HYDROLOGIC APPLICATION OF DIGITAL RADAR DATA

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1. INTRODUCTION

The distribution of rainfall as described by conventional rain gage observations is probably the least representative of any of the hydrometeorological variables of general economic significance. The remote-sensing capability of radar allows it to detect rainfall patterns instantaneously with considerable accuracy. Until recently, the operational use of quantitative radar data has been limited due to the laborious task of manually processing these data. At this time automatic radar-signal processing techniques, pioneered by National Severe Storms Laboratory (NSSL), are undergoing operational testing and evaluation as part of the Digitized Radar Experiment (D/RADEX) of the National Weather Service (NWS). This automatic computer processing of digital radar data in the real-time adds a new dimension to the hydrologic application of radar data.

D/RADEX comprises a network of four NWS WSR-57 weather radars located in the midwestern United States (Kansas City, Mo.; Monett, Mo.; Oklahoma City, Okla.; and Stephenville, Tex.) and a special test site at Pittsburgh, Pa. Each of these 10-cm radars is equipped with a video integrator and processor (VIP), a data processing system consisting of a Data General Nova 1200 minicomputer, and peripheral devices (McGrew, 1972). The integrator output of each of 115 one nmi range bins is quantized into one of 10 levels (digits 0 through 9) representing returned power bands varying in width from 4.5 to 6.5 dB. These raw data are collected in a 2-degree by 1 nmi format corresponding directly to the radar reception process. For transmission and display on the teletype device these data are converted to a Cartesian format called an "I-J matrix," see Figure 1.

One of the objectives of D/RADEX is to test, evaluate, and improve hydrological forecasting techniques based in part or in whole on radar data. This paper, a continuation of the work discussed by Hudlow (1972), describes the attempt to utilize digital radar data, in the form of areal rainfall estimates, in operational hydrology.

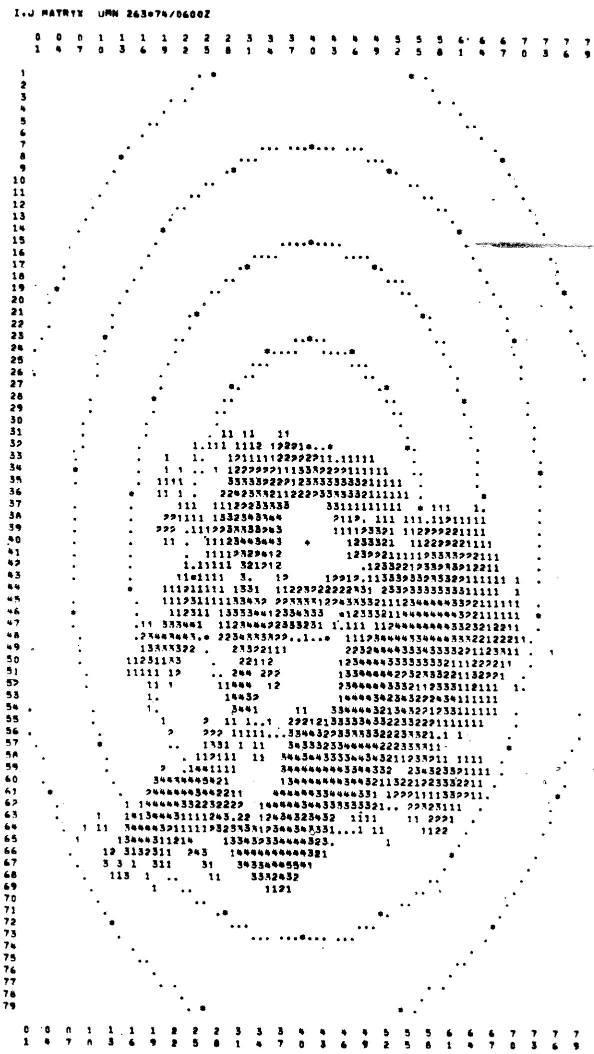

Figure 1. "I-J" matrix presentation of digital radar intensity values. Each display value represents the maximum digit falling within a 3 nmi by 3 nmi box.

