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USE OF DIGITAL RADAR DATA IN OPERATIONAL HYDROLOGY

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BY

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INTRODUCTION

The weather radar is an important sensor for operational hydrology, since it provides the capability to record the distribution of precipitation almost continuously in time and space within the domain useful for hydrologic applications. Until recently, its operational use has been limited due to the laborious task of manually processing radar data. Now, after several years of effort, an automatic radar-signal processing and data communication system designed for National Weather Service (NWS) operations is complete and is undergoing testing and evaluation as part of the "Digitized Radar Experiments" (D/RADEX).

One of the purposes of this paper is to describe the operational experiment which comprises the radar hydrology subprogram of D/RADEX. Much of the paper pertains to how analyses of radar and rain-gage data from D/RADEX can be used to refine the methodology for estimating rainfall by remote sensing with radar.

One of the most fruitful advances in river and flood forecasting will be achieved by acquiring improved precipitation inputs for streamflow synthesis. Precipitation data of sufficient temporal and spatial detail (as digitized radar data can provide) are required to accurately synthesize the temporal distribution and quantity of streamflow. The precipitation data must also be made available to the river forecaster in approximately real time to ensure a "timely" forecast. The optimum spatial resolution of the precipitation inputs changes as a function of variability in time and space of the precipitation, the magnitude of the precipitation event, and the hydraulic and geometric characteristics of the watershed--especially the area of the watershed above the forecast point. The operational rain-gage network often fails to provide the spatial resolution required to adequately specify the rainfall inputs to a runoff model. This is particularly true for geographic regions which receive a significant portion of their rainfall from convective and thunderstorm activity.

The engineering advances in recent years in mini-computers and signal processing and digitizing equipment now makes it feasible to process and communicate weather radar data in "real time." Yet, an optimum operational system

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must provide accurate, as well as timely, information. Unknown meteorological and hardware variabilities and sampling deficiencies, especially at far ranges, can result in large errors accompanying the radar precipitation estimates. A carefully designed and executed program of hardware calibration will reduce the errors due to hardware variability to a tolerable level. Variabilities which produce alterations in the relationship between reflectivity and the characteristics of the transmitted energy and in the relationship between rainfall rate and reflectivity, that are meteorological in origin, are considerably more difficult to explain. For this reason, it is desireable to supplement the radar measurements with independent measurements made at selected points underneath the radar "umbrella."

A mini-computer located at the radar site and a "Device for Automatic Remote Data Collection" (DARDC) located at the rain-gage site make it feasible to automatically interrogate a remote rain gage(s). Flanders and Schiesl (1972) describe the design of the DARDC. The mini-computer also serves as a computational facility for combining the radar and rain-gage data in real time according to specified objective criteria. The biggest problem with this approach rests with the difficulty in objectively relating the point rain-gage measurements made at the surface to the volume radar measurements made at some distance above the surface. This is especially true in convective rainfall regimes, where the spatial variability of the precipitation can be quite large.

The problems associated with using precipitation data from several telemetered rain gages to adjust the radar precipitation fields are discussed in a latter section of this paper. It may prove desirable to also include meteorological data derived from atmospheric soundings as another source of information which can be used in specifying objective criteria needed for the adjustment scheme: or, it may be possible to account for changes in the objective criteria originating from meteorological causes by relating the adjustment factors to a statistical analysis of pattern characteristics. The latter possiblity--a statistical approach--is treated as part of this paper.

The scope of this paper is restricted to plans for the use of digitized radar data in hydrologic applications within an operational environment and as part of D/RADEX. Other authors have traced the history as well as considered the future of automatic radar systems which can provide real-time meteorological and hydrological services (e.g., see Flanders and Bigler (1971) and Kessler and Wilson (1971)).

DESCRIPTION OF "DIGITIZED RADAR EXPERIMENTS" (D/RADEX

Since the theme of this paper is concerned with the application of digital radar data from an automatic system such as the one used for D/RADEX, a brief description of D/RADEX is given here. For additional information pertaining to D/RADEX refer to McGrew (1972) and Hudlow (1972).

For D/RADEX, WSR-57 (10cm) radars located at Monnett, Missouri, Kansas City, Missouri, Oklahoma City, Oklahoma, and Fort Worth, Texas were implemented the Spring of 1972 with processing and communication hardware. Figure 1 illustrates the radar network for D/RADEX. The radii of the circles are 125 n mi, which is the maximum range that radar data are collected for D/RADEX. Also shown in Fig. 1 are the areas of the River Forecast Centers (RFC's) which fall within the D/RADEX net. These three RFC's, located at Kansas City, Tulsa, and Fort Worth, are contributing to the objectives of D/RADEX by providing streamflow verifications and by furnishing evaluations of the benefits gained from operational use of radar precipitation data.

Each automatic system basically consists of a signal processor, an analog to digital converter, a mini-computer for editing and preprocessing, a dual magnetic-tape system and communication equipment. Figure 2 is a block diagram illustrating the arrangement of the basic components of the data-processing system.

The exact configuration of the automated system probably will change with time as the system is updated to remain abreast of the "state of the art"--much will be learned from D/RADEX. Evaluation and feedback from the RFC's and the field radar units will be invaluable, since these evaluations will be based on the performance of the system under operational conditions.

The radar video is digitized at a spatial resolution of 2 degrees in azimuth by 1 n mi in range. Two degrees is the beam width of the WSR-57 radar. One can consider the digital array to consist of data bins of size 2° x 1 n mi and each data bin contains an integer value between 0 and 9 (10 levels). Each integer corresponds to a level of power return which is related to a precipitation intensity.

The crux of the operational hydrology experiment for D/RADEX consists of deriving time integrated and spatially averaged precipitation estimates from the radar data. The fundamental computational algorithm can best be illustrated with an example. Figure 3 shows the radar data bins which fall within a subwatershed located in the Fort Worth area. This is a drainage area for Clear Creek which lies north-north west of Fort Worth, just outside the ground clutter pattern.

