Reprinted from Preprint Volume: 21st Conf. on Radar Meteorology, Sept. 19-23, 1983, Edmonton, Alta., Canada. Published by the American Meteorological Society, Boston, Mass.

PROPOSED OFF-SITE PRECIPITATION PROCESSING SYSTEM FOR NEXRAD

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1. INTRODUCTION

The process of quantitative hydrologic forecasting consists of acquiring information about the states of the hydrologic cycle, assembling this information in an intelligent form, and putting the information into models and procedures to predict the future states of a hydrologic (for example, river) system or subsystem. Often, the single most important hydrometeorological input to a streamflow prediction model is precipitation. Yet, because of its large variability in space and time, precipitation frequently is difficult to measure accurately without a very dense automated raingage network.

Land-based weather radar potentially is a very important remote sensor providing the capability to measure precipitation continually in time and space out to distances of approximately 200 km from the radar site. Real-time processing of the radar data is possible if the radar is equipped with a computer and digital signal processing equipment, as will be the case for the Nation's network of Next Generation Weather Radars (NEXRAD) [NEXRAD Program Development Plan, 1980; Bonewitz, 1981].

Using data from NEXRAD, combined with available rain gage data, it should be possible to realize large improvements in the accuracy of estimating areal precipitation. These improvements should, in turn, lead to large economic benefits resulting from better hydrometeorological forecasts. Bussell et al. (1978) suggest that a radar network, supplemented by rain gages, is the most cost effective network design for England, where the radar network serves both the meteorological and hydrological communities. Such a network strategy also seems applicable in the United States where the existence of the network radars can be justified on the basis of meteorological applications alone; although, the potential benefits to be realized from the use of radar data for hydrologic forecasting are probably comparable in magnitude to those resulting from purely meteorological applications. Willis et al. (1981), as part of a cost/benefit analysis for NEXRAD, estimated that the average annual benefit from NEXRAD data resulting from reductions in losses from flooding could amount to about $250M per year. This constitutes the largest potential saving, to be realized from the use of NEXRAD information, of any of the 9 weather hazards considered by Willis et al. (1981). In fact, improved flood warnings alone were estimated to provide 44% of the total benefits from improved prediction of weather induced hazards. Tornadoes were second with 32%.

Benefits of more than those attributed just to the alleviation of flood losses, should be accrued from the application of improved precipitation measurements from radar to support a variety of water management and agricultural activities. However, full benefits, at least for hydrologic applications, can be realized only if the precipitation estimates from radar are consistently accurate and reliable, i.e. they must be quantitatively meaningful to a precision which is acceptable for a particular hydrologic application.

Figure 1 helps illustrate the importance of accurate precipitation estimates in the derivation of runoff forecasts. This figure illustrates that the transformation of precipitation to runoff is nonlinear and can have the effect of magnifying errors. The total precipitation error for a single storm event,

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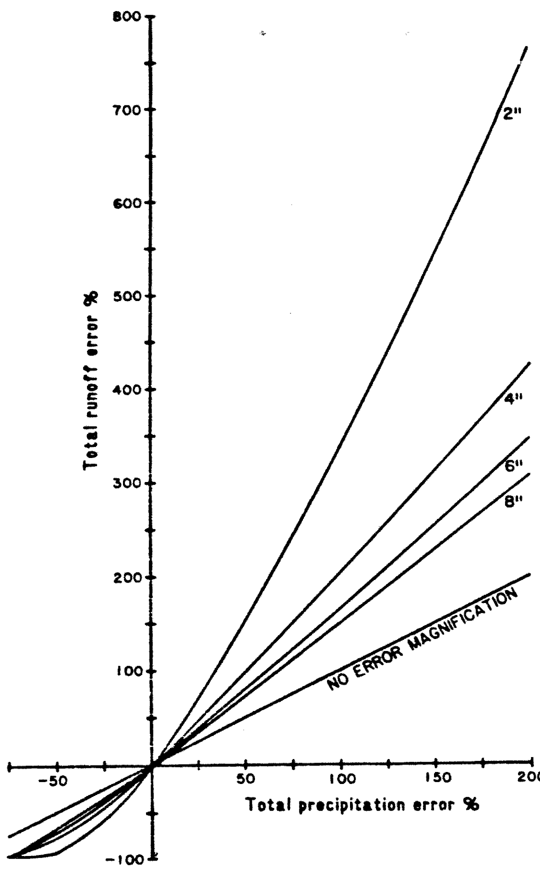


Fig. 1. Example illustration of magnification of precipitation error in runoff estimates using a rainfall-runoff prediction model which is assumed to have no error.

expressed as percent error, is compared to the corresponding total percent runoff error. The rainfall-runoff model used for this figure is the widely applied SCS method (USDA-SCS, 1964) with an SCS curve number of 75, which is representative of a fairly quick-responding basin with slow infiltration under average soil moisture conditions; basins with more infiltration would produce even greater magnification of errors. Notice that the degree of error magnification decreases for events with larger total precipitation amounts since a higher proportion of precipitation runs off.

