Advanced Weather Radar Systems in Europe: The COST 75 Action

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ABSTRACT

The European Union COST (Cooperation in Science and Technology) action on advanced weather radar systems is described. The associated five-year research project, which began in early 1993, has the objective to develop guideline specifications for a future generation of European operational radar systems. The authors describe the status of the project, the results reached so far in assessing and reviewing the potential improvements to conventional radars, the products and application of Doppler radar data, the contribution of polarimetric radars to the improvement of quantitative precipitation measurements and for nowcasting, and the possible development of electronically scanned systems. Problems to be tackled in the remaining years of the project are assessments of future technological feasibility, market forecasts, and cost/benefit investigations for the varied requirement profiles across Europe. It is intended to generate a high-level specification for the next generation of weather radars in Europe.

1. Introduction

Following the approval of the European Union COST (Cooperation in Science and Technology) senior officials, the constituent assembly of the management committee for the COST action 75 (COST 75) on advanced weather radar systems was held in Brussels in January 1993. The resulting memorandum of understanding (MOU) for the implementation of a five-year European research project on advanced weather radar systems stated:

> The main objective of the project is to coordinate and to advance European research on the assessment of the utility and viability of advanced weather radars, in order to develop a guideline specification for a future generation of operational systems. This is expected to enhance the efforts which are being or will be made by states participating in European co-operation in the field of scientific and technical research (COST) in developing further their weather radar networks. Meetings and some study costs are funded by the European Commission. Research or development are not being provided by COST, but need to be covered from existing national programmes.

In early 1993 the MOU was signed by Czechoslovakia, Finland, France, Germany, Hungary, Italy, Slovenia, Spain, Switzerland, the Netherlands, and the United Kingdom. Since then Belgium, Croatia, Greece, Poland, Portugal, and Sweden have joined. The Czech Republic and Slovakia now represent the former Czechoslovakia. Austria has participated as permanent observer from the beginning and has been a full member since early 1996. The National Institute of Meteorology and Hydrology, Bucharest, Romania, has been accepted as permanent observer since 1995. These European countries operate over 100 weather radars operationally and about 10 in addition with polarization diver-

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sity for research purposes. Eastern European countries are just progressing in installing Doppler radars. So the main interest and expertise contributing to COST 75 comes from networks of single polarization Doppler (in some cases) radars operated by the national weather services. Research institutions as well as industry involved in radar system developments have been invited to discuss applications of advanced methods and technologies in an operational environment and to assess technological projections into the next century.

An area of uncertainty remains: the development of future requirements. Already visible is the effort to develop further weather nowcasting techniques for a broad field of local users. Weather radars, if they can be operated in flexible and adaptive modes, can contribute to this field of economic interest. Further discussions need to clarify how more advanced radars may contribute to the tailoring of more specified products and how to distribute these in the growing multimedia world.

In order to cover the broad field of envisaged research, four working groups were established.

- Working Group 1: Advanced data processing with conventional and future radars, chaired by J. Joss, Switzerland.
- Working Group 2: Doppler radars, chaired by C. Collier, United Kingdom.
- Working Group 3: Multiparameter radars, chaired by A. Illingworth, United Kingdom.
- Working Group 4: Electronically scanned systems, chaired by W. Randeu, Austria.

Here, we outline the status of the project to date, the main results achieved so far, and the problems to be tackled in the remaining years. The paper is structured according to the working groups, although it is the aim of the project to integrate the findings of the working groups.

Important events were the COST 75 International Seminar on Advanced Weather Radar Systems, held 20–23 September 1994 in Brussels, which included more than 80 contributions from outside of Europe as well (Collier 1995). A COST 75 Workshop on Improved Rainfall Estimates using Polarisation Diversity Radar was held 3–4 July 1995 at the University of Reading, United Kingdom, and a Workshop on Doppler Weather Radar on 22–23 October 1996 at Villa Chiozza, Cervignano del Friuli, Italy. The final international seminar is scheduled for March 1998 in Lugano, Switzerland.

2. Improvements of current weather radar systems

This topic has been mainly discussed during committee meetings and workshops held throughout the project, in the sense of advanced data processing rather than in the sense of advancing techniques such as Doppler, multiparameter, or electronic scanning systems to be covered by the other working groups and discussed later in this paper. Hardware options, such as dual Pulse Repetition Frequency (PRF), dual frequency, and FM–CW systems, however, were included.

In the near future, most European users will have to work with existing radar systems, which are often far from being used to the limits of their potential. Therefore, the potential for development of methods used with existing systems and an indication for further improvements will be assessed in this section. An overview of European operational weather radar systems (Joss 1995) is given in Table 1.

a. Calibration for the radar hardware

Much effort has been dedicated to discussing the importance of the calibration of the current radar systems to hydrological applications. The precision required for *quantitative* radar measurements, such as needed to issue flood warnings, is far more demanding than for a *qualitative* use of radar, for example, for just following and extrapolating echoes in time and space. The concept of calibration, clutter elimination, profile correction, and adjustment with rain gauges, therefore, receives much attention. The basis of calibration, the requirements, and the results obtained in Germany and Switzerland are described in some detail by Joss et al. (1996). Excellent stability of system parameters during normal operation was found to be well within 0.2 dBZ (3% of rain rate). This result fulfills the needs for estimates of rain amount and flood warning but unfortunately only concerns instrumental aspects. It means that, for a well-maintained radar, errors caused by the equipment can be neglected compared with variations related to weather processes [that is, the vertical profile, inhomogeneous beam-filling, Z–R (reflectivity–rain rate) re-

TABLE 1. Some parameters and scan strategies of the operational radars used in COST countries. The letters in the last column indicate the method used for removing clutter in each country (M—clutter map; D—Doppler measurements; S—signal statistics; P—polarization; R—resolution; I—interpolation), as explained in more detail in the text.

Country	**No. of radars**	**Frequency bands**	**Number of elevations/ repet. time (min)**	**RPM (min^{-1})**	**PRF (s^{-1})**	**Clutter discrimination**
Austria	4	C	21/10;5	4, 5	600	M,D,S,R,I
Croatia	1	S	14/10	2–3	600	M
Czech Republic	2	X,S,C	13;20/10;10	3	250; 556	M,D,I
Denmark	2	C	10/10	2–6	250–1200	M,S
Finland	6	X,C	11/15	2–6	250–1200	M,D
France	13	C,S	3/3	0.84	250–330	S,I
Germany	10	C	19/15	3	600–1200	M,D,I
Greece	4	C,S	4/10	3	250	—
Hungary	3	X,S	4/5	3	250	—
Ireland	2	C	10/15	2–6	250–1200	—
Italy	14	X,C	10/15	2–6	300–1200	M,D,P,I
Netherlands	2	C	4/10	3	250	S
Norway	1	C	12/10	6	250–1200	M,D
Poland	2	C,X	14/10	6	250	M,D
Portugal	1	C	13/15	3	250	M,S,I
Romania	3	X,S	10/25	1–6	250	M
Slovakia	2	X,S	15/15;30	6	250	M
Slovenia	2	C	16/7.5	3	250–1200	M
Spain	12	C,S	20/10	2–6	250–1200	M,D
Sweden	11	C	10–15/15,5	2–6	250–1200	M,D
Switzerland	3	C	20/5	3–6	600–1200	M,D,S,R,I
United Kingdom	12	C	4/5	1–3	300–1200	—

lationship, attenuation, etc.]. Furthermore, it is concluded that considerable redundancy is needed when determining relevant parameters for automatic fault monitoring and remote diagnosis to allow system deficiencies to be identified at an early stage. This is a very important feature for unmanned, automated equipment intended to issue flood warnings.

b. Adjustment of radar data using independent data, for example, rain gauges

Agreement exists among participating countries that we should use rain gauges for adjustment, but adjustment should be carried out only after having verified the accuracy and the stability of the radar hardware with microwave test equipment and after having corrected for the other errors mentioned in the previous paragraph. When are adjustments reasonable? Are adjustments in real time helpful? The integration time required for optimum adjustment depends upon the application. We should modify the data only if the standard error of estimate (representativity) of the gauges is smaller than the bias caused by other errors (Smith et al. 1990). However, the high variability of precipitation in time and space strongly reduces the representativity of rain gauges. Hence, much effort continues to be dedicated to finding the optimum way of using ground truth for adjustment.

