Prepared for the Preprint Volume: 22nd Conference on Radar Meteorology, September 10-14, 1984, Zurich, Switzerland. Published by the American Meteorological Society, Boston, Mass.

VALIDATION OF THE "ON-SITE" PRECIPITATION PROCESSING SYSTEM FOR NEXRAD

Peter R. Ahnert, Michael D. Hudlow, and Edward R. Johnson

Hydrologic Research Laboratory
National Weather Service, NOAA
Silver Spring, Maryland

1. INTRODUCTION

Accurate precipitation estimates are extremely important to the severe weather forecasting (flood and flash flood) and water management activities of the U.S. Department of Commerce's National Weather Service (NWS) as well as being useful to other user agencies of the Next Generation Weather Radar (NEXRAD). Experience has shown that radar precipitation data, when properly calibrated using a limited number of gages, can be a major source for these estimates.

A comprehensive real-time multisensor precipitation analysis system is being developed by the Hydrologic Research Laboratory (HRL) of the NWS. This system is envisioned as providing estimates of optimal accuracy over the entire conterminous U.S., and plans are to implement this system coincident with the implementation of the NEXRAD system beginning in 1988. This system consists of two primary processing stages. The "on-site" processing (Ahnert et al., 1983) will take place on the NEXRAD applications computer (Radar Product Generator) located at or near the radar site. The estimates from this first stage of processing will be used for NEXRAD real-time graphical displays and for input to local forecast procedures at the local forecast offices and river forecast centers and will be sent to a regional/national center(s) for the second stage or off-site processing. During the off-site processing (Hudlow et al., 1983) estimates will be further quality controlled and refined using satellite data and additional gage data. The final optimal estimates will be input to hydrologic models and made available for use locally by forecasters. This paper describes the validation tests conducted with the "On-Site" Precipitation Processing System developed by the Radar Hydrology Group (RHG) of HRL.

The detailed functional specifications for the "On-Site" Precipitation Processing System were converted to FORTRAN 77 computer code and implemented on the NWS's Office of Hydrology PRIME 750 computer system during the summer and fall of 1983. Three of the five major processing components were coded and implemented by a scientific programmer under contract to HRL. The other two were implemented by the RHG in order to accelerate the validation schedule. The contracted programmer had no prior background in radar meteorology or hydrology and the ease with which he was able to convert the functional specifications into a running set of software clearly demonstrated that, with the source scientist available to answer specific questions, the functional specifications provide an acceptable description of the system.

The proposed "On-Site" Precipitation Processing System was described in a paper presented at the 21st AMS Radar Meteorology Conference (Ahnert et al., 1983), so a detailed description will not be repeated here. An updated version of the system block diagram (Figure 1) reveals that only the structure of the gage data acquisition process has been changed substantially from the proposed design. Instead of polling gages directly, each NEXRAD site will receive its gage data in the Standard Hydrologic Exchange Format (SHEF) (Bonnin and Cox, 1983) from one or more local/regional/national gage data acquisition and/or storage systems. These systems will be informed whenever precipitation begins at a NEXRAD site so that polling of gages under the radar umbrella can be initiated. The precipitation detection function also will be used to identify times at which many stages of the processing can be abbreviated because it isn't raining or hasn't rained in the past hour. Another change to the proposed design involves the logic within the time continuity test. These changes make the maximum acceptable rate of change in the ratio of the volumetric precipitation rates for adjacent scans a function of echo area. This makes it possible to set thresholds which are not overly conservative. Finally, based on the results of the validation tests described herein, we plan to modify the hybrid scan construction to enable the use of higher tilts in predefined range-azimuth sectors where mountain clutter is a problem.

Verification of the algorithms includes testing the total system with actual data and testing each component for computational accuracy. The code was informally verified after being implemented by manually comparing the final code to the functional descriptions. In addition, each major computational step was checked by manually computing intermediate results for selected time periods and locations and comparing these with values output by the system. Testing

