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OBJECTIVE FORECASTING USING RADAR DATA: A REVIEW

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SUMMARY

The usefulness of radar in monitoring precipitation areas has been recognised for many years. However, progress in the development of objective procedures for tracking radar echoes was restricted by the lack of availability in real-time of high quality digital data. This review is intended to highlight different approaches to tracking radar echoes, and making objective forecasts of echo patterns. The advantages and disadvantages of various techniques are discussed with a view to recommending a course of action to be undertaken as part of the work in the Meteorological Office Short Period Weather Forecasting Pilot Project.

1 INTRODUCTION

The operational implementation of weather radar systems almost thirty years ago led to a rapid appreciation of the possible contribution real-time data might make to short-term (a few hours ahead) forecasting of precipitation. Procedures were developed for the extrapolation of echo motion, based on the persistence of certain echo properties (Ligda, 1953, Russo and Bowne, 1961 and Boucher, 1961). Ligda (1957) has demonstrated the potential usefulness of a radar network by producing a radar data montage.

It was shown (Noel and Fleisher, 1960, Kessler, 1961, 1966, Noel, 1962, Boucher, 1963, Kessler and Russo, 1963, and Wilson, 1966) that the maximum correlation between a pair of successive PPI (plan position indicator) patterns (the optimum vector displacement between two patterns) depended upon the statistical characteristics of the echoes contained within them. This led to the observation that a wide scatter in maximum correlation coefficients between PPI patterns occurred with different synoptic conditions, higher correlations being obtained for widespread rainfall than for thunderstorms (for example, see Wilson, 1966).

In attempting to extend this work it was necessary to develop computer-based objective pattern recognition techniques (Hilst and Russo, 1960, Ball, 1965, Haralick and Kelly, 1969, Duda and Blackmer, 1972). During the late 1960's satellite technology had reached the stage where high resolution cloud data were available, and pattern recognition techniques were developed in response to this new form of data (Leese, Novak and Clark, 1970, Smith and Phillips, 1971). Indeed much recent work on objective forecasting using radar data has been based upon techniques developed for use with satellite cloud data.

During the last few years several other objective computer techniques have been developed for the description and forecasting of radar echo areas, (for example, Wolf et al, 1988, Blackmer et al, 1973, Zittel, 1976) and it is largely upon this recent work that this review concentrates. Methods of describing objectively radar echo areas will be described, leading to discussion of methods of objective forecasting. Since all objective forecasting techniques claim some degree of success, a comparison of techniques is presented which is used to discuss an approach to objective forecasting appropriate to the Meteorological Office Short Period Weather Forecasting Pilot Project.

2 THE OBJECTIVE DESCRIPTION OF INDIVIDUAL PRECIPITATION ECHOES

Several methods of describing precipitation echoes have been proposed, mainly with the purpose of the eventual use of the objective description within statistical analyses or forecasting procedures, or, to a lesser extent, for condensing the volume of data sent from radars to users by data transmission systems. They are objective contouring of echo areas, fourier analysis techniques, a bivariate normal distribution echo description and thresholding and clustering of echoes.

2.1 Contouring

The most conceptually simple method is that of contouring. This technique applies to a single selectable echo intensity threshold, and must be repeated if several thresholds are needed for a complete description of an echo.

Duda and Blackmer (1972) have investigated a technique, originally proposed by Brice and Fennerma (1970), which computes the 'directed' boundaries for a digital picture. For each element E_{ij} of a picture there are four elementary boundary vectors V_1, V_2, V_4, V_8, defined in Figure 1a. These vectors encircle the element in a counter-clockwise fashion as shown in Figure 1a, and are known as the 'directed' boundaries of each picture element. A four bit binary number V_{ij} indicates the presence or absence of each boundary vector. Initially all vectors are absent, and the program scans the picture inserting vectors whenever there is a transition from a zero value to a non zero value across the boundary. The picture may be displayed using certain line printer characters (letters, arrows, dashes etc) to represent various configurations of vectors, for example L to represent $\downarrow\rightarrow$, and V to represent $\downarrow\rightarrow\uparrow$, Figure 1b. Similar techniques have been described by many workers in connection with the contouring of a variety of fields of meteorolgical data.

2.2 Fourier Analysis

A description of the contours of a digitally-defined echo area may be derived from a Fourier series expansion (Duda and Blackmer, 1972, Östlund, 1974, Zittel, 1976). Consider x(s) and y(s) to be the x and y co-ordinates of a point on the arc length s measured from some arbitrary initial point. The x and y are periodic functions, repeating when the arc length equals the perimeter P, and they can be expanded in a Fourier series:

$$x(s) = a_o + \sum_{n=1}^{\infty} a_n \cos(n\omega s - \theta_n)$$

$$y(s) = b_o + \sum_{n=1}^{\infty} b_n \cos(n\omega s - \theta_n)$$

where $\omega = 2\pi/P$, a_n and b_n are the amplitudes of the n_{th} harmonic (see for example Duda and Blackmer, 1972). Figure 2 illustrates fourier approximations to a digital contour, and it can be seen that as few as five harmonics may be used to provide quite a detailed description of an echo if only one intensity level is used. Using a multiple thresholding technique (Section 2.4), it is possible to give a complete three dimesnional description of a radar echo (Barclay and Wilk, 1970), which may be used for transmitting the radar information from a radar site to a user. This assumes the user is capable of understanding the transmission, and therefore may not be an ideal solution in many cases, where the user does not possess computing facilities.

Fourier analysis is used within pattern recognition procedures which require knowledge of the shape of the echo for the purpose of assessing pattern motion. An example of such a procedure has been described by Muench (1976), in which a harmonic analysis of the pattern between the edges is made, and the phase angles of significant amplitudes are stored, Figure 3. The analysis provides the locations of the edges and peaks in the harmonics, which, when matched with corresponding edges and peaks at a later time, give echo displacement vectors.

