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PROPOSED "ON-SITE" PRECIPITATION PROCESSING SYSTEM FOR NEXRAD

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1. INTRODUCTION

Areal quantitative rainfall estimates often are the single most important input to hydrologic models and forecasting procedures being used by the hydrologic field components of the National Weather Service (River Forecast Centers, Weather Service Forecast Offices, and Weather Service Offices). Unfortunately, the data collection systems currently being employed are frequently inadequate to describe the timing, duration, and amounts of rainfall occurring in the storm systems producing the flooding problems. The potential has been shown for timely digital radar-rainfall estimates, as will be provided by the Next Generation Weather Radar (NEXRAD) system, to be used operationally to partially fill this information gap. However, in order to use the digital radar-rainfall estimates in a reliable way for quantitative hydrometeorological purposes, the data must be consistently accurate.

Experiences with the applications of digital radar-rainfall data in the past have illustrated that numerous problems may occur as a result of variance in meteorological conditions and radar system characteristics. Data affected by equipment calibration errors, spurious signals, anomalous propagation, and other contamination sources, if gone unchecked, will often result in errors unacceptable for most numerical applications.

Some quality control will take place prior to the radar-rainfall estimation process. It is hoped that the effects from data contamination problems will be minimized during the data acquisition and signal processing stages of the NEXRAD processing stream. However, there remains a definite need for a number of additional quality control and correction procedures at various points during the "on-site" radar-rainfall estimation process.

The initial set of NEXRAD applications software for the "on-site" Radar Product Generator (RPG) will be developed by the system contractor based on detailed algorithm descriptions supplied by the Government (NEXRAD, 1982). In the case of the precipitation processing system, a comprehensive set of algorithms have been developed by the Radar Hydrology Group of the National Weather Service's Hydrologic Research Laboratory. The procedures used are based on experiences with real-time rainfall estimation from the D/RADEX system, the GATE project, and other experimental projects, as well as an analysis of methods for improving applications of weather radar to hydrometeorology.

Validation of a set of five algorithms employing the procedures described herein is in progress and, therefore, changes in various processing details should be expected. However, at a minimum, the current specifications are representative of the computational effort required. We believe that the procedures included are those minimally sufficient to provide the accuracy required for the numerical applications of these data and to provide graphical products useful to the forecaster. Further quality control is expected at the regional/national processing level to make use of the availability of additional data from other sources as well as data from other NEXRAD sites with overlapping coverage. This "off-site" processing is covered in a companion paper in these conference preprints entitled 'Proposed Off-Site Precipitation Processing System for NEXRAD' by Hudlow et al.

Figure 1 contains a block diagram outlining the steps within the "on-site" precipitation processing system. We believe that this system will result in enormous benefits in improved flood and flash flood forecasting, water resource management, and other hydrometeorological applications possible if quality radar-rainfall estimates are made available through NEXRAD.

2. REFLECTIVITY DATA INPUTS

Characteristics for the input data are listed in table 1. Some of the important preprocessing steps expected before data are input to this system are:

1) oxygen absorption correction,
2) assignment of zero values to all reflectivities below the noise threshold,

