned. The quantity of data which has to be handled is very large, but the steady advances in data processing at reasonable costs are making such systems more feasible. Whilst human interpretation of the pictorial representation of a particularly complex situation may be difficult, it is considered by some to be an advance on any previous format, and it may well be improved in time. Such a three-dimensional format could conceivably be applied to tropical storm observation, provided that attenuation was not too severe.
There is now an increasing number of well-documented cases of improved flood-warnings, in particular, and of water management, in general, resulting from the intelligent use of radar data. There are instances where small weather systems have been completely missed by a conventionally-spaced raingauge network. In fact, radars and raingauges should be seen as complementary, not in competition. The former are far better at measuring areal precipitation, the latter at making point measurements. It is now an accepted convention that gauges can be put to good use to "calibrate" the radar in real time; in other words, the accuracy of the radar can be improved by a small number of point comparisons with telemetered gauges connected to the processor. For this to be true, it is necessary for the gauge sites to be carefully selected and for any special circumstances, eg the presence of orographic rain, to be understood. Work is continuing on these matters in a number of countries.

Progress in the measurement of hail and snow is still well behind that of measuring rainfall; the same research effort has not been made. There is, however, every reason to believe that real advances will be made in the next decade. The detection of hail is of particular importance in those countries where precipitation enhancement projects have been set up, that is, where severe damage can be done by hail falling on valuable crops.

One of the more positive forms of progress since CIMO-VII has been in the merging or compositing of data not only from two or more conventional weather radars but also between radars, satellites and more common meteorological sensors (eg automatic weather stations). It is a further step to a "mesoscale analysis centre" where data from different sources can be displayed, merged where appropriate and modified by an experienced forecaster if necessary. In addition, merged radar data, with or without that from other sources, can be transmitted by conventional means (eg telephone lines) to other offices or to other countries.

The cost benefits of radar systems, either singly or in a network, cannot be accurately defined; certain aspects are unquantifiable. Nevertheless, in many regions, some justification is very clear in terms of the saving of property if flood-warnings or storm-warnings are advanced by even less than one hour. The value in human lives is usually inconsiderable. The benefits to be obtained in the construction and agriculture industries and in transport can be very large.

Documentation on meteorological radar is now considerable. Many of the papers have been generated by the Conferences on Radar Meteorology, sponsored by the American Meteorological Society. Whilst they are wide-ranging, they are mostly written by researchers and are sometimes diverse in opinions. They must appear formidable and discouraging to the increasing number of meteorologists and hydrologists who are turning to radar as an operational tool but who are unfamiliar with the theory and practice. A textbook such as Battan's "Radar Observation of the Atmosphere" (1973) deals most excellently with the theory but does little more than touch upon modern-day practice. WHO Technical Note No 76 "Use of Ground-Based Radar in Meteorology" was published in 1967 and is now quite out-of-date. A basic, comprehensive, operationally-oriented document is required, not only for the benefit of those who have not become involved in radar but also as a reference for those who have. A re-written Technical Note seems essential. Two useful and interesting papers for general reading are Browning (1978) and Wilson et al (1979).
In looking to the future, it can be reported that several countries are already planning new networks, mostly with conventional radars, some with Doppler radars as well. It is likely that more will do so in the next decade and exchange of radar data between neighbouring countries is probable. Advice will be required by those meteorological services which have not yet adopted radar systems. It is hoped that such advice can be provided by WMO in order that implementation may be achieved and common standards of performance reached.

Until radar systems and networks have been implemented and are producing data, it will not be possible to realize the full potential and to determine and solve the whole range of problems involved in accuracy. Nevertheless, the optimistic view is that, within the next two or three decades, the accuracy of radar will become such that it will be the major source of precipitation data which will be input to meteorological and hydrological models. These will provide precipitation predictions of a quality not at present envisaged, especially when merged with satellite data. However, much careful work will be required from radar meteorologists before this state can be attained.

Most of the preceding remarks refer to conventional (non-coherent) radars. There is the possibility, strongly supported by some leaders in the field, that the major step in the 1980s will be in the implementation of operational Doppler systems, particularly in those countries where severe storms are a recurring problem. Although work has continued over the last four years on the use of Doppler radar, it has not yet gone far beyond the research and development phase. Nevertheless, those countries intending to adopt it include some which wish to measure wind-shear on an operational basis as well as to observe severe storms more closely.

Whatever precise form operational radar development takes, there is an interesting period ahead for the radar meteorologist.

2. INVENTORY OF NEW DEVELOPMENTS

2.1 Commentary

a. A questionnaire on radar development was sent to all Member countries of WMO. The main purpose was to update the information provided by questionnaires for CIMO-VII. On this occasion replies were received from 47 countries, as against 61 four years ago. The number is disappointing. It is known that:

i. At least 23 of those countries which did not respond operate weather radars in some form. It is not thought that any of these radars are particularly sophisticated.

ii. Five of those who replied do not use weather radar.

iii. Some returns did not include all those radars used by other authorities in their countries.

b. It is estimated that there are now between 600 and 650 weather radars in use throughout the world. Of these, there are about equal numbers of C-band (5 cm) and X-band (3 cm) - some 200 each, with S-band (10 cm) slightly less. There are about 60 dual-wavelength radars, half "X-band/S-band," half "K-band/X-band." (K-band = 0.86 cm.) These are mostly used in USSR or in neighbouring countries.
c. It is uncertain how many systems include automatic processing and outputting of data; the number is probably between 50 and 70. In addition, well over 200 appear to have some measure of processing, either analogue or digital, beyond the conventional PPI/RHI displays.

d. The vast majority of new radars are either C-band or S-band; it is now accepted that, due to the attenuation produced by water drops absorption at 3 cm wavelengths, X-band radars have only limited value for precipitation measurement in most parts of the world unless used in a differential dual wavelength system depending on either reflectivity or attenuation.