Such a single-event comparison helps to illustrate the idea of error magnification in the precipitation to runoff conversion process, but it does not give the complete picture. The continuous conceptual models used in the National Weather Service River Forecast System (NWSRFS) [Hudlow and Brazil, 1983] have long memory (as does the true hydrologic system). As a result, errors in one event will impact forecasting accuracy in subsequent events, and any long-term bias in precipitation estimates can have a large cumulative impact on forecast accuracy. Finally, it is important to recognize that relatively small errors in runoff predictions can result in large economic impacts for some applications. For example, Day (1970) has evaluated existing and potential flood warning benefits for several river basins, including the Susquehanna River Basin. It is clear from Day's work, that needless sandbagging or evacuation of people and property, because of an erroneously high flood forecast, can result in the loss of several hundred dollars per residential household alone.

Because of the rather stringent requirements for quantitative accuracy as described above and because raw data from weather radars, as from most remote sensors, are characteristically in error due to equipment and/or meteorological variabilities, it is critical that the processing stream for NEXRAD data include adequate data processing, quality control, and analysis steps. The objective of the proposed off-site processing system described herein, together with the "on-site" processing system described by Ahnert et al. (1983) in a companion paper elsewhere in this same collection of conference preprints, is to provide consistently reliable quantitative precipitation estimates for subsequent use in numerical hydrometeorological applications.

2. PRIMARY COMPONENTS OF STAGE II PROCESSING SYSTEM

Ahnert et al. (1983) describe the proposed "on-site" precipitation processing system for NEXRAD. The "on-site" system comprises those software components which can best be executed on the Radar Product Generator (RPG -- the primary NEXRAD computer) located at the NEXRAD site or a nearby local weather office. The philosophy of the "on-site" processing system design is to process the data to a level of refinement that can be achieved relatively cheaply (with respect to computer resources) yet provide an accuracy that will make the precipitation estimates useful for local applications. Also, it is important that the integrity of the data be maintained for further processing and refinement at one or more off-site super-mini or main frame computers. In this paper, we will refer to the processing for the "on-site" and off-site systems as the Stage I and Stage II processing, respectively.

Precipitation estimates from the Stage I processing, which will be updated as frequently as every 5 min, will be made available in graphics display format, as well as digital array format, to the approximately 50 Weather Service Forecast Offices (WSFO's) for their real-time use in monitoring flash flooding potential. Hourly rainfall accumulation estimates will be transmitted after Stage I processing to the 12 NWS River Forecast Centers (RFC's) scattered across the 48 conterminous states (provisions are being considered for updating these estimates every 30 min). The hourly rainfall data received at each RFC, from the multiple radar sites providing coverage of an RFC's area of responsibility, will be further processed for input to hydrologic models and prediction procedures on a computer at the RFC and/or a centrally located computer.

Figure 2 is a block diagram illustrating the basic components of the planned Stage II processing system. A brief description of the various components is presented in Sections 2.1 through 2.7.