2.3 Bivariate normal distribution

A further technique for describing echoes has been proposed by Wiggert et al (1976). This technique uses an unnormalised bivariate normal distribution, f(x,y), where,

$$f(x,y) = \exp\left\{-\frac{1}{2(1-\rho^2)}\left[\left(\frac{x-\mu_x}{\sigma_x}\right)^2 + \left(\frac{y-\mu_y}{\sigma_y}\right)^2 - 2\left(\frac{x-\mu_x}{\sigma_x}\right)\left(\frac{y-\mu_y}{\sigma_y}\right)\right]\right\}$$

σ = correlation coefficient
μ_x = average x-value $\equiv \bar{x}$ (ie average echo area, n mi^2)
μ_y = average y-value $\equiv \bar{y}$ (ie average rain rate, mm n mi^2 hr^{-1})
σ_x = variance in x
σ_y = variance in y

$$W = \Sigma f_{i,j} = \text{weight}, \quad \overline{x^2} = \frac{1}{W} \Sigma_{i,j}\, x^2 f_{i,j}$$

In three dimensions, a bivariate normal distribution has contours that are ellipses, and has cross-sections that are normal distributions. The description of the echo is contained in the weight and centroid, together with the second moments of the bivariate normal distribution of the echo area. All local maxima are found within each echo, Figure 4. It is claimed by Wiggert et al (1976) that this technique is better than simple fourier analysis, as it gives a method of describing the interior of an echo. However, its added complexity is really useful only in dealing with large intense thunderstorms which have well defined interior maxima, and is not practical for frontal rainfall which may be very uniform, or contain complex cells within a larger scale fragmented rain area.

2.4 Clustering

When echoes are well separated, for example in the case of some thunderstorms, there is no difficulty, in principle, in defining then objectively using a threshold technique such as that proposed by Barclay and Wilk (1970) or Crane (1976). However, there are many occasions when echo areas are very complex, and a simple intensity threshold does not isolate individual echoes clearly for analysis. This is especially true in the case of widespread frontal rain.

To overcome this problem clustering procedures, aimed at isolating data into homogenous subcategories, such as particular cloud types or particular shapes of rain area, have been proposed (Ball, 1965, Haralick and Kelly, 1969, Endlich et al, 1971) and implemented (Duda and Blackmer, 1972, Wolf et al, 1977). However, difficulties arise in defining an initial grouping in which to begin allocating areas of cloud or radar echoes, and in determining the true number of clusters.

Duda and Blackmer (1972) have suggested a method of clustering based on the sequential lowering of an initially high intensity threshold, this being referred to by them as hierarchical clustering. The technique has been developed by Smith (1975), although not all clusters recognised undergo a matching procedure as to do so increases computation time significantly. Clusters smaller than a pre-defined size are ignored. Östlund (1974) and Wiggert et al (1976) use an 'eight-surrounding-points' search (within a radius of height points) to isolate cluster areas. For each point above a threshold a search within a radius of eight surrounding points is made to see if any of these points are occupied by echo above the threshold. This is repeated until no such points are found. On finding such an echo in the surrounding area, the central echo is assumed to belong to the same cluster as the echo so found. A grid length of about 1.6 km (1 mi) was used, so that echoes within about 13km (~8 x 1.6km) of each other were regarded as belonging to the same echo cluster. Wolf et al (1977) have adopted a 'touching' algorithm, that is members of a cloud (in their case) group must touch at least one other member of the group.

3 ECHO SIGNIFICANCE

If some echoes are not to be considered for matching at different times or for statistical analysis, in order to reduce computation times, then some measure of echo significance is required. At its simplest level echo significance may be based on echo size only, that is echoes smaller than a predefined size are ignored.

Duda and Blackmer (1972) have pointed out that in considering echo significance, the following parameters can be examined: intensity, size, height, shape, motion, rapid changes in intensity, shape or size, and merging with or splitting from other echoes. Intensity and size are probably the most important parameters. They have suggested the following empirical weighting factor, based on an assumed $Z \propto R^{1.6}$ relationship, as a first step towards the evolution of a complete significance parameter:

$$\text{weight} = 100 \log_{10} \left[\left(\frac{Z_{max}}{Z_{ref}} \right)^{0.5} \cdot \left(\frac{\Sigma Z^{1/1.6}}{Z_{ref}^{1/1.6}} \right) \right]$$

Where Z_{max} is the largest reflectivity factor measured, and Z_{ref} is a reference value arbitrarily defined. The echo size is contained in ΣZ. Although this weight does not take account of all the parameters mentioned above, it nevertheless was found to produce plausible results, when objective forecasts prepared using it were compared with actual echo patterns. Most subsequent work has not taken the problem of echo significance much further. Muench and Lamkin (1976) and Wolf et al (1977) have developed further empirical techniques (see section 4), which are claimed to be very effective in providing objective 'guidance' for operational forecasters. However, such a procedure can be misleading as echoes may travel in what Hill and Browning (1978) refer to as 'skeletal' form - low intensity and variable size and shape - yet develop later to produce significant rainfall over areas of high land.

4 TRACKING ECHOES

Tracking individual echo areas, or large areas of echo from one radar picture to the next, involves some kind of echo matching or echo correlation. Once the echo movement is defined then short-period forecasts may be made (neglecting development and decay of course).

4.1 The relationship between echo movement and wind velocity

Some work (for example Tatehira and Makino, 1974, Tatehira et al, 1976) has been reported in which regression relationships between echo movement and wind velocity have been identified. Tatehira et al (1976) have used the 700 mb wind velocity to advect echo areas, and have claimed a distinct improvement over persistence forecasts, whilst indicating that such forecasts were not as good as those made using a pattern matching procedure. However, Smith (1975) in a study of a variety of echo patterns, and also Shearman (1977) in a study of rainfall patterns report that no reliable correlations were found between echo movement and wind velocity at any level.

4.2 Echo controids

If echoes can be isolated easily, then the simplest pattern matching procedure is one using the centroid of each echo. Echo centroids at one time may be matched with those at a subsequent time. Constraints are usually applied to the calculated echo motion to aid the matching procedure, for example echoes are not normally considered to move at speeds greater than 120 km hr^{-1}.