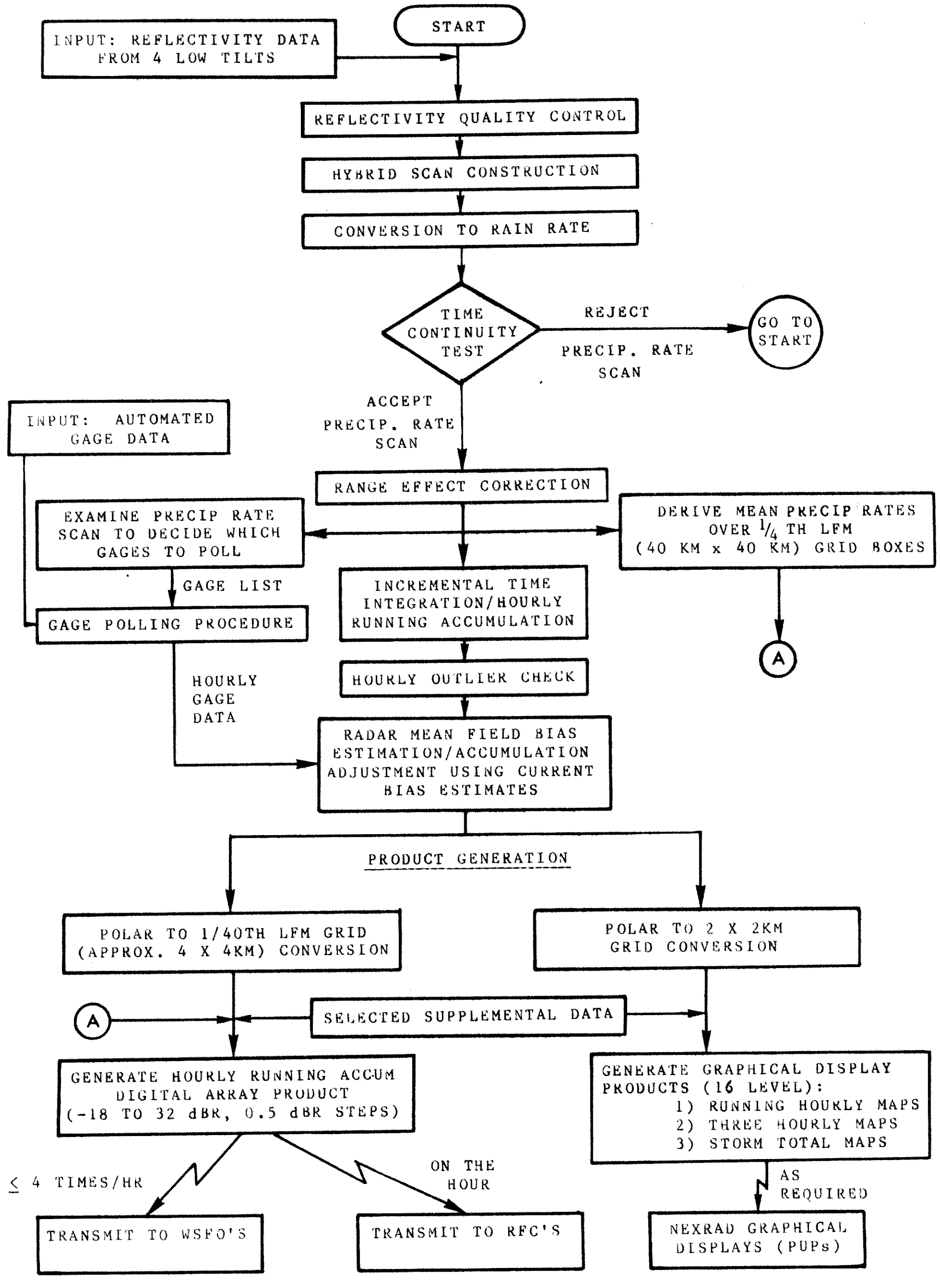

Fig. 1. Block diagram of the "On-Site" Precipitation Processing System.

3) where possible, suppression of ground clutter, anomalous propagation, and other interference to below 10 dBZ with minimal (<2 dBZ) degradation in reflectivity estimates,

4) conversion to equivalent reflectivity factor data, and

5) where possible, corrections for any other known losses resulting in biases totaling 1 dBZ or more.

Data from four sequentially obtained contiguous low tilts are being included to:

1) assist in the reduction of ground clutter, anomalous propagation, RF interference, and spurious noise which may still be present,

2) reduce effects of abnormal beam refractions and losses,

3) improve range performance, and

4) result in the use of data from a more uniform altitude versus range.

3. REFLECTIVITY QUALITY CONTROL

It has been found that precipitation estimates can be adversely affected by partial or complete blocking of the radar beam, especially when the radar is located in hilly terrain or within cities (Harrold et al., 1974; Wilson, 1975; Aniol and Riedl, 1979; Harju and Puhakka, 1980). The correction can be computed from the percent blockage of the two-way beam intensity. Table 2 specifies the corrections in 1 dBZ steps.