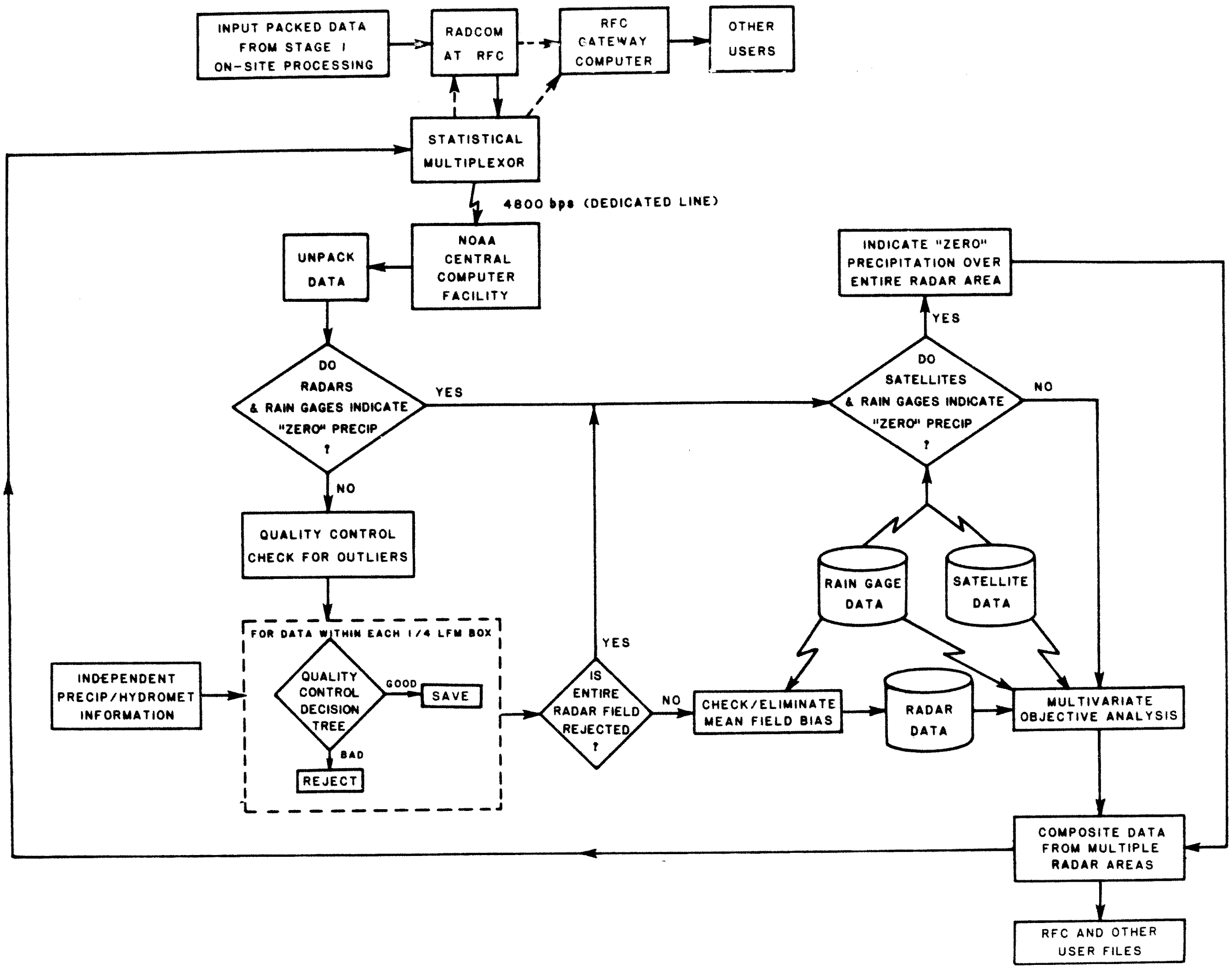


Fig. 2. Block diagram illustrating the basic components of the planned NEXRAD Stage II processing system.

2.1 Communications and Data Input

The data inputs to the Stage II processing system, as mentioned above, will originate as output from the Stage I processing system described by Ahnert et al. (1983). Table 1 summarizes the characteristics of these data inputs. A Radar Communication System (RADCOM, formerly called RADCOMP) will be used to automatically retrieve the data from the multiple radars which provide coverage of an RFC's area of forecast responsibility [Ahnert et al., 1981]. After arriving at the RFC's, the data will either be further processed on a local super-mini computer and/or they will be relayed via a statistical multiplexor and a dedicated line to the NOAA Central Computer Facility (NCCF). Current development work is being carried out under the assumption that all of the Stage II processing will take place at the NCCF, since the RFC's do not now have local computing facilities sufficient to handle the Stage II processing requirements. However, increases in computer resources at the RFC's being planned for the future could result in some Stage II processing at the RFC's. In any case, it will be necessary to maintain a communications link(s) with the NCCF, since precipitation analyses from Stage II processing will be required both at the RFC and the NCCF and because certain hydrometeorological information available on the NCCF will be required.

As shown in Table 1, two basic types of radar precipitation data enter the Stage II processing system: hourly accumulations for grid sizes equal to 1/40th the Limited Fine Mesh (LFM) grid [Greene and Hudlow, 1982] and instantaneous areal average precipitation rates for grid sizes equal to ¼ th the LFM grid. The 1/40 th LFM (nominal 4-km) resolution data are the primary data used for analysis during Stage II processing. The ¼ th LFM (nominal 40-km) resolution data are used primarily as a basis for performing the decision-tree quality control step described in Section 2.3.

Accompanying the radar precipitation data are supplemental data as identified in Table 1. These supplemental data include hourly precipitation accumulations from selected automated rain gages under each radar umbrella. Other supplemental data include "housekeeping" information, pertinent transfer coefficients, and quality control indicators from Stage I processing.

Table 1. Characteristics of data inputs to Stage II processing from NEXRAD RPG (Stage I processing).

RADAR PRECIPITATION DATA	SUPPLEMENTAL DATA
Hourly Accumulations (or Mean Hourly Rates) with Following Attributes: • dBR values covering a dynamic range from -18 to 32 dBR in 0.5 dBR intervals out to a distance of 230 km from the radar. • Values are for grid sizes equal to 1/40th the Limited Fine Mesh (LFM) grid (varies from 3.5 km to 4.5 km grid-mesh size over the U.S.).	Hourly Rain-Gage Accumulations for the Most Recent 2 Hours for Selected Automatic Gages Under Radar Umbrella. Housekeeping Information Such as Date/Time Group, Radar ID, and System Calibration and Operational Status Indicators. Pertinent Transfer Coefficients Applied in Stage I Processing Such as the Coefficients Used to Build the Reflectivity to Rainfall Rate Conversion Table.
Instantaneous Mean Precipitation Rates • dBR values covering a dynamic range from -18 to 30 dBR in 6 dBR intervals out to a distance of 230 km from the radar. • Values are for grid sizes equal to 1/4th the LFM grid (varies from 35 km to 45 km over the U.S.)	Quality Control Indicators From Stage I Processing, Including: • Total number of isolated bins eliminated from all data used to construct each hybrid scan. • Percent reduction in echo area between base and second tilts for each hybrid scan. • Bi-scan ratio for each hybrid scan. • Time continuity flag for each hybrid scan. • Number of interpolated outliers for each hourly accumulation scan (new scan each 5 minutes). • Bias estimate and its error variance for each hourly accumulation scan.