This technique has been developed by Wilk and Gray (1970) (for radar echo), and Endlich et al (1971) and Wolf et al (1977) (for clouds) with some success for weather situations characterised by isolated echo or cloud, for example isolated thunderstorms. Barclay and Wilk (1970) and Zittel (1976) have used a linear least squares positional fit through the centroid positions of echoes as a function of time to specify displacement vectors. Difficulties arise when echoes (or cloud areas)split or merge, and clustering techniques (section 2.4) have been developed which show some success in overcoming this problem.

4.3 Cross-correlation

Cross-correlation techniques may also be used to match portions of one radar picture with portions of subsequent pictures (Wilson, 1964, 1966 for radar data, Leese et al, 1970 and Smith and Phillips, 1971 for clouds). This procedure has the advantage of taking into account the detailed shape of the echo being tracked, and decreases the chances of mis-matching echoes, although the procedure uses only one level of intensity at a time.

If all the echoes in a radar picture move together, and if there are no significant size, shape or intensity changes from one picture to the next, then conceptually the simplest matching procedure is to cross-correlate an entire picture with an entire picture at a subsequent time. This technique has proved to be very successful within these limitations (Zawadzki, 1973, Austin and Bellon, 1974, Hill et al, 1977). Cases of developing convective activity and orographic rainfall are not suited to this technique but widespread rainfall over lowland areas on occasions may be analysed successfully. Although the procedure may require minimal computer resources when correlating an entire picture, and therefore may be used within a minicomputer, computer usage can increase significantly if several subsections of a picture are cross-correlated and a small minicomputer may become inadequate for the task. The splitting of a pattern into subsections will be necessary when echoes move with different velocities.

4.4 Complex methods

The description of echoes using fourier analysis techniques provides the locations of the edges and peaks in the harmonics, which may be matched at separate times to give echo displacement vectors (Muench, 1976). Similarly analyses using other statistical echo distributions may also be used to match echoes.

These techniques often use all the intensity information within an echo area to obtain a match. For example Duda and Blackmer (1972) and Blackmer et al (1973) minimise the following expression when searching for two matching echoes or echo areas:

$$\sum_x \sum_y \left[I_n(x,y) - I_o(x - x_d,\, y - y_d) \right]^2$$

where $I_o(x,y)$ and $I_n(x,y)$ are the intensity integers in the old and new radar pictures respectively. $I_o(x-x_d, y-y_d)$ corresponds to displacing the old echo x_d to the east and y_d to the north. Various modifications were made to this expression to cater for echoes moving into and out of the picture, and to allow for occasional large errors by examining the sum of the [magnitude of the] errors. The latter modification provided the means for iterative echo matching so that merging and splitting could be allowed for.

After matching cloud centroids, Wolf et al (1977) derive a measure of 'goodness of fit' based on empirical formulae relating the statistics of the distribution of derived vector displacements to the intensity and size of cloud areas. This appears to work well for isolated cloud areas, but it is doubtful to what extent it would be effective for more uniform frontal cloud.

4.5 Scale of the input data

Wilson (1966) has investigated radar echo movement on a variety of scales, and found that the predictability of the small-scale features (8-16 km) is very short, only a matter of minutes. It was found that the motion of features on scales greater than about 60 km may be extrapolated for one or two hours. Figures 5 and 6 illustrate the decay of maximum correlation coefficient between forecast and actual data fields with time for a case of thunderstorms and a case of more widespread frontal rainfall. The full lines in these figures represent data from which all wavelengths below various thresholds have been removed. Dashed lines are for data applicable to particular narrow wavelength bands, and the curves marked 'original' contain all wavelengths present in the basic, unfiltered data. These figures demonstrate that objective forecasts for a few hours ahead of widespread frontal rainfall are likely to be more accurate than those for convective rainfall. Also, whatever the type of rainfall, larger scales of echo movement are likely to be more predictable than the smaller scales.

In order to attempt forecasts for several hours ahead it is necessary to consider only the larger scales of motion. This calls for the input data to be smoothed. Wilson (1966) used an averaging area around each data point of 2 x 2 or 4 x 4 grid squares. The averaging operator essentially removed all wavelengths less than twice the grid length. After this simple averaging, Shuman's two-dimensional, 9-point smoothing operator was applied to the data (Shuman, 1957). This operator had the property of strongly suppressing wavelengths less than four times the grid length, while retaining, essentially unchanged, wavelengths greater than six times the grid length.

More recent work (Tatehira et al, 1976, Hill et al, 1977) has supported the need for data smoothing if forecasts for several hours ahead are to be attempted. The above workers considered only smoothing in the horizontal which may be undesirable with individual convective storms. Green (1972) has advocated the use of vertically-integrated liquid water content (VIL) data in objective echo tracking procedures, thereby suggesting that smoothing spatially in height improves the forecasting capability of objective echo tracking techniques. However this places heavy demands on data processing, and for a given expenditure could limit the time resolution achievable.

4.6 Evaluation of methods of echo tracking

It is difficult to assess objectively the relative performance of the several different methods of extrapolating echo movement, as most of the techniques claim to be successful in a limited sense, and have been used in different weather situations. However Elvander (1976) (see also Alaka et al, 1977) has described a series of experiments using the following three different techniques:

Model A: a cross-correlation technique similar to that used by Austin and Bellon (1974), and referred to by Elvander (1976) as the Canadian model (section 3.3 above).

Model B: a technique involving the tracking of individual echoes using a linear least squares extrapolation of the motion of the echo centroid as described by Barclay and Wilk (1970) and Wilk and Gray (1970), and referred to by Elvander (1976) as the National Severe Storms Laboratory model (section 3.2 above).

Model C: a technique involving the tracking of individual echoes by considering the entire echo complex, and some measurements related to individual echoes as described by Duda and Blackmer (1972) and refined by Blackmer et al (1973). This technique was referred to as the Stanford Research Institute model by Elvander (1976) (section 3.4 above).