Different adjustment strategies are applied in different European countries. The United Kingdom uses real-time adjustments and Switzerland is preparing to do so. Off-line adjustments are used in Germany and Switzerland, and Spain is planning to follow soon. Experience of comparing data from radar, gauges, and river flow in Switzerland during the past seven years is described in Joss et al. (1995). The results show agreement between monthly amounts estimated by different instruments but on occasion show significant differences caused by beam blockage and beam broadening.

c. Radar scanning procedures

In the past, judging by the results obtained at close ranges where problems caused by limited radar horizon can be neglected and with limited computing power, we were tempted to use uncorrected data from the lowest antenna elevation only to estimate precipitation at ground level. At longer ranges, however, the beam broadens, and the curvature of the earth and the horizon cause dominant errors in estimating precipitation. There, we can significantly improve measurements by applying corrections based on the vertical profile of reflectivity and estimating the degree of beam blockage (Harrold et al. 1974; Joss and Lee 1995). For best results with such a correction, we need the full volume information. This, however, needs more measurement time. An electronically scanned antenna would ease such a task significantly, but even with today's mechanical scanned radars, when using the flexibility of existing hardware, for example, by optimizing the rotation rate and pulse repetition frequency, we may improve the quality of radar data and obtain fast update rates. First steps are already reflected in the scan procedures adopted in different countries.

An overview of the strategies for scanning the volume as used in 15 countries is documented in Joss (1995). Table 1 contains the principal characteristics of radars in existing networks of COST countries. In Europe X to S band is applied because, for quantitative work including snow and rain, a compromise is needed between errors arising from attenuation and non-Raleigh scattering at shorter wavelength. These errors are caused at longer wavelength by reduced beam resolution at farther ranges and increased ground clutter at all ranges where the beam, or its sidelobes, may hit the ground in normal as well as anomalous propagation situations. The chosen parameters reflect the compromise in each country (e.g., in Finland, where snow measurements with high spatial resolution are desired, C- or even X-band radars have a better cost/benefit ratio than S-band radars). In Spain, where severe thunderstorms containing hail are of most importance, the "best compromise" is shifted toward longer wavelength. This compromise needs careful analysis involving the dominant rain rate of interest, the average distance of storms from the radar, and the price of the radar. Table 1 reflects the pulse repetition frequency, the speed of antenna rotation, number of elevations, and resulting repetition time for the complete (volume) scan. These parameters reflect the compromises needed between speed of update, detail of result, and its statistical error.

d. Elimination of clutter and anomalous propagation effects

A fundamental requirement for quantitative precipitation measurements is the quantitative removal

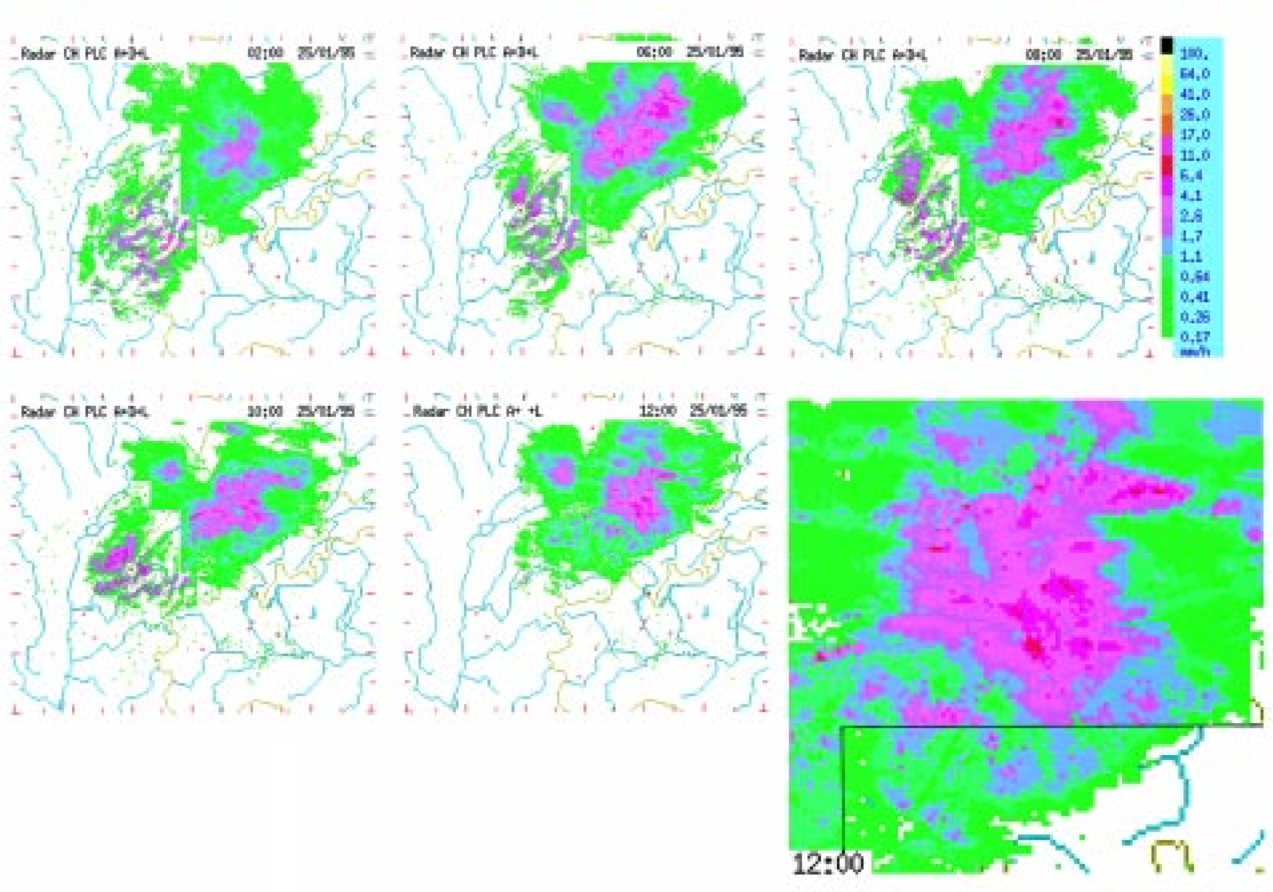

FIG. 1. The composites of the three Swiss radars show the best estimate of rain rate in mm h^{-1} at the ground. Two of the radars, Albis (northeast) and Lema (southeast), are of the Dopplerized third generation, whereas the southwestern system (La Dôle) is of the non-Dopplerized second generation. The new systems provide extrapolations to the ground level by using profile corrections. They further apply five algorithms for clutter suppression to every pixel of $1° \times 1° \times 83$ m, as described in the text, whereas the older radar uses just a clutter map. In the 12:00 plane, lower middle, only results from the new radars are shown. This clearly demonstrates improvements compared to the spotty information from the older southwestern radar. The enlarged figure, lower right, shows residual differences between the two new radars. They can be distinguished at a line west to east, approximately one-third of image extent from south.

of ground clutter without losing any signal from the precipitation. None of the numerous methods already known and applied work to full satisfaction. The most promising strategy is to apply a combination.

An overview on the ground clutter removal algorithms used in 10 countries so far is documented in Joss (1995). They can be divided into six groups.

1) *Map.* A clutter map, provided and updated on clear day measurements marks and eliminates all pixels judged to contain clutter.
2) *Doppler.* On the basis of using the radial velocity, data having "nonzero velocity" using Fourier transform and other filter cancelers is classified as precipitation.
3) *Statistical.* Elimination of clutter signals on the bases of noncoherent signal statistics in time and space.
4) *Resolution.* Advantage to recognize and remove clutter is taken from the characteristics of clutter to appear in spots, leaving valid information in between. Its retrieval (interpolation) is eased if using short pulse length and sampling gates.
5) *Interpolation.* After clutter has been eliminated, the blind zones have to be filled using vertically or horizontally adjacent information.
6) *Polarization.* Recognizes clutter by the distinct polarization signatures of various polarimetric parameters.

The first five methods are being tested in Switzerland for the new, third generation of radars. The first experience is promising (Lee et al. 1995).