2.2 Zero Precipitation and Outlier Quality Control Checks

In order to improve processing efficiency for those cases in which the radar and the supplemental rain-gage data indicate "zero" (actually some insignificant very low threshold) precipitation amount over the total radar field of view, some of the processing steps will be bypassed (Figure 2). However, a precipitation analysis will still be performed using data from the rain-gage network and/or satellite data available at the NCCF if they indicate significant precipitation has occurred during the past hour.

For those cases of "nonzero" radar precipitation, the next processing step involves a check for large outliers in the 4-km data field. Spuriously high values could exist although outlier checks and corrections were performed during Stage I processing. The primary source of such values would be errors in data communication.

Various methods for identification and elimination of "point" outliers are available. Ahnert et al. (1983) discuss the approach planned for Stage I processing, which will include interpolation to recover estimates for rejected outliers, but only in those cases of isolated "point" outliers.

Major progress toward establishing a framework for automatic screening of outliers has been recently reported by Bissell (1981). Bissell's approach is based on using a log normal distribution to represent the probability of occurrence of various precipitation magnitudes. From analysis of historical data, the initial probability distribution can be derived for use in setting an upper bound(s), which if exceeded would indicate that the data value should be flagged and/or rejected. His approach also includes provisions to adjust the upper bound(s) to allow for "current" conditions as revealed through, for example, recent observations in the same time series for which the value is being tested and probability of precipitation forecasts (POP's).

An adaptation of Bissell's methodology will be used for the "point" outlier quality control step in the Stage II processing. An inherent advantage in the use of this technique with digital radar fields is that information on spatial continuity and structure also should be useful in refining the probability threshold(s) that define the upper bound(s) for data flagging and/or rejection.

2.3 Quality Control Decision Tree

The next step of the Stage II processing is to pass the 1/4 th LFM radar data through a decision-tree process (Table 2). The object is to identify those 1/4 th LFM grid boxes containing bad data [resulting from anomalous propagation (AP) or other spurious sources] and to reject those data from further analysis. Figure 3 is an example illustration of this concept, in which

RADAR "SEES NO PRECIP" DURING HOUR

ROUTE 1 (R1): RADAR NO PRECIP CASE

Question	Decision[a]/ Branch Combinations	Probability Δ
Do satellite IR data indicate zero cloud for instantaneous times of satellite data? (Use at least 2 times.)	1. Yes: Cont. R1	0.3
	2. No: Cont. R1	0
Do Manually Digitized Radar (MDR)[c] data indicate zero echo for instantaneous time(s) of MDR?	3. Yes: (1,3; S[b])	0.3
	4. No: Cont. R1	0
Are system calibration and operational status indicators normal during the hour?	5. Yes: Cont. R1	0.15
	6. No: Cont. R1	0
Is time continuity of hybrid scans from Stage I processing normal during the hour?	7. Yes: (1,4,5,7; S) (2,3,5,7; S)	0.15
	8. No: Cont. R1	0
If rain gage(s) exist(s) in box, did it report measurable rain during hour?	9. Yes: Cont. R1	0
	10. No: (1,4,5,8,10; S) (1,4,6,7,10; S) (1,4,6,8,10; S) (2,3,5,8,10; S) (2,3,6,7,10; S) (2,3,6,8,10; S)	0.3
	//////////////////////	
Is bias adjustment factor from Stage I processing abnormally high for the hour?	11. Yes: To conserve space, the sets	0
	12. No: of numbers indicating accep-	0.15
Do probability of precipitation forecasts and other hydrometeorological information indicate high probability of precip?	13. Yes: tance are not reproduced for the remainder	0
	14. No: of the Table. Any decision combination which produces a 0.6 probability level results in saving data.	0.15

RADAR "SEES PRECIP" DURING HOUR

ROUTE 2 (R2): RADAR SPURIOUS "PRECIP" CASE

Question	Decision[a]/ Branch Combinations	Probability Δ
Do satellite IR data indicate zero cloud for instantaneous times of satellite data when compared to corresponding times of radar data? (Use at least 2 times)	1. Yes: Cont. R2	0
	2. No: Cont. R2	0.3
Do MDR data indicate zero echo for instantaneous time(s) of MDR data when compared to corresponding times of radar data?	3. Yes: Cont. R2	0
	4. No: (2,4; R3[d])	0.3
Are system calibration and operational status indicators normal during the hour?	5. Yes: Cont. R2	0.15
	6. No: Cont. R2	0
Is time continuity of hybrid scans from Stage I processing normal during the hour?	7. Yes: (2,3,5,7; R3) (1,4,5,7; R3)	0.15
	8. No: Cont. R2	0
Does % reduction in echo area between base and 2nd tilts and bi-scan ratios for hybrid scans indicate probability of AP?	9. Yes: Cont. R2	0
	10: No: (1,4,5,8,10; R3) (1,4,6,7,10; R3) (2,3,5,8,10; R3) (2,3,6,7,10; R3)	0.15
	//////////////////////	
If rain gage(s) exist(s) in box, did it report reasonable rain during hour?	11. Yes: To conserve space, the	0.3
	12. No: sets of numbers indicating ac-	0
Is bias adjustment factor from Stage I processing abnormally low for the hour?	13. Yes: ceptance are not reproduced	0
	14. No: for the remainder of the Table.	0.15
Are atmospheric conditions in boundary layer subject to abnormal beam refraction?	15. Yes: Any decision combination which	0
	16. No: produces a 0.6 probability	0.075
Do probability of precipitation forecasts and other hydrometeorological information indicate high probability of precip?	17. Yes: level results in transfer to R3.	0.075
	18. No: Reject data	0