2. HYDROLOGIC APPLICATION

Radar presents an ideal tool for hydrological purposes in its capability to provide estimates of precipitation which has fallen over a watershed. Although the success of radar for this purpose depends on minimizing errors inherent in radar measurements and their relationship to rainfall rates (Smith, et al., 1974), these uncertainties are compensated for by the instantaneous remote-sensing capability of radar which allows it to give complete areal coverage and to detect accurately the spatial discontinuities and temporal fluctuations associated with rainfall patterns. This feature alone makes radar a powerful tool for observing and deriving areal rainfall estimates. Further by combining radar derived rainfall patterns with rain gage data the best possible definition of rainfall patterns may be obtained.

2.1 Data Requirements

When quantitative areal rainfall estimates are derived from radar data collected at successive scan intervals, Δt apart, the accuracy of the total rainfall amount is a function of the sample interval Δt, the basin size, and the storm size, intensity, and speed of movement. This problem was first recognized by McCallister, et al., (1966) who attempted to make precipitation estimates based on data collected at a 30 min scan interval. McCallister tried to solve this problem by interpolating min scan from the 30 min data. This procedure requires an accurate indicator of individual echo movements which is impractical to obtain in a real-time, mini-computer environment (Greene and Clark, 1974).

The effect of the scan time interval at which radar data is collected upon areal rainfall estimates has been investigated through the use of simulation techniques. Results of this investigation also gives some insight into the inter-relationships of the radar scan interval and basin or grid sizes. The procedure used was to simulate storms by use of the Gaussian distribution (Court, 1961)

$$R = R_{max} (\exp (-a^2r^2) \qquad (1)$$

Here R is the rainfall rate along an isohyet which is at a distance r from the center of the storm with a maximum rainfall rate R_{max}, and a is a constant which defines the scale and circularity of the model storm.

Simulated storms were moved at various speeds across a networks of several watershed (basin) grid sizes. Sampling within the grid was randomized by use of Monte-Carlo techniques. Results for a model storm having a maximum rainfall intensity of 5 inches per hour and moving at 20 knots over a 5 nmi x 5 nmi grid (25 nmi^2 watershed) are presented in Figure 2. As would be expected, the root-mean-square error (RMSE) in total rainfall increases as the sample time interval Δt is increased. For operational hydrologic purposes a scan interval of greater than 12 minutes in unacceptable and a scan interval of less than 10 min is desirable. Presently D/RADEX radar sites are sampling at 12 min intervals. These results demonstrate the need for a continuous record of storm radar rainfall data, i.e., the radar must collect data continuously at a specified scan interval during periods in which significant rainfall occurs under the radar umbrella.

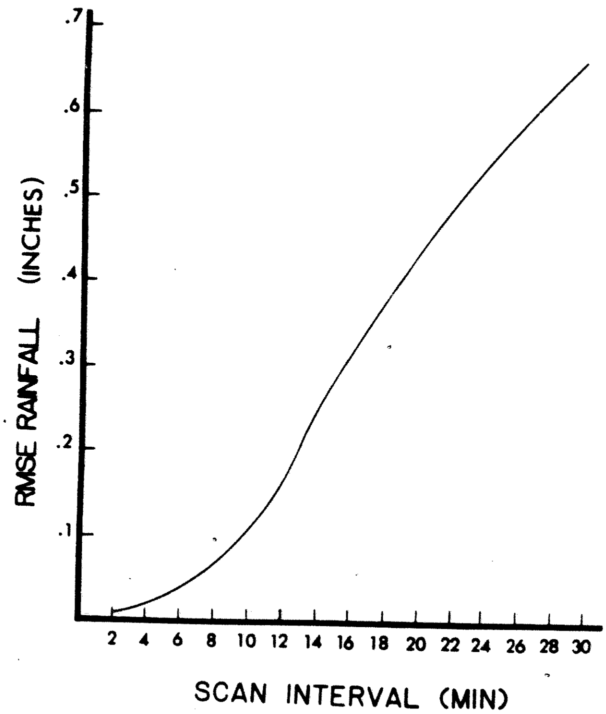

Figure 2. RMSE in hourly rainfall totals obtained by use of model storm simulation.

