Inter-Agency Research Committee on the Hydrological Use of Weather Radar

Fourth Report

1999 to 2002

Report prepared on behalf of the Committee by CEH Wallingford

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Preface

Compiling a report on the work of a Committee such as this is never an easy task. By its very nature the Committee's activities and discussions are wide ranging: however this is where it adds real value. In widening the representation slightly, the group now provides representation from across the private sector, the University community and the relevant Governmental Departments and Agencies across the UK. This is a powerful grouping, which I am sure has more to offer than we have achieved to date.

More than ever, radar meteorologists and hydrologists are finding that there is considerable scope for collaboration with a range of other disciplines, and that through this collaboration the quality of both radar-based measurements and forecasts can be greatly improved. The work of the European COST Action 717 on the use of radar data in meteorological and hydrological models has shown what can be achieved when this collaboration is formalised, and what focus this can give to solving the practical operational problems and policy decisions that many of us face.

This, of course, has the advantage of enabling us to see more clearly the benefits that can be obtained from weather radar, and therefore subsequently help to make priority decisions about the investment needed to deliver these benefits. A number of Agencies have made the decision to invest in the capabilities of weather radar and are already realising the benefits. For example, the quality and resolution of the UK weather radar network, and associated forecast products, has significantly and demonstrably improved over recent years with a tangible impact on the ability to help protect property and lives from the risk of flooding. This would not have been achieved without a community effort.

In the environment we all currently work within, it is increasingly difficult to give support, both in time and effort, to groups such as this. I am therefore grateful to the members of the Committee and the organisations they belong to for their continued support and sponsorship of the activities we have undertaken during this session – many thanks. As well as stepping down from the Chairmanship, this is also the end of my representation on this Committee. It is therefore an opportunity to wish those who remain , and in particular the new Chairman Dr Chris Haggett from the Environment Agency, every success in taking the programme of work forward.

Professor Paul Hardaker, CMet
Committee Chairman (1999-2002)

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Inter-Agency Research Committee on the Hydrological Use of Weather Radar

1. Introduction

In September 2002 the World Meteorological Organisation's World Weather Research Programme held its first conference on Quantitative Precipitation Forecasting, at the University of Reading in the UK. A common theme that underpinned this meeting was the importance of weather radar to a range of applications, and in particular hydrology. Whilst radar is considered a fundamental tool for providing both measurement and forecast information, it is clear that there is still much more value to be gained from radar data.

Research and development efforts continue to focus on improving the quality of the radar information obtained, but there are inevitably physical limits to these techniques. With this in mind there is a growing interest from the modelling community to come together with those working with radar technologies to overcome these issues. Recent years have shown good progress here, several examples of which can be found within Europe's COST 717 Action on the 'Use of radar data in NWP and hydrological models', within which the UK has provided strong leadership.

Closer to home, since 1998 we have seen an ever increasing threat to the radar network from wind farm developments across the UK, but more particularly in Scotland. This places significant risk on the ability of radars to provide the necessary information that helps mitigate against rainfall-related flood risk. The Committee views this as an extremely serious issue and has made what representation it can through the radar network operators and regional governments to protect this important capability – this work must continue.

On a more positive note, during the period of this session the Environment Agency revised its National Weather Radar Strategy. This is an important document, outlining the Agency's requirements from radar over the next 10 years in order for it to meet its flood warning targets – this is available on the Committee's web site. In addition the Agency took delivery of the new Hyrad radar display and processing system, which gives the operational flood forecasting and warning centres a much improved data access and visualisation capability. This is underpinned by a new centralised national communications infrastructure for receiving products and services, including radar information, from the Met Office.

The Met Office have upgraded the transmitted and receiver systems in the radar network in England and Wales to pull-through new technological advances into the network capability. It is hoped that when new partnership agreements are in place for Northern Ireland and Scotland that similar upgrades can be rolled out to complete the work for the whole UK network. These technical advances mean that for the first time polar radar data at full resolutions (750 m by 1 degree in azimuth) are available centrally from the radar sites. Performance measurements show that the radars in the UK network have never been as accurate and there is a clear continuing trend of reducing the uncertainty in estimates of rainfall.

2. Community Plan – a review of Committee activities

In this session the Committee's focus was on providing greater integration with national and international radar-related programmes of work, and at the same time improving the dissemination of information to the wider community of those who benefit from radar information. With this in mind three strategic area were proposed.

Strategic Area 1	Strategic Area 2	Strategic Area 3
Integration with NERC and the UK's National Programmes	Improved dissemination of information to the UK community	Providing co-ordinated UK support to current International Projects

A number of key deliverables were identified under each Strategic Area, and a lead contact for each area was assigned to report on progress against these deliverables. A brief progress report is presented below, together with an outline milestone report at Appendix 1.