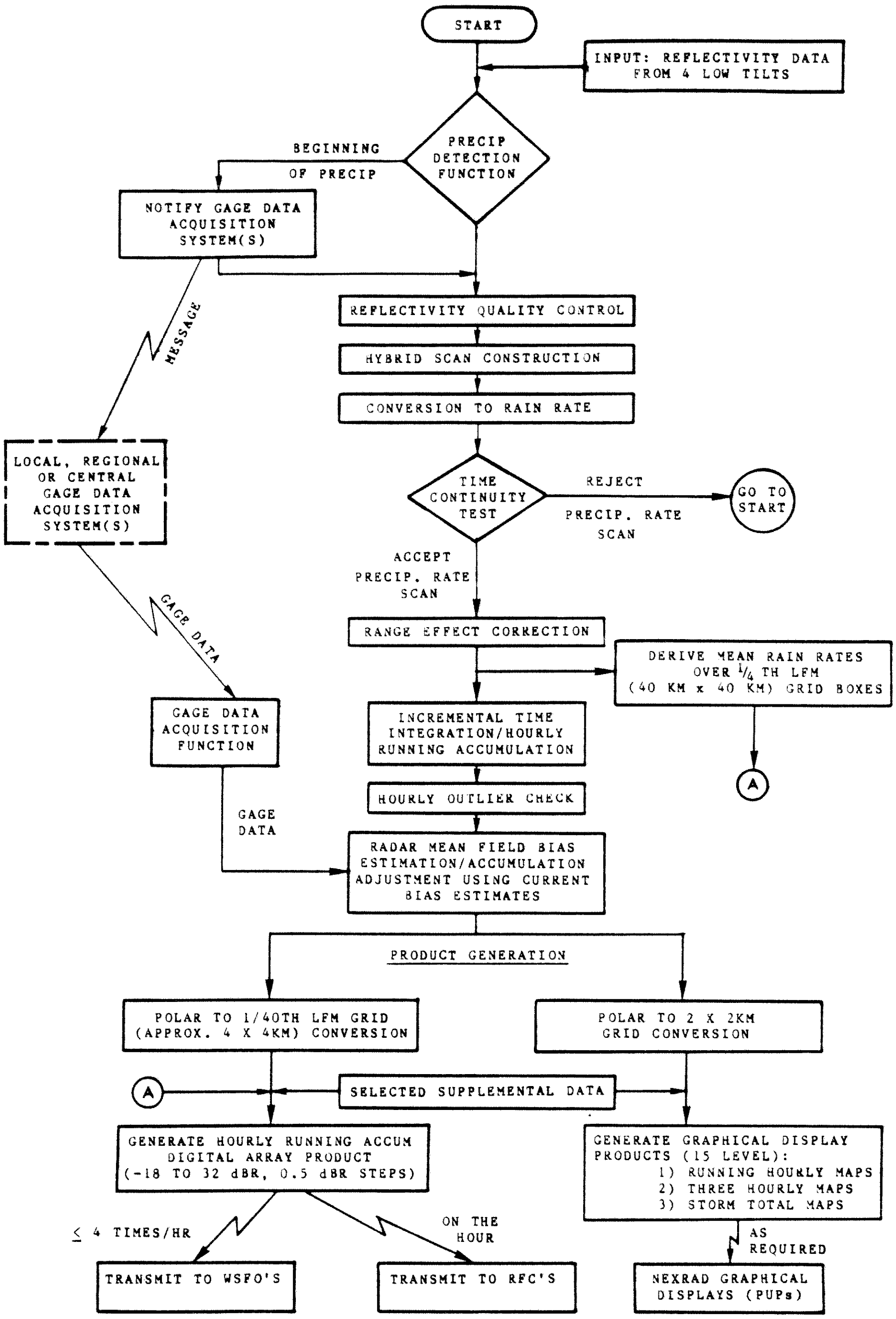

Fig. 1. Block diagram of the "On-Site" Precipitation Processing System.

using actual data was done for a 5 1/4 hour case which was acquired as part of the Prototype Regional Observing and Forecasting Service's (PROFS) summer 1983 forecasting exercise from the National Center for Atmospheric Research (NCAR) CP2 radar. The CP2 radar has technical characteristics similar to those planned for NEXRAD. The paper emphasizes the results of these tests and assesses the operational readiness of the proposed "on-site" precipitation processing system.

All 5 1/4 hours of the test data were run through the entire "on-site" precipitation processing system and the hourly precipitation estimates compared with independent gage values. In addition, the effects of various components in the system on the hourly accumulations were tested for one selected hour (21-22Z). This was done by computing changes in the 1/40th LFM (approximately 4 km x 4 km resolution) Hourly Digital Array Product when components were removed or altered. Statistics of the precipitation accumulation difference fields were computed separately for five different regions of the hourly accumulation field (Figure 2) for each of the component tests.

The next section of the paper describes the case study data used in the validation tests. Following this are sections describing the test results for each component within the system. It is assumed that the reader will refer to the prior paper by Ahnert et al. (1983) for the design details of the processing system components to aid in the interpretation of the test results presented below. Toward the end of the paper a comparison between the radar accumulation estimates and gage values is presented as well as an overall assessment of the system performance.

2. DATA

The NCAR CP2 Doppler radar located approximately 25 km east of Boulder, Colorado was operated by PROFS during the summer of 1983 for its operational forecast exercise and for the purpose of evaluating selected NEXRAD algorithms. In consultation with PROFS (Smart, 1983), the July 23, 1983 case was selected because of the existence of a flash flood producing storm to the southwest of Denver, Colorado, which produced over a half-million dollars in damages (NOAA, 1983a) from heavy rain alone. The following, taken from Storm Data (NOAA, 1983a) summarizes the nature and severity of the storm:

> Storm Data - July 23 --
>
> "Another round of heavy thunderstorms blasted Denver and areas just to the south of the city. Douglas County was hardest hit; golfball size hail fell in and to the north of Parker between 1:30 and 2:15 PM MST. Many homes at Pinery, a subdivision just north of Parker had windows broken and paint stripped by the storm; some vehicles were dented by the large stones. In Parker, 1.90 inches of rain fell in just 30 minutes. Many roads in Douglas County were washed out, and at least one bridge was damaged. Up to two inches of rain fell in Lakewood and Littleton was drenched by 1.60 inches in 15 minutes. A department store in Lakewood suffered water damage when a pipe handling runoff broke sending four inches of water onto the floor of the store. The rain also spread to Brighton, north of Denver, and to the east as far as Deer Trail; both spots had about an inch of rain in 30 minutes."

NCAR CP2 data were collected from 1813Z to 2326Z July 23, 1983. PROFS extracted the reflectivity data for the 4 low tilts from the field tapes, converted the data into Universal Tape Format (UTF) (Barnes, 1980), and sent them to the RHG in December 1983.

The characteristics of the data collected by the NCAR CP2 radar are similar to those planned for NEXRAD data collected during periods of precipitation (Table 1). In order that the input data better match minimal NEXRAD requirements, the CP2 data were averaged from 1° x 150 m values to 1° x 1 km values in rainfall rate units and then converted back to dBZe. In addition, the dynamic range was reduced to 0 to 71 dBZe and the precision was degraded to 0.5 dBZe. A major difference in the NEXRAD and CP2 radar data characteristics, important in areas affected by ground clutter, is the absence of clutter suppression from the CP2 data. Clutter suppression may result in improvements in NEXRAD precipitation estimates in clutter areas. However, care will have to be taken to ensure that good data are not being eliminated along with the clutter.

In addition to the radar data, verification data collected by PROFS' chase teams and other observers were acquired from PROFS. These reports are referenced by towns and roads and thus had to be converted to radar azimuth and range. This was done by first determining the latitude and longitude of the report and then converting to range and azimuth from the radar using the known difference (between the report and radar site coordinates) in degrees of latitude and longitude. Additional independent data were obtained from the National Climatic Data Center's Hourly Precipitation Data for Colorado (NOAA, 1983b). The latitude and longitude coordinates of each gage also were converted to range-azimuth coordinates so that comparisons could be made.