e. It is noted that newly-installed radars have relatively narrow beamwidths, usually 1° for C-band, but up to 1.6° for S-band. (It is necessary to keep the beamwidth as low as possible in order that reasonable ranges can normally be achieved without

i. detecting large numbers of permanent echoes,

ii. intersecting the melting layer and thus producing enhanced returned signals,

and

iii. allowing the radar beam to be only partially filled by precipitation, resulting in the returned signals being lower in value than they should.)

f. About 18 countries are measuring precipitation directly by means of automatic processing. The number of automatic systems overall is probably between 50 and 70. The number of countries providing radar-derived integrated rainfall data for catchments and sub-catchments is very small, probably not more than five or six.

g. Seven countries merge data from more than one radar, though some of these achieve this by manual overlays, not by digital process. However a greater number of countries express the intention of doing so automatically in the future.

h. An even smaller group, four, merge radar data with that from satellites, whilst about eight compare the radar data on a regular basis with raingauge data, either in real-time or historically.

i. In my Report for CIMO-VII, I listed the General Developments made in equipment since mid-1960s. (See CIMO-VII/Doc 30, ADD.1, Appendix paras 7 and 8.) Over the last four years there is less that is new in concept to report. The increase in activity is mainly absorbed in putting into operational practice the ideas developed during the previous decade or in improving those areas which still require attention for instance, either in radar accuracy or in software.

2.2 Specific New Developments since CIMO-VII Report

a. SHARP. AES, Canada.

Objective pattern-matching forecast procedure using digital, horizontal slice radar maps with on-line computer.

(Bellon and Austin, 1978; Crozier, 1979; Bellon et al, 1980.)
b. European Weather Radar Project. COST 72, EEC, Brussels.

Study of technical and financial aspects of a co-ordinated approach to a Western European network. Study of wide-ranging aspects of measurement of precipitation by radar and exchange of data across national boundaries.

(Clift, 1981.)

c. Network plans. Deutschet Wetterdienst, FRG.

Plans for implementation of seven C-band radar network; problems and possibilities.

(Attmannspacher and Riedl, 1980.)


Comparisons of four ship-borne radar systems before and during GATE exercise.

(Hudlow et al, 1979.)


Single C-band radar system to permit water management for flood control and resource facilities.

(Kodama, 1978; Ishizaki et al, 1979.)


Use of two C-band radars with digital processing and three-dimensional displays in mountainous country.

(Joss, 1978.)

g. Short Period Weather Forecasting Pilot Project. Meteorological Office, UK.

Use of merged data from several radars together with data from satellites and, later, from more conventional sources also, in order to provide forecasts, principally of precipitation, for the period 0-6 hours ahead.

(Browning, 1980; Collier, 1980.)

h. FRONTIERS. Meteorological Office, UK.

Whole-system design approach with digital data handling from observational input to disseminated forecast product. Interactive video display with forecaster permanently involved.

(Browning, 1979 and 1981.)

Establishment of unmanned radar to provide quantitative precipitation data in real time for use in an operational hydrological forecasting system. Associated hydrological research.

(Collier, Cole and Robertson, 1980.)

j. D/RADEX (continued). NWS, USA.

DVIP, computer, 16 levels of intensity in radial bins to 125 nautical miles, conversion to cartesian grids, accumulated rainfall, estimates of echo motion, maximum intensities; determination of echo tops and of Vertically Integrated Liquid Water Content (VIL) values; severe weather package. Four radars currently in network.

(Saffle, 1976.)

k. Digital Radar Data HIPLEX. Bureau of Reclamation, USA.

Computer processing of data gathered as part of development of weather modification for precipitation management.

(Schroeder and Klazura, 1978.)

l. RADAP. NWS, USA.

System for automated collection, processing, display and communications, with operator interaction; for the improvement of short-term forecasts.

(Shreeve, 1980)

m. HEPAP. NWS, USA.

Hydrological rainfall analysis project.

(Greene et al, 1979.)

2.3 National Projects

(Note: projects, selected from returned questionnaires, of apparent greatest interest. Those reported for CIMO-VII not repeated unless significant progress or change.)

a. Australia

Fourteen radars type WF44 (10 cm, 750 kW, 3°, 0.35/1.5 μs, 275 pps) used for flash flood warnings, tracking and observing tropical cyclones in addition to conventional aviation and public service forecasting; studies of fronts and of storms carried out.

b. Canada

Five radars type WSR 507, previously reported, now in operation with SCEPTRE processing systems. Planning all-digital radar data transmissions. Planning to introduce Doppler for research in 3 years' time. In addition to five radars type FPS 101
c. China, People's Republic of China

14 (Radar type 711 (3 cm, 75 kW, 1.5°, 1 μs, 400 pps)
   " " 713 (5.4 cm, 250 kW, 1.3°, 2 μs, 200 pps)

Type 713 used for quantitative measurement.

d. Czechoslovakia

Two radars type MRL 2 (3 cm, 150 kW, 0.74°, 1 μs/2 μs, 600/300 pps)
One " " MRL 5 (3 cm, 250 kW, 0.5°, 1 μs/2 μs, 500/250 pps; 10 cm, 800 kW, 1.5°, 1 μs/2 μs, 500/250 pps)

Quantitative measurements carried out; also used for hydrological and research purposes.

Note: error in CIMO-VII Report: radar type RM, still in use, is 3 cm, not 9 as stated.

e. Finland

One radar type NRL 5 (3 cm, 250 kW, 0.5°, 1 μs/2 μs, 500/250 pps; 10 cm, 800 kW, 1.5°, 1 μs/2 μs, 500/250 pps)
One radar type MRL 2 (3 cm, 200 kW, 0.7°, 1 μs/2 μs, 600/300 pps)

In addition: one radar type RMT1-L.