Figure 1 illustrates the improvements obtained with the new clutter suppression as compared to the old way of just using a clutter map. Data from the two newly installed Swiss radars, Lema (southeast 1625 m above sea level) and Albis (northeast 928 m), both Doppler C-band radars using a 1° beam, are composited with the third older Swiss radar, La Dôle (southwest 1680 m). Data from the old radar show far more "holes" in the echo, leftover from the old strategy of clutter suppression alone. Differences in displayed rain rate between the two new radars in the east are also noticeable in the 1200 UTC zoom image at the west–east borderline between the two composite parts. This reflects problems of compositing information from several radars. In this case, the two radars are of exactly the same type and the common ability to measure reflectivity is much better than the observed difference (Della Bruna et al. 1995). At the borderline the step amounts to about 3 dB of reflectivity equivalent to 60% of rain rate. It demonstrates that the correction procedure and the compositing algorithm still need perfecting: to avoid overcorrection, the error caused by differences of visibility height between the northern and the southern radar are not fully compensated. At the borderline the northern radar sees echos already above 2.5-km altitude, whereas the southern radar there sees only echos above 4.5-km altitude. This results in the 3 dB more reflectivity seen by the northern radar.

e. Approaches for improving precipitation estimates

At short ranges, where the beam is small, the bright band can cause important overestimation of surface precipitation. Several authors have described methods of reducing these errors, for example, Smith (1986). At longer ranges, however, significant and increasing underestimation of precipitation is observed. The percentage of precipitation seen by a radar (as compared to gauges) relates closely to the visibility of precipitation above the ground, which is influenced by earth curvature, terrain beam blocking, and beam broadening at longer ranges. Indeed, with increasing distance, the earth curvature and beam broadening become the dominant sources of error (Kitchen and Jackson 1993). Note that the visibility height of the radar is defined by the height to which an echo must reach to be seen. Joss and Lee (1995) propose ways to significantly improve clutter suppression and rain measurements by applying corrections based on the vertical profile of reflectivity and the visibility by the radar for each pixel.

Similar methods are applied in different countries. Finland (Koistinen 1986), Slovenia (Divjak and Rakovec 1995), and Switzerland (Joss and Lee 1995) use measurements aloft for obtaining a better estimate of the precipitation reaching the ground. Profile corrections are probably the most efficient, easiest, and cheapest way to obtain better results. Climatological "average profiles," together with a rough guess of the visibility height, give significant improvement (Joss and Waldvogel 1990).

We conclude that, at long ranges of more than 100 km, an important reduction of intensity may be caused by earth curvature and incomplete beam filling. At short ranges, the bright band can lead to considerable overestimates. Therefore, quantitative estimates of precipitation may significantly be improved if corrections including our understanding of the precipitation evolution and the knowledge of what the radar really can measure are used. For example, corrections are needed for reduced visibility because of earth curvature, beam broadening, and orographic beam blockage in combination with variations of reflectivity with height (vertical profile).

f. Attenuation

The quantification of attenuation effects, particular for C-band radars, caused by heavy precipitation as well as by the radomes is a topic of central interest in Europe where most radars operate at this frequency. This problem is particularly important in severe storm situations. No reliable solution is available at present, although, as we shall see, polarization diversity may offer a solution.

3. Doppler weather radars

Over the last few years, radar manufactures have increasingly offered Doppler weather radars as a standard product. Indeed, manufacturers generally regard a non-Doppler radar as an uneconomic proposition to produce, although they do offer to upgrade a non-Doppler radar to Doppler operation. It is clear that Doppler radars are rapidly becoming the operational standard, although some countries in Europe utilize Doppler data much more than others for operational weather forecasting. For example, Sweden and Finland provide Doppler wind information routinely to forecasters, whereas in

France such information is not available for weather forecasting. Other countries are presently considering how best to use Doppler products operationally.

With this background, COST 75 established a working group with the specific tasks of identifying the requirements for Doppler data and how these data are, and can be, used to address specific problems. The aim is to clarify where there are gaps in our knowledge of Doppler radar and to develop a review program into operational Doppler radar leading to an outline specification of the next generation of systems for Europe.

Membership of the working group includes representatives of Austria, Finland, France, Germany, Italy, Sweden, and the United Kingdom, although all participants in the action COST 75 have provided valuable information and comments on the material produced by the working group. In this section, some of the information collated so far is discussed.

a. Distribution and type of Doppler radars in Europe

Figure 2 shows the current deployment of Doppler radars in Europe. While some countries have extensive networks, for example, Spain and Sweden, other countries have none, for example, France (excluding research radars). This situation reflects the continuing uncertainty of some countries of the benefits of Doppler radar to operational meteorology while recognizing the obvious research benefits. Nevertheless, there has been a rapid growth in the use of Doppler radars of the last 12 years or so. In 1982 there was only one such radar in Europe. Doppler radars in Europe are generally low power, about 30% of the power of the U.S. WSR-88D/NEXRAD radars. Both magnetron- (Enterprise Electronics Corporation, Gematronik, Ericsson, Siemens Plessey) and klystron- (Segnalamento Marittimo ed Aereo) based systems are deployed. The magnetron systems use stabilized power supplies and phase-locking technologies to achieve the level of coherence necessary for most aspects of Doppler operation. There are no WSR-88D-type systems in Europe.

b. Requirements for Doppler radar data in Europe

The main requirements for Doppler radars in Europe have been identified as

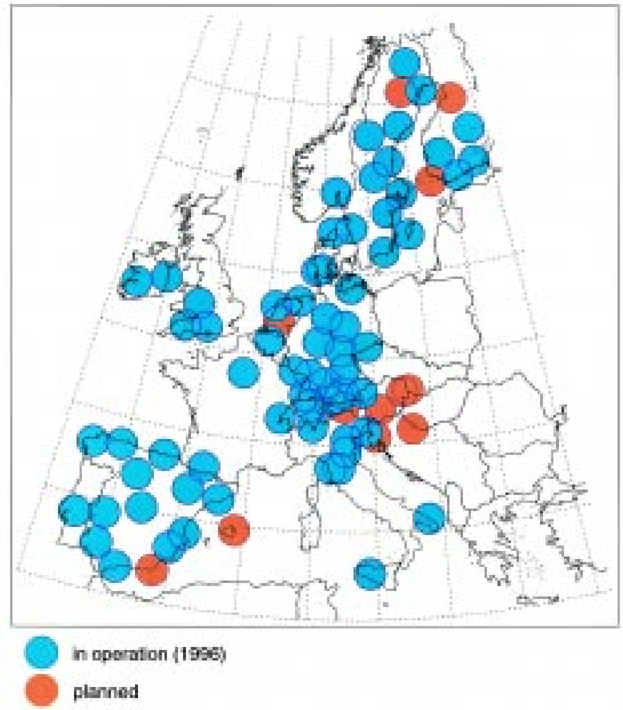

FIG. 2. Doppler weather radars in Europe used for operational services and for research. The circles indicate a radius of 100 km, which is the typical quantitative range to which radars in Europe are used to make measurements of precipitation. Often Doppler measurements are used up to 120 km, whereas reflectivity measurements are evaluated up to 230 km.

- ground clutter rejection including anomalous propagation echo suppression;
- low-level winds for deriving wind shear and divergence for aviation forecasting;
- wind data for numerical weather prediction (NWP) data assimilation; and
- nowcasting gust fronts, mesocyclones, and thunderstorms.

The priority of the individual requirements varies from northern to southern Europe related to the frequency of occurrence of severe storms and significance of snow and icing problems. In very general terms, the emphasis in northern Europe is on using Doppler radar for ground clutter rejection and wind profiling by the velocity azimuth display technique (VAD); see below. Research into the use of both VAD and radial winds within the data simulation procedures of NWP models is being undertaken in several countries, notably Sweden and the United Kingdom. In southern Europe, severe storms occur more frequently than in northern

Europe, and the use of Doppler radar data for nowcasting these events, and associated phenomena such as tornadoes and downbursts, is an important requirement. Such a requirement is being considered further in connection with the need for electronic scanning radar antennas since algorithms developed to detect these phenomena require the rapid acquisition of four-dimensional data.