2.1. Strategic Area 1 – integration with NERC and the UK's national programmes

A recent report by the Institution of Civil Engineers concluded that the Research Councils have failed to nurture cross-boundary projects in the area of flood risk management – the Committee has tried hard to foster this kind of collaboration between the Agencies and the Research Community. A number of programmes are already underway that provide bi- and tri-lateral co-ordination, but the Committee remains the only forum in which all the hydrological users of radar data can come together to discuss and review progress, and to provide a collective view on best practice.

Rather than seek to have separate representation, the Committee has worked through the representation of its members on these various groups and programmes to promote its collective view. It has had limited progress to date, but it does have a strong grounding on which to provide a valuable source of expertise and excellence in both technical and scientific understanding. Through improved dissemination and representation the Committee is now able to provide more of its relevant information to a much wider community.

One example has been the involvement of members of the Committee in the Hydrological Radar Experiment (HYREX),a NERC Special Topic Research Programme. The impetus for HYREX arose from a desire of the Committee to better understand radar-derived rainfall variability, and how this impacts on river flow at the catchment scale. The programme instrumented the Brue catchment in Somerset and collated the data in an integrated dataset for community use. During this session the Environment Agency have continued to maintain a dense raingauge network in the Brue catchment until Spring 2000, with data being quality controlled and archived at CEH, partly under MAFF funding. Weather radar data over the same period were supplied to CEH by the Met Office. The completed dataset is now available via the British Atmospheric Data Centre (BADC) web site for use by the international scientific community; the web address is http://badc.nerc.ac.uk/data/hyrex/. A special issue of the journal Hydrology and Earth System Sciences contains papers reporting the main research results (Moore, R.J. and Hall, M.J. eds. 2000 Special Issue. HYREX: the HYdrological Radar Experiment. *Hydrology and Earth System Sciences*, **4(4)**, 681pp); copies of this Special Issue are available from the Committee Technical Secretary at CEH Wallingford.

2.2. Strategic Area 2 – improved dissemination of information to the UK community

The Committee's dissemination strategy has two aims. The first has been to provide updated web pages where information can be made widely available to the community at large. The Rutherford-Appleton Laboratory has helped to establish and host the new and updated web site at www.iac.rl.ac.uk. This contains information on the constitution of the Committee, a list of members, and links to their respective organisations. Committee papers, including the Triennial Reports, are also available on the site. Interested readers will also find links to related programmes, such as relevant COST Actions (http://cost.cordis.lu).

During this session a report was produced that reviews the user requirements of the European Water Utilities. This report stresses the benefits of radar data to predictive real-time control, planning and design, and the verification of flow surveys. It identified the continuing need to improve the quality of high resolution radar data and the need to unlock the potential that radar brings to spatial and time series design work. Verification studies with radar would also benefit from improvements in these areas, together with more consistent radar calibration methodologies. The report is expected to be made available through the Committee's web site during 2003.

In addition, a series of technical notes presented at Committee meetings have now been made available on the web site. The Committee intends to extend this series of notes significantly over the next session. Current technical notes include:

- Research and development recommendations for research related to weather radar.
- A proposed new scan strategy for the UK radar network.
- The Bolton Propagation Experiment - estimating rainfall rates using attenuation of microwave links.
- Evaluating the current operational radar scheme for bright band correction.
- A proposed modification to the existing scheme used operationally for correcting attenuation due to heavy rainfall.

The second dissemination strategy aim is to ensure that key information is reviewed by the Committee and that the various Agency representatives are able to both provide input on best practice and take back information into their own organisations. To ensure that this process is comprehensive, the Committee has reviewed its membership to make certain it is able to represent all the UK communities who have a significant hydrological use of radar data. Throughout this session the Committee also continued to co-opt senior members of the research community to ensure that the valuable links and different perspectives between the Agencies, University community and the private sector Water PLCs are maintained.

2.3. Strategic Area 3 - providing co-ordinated UK support to current International projects

The European COST-75 final report made a series of recommendations concerning all aspects of modern weather radar data processing plus suggestions for the future development of operational weather radars. These recommendations are reproduced in full in Appendix 4 for information and reference. Of specific interest to the UK are the following:

- Algorithms for precipitation estimation: Vertical Reflectivity Profile (VPR) and clutter corrections should be applied in real-time before data are used by hydrologists.
- Doppler radar: Wind information derived from Doppler radars provide useful information for forecasters, and should be assimilated into numerical weather prediction models through VAD profiles and/or the radial velocities.
- Polarisation diversity radar: The use of polarisation diversity radar offers a range of techniques which may improve radar data quality control procedures, and hence lead to improved precipitation estimation.