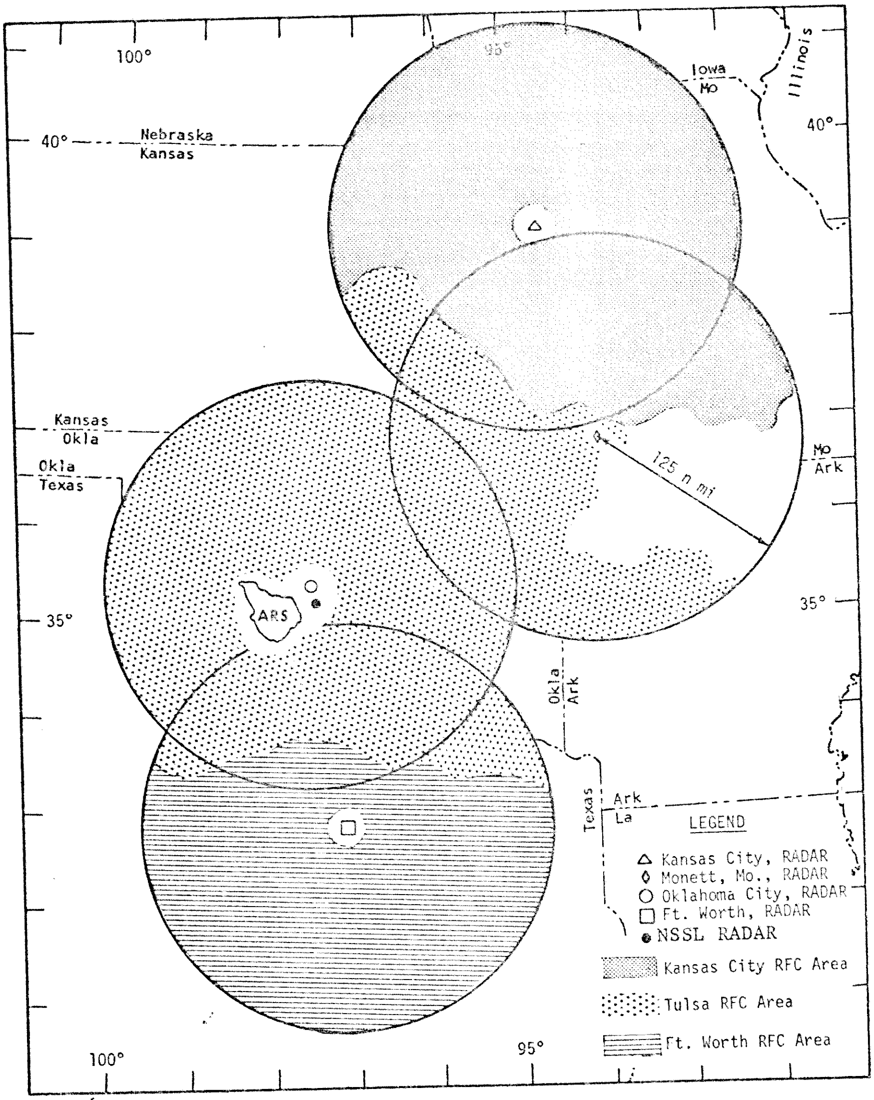

Figure 1. D/RADEX Network Radars, NOAA NSSL Radar, Department of Agriculture ARS Rain-Gage Network, and RFC Coverages.

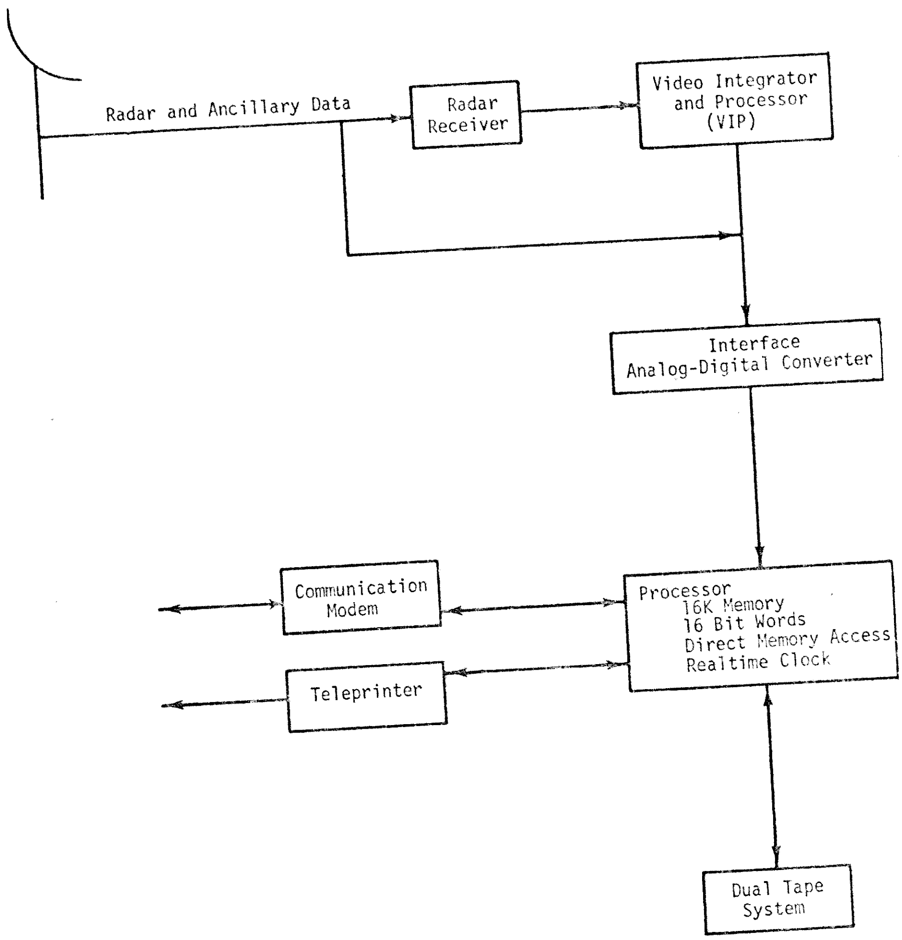

Figure 2. The D/RADEX Hardware Configuration.

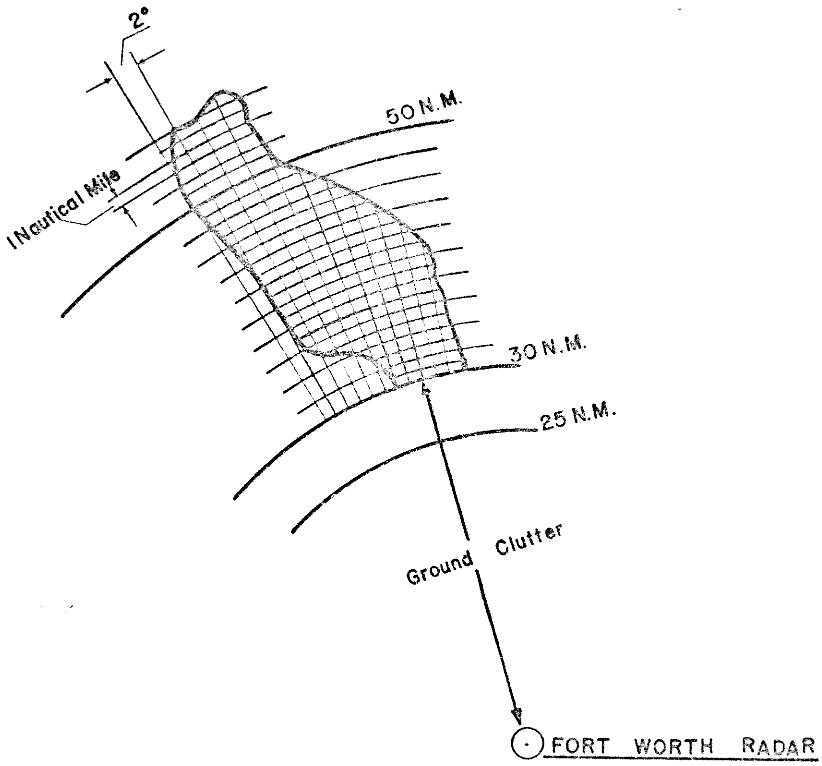

Figure 3. Illustration of the Radar Data Bins (2^{o} x 1 n mi) Contained in the Clear Creek Watershed near Fort Worth, Texas.

For this example, the total number of bins contained within the boundary of the watershed is 170. After converting the radar intensity digits into rainfall rates using the equations described in the next section, the average precipitation flux over the watershed is given by

$$\overline{R} = \frac{\sum_{i=1}^{i=170} (R_i r_i)}{170 \cdot \sum_{i=1}^{i=170} r_i} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where R_i is the rainfall rate for the ith radar data bin and r_i is the range to the bin. The rainfall rates are weighted by $(r_i/\Sigma r_i)$ to compensate for the change in area of the radar bins, which vary in direct proportion to range away from the radar. Equation (1) gives the spatially averaged rainfall rate for an instant in time. To obtain the total amount of precipitation deposited during an interval of time, trapezoidal integration is applied, giving

$$\overline{P} = \frac{(\overline{R}_1 + \overline{R}_2)}{2} \Delta T \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

where $\overline{P}$ is the accumulative precipitation deposited from Time 1 to Time 2 over the watershed; $\overline{R}_1$ and $\overline{R}_2$ are the average rainfall rates from Time 1 and Time 2, respectively; and ΔT = Time 2 minus Time 1. Optimumly, ΔT should not exceed 15 min.

