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U.S. DEPARTMENT OF THE INTERIOR
Bureau of Reclamation

Technical Service Center
Civil Engineering Services
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by

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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Most of the work for this supplemental report was performed and coordinated by Dr. Arlin B. Super, since retired. Programming and data support was provided by Ra Aman, Linda Rogers, and Anne Reynolds. In additional, we had useful feedback from several NWS (National Weather Service) personnel. Reviewer comments by Curt Hartzell and Mark Fresch were very helpful.

U.S. Department of the Interior
Mission Statement

The Mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to tribes.

Bureau of Reclamation
Mission Statement

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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ABSTRACT

This report documents an extension of work done on the Snow Accumulation Algorithm (SAA) development for NEXRAD WSR-88D radars. An expansion of operational testing using Level III data shows that the algorithm continues to be robust. For the 1998-1999 season (November - April) a variety of accumulation products were made available on the Internet for five radars across the Dakotas and Minnesota, including a regional mosaic. The Z_e-S relationship used was 150 $R^{2.0}$. That network was expanded to 10 radars for the 1999-2000 winter season.

Issues involving the vertical gradient of reflectivity and snowfall continued to be prominent. The vertical gradient of falling snow was used to generate a range correction which boosts integrations by a factor of three at 230 km. The use of this correction scheme appears to be appropriate when compared to surface observations. Experimental work was performed that reduces the effects of virga at far ranges. A visualization routine was created to display the vertical gradient in the lowest 5 km of altitude above the radar. Parts of that routine may be useful in future efforts to reduce virga and bright band effects.

Future work should continue to examine the vertical gradient issue to identify the best style of algorithm. One that can simultaneously adjust for virga, bright band, and range correction would be preferred. In addition, individual radar hybrid scan and occultation files can be adjusted by hand editing to reduce blemishes in the SAA product.

1. INTRODUCTION

Approximately 160 NEXRAD (NEXt generation weather RADar) units were installed across the United States during the period 1991-1997 (Fulton et al., 1998). Individual radars in this network are also referred to as the WSR-88D (Weather Surveillance Radar - 1988 Doppler). The NEXRAD network represents a major upgrade and improvement over the aging systems it replaced (Crum et al., 1993). The NEXRAD network of WSR-88Ds is operated by three Federal agencies, the National Weather Service, the Federal Aviation Administration, and the U.S. Air Force. Consequently, NEXRAD is a tri-agency cooperative effort among the Departments of Commerce, Transportation, and Defense.

The sole precipitation algorithm available on the WSR-88Ds has been the PPS (Precipitation Preprocessing Subsystem), designed for rainfall but calibrated with data for tropical cumulus clouds. National Weather Service (NWS) forecasters and others have a current need of an SAA (Snow Accumulation Algorithm) capable of providing reasonably accurate real-time snow water equivalent (S) and snow depth (SD) estimates based on effective reflectivity (Z_e). Awareness of PPS limitations with snow led the NEXRAD OSF (Operational Support Facility) in Norman, Oklahoma, to sponsor Reclamation (Bureau of Reclamation) efforts to develop the SAA described by Super and Holroyd (1996, 1997, 1998).

Implementation of the SAA in the NEXRAD network is presently awaiting hardware and software upgrades to that system. This report presents the efforts supported by OSF (Operational Support Facility) and the NOAA (National Oceanic and Atmospheric Administration) Office of Global Programs GEWEX (Global Energy and Water Cycle Experiment) GCIP (Continental-Scale International Project) to refine the SAA to improve its performance in a variety of challenging weather situations.

2. TASK SUMMARIES

Supplement Number 3 to the original Memorandum of Understanding (MOU) covers the period from 1 June 1998 to 1 October 1999, with a final 2 month extension for writing this report. The statement of work (slightly reformatted for clarity) is:

> The Reclamation TSC (Technical Service Center) investigations may include the following:
> ...examine additional data sets to optimize the Z_e-S relations for regions such as Alaska and the Sierra Nevada where the '96/'97 data were very sparse;
> ...investigate whether at least a seasonal average vertical profile of Z_e should be used as part of a range correction scheme;
> ...develop a "warning message" for the radar operators when bright band contamination appears likely.

The work includes cooperation with OSF in a timely manner for arising questions about the SAA. Work done under other funding (GCIP, Reclamation's Research and Technology Transfer Program), but related to the SAA, was expected to be forwarded to OSF.

3. GCIP SUPPORT

3.1 A GCIP Report

Most of the SAA effort during this reporting period was done in support of NOAA's GCIP program. The following is an overview, based on a presentation, *A Demonstration of the Operational Use of*

Reclamation's NEXRAD Snow Accumulation Algorithm for Estimating Snow Water Equivalent, by Arlin B. Super and Edmond W. Holroyd, III, made at a GCIP conference held 17-18 May 1999, at the University of Maryland.

The NEXRAD SAA (Snow Accumulation Algorithm) was developed for Level II data. It was thereby limited in application to past events using Level II data tapes and to a few real-time operations at those radar sites using the WDSS (Warning Decision Support System) computer software. Forecasters who were fortunate to have the use of the SAA appreciated its help in understanding regional snowfalls and were reluctant to yield the system to other users. Distribution of the algorithm to all northern (snowy) sites is waiting for future improvements to the NEXRAD hardware and software systems everywhere.

In the interim, Reclamation wanted to study SAA performance in the Missouri and Mississippi River Basins. To do so, the SAA was modified to accept Level III data in near real time from a NIDS (NEXRAD Information Dissemination System) vendor. The resolution of Level III data is only 4 or 5 dBZ, depending on volume coverage pattern, while Level II data are at 0.5 dBZ resolution. Angular and range resolutions are the same, but no more than the first four tilts are available with NIDS data. Occultation and hybrid scan adjustments and the Z_e-S relation remained the same as with Level II data. Use of the NIDS data did not seriously degrade the snow accumulation estimates.

During the first winter of testing, SAA accumulations (S and SD products) were provided for five radars (Bismark, KBIS; Aberdeen, KABR; Grand Forks, KMVX; Minneapolis, KMPX, the required site; and Duluth, KDLH). Accumulation updates were provided hourly for all five radars according to the approximate 4 km HRAP grid specified by the National Weather Service (NWS) National Operational Hydrologic Remote Sensing Center (NOHRSC), in Chanhassen, MN. A five-radar composite was also available.

For each site, S and SD products were made available via FTP and on the Internet for the past 1-hr, 2-hr, 3-hr, and 6-hr periods ending at the top of the hour and for fixed 6-hr and 24-hr periods. The merged composite S and SD products were available for the past 3-hr and 6-hr periods ending at the top of the hour and for fixed 24-hr periods. The fixed 6-hr products ended at 00, 06, 12, and 18 UTC, and the 24-hr products ended at 12 UTC. The fixed 6-hr and 24-hr products were available for 7 days. Such products were made available for a half year but were suspended in May for the warm season. To examine the products, go to the Internet URL <http://www.usbr.gov/rsmg>, then select NEXRAD Snow Algorithm Products.

The operational, real-time use of NIDS data revealed some areas of concern. Tuning the SAA to be most accurate in major snowstorms has resulted in a sensitivity to virga, which was being reported at far ranges as precipitation. Virga is recognized by rings of remote accumulations, with none at close ranges. Techniques for excluding virga are being refined and tested (see Section 7.4).