There remains uncertainty in Europe as to how to use Doppler radar data effectively within an operational, as opposed to research, environment. In the United States, the introduction of the WSR-88D radar has led to significant improvements in the accuracy of storm warnings. It has increased the lead time for tornado warnings from between zero and 4 min to as much as 20 min and in a few cases more than 20 min (Polger et al. 1994). However, the large number of products (Klazura and Imy 1993) has been developed for selection by a human forecaster experienced in mesoscale meteorology. The methods of using Doppler radar data developed in the United States have not, in general, been exploited in Europe. In particular, techniques of improved severe storm warning are not being used extensively as these events are less frequent over much of Europe. However, work is under way to develop methods of using Doppler data operationally. There is a need to develop products specified to user needs, which can be absorbed operationally by nonspecialists or by using totally automated procedures.

c. *Basic understanding of Doppler measurements*

There are a number of areas that need to be clarified before the specification of the next generation of radars in Europe can be finalized. For example, what is called spectral width is subject to uncertainties depending upon how it is measured and what Nyquist interval and signal to noise ratio are present in the system (Keeler and Passarelli 1990; Doviak and Zrnic 1984). Work has been instigated within COST 75 to investigate this further. Range folding and velocity aliasing are problems that need to be dealt with to ensure that Doppler data are presented to users in an easy to assimilate way. The basis of the techniques to deal with these problems are now understood (e.g., Doviak and Zrnic 1984; Collier 1996).

d. *Clutter suppression*

The clutter suppression capabilities of Doppler radar have only been used operationally in a few locations in Europe. However, currently this is a very active area of research in the United States and in Europe. There is a need for performance verification studies, as removing echoes having zero speed can effect the echo pattern very much. Spectral broadening of echoes may lead to the retention of some clutter and/or the removal of some rain. This problem may be addressed by using the Doppler spectrum and employing a range of clutter filters. However, it is already clear that Doppler techniques alone are not sufficient (Joss and Lee 1995).

e. *Clear air detection capability*

The detection of clear air phenomena, while being much studied in the United States, has been largely ignored in Europe. There is an increasing recognition that important forecast information could be obtained from such observations, as discussed next.

There remains doubt as to what the clear air scattering mechanisms are in Europe. In northern European countries in summer, clear air echoes are detected to 50–60-km range and 1–2-km altitude, whereas in winter such echoes are rarely seen. It is felt that humidity gradients as well as insects must be responsible for these echoes. In Spain, clear air echoes are detected to 100 km range with C-band radar. These echoes are mostly due to insects. Achtemeier (1991) discussed in some detail radar observations of insects in flight. More recently, Wilson et al. (1994) discussed the origin of clear air echoes associating them with both particulate (birds and insects) and Bragg scattering (refractive index inhomogeneities).

Further studies under the aegis of COST 75 are planned. It is clearly important to ascertain the likely frequency of occurrence of clear air echoes across Europe in order that the next generation of radars may be specified with the correct sensitivity if clear air detection is an important requirement.

f. *Radial and vertical profile winds*

Doppler radars are capable of providing both radial and vertical profiles of horizontal wind. Vertical wind profiles are derived using a number of different methods: VAD, volume velocity processing (VVP), and uniform wind. These techniques assume approximate linearity of the wind field and therefore are not generally applicable to convective storm internal circulations. For more stratiform

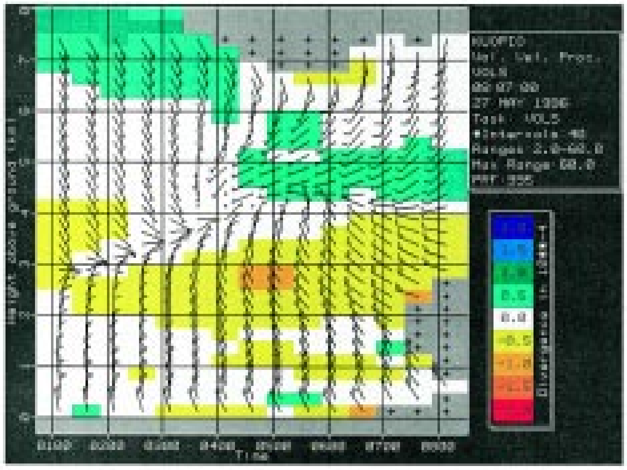

FIG. 3. Time–height cross section of VVP wind soundings derived from the Finnish Doppler radar at Kuopio at 0100–0800 UTC 27 May 1996. The color background exhibits the radar derived distribution of divergence 10^{-4} s^{-1}. Crosses indicate points where the signal is either too weak or does not pass the quality thresholds as, for example, signal coherency. The case is related to a passage of deepening frontal wave followed by cold air advection.

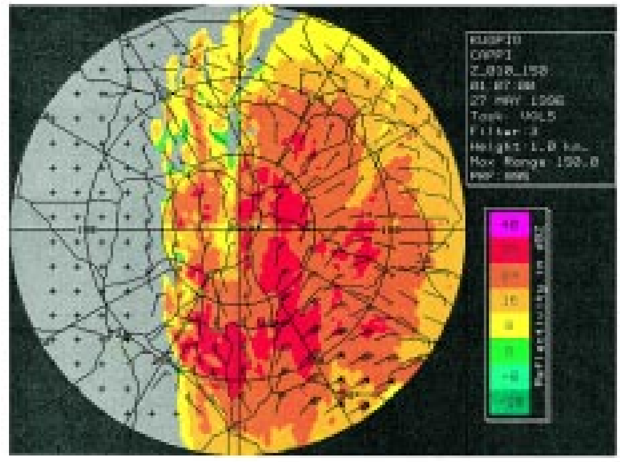

FIG. 4. Horizontal wind field at the constant altitude plan position indicator (CAPPI) height of 1 km, derived by VVP processing in 30 km long and 30° wide volume segments, and then interpolated to a grid of 10 km × 10 km resolution at the Kuopio Doppler radar at 0107 UTC 27 May 1996. The color background exhibits the slightly smoothed dBZ field at the CAPPI height of 1 km.

situations, however, these methods show consistent results as demonstrated by the Finnish radar network, in Figs. 3 and 4 (see also Scialom and Testud 1986; Andersson 1995). The subjective three-year experience in Finland of meteorologists using VVP winds together with soundings from a high-resolution limited area numerical model at the radar sites suggests that VVP winds are accurate and reliable for purposes of the operational weather service.

There remains the requirement to convince users that VAD winds may be taken as actual measurements of wind. Work is under way in several European countries to develop ways of incorporating Doppler winds (both VAD and radial winds) into the data assimilation procedures of mesoscale NWP models.

The accuracy of VAD winds is now being investigated operationally in several European countries. In Sweden, the Swedish Meteorological and Hydrological Institute carries out wind profile measurements routinely every 3 h. These measurements have a resolution of 30 m up to an altitude of 500 m and a resolution of 100 m thereafter. Assessment of the temporal continuity of these measurements has been carried out showing excellent consistency. Comparisons of Doppler wind profiles above the radar site were made with wind profiles from radiosonde data within some minutes, showing that the differences between the two sets of measurements are comparable with the differences obtained from radiosonde ascents made some 20 km apart (Kitchen 1989).

The assimilation of Doppler wind information with either radial wind components or VAD profiles is also expected to be relatively straightforward. The U.S. pilot studies (e.g., Lilly 1990) have indicated the exciting possibilities of using Doppler wind information in this way. However, to ensure reliability and consistency it may be necessary to use methodologies both adjoint and variational methodologies similar to that described by Qui and Xu (1994) and Laroche and Zawadzki (1994).

g. New Doppler radar products

Crum and Alberty (1993) describe the flow of WSR-88D base data from the radar data acquisition to display as products for the radar forecaster. Similar types of products have been developed from Terminal Doppler Weather Radar (TDWR) data. Hermes et al. (1993) describe in detail the gust-front detection and wind shift algorithms for the TDWR. Reviewing the characteristic features of the Doppler methods used in NEXRAD (WSR-88D) and TDWR, it appears, at first sight, that there is little scope to develop further products.