3. REFLECTIVITY QUALITY CONTROL

Several quality control procedures are applied to the reflectivity data before construction of the hybrid scan and conversion to rainfall rates. These include checks to remove isolated and extreme values, corrections for partial and complete beam occultations, and a simple vertical echo continuity check. The occultation corrections were not tested using actual data, since site survey data or sufficient records of archived radar data to determine occulted azimuths were not available, but the computational validity of the software has been verified. When blocking takes place, such as in the Rocky Mountain areas covered by the CP2 radar, occultation corrections should substantially improve the estimates of rainfall for some partially or completely blocked regions.

An average of 262 isolated bins were removed from each set of four reflectivity data annuli used to construct the hybrid scan at each time step. The effect of removing the isolated bin check on the 21 to 22Z 1/40th LFM (approximately 4 km x 4 km) resolution Hourly Digital Array Product is summarized in Table 2A for five selected regions (Figure 2). Although the overall effect, when averaged over a large region, is small, the removal of isolated echoes (aircraft, towers, buildings, etc.) will have a significant effect at individual grid boxes, especially at some radar sites.

A few accumulations in the two Rocky Mountain clutter regions (Regions 4 and 5) had values which unexpectedly decreased when the isolated bin check was removed. This probably is because not removing isolated bins (some of which had very high reflectivity in the mountains) leads to some bins having higher hourly accumulations which are then replaced with interpolated values by the hourly outlier check later in the processing.

Removing the check for extreme reflectivity values (outliers) resulted in a very large increase in the hourly accumulations in the mountain clutter regions (50-100 percent averaged over Regions 4 and 5) (Table 2B). This check removes values greater than 65 dBZe (or any other specified threshold) by interpolating using

TABLE 1.

	Minimum NEXRAD Requirements (during precipitation)	CP2 (Storm mode)
Bin Size	1° X 1 km	1° X 150 m
Range	1 km to 230 km	1 km to 160 km
Elevations (approx.)	0.5, 1.5, 2.5, 3.5 ...	0.5, 1.5, 2.5, 3.5 ...
Scanning	Sequential, 4 complete scans within approx. 2 minutes	Sequential, 4 complete scans within approx. 1.5 minutes
Frequency	Approx. once every 5 minutes during normal operation	Approx. once every 5 minutes occasionally once every 10 minutes
Dynamic Range	0 to 71 dBZe	-10 to 80 dBZe
Precision	1 dBZe	0.01 dBZe
Number of Samples	Not specified	64/gate
Clutter Suppression	Applied in known clutter areas	Not applied

Table 2.

Result of "Action" on 21-22Z 1/40th LFM Hourly Digital Array Product for the five test regions shown in figure 2. Unless otherwise noted, the normal hybrid construction was used. Symbols are defined as follows:

- $\bar{\Delta}$(mm) - Accumulation change in mm averaged over each of the test regions.
- $\bar{\Delta}_{[ABS]}$(%) - Percent accumultation (or absolute accumulation) change averaged over each of the test regions.
- $\downarrow_{max}$(mm or %) - Maximum accumulation decrease in mm (or %) for any one grid box.
- $\uparrow_{max}$(mm or %) - Maximum accumulation increase in mm (or %) for any one grid box.
- $AR_{\Delta>.25}$(%) - Percent of total area in region at which an accumulation change of at least 0.25 mm occurred.

"ACTION"	REGION	$\bar{\Delta}$(mm)	$\bar{\Delta}$(%)	$\downarrow_{max}$(mm)	$\uparrow_{max}$(mm)	$AR_{\Delta>.25}$(%)
A. Remove isolated bin check	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.4	0.1	0.3	0.1
	3	0.0	0.3	0.1	0.0	0.0
	4	-0.0	-0.4	6	0.5	4
	5	-0.1	-0.2	13	0.9	3
B. Remove extreme value check	1	0.0	0.4	0.0	7	0.6
	2	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0
	4	6	50	9	221	10
	5	36	108	16	872	30
C. Remove tilt test (use bi-scan maximization instead of 2nd tilt beyond 50 km)	1	2	16	0.0	19	70
	2	0.6	92	0.5	76	32
	3	0.0	0.0	0.0	0.0	0
	4	23	194	9	247	51
	5	40	119	16	872	47
D. Remove hybrid construction (use low tilt at all ranges)	1	-1	-10	49	176	92
	2	1	208	1	126	44
	3	21	999	2	152	78
	4	89	765	95	729	92
	5	-18	-53	187	454	93
E. Replace normal hybrid with sectorized hybrid	1	2	15	0.0	18	70
	2	0.5	72	0.9	70	30
	3	0.0	0.0	0.0	0.0	0.0
	4	-7	-53	119	79	75
	5	-32	-93	200	110	84
F. Remove bi-scan maximization and tilt test, compared to run without tilt test	1	-5	-39	51	0.0	90
	2	-0.1	-11	1	0.4	20
	3	0.0	0.0	0.0	0.0	0
	4	-0.2	-0.6	28	9	19
	5	-47	-63	630	22	74
G. Average 1° x 1 km reflectivity values to 1° x 2 km values before conversion to rainfall rate (in Z)	1	0.2	2	0.0	5	25
	2	0.0	2	0.1	0.3	0.7
	3	0.0	6	0.0	0.8	4
	4	2	13	8	20	36
	5	4	12	13	52	55

"ACTION"	REGION	$\bar{\Delta}$(mm)	$\bar{\Delta}_{ABS}$(%)	$\downarrow_{max}$(%)	$\uparrow_{max}$(%)	$AR_{\Delta>.25}$(%)
H. Store rates to nearest 0.05 dBR instead of 0.5 dBR	1	0.0	1	14	5	17
	2	0.0	2	15	>999	0.9
	3	0.0	0.6	4	1	0.0
	4	0.0	1	7	15	8
	5	0.1	1	5	12	10
I. Use every other scan (approx. every 10 min.)	1	-0.1	13	55	30	78
	2	0.0	15	57	57	12
	3	-0.0	8	24	3	6
	4	0.2	8	21	54	42
	5	-0.5	9	27	65	62
J. Remove hourly outlier check	1	0.0	0.0	0.0	0.0	0.0
	2	0.0	0.0	0.0	0.0	0.0
	3	0.0	0.0	0.0	0.0	0.0
	4	1	9	0.0	347	0.7
	5	0.4	1	0.0	37	1