Timely quantitative estimates of precipitation based on a continuous set of digital radar data have application to two important hydrologic forecast problems, viz., river stage and flash-flood monitoring.

2.2 River Stage Forecasting

One of the primary objectives of the radar hydrology program is to develop river stage forecasting techniques based on digital radar data. This is being done semi-operationally at each River Forecast Center (RFC) by developing procedures and using radar data as inputs for streamflow synthesis in hydrologic models.

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UMN    10  X  10  GRID HYDRO     263*74/0600Z-263*74/0900Z

   0  0  1  1  1  1  2  2
   4  7  0  3  6  9  2  5

10              1
11        11   111111111
12     1 1      12211111
13    1 11  +   11111111
14     111      1111111111
15    11111   111111111
16   1111111122111111
17      11111112111111
18    11111111221111
19    11111222322211
20 1111222233222211
21  11112221111111
22  1111111111
23  1111111
24   111

   0  0  1  1  1  1  2  2
   4  7  0  3  6  9  2  5

SDHA12 UMN DRØS 5
 74 263   6   0
 74 263   9   0


LINE 4:    0   0   0   0   0   1   0   0   0   0   0   0   0   0   0
LINE 6:    0   0   0   0   0   0   0   0   0   0   0   0   0   1   0
LINE 7:    2   0   0   1   1  11  19   5   4  16   0   0   6  12  39
LINE 8:   33  24  18  18  25  61  53  34  13  10   1   9   2   0   0
LINE 9:    0   1   1   7  27  54  73  63 112  91 101  10   4   1   0
LINE 10:   0   0   0   0   0   1   6  31  50  93  82  25   0   0   0
LINE 11:   0   0   0   0   0   0   0   4  28

SDHA22  UMN
 74 263   6   0
 74 263   9   0

 0   0   0   0   0   3   4   6   0   2

NO  AP  INDICATED
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Figure 3. Example of hydrologic message transmitted to the RFC.

The D/RADEX processing system derives areal rainfall values, accumulates and transmits these totals via low speed dial-up telephone ASR33 teletype communications system to the appropriate RFC each three hours. These three-hourly rainfall estimates are furnished to the RFC in two forms: a "HYDRO" grid representing fictitious 10 nmi x 10 nmi watersheds under the radar umbrella and mean basin precipitation values for defined watersheds. An example of a typical HYDRO message is shown in Figure 3.

The grid message presents a coded value representing the average rainfall accumulated during a 3-hour period over a 10 nmi x 10 nmi (100 nmi^2) watershed. The code values and the corresponding rainfall totals are given in Table 1. The purpose of the grid output is to eliminate the size and shape problems encountered in the watershed method and to give the forecaster a picture of the precipitation pattern for subjective interpretation.

The watershed portion of the data consists of basin average precipitation (in hundredths of an inch) for operationally defined watersheds, and precipitation totals for several 50 nmi^2 control areas centered over raingages (see Hudlow, 1972). The control values are used for quality control purposes by comparing with rain gage recorded amounts on a real-time basis.

Table 1. GRID HYDRO CODE

Code Value	Rainfall Amount (Inches)
1	0.00 - 0.50
2	0.51 - 1.00
3	1.01 - 1.50
4	1.51 - 2.00
5	2.01 - 2.50
6	2.51 - 3.00
7	3.01 - 3.50
8	3.51 - 4.00
9	4.00 - 10.00

This HYDRO message is received automatically from the radar sites every 3 hours and simultaneously printed on hard copy and punched on to 8-channel punched paper tape. Data in the paper tape form must be manually removed (in some cases converted to another medium) and input into a computer file for access by the operational hydrologic forecast programs. One form of the outputs from this program is the forecast flow hydrographs. Figure 4 is a comparison of the forecast hydrographs computed independently by us of raingage data and digital radar data with the observed hydrograph. Although the radar forecast crest flow was low, the radar forecast was much more realistic than the forecast based on raingage data.