The SAA, during a cold arctic airmass snowstorm (see Section 3.2), seriously underestimated snow accumulations because of the shallow nature of the storm and some microphysical considerations.

Surface observations of snowfall throughout the areas of the five radars were collected for the entire winter, along with upper air soundings. Serious errors were produced by the network of cooperative gages in reporting snowfall and varying exposures to the wind, resulting in noisy data. Therefore, it was not possible to have precise surface data, especially in windy conditions, for performance verification of the SAA. Further testing is being conducted to see if the surface data, from sites inferior to the sheltered sites used for SAA development, are useful for verification of accumulations.

The SAA uses a range correction scheme to adjust for severe underestimation as a factor of range. A range correction factor (see Section 5) was determined using the vertical gradient of Level II Z_e and S as observed by the lowest 5 antenna tilts in a circle of about 35 km radius from the Minneapolis radar. The correction factor is of the form of a multiplier factor, $F = C1 + C2*R + C3*R^2$, for range R and empirical coefficients C1, C2, and C3. The relation was found to work well (see Section 5.2) to about 200 km (the beam center height above the radar is 4.1 km at 200 km, 5.1 km at 230 km) in deep storms. Beyond that range and in shallower storms at closer range, the correction becomes inadequate as the radar beam climbs above the precipitation and the reflectivities become less than the minimum threshold, currently 4 dBZ, making correction impossible. The range correction used for Minneapolis appeared to be working well for all locations. A linear plot (see Section 5.4) of the ratio between the radar estimate of precipitation and that measured by cooperative gages showed the expected scatter but no obvious range bias. Preliminary indications from this large data set are that the range correction coefficients are appropriate and not in need of adjustment.

The 5-radar composite showed that Duluth was seriously underestimating precipitation because of likely calibration errors. Also, Bismark may have had smaller calibration errors. The composite products showed no discontinuity along the lines of equal distance between the radars for Aberdeen, Grand Forks, and Minneapolis.

During the winter of 1999-2000, the operational test will be continued and expanded westward to include five WSR-88Ds near the cities of Minot, North Dakota; Rapid City, South Dakota; Glasgow, Montana; Billings, Montana; and Great Falls, Montana.

The following default adaptable parameters are being used for the northern plains states: minimum reflectivity = 4 dBZ, maximum reflectivity = 40 dBZ: alpha = 150, beta = 2.0, range correction factor for R > 35 km: $F = 1.04607 - 0.0029590*R + 0.0000506*R^2$ for range R.

3.2 An Arctic Airmass Snowfall

The storm of 2-3 January 1999, at Minneapolis and Aberdeen, was during an arctic outbreak. The SAA operating on NIDS data greatly underestimated, by a factor of about 2 or 3, the snowfall in both liquid equivalent and depth. Our analysis contained these points:

1. In a preliminary attempt to reduce the virga contamination, the minimum threshold had been increased to +10 dBZ. The weak reflectivities from the arctic outbreak were thereby excluded from the accumulations. Therefore, the minimum threshold has been changed back to +4 dBZ since mid-January 1999to produce more accurate accumulations for storms in arctic air masses. That will increase the virga problem, which is recognizable by a ring of supposed accumulations at far ranges while there is no accumulation near the radar.

2. The storm clouds were quite shallow, with a very steep vertical profile of reflectivity (VPR). Depending on the depth of the precipitating clouds, even the lowest tilt beam would begin to have beam filling problems fairly near the radar, and would overshoot the clouds at greater ranges.

3. Rawinsonde data showed that the region for the rapidly growing dendrites (where temperatures were -13 to -17 °C and relative humidities near 100 percent) was shallow and just above the surface. So the radar was mostly scanning above the rapid growth zone resulting in underestimation by the SAA (see point 4 below). This explains why the radar was seeing small dBZ values and yet it was sometimes snowing at moderate to heavy rates.

4. The SAA underestimated snow water equivalent. The Z_e-S relation used was not optimum for this storm. Z_e=50 $S^{.0}$ would have been better and would have tripled the snowfall. Using default adaptable parameters (Z_e=150 $S^{2.0}$), optimized for best overall performance, results in poor SAA products in some cases.   If the SAA had been run on-site, the adaptable parameters could have been changed, depending on the storm type.

5. The default snow density (1/14) routinely used was too great for this storm. SD is calculated by dividing S by the snow density. S was already underestimated. Therefore the default density resulted in an even greater underestimation of snow depth. The snow density is an adaptable parameter that could also have been changed if the SAA were running on-site.

This case demonstrates that “one size” does not fit all. Although the SAA is producing daily and storm totals of S within about 0.20 inches of quality surface measurements according to the Level II data tests, the problem is that Reclamation is not changing a few adaptable parameters as changing conditions dictate.

Vertical profiles of reflectivity, described in Section 7.3, for the 2 days and two radars are shown in figure 1. Profiles were generated with the coding presented in appendix A for the purpose of understanding the virga problem. The left two columns are for January 2 and 3 for KMPX, and the right two columns are for KABR. Each column contains 24 graphs, one per hour, with time progressing downwards. The graph for the hour ending at 12 UTC (near sunrise) is at the bottom. For each graph, the vertical axis is altitude above the radar from 0 to 5 km. The horizontal axis is cumulative percent of range bins at each altitude, generated from all available tilts of NIDS data. Far ranges cannot contribute to the bottom of each graph because of the beam height. The coloring, as shown by the key, indicates the magnitude of reflectivity.

The upper left graphs, for KMPX, show an apparent virga pattern because the storm is at far ranges where the lowest beam of the radar cannot see the lower altitudes. In the middle of the left column it is seen that the snow, when it is close enough to be seen at