For D/RADEX, precipitation amounts are derived from the digital data for an approximate total of 700 sub-watersheds which are located in the three RFC areas shown in Fig. 1. The hydrologic coverage illustrated in Fig. 1 for the entire D/RADEX network totals 140,000 $(n\ mi)^2$. The average size of the 700 watersheds is 200 $(n\ mi)^2$ and they range in size from a few $(n\ mi)^2$ up to larger than 1000 $(n\ mi)^2$.

RADAR THEORY

By the mid-1940's it was recognized that the amount of power returned to a radar from hydrometeor targets was related quantitatively to the intensity of precipitation. However, operational application of radar data in hydrology, through the years, has lagged the radar theory primarily due to the cumbersome task of manually processing the vast amounts of data that radar signals produce.

Now, with the recent advances in electronic processing and communication equipment and mini-computers, it becomes possible to disseminate radar-rainfall estimates to river forecast centers in real time.

Radar Equation and Z-R Relationship.--The usual approach for obtaining quantitative precipitation estimates from weather radar measurements requires the use of an empirical relationship between rain rate and reflectivity factor. The reflectivity factor is related to that portion of the transmitted energy which is back-scattered to the radar receiver.

The average power, $\bar{P}_r$, returned to the radar receiver from a volume of precipitation particles filling the radar beam is given by

$$\bar{P}_r = \frac{C|K|^2 Z}{r^2} \qquad \qquad (3)$$

where C is a constant that depends on the radar equipment, r is the slant range to the target, and

$$K = \frac{(m^2-1)}{(m^2+2)} \qquad \qquad (4)$$

where m is the complex index of refraction of the precipitation particles. The Probert-Jones (1962) formulation for C was adopted for D/RADEX. Z is the target reflectivity factor and is defined from the Rayleigh approximation to the Mie scattering theory as

$$Z = \sum_{i=1}^{i=n} (d_i)^6 \qquad \qquad (5)$$

where d_i is the diameter of the ith raindrop in the sample and the summation is for all drops (n) within the volume illuminated by the radar pulse, normalized to a unit volume.

Empirical relationships relating rainfall rate to the reflectivity factor have been derived by numerous investigators and for several geographic locations. There is no unique relationship between rainfall rate and reflectivity because the functional relationship depends on the size distribution of raindrops within the volume undergoing measurement, and in turn, the drop-size distribution is a function of many climatological and meteorological factors. One of the most referred to simply as non-beam filling, for those ranges where non-beam filling becomes a serious problem. One way this can be done is by comparison with rain-gage data at various ranges.

Wilson (1971) has investigated the accurateness of WSR-57 data as a function of distance from the radar by comparing radar data collected at the National Severe Storm Center at Norman, Oklahoma to rain-gage data for six range increments between 15 and 120 n mi. Wilson used data primarily consisting of thunderstorm events occurring in 1968, 1969, and 1970. The radar data were collected at a base antenna angle of zero degrees. A total of 120 hours of storm data were used in the analysis. The results from Wilson's study can be approximated with the following expression:

$$R_a = R_u \cdot (c_1 10^{c_2 r^2}) \text{ for } r \geq r_c \quad \ldots\ldots\ldots\ldots (7)$$

where the term in parenthesis is a multiplicative adjustment factor which compensates for the effects of range degradation (non-beam filling) at radar ranges greater than a critical range, r_c, and R_u and R_a are the unadjusted and adjusted radar rainfall estimates, respectively, and c_1 and c_2 are empirically derived coefficients.

For the results presented by Wilson (1971), which are based on the Oklahoma data described above, the adjustment factor in Eq. (7) varies from about 1.0 at r_c = 70 n mi to about 4.5 at 125 n mi. The c_1 and c_2 coefficients will be allowed to vary as a function of storm type by relating them to echo statistics. Until this refinement can be included, it should be stressed that the use of Eq. (7), with the single set of coefficients, carries with it the assumption of mean thunderstorm conditions in Oklahoma. Any individual event can depart markedly from this mean condition. For statiform precipitation range degradation becomes a more serious problem. Also, c_1 and c_2 will depend on the type of radar, the base antenna angle, and terrain features.

ERROR SOURCES AND REFINEMENT OF ESTIMATES

Other authors have discussed at length the factors affecting the accuracy of radar measurements of rainfall (e.g. see Wilson, 1968). Here it is sufficient to categorize the errors as originating from three general sources, which are:

1. Hardware, sampling, and processing uncertainty--includes radar calibration errors as well as any errors induced in collecting, processing, and digitizing the radar signals,
2. Meteorological variability in time and/or space which results in unpre-

commonly used relationships is the one resulting from a slight revision of the equation proposed by Marshall and Palmer (1948), i.e.,

$$Z = 200R^{1.6} \qquad (6)$$

where R is the rainfall rate in mm/hr. Equation (6) is a median relationship representative of many, but far from all, rains. For additional information on Z-R relationships see, e.g., Stout and Muller (1968).

Equation (6) is used for deriving the radar rainfall estimates for the hydrology experiment of D/RADEX. If it becomes apparent as the experiment proceeds that Eq. (6) results in a consistent bias, another relationship or other relationships will be adopted. Regardless, although an unbiased Z-R relationship is obtained which corresponds to the average meteorological condition for the climatological region, there can exist sizeable departures from this mean relationship due to storm to storm and within storm variability.

Empirical Adjustment for Non-Beam Filling.--Equation (3) is valid only when the radar beam is filled with precipitation particles. There is no explicit method of determining the degree of beam filling from radar measurements alone. The likelihood of intercepting an adequate sample within the beam decreases as the distance to the target increases, because the radar beam widens and ascends above the surface of the earth as it travels away from the radar, until eventually even the tallest storms will no longer fill the radar beam.

Most experimental evidence indicates that quantitative rainfall estimates derived from weather radars, with beam widths of 2° or less, remain relatively undegraded (due to non-beam filling) out to ranges of about 60 or 70 miles. The WSR-57 S-Band radar, which remains the basic network sensor for the NWS radar network, has a 2-degree beam width. Beyond about 70 miles measurement errors increase quite rapidly, thus causing many investigators to recommend against using weather radars for deriving quantitative rainfall estimates beyond this range. However, we must not lose sight of the fact that much information content exists, for many of the storms that are of the most hydrologic significance, at ranges beyond 70 miles. Also, costs preclude the National Weather Service from installing and maintaining sufficient numbers of the radars and automatic digitizing systems to provide coverage at radar ranges less than 70 miles for all areas in the United States.

For D/RADEX the radar data are digitized and processed out to ranges of 125 n mi which is essentially the current network spacing for radar reporting of weather events. It is possible to derive statistics that give the average error caused by nonrepresentative beam sampling and non-beam filling, heretofore dictable departures from the adopted Z-R relationship and, occasionally, anomalous propagation and

3. Range dependent errors produced by non-beam filling and variations in the sampling altitude.

Error source No. 1 can be maintained at a tolerable level by judicious selection, use, and calibration of the hardware. However, Nos. 2 and 3 are more troublesome, since sizeable departures from the mean Z-R and range adjustment relationships can occur for an individual event and variations also take place during the life of the event in space and time. The magnitude of the error from these sources, particularly that due to the variability of the Z-R relationship and sampling error, can be lowered appreciably through spatial averaging and/or temporal integration--an approach especially suitable for many hydrologic applications, including the primary one considered in D/RADEX; since obtaining the average amount of precipitation over a specified area deposited during a given time interval is often the objective.