Quantitative measurements and research projects carried out; also involved in data for warning system for acquaplaning.

(Sängbo, 1979.)

f. France

Five radars type TRS 2730 (5.4 cm, 250 kW, 1.25°, 2 μs, 330 pps)
Three " " DLM 10 (MELD1) (10 cm, 700 kW, 1.8°, 0.5/2 μs, 1000/250 pps)

In addition: 6 radars type ORP330 (overseas).

Quantitative measurements and research being carried out using TRS 2730 and MELD1; hydrological studies also in hand; dangerous phenomena being detected. Automatic processing of data from TRS 2730; digital transmission. Doppler radar used for research.

g. Federal Republic of Germany

Four radars type 200 RMT-2a (3 cm, 200 kW, 1.2°, 0.5/3 μs, 1200/200 pps)
One " " WR100-2 (5.4 cm, 250 kW, 1.6°, 2/3 μs, 250 pps)
Nine " " WR100-5 (5.4 cm, 250 kW, 1°/1.5°, 2 μs, 250 pps)

In addition: one type 41.

Quantitative representation of precipitation intensity; with either VIP or DVIP, one with computer. Transmission by telephone line. Operational Doppler under consideration.
h. Hungary

One radar type MRL-5 (3 cm, 250 kW, 0.5°, 1 μs/2 μs, 500/250 pps)
One " " MRL-1 (3 cm, 140 kW, 0.75°, 1 μs/2 μs, 600/300 pps)

Merging of data planned - between radars and between radars and satellites.
Development of new system commencing.

i. India

Development of automatic processing and DVIP in progress; for hydrological purposes also. Eight 10 cm radars used for cyclone detection and warnings.

j. Israel

One radar type WR-100-5 (5.4 cm, 250 kW, 1.6°, 2 μs, 1200/240 pps)
One " " 200 RMT-1C (3 cm, 200 kW, 1.65°, 0.5/3 μs, 1200/240 pps)

Automatic processing of data from 5.4 cm set; radar values compared with rain-gauges. In addition to quantitative measurements participation in Precipitation Enhancement Project. Development of colour display.

k. Italy

Two radar type 46C (5.4 cm, 250 kW, 1.5°, 2 μs, 300 pps)
One " " 43AX (3 cm, 75 kW, 0.6°/2.8°, 0.5/2 μs, 1000/250 pps)
Two " " M50 (3 cm, 35 kW, 0.6°/1.4°, 0.5/3 μs, 1200/200 pps)
Two " " M200 (3 cm, 180 kW, 0.6°/1.4°, 0.5/3 μs, 1200/200 pps)

Plans to use colour displays on 46C radars, coverage to 180 km, resolution 1 km. Reflectivity values being studied. One M200 radar used for hail detection and study of structure of Cb; real-time data processing. Five more type 46C on order.

l. Japan

Nineteen radars type JMA-MR (5.6 cm, 250 kW, 1.4°, 2 μs, 260 pps)
One " " JMA-KR78 (10 cm, 1500 kW, 1.25°, 3.5 μs, 160 pps)
Two " " JMA-AMR (5.6 cm, 100 kW, 2.6°, 1 μs, 1040 pps)
One " " MRI-KR (5.6 cm, 250 kW, 1.7°, 0.5/2 μs 280/896/1120 pps)
One " " CPM-5A (8.6 cm, 40 kW, - , 0.5 μs, 500 pps)
One " " TW-1011A (3 cm, 30 kW, - , 0.25 μs, 4000 pps)

DVIP for JMA-KR. Ground clutter rejector and turbulence detector for JKA-AMR. Studies for automated processing systems in progress. Radar-raingauge calibration under consideration. Radars used for fixing centre position of cyclones and observing associated rainbands. Three radars used for hydrological purposes and are for propagation v. rainfall. Doppler radar used for research.

m. Libya

One radar type RC5 (5.6 cm, 250 kW, 1.5°, 0.5/2 μs, 600/250 pps)

Interfaced to computer for display and hard copy unit. Data storage on disc.
n. New Zealand

Five radars type CR353 (10 cm, 600 kW, 2.8°, 2 μs, 350 pps)

Carrying out feasibility study on introduction of precipitation surveillance radars.

o. Pakistan

One radar type JMA 109A (5.6 cm, 300 kW, 1.4°, 2 μs, 250 pps)

Three " " 42/42A (3 cm, 75 kW, 0.6°/2.8°, 0.5/2 μs, 250 pps)

One " " WR100-5/WSR74 (5.4 cm, 250 kW, 1.0°, 3 μs, 259 pps)

Some automatic processing. Planning to introduce Doppler radar for operational purposes.

p. Philippines

One radar type TW-1163A (5.6 cm, 250 kW, 1.9°, 2.9 μs, 260 pps)

One " " JME-1182 (10 cm, 600 kW, 2.5°, 2 μs, 200 pps)

One " " WSR-57M (10 cm, 500 kW, 2.2°, 0.5/4 μs, 545/164 pps)

Four " " WSR-77 (10 cm, 500 kW, 2.2°, 0.5/4 μs, 600/150 pps)

One " " (Mobile) (3 cm, 3 kW, 1.9°, 0.05 μs, 400 pps)

Mobile radar for research and quantitative measurement.

Others used for detecting and tracking tropical cyclones.

q. Sweden

Six radars type 200 RMT-1C (3 cm, 200 kW, 1.2°, 0.5/3 μs, 1200/200 pps)

One " " 200 RMT-3A (3 cm, 200 kW, 0.65/3.5°, 0.5/3 μs, 1200/200 pps)

Digital automatic processing for transmission by switched telephone network. Planning for large radar network. Also to introduce Doppler radar for operational and research purposes and to improve precision measurements in areas of clutter.

r. Switzerland

Two radars type WSR-74C (5.4 cm, 250 kW, 1.7°, 2 μs, 259 pps)

One " " SFR (10 cm, 400 kW, 1.6°, 1 μs, 250 pps)

One " " Flt Gt (3 cm, 150 kW, 2.4°, 0.3 μs, 2000 pps)

Digital processing of WSR-74C, frequency-shift modem transmission of large data sets. Three-dimensional cartesian colour displays. Comparison with other sensors now; with satellites in the future. Considerable investigational work on accuracy, reflectivity, etc in mountainous regions. Other radars for quantitative measurement and research with colour PPI/RHI.