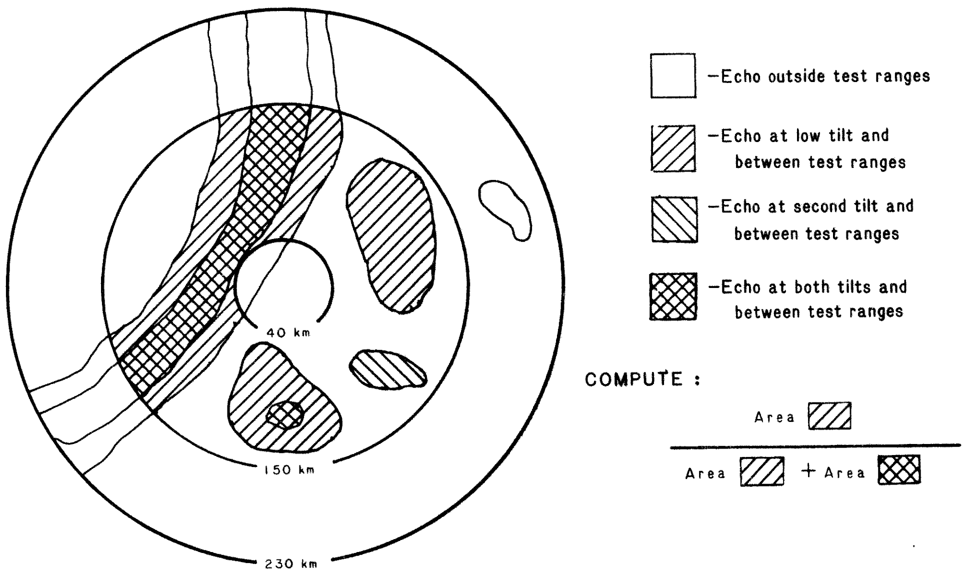

Fig. 2. Illustration of the fractional area reduction calculation for the spatial continuity test.

Table 1. Equivalent reflectivity factor data characteristics.

Bin Size : 1° X 1 km

Range : 1 km to 230 km

Elevations : Four contiguous low tilts, approx. as follows:

Elev.(degrees)	Range(Km)
3.5	1- 20
2.5	21- 40
1.5	41-230
0.5	41-230

Scanning : Sequential, complete scans within approx. 2 minutes.

Frequency : Approx. once every 5 min. during normal operation.

Dynamic Range : 0 to 70 dBZ

Precision : 1 dBZ

Table 2. Corrections for Partially Blocked Bins.

Correction(dBZ)	Occultation(%)
0	0-10
1	11-29
2	30-43
3	44-55
4	56-60

Because adjustments applied to bins blocked more than 60% could produce large errors in the rainfall estimates, these bins are considered completely blocked. If the complete blocking extends over 2 degrees or less in azimuth, the values are replaced with a radial average of the pair of neighboring non-completely blocked values at the same range.

At ranges beyond about 40 km, plans are to use reflectivity data from either the lowest or second lowest tilt or a combination of both (see Hybrid Scan Construction below). Because the lowest tilt is also the tilt most likely to be severely contaminated during anomalous propagation conditions, a simple spatial continuity check is included to decide when to exclude the lowest tilt from further processing. Whenever significant echoes are present at the lowest tilt, the fraction of echo area eliminated in going to the second tilt is computed as illustrated in figure 2. Whenever this fraction exceeds an acceptable threshold, the lowest tilt is not used for the hybrid scan construction. Additional quality control steps performed include setting isolated values to zero and checking for and adjusting extreme values (outliers) where appropriate.

4. HYBRID SCAN CONSTRUCTION

In order to reduce the effects of clutter near the site and improve the range performance over what would be achievable using only one tilt, annuli from the four lowest tilts are combined to form a hybrid reflectivity scan (Hudlow et al., 1976; GATE, 1976). The hybrid scan construction is illustrated in figure 3. Beyond 40 km the maximum value for each range and azimuth from the two lowest tilts is chosen for use in the hybrid, unless the lowest tilt was discarded based on the tilt test described earlier. In that case, the second tilt is used beyond 40 km. This procedure, known as maximization of bi-scan reflectivity was applied during GATE and was found to improve the range performance of the Oceanographer's shipboard radar (GATE, 1976; Richards & Hudlow, 1977; Hudlow et al., 1979) (figure 5). This resulted from the fact that the lowest tilt (0.6°) occasionally had a "true" antenna tilt of less than 0.6° as a result of the pitch and roll of the ship. This caused significant beam losses at further ranges