However, products not included in the WSR-88D system that could be of importance in Europe include the following:

- probability of icing by detection of shear zones and embedded convection (Pobanz et al. 1994);
- indication of the stage of development of particular weather types, possibly derived from measurements of spectral width (Hardaker and Collier 1995) from which may be derived the eddy dissipation rate (Cohn 1995);
- thermodynamic parameters derived with the aid of microphysical models (Hauser et al. 1988); and
- anomalous propagation identified from eddy-dissipation-derived measurements of C_n^2 (Wesely 1976; Brewster and Zrnic 1986).

h. Scan strategies and networking

While some European countries use only Doppler radars, other countries have a mixture of Doppler and non-Doppler systems. Volumetric products, usually derived from reflectivity, are regarded to be of equal or greater importance than Doppler wind products. In addition, most countries wish to produce network composite images, so individual radars cannot be operated without regard to other systems. One option implemented in the United Kingdom and elsewhere is to gather volume products in non-Doppler mode for (say) 10 min in every 15-min period, allowing Doppler operation in the remaining 5 min. An alternative approach has been implemented in Switzerland in which both reflectivity and Doppler data are collected continuously for 20 elevations on a 5-min cycle time (Joss and Lee 1995).

However, in rapidly changing convective situations, Doppler data every 10–15 min, as collected in the United Kingdom and elsewhere, is too infrequent. The WSR-88D employs one of four volume scan strategies that require 5–10 min to complete with Doppler wind information being interleaved with reflectivity data. These include clear air strategies (five elevations every 10 min, 0.5°–4.5°) and a precipitation severe weather strategy (14 elevations every 5 min, 0.5°–19.5°). The dominant user requirement will decide what strategy to employ in different parts of Europe. The international exchange of wide-area reflectivity data will also be an important consideration. Since Doppler radar network densities in parts of Europe are sparse, they are unlikely to provide all the required wind measurements. The possible use of complementary data supplied from bistatic multiple-Doppler radar networks (Wurman et al. 1993) is being investigated by some countries in Europe. However, it is perhaps more likely that Doppler winds will be assimilated into numerical models if the difficulties alluded to in section 3f can be overcome.

4. Multiparameter radars

Most operational weather radars transmit at a single frequency and polarization and measure the intensity and the Doppler shift of the return power. A COST 75 working group is concerned with the additional information available from multiparameter radars that exploit either the polarization properties of the radar returns or compare the return power at several different frequencies. We are fortunate in Europe to have several powerful multiparameter radars that are currently used for research. It is useful to consider whether such techniques are appropriate for incorporation within future operational radar networks.

Two particular themes where multiparameter radars could have the most benefit in an operational environment are

- improved quantitative estimates of rainfall rates at the ground, and
- identification of severe weather hazards, connected, for example, with hail.

Many published research papers indicate how multiparameter techniques can contribute to these two topics, but it must still be demonstrated that they can produce a positive and economic impact in an operational environment.

This work so far culminated in a 2-day open workshop that was held in Reading, United Kingdom, on 3–4 July 1995. One aim was to identify areas where advanced polarization diversity radar could provide improved rainfall rates. Results from polarization diversity radars in Austria, Italy, Germany, and the United Kingdom were presented; such radars compare the radar returns using vertically and horizontally polarized transmitted radiation. Observations from dual frequency radars in eastern Europe were also presented and discussed (e.g., Brylev et al. 1995).

a. Polarization techniques

The number of additional independent parameters available from polarization diversity radars can appear bewildering. We shall initially consider linear polarization, as this is used by most radars in Europe. A parallel set of variables exists for circular polarization and observations made using one polarization basis can, in theory, be converted to the other.

Radar transmitting pulses that are alternately horizontally and vertically polarized can measure Z_H and Z_V, the reflectivities for the two polarizations, and, with the addition of a cross-polar receiver, the orthogonal reflectivity Z_{VH} can be recorded. If the radar is Dopplerized, then the difference in the phases of the returns in the two polarizations ($\phi_{DP} = \phi_V - \phi_H$) can be estimated.

The application of the three major parameters besides Z as defined for a polarisation diversity radar are summarized briefly below.

The differential reflectivity $Z_{DR} = 10 \log (Z_H/Z_V)$ senses the mean shape of the hydrometeors. Raindrops are oblate to a degree that depends upon their size, so Z_{DR} is a measure of mean raindrop size, and a combination of Z and Z_{DR} provides an estimate of the actual drop-size distribution that will, on average, yield a more accurate rainfall rate than from Z alone. Interpretation of Z_{DR} for ice is more difficult. Tiny ice particles as needles or plates falling horizontally oriented give high values. Hailstones tumble as they fall and so should be associated with zero Z_{DR}.

The linear depolarization ratio LDR = $10 \log(Z_{VH}/Z_{HH})$ is a measure of the shape, the refractive index, and the fall mode of the precipitation particles. The highest cross-polar returns are associated with particles that are both wet and oblate and tumble as they fall. LDR is an excellent detector of wet ice. In convective clouds LDR can locate regions of small hail particles that are wet, and in stratiform systems LDR can identify melting snow that causes the enhanced reflectivity known as the bright band. Clutter is also associated with high LDR.

The specific differential propagation phase shift K_{DP}, the rate of change of ϕ_{DP} with range, is a forward propagation effect. As the radar wave advances through a region containing oblate raindrops, its velocity for horizontal polarization falls below that for vertical polarization, and so the phase difference ϕ_{DP} between the two polarizations increases with range. In theory, K_{DP} is more closely related to the rainfall rate than Z. In severe thunderstorms, the value of Z is dominated by the returns from the hail. The K_{DP} may provide a better estimate of rain rate as its response is usually controlled by raindrops; most hailstones tumble as they fall and therefore usually do not contribute substantially to K_{DP}.

The circular depolarisation (CDR) is the ratio of the cross-polar to copolar return for circular transmitted radiation. The highest values of CDR are associated with particles that are wet and oblate irrespectively of fall mode. Heavy rain and wet hail show increased values.

It is also possible to define various correlation parameters between the time series of the fluctuating radar reflectivity estimates. This is an area of active research, and it seems premature to recommend its implementation in an operational environment.

b. Recommendations for applications and further research

1) Improved estimate of rainfall from polarization radar

It is well known that rain-rate validation on an event basis by gauges is difficult because of the poor spatial representativity of gauges (e.g., Gorgucci et al. 1995) and the different measurement conditions for radar and gauges (see section 2). With this in mind, and given that C-band frequencies are mainly used operationally in Europe, we try to check whether, and which, multiparameter methods work reliably at C-band frequencies.

At S-band frequencies, improvement at short range by improved characterization of drop-size distribution (DSD) using Z_{DR} has already been demonstrated (Goddard and Cherry 1984).

Theory shows that for C-band frequencies, Z_{DR} values are needed at an accuracy of 0.1–0.2 dB, which implies that stable correction algorithms for propagation effects at C-band frequencies need to be further developed and demonstrated (Aydin et al. 1989; Bringi et al. 1990; Chandra et al. 1994). The potential for improved rainfall via better DSD estimates in heavier rain at short ranges needs to be studied in detail as well as correction schemes for a hail–rain mixture.

It has frequently been demonstrated that LDR is very useful for identifying the bright band of enhanced reflectivity associated with melting snow, which may cause overestimation of rainfall rate (Illingworth and Caylor 1989). Different hydrometeors can be identified more definitely by use of LDR (e.g., Höller et al. 1994; Hagen et al. 1995).