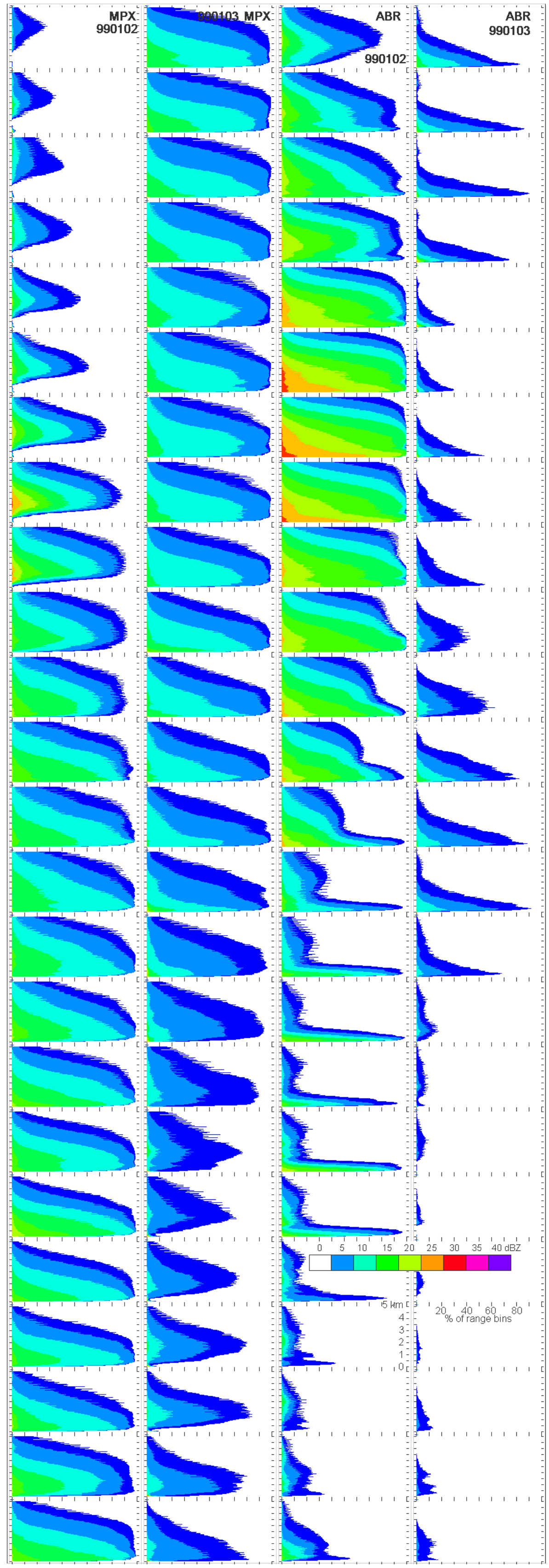

Figure 1.—Vertical profiles of reflectivity during a shallow snowstorm in arctic air.

the lower altitudes, is actually widespread (nearly 100 percent coverage) at the surface. Thereafter the vertical gradient is strong and continues that way through the next day in the second column.

The storm arrived earlier at KABR and with a greater intensity (third column) but similar vertical gradient. In the bottom part of the third column, most of the sky becomes echo free, except for the lowest altitudes, which are sampled only close to the radar. It is not known if that pattern represents exceedingly shallow snow or anomalous propagation producing ground clutter reflections during the night hours. Near sunrise (bottom of column 3) and thereafter on the second day (right column) the pattern appears to represent genuine shallow snow observable only close to the radar. At far ranges the radar beam climbs above this shallow snow and fails to accurately indicate the precipitation intensity near the surface.

When the SAA is integrated into the WSR-88D baseline, users will be able to change adaptable parameters as conditions change. More study is needed to optimize adaptable parameters for different storm types.

4. ADDITIONAL Z_e-S DATA SETS

4.1 Anchorage, Alaska

In Section 9.5 of Super and Holroyd (1998), we indicated the data set from Alaska was severely limited for the 1996-97 season and could not be analyzed. We inquired at the Anchorage office about more recent data sets. The problems continue. Available gage data are in locations with serious radar blockage. We cannot derive reliable alpha and beta constants for the Anchorage area without installation of a special gage network, which is beyond our scope of work. In addition, not much Level II data has been recorded for Anchorage during winter storms. Therefore, no Z_e-S relationship is provided for this important climate zone.

4.2 Seattle, Washington

Work with the KATX, Seattle, Washington, radar data and gages was not completed. Preliminary indications were that the results would be poor. KATX is at an elevation of only 181 m, which is almost always below the melting level. Consequently, the primary problems (Westrick et al., 1999) for the SAA are bright band contamination and beam blockage from surrounding higher terrain. Furthermore, there is considerable vertical separation between the lowest unblocked radar beam and the surface where the snow gages are located. Experience indicates that there is appreciable precipitation growth in layers near the surface in winter orographic situations. The radar beam cannot view this growth zone in the Cascades east of Seattle. Therefore it is expected that a very small alpha would result.

Table 1.—Basic parameters for the California gages and the NEXRAD radar beam above each

Gage site	Azim. deg.	Range km	Elev. m	Tilt deg.	Corr. DBZ	R^2	n	Alpha	Beta	Clearance m
Brush Creek	46.0	31.9	1085	2.40	0	0.402	29	20.0	2.1	363
De Sabla	359.7	42.2	826	1.45	0	0.122	15	25.0	2.3	392
Camptonville	95.4	48.2	840	1.45	+3	0.081	38	10.0	2.2	560
La Porte	68.5	57.5	1518	2.40	0	0.261	66	5.0	1.9	1,123
Grizzly Ridge	59.9	94.9	2103	2.40	0	0.159	60	0.9	1.8	2,425
Lake Davis	65.7	106.8	1758	2.40	0	0.180	44	0.1	2.2	3,405
Sierraville	84.2	106.9	1516	2.40	0	0.014	27	0.5	1.8	3,649

4.3 Sierra Nevada, California

Our work has revealed that the KBBX, Beale AFB radar site, at an elevation of 61 m, is poor with respect to viewing precipitation development over the Sierra Nevada range. The lowest elevation scan and even some of the second and third elevation scans are blocked over the mountainous terrain.

All seven hourly ETI gages listed in table 1 were operated by the California Department of Water Resources. They had load sensors with 0.04 inch (1 mm) resolution. Our best (number of hours of unmelted snow) gage site was at La Porte, yet the gage was far below the lowest unblocked beam. A snowboard was observed about 0.5 km away from the La Porte site by Pete and Jim Burkholder, who provided occasional air temperatures and remarks about the storms.

Analyses from all gages yielded small alpha values (as shown in table 1), indicative of having the radar beam examine light snow far above the growth zone and even farther above the surface gages. That table lists the occultation correction (Corr.), correlation coefficient (R^2) for the relation between the SAA - S and gage values, the number of data points (n), and the clearance between the radar beam center and the gage elevation.

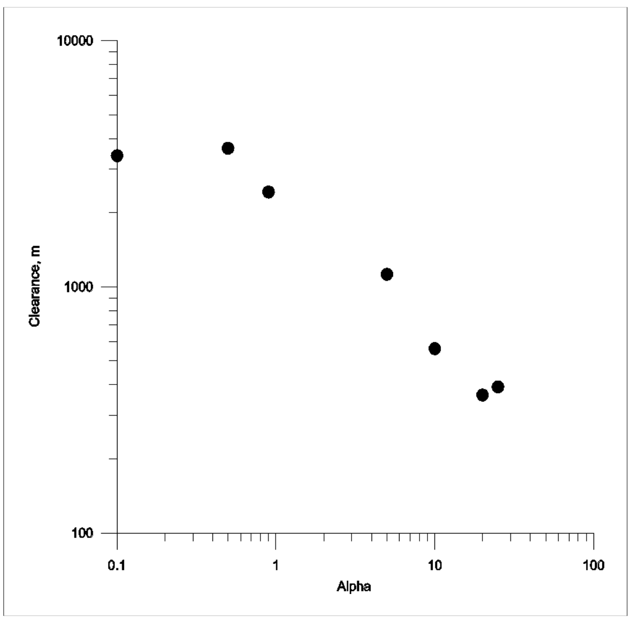

Figure 2.—A nearly linear relation exists between the logarithms of alpha and ground clearance of the radar beam.

For our analyses, wet snow or rain events were excluded. It appears that the clearance between the radar beam center and the gage elevation strongly affects the value of alpha, as shown in figure. 2. All seven gages are plotted, with the left-most point (smallest alpha) probably being offset from the apparent linear relation by poor data resolution in the calculation of alpha. As the ground clearance increases, alpha decreases. That indicates a strong vertical gradient in reflectivity. In areas with strong orographic uplift, such as the Sierra Nevadas, the greatest growth in precipitation is in the layers of the atmosphere close to the surface. There is, therefore, a strong decrease in reflectivity with altitude.