The Met Office and the Environment Agency are actioning these recommendations through the joint support of an integrated programme of development activities and, in the case of the latter, through the procurement of a new radar in SE England, for which the Agency is providing 90% of the funding.

There are currently two further COST Actions underway that are relevant to the work of the Committee. Both the Met Office and NERC are participating in the COST Action 717 on the assimilation of radar data into hydrological and meteorological models (www.smhi.se/cost717), and in addition the Met Office and RAL are participating in the COST-720 Action on Integrated Observing Systems (www.cost720.rl.ac.uk).

Further afield, the United Nation's World Weather Research Programme (WWRP) held a major inter-comparison project in this session of the Committee. During and just after the Sydney Olympic Games in 2001 the UK, represented by the Met Office and the University of Salford, took part in a comparison of nowcasting systems organised by the WWRP and hosted by the Bureau of Meteorology, Australia. A version of the GANDOLF system was implemented using local radar and mesoscale model data, and a number of case studies have been collated. The performance of GANDOLF and the other participating systems is being analysed and the University of Salford are exploring the possibility of using 4 Dimensional Variational (4DVAR) wind fields, derived from Doppler radar data, for forecasting convective development for up to one hour ahead.

3. A summary of key strategic issues that still remain for the UK

As long as radar continues to be used for rainfall measurement there will be programmes of work aimed at making these measurements more accurate. However the value that can be obtained from such activities becomes less and less as the techniques approach the physical limits of uncertainty in the observations. However there are a number of key activities in the UK where benefits can still be realised. These are outlined below.

- Recent improvements to the UK network radar processing have now made it possible to obtain polar data at original resolution. This has several knock-on benefits, such as higher resolution data both in the vertical and horizontal. Investigation of the improvements that additional elevation scan data brings to both vertical reflectivity profile correction and thunderstorm forecasting deserves further investigation.

- New techniques are being developed to provide real-time calibration and adjustment of operational radars. These include both the use of complementary data from radio-propagation links and a more optimal use of naturally occurring non-precipitation targets. These require operational assessment.

- For some time, studies have been conducted on the benefits of polarisation-diversity radars. However there has been uncertainty in how much of this benefit can be realised in an operational environment, using a frequency that is susceptible to propagation effects, such as C-band. An operational demonstration radar will soon be established in the south-east of England, which will provide a long overdue assessment of capability on which a decision for future investment can be based.

The more recent focus on Quantitative Precipitation Forecasting (QPF) has been triggered by an increase in capability of higher resolution numerical models and improved observational data, of which radar is a key part. In Europe the work of COST 717 has been a welcome initiative to bring hydrologists and meteorologist together to tackle these issues collectively. Within this wide field of activities there are a number of significant areas that deserve greater focus, and these are outlined here, emphasising particularly the radar component.

- Convective rainfall is notoriously difficult to forecast because of its spatial and temporal variability. However as the resolution of models increases, then there is a need to represent this convection, including its surface impacts, more explicitly. This has many benefits including enhanced thunderstorm nowcasts, improved flood forecasting and unlocking the ability to provide predictive real-time control systems based on spatially distributed rainfall data. The direct assimilation of radar information is key to this improvement, but as yet experience is limited in an operational environment.

- Often the radar measurements have within them inherent information on the quality and accuracy of the data itself. By using this information to a greater extent it is possible to significantly improve the error characteristics of the data. This in turn is critically important in gaining maximum value from the assimilation of the data into numerical models. Much more work needs to be done to improve the understanding of error characteristics and in optimising this within assimilation procedures for both radar-derived precipitation and wind field information.
- The discontinuous nature of precipitation fields makes it difficult to undertake verification and validation of the performance of measurements and forecast information. This is important in understanding where skill is added and where improvement needs to be made. There is still significant potential here to make much greater use of spatial techniques that will improve on current verification methodologies.

The value of radar data in environmental impact work has yet to be fully realised. This will require radar archive data to be integrated into long time series data from raingauge networks, both to provide the longevity of observations from radar, but also to improve on the spatial representativeness of the gauges. The ability of the information to be used in planning and design work, as well as offering a powerful source of verification information, will be greatly enhanced.

For many years radar information has been used in wet deposition modelling tools to provide more detailed spatial information on the wash-out of atmospheric pollutants. However it is still not common to find operational radar data combined with other sources of information to enhance both understanding in physical processes and an ability to more accurately predict and mitigate outcomes in a number of weather sensitive applications. Whilst there has been a much closer link over recent years between the meteorological and hydrological communities, there is much greater scope to build on this collaboration in the wider natural and physical sciences.