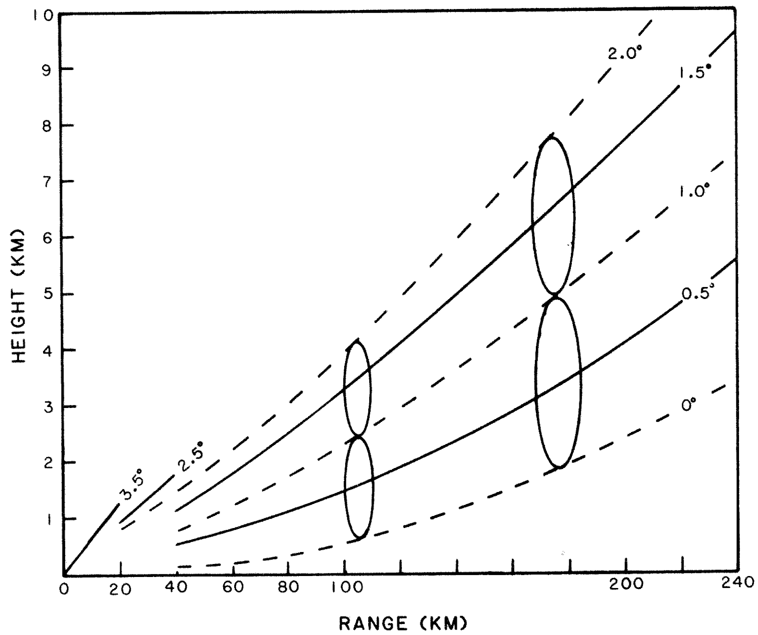

Fig. 3. Hybrid scan construction. Beyond 40 km, bi-scan maximization is used or the 1.5° tilt is used alone. Vertical scale exaggerated by a factor of 20. Based on the U.S. Standard Atmosphere and equations from Greene (1971).

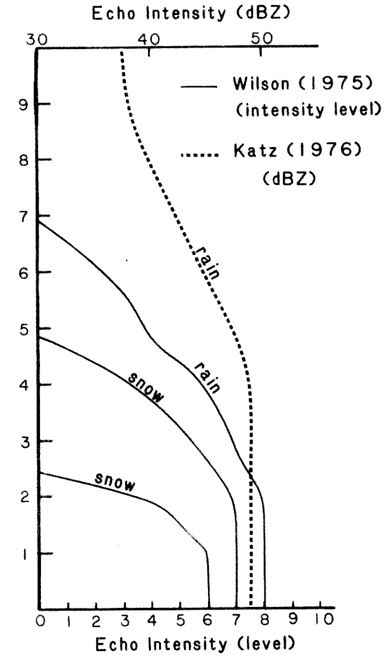

Fig. 4. Reflectivity intensity versus altitude for echoes at Wallops Island, Va. (Katz, 1976) and for the Lake Ontario basin (Wilson, 1975).

in the low tilt. Picking the maximum from the two low tilts compensated for this effect. With NEXRAD, the lowest tilt may have beam losses at further ranges as a result of terrain blocking or an occasional abnormal vertical variation in the refractive index. Bi-scan maximization will help compensate for these effects, while allowing the use of the lowest tilt in order to detect shallow precipitation at further ranges. The only known drawbacks to this technique are potential increases in the area influenced by bright band effects and the possibility of enchanced detection of virga.

5. CONVERSION TO RAINFALL RATE

Hybrid scan data are converted into rainfall rate estimates using the Z-R relationship,

$$Z = 300\ R^{1.4},$$

where Z is the equivalent reflectivity factor in mm^6/m^3 and R is the rainfall rate in mm/hr. The coefficients chosen for the Z-R relationship may be changed later based on NEXRAD data analyses. The coefficients chosen are not as critical as one may expect, since a mean bias adjustment using gage data will be done, and also since errors caused by the Z-R relationship used tend to cancel as data are averaged over greater space and time scales (Hudlow & Arkell, 1978). Adjacent 1° by 1 km values are then averaged to form the 1° by 2 km precipitation rate scan. After these computations, the resultant rainfall rate values are converted to the nearest 0.5 dBR ($dBR = 10 \log[R/(1\ mm\ hr^{-1})]$).