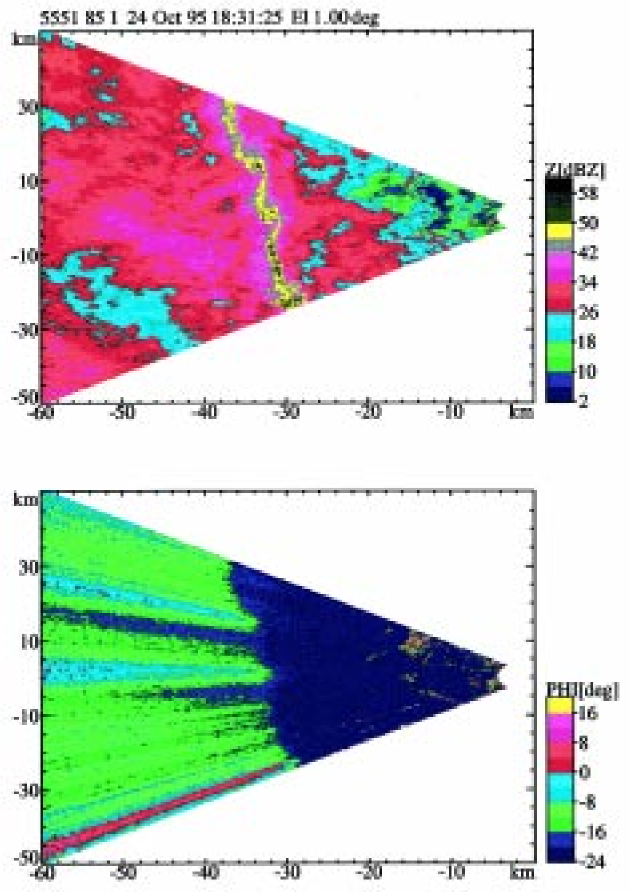

FIG. 5. Plots of reflectivity (Z) and differential phase (PHI) from a low-level scan (1° elevation) through a narrow rainband of a cold front 30 km to the west of the Chilbolton radar, United Kingdom. In the rainband, Z values exceed 50 dBZ and the differential phase between horizontal and vertical returns increased in the mean by about 12°. Measurements of increased differential phase of up to 30° are caused by increased rain intensities through longer path lengths across the rainband. A gauge recorded rainfall rates of over 150 mm h^{-1} as the rainband passed by. This demonstrates the potential of the differential propagation phase for quantitative rain-rate estimations.

Further verifications should stabilize these algorithms and improve the quantification of the different hydrometeor contents in the dynamical frame of a cloud system in order to intercompare developments with cloud models (Höller 1995).

Such quantitative measurements call for correction procedures to eliminate propagation effects, especially at C-band frequencies. Applications, then, are contributions to estimate rain profiles (including the bright band) more accurately and to estimate the use for numerical weather prediction models. For future operational applications, the cost/benefit of adding LDR techniques needs to be quantified.

The specific differential propagation phase shift K_{DP} promises to improve rain-rate estimates, especially for heavy rain and if hail is present (Balakrishnan and Zrnic 1990). The beam must be in the rain, which is a problem at long ranges when the 0°C level is close to the surface (Blackman and Illingworth 1995; Goddard et al. 1994). Unlike Z_{DR} and LDR, there are no attenuation problems at C-band frequencies. Further investigations are ongoing and are planned to demonstrate the accuracy, quality, and interpretability of K_{DP} in dependance of rain rate, dwell time, and Mie scattering effects. A clear example is shown in Fig. 5, where there is an increase of the differential phase between horizontal and vertical returns by up to 30° by a narrow intense rainband as measured by the Chilbolton (United Kingdom) research radar.

At C-band frequencies, the use of Z_{DR} to improve rain-rate estimations by estimating drop sizes can be affected by differential attenuation that biases Z_{DR} negatively with increasing range. This negative bias, however, may itself provide a means of estimating the attenuation of Z.

The recognition of attenuation itself can be improved by depolarization measurements, either of LDR or the circular depolarization ratio CDR if circular polarized radiation is feasible.

2) QUANTITATIVE MEASUREMENTS OF SNOW

The use of polarization for better estimates of precipitating snow has received little attention and is an open question. Forecasting and nowcasting snow on the ground is an objective particularly at higher grounds and in northern Europe. Polarization methods can measure the height of the bright band (freezing level) very accurately, but the resolution will degrade with distance as the beamwidth increases. This so-far neglected topic should be addressed in the future.

3) HAIL AND SEVERE WEATHER DETECTION

The research on deep convective systems by combined use of polarimetric and Doppler radar measurements during the last 10 years or so has significantly increased our knowledge of the precipitation forming process coupled with the dynamics of these storms (Höller et al. 1994; Meischner et al. 1991). In southern Germany some 200 thunderstorm systems were investigated over a period of 6 yr and were documented, covering significant times of their life cycle. The results of these 6 yr

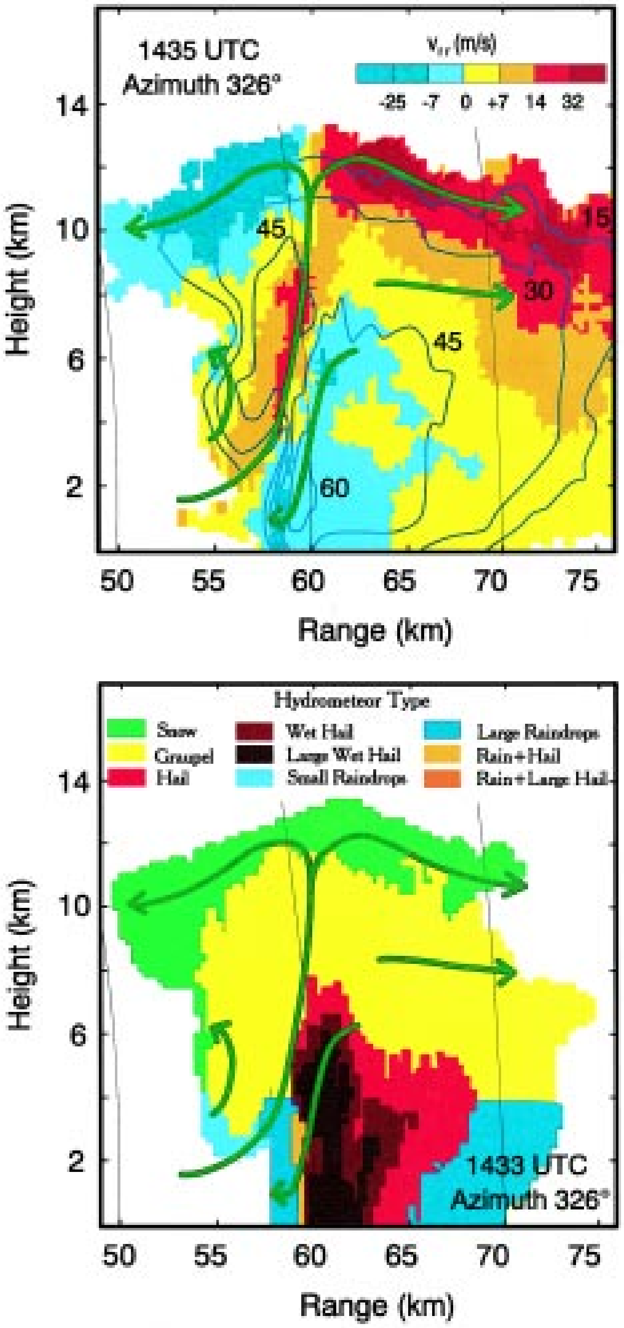

FIG. 6. Vertical section (RHI) taken by POLDIRAD through the center of a severe hailstorm that occured in southern Germany on 30 June 1990 (see Höller et al. 1994). The upper panel shows storm-relative radial velocity v_r overlayed by reflectivity contours (solid lines) labeled in dBZ. The lower panel indicates the different types of hydrometeors as derived from Z_{DR} and LDR measurements taken 2 min earlier at the same azimuth. The bold arrows illustrate possible streamlines.

show that of the 200 observed systems, about 67% occurred as single cell, 29% as multicell, and 4% as supercell storms. Frequently, single or multicells were observed to be organized at line structures. The damage potential increases with the degree of organization. The observed hail categories significantly increase from single-cell-type storms via multicells and squall lines to supercell storms (Höller 1994).

Figure 6 shows the microphysical structure embedded within the dynamical structure of a single-cell thunderstorm as a vertical section (RHI) observed with the polarimetric Doppler radar of the German Aerospace Research Establishment (DLR) in Oberpfaffenhofen, Germany. The simultaneous use and display of combined polarimetric and Doppler measurements contribute to storm type and life stage recognition, supplying improvements in nowcasting capability.