ROUTE 3 (R3): RADAR PRECIP CASE

Question	Decision/ Branch Combinations	Probability Δ
Does magnitude of hourly precip estimate over box indicate exceedance of bound(s) of log-normal probability distribution? The bound(s) are defined based on historical data and information on current hydrometeorological conditions, forecast precipitation, and estimated precipitation from rain gages and/or satellites.	Yes: Reject and/or flag data	0
	No: Save data	0.6

a Only those combinations which result in saving data are indicated by the sets of numbers which show the path traversed. The numbers in the sets correspond to the individual numbers attached to each yes or no answer. The probability of acceptance level is taken to be 0.6.

b "S" indicates "save data."

c MDR data currently are manually coded each hour from the six-level isocontoured displays on the NWS radars [Smith, D.L., 1980]. Because these data are coded by a person, who may eliminate certain bad data during the coding process, they provide some degree of independent check of the automatically processed data. It is not certain that MDR data will be available once NEXRAD is implemented.

d "R3" means "transfer to Route 3."

Table 2. Illustration of the decision-tree concept for quality control of radar data at the Stage II processing level using $^1/_4$th LFM-grid size boxes. The probability levels and branch logic are subject to change as development and testing continue.

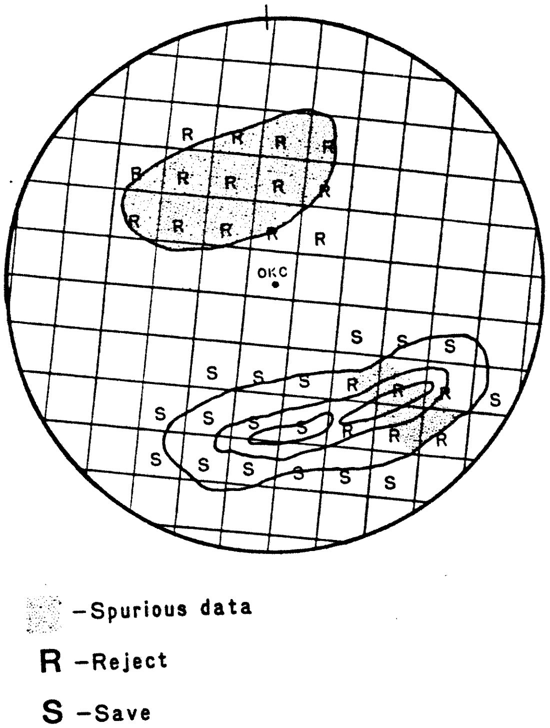


Fig. 3. Example results of data screening using the decision-tree quality control approach.

all data in the northern part of the field are rejected as being probably produced by AP. Also, an azimuthal sector is rejected from the precipitation pattern in the southern part of the array as being probably produced by some type of spurious noise injected into the data field during a momentary period of the antenna rotation. These spurious data already would have been eliminated if the individual 4-km bin values had exceeded the upper bound set for the outlier check described above.

The 1/4 th LFM size grid boxes are used for the decision-tree portion of the processing because this is believed to be about the finest spatial scale for which many of the tests in the tree would be meaningful. For example, satellite infrared (IR) data are a primary source of information for comparison with the radar data. However, because of potential navigational errors in the satellite data and because the top parts of the cloud sensed by the satellite may be displaced in space, as well as time, from the precipitation falling out of the cloud, comparison of the radar and satellite data should be done at a scale which is significantly larger than the basic resolution of the instruments. Although 1/4 th LFM grid boxes are being used for the decision-tree processing, all 1/40th LFM grid values within "bad" boxes also are rejerted onnce a decision to reject is made.

The decision tree is divided into three basic routes: 1) radar no precipitation case, 2) radar spurious "precipitation" case, and 3) radar precipitation case (Table 2). For route 1, it is known in advance that the radar detected no precipitation within the 1/4 th LrM box during the hour. The purpose of route 1 is to determine if the radar should have detected precipitation in a box which indicated no precipitation. The logic of route 2 is designed a priori with the intent of identifying, as early in the processing as possible, those boxes containing all spurious "precipitation" data, e.g. those situations in which a box contains AP with no precipitation. At any point along route 2, when it is decided that precipitation in fact exists in a box, the processing is immediately branched to route 3. Route 3 is designed for the case in which it has been determined that precipitation probably exists in a box, but for which spurious data or large errors may accompany the precipitation.