Considerable research with SFR in measurement of hail on basis of hail kinetic energy.
s. Thailand

One radar type WSR-74S (10 cm, 400 kW, 2.25°, 1/4 μs, 545/164 pps)
One " " 21/16C (3 cm, 25 kW, 10/18°, 0.75 μs, 3200 pps)
Two " " WTR 2 (5.6 cm, 75 kW, 1.6°, 2 μs, 400 pps)
One " " JMA118 (10 cm, 600 kW, 2.6°, 2 μs, 200 pps)

DVIP with WSR-74S: quantitative measurements of areal rainfall compared with existing network of raingauges.

Investigation into values of constants a, b.
Detection and observation of tropical storms and cyclones; predictions of tracks; trends of phenomena related to intensity; investigation of rain bands combined with synoptic situations for rainfall forecasting.

Tunisia

One radar type ORP 310 (3 cm, 8 kW, 1.5°, 2 μs, 500 pps)
One " " MELODI (10 cm, 800 kW, 1.15°, 0.5/2 μs, 1000/250 pps)

Comparison project with 25 raingauges to determine constants a, b.

United Kingdom

Two radars type 43S (10 cm, 650 kW, 2°, 2 μs, 275 pps)
One " " 43C (5.4 cm, 240 kW, 1°, 2 μs, 300 pps)
One " " 450 (5.4 cm, 250 kW, 1°, 2 μs, 300 pps)

(Also six 3 cm radars purely for local detection purposes.)

Automatic processing, transmission by telephone line, merging of data from four radars and with that from satellite; precipitation forecasts (subjective and objective) for 0-6 hours; research on accuracy. Plans for further radars.

Colour cartesian-form displays; storage of pictures for replay; sub-catchment totals.

v. United States

Fifty-one radars type WSR 57 (10 cm, 410 kW, 2°, 0.5/4 μs, 545/164 pps)
Eight " " WSR 74S (10 cm, 556 kW, 2°, 1/4 μs, 545/164 pps)
Sixty-two " " WSR 74C (5.4 cm, 250 kW, 1.6°, 3 μs, 265 pps)
Seventy " " FPS 77 (5.4 cm, 350 kW, 1.6°, 2 μs, 186/324 pps)

Four station network with automatic processing, DVIP and cartesian colour or alphanumeric displays; output by telephone line. Accumulated rainfall. Cartesian grid map display of location and height of all echoes. Grid map display of Vertically Integrated Liquid Water Content (VIL) values to aid in identifying potentially severe echoes. Experiments to forecast motion of echo fields. Severe weather package.

Many research projects with radars in addition to those listed.

Planning to introduce Doppler for both operational and research purposes.
w. USSR

Thirty type MRL-1 (3 cm, 210 kW, 0.7°, 1/2 μs, 600/300 pps; 0.85 cm, 65 kW, 0.7°, 1/2 μs, 600/300 pps)
110 " " MRL-2 (3 cm, 210 kW, 0.7°, 1/2 μs, 600/300 pps)
25 " " MRL-5 (3 cm, 210 kW, 1°, 1/2 μs, 500/250 pps; 10 cm, 510 kW, 1.5°, 1/2 μs, 500/250 pps)

Automatic processing equipment designed and brought into operation; transmission by telephone line; some merging of radar data, also with data from satellites and from conventional meteorological sources.

Doppler in use for research purposes.

x. Yugoslavia

Eight radars type RG-34A (10 cm, 400 kW, 2°, 2 μs, 200 pps)
One " " MRL-1 (3 cm, 250 kW, 0.3°, 1/2 μs, 600/300 pps; 0.86 cm, 65 kW, 0.19°, 1/2 μs, 600/300 pps)
Twenty " " No 3 Mk 7 (10 cm, 200 kW, 4.5°, 0.55 μs, 1500 pps)

Data composited with that from other meteorological sources. Major interest in hail suppression project. Planned to introduce Doppler for operational work and for research.

3. NEW TECHNIQUES AND APPLICATIONS

The major new techniques developed or adopted since CIMO-VII are set out below. They are relatively few in number but at least several of them may have a significant influence on the course of radar activity in the future.

One of the more interesting developments which has taken place is the facility whereby a cartesian-form radar picture can be seen three-dimensionally, in plan or in elevation from the front or from the side, the whole being shown on one colour television screen. Thus, a relatively comprehensive representation of the atmosphere being scanned can be displayed. As the main beneficiary from such a display is aviation, the values shown in pixels are maximum rather than mean precipitation. The picture is, of course, built up by a number of scans at different elevations, in the manner of CAPPI-graph. Seven levels of precipitation can be displayed. The maximum height is 12 km and the plan grid size is 430 x 400 km. (Joss, 1978; Crozier, 1979.)

Amongst interesting approaches to the problem of removing ground clutter from displays of precipitation is that being tried by the Japanese; this takes note of the difference in the form of echo from precipitation (of any type) compared with that from solid objects such as buildings or hills. Thus, in a manner rather similar to the Moving Target Indicator (MTI) system used to detect aircraft, criteria can be set in the computer program to select only what it is desired to see. This holds out some promise of advantage over methods of clutter cancellation wherein maps of unwanted echoes are stored and the areas affected are discounted in precipitation measurement, interpolated figures being included if statistically appropriate. It is not possible with the latter method to subtract the clutter from the overall echo to obtain precipitation for two reasons because:
a. the clutter echo is likely to be very much larger than that from precipitation

and

b. its value will increase to an unknown extent with wetting.