Even for mesoscale hydrologic applications, it is difficult to obtain the desired accuracy from radar measurements alone. This is especially true in an operational environment. For this reason, it is preferable to integrate other independent data with the radar data in order to attain the best possible answer. The decisive advantage of the radar is its ability to provide a timely product with ample spatial detail. Accompanying these advantages is the associated disadvantage of loss in absolute accuracy compared to that achievable at a point using a point sensor. A logical possibility would consist of combining a few point measurements with the areal radar measurements in order to benefit from the best features of both types of sensing. This possibility is given closer scrutiny in subsequent sections of this paper.

<u>Approximate Magnitude of Error</u>.--At the time of the writing of this paper, only limited and preliminary error analysis have been made from D/RADEX data. Most cases considered in the limited number of comparisons made to date indicate that the magnitudes of the radar-rainfall estimates are smaller than those derived from rain-gage networks. The underestimates are not too surprising, since as pointed out by Jones and Bigler (1966, pp. 11-14), many previous investigators have observed the tendency for radar to underestimate the magnitudes of rainfall unless the theoretical radar equation is adjusted by a factor derived from an experimental comparison with independent data (e.g., with a rain-gage network). Once sufficient D/RADEX data have been analyzed to establish the magnitude of the bias, the average bias can be removed by applying an empirical adjustment to the radar equation. However, due to deviations away from the mean,

a considerable portion of the variance will remain unexplained by the average bias adjustment.

Based on the findings of previous investigators, it is possible to assess the average error accompanying radar precipitation measurements if the following standard operational conditions are fulfilled:

1. Equipment capable of stable and reliable measurements is used,
2. Suitable calibration, sampling, and processing procedures are followed,
3. Areas of measurement are restricted to ranges less than 70 miles,
4. Attenuation caused by rainfall is small and
5. Seasonable adjustment is applied to the radar data based on a comparison with rain-gage data.

Two experiments conducted under conditions which largely satisfy the five criteria described above and which produced sufficient data for meaningful error analyses are those described by Barovikov and Kostarev (1970) and Wilson (1971). From the results reported by these authors, it is concluded that rainfall estimates can be derived from radar data alone with the error, <u>on the average</u>, held to within a factor of 2. This error limit pertains to storm totals of 1 mm or more and to areal averages over 50 $(mi)^2$ or greater. The error could be greater or less for a specific event but evidence from these two studies indicate that a large percentage of the estimates will be within a factor of 2 if the criteria listed above are fulfilled. Since a factor of 2 error is considerably worse than optimum, refinements are sought for D/RADEX.

<u>Possibilities for Refinement</u>.--Two refinements which potentially can improve the radar estimates are:

1. Use of independent data and objective analysis techniques and
2. Use of vertical radar data.

For example, item 1 may include the integration of rain-gage data from several scattered gages with the radar data. Also, drop-size data and/or data from atmospheric soundings can prove valuable. Cataneo (1970) used multiple regression techniques to relate the multiplicative coefficient in the Z-R relationship to sounding parameters and showed that improvements can be gained over the strict use of the Marshall-Palmer relationship. It should be possible to account implicitly for a significant portion of the meteorological and drop-size variability by combining information about the statistical structure of the echo pattern and rain-gage data according to an objective analysis procedure. This possibility is duscussed in greater detail in subsequent sections.

Item 2--use of vertical data--can be accomplished by collecting data for a sequence of antenna tilt angles. This provides additional information useful for delineating (1) vertical distributions of liquid water, (2) constant altitude fields and (3) areas of anomalous propagation (AP). Clark, Canipe, and Greene (1972) show an example of how 3-dimensional digital data can be used to obtain closer correspondence between precipitation patterns derived from radar and rain-gage data. The biggest initial benefit that should be gained from the use of tilt-angle data for hydrologic applications is the capability to detect and delete, in many instances, the return from AP.

RADAR AND RAIN-GAGE STUDIES DESIGNED TO IMPROVE RADAR ACCURACY

As explained earlier, refinements are sought for obtaining more precise estimates of precipitation from radar data. Efforts should continue to refine the radar and rain-rate equations and the calibration procedures so that, if possible, reliable estimates can be derived exclusively from radar measurements; thus eliminating, or at least reducing, the need for integrating telemetered rain-gage data with the radar data. However, rain-gage measurements will be required to supplement the radar measurements for several years hence. While the last 25 years of radar research has lead to many advances in data interpretation and data processing techniques and has provided much scientific knowledge in many areas of atmospheric physics, the accuracy of quantitative precipitation estimates, made in an operational environment, remains less than optimum.

Due to the many uncertainties surrounding the use of radar for precipitation measurement, it is unlikely that an average accuracy exceeding that specified above (factor of 2) can be achieved from radar measurements alone, within the forseeable future. Nonetheless, the radar represents an extremely important tool for the hydrologist by virtue of its capability to provide fine spatial detail in real time. In the remainder of this section procedures are described which pertain to the improvement of the radar precipitation estimates for D/RADEX.

The general approach considered here for acquiring the data base necessary to develop objective procedures, which use echo statistics and telemetered rain-gage data to facilitate adjustment of radar precipitation fields, consists of performing radar and rain-gage comparison studies using available historic data. The studies will lead to empirical relationships which can be used to (1) remove the average bias for a climatological locality (2) make range adjustments at far ranges as well as derive overall echo intensity adjustments by performing a real-time statistical analysis on the echo patterns using the mini-computer, and (3) formulate an objective analysis algorithm which applies echo statistics and telemetered rain-gage data to check and refine the final radar estimates.

While most of the procedures suggested in this section are statistical in nature, they are not without physical basis. Echo statistics are shown to be related to the meteorological conditions and the type of precipitation; and, the relationship between radar and rain-gage amount is considered meteorologically dependent.

Statistical Characterization of Echo Patterns.--A kinematic relationship which describes the instantaneous horizontal distribution of radar intensity at low altitudes within tropical radar echoes was derived by Hudlow (1971). The statistical expression takes the form of an exponential model which relates power received by the radar at a threshold, $\overline{P}_{rt}$, to the square root of the echo area, $\sqrt{A_{et}}$, persisting at and above the power threshold, t:

$$\overline{P}_{rt} = \overline{P}_{rm} 10^{-b\sqrt{A_{et}}} \qquad (8)$$

where $\overline{P}_{rm}$ and b are intercept and slope coefficients, respectively.

Figures 4 and 5 schematically illustrate Eq. (8). In hydrologic phraseology, Eq. (8) is analogous to a depth-area expression for precipitation amounts and, in fact, Eq. (8) can be transformed to a similar expression by substituting rainfall rate for received power through the use of Eqs. (3) and (6).

Although the basic form of Eq. (8) can be shown applicable to showery and thunderstorm rainfall in a wide variety of geographic locations and climatological regimes, the intercept and slope coefficients can differ greatly from one location to another. Also, $\overline{P}_{rm}$ and b will vary at the same location as the function of (1) the storm generation mechanism (2) size of the storm and (3) stage of development. Because $\overline{P}_{rm}$ and b alter with changes in the precipitation morphology, it is likely that statistically significant relationships exist between the empirical coefficients used in the rainfall estimation equations and $\overline{P}_{rm}$ and b. Assuming this is so, the radar rainfall estimates might be refined by (1) performing a real-time least squares analysis on the echo pattern to determine $\overline{P}_{rm}$ and b and (2) using $\overline{P}_{rm}$ and b to predict how much the empirical coefficients in the rainfall-prediction equation should be modified. An example of this procedure could consist of relating c_1 and c_2, appearing in Eq. (7), to $\overline{P}_{rm}$ and b.