All data which passes the screening of the decision tree is thereafter assumed "good" precipitation data for input to subsequent stages of the processing. The multivariate objective analysis system described in Section 2.5 is being designed in a general way so that it can perform an analysis of all or any part of the radar precipitation field that is retained as good data. It is hoped that NEXRAD, with its modern electronics and enhanced signal processing, will provide clean data which, in most cases, will pass the screening tests.

2.4 Mean Field Bias Elimination

A procedure applied during Stage I processing will use selected telemetered rain-gage data and a Kalman filter to apply first order corrections for mean biases which may exist in the hourly precipitation accumulation fields [Ahnert et al., 1983]. Because the accumulation fields have undergone additional processing steps at the Stage II level and since a greater density of rain-gage data may be available at a regional/central facility, it is important to again check each "nonzero" hourly accumulation field before the data are passed to the multivariate analysis system, in an attempt to further correct for any residual systematic bias.

The bias removal procedure applied at the Stage II processing level may be an adaptation of the Kalman filtering algorithm described by Ahnert et al. (1983), or a simpler procedure might be adequate if sufficient rain-gage data are available.

2.5 Multivariate Objective Analysis

The objective analysis model is based on the linear regression equation of the form:

$$Z = X_G \alpha_G + X_R \alpha_R \quad (1)$$

where: Z is a vector of the final estimates of rainfall,

X_G, X_R are matrices composed of rain-gage and radar observations, respectively, and

α_G, α_R are vectors of appropriate coefficients.

The solution of eq. (1) is

$$\begin{vmatrix} \alpha_G \\ \\ \alpha_R \end{vmatrix} = \begin{vmatrix} X_G^T X_G & X_G^T X_R \\ \\ X_R^T X_G & X_R^T X_R \end{vmatrix}^{-1} \cdot \begin{vmatrix} X_G^T Z \\ \\ X_R^T Z \end{vmatrix} , \quad (2)$$

where the superscript T is used to denote the matrix transpose.

If X_G and X_R are given in standardized form, then all the matrices on the right hand side of (2) are correlation matrices. The $X_G^T Z$ and $X_R^T Z$ are unknown but can be estimated from the correlation model of the $X_G^T X_G$ and $X_R^T X_G$ terms. If the radar data are given on a Cartesian grid, the actual correlogram of $X_R^T X_G$ can be used to estimate $X_R^T Z$. For the $X_G^T Z$ term, however, the functional model needs to be used. The $X_G^T X_G$ term is approximated with a two dimensional Gauss-type function of the form

$$f(x,y) = \rho \exp \left[- \frac{\frac{x^2}{\sigma_x^2} - 2\alpha \frac{xy}{\sigma_x \sigma_y} + \frac{y^2}{\sigma_y^2}}{2(1-\alpha^2)} \right] , \quad (3)$$

where $\rho, \alpha, \sigma_x, \sigma_y$ are the parameters. Function (3) permits modeling of an anisotropic correlation structure.

In actual analysis, (1) is being solved for each grid point in turn, taking into consideration the surrounding rain gages and radar bins. In work to date using daily accumulations, it has been found that thre is usually high local autocorrelation among the radar data bins. Thus, including only one or two radar data values into the regression equation allows utilization of virtually all information contained in the data pertinent to estimation for a particular grid point. Presumably, more radar values will be included for shorter duration data.

The algorithm of the model is as follows:

1) Compute correlation matrices:

   $X_G^T X_G$, $X_G^T X_R$, and $X_R^T X_R$.

2) Approximate matrix $X_G^T X_G$ with function (3).

3) For each grid point:

   3a) Locate the surrounding radar and rain gage points.

   3b) Determine $X_G^T Z$ and $X_R^T Z$ based on the distances from the grid point to the chosen data points and the correlation model given by function (3).

   3c) Solve eq. (2).

   3d) Find the final estimate from (1).

A full description of the model is given in Crawford (1977), Krajewski and Crawford (1982); and Krajewski (1983).

In order to evaluate the model performance, a numerical experiment was designed. In that experiment, radar and rain-gage fields are generated by imposing noise on so-called original fields [which were taken to be high quality radar data fields from the GARP Atlantic Tropical Experiment (GATE)]. The generated fields are then merged using the above described model, and the obtained field of precipitation is compared against the original field. A detailed description of the experiment can be found in Greene et al. (1980) and Krajewski (1983). An example is presented in Figure 4 for a daily field from GATE [Hudlow and Patterson, 1979].