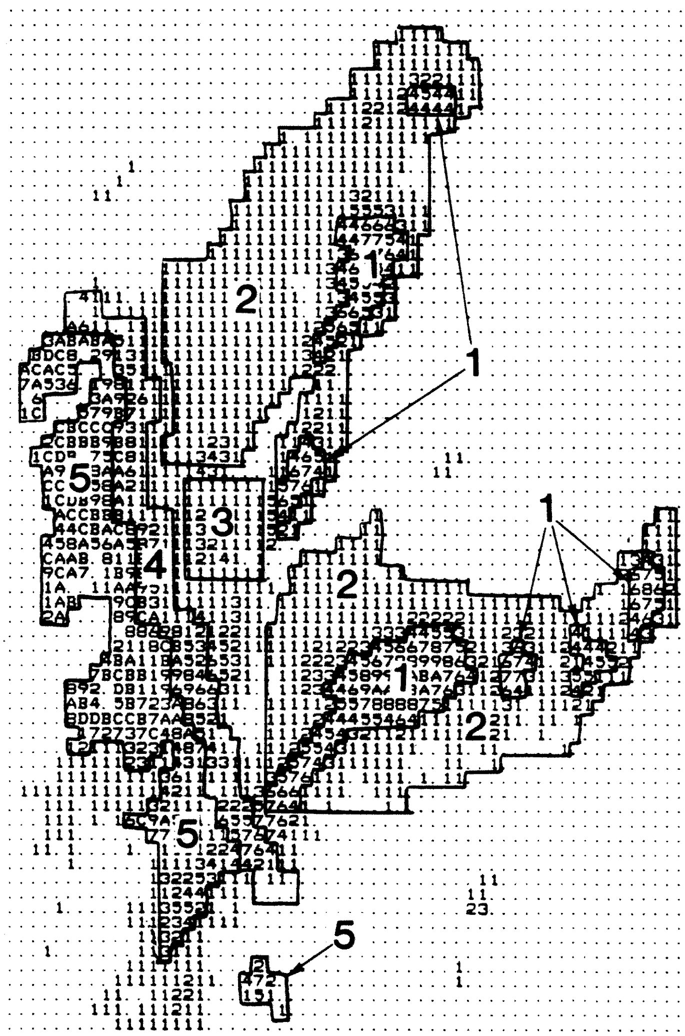

Fig. 2. 21-22Z 1/40th LFM (approx. 4 km x 4 km) Hourly Digital Array Product with regions used in validation tests illustrated. Region 1--heavy rain areas (> 3 mm), Region 2--light rain areas (<3 mm), Region 3--close-in radar clutter, Region 4--leading edge of Rocky Mtns., Region 5--Rocky Mtns. Accumulation class intervals used are the same as in Fig. 3, although Hourly Digital Array Product has a much higher intensity precision than that depicted here. Normal hybrid processing was used in obtaining these estimates.

surrounding values or, if surrounding values are also extreme, by replacing them with a low value. Note that the effect of the mountains in Regions 4 and 5 simulates what may occur during periods of anomalous propagation (AP) in otherwise unobstructed regions. Only one 1/40th LFM grid box accumulation was affected in the rain area (Region 1), a result of very high reflectivities in an intense hail column (PROFS, 1983). One can conclude from these results that the extreme value check will help reduce anomalously high reflectivity values resulting from hail, AP, and clutter.

The vertical echo continuity check throws out the lowest tilt (0.5°) whenever more than 50 percent (an adjustable parameter) of the echoes at the low tilt disappear at the second tilt. For the PROFS CP2 data, because of the mountain clutter, this occurs for each scan set from 1813 to 2246Z. After 2246Z, rain had spread over a large enough area so that the 50 percent threshold was no longer reached and the low tilt was accepted. This test was designed to detect and remove some types of AP, and not designed to be foolproof. Since the mountain clutter mimics a case of unexpected AP, and the low tilt was rejected for most of the period, the test performed successfully. When AP is accompanied by larger areas of precipitation, it is probably better to accept the low tilt since the low tilt will provide better rainfall estimates in clutter free areas. The tilt test performed exactly in this manner.

With the full system running and using the normal hybrid construction, the tilt test results in rejection of the low tilt for all scans used in the 21-22Z hourly accumulation. The second tilt is used in its place at ranges beyond 50 km. When the tilt test is removed, the low tilt is accepted for all times. In constructing the hybrid, the maximum reflectivity from the lowest and second lowest tilt for each range and azimuth is then used. Therefore removing the tilt test can only lead to increased reflectivities in the hybrid scan at further ranges (beyond 50 km — adjustable) where the low two tilts are used. The region near the radar (Region 3) is not affected since the same upper two tilts are used whether or not the tilt test is conducted. In fact, without the tilt test, false rainfall accumulation values due to clutter in the mountain regions (Regions 4 and 5) increase by 120 to 190 percent for the 21 to 22Z period (Table 2C). This reflects the important potential the tilt test has to reduce not only clutter, but also to reduce the effects of AP, which is its intended purpose. In the rain areas, removing the tilt test (i.e., accepting the low tilt) resulted in increases also (16 to 92 percent) but the average accumulation increase in both rain areas was less than 2 mm compared to 40 mm in the mountain clutter areas. Some of the increase is probably due to some clutter showing up in the rain areas (e.g., one grid box in the light rain area jumped up from <3 mm to about 76 mm) when the low tilt is accepted. In addition some of the increase is probably due to more compete beam filling (especially in light shallow precipitation layers) and the fact that observed reflectivity often decreases with height in lighter rain areas.

Although the tilt test performed well for this case, these results indicate that under certain conditions the current version of the tilt test may mistake decreases in reflectivity with height in light rain for AP. The low tilt would be thrown out and the light rain would be lost. Refinements to the tilt test will be investigated in hopes of alleviating this problem.