6. TEMPORAL CONTINUITY TEST

This test examines the time continuity of the total field volumetric water accumulation rate on a scan to scan basis. The equation used is

$$V_w(r_1 \rightarrow r_2) = \int_0^{360} \int_{r_1}^{r_2} R\ (mm/hr)\ dr\ d\Theta$$

where R is the rainfall rate converted to mm/hr, r_1 and r_2 are specified/computed range boundaries, and V_w is the total volumetric water accumulation rate in mm^3/hr. Hogg (1978) used a different approach to examine time continuity on a range ring basis as a test to flag bad precipitation rate data. Our test begins with the calculation of $V_w(1 \rightarrow 230)$ for the new precipitation rate scan. This is compared to $V_w(1 \rightarrow 230)$ from the last good precipitation rate scan. Based on the time between scans, area being considered, and a maximum expected rate of increase/decrease in V_w, a decision is made to keep or tentatively to discard the current scan. Before discarding, the increase/decrease in $V_w(1 \rightarrow r_I<230)$ is examined. This is done because changes along the outer edge could have been caused by precipitation areas entering or leaving the field of view. The inner radius (r_I) is computed based on the time between scans and a climatologically derived maximum storm translation speed. If the increase/decrease in $V_w(1 \rightarrow r_I<230km)$ also exceeds a computed threshold the scan is considered bad and is excluded from further processing. The test is not conducted when the time between scans exceeds approximately 15 minutes.

The intent of this test is not to identify all bad scans of data. However, it does provide a simple method to remove scan(s) which indicate sudden and physically unreasonable echo development/decay.

7. RANGE EFFECT CORRECTION

Signal degradation and partial beam filling, on the average, reduce precipitation rate estimates at further ranges (Wilson, 1975; Hudlow et al., 1979) (figure 5). Geotis (1978) found no apparent relation between this range effect and echo height and therefore attributed the effect to partial horizontal beam filling and the fact that averaging is done over larger areas at further ranges. However, looking at both figures 3 and 4 we can see that, especially for the case of shallow precipitation regimes and at further ranges, an average reduction in intensity due to partial vertical beam filling is also expected. Wilson and Pollock (1972) found this to be the case during hurricane Agnes (figure 6).

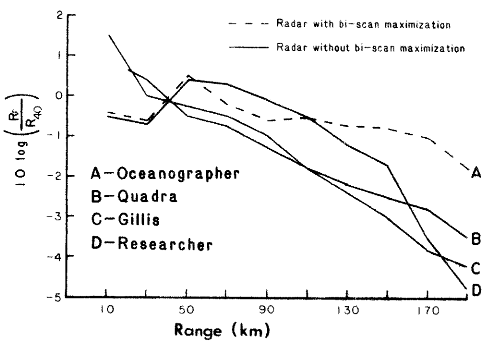

Fig. 5. Range performance of rainfall estimates as a function of range for the four radars used in GATE. Variabilities also due to actual climatological effects, use of different radars and stabilization platforms, and different locations of radars (Hudlow et al., 1979).

The multi-tilt compositing and bi-scan maximization is expected to significantly reduce the range degradation as it did during GATE (figure 5), but an additional correction will be required. Because the extent of partial beam filling is probably correlated with the echo intensity, as well as range, we believe that the range correction also should be made a function of rainfall rate(R), as well as range(r). We propose the following as a suitable form of the correction equation to be used:

$$R_{corr}(\text{mm/hr}) = a[(R(\text{mm/hr}))^b r^c]$$

where a,b,c are coefficients to be determined based on site data. The coefficients will vary seasonally as well as from site to site as was shown by Wilson (1975). Initial estimates of these coefficients will most likely be determined from a knowledge of the radar beam characteristics, local storm climatology and terrain, and prior studies of radar range effects.