2.6 Mosaicking

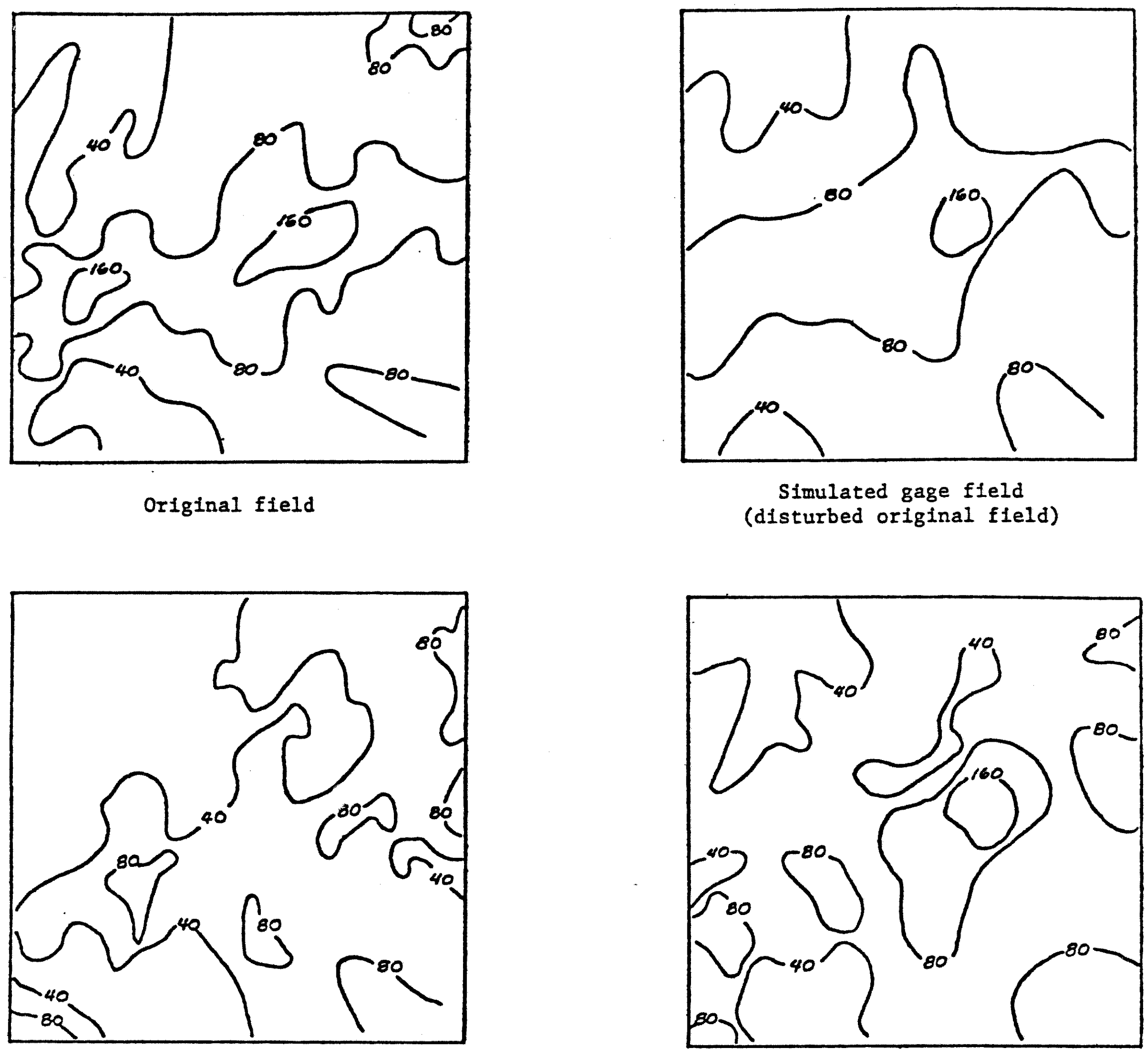
Once the data from each individual radar have passed through the processing stream, the data must be composited from the multiple radars and placed into regional/national arrays. The fact that all the data are in a standardized coordinate system facilitates this process since the corresponding 1/40th LFM grid boxes will precisely overlay in areas of overlap between radars.

Various mosaicking techniques will be considered. It is anticipated that a relatively simple approach will suffice, since the data from all of the individal radars generally should be of high quality at this stage of processing. One candidate procedure will be the one used during Phase III of the GATE project [Patterson et al., 1979]. This procedure consisted of simply averaging the nonzero precipitation amounts for the common data bins.

Other merging techniques, including maximization and weighted averaging, were tested during GATE, but the simple averaging procedure proved to give the best results when compared with independent rain-gage data. Wilson (1975) also used an averaging approach for merging the data from the Buffalo and Oswego radars used during the International Field Year for the Great Lakes (IFYGL), but only in a 15 mi overlap zone between the radars. This was done to preserve continuity in the precipitation field. At other points of overlap, Wilson used the data from the radar whose beam was calculated to be closest to the earth. Another approach that should be examined would include weighting of data from each individual radar in inverse proportion to distance from the radar or beam height above the earth. With this approach, a capability to modify uniform range dependent weighting would probably be necessary for those cases in which the range performance of a particular radar(s) is abnormally affected by topography or other factors.