4. HYBRID SCAN CONSTRUCTION

The hybrid scan is a single reflectivity scan composed of data from the low 4 tilts. Closer in, higher tilts are used to reduce clutter. At further ranges either the maxima from the low two tilts are used (bi-scan maximization) or the second tilt values are used alone (whenever the tilt test rejects the low tilt). The effects of removing the hybrid construction and instead using the low tilt at all ranges are summarized in Table 2D.

As was mentioned earlier, for the 21-22Z case the low tilt was not used in the normal hybrid processing, so that at further ranges removing the hybrid construction means that the low tilt is used in place of the second tilt. A large average percent increase (>999 percent or up to 152 mm for a single value) in the accumulation estimates due to clutter appears in the previously virtually echo-free areas near the radar (Region 3). The values in the front range show a very large increase (765 percent), since the low tilt intercepts foothills overlooked by the second tilt. Because of the blockages induced by the foothills when the low tilt is used, Region 5 clutter shows an overall decrease (-53 percent) although large increases occur in some areas. Heavy rain areas show a slight decrease (-10 percent) using the low tilt agreeing with the observation that reflectivities sometimes increase with height in very strong cells. Rainfall estimates for light rain showed large increases (194 percent averaged over entire region) in about half the areas covered when only the low tilt was used instead of using only the second tilt. The likely reasons for this were described earlier.

Clutter problems associated with mountainous terrain were not addressed in the original algorithm design. However, even with 30 dBZe clutter suppression in the reflectivity channel, as specified for the NEXRAD design, mountain echoes (which often exceed 50 dBZe) would still be present. In addition, mountains may hide storms from the radar at the lower one or two tilts. A modification to the hybrid construction which permits using the higher tilts above the mountains was tested. This sectorized hybrid processing specifies that, for predefined range-azimuth sectors, lower tilt values are to be replaced by higher tilt values during the hybrid scan construction. Use of the sectorized hybrid approach produced considerable improvement by reducing or eliminating the intensity and area covered by mountain clutter (Table 2E). The remaining echoes are probably due to side lobe returns and/or precipitation, since precipitation did occur in the mountains on the afternoon of July 23. Because of the clutter reduction with the sectorized hybrid construction, most scan sets passed the tilt test. Thus, in addition to improving results over the mountains, the sectorized hybrid also improved results in the precipitation areas, since the lowest tilt was accepted for use in areas east of the mountains.

Table 2F shows the results from excluding both the tilt test and bi-scan maximization, compared to excluding only the tilt test (using maximum from lowest two tilts) for the normal hybrid scan construction. Removing the bi-scan and using only the low tilt reduces both the rainfall and clutter values. Using bi-scan maximization in the heavy rain areas increases the 21-22Z accumulations by 39 percent indicating that for heavy rain areas, as mentioned earlier, measured reflectivities were increasing with height.

5. CONVERSION TO RAINFALL RATE

As part of the process of converting to rainfall rates, the higher resolution reflectivity values must be averaged to form the 1° by 2 km precipitation rate scan. The system specifications state that this averaging should be done in rainfall rate units. Table 2G illustrates that averaging in Z before conversion to rainfall rate will introduce additional errors in the estimates. Similar tests were performed by averaging in dBZe which produced even larger errors (results not shown in Table 2).

The rainfall rate values, according to the specifications, are to be stored (for internal computations) to at least the nearest 0.5 dBR. Table 2H shows that increasing the precision to 0.05 dBR only affected a small percentage (<10 percent except in Region 1) of the area in each region by more than 0.25 mm. However, the maximum percent change in the accumulation for any one grid box was substantial (>10 percent for Regions 1, 4, and 5). Reducing the required internal precision to 1 dBR from 0.5 dBR affects a larger percentage of the area (>15 percent of Regions 1, 4, and 5) and the average absolute percent changes are larger (results not shown in Table 2) than for the increased precision case.

6. TEMPORAL CONTINUITY TEST

The temporal continuity check computes the ratio of the volumetric precipitation rate for adjacent hybrid scan times and compares the ratio to a computed threshold. The test rejected two scans from the 5 1/4 hours of PROFS data at 1859 and 1931Z. An examination of the data at 1931Z reveals that no echoes are present over the entire scan, while the scan before and after appear normal within both precipitation and clutter areas. For the 1859 scan, the volumetric precipitation rate dropped from 14000 mm km^2/hr at 1851 to 4000 mm km^2/hr at 1859 and then back to 12500 mm km^2/hr for the subsequent scan at 1906.

Another series of tests were performed by artificially altering the rainfall rate values. Doubling the rainfall rate values for one selected scan resulted in that scan being rejected. Reducing all rainfall rate values by 20 percent for one selected scan resulted in that scan being rejected.

These tests indicated the procedure has the potential to detect and remove scans which contain spurious noise or loss of data or sudden AP. In no cases did the test remove any scans considered to be good.

7. RANGE EFFECT CORRECTION

Because the CP2 radar data has a maximum radius of only 160 km, the range degradation of the precipitation estimate is probably small. In addition, 5 1/4 hours of data are not sufficient to estimate the range effect coefficients. Therefore, the coefficients were set to produce 0.0 dBR corrections.

8. PERFORMING THE ACCUMULATIONS

In order to verify the requirements for reflectivity data every 5 minutes, rainfall estimates were computed using every other scan (every 10 minutes). The mean absolute percent differences (Table 2I) for the various regions for the 21-22Z 1/40th LFM accumulations reveal significant errors (as large as 15 percent) as a result of the longer (aprox. 10 min.) sampling interval. These results agree well with those obtained during GATE (Hudlow & Arkell, 1978).

The hourly extreme value check replaces accumulations greater than 400 mm (an adjustable parameter) with an interpolated value. Removing this check resulted in large increases (up to 350% (150 mm)) in the 21-22Z 1/40th LFM accumulations for four grid boxes in the mountain clutter regions (Table 2J).