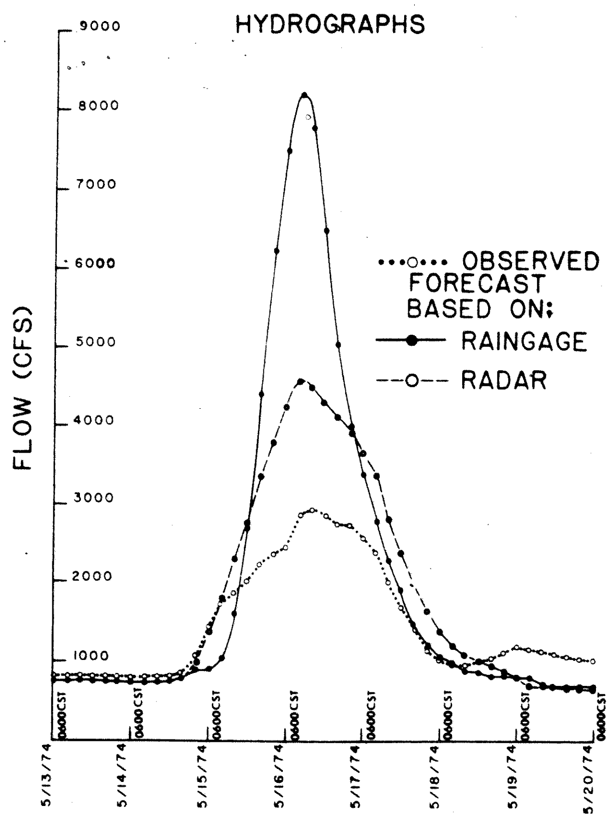

Figure 4. Comparison of predicted hydrographs based on radar and raingage data with the observed flow for a basin on the Illinois River near Tahlequah, Oklahoma.

Evaluation of the limited storm cases in which a consistent set of radar data has been collected reveals that radar derived forecast hydrographs compare favorably with those computed from raingage data. Further the radar forecast can be made and transmitted to the public in a matter of minutes versus a matter of hours needed for the raingage derived forecasts (Tetzloff, 1974).

2.3 Flash-flood Monitoring

Observation of rainfall on a fine temporal and spatial sale and accurate prediction in the short period (0-2 hr) are prime ingredients of a flash flood monitoring system. In addition to quantitative precipitation measurements, the observational system should include information as to the speed, components of motion, configuration, and orientation of the storm system. Given this information the system developed for D/RADEX provides the user with an estimate of how much rain falls in a given time interval over a given basin in real-time.

The objectives of the current development effort are:

1) To derive rainfall from digital radar data each 10-12 min and to obtain accumulated totals of these estimates on a 2 nmi x 2 nmi grid for the region within the effective hydrological range of the radar.

2) To provide guidance to the forecaster by making a short period (2 hr or less) prediction of spatially accumulated rainfall.

The prediction of rainfall is formed by extrapolating observed rainfall patterns through the use of mean motion vectors obtained from a pattern recognition analysis of the rainfall patterns observed by radar. The procedure used to compute the mean pattern motion vector is to obtain the best pattern match between sequential radar derived precipitation patterns by use of cross-correlation techniques. The technique thought to be the most amenable to the radar mini-computer environment is an adaptation of the binary matching procedure used to determine cloud pattern motions from satellite image data (Leese, et al., 1970). The application of this technique to flash-flood prediction is discussed in detail by Greene and Clark (1974).