The knowledge of the relation between storm type and possible hazards as hail, heavy rain, lightning, and gusts and their appearance relative to storm structure, storm dynamics, and state of life cycle clearly is an important potential for forecasting and nowcasting these events. It needs to be further condensed to conceptual models, and its superiority to complementary methods such as reflectivity observation, satellite observations, lightning observations, and numerical weather prediction modeling needs to be further investigated and demonstrated. This task, at least in its completeness, is beyond the scope of COST 75, but this knowledge will contribute toward improved nowcasting techniques.

4) Clutter and anomalous propagation

Polarization diversity techniques in combination with techniques using conventional reflectivity and Doppler could lead to an improvement of clutter identification. Birds can strongly bias Doppler velocities. Birds may be flagged by Z_{DR} and LDR will improve clutter identification (e.g., Wilson et al. 1995). Anomalous propagation echoes remain problematic. It may be possible to use Doppler filtering techniques similar to those used for ground clutter removal in normal propagation conditions but in combination with polarization techniques. Further research is necessary to develop and validate such combined approaches.

5) Dual wavelength techniques

We need to make the best use of existing dual wavelength systems for hail detection–discrimination and for rain-rate estimates via attenuation–

reflectivity combination. Systems in Europe are used more for research than for operational work because of their complexity (e.g., Russchenberg 1995; Dombai and Nagy 1995). Much work in the 1970s carried out in the United States has not been developed further. Using the systems in use in Europe, we will be able to quantify the benefit and limitations in today's technical environment. Topics to be tackled further are dynamic range problems for low and high attenuation, beam matching, complications due to Mie versus Rayleigh scattering, and the use for clutter detection.

6) Basis of polarization

Most European polarimetric radars use linear polarization, although elliptical polarizations are available. Circular polarization has the advantage that no fast switching of the polarization of the transmitted pulse is needed to estimate the parameters of meteorological interest. The K_{DP} from circular polarization may be less noisy than that from linear because no temporal interpolation of phases is needed. CDR is more sensitive to drop shape for light rain than Z_{DR}. CDR is not as good as Z_{DR} for hail detection (e.g., Jopson and Holt 1995) and is not able to detect weak echoes. Future work will concentrate on examining the quality of K_{DP} and CDR data from circular polarization and the potential benefits for applications.

These polarization techniques need to be demonstrated and compared with single-polarization and Doppler techniques in an operational environment. Such a project is planned and will contribute to the final recommendations of COST 75.

7) Hardware aspects

Important aspects of possible future applications of multiparameter measurements in an operational environment are the additional costs in relation to the improved benefits. The most important items for future work are the following:

- quantification of the effect of a radome on polarization measurements;
- cost estimations for the retrofit upgrading of existing radars (e.g., an extra receiving channel to estimate LDR or a fast transmit switch for Z_{DR} and K_{DP} in comparison with a slow transmit switch and a dual *T*/*R* module and additional software);
- how to assure high quality Z_{DR} measurements with an accuracy up to 0.1 dB;
- provide automatic *Z* calibration by dual polarization systems using K_{DP} together with Z_{DR}; and
- estimate installation costs and added value of using circular polarization.

5. Electronic scanning radars

Over the last 10 years, defense radars have been developed using electronic scanning technology. In parallel, VHF–UHF radars have employed this method to provide wind measurements in the troposphere and stratosphere. Work is ongoing to investigate the future design of air traffic control (ATC) radars and electronic scanning is being considered.

Weather radars with electronically scanning ("E-scan," phased array) antennas are expected to provide higher measurement speed and flexibility, resulting in reduced tropospheric volume acquisition times, an easier recognition of short duration weather phenomena, and better adaptation to the signal characteristics of precipitation and clutter echoes. In fact, an E-scan weather radar is not just a conventional radar equipped with a new, more complicated and expensive, antenna, but needs major additional modifications in the transmitter–receiver chain as well as in the signal processing and interpretation algorithms. A complete new system design may be the most economical approach.

For example, a full exploitation of the E-scan radar's cycle time reduction would not be possible without providing special measures for the intensity dwell-time reduction, which in turn generate problems with Doppler compatibility (need for Doppler-immune compression–modulation schemes). Furthermore, the E-scan radar's ability of deliberately choosing the illumination and reception direction is offering new possibilities in clutter detection–correction, to be obtained from pseudoextended dwell times for clutter-suspicious pointings (resampling of that pointing after the precipitation decorrelation time). Finally, as with each new technique, technological and economical problems must be taken into account by both the system manufacturers as well as the potential users, to whom it has to be demonstrated what advantages at which price they would receive from different complexities of E-scan weather radars. The technology needed is now available and is being applied in military systems. However, the price remains high, and further development is required to be economically justifiable in civilian meteorological applications.

On a worldwide basis, planning for phased-array antennas in weather radars go back to the early 1980s, when the National Center for Atmospheric Research (NCAR) held its Rapid Scan Doppler Radar Workshop (Carbone and Carpenter 1983; Keeler and Frush 1983; Carbone et al. 1985).[1] In Europe (excluding the former Soviet Union), first discussions on this new technique have ocurred (Joss and Collier 1991; Josefsson 1991). Their conclusion was that it was too early to realistically apply E-scanning in operational weather radars, which is now a theme of COST 75's working program.

The Working Group on Electronic Scanning Systems was established to deal with these topics:

a) justification of E-scan antennas in weather radars;
b) development and testing of scanning strategies for different observational needs;
c) investigation of the compatibility between E-scanning and other advanced techniques (e.g., Doppler, multiparameter);
d) development of a catalog of required antenna specifications, including implementability considerations;
e) carrying out an antenna availability survey, identification of existing suitable devices;
f) collection–estimation of E-scan antenna reliability data (e.g., mean time between failure),
g) develop specifications and requirements for subsystems complementing the E-scan antenna,
h) perform a market survey for E-scan weather radars (identification of interested user groups, generate overall price projection estimates), and
i) investigate the possibility of initiating a "COST 75 Pilot Project" aiming at the design, production, and testing of a "European E-scan weather radar prototype."

The following sections present an overview of topics discussed and decisions/definitions tentatively agreed on so far.

a. User requirements and expected benefits

Concentrating on the discussion of operational weather radars, the main advantage in applying E-scan principles is the reduction of observation cycle time. Present radars with mechanical scanning have full-volume scans as short as 5 min, while E-scan radars, due to PRF and dwell times being adaptable to the type and distribution in range of target characteristics, are estimated to provide full-volume observation durations around 1 min (Keeler and Frush 1983).

There exists general agreement that in atmospheric research and cloud physics such short cycle times are needed in order to avoid overlooking spatially and temporally limited structures like microbursts or hail shafts, whose development and lifetimes can be a few minutes only. The question of whether the 1-min cycle time would really be needed in practical, operational applications was heavily discussed and received finally a number of supporting arguments from applications like urban hydrology, microburst detection in aviation and general meteorology, hail, and other severe weather detection and warning (Waters and Collier 1995). The quantitative use of radar-derived precipitation rates or cumulations would also benefit from the reduced cycle time, considering that at today's radar image spatial resolution (typically 1 km pixel^{-1}) a storm can move over several pixels during conventional radar cycle times. It was proposed to demonstrate the quantitative superiority of the 1-min scan sequence over the conventional longer one, using radar data having been acquired with high temporal resolution.

b. E-scan antennas

A considerable part of the group's activities concerns available E-scan antenna specifications and technology. The group consists of European industry (Alenia, Ericsson, Siemens/Plessey, Segnalamento Marittimo ed Aereo, Thomson-CSF), complemented by participants from relevant research organizations (DLR) or universities (TU-Graz, TU Delft), and weather services (France, Switzerland, United Kingdom) as potential users. In addition, links were established to groups working on related matters outside the COST domain [e.g., NCAR and the Federal Aviation Administration (FAA) in the United States and the Main Geophysical Observatory (MGO) in St. Petersburg, Russia, together with a Russian radar manufacturer].

The major portion of work was spent on the definition of required and available antenna specifications needed for a dedicated E-scan weather radar [as opposed to multifunction radars, like the

[1]See also material prepared for NCAR's Rapid Scan Doppler Workshop held in 1983 (Keeler et al. 1983).