Finally, the benefits of the radar network to rainfall measurement, forecasting and impact studies are being weakened by pressure on the radars to be moved to sub-optimal sites because of much tighter planning constraints and new initiatives such as wind farm development. This is despite the development of tools that give a much greater understanding of the respective benefits of siting a radar in a particular location. It is ironic that as our capability to assess the value of the information improves, our ability to unlock this value becomes ever more difficult.

4. A look forward to the next Committee session

Raising awareness of the work with radar and the benefits that can be obtained from this will continue to be a focus for the Committee in the coming session. This will build on the strong foundations already laid down in earlier sessions. In addition the Committee will address two further strategic areas on bringing research findings into operations, and identifying and addressing service delivery needs of operational agencies.

Strategic Area 1	**Strategic Area 2**	**Strategic Area 3**
Bringing research findings into operational use	Identifying and addressing service delivery needs of operating agencies	Raising awareness in the wider community

These Strategic Areas offer a valuable emphasis on the pull-through of best practice into an operational environment and in breaking down barriers to delivering these capabilities to where they can have maximum benefit.

Appendix 1: Community Plan Milestone Report

Strategic Area 1 - Lead Contact: Paul Hardaker **Integration with NERC and the UK's National Programmes**	**Date Achieved**
• Co-ordinate the Committee reporting cycle to feed into the NERC strategy cycle (Paul Hardaker) *The session report and bibliography will be released to NERC and the Agencies for inclusion in the next planning cycle.*	28 April 03
• Ensure the Committee provides the necessary support to both NERC and National programmes on weather radar (Paul Hardaker) *The visibility of the IAC was raised with both NERC and NCAS through discussions with their respective Programme Directors.*	26 April 01
• Identify the strategic fit with NERC and Government Agencies (Paul Hardaker) *A brief paper was provided identifying areas where the Committee could provide useful supporting information to NERC and Agency programmes.*	20 Oct 00
• Write an article on activities of the committee for NERC's quarterly magazine "Planet Earth" (Paul Hardaker and Chris Haggett) *An article will be produced to coincide with the release of the Session report.*	Not yet completed

Strategic Area 2 - Lead Contact: Chris Haggett **Improved dissemination of information to the UK community**	**Date Achieved**
• Offer input and representation on radar related activities to DEFRA-EA programme (Linda Aucott) *Linda Aucott attended DEFRA/EA R&D Theme Advisory Group meetings on 30 August 2001 and 21 March 2002 and a copy of the current R&D programme was circulated to IAC members. Details of the R&D projects are available through the Committee's web pages. At present there are no projects in progress in the joint programme specifically on weather radar but several projects including T1 Rainfall Forecasting, T8 Real Time Modelling and T9 Antecedent Conditions include elements of radar use. Committee members continue to champion research on radar related activities in the appropriate fora. In addition the Committee was briefed on the EA weather radar strategy.*	30 Aug 01
• Representation on related community QPF activities (Chris Collier) *During 2001 the Universities Weather Research Network (UWERN) developed a thematic research programme proposal on Quantitative Precipitation Forecasting (QPF). Progress was slowed on this prior to the formation of the NERC Centre for Atmospheric Science (NCAS), which led to a complementary proposal by NERC, Met Office and University of Reading research programme, known as the Science of Rainstorms with Application to Flooding (SRAF). This has given new impetus to specify a NERC funded research proposal including a range of topics from radar measurements of precipitation to the assimilation of radar data into hydrological and meteorological models. Preparatory work is being led by Professor Collier of the University of Salford with a view to submitting proposals in late 2002. During this period Chris Collier made a presentation to the Royal Society on the importance of QPF work, published as Phil. Trans. R. Soc. Lond. A, 2002, 360, 1345-1361.*	26 April 01

Strategic Area 2 - Lead Contact: Chris Haggett **Improved dissemination of information to the UK community**	**Date Achieved**
• Host a workshop that co-ordinates with the UK COST-717 meeting, bringing together those interested in the UK community (Dawson Wray) *It was decided that this would add little value to the current meetings programmes. In particular, the UK community had opportunity to provide input on COST-717 work at the European Radar Conference (ERAD).*	Closed
• Provide a list of requirements for consideration by the Met Office weather radar archiving project and for weather radar requirements in BADC (Bob Moore) *The requirements of a radar data archive to support the needs of the research community were reviewed by the Committee. A position statement is included as an Appendix to this report. This statement was provided for consideration by the Met Office weather radar archiving project and for weather radar requirements in BADC.*	26 April 01
• Establish Web page with access to information about membership, on-line documents produced, and meetings agendas and minutes (John Goddard) *The web page is now on-line at www.iac.rl.ac.uk.*	20 Oct 00
• Deliver session report with bibliography, looking where possible for wider circulation through a range of differing channels (Committee Secretary) *The end of Session Report covers the period 2000-2002 and completion was delayed due to heavy workload commitments on the out-going chairman. The report is focused on information sources rather than providing an elaborate overview of research activities presently undertaken in this area. The bibliography has been reviewed and updated and sorted according to research topics to improve accessibility.*	28 April 03
• Review Committee membership (Paul Hardaker) *A review identified that the Committee membership required widening to include representation from key user groups from Northern Ireland and the private sector Water community. Representation has now been sought from these groups.*	6 Dec 01
• Identify Water PLC user problems and 10 year aims (Graham Squibbs) *A discussion paper has been produced and presented to the Committee. It is expected that this will be made available in the near future through the Committee's web pages.*	4 Dec 02
• Documentation of scientific notes for users (Anthony Illingworth) *This was established in the autumn of 2002 and notes continue to be provided and placed on the Committee's web site.*	14 Sept 02