A storm that demonstrated that digital radar data can be an invaluable tool in flash-flood forecasting occurred in the Central United States on October 10-11, 1973. The National Severe Storms Laboratory (NSSL) at Norman, Oklahoma, collected and archived digital radar data for this storm. These data were processed by use of the flash-flood monitoring software developed under the D/RADEX project. Sample outputs derived from data for the period 1800 to 2000 CST October 10, 1973,

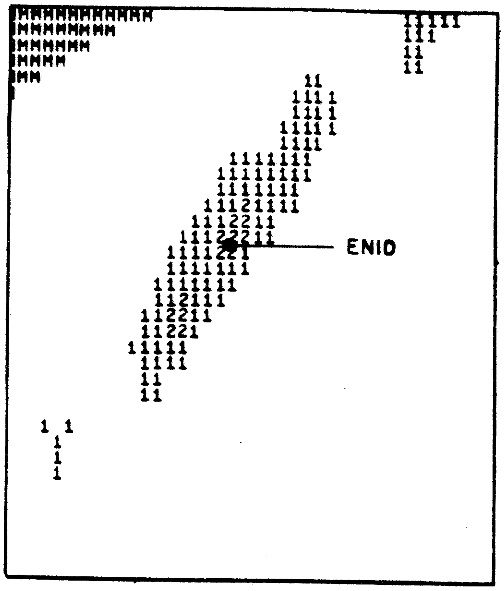

Figure 5. Radar derived rainfall totals (inches), 1800 to 1830 CST, 10 October 1973.

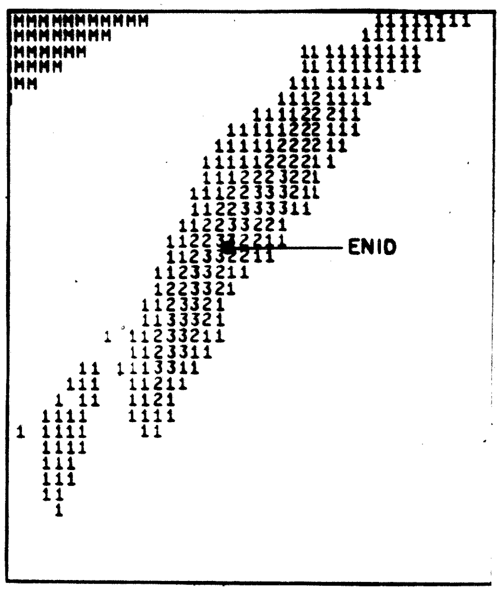

Figure 6. Radar derived rainfall totals (inches), 1800 to 1900 CST, 10 October 1973.

are presented in Figure 5 through 8. This storm system displayed two characteristic indicators of flash-flood producing storms: echoes of moderate or strong intensity, and persistent or quasi-stationary echo patterns. This is illustrated in Figures 5, 6, and 7, by the large radar inferred rainfall accumulations which occurred in short-time intervals. Figure 7 shows maximum 2-hr areal rainfall totals of 7 inches which, if displayed to the forecaster in real-time, will assist greatly in the preparation of flash-flood warnings.

The large scale motion of this storm system was adequately identified and described by the binary matching procedure; however, individual features that formed and propagated northward along the frontal zone were masked out by the threshold procedure in the binary matching routine. This led to errors in the 1-hr extrapolation totals valid for 2000 CST, Figure 8. The smaller scale features could be identified and tracked if a cluster tracking procedure, such as developed by Duda, et al., (1972), were employed. The problem is that sophisticated tracking procedure have storage and processing time requirements that do not lend to the radar mini-computer.

3. EVALUATION

3.1 Problem Areas

Two obstacles in the attempt to use operationally digital radar data are:

1) under certain atmospheric conditions anomalous propagation (AP) returns polute radar rainfall estimates, and

2) under certain operational conditions severe storm surveillance and regular hydrologic data collection are incompatible.

The impact of these difficulties is that usable data are collected and transmitted to the RFC for only approximately one-quarter of the 3-hr message periods covering significant rainfall events. This inconsistent receipt of data presents a major problem to the forecaster attempting to use the data. It is difficult to derive a forecast when a one or two-hour period of the heaviest rainfall is missing from the data set.