However, the MTI method has not yet been perfected, as it does not extract the whole of the clutter echo, though it does leave a more manageable residue. (Aoyagi, 1978; et al., 1980.)

A development which might lead to greater accuracy of precipitation measurement is one, being tried by a small number of countries, which depends on the shape of rain drops, (and of other precipitation particles). Rain drops, due to motion, are oblate, rather than spherical; thus, they will present a different echoing area to a horizontally-polarised radar beam from that to a vertically-polarised beam. A technique has been used experimentally to switch rapidly from one to the other with a high-resolution S-band radar. Within small volumes, estimated rainfall rates have been found to be more accurate than with conventional radars. At present, however, the distance to which measurement can be made is limited to 30 or 40 kms, which is quite unacceptable for operational purposes. It is not immediately clear how this will be increased, but the possibility cannot be discarded. The technique also permits clear indication of snow or hail. (Cherry et al., 1980.)

The measurement of Vertically Integrated Liquid Water Content (VIL) is being studied in the USA. It was one of the sub-projects of D/RADEX. The "zero-tilt" precipitation field (ie that measured with the radar antenna at or near to 0°) is of great significance in the prediction of severe weather; however, several research workers have determined that the integration of a thunderstorm's echo intensities through the whole storm's depth, that is, the VIL, is of greater significance as an indicator of severe thunderstorms. The difficulties of making VIL measurements with an operational system are three-fold. Firstly, there is the problem of finding sufficient time to make the vertical scans required whilst the radar is being used in a programmed PPI role. Secondly, there is a considerable data load to be handled - not in itself beyond the capability of a modern processor but rather a heavy burden to one dealing with a number of other tasks simultaneously. Thirdly, for the most accurate results, a radar with good resolution and a vertical scan programme with correctly-spaced intervals are required. In addition, it must be borne in mind that under the conditions when the measurements are of greatest significance, attenuation of the radar beam is likely to be at its highest; therefore the methodology is applicable only when an S-band radar is in use. (McCann, 1978.)

a. Though not strictly in the category of new techniques, work on accuracy continues in a number of countries. In CIMO-VII/Doc 30, Appendix, para 1.10, statements are made - too long to be repeated here, but shown in Appendix - as to the accuracy believed to be attainable in 1977. In 1981, no worker in the radar field is likely to make any higher claims. In the intervening four years much thought has been given to the reasons for the inherent inaccuracies and for the variations which occur. The most significant development has probably been the realisation of the effect of orographic rain (and resulting rain shadows). This can be demonstrated as a significant cause of differences between radar and raingauge readings. It places emphasis on the need not only to site calibration gauges carefully but also to understand, and to take account of, the processes which cause discrepancies. It is to be noted that the existence of a radar system or preferably of a network, allows studies in greater depth than before to be made of precipitation systems. (Funada et al., 1978; Collier, 1981)
b. Work continues in determining the optimum Z/R relationships, mostly by historical comparison of radar/raingauge measurements. Although disagreement exists, as demonstrated by study of the relevant papers, there is movement towards incorporation of real-time evaluation in operational programmes. Omitted from the CIMO-VII Report, the method of sequential analysis by Cain and Smith (1976) provides a good basis. For the present, however, most workers adopt standard values for a, b (in \( Z = aR^b \)), the most commonly used being 200 and 1.6 in temperate latitudes. Any adjustment to precipitation measurement by means of raingauge comparison then takes into account wrong assessment of a, b in addition to other possible sources of error. Greater accuracy, though still not satisfactory, is obtained by changing a, b according to the type of rainfall or precipitation. Wilson and Brandes (1979), in their valuable paper, state that "It appears that the primary causes of error in radar measurements of rainfall result from variations in the Z/R relationship caused by microphysical and kinematic processes that affect the drop-size distribution and drop-fall speeds. Drop-size measurements and radar rainfall error patterns indicate that the variations occur from storm to storm in a systematic and perhaps predictable manner. The radar tends to overestimate light rainfall and to underestimate heavy rainfall. The search for systematic error/patterns holds promise, but until such patterns can be unambiguously established it will be necessary to use gauges to adjust the radar."

c. The important problem of the "bright band," or the intersection of the melting layer, remains to be solved in operational terms. An interesting paper, Collier et al (1980), discusses a study of bright bands with a high-resolution 3-D radar. It suggested that such a radar "allows the automatic classification of observed echoes into showers, stratiform rain with bright band and ground clutter." Such radars are, however, primarily research tools. Browning (1981), in accepting that simple methods for identifying echo intensity associated with bright band have not succeeded, says that: "Part of the problem lies in the inhomogeneous distribution of precipitation which tends to obscure any simple signature due to the bright band alone, --- the best that can be expected is a rather crude correction." He believes that it will be easier to determine the effect of the bright band by using an interactive display, from which the forecaster analyst can then decide on a realistic bright-band profile and set up automatic correction procedures.