To gain a better physical understanding of how $\overline{P}_{rm}$ and b alter with the type of precipitation, it is convenient to interpret Eq. (8) in 3-dimensions--

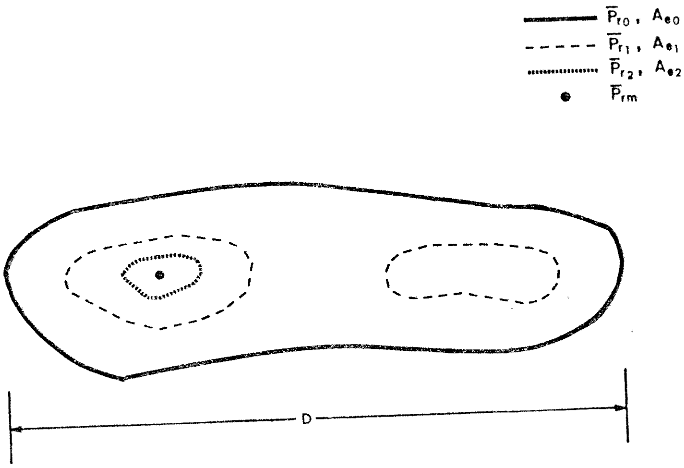

Figure 4. Hypothetical Schematic of a Multi-Core Radar Echo with Length D.

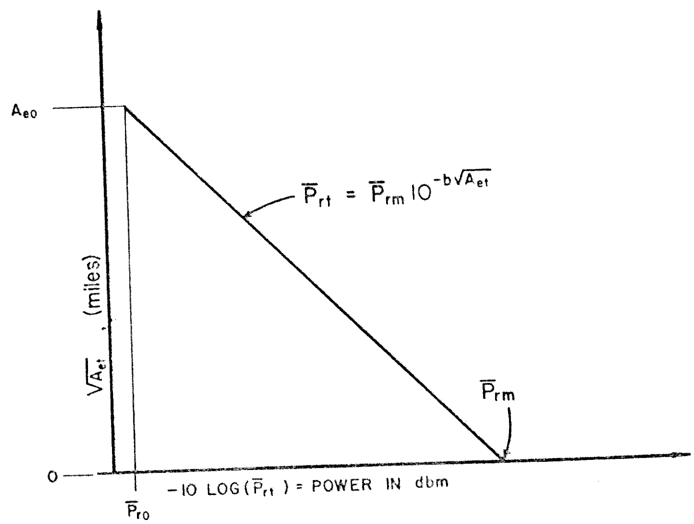

Figure 5. Hypothetical Plot of the Square Root of the Radar Echo Area Persisting at a Threshold (t) Versus the Threshold Power Measured by the Radar.

the two horizontal space dimensions and a vertical dimension consisting of intensity. The 3-dimensional field comprises a "precipitation mountain," where the height and steepness of the mountain are given by $\overline{P}_{rm}$ and b, respectively. The height ($\overline{P}_{rm}$) and the steepness (b) depend on the type of precipitation. For example, the profile generated by warm front precipitation should be shallower with a more gentle slope than that associated with cold frontal activity.

Radar Comparisons and Use of a Dense Rain-gage Network.--The 4-station D/RADEX network is illustrated in Fig. 1. Also shown in Fig. 1 is the location of the WSR-57 radar used by the National Severe Storms Laboratory (NSSL), NOAA and the location of the dense rain-gage network which is maintained by the Agricultural Research Service (ARS), Chickasha, Oklahoma. A description of the NSSL radar system is given by Wilk and Gray (1970). The boundary of the ARS rain-gage network is outlined in Fig. 1 by the pear shaped configuration located west of Oklahoma City (OKC) and NSSL. The ARS network covering 1100 sq. mi contains over 200 rain gages giving an average density of one rain gage about each 6 sq. mi. Nicks (1971) describes the collection and processing of the ARS rain-gage data.

The OKC and NSSL radars (both WSR-57's) are located within 15 miles of each other and each has a commanding view of the ARS rain-gage network. This arrangement provides an opportunity to make intercomparison studies between the OKC and the NSSL radars and the ARS rain-gage network. In preparation for the beginning of the 1973 Spring rainy season, intercomparison studies using the data collected in 1972, are underway.

Based on the intercomparison studies, the OKC radar data can be refined to give a data base with reasonable accuracy.

Once confidence is established in the OKC data, it can be used to check the accurateness of the Fort Worth (GSW) and the Monett (UMN) radar data within the overlap areas between OKC and GSW and between OKC and UMN. Using the same approach, the UMN data can be used to check the quality of the Kansas City (MKC) radar data inside the overlap area between UMN and MKC.

Upon completion of the radar and rain-gage studies described in this section, adjustments can be applied to the rainfall estimation equations to compensate for any average bias that appears in the 1972 data.

Use of Telemetered Rain-gage Data and Echo Statistics in Real Time.-- In the preceding section an approach was described for removing the average bias, for a given locality and radar, from the rainfall estimation equation. This section is concerned with procedures that may be used to improve radar precipitation estimates for individual events via real-time adjustment based on telemetered rain-gage data and echo statistics. The goal is to develop objective techniques which can be used for adjusting storm totals or precipitation amounts accumulated during a specified time interval, e.g., 3 hours--the primary time interval used in D/RADEX between transmissions to the river forecast centers. Some of the techniques discussed in this section are untested to date but nevertheless, are offered as logical approaches to a complex problem that can be supported by theory and the results from other studies.

With the capability provided by the DARDC and D/RADEX hardware, it is operationally feasible to automatically interrogate as many as 15 to 20 rain gages situated underneath a radar umbrella. Figure 6 is a block diagram illustrating the function of the various components of the automatic interrogation and processing system. Rain-gage data are input to DARDC in a Binary Coded Decimal (BCD) format. Prior to transmission, DARDC converts the BCD information to characters in accordance with the American Standard Code for Information Interchange (ASCII). The data can be sent to the radar site over telephone lines or by radio. The mini-computer is programmed to automatically initiate "call-up" of the rain gages at specified times and/or when the radar indicates precipitation accumulations exceeding predefined levels.

Possible network designs that might be used in positioning 15 to 20 telemetered rain gages are:

1. Clustered gages,
2. Isolated and scattered gages and
3. Combination using both clustered and scattered gages.

Each of these network configurations possess advantages and disadvantages. In practice it is desirable, if not mandatory, to use existing gages which were installed originally for other purposes than the one considered here. For example, Fig. 7 depicts a rain-gage network, composed of 6 hourly reporting stations and/or telemtered gages, in the OKC radar area. This network is made-up of isolated and scattered rain gages (network design No. 2). This type of design will be prevalent among existent networks.