2.7. Precipitation Data Distribution and Use

The final precipitation analyses from the Stage II processing will be packaged in several forms for distribution to the users, including: 1) the hourly 4-km resolution precipitation estimates will be retained on regional/national files for access by authorized users, 2) the hourly 4-km estimates will be integrated for



Original field

Simulated gage field
(disturbed original field)

Simulated radar field
(disturbed original field)

Rainfall analysis based
on simulated fields

Fig. 4. Sample results from the numerical experiment for analysis of daily data from the GATE project for Jume 28, 1974. The scale of each panel is approximately 150 km on a side.

other durations (e.g., 3-hourly, 6-hourly, and daily) and mean areal values will be computed for watersheds, and 3) the hourly 4-km estimates will be compacted and packaged for national/regional graphics displays over the Automated Field Operations and Services (AFOS) system or its successor(s).

Some of the uses envisioned for the precipitation data corresponding to the above three categories include:

1) input for deriving the products in categories (2) and (3); establishment of initial conditions and verification of numerical/statistical meteorological models/procedures to forecast precipitation and other meteorological variables; "ground truth" for independent satellite precipitation estimation procedures such as the one based on the Scofield/Oliver method (Scofield and Oliver, 1977) which has been semiautomated using an Interactive Flash Flood Analyzer (IFFA) [Moses, 1980]; and support of climatic, agricultural, and water-resources assessments.

2) inputs for river and flood forecasting models and procedures, including those ranging from the intermediate, and larger, flash-flood scales (>2 hr) to time scales of days or months associated with the Extended Streamflow Prediction program of the NWS River Forecast System (NWSRFS).

3) displays for use by all NWS field offices and external users as authorized in support of daily operational forecasting activities including the monitoring of soil moisture and flash-flood potential.

3. CONCLUDING REMARKS

The framework for an off-site precipitation processing system for NEXRAD has been proposed. This Stage II of processing will complement and expand upon the "on-site" processing system described by Ahnert et al. (1983). The combined systems are designed to provide a hierarchy of processing aimed at producing the highest quality of data possible at the earliest stage of processing. The Stage I processing prepares the data for input to Stage II processing and performs a number of quality control checks and data refinements which should provide to the local NWS field offices and forecasters timely precipitation products that will be extremely useful in support of their flash-flood warning program and other quick response applications. Stage II processing performs additional refinements, quality control checks, multivariate objective analyses, and compositing of multiple radar data fields. After completion of Stage II processing, it is anticipated that the precipitation estimates will be of sufficient quality and accuracy for direct input to continuous conceptual hydrologic models and for other quantitative applications. In addition, compacted analyses from the Stage II processing can be made available at the local field offices with a 1-2 hour time delay. Even with this time delay, Stage II precipitation estimates should be very valuable to the WSFO's as input to procedures for predicting flash-flood events occurring on a 2-6 hour time scale, as an accurate source of precipitation information for updating flash-flood watches and warnings, and for use in other forecasting (such as agriculture and fire weather) applications.

Efforts are underway to code and test the various components of the Stage I and II processing systems, to test each system in its entirety, and ultimately to test both systems in an integrated fashion. The primary radar test bed which will be used for development and testing is the NWS Radar Data Processor II (RADAP II, formerly called D/RADEX) network [Greene et al., 1983] located in the south central and Appalachian regions of the country. The south central network, consisting of six NWS radars equipped with RADAP II equipment, will be especially appropriate for development and testing of the Stage II processing system, since it covers almost all (about 90%) of the area of forecast responsibility for the Tulsa RFC (portions of seven states). This will enable a full system check, including compositing of precipitation estimates from multiple radars and derivation of mean areal precipitation estimates for input to the NWS River Forecast System for all of the watersheds in a large river system (i.e. the Arkansas River basin).

The application of digital radar data in general and NEXRAD data in particular to hydrometeorological forecasting problems is an important, but not sole, ingredient of a broader project activity within the NWS's Office of Hydrology, referred to as the Hydrologic Rainfall Analysis Project (HRAP) [Greene et al., 1979]. HRAP is directed toward development and operational testing of automatic objective processing techniques that use precipitation information from multiple sensors to derive "optimal" precipitation estimates for a standardized grid network and for various larger size areas such as watersheds and counties. Rain-gage and satellite, as well as radar, data are important inputs to the HRAP quality control and estimation procedures. Requirements for a mix of rain-gage and remotely sensed data will continue in the future, although it should be possible to extract more useful information from the remotely sensed data with improved data acquisition and processing systems such as that planned for NEXRAD.

Technologically, the processing system proposed herein is physically reasonable and achievable. The data management and computer resource issues will be formidable but not unattainable. It is important that the initial Stage I and II Precipitation Processing Systems for NEXRAD be completed prior to field implementation of NEXRAD units beginning in 1987. During the interim period, attention will be directed toward the development, testing, and refinement of the Stage I and Stage II processing systems so that the NEXRAD data can be effectively utilized when the new systems are brought on line operationally.

4. ACKNOWLEDGEMENTS

The authors express their appreciation to Mrs. Lianne Iseley who assisted with much of the editorial and graphics work, to John Menard and Stephen Ambrose for assistance with several of the figures, and to Mrs. Laura Davis and Mrs. Ruth Ripkin for layout and typing of the manuscript.

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