d. A further cause of inaccuracy to which greater attention is now being paid is the effect of radome losses. Although the existence of these and of beam distortion has been known to radar specialists for many years, the meteorologist has tended to ignore them - understandably, in view of other problems. It is now apparent that effects vary according to the material used and the finish, the size of the radome, its cleanliness and, obviously, the rate of rainfall. Wilson (1978) suggests that two-way attenuation due to rainwater on the radome seldom exceeds 1 dB even at rainfall rates greater than 40 mm/hr. On the other hand Kodaira (1980) calculates that for a C-band radar in a 5.5 m radome, at a rainfall rate of 40 mm/hr, the attenuation will be in the order of 3.6 dB. Experience in UK, as yet undocumented, is that losses can be as high as 5 dB at 80 mm/hr with a large, inflated radome unless care is taken to keep the radome clean and to ensure a high run-of characteristic of the surface. With a 6.7 m metal space frame radome, however, the loss is very much less, probably between the Wilson and Kodaira figures. Switzerland have emphasised the need for the radome material to be correctly matched to the wavelength of the radar.
The last four years have not seen much increase in the documentation on the measurement of snow. It may be that there is not the same interest in measuring either the amount of snow or its water equivalent, since it does not usually lead to immediate flooding. On the other hand it can have an immediate effect on airfields and highways. Collier and Larke (1978), in a study of a case during the Dee Valley Project, demonstrated that the estimates of areal snow depth using a calibrated radar are similar to those for areal rainfall, though, in order to avoid horizontal drift of snow between the radar beam and the calibration sites, the range was restricted to 50 km. On the evidence of this case, carried out in hilly terrain, the radar measurement of areal depth can be as near as 13% to that measured physically, unless there is surface melting when a much larger difference occurs. Boucher (1978) and (1980) describes measurements made in USA using X-band radars. He emphasises the difference in results obtained in dry snow falling through sub-zero temperatures and those obtained with snow falling through the melting layer. Also restricting results to within 50 km, he devised a program for the processor whereby he achieved close correlation with surface readings using a regression line for 166 data points. It seems from overall evidence that radar measurements are likely to be within ±20 to 30% of "ground truth" measurements. It may be possible to provide very short-term snow depth forecasts (eg for one or two hours) of sufficient accuracy for runway and highway warnings.

In recent years there has been more interest in detection and measurement of hail. Primarily because of damage caused to crops, Precipitation Enhancement Projects or Hail Suppression Projects have been undertaken with a view to preventing the build-up of ice crystals into hailstones of dangerous size. The method is to seed the clouds whilst the hailstones are still small and thus to encourage them to turn into water drops. Seeding, with silver iodide crystals, either by firing rockets (or by dropping from aircraft), is costly; therefore it is essential to observe, track and measure potentially dangerous hailstorms with some accuracy. In this a radar can be a valuable tool, though there are problems in measuring large diameter hailstones due to their high spatial and temporal variability. The results of experiments carried out by a number of workers are not uniform. One of the main difficulties is that an echo from rain can be so large that it is difficult to be sure what proportion is due to hail or whether hail is being detected at all. As many as 50% of cells which meet the criteria for seeding produced no hail in one experiment. Measurements have been carried out with single wavelength radars, dual wavelength radars, dual or circular polarisation radars and Doppler radars. S-band radars are virtually essential for a single wavelength radar due to the severe attenuation which shorter wavelengths can suffer. It is apparent that considerably more work is needed to establish usable techniques, but in Switzerland there has been some success in the comparison of S-band radar measurements with hailpad data. Hailpads consist of foam rubber plates covered with thin aluminium foil; they measure the kinetic energy of the hailstones which strike them. Recently, up to 335 hailpads were used with the hail cells at ranges to 40 km. Kinetic energies derived from the two methods of measuring were compared for 195 cells. The conclusions drawn from this and from previous studies (in Switzerland, USSR, USA, Canada and South Africa) by Waldvogel (1981) are as follows:

(1) **Hail Detection**

1.1 Hail cells can be detected at a very early stage in their development even with a simple X-band radar.
1.2 If the height of the 45 dBZ contour is more than 1.4 km above the 0°C Celsius level, the cell is a "hail cell."

Note that 45 dBZ means that $45 = 10 \log Z$, where $Z$ is defined as the radar reflectivity factor in the empirical equation $Z = aR^b$, $R$ being rainfall, a and b constants, and $Z$ itself is equal to $\sum D^2$ where $D$ is the drop diameter.

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

1.4 Different simple hail criteria from different places in the world look very similar.

(2) Hail Measurement

2.1 Heavy hailfalls can be measured with a simple 10 cm radar.

2.2 A generally valid relationship between the flux of the kinetic energy ($\Phi$) of the hailstones and the radar reflectivity ($Z$) exists.

$$\Phi = 5 \times 10^{-6} \times Z^{0.84}$$

2.3 The ensemble of hailstones during a heavy hailfall can be treated as Rayleigh scatterers.

2.4 Radar reflectivities due to rain or hail can be "separated" with a simple solution for time and/or area integrated quantities of large hailfalls.

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

2.6 Medium and light hailfalls are more complicated: the main problems are the separation of rain from hail reflections and the representivity of the hailpad measurements. (Waldvogel, 1981, et al 1979, 1980; Srivastava, 1977; Dye et al, 1976)

There is only one paper to mention since CIMO-VII on the subject of the detection of dust or sand storms. This calculates the dust storm radar detection range; it presupposes that dust particles can be treated as having reflectivity calculable in the same terms as precipitation particles. On this basis, an X-band will detect dust particles of effective scattering cross-section per unit volume of $10^{-13}$ cm to ranges of 120 km. However, such sizes are rare; ranges of 20 to 30 km seem more likely for dust sizes common in most parts of the world.

The application of conventional radars to detecting and observing tropical storms and cyclones was described in the CIMO-VII Report. There is nothing of consequence to add. The use of Doppler radar has been developed further in respect of studying the structure of storms. This will be covered in the appropriate Section of this Report.
4. DOPPLER RADARS

Over the last four years there has been a marked growth in interest in the use of Doppler radar for meteorological purposes. This interest, confined almost exclusively to research and development in the past, is now moving slowly into operational spheres in a small number of countries, in particular in USA where much of the work has been carried out. Significant steps have been taken towards relating Doppler return echoes to meteorological phenomena in such a way that operational systems become viable. A number of interesting, wide-ranging papers are now available, including that of Doviak et al (1979) which covers the theory in some detail and that of Serafin et al (1980) which predicts the use to be made of Doppler systems in the 1980s.