4.4 Chicago, Illinois

Work by Arlin Super on the KLOT, Chicago, Illinois, data set was not completed before his retirement. He learned that most of the 25 gages in the area were not adequately shielded against wind effects. The main siting priority was to minimize vandalism damage to the gages, to the extent that gages were sometimes put on top of buildings. Due to the poor quality of gage data, no comparisons with radar data could be made.

4.5 Medford, Oregon

Through a different project, Hartzell and Super (2000) compared reflectivity data from the KMAX, Medford, Oregon, radar to gage data. The Medford radar is sited at high elevation (2300 m) and, therefore, overlooks low elevation precipitation. All six gages in the study are located at elevations lower than 1250 m. The two gages exposed to snow are of the heated tipping bucket type (known to be inaccurate) and have no Alter shields to reduce wind effects. The following adaptable parameters are being used: minimum reflectivity = 4 dBZ, maximum reflectivity = 40 dBZ: alpha = 100, beta = 2.0, range correction factor for R > 35 km: $F = 1.0 - 0.00500 * R + 0.0001428 * R^2$.

Analysis and verification was difficult because of mountainous terrain and other factors. However, this SAA with the indicated range correction factor significantly improved the WSR-88D precipitation estimates over the default $Z_e = 300 R^{1.4}$ relationship. Using six gages, from 33 to 179 km range, for 26 storm day totals, the default relation yielded radar estimates of precipitation with a median at 17 percent of actual. For the same data set, the SAA with the range correction produced a median at 97 percent of actual precipitation. Work on this Reclamation project continues, but such work was not part of this study and is mentioned only for general interest.

5. RANGE CORRECTION

Two ways were investigated to deal with range correction. The simplest way is to make alpha a function of range, calibrated by precision gage data from adequately sheltered locations. Another way is to examine the vertical profile of reflectivity or calculated S at a particular range and use the seasonal gradient values at the first five tilts to create a range correction relationship for farther ranges. Other empirical techniques may be applicable.

5.1 A Range-Dependent Alpha

Figure 3 shows the combined results of calculating an alpha that is range dependent. Six radars (KCLE = Cleveland, Ohio; KMPX = Minneapolis, Minnesota; KENX = Albany, New York; KFTG = Denver, Colorado; KGJX = Grand Junction, Colorado; KBBX = Beale Air Force Base, California) are represented and all reasonable gage information is included. While beta was fixed at 2.0 for most cases, the KBBX points are for the alpha values with beta close to 2.0 (± 0.3), as in table 1; the unusually small alpha values did not encourage greater precision with a fixed beta.

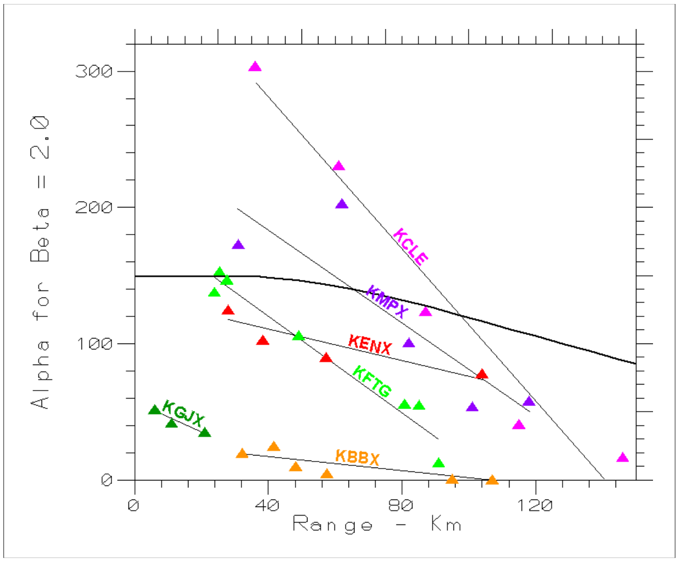

Figure 3.—Plots of individual relations for the variation of alpha with range. The thick curved line is the VPR range correction used for the 1998-1999 season for the northern plains states.

The straight lines, labeled with the radar station identifier, are generally close fits to the array of points (colored triangles) for that particular radar and its snow gage data. However, the lines certainly do not overlap; they are site specific.

The KCLE data are dominated by shallow lake effect storms, which the radar beam overshoots at far ranges.

The KGJX and KBBX radars, at elevations differing by about 10,000 feet, look at strongly orographic snowfalls which generate most of their precipitation growth in the layers close to the ground. To avoid ground clutter, higher tilt radar data had to be used. However, that overshoots the growth zone, resulting in the need for smaller alpha values to calculate the correct surface precipitation.

All these straight lines present a mathematical problem. A range correction would be the ratio of a standard alpha, such as 150, and the alpha values along the line. The corrections would go infinite (inverse of zero) where the lines intersect the range axis and then negative at farther ranges. Therefore, straight lines are inappropriate for range correction, even though the lines are derived from real, precision surface measurements. For comparison, the NIDS version of the SAA had a quadratic relationship for a range correction factor, as described below in Section 5.2. That relation is converted to an equivalent function of alpha varying with range and is shown as the thick curved line in figure 3. Alpha is 150 until 36 km. Thereafter, alpha changes to a parabolic curve resulting in a correction factor of about 3 (alpha of 50) at 230 km. The parabolic relationship avoids infinite corrections but is a distortion of the actual relationship.

Table 2.—Data used in the derivation of a range correction for the Minneapolis NEXRAD radar

Tilt	Meters	R, km	Ratio	Inv.
0.50	378	35.0	1.000	1.000
1.45	958	73.4	0.890	1.124
2.40	1,538	103.7	0.780	1.282
3.35	2,117	129.5	0.670	1.493
4.30	2,696	152.4	0.560	1.786

col 1= NEXRAD antenna tilt angle - degrees - VCP21
col 2= center of beam above radar at 35 km range (meters)
col 3= range,km to 0.5 deg beam center for altitude of col 2
col 4= ratio of S to 35 km, 0.5 deg. tilt value; linear to 0.56 at 4.3 deg.
col 5= correction factor (reciprocal of col 4)

5.2 Range Correction from a Seasonal Averaged Vertical Profile of S

The range correction scheme previously developed for nine Minnesota snow storms of the 1996-97 winter, described by Super (1998), was revisited. All the radar data were used in new calculations with a somewhat different Z_e-S relationship discussed by Super and Holroyd (1998). The results were quite similar, with the median vertical profile of Z_e suggesting about a 20 percent decrease in Z_e per kilometer of height above the ground. Alternatively, a seasonal average or median gradient can be derived for S rather than Z_e.