A comparison of these models is given in Table 1. This table includes a comparison of the computer requirements for each model, related to the Digital Equipment Corporation PDP11 series of computers. Since only limited details of the actual computer usage are available in the literature, the assessment is largely based on the present authors experience. Although CPU times appear low for all techniques, it is important that the minimum of computer time is used if forecasts are to be produced for operational dissemination. It was concluded by Elvander (1976) that the simple cross-correlation model was the most effective when used with zero tilt (ie low altitude) reflectivity data, but the linear least squares interpolation of echo centroids was the most effective method when VIL data were used. However it should be noted that additional computer time is required in order to produce the VIL data. The data used in the experiments were representative only of convective rainfall; no stratiform rainfall cases were considered.

These conclusions were based upon forecasts up to ninety minutes ahead, using instantaneous pictures at both ten minutes and thirty minute intervals. Forecasts made using input data at ten minute intervals were usually about 20-40% more accurate than forecasts made using data at 30 minute intervals for Models B and C. The increase in accuracy for Model A using the more frequent data was about 10-20%. However, the differences between all three techniques were generally small for forecasts using data at ten minute intervals, and the cross-correlation technique was significantly better only using zero tilt reflectivity data when the data were input at thirty minute intervals.

No assessment of the three models specified above has been carried out using radar echo data obtained from observations of stratiform rainfall. Hill et al (1977) have demonstrated that a version of model A does provide

ECHO TRACKING METHOD	PRINCIPAL REFERENCES	WEATHER TYPES FOR WHICH TECHNIQUE MOST EFFECTIVE	OBJECTIVE DESCRIPTION OF ECHOES?	ABILITY OF METHOD TO FOLLOW INDIVIDUAL CELLS	ABILITY OF MODEL TO COPE WITH DIFFERENTIAL MOTION OVER SECTIONS OF THE PPI	COMPUTER CORE REQUIREMENTS (16 bit words)	COMPUTER C.P.U. TIME REQUIRED PER FORECAST (referred to PDP11 series computers)		COMPARATIVE METHOD PERFORMANCE ON SCALE OF 3 (assessed over several data samples using a Critical Success Index as defined by Elvander (1976)
							Using Reflectivity data	Using VIL data	
Cross-correlation									
(i) Entire PPI	Austin and Bellon (1974)	All	None	No	No	$\sim$ 16K	$\sim$ 15 secs	$\sim$ 1 min	1 if instantaneous low altitude reflectivity data used 2 if VIL data used
(ii) Subsections of PPI	Hill et al (1977	All	Very limited	Yes (provided areas are small enough)	Yes (provided areas are small enough)	$\sim$ 24K	$\sim$ 1.5 mins	$\sim$ 2.2 mins	untested
Echo controids	Barclay and Wilk (1970) Wolf et al (1977)	Convective rainfall - thresholding and clustering technique enable effective use with other weather types	Limited	Yes	Yes	$\sim$ 24K	$\sim$ 30 secs ($\sim$2.2 mins if complex)	$\sim$1.2 mins ($\sim$3 mins if complex)	2 if instantaneous low altitude reflectivity data used 1 if VIL data used
Weighted Echo Centroids using an optimization of the squared errors or the sum of the magnitude of the errors	Duda and Blackmer (1972) Blackmer et al (1973) Ostlund (1974)	Convective rainfall - as for echo centroids	Detailed	Yes	Yes	$>$ 32K	$\sim$ 2-10 mins depending on complexity	$\sim$ 3-11 mins	3

TABLE 1: COMPARISON OF OBJECTIVE FORECASTING TECHNIQUES USING RADAR ECHO DATA

quite successful forecasts up to six hours ahead for one case of frontal rainfall using data smoothed over a grid length of 20 km. However, both Browning et al (1974) and Hill and Browning (1978) have presented data showing significant differential motion of mesoscale precipitation areas within frontal systems which model A is not suited to coping with. More work is required to investigate the performance of all these models in frontal rainfall situations.

5 ECHO DEVELOPMENT

When echoes have been identified, and their displacement vectors deduced, then a quantitative forecast based purely on extrapolation may be made. Unfortunately echo areas change their size, intensity, speed and direction of movement on time scales from hours to as short as a few minutes, depending upon the synoptic situation and the local orography.

Wilson (1966) and Austin and Bellon (1974) have indicated how the maximum cross-correlation coefficient, derived by comparing objective forecasts based purely on extrapolation with their corresponding actual patterns, decreases with time for compact storms, scattered echo and squall lines, Figure 7. This figure suggests that useful forecasts may only be made for in excess of 30 minutes ahead when echoes are well defined, and their movement is uniform. Hill et al (1977) have demonstrated that extrapolation forecasts up to six hours ahead could be made for a case of frontal rainfall and Hill and Browning (1978) have shown that individual echoes (with dimensions of the order of tens of kilometres) associated with weak convection aloft could be tracked for several hours within the warm sectors of depressions. Similarly Takeda and Imai (1976) have observed echoes (with maximum dimensions of the order of ten kilometres) associated with strongly convective situations which could be continuously identified for at least one or two hours. It seems clear, therefore, that the number of hours ahead for which a simple extrapolation forecast may be useful depends upon the type of synoptic situation. However, if the echo pattern develops significantly then other techniques must be employed.

Schaffner (1976) has suggested the following general approach: (i) the running of a set of programs for characterising the present echo pattern, its motion, and its evolution, followed by (ii) the running of a numerical model of the evolution of radar echo patterns using radar data as one input. Other inputs would be based on data from meteorological variables (for example wind velocity), objectively adjusted by interpolation in terms of the previous echo characterisations, and initialised with the actual present echo pattern. Three areas requiring further study were identified:

(a) the formulation of numerical models using an echo diffusion equation to simulate the evolution of radar echoes,

(b) the determination of appropriate characteristics of actual echo patterns,

(c) the determination of objective procedures for adjusting the numerical dynamical model in terms of these characteristics.