A study of the questionnaires returned to WMO this year reveals that, of the 47 submissions, only 3 countries are currently using Doppler radar, all solely for research purposes. Seven countries expect to install Doppler systems within a few years; five of these intend to use it for operational as well as research purposes. It is likely that there are several countries awaiting the experience of others before deciding on its merits.

It is convenient, though possibly an over-simplification, to say that Doppler radar has two distinct primary uses. Firstly, there is the detection and measurement of wind shear (or the vertical profile of horizontal winds), of great value at a large number of airports over much of the world. The other primary use, limited to countries which are prone to hurricanes, cyclones and severe storms in general, is its ability to give advanced warning of such phenomena; moreover, it can provide more information on their intensity and structure than any other practical means.

It must be recorded that Doppler systems are inherently more expensive than conventional radars; they call for greater processing power and for more maintenance effort. These facts may restrict its use at present, though a radar which can measure reflectivity for intensity measurements and has Doppler capability is attractive in principle. USA instituted a Joint Doppler Operational Project in 1976 between four interested authorities (two research institutes and two operationally oriented bodies) (Staffs, 1979). The final report recommends that the next generation of radars for operational use in USA shall be Doppler.

Doppler radar can only provide data if there are particles in the atmosphere to act as scatterers, normally precipitation but occasionally insects (or birds). Under certain circumstances the radar will detect inhomogeneities of refractive index, thus allowing some indication of clear air turbulence, though it would be dangerous to assume that the absence of such indication meant that turbulence did not exist. It must also be pointed out that in order to achieve any degree of accuracy when scatterers are present, these scatterers must be moving at the same velocity as the air around them. The results will be further confused if the particle fall velocity is large in relation to the horizontal wind-speed.

Two basic limitations are the maximum unambiguous velocity ($V_{\text{max}}$) and the maximum unambiguous range ($R_{\text{max}}$). These are given by $V_{\text{max}} = \pm \text{p.r.f.} \cdot \lambda / 4$ (where p.r.f. is the pulse repetition frequency and $\lambda$ the wavelength) and $R_{\text{max}} = c/(2 \text{p.r.f})$ (where $c$ is the speed of light). Thus, both $V_{\text{max}}$ and $R_{\text{max}}$ depend on the p.r.f.

Increasing this improves $V_{\text{max}}$ but worsens $R_{\text{max}}$. On the other hand, the use of S-band
(10 cm wavelength), rather than C-band (5 cm) or X-band (3 cm), will give better Vmax without affecting Rmax. It also decreases the attenuation problem. Processing, relying on spatial continuity, can overcome the limitations to some extent but the results may still be confusing to an inexperienced operator. An example of the figures obtainable for C-band radars (Nutter et al, 1979) with three choices of p.r.f. are Vmax = 40, 20 or 10 m/sec and Rmax = 51, 102 and 204 km.

Since a Doppler radar only possesses the basic ability to measure the radial velocity of scatterers and allows the observer to deduce the wind direction, it is apparent that to obtain a complete picture of that part of the atmosphere being investigated, two or even three radars are desirable. Much of the research work has been carried out with multiple systems. Wilson et al (1980b), in a valuable paper on which the writer has drawn heavily, state that "Doppler weather radar is proving enormously successful as a research tool for deducing air motions within storms and in clear air" when the radial components from two or more radars are combined, but they emphasise that "for operational applications these techniques are presently impractical because of the large number of Doppler radars that would be required for a national network and the difficulty of combining data from multiple radars in real time." Happily, the research programmes have shown that data from a single Doppler radar, after processing, can present on suitable colour displays identification of the vertical variation of wind with height in widespread precipitation, frontal boundaries, gust fronts, tornadoes, hurricane winds, wind shears dangerous to aircraft, and winds in the boundary layer in clear air.

Wilson et al (1980b) recommend that in regions where severe storms occur, the radars should be 10 cm wavelength (C-band) with beamwidth of 1° and that automatic procedures for removing velocity and range ambiguities should be incorporated. Shorter wavelengths, 5 cm (C-band) or 3 cm (X-band), with radars of smaller size and lower cost, may be adequate in other regions and particularly when used primarily for wind-shear purposes, despite limitations in Vmax. However, the writer is not aware of the existence of standardised Doppler radar systems which will perform the functions listed in para 7; it seems likely that at least 5 years will elapse before such are available.

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

The above, fairly general, statement on the measurement of vertical wind profiles is developed in practical terms by Strauch in a paper (1979) specifically concerned with airfield applications. It is, of course, at airfields that the real concern with low level wind shear exists. He states that: "A wind shear warning system should be able to detect wind shears along approach and departure paths and provide warnings of dangerous winds that may propagate into these paths. It must have all-weather capability. Dangerous wind shear regions may be only a few kilometres in size, so measurement of wind profiles at only one point at an airport does not provide sufficient information. However, measurement of the vertical profiles of the horizontal wind and its temporal change provides valuable information in many meteorological conditions."
In principle, the installation of a Doppler radar to look along the approach and departure paths of aircraft seems fairly straightforward. It is highly desirable, however, that a prolonged test be carried out under all conditions at some major airport(s) to allow development and to prove the operational practicability of the system. It is advisable to keep the system simple initially. The problems which have to be dealt with include:

a. ground clutter, which is unavoidable at low level and which cannot be removed by MTI (moving target indicator) methods without the risk of removing some wind information also;

b. the relationship between particle speed and wind speed, which approximates to 1:1 in widespread precipitation but is much less certain in convective conditions;

c. the radar height resolution, which may be insufficient to detect the precise characteristics of the wind profile. (There are limitations to the speed of antenna movement in terms of dwell time for sampling purposes and to the minimum time for data processing.)