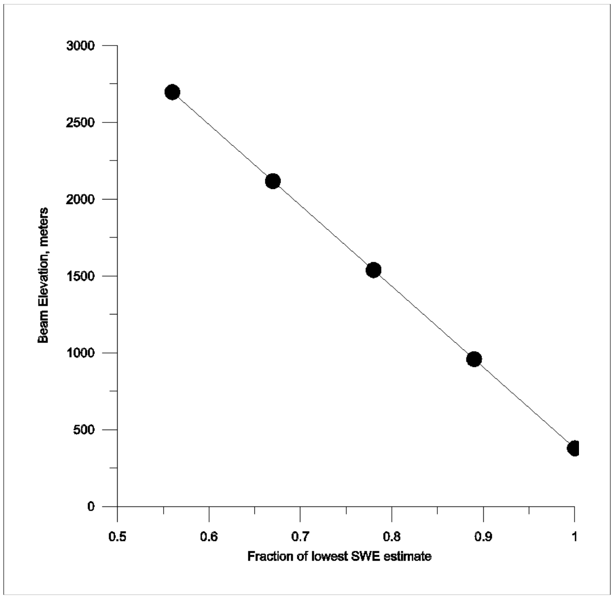

Figure 4.—A linear relation is assumed for the vertical gradient of S for the first five tilts at the 35 km range.

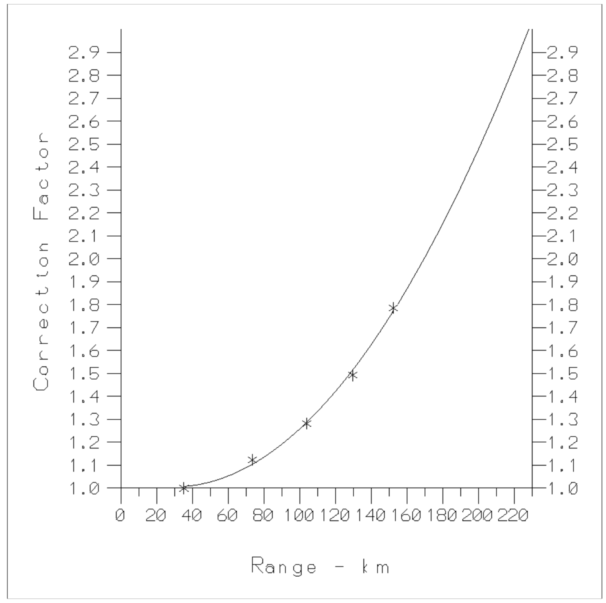

Figure 5.—A plot of the correction factor with range, based on the vertical gradient of S.

Table 2 presents data used in a range correction derivation based on a vertical gradient of apparent S. Listed in the first two columns are the angles for the first five tilts of the radar antenna and the altitudes above the radar of the beam centers at a range of 35 km. The 0.5 degree beam intersects those same altitudes at the ranges indicated in the third column. A linear vertical gradient in S was defined, based on nine Minnesota storms. The ratio of the S aloft to that in the 0.5 degree beam at 35 km is listed in the fourth column, based on a median value of 0.56 at the 4.3 degree tilt. Between the two end points, the relation is assumed to be linear and is plotted in figure 4. The inverse of that ratio, in the fifth column, is the correction factor needed to convert S aloft to S near the surface (approximate elevation of the radar), based on the vertical gradient. Figure 5 shows a plot of that correction factor against the ranges of column 3. The parabolic fit to the five points gives the relation,

$$F = 1.04607 - 0.0029590*R + 0.0000506*R^2$$

for correction factor F and range R (km). That relation is being used for all radars of the northern plains in our real-time calculations of S from NIDS data. It produces a correction factor of 3.0 at 230 km range. However, by that extreme range, the lowest radar beam is usually overshooting the clouds and no correction is possible.

The range correction parameters were determined from quality precipitation and snow depth data from sheltered instruments near the KMPX radar. For the 1998-1999 season, we had to rely on cooperative observers and other volunteers to report their snow observations. None of the sites were inspected for quality, including determining if the sites were sheltered from winds. Therefore, the snow depths from these surface sites may be greatly distorted by drifting and scouring. The timings of the observations were generally irregular, not at some standard number like 12:00 UTC. These must suffice because there are no other data.

A program was written to extract S accumulations from 24-hour files generated by the SAA for pixels directly over reported surface measurements of snow and/or snow depth. For simplicity, S was converted to an SAA-derived SD using a snow density of 0.10. All data from 8 November 1998 through 27 February 1999 were examined. Table 3 indicates the number of observations.

Table 3.—Left: The numbers of simultaneous daily radar and surface measurements of SD for the various radars from November 1998 through February 1999 for three intensity thresholds. Right: The SAA/SD ratios and square of the correlation coefficient (R^2) for ratios vs range for SD≥1.0 inch

Data pairs						Average SAA/SD ratios, ρ =snow density						
KBIS	KABR	KMVX	KMPX	KDLH	Thresholds	KBIS	KABR	KMVX	KMPX	KDLH	All	
288	528	235	892	621	all S, SD	1.33	1.04	1.48	1.25	1.60	1.24	ratio ρ=1/10
8	42	17	55	11	SD≥1.0"	0.95	0.74	1.06	0.90	1.14	0.88	ratio ρ=1/14
2	19	5	22	3	SD≥3.0"	.110	0.41	0.45	0.12	0.62	0.14	R^2

Ratios of surface measurements to 24-hour SAA accumulations for S and SD were made and plotted against range from the radar. The S graphs for the individual radars had too few data points to be meaningful. Plotting together all points for all radars resulted in graphs too noisy for interpretation. Figures 6 a-e show the SAA/SD (derived/observed) ratios for the five radars along with a reference line for perfect agreement and no range distortion. The points are classified according to accumulation thresholds. The x points are for S of at least 0.10 inch or SD of at least 1.0 inch. The boxes are for SD of at least 3.0 inches. There is much scatter in the five graphs, as expected for presumably unsheltered locations and various timing offsets. Isolating the heaviest storms did not decrease the scatter.

Least squares fits (not shown) of range to the logarithm of the SAA/SD ratio confirmed nearly pure scatter and only a slight trend for a decreasing SAA/SD ratio with range. The square of the correlation coefficient (R^2) is given as the bottom line at the right of table 3, with only 1.4 percent of the scatter explained by range when all data are combined. The average of the logarithm of the ratio is converted back to the ratio at the right side of table 3 for two assumed snow densities, 1/10 (as plotted in figures 6a-e) and 1/14 (closer to actual). For the lesser density, the average ratios are close to unity, indicating an alpha that is nearly correct.

If the range correction was in significant error, then the data points should noticeably diverge from the horizontal reference line near 230 km. There seems to be no systematic bias with range for these data sets. The data noise is much greater than any range effect. Therefore, there is no justification at present to change the range correction that was derived from vertical gradient data.