Schaffner (1976) has attempted the first of these studies, but the use of a diffusion equation which suggests that changes in the shape and intensity of echoes are expected to occur on a time scale of many hours (the diffusion time scale) is doubtful, and the technique is complex, involving parameters with many degrees of freedom. Hill et al (1977) have investigated a simplified version of Schaffner's development equation, but found no improvement over simple extrapolation for periods in excess of two hours ahead.

Empirical relationships between echo development, echo size and intensity, and the rate of change of these quantities have been used with radar data to update precipitation probability forecasts which have been issued before the reception of the radar data (Moore and Smith, 1972, Gilhousen, 1974, Moore et al, 1974). This was achieved by the use of regression equations relating the presence or absence of radar echoes in particular areas to the probability of precipitation in other nearby areas. Moore and Smith (1972) have demonstrated a 5% to 10% improvement in probability forecasts using radar data over probability forecasts not using radar data. Zucherberg (1976) has examined the geometry of a typical shower situation, whose echo distribution is assumed to be represented by a binomial distribution. The geometrical elements of the echo distribution are used to provide the most likely development of an echo pattern. Clearly this technique is only likely to meet with success for shower situations, and no forecasts have been presented which may be used to assess its performance.

Meteorological conditions for which large echo development is possible due to the interaction of the low level flow with orography, have been identified by Browning et al (1974, 1975) and Nash and Browning (1977). However there is a need to operate radars routinely to build up a mesoscale precipitation climatology of orographic enhancement to be used in making forecasts of a radar echo pattern. Harrold (1975) suggested a method of using radar data with data from a fine scale numerical model, such as that proposed by Collier (1975, 1977), to determine the orographic rainfall enhancement efficiency (Bergeron, 1965, Browning et al, 1975) upwind of an orographic area for which forecasts are required. Such a technique requires a suitable orographic area upwind of the area of interest, which is not always available, and therefore the technique is not generally applicable. A more general approach is likely to use the output from cloud physical models such as that described by Bader and Roach (1977). These models may then be formulated in such a way as to allow them to be driven by the output of coarser numerical-dynamical models (Jonas, 1976, Bell, 1978).

6 CONCLUSIONS AND FUTURE WORK

No particular objective procedure for the extrapolation of echo motion appears to be very significantly more successful than any of the other procedures discussed here. More trials of different procedures under operational conditions and for different weather types would be very useful. Certainly the cross-correlation technique using the whole radar picture is conceptually simple, and performs reliably when the echo pattern does not change rapidly with time. On the other hand, on occasions when significant differential echo motion occurs over short distances, this technique requires sub-sections of the radar picture to be defined and several cross-correlations to be carried out. Duda and Blackmer (1972) describe cases of convective rainfall in which echoes split, merge, and move in directions up to forty degrees different from one another within areas as small as 20 km x 20 km. Similarly Browning et al (1974) report mesoscale precipitation areas within the warm sector of a depression, which moves at speeds up to 60 km hr^{-1} different from one another over a distance of 100 km. The tracking of individual echoes by its very nature ensures that differential motion is dealt with, although the software is likely to be more complicated than that in the global cross-correlation procedures. On balance a high degree of sophistication does not appear to be justified, considering the penalty on computing time compared with the small forecast improvement usually achieved. Further work with relatively simple centroid techniques within minicomputers is desirable to investigate the practicalities of using such methods in an operational environment. Simple experiments carried out at the Meteorlogical Office Radar Research Laboratory suggest that it is practical to develop a basic echo centroid tracking technique within a limited core minicomputer. The importance of smoothing the input data to objective procedures if forecasts for several hours ahead are to be attempted, has been stressed. Further work on the effects of various smoothing operators would provide useful indications of the success likely to be achieved with purely objective procedures.

It is felt that the simplest, and possibly the most effective way of dealing with echo development, and errors in the forecasts arising from deficiencies in the objective technique employed, is to allow a human operator the flexibility to interact with an objective forecast in an iterative way. Orographic development may be allowed for by the manual selection of an oppropriate category, derived from a mesoscale precipitation climatology.

In summary therefore, it is recommended that work on objective short-period forecasting within the Meteorological Office Short-Period Forecasting Pilot Project (Browning, 1977) should begin with the development of a simple echo centroid tracking procedure using spatially smoothed input data. The resulting forecast should then be enhanced using a high degree of interaction between a forecaster and the computer software. The details of this interaction are presently under consideration, and will be the subject of a separate report.