8. PERFORMING THE ACCUMULATIONS

Every time a new scan set is processed (approx. every 5 min.), new hourly accumulations are computed for use in generating the running

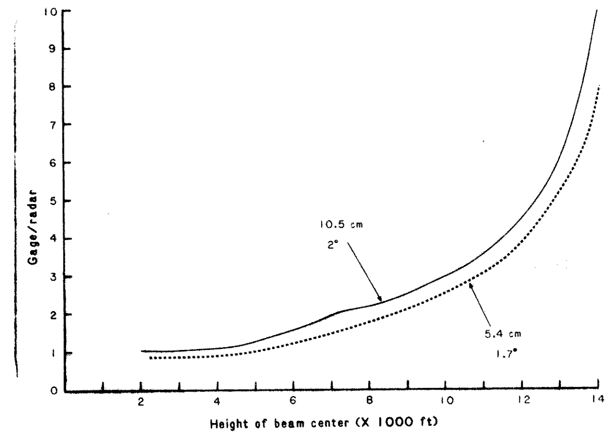

Fig. 6. Effect of beam height on the agreement between rainfall measurements from gages and radar for two radars during hurricane Agnes (Wilson & Pollock, 1972).

hourly or clock hour and the three hourly accumulation products. In addition, the scan-to-scan accumulations are computed. These are later used in updating the storm total product.

The first step in computing the hourly and scan-to-scan accumulations is to estimate the accumulations for the scan-to-scan period using the precipitation rate estimates for the current and most recent good scan. At first, it may appear that this should be done by simply averaging, for each 1° by 2 km bin, the precipitation rates for the two scans and multiplying by the time between them. However, the error associated with these accumulation estimates will grow rapidly as the time between scans increases, especially since these estimates will be used for generating as short as hourly accumulation products with a fine spatial resolution (aprox. 4 km^2 to 16 km^2 grid box areas). See table 3.

Table 3. Mean absolute percent difference between 4 km X 4 km hourly accumulations using 5 min. base sampling intervals and those from longer sampling intervals (Hudlow & Arkell, 1978).

Sampling Interval(min.)	Difference(%)
10	15
15	25
30	55
60	120

Although normally a five minute sampling interval is expected, there will be times when this interval will be significantly longer due to a system malfunction or temporary system shutdown. Therefore, we decided to design the accumulation procedure in such a way that it would provide accumulation information for as much of the scan-to-scan period as is reasonable, even when the time between scans exceeds 5 min.

The maximum occasional error, due to an increased sampling interval which we believe is tolerable, is about 50%. Therefore, the maximum sampling interval over which incremental period accumulations are computed using simple averages is set to 30 minutes.

When the sampling interval exceeds 30 minutes the excess time, centered midway between the two scan times, is flagged as a missing period. Separate incremental period accumulations are then computed for the 15-minute periods before and after the missing period. Each of these is computed using the single scan at either its beginning or end and the assumption of constant rain rates. The error due to a larger sampling interval for these 15-minute incremental period accumulations should be less than or equal to 50% in each case. The one or two incremental period accumulation scan(s) and the beginning and ending times for a missing period, if any, are then saved for use in computing the hourly accumulations.

If a clock hour was passed during the scan-to-scan period, the hourly accumulations for the most recently completed clock hour are computed. Otherwise, the hourly running accumulations for the hour ending with the current scan time are computed.

Before hourly accumulations are computed, the length of missing periods falling within the hour is checked. If more than 10 minutes are missing, no hourly accumulation is computed.

The hourly accumulations are computed by summing the accumulations from the incremental period accumulation scan sets which fall within the hour and a fractional portion of those that cross the beginning and end of the hourly period.

A check is then made for unreasonably high hourly accumulation values (outliers). These values are replaced by interpolated values when none of the eight neighboring values are outliers. This check is made in spite of the fact that instantaneous reflectivity values are checked for outliers because clutter which passes the reflectivity outlier check could, if it remains at a relatively high level for most of the hour, produce ridiculous hourly accumulations.

A scan-to-scan accumulation scan set is also required. It is used for computing the storm totals. The scan-to-scan accumulations are set equal to the single incremental period accumulations or, if two were produced, the sum of both incremental period accumulations.

9. GAGE-RADAR ADJUSTMENT

In spite of efforts to maintain a high level of quantitative accuracy in estimating precipitation from radar data, there are sure to be errors in these estimates. In fact, errors of ±5 dBR (a factor of 3) or more can occur due to a wide variety of causes including hardware calibration, anomalous propagation, wet radome attenuation, poor choice of Z-R relationship for the particular storm system, etc. While some of these errors will be localized or perhaps range dependent, others will often produce a uniform multiplicative bias in the radar estimated precipitation. In order to correct for these errors, a procedure has been developed to compare hourly precipitation from rain gages to associated radar values and estimate the radar mean field multiplicative bias.