6. BRIGHT-BAND WARNING

The vertical profile of Z_e can reveal bright band effects. However, at far range the effects get blended with dry snow and light rain because of the larger vertical extent of the radar beam with range. Virga can sometimes look like a weak bright band effect, producing a maximum in reflectivity near cloud base. Correct identification of bright band effects needs confirmation from an outside data source. Rawinsondes can provide the altitude of the melting level but they are often widely separated in distance from the radars; the NEXRAD network is much denser than the rawinsonde network. Furthermore,

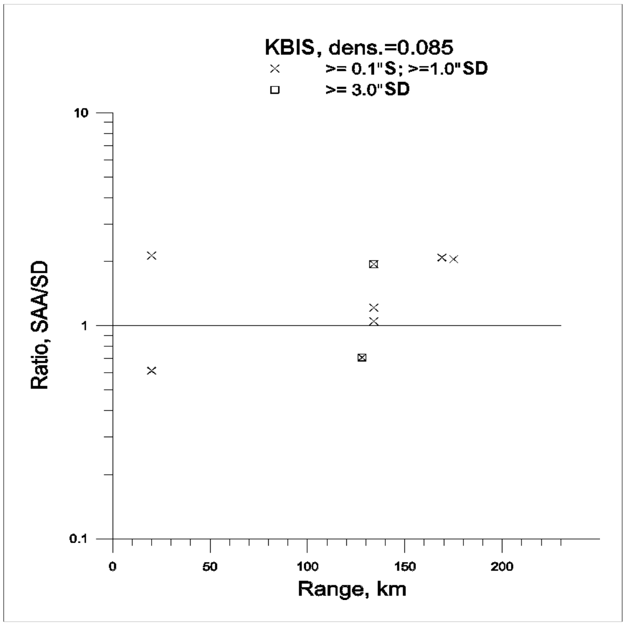

Figure 6a.—The SAA/SD ratio for KBIS is mostly within a factor of 2 of equivalence, with no obvious range bias.

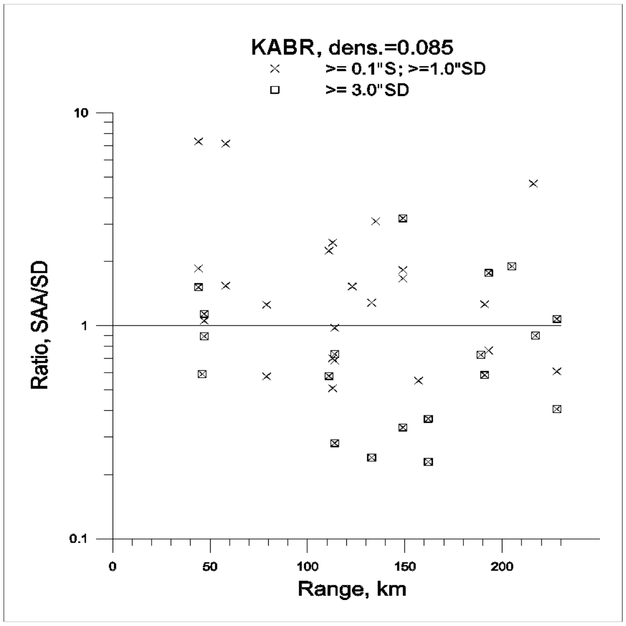

Figure 6b.—The SAA/SD ratio for KABR shows much noise and little if any range bias.

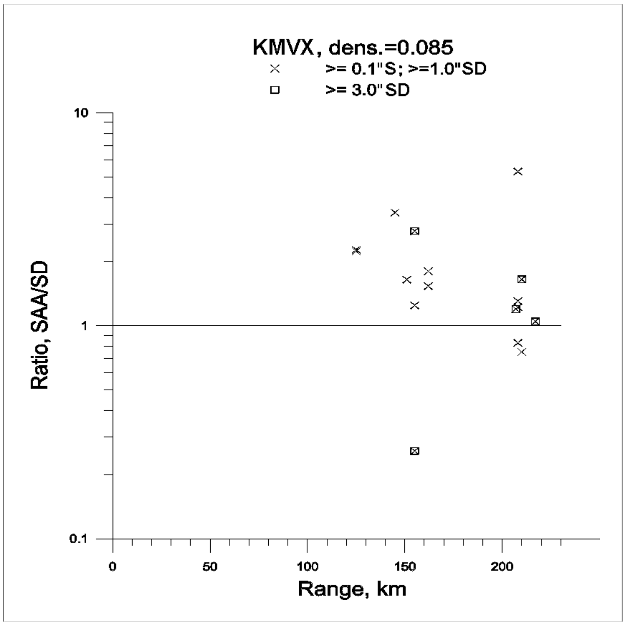

Figure 6c.—Most surface data for KMVX are at remote ranges and show a possible offset of the ratio from unity.

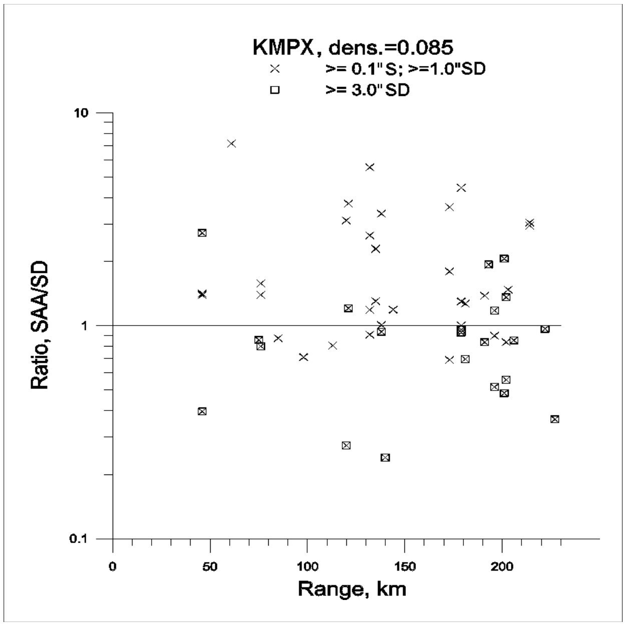

Figure 6d.—Most data for KMPX are within a factor of 3 of unity with no obvious range bias.

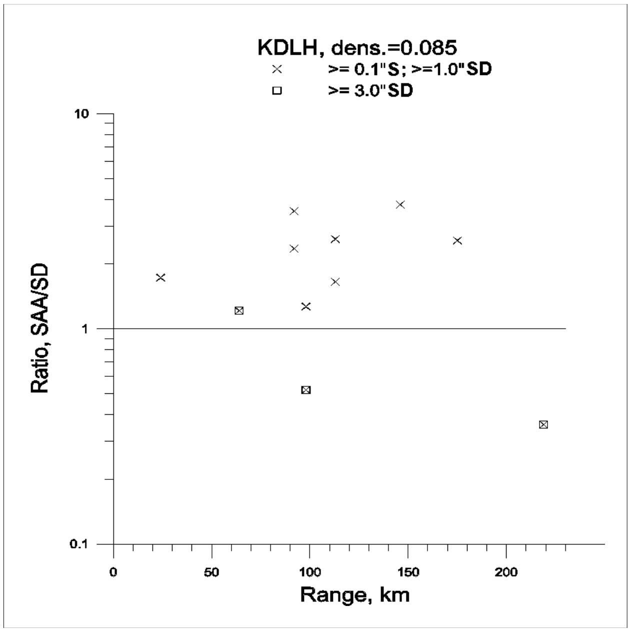

Figure 6e.—The light precipitation data are offset from unity in the opposite direction from the few heavier data for KDLH.

rawinsonde data are available only twice per day. Altitudes of the melting level can vary significantly in 12 hours, especially before and after precipitating weather systems. The numerical model (Eta, Rapid Update Cycle) can indicate the melting level between the rawinsonde observation times and can even identify gradients across the field of view of a radar. However, it is beyond the scope of this effort to modify the SAA code to ingest melting level data. Such is needed to distinguish some bright band effects from other vertical gradient reversals. However, there needs to be caution in the use of melting level data. I have recently observed a case in which there was a layer of air in a precipitating system that was nearly isothermal at a temperature close to 0 °C for a depth of over 1 km. Assuming a bright band of only a few hundreds of meters depth based on derived melting level data would be unreliable in such a situation. Therefore, a bright band warning could not be provided without further study.