Strategic Area 3 - Lead Contact: Han Dawei **Providing co-ordinated UK support to current International projects**	**Date Achieved**
• Have formal representation at COST-717 (Bob Moore) *COST-717 is an EU Cooperation in Science and Technology Action entitled "Use of radar observations in hydrological and NWP models" running for 5 years from October 1999. It aims to identify how to make best use of radar information in hydrological and numerical weather prediction (NWP) models. In carrying out its work three working groups were established: WG1 – Using radar information in hydrological models; WG2: Using radar observations in parameterisation and validation of atmospheric models; and WG3: Using radar information for*	20 Oct 00

Strategic Area 3 - Lead Contact: Han Dawei **Providing co-ordinated UK support to current International projects**	**Date Achieved**
assimilation in atmospheric models. Three members of the Inter-Agency Committee have been involved in the action: Paul Hardaker through its formulation and inception, Bob Moore as one of two UK representatives on the Management Committee and member of WG 1, and Chris Collier as an invited expert to WG1. The Technical Secretary, Susanne Mecklenburg, also served as invited expert under WG1. Further information on the purpose and activities of COST-717 are available on its web site: http:/www.smhi.se/cost717/.	
• Have formal representation at COST-720 (John Goddard) *John Goddard and John Nash are now providing UK representation.*	6 Dec 01
• Provide a co-ordinated Working Paper input from the UK into COST-717 (John Burns) *It was felt more relevant to provide the input in a more focused way through the existing working group representation.*	Closed
• Host a session as part of an appropriate meeting on the work using radio propagation techniques to estimate rainfall (Anthony Holt) *Due to illness this has not yet been completed. A meeting is planned to present the findings after the end of this field experiment, which is expected to be in 2003/04. This work has now been extended to include European trial sites as part of a wider EU Framework funded initiative.*	Not yet completed
• Produce a technical report on the feasibility of radio propagation methods together with weather radar for rainfall estimation (Anthony Holt) *A technical note has been provided for the web pages.*	14 Sept 02
• Provide a UK community response to the COST-75 final report, with recommendations to Agencies (Chris Collier and Paul Hardaker) *A report was provided to the Committee and recommendations are summarised within this final report.*	28 April 03
• Brief the Committee on the outcomes of the WWRP Nowcasting inter-comparison project (Chris Collier) *A version of the GANDOLF system was implemented using local radar and mesoscale model data, and a number of case studies have been collated. The performance of GANDOLF and the other participating systems is being analysed and the University of Salford are exploring the possibility of using 4 Dimensional Variational (4DVAR) wind fields, derived from Doppler radar data, for forecasting convective development for up to one hour ahead.*	4 Dec 02
• Integration with Framework 5 European Projects (Chris Collier and Anthony Holt) *Members of the Committee have provided input to Framework proposals that they have been involved in throughout the period of this session. Two particular examples include:* *CARPE DIEM: a project to look at improving the use of radar and NWP models in the prediction and management of floods http://carpediem.am.ub.es.* *MANTISSA: a project investigating the use of microwave propagation links to improve estimates of rainfall in urban and rural catchments that are difficult to instrument http://prswww.essex.ac.uk/mantissa/index.html.*	28 April 03

Appendix 2: Committee Constitution and Terms of Reference

A2.1. Constitution

The Committee comprises members appointed by the following supporting agencies:

Met Office	-	1
DEFRA	-	1
EA	-	1
NERC	-	1
CLRC	-	1
SEPA	-	1
DARD	-	1
States of Jersey	-	1
UK Water PLCs	-	1

and up to four members (of which at least two should be from Higher Education Institutes and/or research organisations) to be co-opted for a two year period at the invitation of the Committee. The Chairman is appointed from amongst the representatives of the supporting agencies for a two year term of office. The Secretary to the Committee is provided by CEH Wallingford.