The bias estimation procedure used is an implementation of a discrete Kalman filter (Gelb, 1974). It presumes that the mean multiplicative bias follows a random walk process, i.e., the bias is equally likely to increase or decrease over the next hour. Based on this model, the best forecast for the next hour is simply the best current estimate. If enough comparable sets of gage-radar samples are generated for a specified hourly period, the forecast from the last estimation one hour earlier is updated using these data. The new data are also used during each execution to estimate a measurement error covariance matrix, which (speaking in loose terms) measures the value of the gage-radar sets as an estimator of the radar bias.

Three classes of errors are included in the measurement "error": 1) gage sensor errors, 2) radar sensor errors, and 3) the sampling "error" introduced by the difference between the point sample at the gage and the areal sample from the radar. All of these are implicitly contained in the measurement error covariance.

If insufficient gage-radar sets for the specified hourly period are obtained, the forecast bias from the last hour becomes the new current bias value and the new forecast bias value is set equal to the current bias value. The estimation error variance also increases each hour by a system noise variance.

If the bias estimators have been propagated forward for an extended period (aprox. 24 hours), they are reset to their long term values at a time when no significant precipitation has occured during the past hour. This is done because, after an extended time without an update using gage-radar sets, the uncertainty of any bias estimate becomes too large to have any meaning.

10. PRODUCT GENERATION/DISTRIBUTION

Two classes of products will be generated from the adjusted running hourly (or clock hour) and adjusted scan-to-scan accumulation scan sets generated above.

The Data Array Products are intended for numerical use at computer facilities external to the NEXRAD system itself. They maintain the full dynamic range and full precision of the data used to generate the product. Data are re-gridded onto a "universal" grid so that data from multiple sites is immediately compatible for rapid mosaicking and communication loadings are reduced. The grids used are supersets of the Limited Fine Mesh (LFM) grid commonly used by the National Weather Service which is based on a polar stereographic projection (Ahnert et al., 1981; Greene & Hudlow, 1982; NWS, 1980).

After compaction to further reduce communications loadings, these data will be transfered to other computer facilities at the River Forecast Centers and Weather Service Forecast Offices for use in automated forecasting models and procedures. For a description of a "Proposed Off-Site Precipitation Processing System for NEXRAD," see the companion paper by that title in these preprints (Hudlow et al., 1983). The system described in that paper will run on data transfered to the regional/national level through the RFCs. The Data Array Products are described below:

1) The Hourly Digital Array Product provides, in compressed form, the hourly running totals or clock hour totals on a 131 by 131 1/40TH LFM grid (aprox. 4 km X 4 km). Dynamic range is -18 to 32 dBR and precision is 0.5 dBR. It is updated once every 5 min. and is transmitted automatically, once per hour[1], to the RFCs and, as required, up to four times per hour, to the WSFOs.

2) Selected Supplemental Data consisting most likely of a compacted 13 by 13 grid of 1/4TH LFM (aprox. 40 km X 40 km) area-averaged precipitation rates (8 coded levels) for one or more scans during the past hour. Other Supplemental Data may also be included (see list below). It is updated once every 5 min. and transmitted automatically, twice per hour, to the RFCs and, as required, to the WSFOs.

The Graphical Products are intended primarily for color graphic displays (at least two) available at each NEXRAD Principle User Processor (PUP). Each NEXRAD site will be able to support up to 16 PUPs simultaneously. The display will have at least a 640 X 512 pixel resolution and 16 color levels. The product display function will include the following capabilities (NEXRAD,1982):

1) Background Map Selection
2) Recentering
3) Magnification
4) Time Lapse Display

The precipitation graphics products will be displayed on a 2 km X 2 km grid out to 230 km and have up to 16 color levels. These products are briefly described below:

1) The Hourly Precip Product provides the hourly running totals or clock hour totals and is updated approx. once every 5 minutes. This product is not generated when more than 10 min. of data are missing from the hourly period.