7. ADDITIONAL EFFORTS

7.1 SAA Code Adjustments

In early November 1998, a bug was reported in the NOSPIKES subroutine. Reclamation determined that the bug existed in all previous versions of the SAA. The bug was activated when a pixel had a reflectivity exceeding the upper threshold (40 dBZ) and all 8 adjacent pixels had no detectable echo. Such is a very rare occurrence. The coding was changed to prevent an ALOG10 of numbers less than or equal to zero.

Coding was further changed to avoid Y2K problems.

Additional coding modifications, shown in the appendices, were created for experimental investigations. Appendix A presents coding modifications to the SAA to make the vertical profile graphs as shown in figures 1 and 7. Appendix B presents a stand-alone program to add many days of SAA output (*.STP files) to show blemishes in the hybrid scan and occultation files. Appendix C presents coding modifications to the SAA to attempt virga removal from the SAA products. The coding of appendices A and C has not been incorporated into the operational versions of the SAA.

7.2 Support Code Development

A separate program (RESIDUAL.FOR, presented in appendix B) was written to ingest many days of daily total (*.STP) files of S accumulations in order to identify residual ground clutter returns or bins overcorrected for clutter. The daily files were partitioned, by the number of radar bins with non-zero accumulations, into three categories of snow fall that might be termed trace-light, moderate, and wide

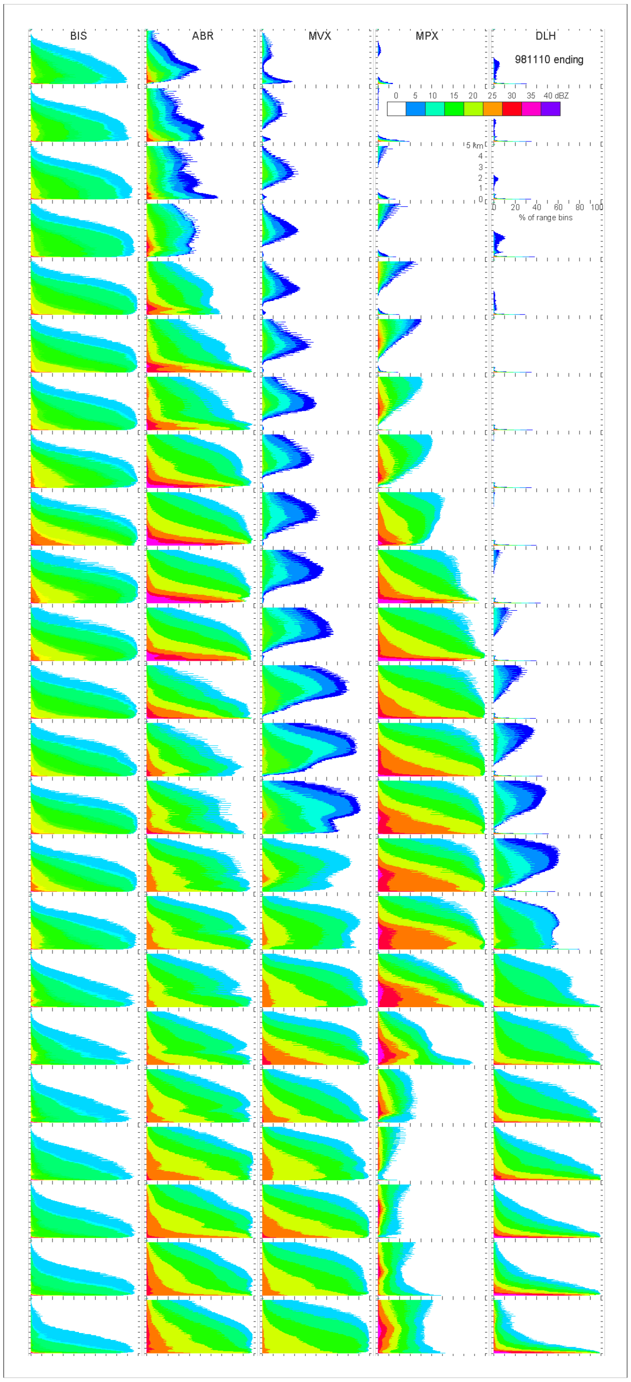

Figure 7a.—Vertical profiles for 10 November 1998.

spread. The trace-light results were good for identifying unsuppressed ground clutter. The wide spread results identified pixels of decreased accumulations having excessive suppression ("holes" in pattern) and occultation problems (radial bands, seen at the top of figure 8). The ASCII formatted hybrid scan file could then be edited by hand to correct the problems. Procedures for hand editing of the occultation file have not been developed.

It was also noticed that "accumulations" sometimes had anomalous propagation (AP) during clear weather. Protection against AP, present in the PPS (Precipitation Preprocessing Subsystem), is not used in the SAA because AP is rarely a problem during snow events.

7.3 Vertical Profile of Reflectivity

Arlin Super, the former manager of the project, and I have repeatedly expressed our opinion that a major contribution to the SAA would be to take into account the vertical profile of reflectivity or of precipitation. However, it was never in Reclamation's scope of work to do so, even though many of our studies documented the need. To study the virga contamination problem, an experimental SAA supplement was developed to visualize the VPR. The coding changes are presented in appendix A. For each hour, the algorithm accumulates (at 0.1 km vertical resolution, 0 to 5 km in altitude above the radar) a cumulative percent of observed reflectivities at 5 dBZ resolution. The output is a simple 8-bit array which must be imported into separate image processing software and annotated there.

Figures 7 a-e give vertical profile examples, in the same style as figure 1, for 10, 11, 16, 18, and 19, November 1998, for five radars in the Dakotas and Minnesota. From left to right, they are KBIS, KABR, KMVX, KMPX, KDLH. On 10-11 November, a large snow storm affected the region, moving in from the southwest. Figure 7a shows profiles with strong vertical gradients, with strongest reflectivities near the ground, for KBIS and KABR on 10 November 1998. The other three radars show virga as the storm nears, later transforming to the precipitation gradient. KMPX and KDLH show some bright band effects at the top of figure 7b. The end of the storm on the 11th shows a transition to shallow echoes.