9. GAGE-RADAR ADJUSTMENT

The Kalman filter portion of the algorithms was tested using simulated sets of radar and gage values. First, synthetic radar values (R) were generated using a multivariate normal process with specified mean, variance and covariance function. As a separate process, a "true bias" (B) is generated for each time step (t,t+1...) such that $B_{t+1} = B_t + \varepsilon_t$ where ε_t is a normally distributed random variable with mean 0 and specified variance (adjustable parameter). For each radar value, the gage value for gage n underneath the radar data bin was simulated such that $G_{nt} = B_t * R_{nt} + \eta_{nt}$ where η_{nt} is a multivariate normal random variable with mean 0 and specified covariance function. The Kalman filter was then run on the generated radar (R_t) and gage (G_t) values in order to estimate B_t at each time step. Figure 3 shows an example of the estimated bias generated by the Kalman filter (dots) and the "true bias" (line) versus time for 30 gages and 100 time steps. Other simulation runs have been made with different numbers of gages and various initial conditions to verify the behavior of the filter for a range of possible real-world situations. So far, the results indicate that the technique is computationally efficient (1.7 CPU seconds/step on a PRIME 750 for 30 gages) and stable (results are reasonable and not overly sensitive to any of the parameters).

The next step will be to test the Kalman filter on actual data for several storms. Data from the RADAP II site in Oklahoma City, Oklahoma (Greene et al., 1983) are being prepared for such a test.

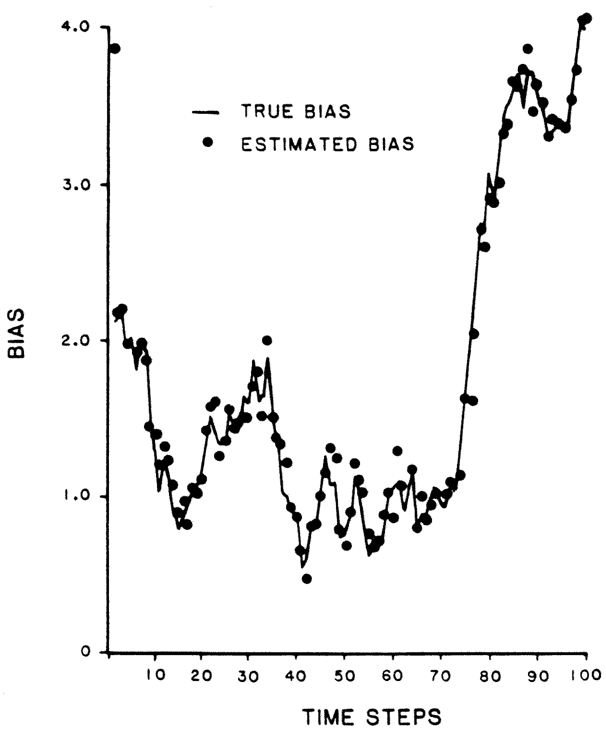

Fig. 3. Estimated bias using Kalman filter compared with "true bias" using 30 sets of simulated hourly radar and gage accumulation values for 100 time steps.

10. PRODUCT GENERATION

Figure 4 shows a sample Hourly Precipitation Product which is of the type generated every 5 minutes using the sectorized hybrid scan. In the color version, a different color is used to display the alphanumeric values falling within each column of code values. Comparison of Figure 4 with Figure 2 illustrates the improvement in mountain clutter removal that is achieved by modifying the normal hybrid construction to include sectorized processing. An even more dramatic overall clutter reduction is apparent when one compares the displays produced by the hybrid processing to the one based just on the low tilt scan (display not shown here). These results confirm the importance of using multiple scans from the lower 4°, or so, of antenna tilt settings in the derivation of the quantitative rainfall products.

Displays analogous to Figure 4 are produced for the 3-Hourly and Storm Total Accumulation Products. In addition, the 1/40th LFM Digital Array Product is updated each 5 min. for use by the river and weather forecast offices as input to numerical analysis and modeling activities.

11. OVERALL PERFORMANCE

Table 3 compares the hourly accumulations generated from the CP2 radar data with available hourly rain gage accumulations. The radar accumulation interval matched to each gage accumulation in Table 3 corresponds to the coded Hourly Precip Product accumulation interval which is selected from the 4 (or 16) 2 km by 2 km grid boxes closest to the gage. Of these, the interval which best matched the gage accumulation is used in the table. This helps account for possible errors in the location of the gage and for strong gradients near the gage. The results indicate that for Regions 1 and 2 heavy precipitation accumulations were estimated very well. With light precipitation, agreement was poorer, but still reasonable. In Regions 4 and 5, the major problem was the Rollinsville storm which produced an inch in an hour and was completely missed. The storm was totally blocked by the intervening mountains and only light echoes, if any, were detected from the top of this storm when the sectorized hybrid was used.

As a system, the algorithms performed very well. The different modules seems to behave the way they were designed to behave and no serious problems were encountered. Modification of the original system design to include sectorized hybrid processing offers promise of significantly reducing the clutter in mountain areas, while still enabling the detection of some storms within and beyond the mountains to the best extent possible.

One potential problem was encountered with the vertical echo continuity test. Even when the sectorized hybrid was used, the percent reduction in echo area between the first and second tilts retained for processing still resulted in the tilt test sometimes exceeding the 50 percent threshold, causing the lower tilt to be rejected, even though the clutter had been reduced significantly. Raising the threshold to 55 percent or higher, so that all these scans were accepted, would have resulted in the lower tilt being accepted, but this probably would also result in the acceptance of more low tilts contaminated by clutter (or AP). Slight modification to the tilt test, such as measuring the percent of the echo area for which, say, a 10 dBZ reduction occurs between the low two tilts, might work better.

12. CONCLUSIONS/RECOMMENDATIONS

The algorithm specifications as currently stated performed very well except in mountainous terrain where a modification to the original design to use a sectorized hybrid approach will improve the performance significantly. Based on the 5 1/4 hour case study, an initial set of parameters for the algorithms can now be specified. Tests indicate that round off and truncation errors may require internal storage of dBR values to a precision greater than the currently specified 0.5 dBR. The four lowest tilts are needed once each 5 minutes during times of precipitation.