Since network design No. 2 commonly occurs in practice, it seems desirable to develop techniques for its use. The scattered gage design has several advantages, which are:

1. A high probability exists that at least one gage will catch rain during the passing of a storm;
2. Since catches at several different ranges are possible, range effects can be examined; and

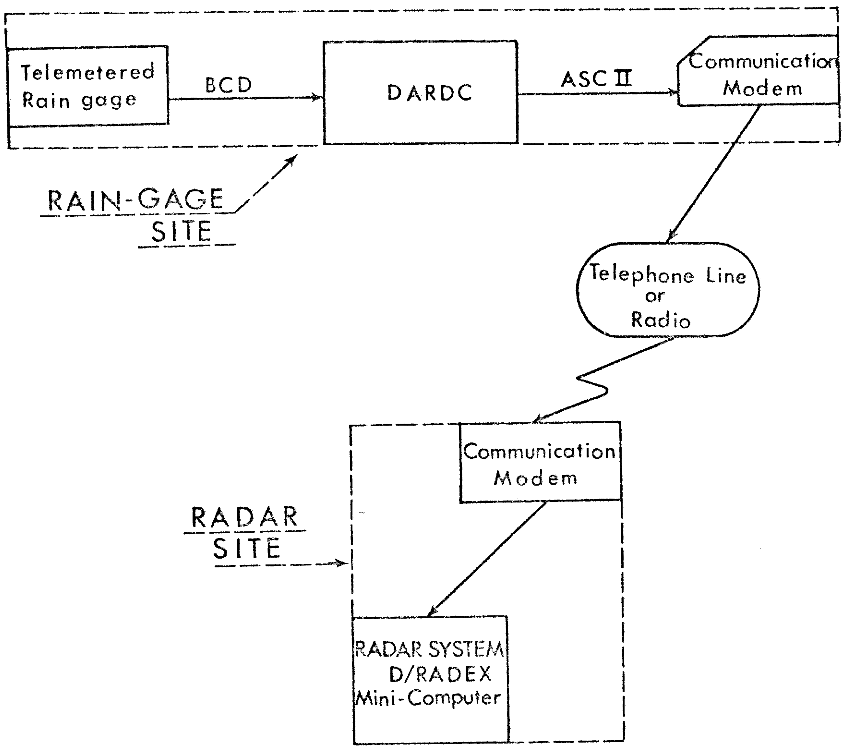

Figure 6. A Block Diagram Showing the Various Components of an Automatic Radar/Rain-Gage Data System.

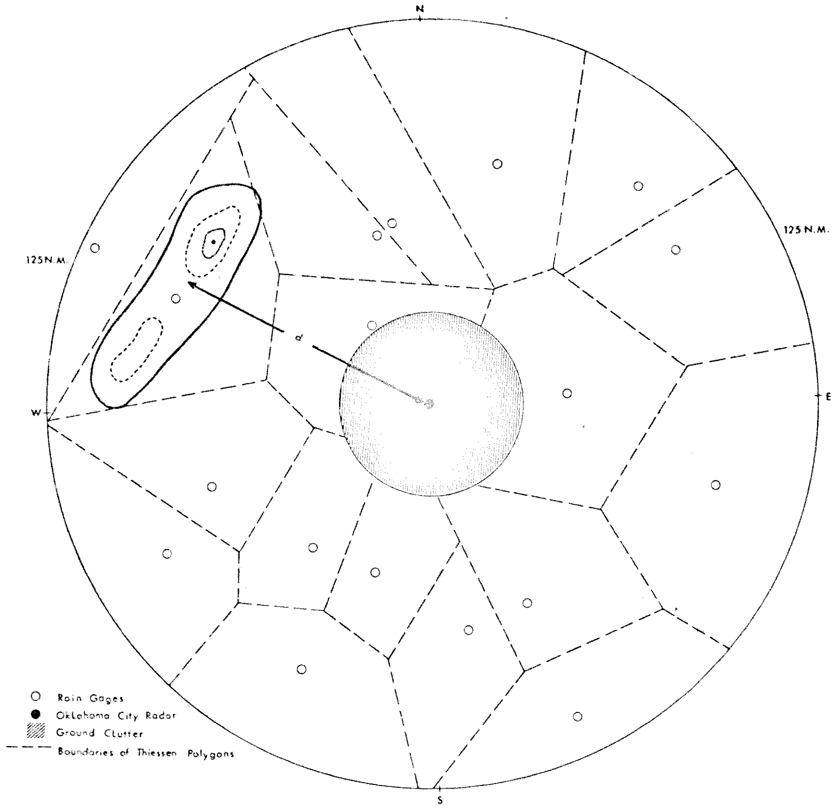

Figure 7. First Order and Telemetered Rain Gages in the OKC Radar Area with a Radar Echo Shown at One of the Rain-Gage Sites.

3. By dispersing the gages, part of the spatial variability in the Z-R relationship may be accounted for.

A major disadvantage accompanying the use of network design No. 2 is the uncertainties associated with relating a volume measurement made with the radar at some distance above the surface of the earth to point collections at the surface from rain gages. This disadvantage is particularly apparent for geographic regions which receive a significant portion of their rainfall from convective and thunderstorm activity with steep spatial gradients.

Some of the sources of error which affect the accuracy of using a few scattered and isolated rain gages to "calibrate" or adjust radar precipitation fields are:

1. Horizontal drift of precipitation because of winds during the journey to the surface--drift of 1 mile or more at r = 100 mi,
2. Miscalibration in range or misorientation in azimuth of the radar hardware--1 mile and 1 degree for WSR-57,
3. Imprecise knowledge of the geographic location of the rain gages--one-half minute of latitude and longitude,
4. Changes in the radar path length due to refractivity variations,
5. Areal nonrepresentativeness of a point rain-gage measurement,
6. Rain-gage errors, and
7. Spatial variability of the Z-R relationship.

With the many sources of error it is fair to ask: "How do we escape the predicament?" The answer to this question is not entirely clear; however, the objective procedures described in this section, which use echo statistics and telemetered rain-gage data to refine radar precipitation fields, provide reason for optimism. To keep things in perspective one must remember that the radar is capable of providing precipitation estimates which, in many instances, are more accurate than those available from sparse rain-gage networks and equally important, with radar, the estimates can be obtained in real time.

Both Wilson (1971) and Huff (1967) have explored the feasibility of using rain gages to calibrate radar data. Huff (1967) concluded that an impractical number of gages are required to reliably calibrate the radar, while Wilson (1971) reported that radar precipitation estimates for a 1000 sq. mi. area could be improved about 30 percent, on the average, by calibrating with a few isolated gages scattered around the area.

Wilson's apparent success in calibrating radar data with a few rain gages can be explained partially by the fact that he performed a logarithmic rather than a linear error analysis. A linear error analysis performed on the same set of data indicates that no improvement is gained from the use of the rain gages to calibrate. The reason for this is found by examining Fig. 8. The error in the precipitation estimates derived from radar tend to decrease as the magnitude of the precipitation increases. If for the larger rainfall amounts, the error associated with the procedure for calibrating the radar with rain gages exceeds the error accompanying the unadjusted radar estimate, the estimate may be degraded by using the rain-gage data to calibrate. A logarithmic error analysis compresses the absolute errors in direct proportion to the magnitude of the rainfall. This accentuates improvements gained in the smaller amounts and surpresses degradations suffered at the higher magnitudes.

As previously emphasized, a significant part of the error encountered in the use of rain gages to adjust radar precipitation fields originates with the mechanics of the procedure used for deriving a gage to radar ratio (g/R); where g and R are precipitation accumulations from the gage and radar, respectively. Wilson (1971) took R to be the average value for a 50 sq. mi circle centered on the gage. This can lead to large errors in convective rainfall, since the gage measurement at the center of the circle can differ significantly from the true average value for the circle.

Another approach which may produce improvements in the determination of g/R consists of using a cross-correlation technique to match echo patterns at two different times. A cross-correlation algorithm which is illustrated by Greene (1972) can be adapted to give the velocity vector defining the translation of the pattern from T_1 to T_2. This dynamic approach provides the capability to derive a path average rainfall rate which is used to define R. The mechanics of the technique consist of deriving path averages along a parallel path to the velocity vector passing over the telemetered rain gage. The length of the path is equal to the distance that the echo pattern would translate between interrogation times. The width of the path, W, will change with distance from the radar and with the magnitude of positioning errors. W should vary from about 1 mi at the closer ranges to a few miles at the furthest ranges.