Terminal Area Surveillance System (TASS) (U.S. Department of Transportation 1995)]. Several degrees of antenna complexity (e.g., phase vs frequency scanning, mix of mechanical steering in azimuth and electronic steering in the elevation, electronic steering in both directions, passive or active multibeam array) were discussed, sidelobe levels, mainlobe excursion angle, and switching speed having been identified as the crucial parameters. Frequency scanning was dropped in favor of phase scanning, in which the stability, speed, and resolution of phase shifters play an important role. An adaptive mainlobe width, which increases with elevation angle and thereby provides a more evenly distributed absolute transversal spatial resolution, helps to reduce cycle time and can be achieved even with a passive array, E-scan in elevation only.

Minimum requirements for sidelobe levels were set to −25 dB with a goal of better than −30 dB close to horizontal, thinking also of adaptive sidelobe level control, in which horizontal sidelobes are always kept low, even when compromising the levels of sidelobes pointing at higher elevation angles. Controversy still exists on the needed elevation excursion angle. While users would like to scan the full tropospheric volume up to 90° elevation angle, not only for completeness reasons, but also for the detection of localized phenomena like a microburst above the radar station, the physics of array antennas as well as technological and cost factors ask for maximum elevation angles between 35° and 70°. In order to fully exploit the advantages of adaptive scanning schemes, agreement could be achieved on the necessity of pulse-to-pulse beam switching, requiring phase shifter switching and settling times on the order of a few microseconds.

Present E-scan antenna availability is rather limited. Microwave landing system (MLS) antennas produced by several manufacturers (e.g., Alcatel/SEL, Alenia, Ericsson, Thomson) are designed close to the C band (5.6–5.65 GHz) as low-power receiving devices only, needing adaption for limiting the transmit power. Prototype active arrays developed in connection with TASS were not considered further at this stage because of their high price. Only two existing "simple" designs with mechanical rotation in azimuth, E-scanning in elevation, could be found on the market [Ericsson missile tracking array (Josefsson 1991); Russian C-band antenna with phase-controlled feed array in a parabolic cylindrical reflector, MGO], both needing some improvements in sidelobe specifications. Further research is needed, starting with the basic version (mechanical–azimuth, E-scan–elevation) and proceeding toward more sophisticated designs as single-face active array with two-dimensional E-scanning overlaid on mechanical azimuth rotation, up to static four-face active arrays.

The combination of E-scanning and dual polarization was discussed only marginally. There are developments toward passive array antennas with dual-polarization capability (Josefsson 1991; Dubost et al. 1996), but they are not yet fully developed and substantially more expensive. The group's impression is that dually polarized phased arrays could be active using low-power patch or slot antennas.

c. *Scanning strategies*

Basic concepts for scanning strategy were developed in a more general way, including self-adaptive scans (concentrate observation time on interesting volumes and jump over clear sky, vary PRF and dwell times depending on echo signal fluctuation and spectral characteristics) and types of pulse compression/modulation. Problems associated with Doppler compatibility are expected to be solved by research and developments being reported in the literature, with a tendency toward stepped-frequency transmit waveforms with multiple, oversampling receivers being observed (Strauch 1988; Keeler et al. 1989; Urkowitz and Bucci 1992).

Specifications for the simulation of scanning cycles and their durations, using weather data, were generated but not yet implemented. One reason is the difficulty of accessing large amounts of coherent raw weather radar data, needed for evaluating the efficiency of proposed algorithms running on hardware of different degrees of complexity and capability and applied to different targets as precipitations, clutter, anomalous propagation, and clear air echoes.

d. *Signal characteristics and processing*

Signal spectral characteristics are expected to play an important role in the processing and interpretation decision tree. The problem of decorrelation and Doppler shift caused by partially changing the target when the antenna is scanning mechanically, and therefore necessarily continuously, must be considered, for conventional radar as well as for E-scan, if mechanically in scanning azimuth.

E-scanning can offer considerable freedom—its degree depends on the antenna complexity—in selecting the instant at which individual beam pointings are sampled, adjusting the number and spacings of these instants according to knowledge obtained from the previous scan or a first quick look by a burst of pulses. This information can be used to adjusted sampling patterns to optimize the ratio of "information retrieved to time spent on the target." On the other hand, it makes processing in the raw data domain with high data rates considerably more complicated and sophisticated. The development and testing of stable algorithms and their implementation in software is expected to be the most time- and money-consuming task for the development of an E-scan weather radar prototype. It could be reduced considerably when carrying out simulations on archived raw weather data.

e. Further work on E-scan weather radars

A considerable amount of information and guidelines toward the establishment of a dedicated E-scan weather radar could be collected and discussed.

Future work shall concentrate on generating technically feasible specifications for an envisaged prototype development with estimated price. A list of benefits to be obtained from the new technique for different users and a market study for E-scan weather radars is being prepared. An operational introduction in Europe, however, will be beyond the year 2005 and requires demonstration systems to be established before that date.

6. Conclusions and outlook

The main objective of the European research project on advanced weather radar systems is to develop a guideline specification for a future generation of operational systems. Areas of research and development are presented, but user requirements and the economical conditions for the upgrading of weather radar networks across Europe need further investigation.

Effort has focused on the actual status and technological developments, including data processing techniques. The potential for using conventional non-Doppler and Doppler systems is recognized. It includes procedures for more accurate precipitation estimates by optimizing scan procedures to obtain full volume data and correcting for errors like beam broadening, partial beam filling, bright band, beam blockage, propagation impairments, and clutter.

Doppler radars are rapidly becoming the operational standard. The additional wind information promises improvements for forecasting through assimilation of radial winds and profiling in the rain volume. In clear air conditions, it can provide information on planetary boundary layer (e.g., convergence). Future Doppler radars should be designed to have a clear air detection capability. Doppler methods are also used for clutter removal. Although the potential improvements for operational weather monitoring and prediction are obvious, effort must be devoted to confirming the degree to which these improvements may be achieved through user-friendly and user-specific products.

The applicability of multiparameter radar products complementing polarization and Doppler measurements for more precise rain-rate estimations and for nowcasting severe weather events have been demonstrated within research environments. Differential reflectivity measurements improve drop-size distribution estimations; estimation of the depolarization ratio contributes to hydrometeor identification, brightband localization, and identification of ground clutter. One challenge is to integrate these techniques based upon the use of polarization radars within the operational environment and to implement correction schemes for propagation effects. Differential phase shift, insensitive to propagation effects, may help to correct for propagation effects and has a great potential for improvements of quantitative rain measurements, including within rain–hail mixtures. The implementation of polarimetric techniques in an operational environment, however, needs further cost/benefit assessments and must be developed to a level where algorithms are stable. Polarimetric Doppler radars remain of fundamental value for atmospheric research as well as for piloting applications.

Electronically scanned systems, developed for military and defense applications, have the potential to satisfy future requirements for high time resolution and flexible scan strategies not achievable with mechanically scanned systems. Hydrology and nowcasting would benefit from the use of such radars, although further investigation of how to realize these benefits is necessary. These advantages have to be assessed against today's cost estimations and cost projections to the future. COST 75 will take up the challenge of defining realistic specifications together with European industry, which could be the basis for a coordinated prototype development project. Besides dedicated E-scan weather radars, multipurpose systems shall also be considered that, on demand, may serve for weather forecast purposes as well as for ATC.

After stimulating technologies for observations, presentation and distribution of products, user requirements, and the market for advanced weather radar products have to be investigated. National weather services competing with private companies need a diversity of user-specific products distributed rapidly in the growing multimedia world. But different climatological conditions, different socioeconomic structures, and the diversity of responsible agencies need to be considered when assessing the future European market for advanced weather radar products. Efforts to develop simple but informative products are needed.

The training of people working in the operational field of advanced weather radar data and data from satellite observations and numerical weather prediction models is of fundamental importance. Within COST 75 this aspect of using advanced radar systems has been, and continues to be, discussed. It is recognized that the optimal use of radar data in operational weather forecasting is likely to be realized by combining these data with that from satellites, numerical models, and conventional meteorological observations. This complex task will require comprehensive training programs.

In summary, the guideline specifications of COST 75 for the new generation of operational European weather radars will be underpinned by the COST 75 assessment of the projected developments of radar technology, including data processing, the projected user requirements of a comprehensively defined European market, and cost/benefit investigations for the projections into the future. We are aware of the uncertainties accentuated by the different socioeconomic structures and requirements across Europe.

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