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FIGURE 1a

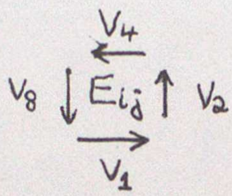
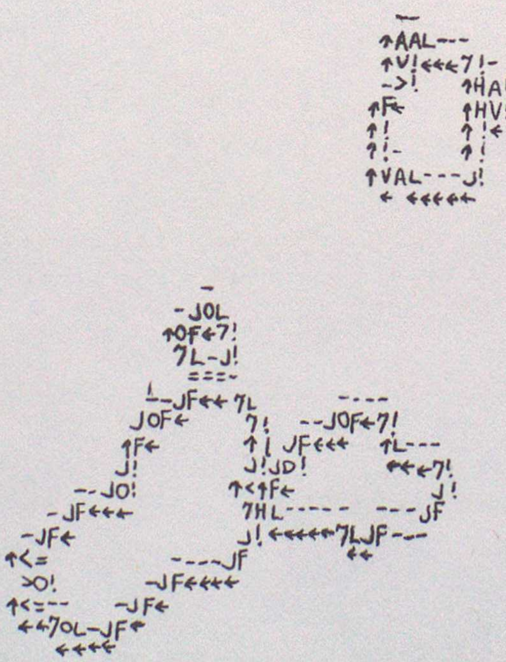
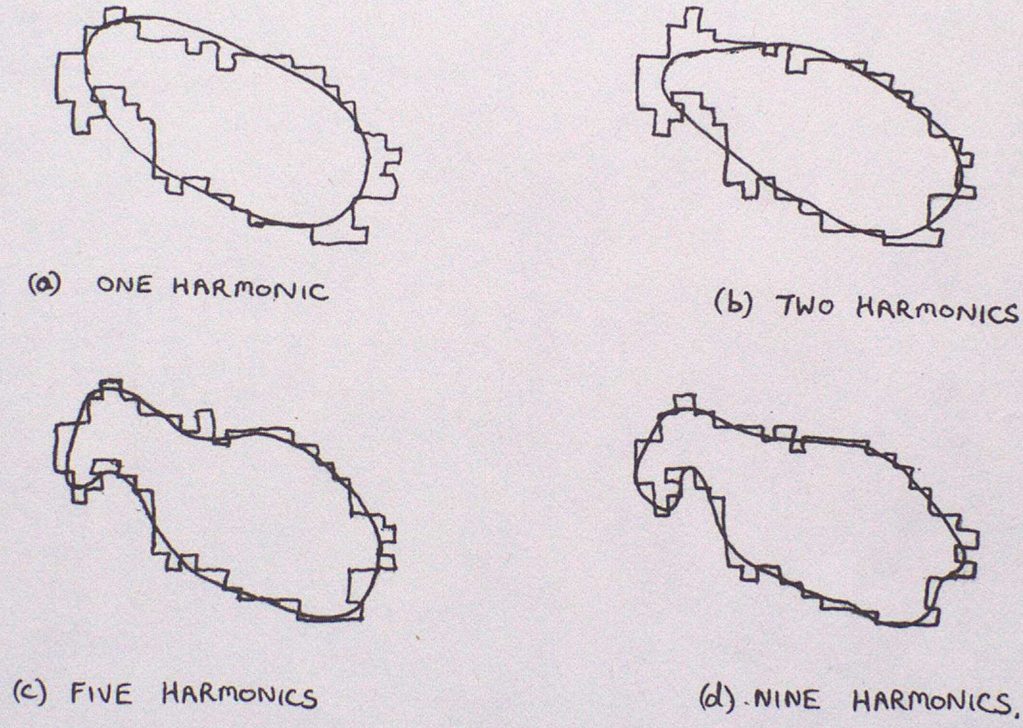


FIGURE 1b



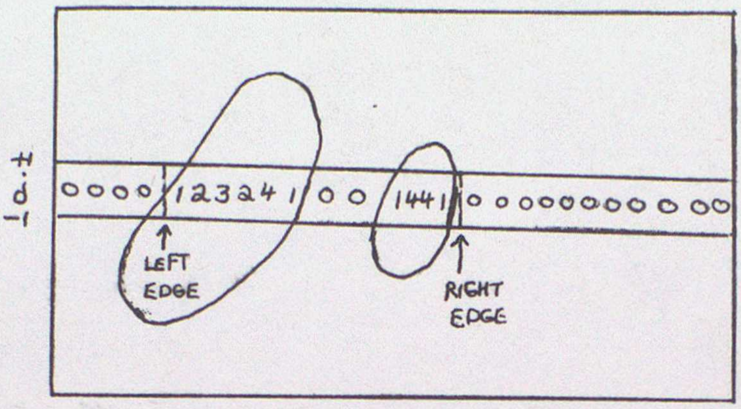
Illustrating (a) the elementary boundary vectors defined for each element E_{ij} of a radar picture as used by Duda and Blackmer (1972), and (b) a radar echo contoured picture derived objectively by Duda and Blackmer (1972). Letters and characters represent various configurations of the boundary vectors.

FIGURE 2



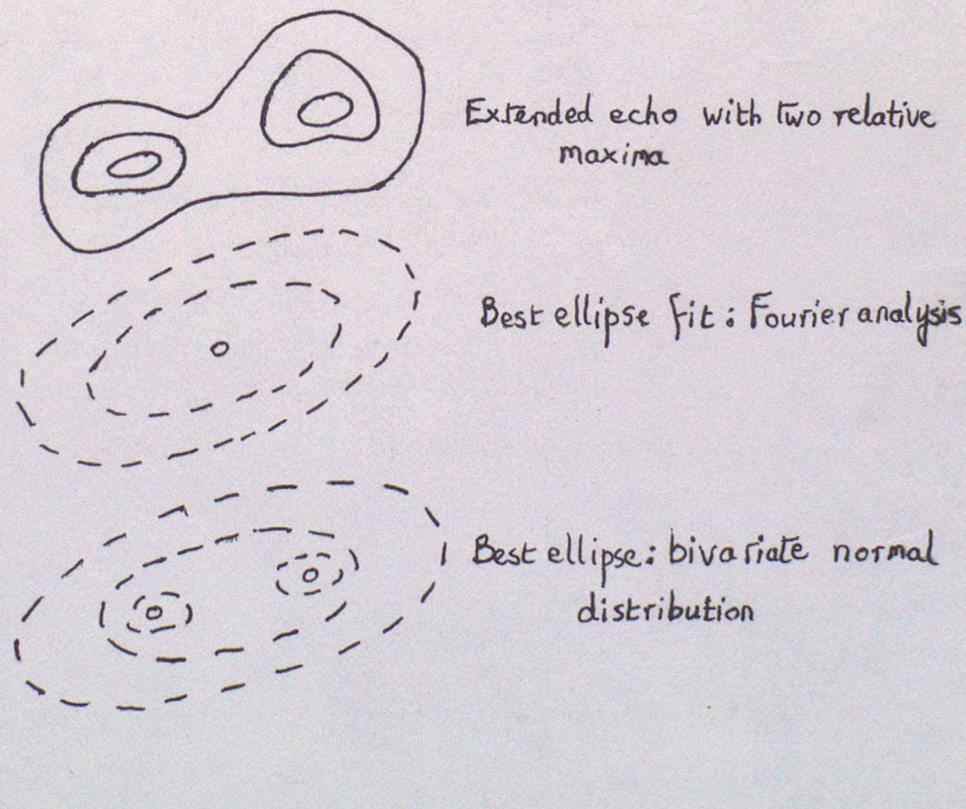
Fourier approximations to a digital contour (after Duda and Blackmer, 1972).