Figure 9 schematically illustrates the cross-correlation technique. The example shown in Fig. 9 is for a radar data collection rate which is twice that of the rain-gage interrogation frequency. The use of the cross-correlation technique offers two distinct advantages--(1) although the precipitation may drift as it descends to the surface, the direction of drift is expected to follow the path used for integration and thus a better correlation should exist between

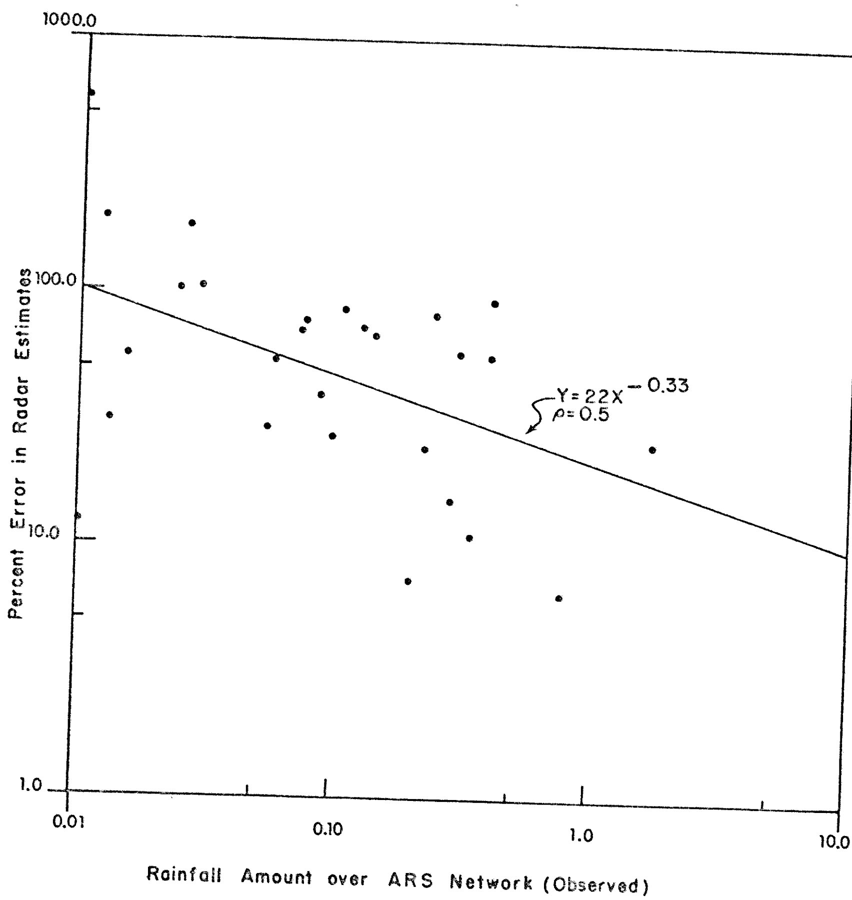

Figure 8. Percent Error in Radar (NSSL) Rainfall Estimates Versus Observed Rainfall Amount for a 1000 sq. mi ARS Network in Oklahoma--Based on Data Presented by Wilson (1971).

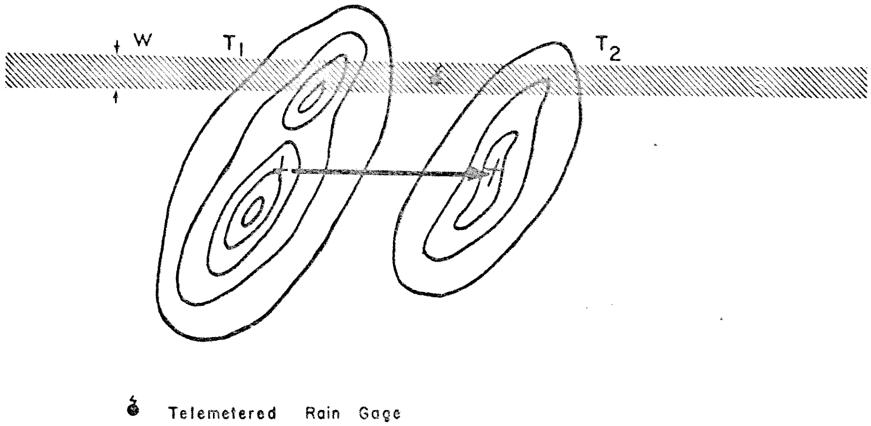

Figure 9. Illustration of Cross-Correlation Technique for Determining the Echo Translation Path Which Passes Over a Telemetered Rain Gage.

the path R and g than if the precipitation had drifted out of the area being sampled and (2) a larger area can normally be used for averaging than if a static area is used: the size of the averaging area (length of path) varies with the speed of translation of the echo.

Improvements in the solution of g/R may be achieved, but the solution will not be unique, since large spatial variability in the g/R's is brought about by spatial changes in the Z-R relationship and range effects. It is unlikely that g/R can be taken as a "true" adjustment factor, even at the point of determination, since there are errors in the rain-gage measurement. An important consideration in the development of an objective analysis procedure is that most of the variability of g/R at a point should be attributable to changes in R and not due to changes in the magnitude of the error accompanying the rain-gage catch for precipitation events of the same type. The cross-correlation technique described above helps in achieving this condition. However, to obtain a stable index of how much R departs from true g, an objective analysis procedure must also include information on the statistical structure of the radar echoes.

As was explained in an earlier section, statistical characteristics of the precipitation pattern are related to the meteorological mechanism that generates the precipitation. Also, g/R is affected by meteorological conditions: an obvious example is the effects of wind speed on the gage catch. Furthermore, Z-R variability is related to the meteorological conditions.

Since meteorological conditions influence the accuracies of the gage catch and the radar measurement and because the characteristics of the echo pattern are correlated with the type of precipitation generated by the meteorological mechanism, an optimum objective analysis procedure for adjusting radar precipitation fields should blend rain-gage data with echo statistics. An objective analysis procedure could consist of (1) performing least squares analysis on the digital radar data to determine $\overline{P}_{rm}$ and b (see Eq. (8)) for subareas of the radar scope, (2) making an initial adjustment to the radar precipitation fields within all subareas by using a regression equation that relates the adjustment factor to $\overline{P}_{rm}$, b, and d; where d is the distance or radar range to the centroid of the echo, and (3) applying a final adjustment which is dependent on the magnitude of the initial adjustment and the gage to radar ratio (g/R), where R can be evaluated for a path from the cross-correlation technique. As shown in Fig. 7, Thiessen pologons might be used to subdivide the radar umbrella into subareas for processing.

The objective analysis procedure described in the foregoing paragraph can be mathematically illustrated as follows:

Initial Adjustment:

$$\bar{P}_{r(adj)} = \bar{P}_{r(unadj)} \cdot \phi_1(d, \bar{P}_{rm}, b) \qquad (9)$$

Final Adjustment:

$$R_{(adj)} = R_{(unadj)} \cdot \phi_2(g/\bar{R}_p, S, \phi_1(d, \bar{P}_{rm}, b)) \qquad (10)$$

and

$$S = \frac{N^k}{1 + \sqrt{\left[(g/\bar{R}_p;\bar{R}_p/g) - \overline{(g/\bar{R}_p;\bar{R}_p/g)}\right]^2}} \qquad (11)$$

where $R_{(adj)}$ and $R_{(unadj)}$ are the rainfall amounts after and prior to adjustment, respectively; $\bar{R}_p$ is the path precipitation as obtained from the cross-correlation technique; ϕ_1 and ϕ_2 imply functional dependence; S is a dispersion parameter which is dependent on the variability of the $g/\bar{R}_p$ ratios among the subareas; N is the number of rain gages underneath the radar umbrella receiving precipitation; and k is an empirical coefficient initially set equal to 1. The ratios in the denominator of Eq. (11) are taken so that they are always unity or greater.