The NWS has placed a high priority on the elimination of these two problem areas:

1) Non-weather echoes exhibit a fluctuation spectrum which is significantly different from that which is typical of precipitation echoes. Independently, Nathanson (1969) and Schaffner (1974) have suggested that these non-weather echoes can be discriminated or flagged on a data point basis. The NWS is supporting the development of such an AP discriminator through a joint research contract with the South Dakota School of Mines and Engineering and the Technology Service Corporation. A report on this work is presented in the preprints of the conference by Johnson, et. al.,(1975).

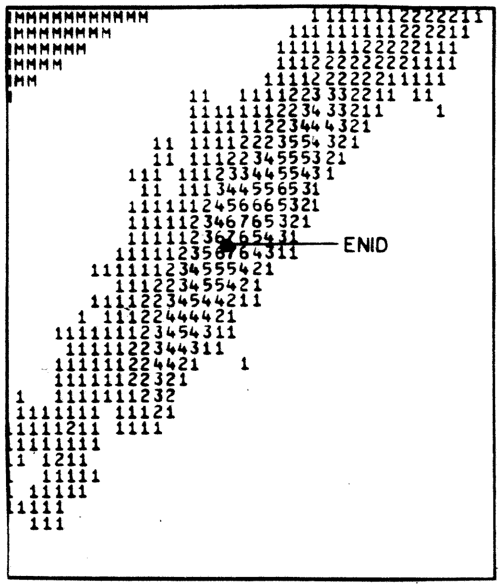

Figure 7. Radar derived rainfall totals (inches), 1800 to 2000 CST, 10 October 1973.

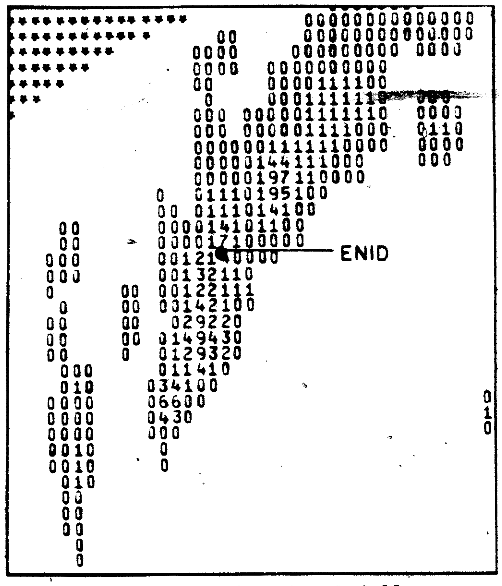

Figure 8. Extrapolated rainfall accumulation (inches), 1900 to 2000 CST, 10 October 1973.

2) The D/RADEX operating system, which controls the automatic collection of data, has been redesigned to allow for regular data scans with minimal interference to severe storm surveillance. The new system allows the 20-sec data scan to be taken within a 5-minute window at 12 minute intervals. Also, the program status is being changed from experimental to operational. In the

Table 2. Correlation of six-hourly rainfall totals estimated from radar with raingage measurements.

Station	Range (nmi)	Correlation Coef.	Slope	Intercept
Monett Radar				
Joplin, Mo.	33	.96	1.00	- .02
Fayetteville,Ark.	55	.98	1.09	- .02
Chanute, Ka.	89	.90	2.76	.06
Fort Smith, Ark.	96	.53	1.44	.13
Tulsa, Okla.	105	.93	2.85	- .04
Oklahoma City Radar				
Fort Sill, Okla.	60	.97	1.11	.00
Hobart, Okla.	75	.80	1.48	- .02
Ponco-City, Okla.	83	.25	1.42	.22
Wichita Falls,Tex.	95	.20	.40	.24
Altos, Okla.	96	.50	2.58	.11
Tulsa, Okla.	96	.81	1.04	.06

operational mode the D/RADEX equipment will operate on a full-time basis thereby reducing the number of missed observational scans.