A2.2. Terms of Reference

1. To identify research needs and opportunities

2. To recommend priorities for future research and to coordinate research activities

3. To seek funding for research.

4. To identify needs for and availability of data and to recommend archiving requirements.

5. To publicise and promote hydrological uses of weather radar.

6. To promote and establish international contacts.

7. To report on its work to the nominating bodies and the water industry generally.

Appendix 3: Committee Membership (1999-2002)

Professor Paul Hardaker *(Chairman)*	Met Office
Ms Linda Aucott	Department of Environment, Food and Rural Affairs, Flood Management Division
Mr John Burns	Scottish Environment Protection Agency
Professor Chris Collier *(co-opted)*	University of Salford, School of Environment and Life Sciences
Dr Howard Oliver and then Dr Susanne Mecklenburg (*Secretary during reporting period*)	Natural Environment Research Council, Centre for Ecology and Hydrology, Wallingford
Dr John Goddard	Central Laboratory for the Research Councils, Rutherford Appleton Laboratory
Dr Richard Griffith and then Dr Dawei Han *(co-opted)*	University of Bristol, Department of Civil Engineering
Dr Chris Haggett	Environment Agency, National Flood Warning Centre
Professor Anthony Holt *(co-opted)*	University of Essex, Department of Mathematics
Dr Anthony Illingworth *(co-opted)*	University of Reading, Joint Centre for Mesoscale Meteorology
Mr David Johnson	States of Jersey Public Services Department
Mr Bob Moore	Natural Environment Research Council, Centre for Ecology and Hydrology, Wallingford
Mr Graham Squibbs	Service Delivery, United Utilities plc
Mr Dawson Wray	Hydrometric Section, Rivers Agency Department of Agricultural and Rural Development

Appendix 4: Summary Recommendations from the European COST Action 75 on Advanced Weather Radar Systems

3. Recommendations

COST-75 reviewed current weather radar systems and how developments are progressing. Examples of best practice are given rather than providing specific detailed recommendations. However, the following recommendations were evolved from this review and consideration of the use of weather radar in Numerical Weather Prediction (NWP):

(i) A forum is created such that the European radar community does not lose focus on important advances in quality control methods for radar data, including the contribution that new technology and integrated observation can bring;

(ii) Greater effort is given to the use of simple models to help in the interpretation of radar information;

(iii) A new COST Action is proposed that brings together the radar and modelling communities (both meteorological and hydrological) to investigate the following priority topics:

(a) the provision of a standard radar data verification and validation dataset for Europe;
(b) gain a greater understanding of the error characteristics of radar data for use in the model data assimilation process;
(c) devise more direct methods for assimilating radar observations into models such that they can contribute in a more significant way to the quality of model output;
(d) quantify the importance of radar data as model grid scales become smaller;
(e) investigate the feasibility of using radar data to drive cloud scale models in an operational environment;
(f) a further new COST Action be considered to examine prospects for integrating observing systems.

Further recommendations are made concerning all aspects of advanced radar systems as follows:

Doppler radar

(i) VAD winds should be taken as an operationally valid method of measuring wind profiles in the lower atmosphere.

(ii) VAD winds should be seen as a complement to radiosonde winds not as a replacement

(iii) Further study of Doppler wind spectra is required.

(iv) Investigation of the use of VADs, VVPs and radial winds as input to NWP should be undertaken.

(v) A basic level of training in Doppler radar commensurate with the maintenance and operational philosophy of the organisation is essential. The use of training datasets is seen as important.

(vi) Some further research is needed to assess the utility of Doppler wind data when networked. New products need to be specified.

(vii) Doppler radar will continue to be central to mesoscale meteorological research.

(viii) There is no operational pressure in Europe to improve on the current level of performance in clear air.

(ix) We conclude that solid state technology including digital receivers shall be introduced to new radar systems in order to improve reliability and sensitivity.

(x) The possibility exists of retrieving temperature profiles using combined data from radar and satellite systems, and deriving vorticity, radial convergence and PV advection from Doppler data. Such data and parameters might be used inconjunction with mesoscale and smaller scale models. These possibilities should be researched.

(xi) It is advisable to consider the age of an existing radar when deciding whether to upgrade to Doppler. It might be better to buy a new Doppler radar.

(xii) A Doppler calibration procedure should be provided with such a design that it can relatively easily be upgraded later to include multiparameter facilities i.e. appropriate microwave plumbing.

(xiii) Any new COST project to consider optimal ways of assimilating data should include consideration of Doppler radar data products.

Multiparameter radar

Polarisation diversity

The following important applications using polarisation diversity seem realisable based on recent observations:

(i) Identification of hail and improved rainfall estimates when hail is present.

(ii) Improved means of correcting for the attenuation of the radar return in regions of very heavy rainfall.