CONCLUDING REMARKS

Computer processing of digital radar data in real-time adds a new dimension of rainfall information for hydrologic applications. The major limitation stems from uncertainties in the absolute calibration. Plans for improving the accuracy of the radar estimates include the use of telemtered rain-gage data and information on the statistical structure of the echo patterns as a basis for monitoring and adjusting the radar precipitation fields.

An optimum objective analysis procedure for adjusting radar precipitation fields should consist of relating the magnitude of the adjustment factors to regression parameters which define the depth-area distribution of the radar echo pattern and to the ratio between gage and radar amounts. This objective approach implicitly accounts for variability in the radar procedures brought about by changing meteorological conditions.

Devices for Automatic Remote Data Collection (DARDC's), which will be placed at selected telemetered rain-gage sites underneath the radar umbrella, convert the rain-gage data into a form suitable for transmission. The mini-computer located at the radar site can be programmed to automatically initiate "call-up" of the rain gages at specified times and/or when the radar indicates precipitation accumulations exceeding predefined levels.

The "Digitized Radar Experiments" (D/RADEX) are providing much to enhance the state of the art on precipitation measurement with radar. D/RADEX consists, in part, of using digital radar data from four National Weather Service (NWS) radars in the south-central United States to derive watershed precipitation products for input to the streamflow forecast models used by the River Forecast Centers (RFC's) located in Kansas City, Tulsa, and Fort Worth. D/RADEX provides a unique opportunity to benefit from evaluations and feedback from the RFC's and the field radar units, since these evaluations will be based on the performance of the system under operational conditions.

Even with limitations stemming from uncertainties in the absolute calibration, the use of radar as another tool for hydrologic forecasting undoubtedly will bring overall forecast improvements. Precipitation averaged over specified space and integrated for some time interval represents an essential ingredient for hydrologic forecasting. Radar is an excellent remote sensor for obtaining spatial definition and temporal integration since it provides the capability to sample almost continually in time and space. Now with the D/RADEX system, it becomes possible to process voluminous amounts of data in real-time with NWS radars; and thus, quantitative radar data can be effectively utilized in operational hydrology.

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REFERENCES

1. Borovikov, A. M. and Kostarev, V. V. (editors) et al., Radar Measurement of Precipitation Rate, Israeli Translation from Russian, U. S. Department of Commerce Clearinghouse for Federal Scientific and Technical Information, Springfield, Va., 1970.

2. Clark, R. A., Canipe, Y. J. and Greene, D. R., "Applications of Digital Radar Data in Both Meteorology and Hydrology," Preprints for 15th Radar Meteorology Conference, American Meteorological Society, Oct. 1972, pp. 93-98.

3. Cataneo, R. and Vercellino, D., "Estimating Rainfall Rate-Radar Reflectivity Relationships for Individual Storms," Preprints for 14th Radar Meteorology Conference, American Meteorological Society, Nov. 1970, pp. 207-208.

4. Flanders, A. F. and Bigler, S. G., "History and Development of Automatic Weather Radar Data Processing," World Meteorological Organization Publication No. 304, 1971, pp. 43-53.

5. Flanders, A. F. and Schiesl, J. W., "Hydrologic Data Collection Via Geostationary Satellite," IEEE Transactions on Geoscience Electronics, Vol. GE-10, No. 1, Jan. 1972, pp 47-51.

6. Greene, D. R., "A Comparison of Echo Predictability: Constant Elevation vs. VIL Radar-Data Patterns," Preprints for 15th Radar Meteorology Conference, American Meteorological Society, Oct. 1972, pp. 111-116.

7. Hudlow, M. D., "Three Dimensional Model of Precipitation Echoes for X-Band Radar Data Collected During BOMEX," BOMEX Bulletin No. 10, CEDDA Office NOAA/EDS, U. S. Department of Commerce, June 1971, pp. 51-63.

8. Hudlow, M. D., "Use of Radar Data from D/RADEX for Operational Hydrology," Preprints for 15th Radar Meteorology Conference, American Meteorological Society, Oct. 1972, pp. 117-123.

9. Huff, F. A., "The Adjustment of Radar Estimates of Storm Mean Rainfall with Rain Gage Data," Journal of Applied Meteorology, AMS, Vol. 6, No. 1, Feb. 1967, pp. 52-56.

10. Jones, R. F. and Bigler, S. G. (chairmen) et al., "Use of Ground-Based Radar in Meteorology," World Meteorological Organization Technical Note No. 78, WMO No. 193.TP99, 1966, pp. 11-14.

11. Kessler, E. and Wilson, J. W., "Radar in an Automated National Weather System," Bulletin of the American Meteorological Society, Nov. 1971, pp. 1062-1069.

12. Marshall, J. S. and Palmer, W., "The Distribution of Raindrops with Size," Journal Meteorology, Vol. 5, No. 4, 1948, pp. 165-166.

13. McGrew, R. G., "Project D/RADEX (Digitized Radar Experiments)," Preprints for 15th Radar Meteorology Conference, American Meteorological Society, Oct. 1972, pp. 101-106.

14. Nicks, A. D., "Agricultural Research Service Precipitation Facilities and Related Studies," ARS 41-176, ARS, U. S. Department of Agriculture, June, 1971, pp. 71-81.

15. Probert-Jones, J. R., "The Radar Equation in Meteorology," Quart, Journal of the Royal Meteorological Society, Vol. 88, 1962, pp. 485-495.

16. Stout, G. E. and Muller, E. A., "Survey of Relationships Between Rainfall Rate and Radar Reflectivity in the Measurement of Precipitation," Journal of Applied Meteorology, AMS, Vol. 7, June 1968, pp. 465-474.

17. Wilk, K. E. and Gray, K. C., "Processing and Analysis Techniques Used with the NSSL Weather Radar System," Preprints for 14th Radar Meteorology Conference, American Meteorological Society, Nov. 1970, pp. 369-374.

18. Wilson, J. W., "Factors Affecting the Accuracy of Radar Rainfall Measurements," Final Rept. 7488-331, The Center for the Environment and Man, Hartford, Oct. 1968.

19. Wilson, J. W., "Use of Rain Gages to Adjust Radar Estimates of Rainfall," Final Rept. CEM 4098-448, The Center for the Environment and Man, Hartford, Sept. 1971.

KEY WORDS: data systems; telemetered rain gages; radar; hydrology; rainfall; statistical analysis; real-time precipitation processing; streamflow forecasting

ABSTRACT: Computer processing of digital radar data in real-time adds a new dimension of rainfall information for hydrologic applications. Objective analysis of telemetered rain-gage data and the statistical structure of echo patterns provide useful information for monitoring and adjusting the radar precipitation fields. The data system which is used to collect, process, and transmit the precipitation data is illustrated. The "Digitized Radar Experiments" (D/RADEX), which are designed to test and evaluate the application of the data system to operational problems in hydrology and meteorology, are described. D/RADEX consists, in part, of using digital radar data from four 10-cm radars in the south-central United States to derive watershed precipitation products for input to the streamflow forecast models used by the National Weather Service River Forecast Centers located in Kansas City, Tulsa, and Fort Worth.