3.2 Radar-Rainfall Relationships

A great many investigations have developed empirical Z-R relationships relating rainfall rate and radar reflectivity. The main feature of these relationships is the disagreement among them. This can be attributed to the following causes: errors in radar calibration, the radar beam is not filled uniformly with hydrometers, and variations in in-cloud drop size distribution due to meteorological factors. The most commonly used equation is the one proposed by Marshall and Palmer, (1948) viz.,

$$Z = 200\ R^{1.6} \qquad (2)$$

Experience gained to date in the hydrologic application of digital radar data in D/RADEX has demonstrated that rainfall rates obtained from the Marshall-Palmer equation must be increased by a factor of "two" to be consistent with the observed data. Applying this factor of two to Equation (2), we obtain

$$Z = 66\ R^{1.6} \qquad (3)$$

Note that in the development and application of Equation (3) no corrections are made for atmospheric absorption, rainfall attenuation, gradient bias, or radome losses.

In the field application of D/RADEX data precipitation estimates obtained by use of Equation (3) are evaluated continually through the use of observed rain gage data and the relationship revised to remove any consistent bias. Correlation coefficients obtained in the evaluation of 6-hr accumulations collected during the period May through October 1974 are presented in Table 2. These correlations are consistent and excellent for ranges within 75 nmi of the radar, but at greater ranges they are not as good. Although these figures are based on a very small data sample, it is apparent that some type of range adjustment factor, as suggested by Wilson (1971), should be used. A range adjustment factor will have to be based on a larger data sample than is presently available. This problem will be attacked as additional data is collected in the D/RADEX program. These adjustment problems could be circumvented by construction of objectively analyzed correction factor maps based on the integration of radar and observed rain gage data as suggested by Brandes (1974).

4. PLANS

As noted previously in this paper, quantitative estimates of precipitation based on radar data have application to two important hydrologic forecast problems; flash flood warning and river stage forecasting. The river stage problem allows for a limited time delay for data collection and analysis, whereas the flash flood problem requires real-time data processing that must be accomplished at the radar site. To be responsive to the flash flood problem and provide the most accurate measure of the areal distribution of precipitation for river flood forecasting, we plan to process digital radar data in two stages; initially on-site in the radar mini-computer and then at a central processing site.

4.1 On-Site Processing

On-site processing will include data collection, AP discrimination, quality control, application to flash-flood monitoring, and accumulation of rainfall estimates for future hydrologic processing. The following scenario is suggested for on-site processing:

1) Collect and digitize data.
2) Tag AP returns.
3) Perform the quality control function in near real-time by comparing radar precipitation estimates with selected raingage data collected automatically through mini-computer interrogation of DARDC (Device for Automatic Remote Data Collection) equipped raingages. Since the on-site computer capabilities do not lend to sophisticated integration and numerical analysis techniques such as proposed by Brandes (1974), methodology remains to be developed to derive an improved estimate of rainfall based on radar data and a sparse amount of raingage data.

4) Accumulate these improved initial rainfall estimates and at selected time intervals transmit these data to a central site for further processing. These accumulated data will be compressed so that an overwhelming quantity of data will not have to be transmitted.

5) Input data to flash flood monitoring routine.

4.2 Central Processing

Collection of radar data at a central site makes the data available for compositing and application of sophisticated processing techniques possible through the use of large scale computer systems. The following processing steps are planned at a central location:

1) Collect accumulated rainfall estimates from radar sites and store data on a disk file or other rapid recovery device for additional processing.

2) Collect detailed raingage data from synoptic and substation network of reporting stations.

3) Obtain the optimal areal distribution of precipitation based on the integration of radar and raingage data through the use of an analysis technique such as the one developed by Brandes (1974). A composite precipitation analysis could be developed from data collected from several sites or all sites within a region. Such an analysis has potential for quantitative precipitation forecast updating and verification as well as other applications.