(iii) Recognition and removal of spurious echoes due to ground clutter and anomalous propagation.

(iv) Automatic self-calibration of absolute values of reflectivity to with 10%.

(v) Nowcasting of damaging weather associated with severe storms, based on discrimination of different hydrometeors and identification of mesoscale organisation.

Multiple frequency and frequency agility

(vi) The reliability of dual frequency radar to identify hail as developed in the former Soviet Union has not been established.

(a) It appears almost impossible to disentangle the reduced reflectivity due to Mie scattering by hail particles at the higher frequency from the reduced reflectivity resulting from the severe attenuation by heavy rainfall at the higher frequency.

(b) Two antennas with well matched beam patterns are needed together with two precisely linear receiver chains. A first step is to demonstrate that in heavy rain the reflectivities recorded at the two frequencies are identical.

(vii) The use of differential attenuation to estimate rainfall appears to have limited application. Again the two radars must have matching beamwidths, but, more importantly, such a system can sense rainfall only over an inherently small dynamic range. The rain must be heavy enough to give appreciable attenuation, but not so heavy as to result in total loss of signal.

Detailed conclusions on polarisation techniques for improved rain rate estimates

(i) High values of co-polar correlation coefficient are an excellent indicator that the target is precipitation and can be used as a check that there is no ground clutter, or, more importantly, anomalous propagation. This procedure should prove reliable and relatively simple to install at both S-band and C-band.

(ii) Rainfall estimates in severe convective storms at S-band.

(a) Z_{DR} alone.
The use of Z_{DR} to provide a measure of mean rain drop size which, when combined with Z, can provide a more accurate rainfall rate. This technique will

fail when hail is present and, in such cases, can produce spuriously high rain rate estimates.

(b) K_{DP} alone.
The use of K_{DP} alone to derive rainfall estimates has the advantage of being unaffected by hail but there are other difficulties associated with K_{DP}. Noise in the phase estimates means that it is not very accurate and considerable spatial filtering over 5 or 10km may be required.

(c) Auto-calibration of Z using Z, Z_{DR} and total phase shift.
A combined use of Z, Z_{DR} and differential phase is recommended which exploits the redundancy of the three parameters in rain. In rain the total phase shift predicted from Z and Z_{DR} should agree with that observed. The value of Z should be scaled until this consistency is obtained and this enables Z to be calibrated absolutely to 0.5dB or 10%. This is a far better figure than can be achieved by a hardware link budget or by comparison with rain gauges.

(d) Z, Z_{DR} and Differential Phase Shift in heavy rain.
Once Z has been calibrated (to 0.5dB) then the consistency between observed Z, Z_{DR} and total differential phase shift can be used to confirm rain is present. If rain is present then, providing Z_{DR} is known to 0.2dB, the rainfall rate can be estimated to 1dB (25%). This is large improvement over the factor of two error when R is derived from Z alone. It is important to use the correct drop shape model to compute Z_{DR}. A good antenna is needed so that no spurious values of Z_{DR} are generated by reflectivity gradients across the beam.

(e) Z, Z_{DR} and Phase Shift to Identify hail.
When Z and Z_{DR} are not consistent with the observed total differential phase shift then hail is present. In this case the hail may render the observed values of Z and Z_{DR} spurious, and the rainfall rate should be estimated from K_{DP} alone.

(iii) Rainfall estimates in severe convective storms at C-band.

(a) Difficulties in Z and Z_{DR} due to attenuation.
The techniques described in (b) at S-band are more difficult to implement at C-band. This is because attenuation is so much larger than observed values of Z and Z_{DR} can be reduced considerably. If rainfall estimates are to be improved then Z_{DR} must be estimated to 0.2dB and this seems very difficult when differential attenuation can easily reduce Z_{DR} by several dB.

(b) Advantages of K_{DP} at C-band.
The value of K_{DP} is unaffected by attenuation or hail, and should provide rainfall estimates to about 6mm/hr; this assumes that any artifacts due to differential phase shift or back-scatter by the larger hail stones can be filtered out without too

much loss of spatial resolution, and that effects due to reflectivity gradients across the beam can be corrected.

(c) Autocalibration of Z using Z, Z_{DR} and total phase shift.
The method outlined at S-band should work at C-band providing paths are chosen were phase shifts are not so large that there are attenuation effects on Z and Z_{DR}.

(d) Correction for attenuation
It seem difficult to correct for attenuation in Z and Z_{DR} on a gate by gate basis because of instabilities caused by small calibration errors. Instead it should be possible to provide an estimate of the total attenuation from the observed differential attenuation given by the negative value of Z_{DR} behind the intense echoes. This attenuation can then be distributed along the beam using the observed differential phase shifts as a weighting.

(iv) Rainfall estimates when hail is absent at C and S band.