FIGURE 3



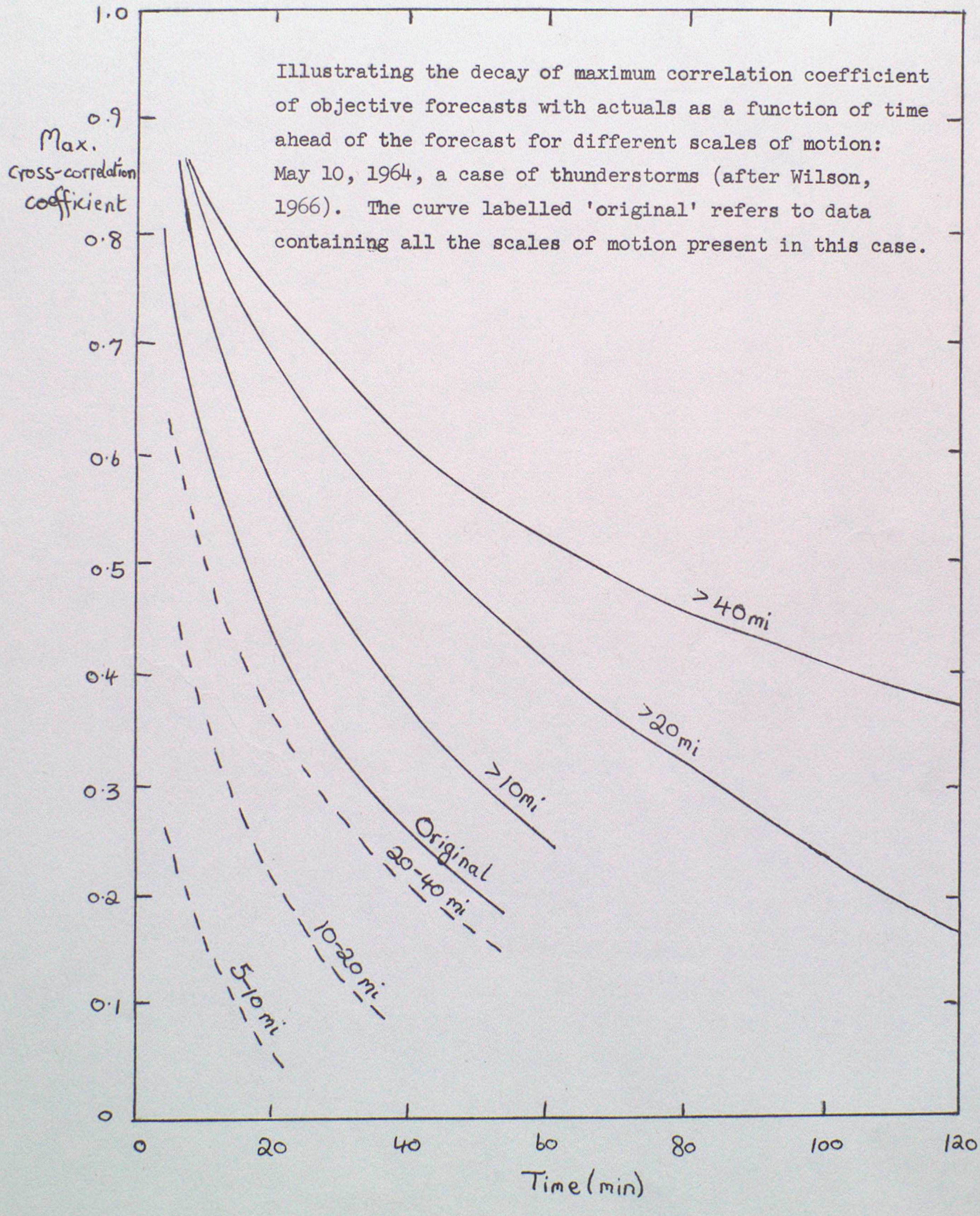
Illustrating the objective technique used by Muench (1976) for obtaining echo position. The values of the row j are replaced by the average of the three rows j-1, j, and j+1. The left edge is $\frac{1}{2}$ grid to the left of the first non-zero value of the three-row average, and the right edge is similarly defined. Arbitrary intensity values are given along row j.

Figure 4



Echo isolation using a bivariate normal distribution (after Wiggert et al, 1976).

FIGURE 5



Illustrating the decay of maximum correlation coefficient of objective forecasts with actuals as a function of time ahead of the forecast for different scales of motion: May 10, 1964, a case of thunderstorms (after Wilson, 1966). The curve labelled 'original' refers to data containing all the scales of motion present in this case.

FIGURE 6

As for figure 5: November 3, 1962, a case of widespread precipitation (after Wilson, 1966).