For the limited purposes of measuring wind shear at or near an airfield it can be assumed that the slant range to which measurements are required will be sufficiently low to avoid any difficulty caused by range ambiguity. As explained in para 6, this will allow greater freedom of choice of $V_{\text{max}}$. Moreover, attenuation due to water droplets is unlikely to be a problem; therefore C-band or even X-band equipment would appear to be acceptable. However, at many locations the radar might be required to measure precipitation intensity to much greater ranges (in the manner of a conventional non-Doppler radar) and to give indication of severe storms and their structure. The detection of wind shear in clear air, i.e., when obtaining echoes from refractive inhomogeneities, is more likely with longer wavelengths. To meet these demands S-band equipment is necessary.

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

a. the measurement of changes in headwind speed which affect landings in particular;

b. the detection of turbulence, set up by large jet aircraft, which affects following aircraft. (In some conditions it would be difficult to separate this from turbulence due to natural phenomena.)

Also of concern to aircraft are gust fronts and "downbursts." Wilson et al (1980b) define the former as "associated with air rapidly descending from the base of a cumulonimbus cloud and spreading out horizontally within several hundred metres of the ground." This air often moves in a very different direction from the established flow. A "downburst" is defined by Fujita (1978) as a surface wind in excess of 17 m/s caused by small-scale downdraughts from the base of a cumulonimbus cloud. Both of these hazards are readily detectable on a Doppler colour display.

Over land, particularly in populated countries, conventional observational means already exist to determine the position of fronts. Nevertheless, Doppler radar may well be useful in some locations, detecting the sharp changes of wind direction frequently associated with fronts, at ranges up to 200 km or more given the right radar parameters.
The ability of Doppler radar to detect and to allow analysis of severe storms is of value to airfield operations but it is of wider interest in regions where such storms are liable to cause loss of life and damage to property, e.g. in the southeastern states of USA, in the Caribbean, the Bay of Bengal and the China Seas. The work of the JDOP (Staffs, 1979) established that velocity measurements could be reliable indicators of the severity of storms. These measurements could often indicate the existence of tornadoes, giving advance warning of their arrival by, say, 20 minutes. One difficulty would seem to be in the selection from a display likely to be crowded with Doppler data, that data specific to a dangerous tornado. Indeed, if the tornado is small in size (though not necessarily in fury) compared with the radar pulse volume, it may go undetected itself; in this case its existence should be deduced from the scale of the cyclone in which it is embedded.

Clear air turbulence measurements, of real-time value to aircraft operations, are also of benefit in the determination of boundary layer winds for short-term forecasting.

Wilson et al (1980b) make a case for using a single Doppler radar to observe the wind flow within a hurricane whilst knowing of no instance where this has been done with a land-based system. They accept that there will be regions within the hurricane where insufficient scatterers exist to provide readings but say that "since maximum winds occur in the wall cloud, it is most likely they will be observed because of the continuous heavy precipitation in the region."

No direct mention has been made of types of display for Doppler radar. Those used in research projects include velocity-azimuth display (VAD), plan-shear indicator (PSI) and various derivatives which present either vertical or horizontal data against azimuth, usually in colour but with some in alphanumerics. A truly operational display has yet to be developed. For a multi-functional radar this would be very complex; alternatively several separate displays could be provided. Papers discussing the subject are by Wilson et al (1980a) and Moringer et al (1960).

The processing task for a single task Doppler radar, e.g. wind shear only, is acceptable; that for two radars detecting and measuring wind shear is considerable but acceptable. A single, multi-task radar demands a very large processing task, whilst that for multiple, multi-task radars is massive.

In attempting to summarise, the writer is left with a number of statements which are not all compatible:

a. The greatest world-wide application of Doppler radar is likely to be in the detection and measurement of wind shear for airport operations.

b. Two or more radars would give more comprehensive data than one; relatively simple, low-powered C-band or X-band radars are possible (but do not at present exist). They may be of no value in clear air. It is possible that some countries will adopt this philosophy when suitable radars are available, but they will no doubt consider also the possible use of acoustic radars or lasers, either in place of Doppler radars or in addition to them.

c. In some countries or regions the advantages of the relatively inexpensive multiple radars are likely to be outweighed by those of a single more complex radar system (which also does not exist except for research purposes) able to provide a much wider range of data; in addition to wind shear information, this
would include precipitation intensity, location of fronts, detection of gust fronts, downbursts, tornadoes, hurricane winds and clear air turbulence. A few countries only are likely to implement these as single operational systems. Even 20-minute warnings of tornadoes could provide sufficient justification. No country is likely to adopt them in multiple systems.

d. Meteorological services with limited budgets will probably await operational proof of the value of Doppler systems (for whatever purpose they are required) before committing themselves to their use.

e. Implementation of operational systems is unlikely before the second half of the present decade.

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APPENDIX

STATEMENT ON ACCURACY (FROM CIMO-VII REPORT)

The main conclusions in this context, arising from the report on the Dee Weather Radar Project (1977) in the UK are as follows:

1. if a radar/raingauge calibration is carried out at the end of each hour, then the radar estimates of hourly rainfall over subcatchments (∼50 km²) differ from the optimum estimates (ie the estimates given by a dense network of raingauges modified by the radar pattern between gauges) by about 15% within 15 km of the calibration gauge, and about 20% at a distance of 20 km;

2. raingauge densities of between about one gauge per 30 km² and one gauge per 200 km² dependent on the type of rain, would be needed to obtain hourly estimates of subcatchment rainfall of the same accuracy as the radar;

3. the accuracy increases as the period of summation is increased. Six-hourly estimates are on average 5% more accurate than three-hour estimates;

4. the accuracy is greater the larger the area of measurement about the calibration site, up to an area of about 500 km², beyond which the calibration becomes unrepresentative. Accuracy decreases markedly over small areas to the extent that point estimates of hourly rainfall differ from the gauge by about 37%.