Providing that the radar beam is dwelling wholly in regions where the temperature is above freezing, which limits the range to 100km or so in the summer.

(a) Autocalibration of Z using Z, Z_{DR} and Total Differential Phase Shift.
The consistency of these three variables in heavier rain provides an excellent and reliable self calibration of the Z return to within 0.5dB or 10%.

(b) The use of calibrated Z and Z_{DR} (accurate to 0.2dB) provide rainfall rates to with 1dB (25%); a considerable improvement over the factor of two error in R derived from Z alone. The total phase shift should be monitored at C-band to check that Z and Z_{DR} are unaffected by attenuation.

When the radar beam may be dwelling in the melting layer or above it.

(c) The presence of the melting layer and enhanced level of reflectivity can be identified by reduced level of co-polar correlation and the increased value of LDR.

Such information can be used to initiate a bright band correction scheme based on the vertical profile of Z. It has yet to be established that the actual value of LDR can be used as an indication of the intensity of the bright band. The lack of an LDR signature at the appropriate height in convective storms can be taken as an indication that the bright band is absent and so the bright band correction scheme should be suppressed. The use of the correct vertical profile correction scheme has a major impact on rainfall estimates at the ground.

(v) Hardware implications.

(a) Z_{DR}.

It is necessary to measure Z_{DR} to 0.5dB for the Z autocalibration technique and to 0.2dB for improved rainfall rates. This requires an antenna with good sidelobe performance so no spurious Z_{DR} artifacts are generated when reflectivity gradients are present. Examination of data quality should confirm if this is happening and in addition should enable any artifacts associated with the radome to be identified. In light rain a consistent field of low values of Z_{DR} should be observed which is reduced to OdB at vertical incidence.

(b) K_{DP}.

The amount of noise in the differential phase measurement is the crucial limitation. Values of 3^0 must be achieved; if transmission of circular and simultaneous reception of horizontal and vertical polarisation can reduce this noise then the potential of the technique would be transformed.

(c) Manufacturers of polarisation diversity radar.

There are two manufacturers of polarisation diversity meteorological radars:
Kavouras inc, 11400 Rupp Drive, Burnsville Minnesota 553337-1279.
Web site: http://www//kavouras.com

Enterprise Electronics Corporation, 128 South Industrial Boulevard, Enterprise, Alabama 36330, USA. Email: eecintl@aol.com

Summary recommendations

(i) The benefits of polarisation techniques at S-band for improving rainfall rates estimates have been demonstrated, but in Europe operational radars operate at C-band where the quantitative application of the polarisation techniques has still to be established beyond doubt.

(ii) The use of C-band polarisation techniques for hydrometeor identification is well established and should be a powerful means of classifying storms and improving nowcasting of future rainfall and severe weather.

(iii) For improved rainfall estimates at C-band data from existing radars in Europe must be examined to establish the following:

(a) The accuracy with which Z_{DR} measurements can be made in hail free rain. 0.5dB is needed for automatic calibration of Z and 0.2dB accuracy to provide rainfall rates of 25% from Z and Z_{DR}.

(b) Differential phase can be estimated with an error of 2 or 3^0.

(iv) Once this has been established then it should be possible to demonstrate the following applications at C-band:

(a) Removal of clutter and anomalous propagation using co-polar correlation.

(b) Automatic calibration of Z to 0.5dB (10%) by the consistency of Z, Z_{DR} and differential phase.

(c) Identification of hail using K_{DP} and improved rain rate estimates when hail is present.

(d) More accurate rainfall form Z and Z_{DR} when there is negligible attenuation.

(e) Correction for attenuation using negative Z_{DR} behind the intense rainfall coupled with differential phase shift measurements.

(f) Identification of melting snow and the bright band using LDR to trigger correction algorithms for the vertical profile of Z in stratiform precipitation but not within embedded convection.

(v) The use of dual frequency for identification of hail requires further research to overcome ambiguities between Mie scattering by hail and attenuation by rain. The use of differential attenuation to estimate rainfall appears limited because of the restricted dynamic range.

(vi) The implementation of these techniques is not trivial. Initially tests in a quasi-operational environment will be needed to establish their robustness. Training will be needed for the interpretation of the output from the algorithms.

Rapid scanning radar

(i) Outline specifications for the Next-Generation European Weather Radar ("NEURAD") have been generated, which are deemed to be well suited as a starting point for prototype rapid scanning radar development and implementation, preferably to be carried out as an international joint project under the umbrella of the EU.

(ii) The collection of user requirements resulted in the need for faster weather volume scan updates, down to around 1 minute per scan.

(iii) Industry is requested to prepare for new user requirements, accepting higher prices for added value, on the timescale 2005 to 2010.