4) Data from the integration analysis will be used as an input into the RFC hydrologic model which is also processed at a central computer site.

4.3 Communications

One weak link in D/RADEX is data communication. When hydrologic data are transmitted from the radar site to the RFC it is received on a teletypewriter device in a printed copy and/or punched paper tape mode. To apply these data to hydrologic models requires manual editing and input into the computer. This time consuming process reduces the efficiency of the total system. The teletype transmission also limits the physical size and, therefore, detail, of the intelligence that can be communicated. Communication of digital radar products should be improved greatly during the next five years when the NWS AFOS (Automation of Field Operations and Services) becomes operational.

AFOS is a new all-electronic system for communications, data storage, data display, and forecast dissemination that the NWS has recently began testing. Under this system all national centers, forecast offices, and observation sites will be linked by a digital communications line called the National Digital Circuit (NDC). Plans are to use AFOS to pass preprocessed radar data to a central site and to transmit flash-flood monitoring products to the forecast office having warning responsibility.

4.4 Expansion

Current planning within the NWS calls for implementation of digitizing systems at all WSR-57 network radar sites and several local warnings radar sites. Timing of the installation of the RAdar DAta Processor (RADAP) systems is contingent upon future resources.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Brandes, E.A., 1974: Radar rainfall pattern optimizing technique. NOAA Technical Memorandum ERL NSSL-67, U.S. Department of Commerce, National Severe Storms Laboratory, Norman, Oklahoma, 16 pp.

Court, A., 1961: Area-depth rainfall formulas. J. Geophys. Res., 66, No. 6, 1923-1931.

Duda, R.O., and R.H. Blackmer, Jr., 1972: Application of pattern recognition techniques to digitized weather radar data. NOAA contract 1-36072, Menlo Park, California, Stanford Research Institute, 135 pp.

Greene, D.R. and R.A. Clark, 1974: The operational use of digital radar data for flash flood monitoring. Flash Floods Symposium IAHS-AISH Publication No. 112, Washington, D.C., Amer. Geophys. Union, 100-105.

Hudlow, M.D., 1972: Use of radar data from D/RADEX for operational hydrology. Preprints 15th Radar Meteorology Conf., Boston, Amer. Meteor. Soc., 117-123.

Johnson, G.N., P.L. Smith, F.E. Nathanson, and L.W. Brooks, 1975: An analysis of techniques for dealing with anomalous propagation. Preprints 16th Radar Meteorology Conf., Boston, Amer. Meteor. Soc.

Leese, J.A., C.S. Novak, and V.R. Taylor, 1970: The determination of cloud pattern motions from geosynchronous satellite image data. Pattern Recognition, 2, Pergamon, London, 279-292.

Marshall, J.S. and W.M. Palmer, 1948: The distribution of raindrops with size. J. Met., 5, 165-166.

McCallister, J.P., J.L. Teague, and C.E. Vicroy, 1966: Operational radar rainfall measurements. Twelfth Conf. on Radar Meteorology, Boston, Amer. Meteor. Soc., 208-215.

McGrew, R.G., 1972: Project D/RADEX (digitized radar experiments). Preprints 15th Radar Meteorology Conf., Boston, Amer. Meteor. Soc., 101-106.

Nathanson, F.E., 1969: Radar Design Principles, McGraw-Hill, New York, 626 pp.

Schaffner, M.R., 1974: Research-study of a self-organizing computer. NASA contract NASW-2276.

Smith, P.L., Jr., K.R. Hardy and K.M. Glover, 1974: Applications of radar to meteorological operations and research. Proceedings of the IEEE, 62, No. 6, 724-745.

Tetzloff. R.P., 1974: Operational use of digitized radar data at the Tulsa River Forecast Center. Unpublished manuscript, 27 pp.

Wilson, J.W., 1971: Use of rain gages to adjust radar estimates of rainfall. Final Rept. CEM 4098-448, The Center for the Environment and Man, Hartford, Conn.