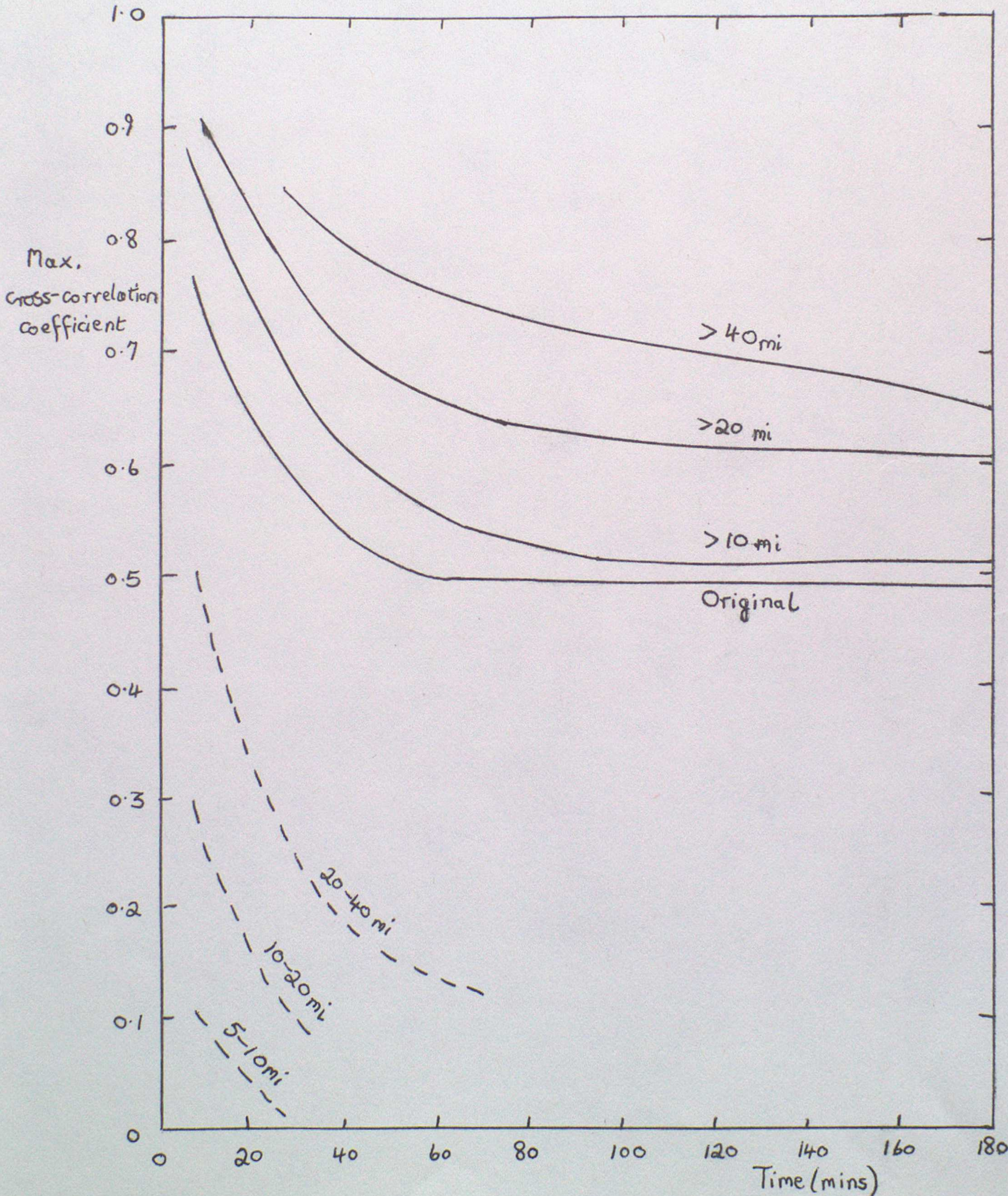
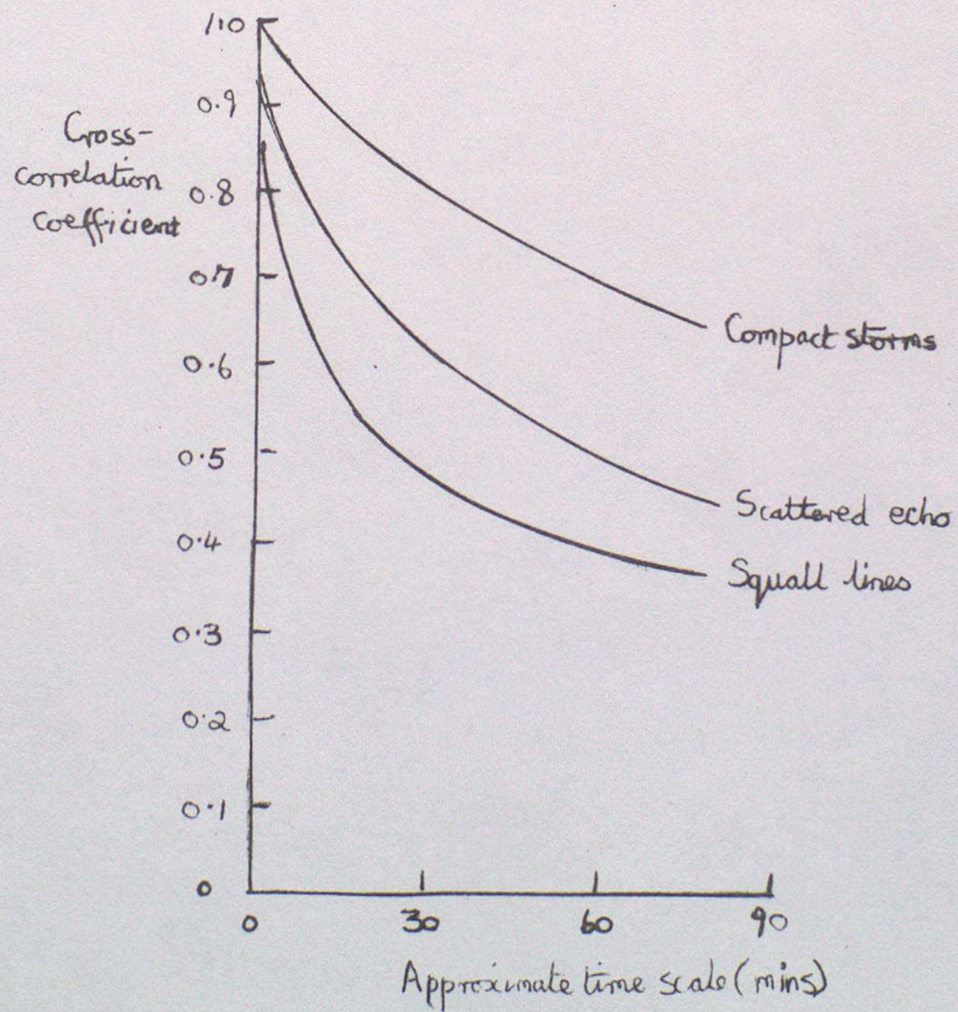


FIGURE 7



Illustrating the maximum cross-correlation coefficient between radar patterns for different time lags and precipitation types (from Harrold, 1975, after Austin and Bellon, 1974).

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