With the completion of the real data tests on the rain-gage adjustment procedure and a few additional refinements to the code to optimize the performance and computer efficiency, the algorithms will be ready for implementation as a real-time processing system. Final testing and documentation for this system is scheduled for completion by August 31, 1984. At that time efforts will be directed toward extension of the NEXRAD applications software development work to include a Flash Flood Alert Algorithm. The Flash Flood Alert Algorithm will use as its primary

ONE HOUR PRECIPITATION

FROM: 21:00Z JULY 23, 1983
TO: 22:00Z JULY 23, 1983
RANGE MARKER INTERVAL: 50 km GRID SPACING: 2 km x 2 km

CODE	mm	CODE	mm	CODE	mm	CODE	mm	CODE	mm
1	0.3 - 1.0	4	2.5 - 4.0	7	10.0 - 15.0	A	40.0 - 65.0	D	150.0 - 250.0
2	1.0 - 1.5	5	4.0 - 6.5	8	15.0 - 25.0	B	65.0 - 100.0	E	> 250.0
3	1.5 - 2.5	6	6.5 - 10.0	9	25.0 - 40.0	C	100.0 - 150.0		

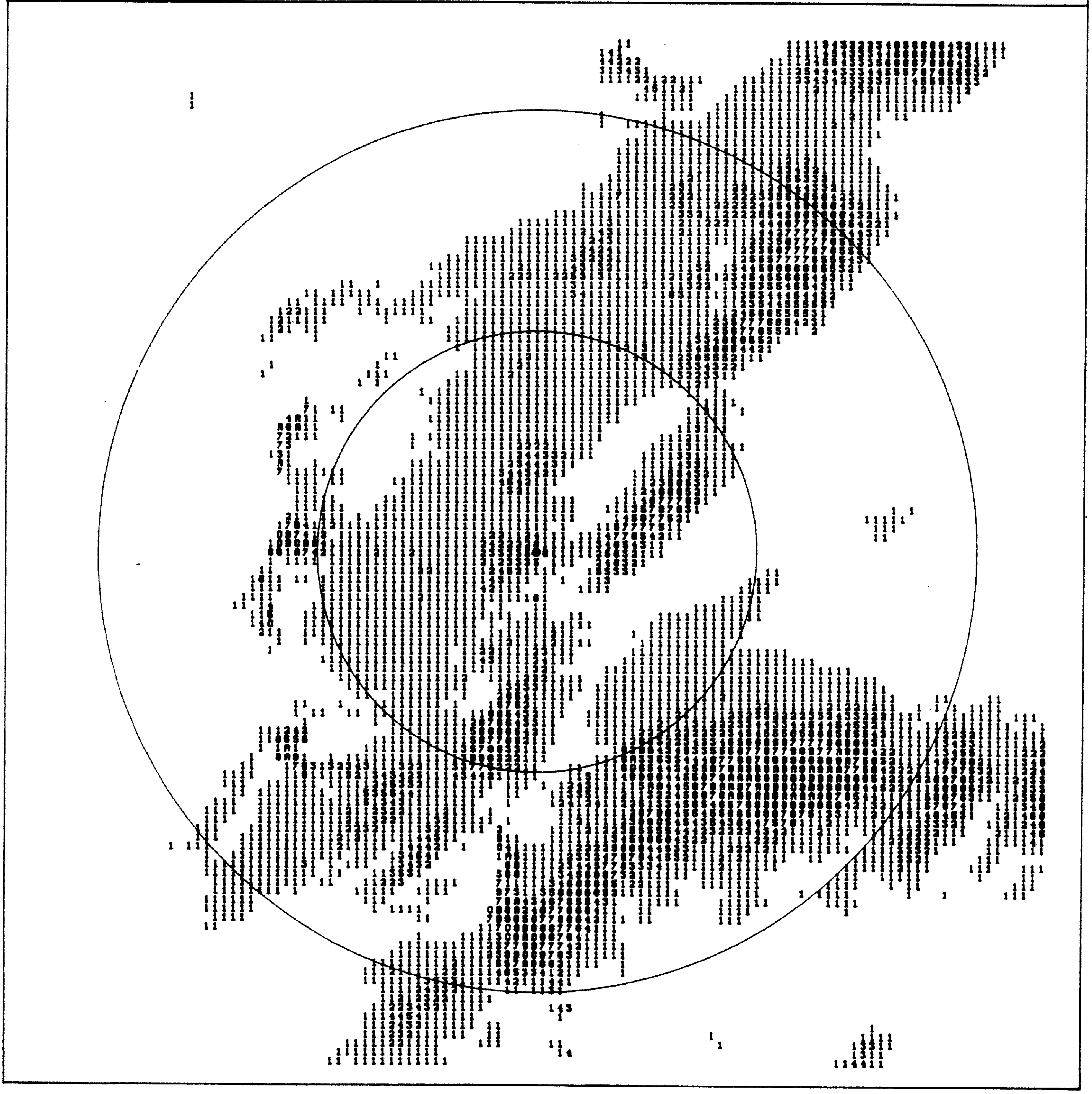

Fig. 4. 2 km x 2 km resolution Hourly Precip Product for 21-22Z generated using the sectorized hybrid processing. Note improvement over Fig. 2 in mountain clutter areas.

Table 3. Comparison of hourly rain gage accumulation with the 2km x 2 km Hourly Precip Product accumulation intervals at the closest 4 and 16 grid boxes to the plotted gage location. Of the closest 4 (or 16) radar estimates, the one which corresponds best to the gage value is listed. Regions 1 and 2 are not blocked by mountains, while in Regions 4 and 5 significant blocking occurs at the low tilt(s).