2) The Three Hour Precip Product gives the three hour total over the past three clock hours and is updated up to once per hour. It is not generated if more than one of the clock hours to be used in computing the totals is missing.

3) The Storm Total Precip Product depicts the total accumulations since the last one-hour break in significant precipitation and is updated approx. once every 5 minutes. This product is generated even when missing periods occur.

During the execution of the above procedures, various supplemental data will be generated and saved. These data will provide various information on how the estimates have been processed up to this point and will be used further downstream during the "off-site" processing as part of the information for performing additional quality control and data adjustment steps before the data are input to hydrometeorological procedures. In addition, these data will be displayable at the PUP, for use by the forecaster in assessing the quality of the precipitation system products. Supplemental data are saved for two hours and includes the following:

- Total number of isolated bins in data used to constuct each hybrid scan,
- Total number of replaced and interpolated outliers in data used to construct each hybrid scan,
- Fractional area reduction from the spatial continuity test for each hybrid scan,
- Ratio of number of lowest scan bins to total number of bins used in the bi-scan maximization for each hybrid scan,
- Time continuity test data quality flags for each precipitation rate scan,
- Instantaneous area-averaged precipitation rates over 1/4TH LFM grid boxes for each precipitation rate scan.
- Total number of interpolated hourly accumulation outliers for each hourly accumulation scan,
- Missing period times,
- Bias estimate and its estimated error variance for each hourly accumulation scan,
- Coefficients used in Z-R conversion table,
- Gage poll values and accumulations, and
- System calibration and operational status indicators.

11. DATA/PRODUCT ARCHIVING

In addition to their operational usefulness, these data will be extremely valuable for post-analyses requiring hourly rainfall estimates at a fine spatial resolution. Therefore, full resolution (1° X 2 km) hourly precipitation data will be archived once per hour at each network NEXRAD site (Elvander, 1983). It will also be possible to archive NEXRAD precipitation products at the PUPs.

12. LIMITATIONS

Although this comprehensive precipitation processing system provides a framework for achieving quality precipitation estimates from NEXRAD, the products generated are limited by the fact that insufficient intelligence is included in the following areas:

1) To identify and adjust for nonhomogeneous biases other than those resulting from range or occultation effects.

2) To account directly for orographic effects.

3) To incorporate explicit considerations of frozen hydrometeor effects, including bright band phenomena.

4) To adapt to a primarily snowfall situation.

5) To correct directly for errors that may be introduced into the reflectivity estimates, as a result of strong reflectivity gradients or wet radome and/or intervening rainfall attenuation.

1 Provisions are being considered to transfer hourly accumulations to the RFCs as frequestly as every 30 min. if future applications require higher time resolutions.

6) To distill and integrate heavy precipitation information into a flash flood alert map.

This system is also limited by a lack of refined specification for some variables and coefficients which are in some cases site specific and which can best be determined only after analyses have been completed using actual NEXRAD siting surveys and radar data.

13. FUTURE DEVELOPMENTS

Overcoming some of the limitations described above is seen as beyond the scope of the planned or near future requirements for NEXRAD hydrometeorological processing. However, to include the capability to generate a flash flood alert map is an important enchancement and will be considered as soon as possible. Some other aspects of the limitations enumerated should be surmountable in the future as resources and experiences dictate. However, some of these problems, such as the nonhomogeneous bias adjustment, will be best addressed at the regional/national processing level.

Improvements could possibly be realized by incorporating additional information available from NEXRAD into the system. Two examples are:

1) To use Doppler velocity and spectrum width data to obtain additional information that might be useful for improving the accuracy of the rainfall estimates.

2) To incorporate information generated by a storm tracking algorithm which may be of value. The temporal and/or spatial continuity of the storm total and cell information on a rainfall pattern entity, or entire field, basis could be used for quality control. In addition, the storm tracking information should be useful for extrapolating rainfall estimates into the future for applications such as the construction of a flash flood alert map.

The most important task, which is in progress, is the complete verification of this system using real data. Current plans are to use archived data from the RADAP II system (Greene et al., 1983) along with archived gage data to test the precipitation processing algorithms. In addition, it is hoped that this system or a scaled down version thereof can be operationally implemented at at least one of the RADAP II sites in the near future.

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