	Hourly Accumulations in Millimeters											
	19 - 20Z			20 - 21Z			21 - 22Z*			22 - 23Z		
Locations	Gage	Radar (closest 4)	Radar (closest 16)	Gage	Radar (closest 4)	Radar (closest 16)	Gage	Radar (closest 4)	Radar (closest 16)	Gage	Radar (closest 4)	Radar (closest 16
Regions 1 & 2												
Parker	0.0	<0.3	<0.3	2.5	6.6-10	2.5-4.0	38.0	6.5-10	25-40	7.6	1.5-2.5	6.5-10
Byers	0.0	<0.3	<0.3	0.0	<0.3	<0.3	0.0	<0.3	<0.3	2.5	0.3-1.0	1.0-1.5
Deer Trail	0.0	<0.3	<0.3	0.0	<0.3	<0.3	0.0	0.3-1.0	0.3-1.0	17.5	10-15	10-15
Denver	0.0	<0.3	<0.3	0.8	0.3-1.0	0.3-1.0	0.0	<0.3	<0.3	2.0	0.3-1.0	0.3-1.0
Nunn	0.0	<0.3	<0.3	0.0	0.3-1.0	0.3-1.0	0.0	0.3-1.0	0.3-1.0	0.0	0.3-1.0	0.3-1.0
Greeley	0.0	<0.3	<0.3	0.0	<0.3	<0.3	0.0	0.3-1.0	0.3-1.0	0.0	0.3-1.0	0.3-1.0
Fort Collins	0.5	0.3-1.0	0.3-1.0	0.25	<0.3	<0.3	0.0	0.3-1.0	0.3-1.0	0.0	<0.3	<0.3
Longmont	0.0	<0.3	<0.3	2.5	0.3-1.0	0.3-1.0	0.0	0.3-1.0	0.3-1.0	0.0	<0.3	<0.3
Regions 4 & 5												
Drake	0.0	0.3-1.0	0.3-1.0	2.5	2.5-4.0	2.5-4.0	0.0	<0.3	<0.3	0.0	<0.3	<0.3
Estes Park	0.0	<0.3	<0.3	2.5	<0.3	<0.3	0.0	<0.3	<0.3	0.0	<0.3	<0.3
Allens Park	0.0	<0.3	<0.3	0.0	<0.3	<0.3	0.0	<0.3	<0.3	0.0	<0.3	<0.3
Grand Lake	0.0	<0.3	<0.3	0.0	<0.3	<0.3	0.0	<0.3	<0.3	0.0	<0.3	<0.3
Rollinsville	0.0	0.3-1.0	0.3-1.0	0.0	<0.3	<0.3	22.9	0.3-1.0	0.3-1.0	7.6	<0.3	0.3-1.0
Lawson	2.5	0.3-1.0	0.3-1.0	2.5	0.3-1.0	0.3-1.0	0.0	<0.3	<0.3	0.0	<0.3	<0.3
Golden	2.5	2.5-4.0	2.5-4.0	0.0	<0.3	<0.3	0.0	<0.3	<0.3	0.0	<0.3	<0.3
Morrison	2.5	0.3-1.0	2.4-4.0	0.0	<0.3	<0.3	0.0	<0.3	<0.3	0.0	0.3-1.0	0.3-1.0
Woodland Park	0.0	<0.3	<0.3		<0.3	<0.3	0.0	0.3-1.0	0.3-1.0	7.6	1.5-2.5	4.0-6.5

*The sectorized hybrid was used during computations of the 21-22Z estimates used in this table. All other values were computed using the normal hybrid.

input the rainfall estimates from the "On-Site" Precipitation Processing System and will incorporate simple hydrologic logic and pattern extrapolation to identify areas of flash flood potential.

13. ACKNOWLEDGEMENTS

The authors would like to thank the NEXRAD Joint System Program Office for providing partial support for the coding of the algorithms, and Paul Tilles of Automated Sciences Group for an excellent job coding three of the five algorithms. Appreciation also is expressed to the PROFS office for assistance in providing the excellent NCAR CP2 radar test data.

The authors also wish to thank Stephen Ambrose, Mary Anne Morrison, and John Menard for perserverence in developing software for the display of polar and cartesian radar reflectivity and rainfall data, and Joseph Fiore for assisting with the coding and debugging of two of the five algorithms. For their expert typing of this manuscript, we are indebted to Ruth Ripkin and Laura Davis. Lianne Isley assisted with the editorial review.

14. REFERENCES

Ahnert, P., M. Hudlow, E. Johnson, D. Greene, and M. Dias, 1983: Proposed "on-site" precipitation processing system for NEXRAD. Preprints, 21st Radar Meteor. Conf., AMS, Boston, Massachusetts.

Barnes, S., 1980: Report on a meeting to establish a common Doppler radar data exchange format. SESAME News No. 5, Bul. AMS, Vol. 61, No. 11, Boston, Massachusetts, 1401-1404.

Bonnin, G. and R. Cox, 1983: An explanation of the Standard Hydrologic Exchange Format (SHEF) and its implementation in the central region. NOAA Tech Memo NWS CR-67, Missouri Basin River Forecast Center, NWS, Kansas City, Missouri.

Greene, D., J. Nilsen, R. Saffle, D. Holmes, M. Hudlow, P. Ahnert, 1983: RADAP II, an interim radar data processor. Preprints, 21st Radar Meteor. Conf., Boston, Massachusetts.

Hudlow, M. and R. Arkell, 1978: Effect of temporal and spatial sampling errors and Z-R variability on accuracy of GATE radar rainfall estimates. Preprints, 18th Radar Meteor. Conf., AMS, Boston, Massachusetts, 342-349.

Hudlow, M., D. Greene, P. Ahnert, W. Krajewski, T. Sivaramakrishnan, M. Dias, and E. Johnson, 1983: Proposed off-site precipitation processing system for NEXRAD. Preprints, 21st Radar Meteor. Conf., AMS, Boston, Massachusetts.

NOAA, 1983a: Storm Data, Vol. 25, No. 7, National Climatic Data Center, NESDIS, NOAA, Asheville, North Carolina.

NOAA, 1983b: Hourly Precipitation Data, Vol. 33, No. 7, National Climatic Data Center, NESDIS, NOAA, Asheville, North Carolina.

PROFS, 1983: Verification data for July 23, 1983, unpublished computer printout, PROFS, NOAA, Environmental Research Laboratories, Boulder, Colorado.

Smart, J., 1983: Discussion of CP2 data collected during the PROFS summer 1983 exercise. Personal communication, PROFS, NOAA, Environmental Research Laboratories, Boulder, Colorado.