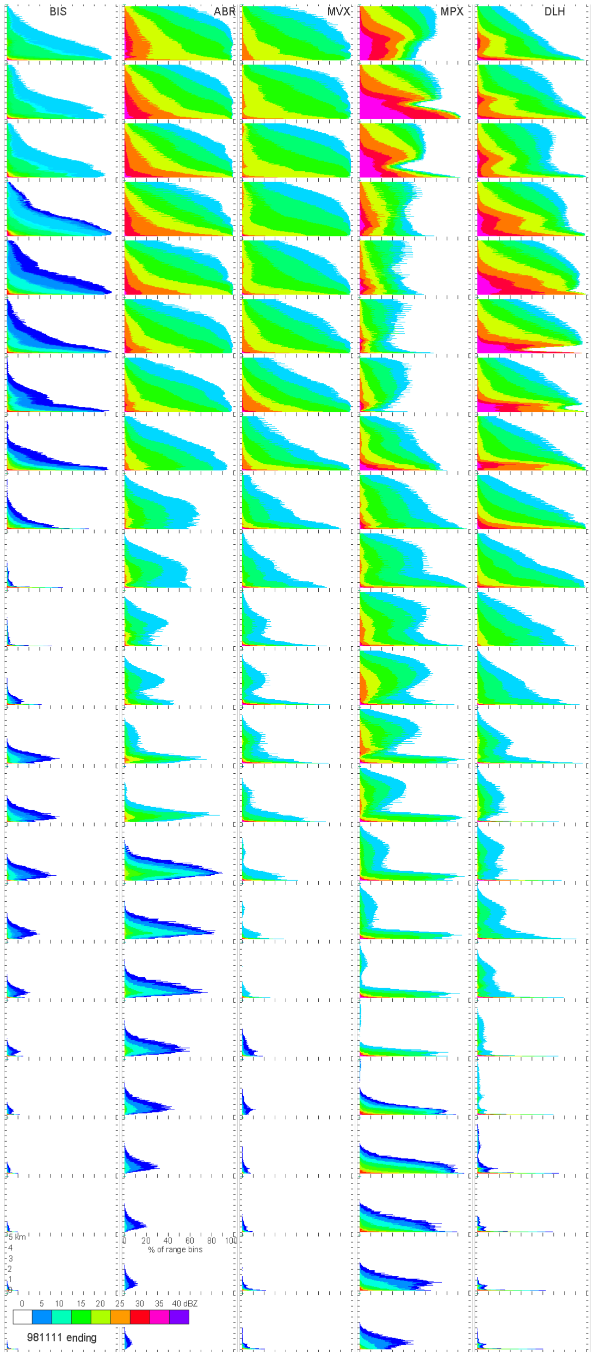

Figure 7b.—Vertical profiles for 11 November 1998.

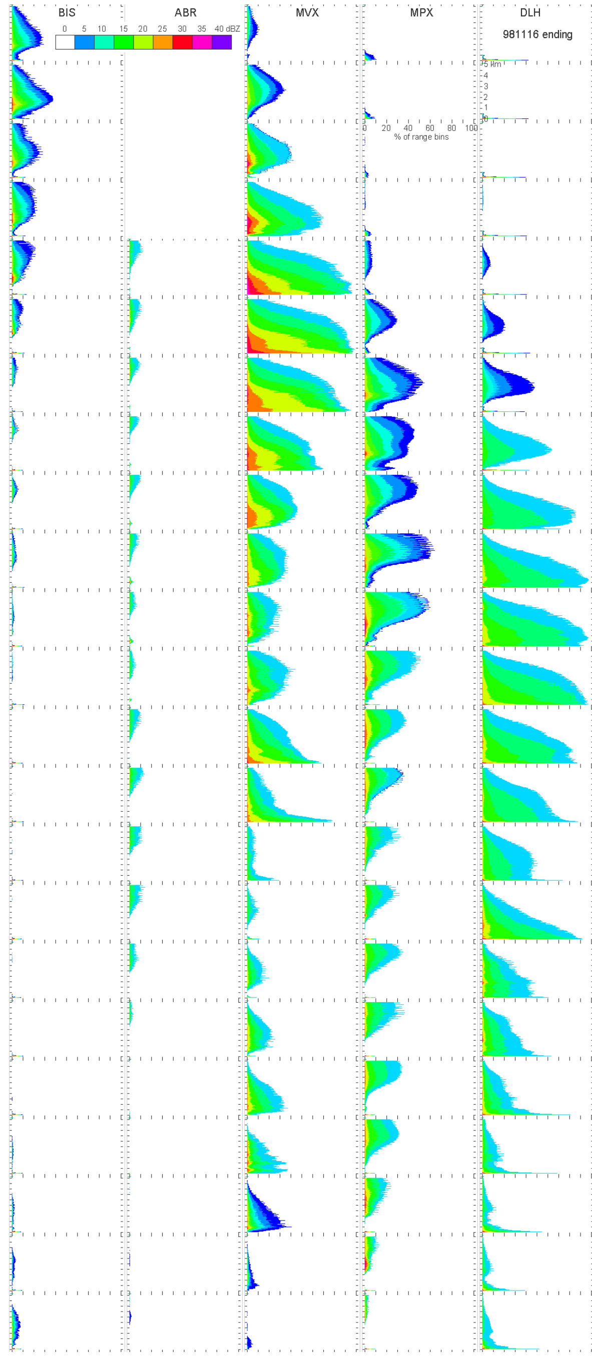

Figure 7c.—Vertical profiles for 16 November 1998.

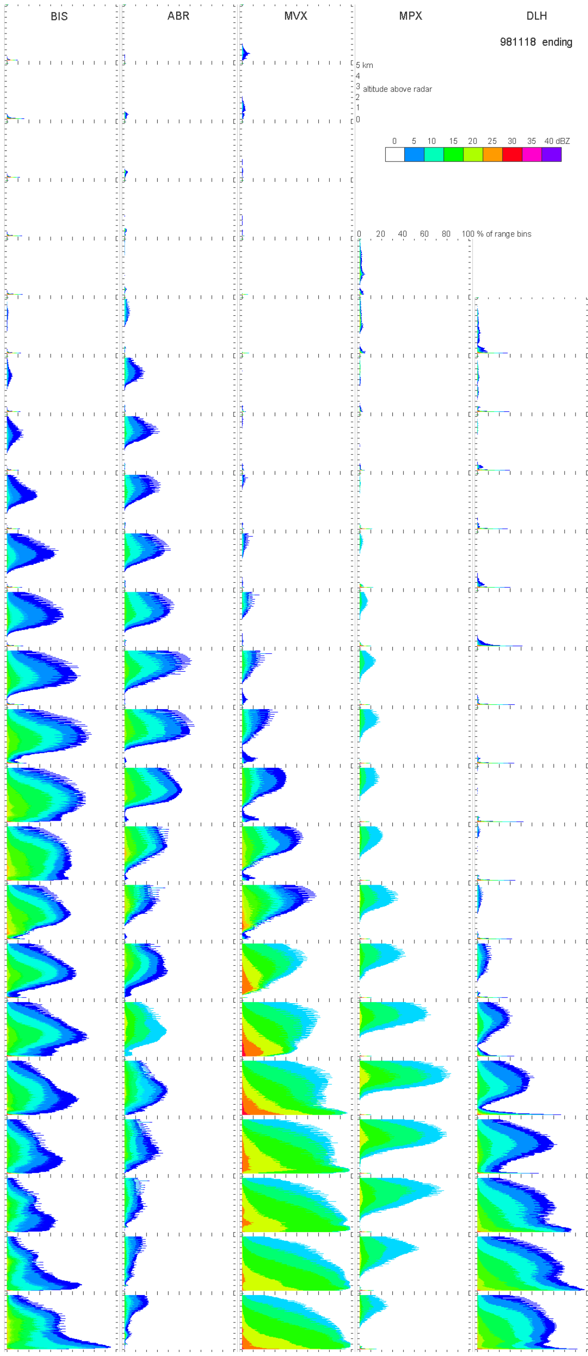

Figure 7d.—Vertical profiles for 18 November 1998.

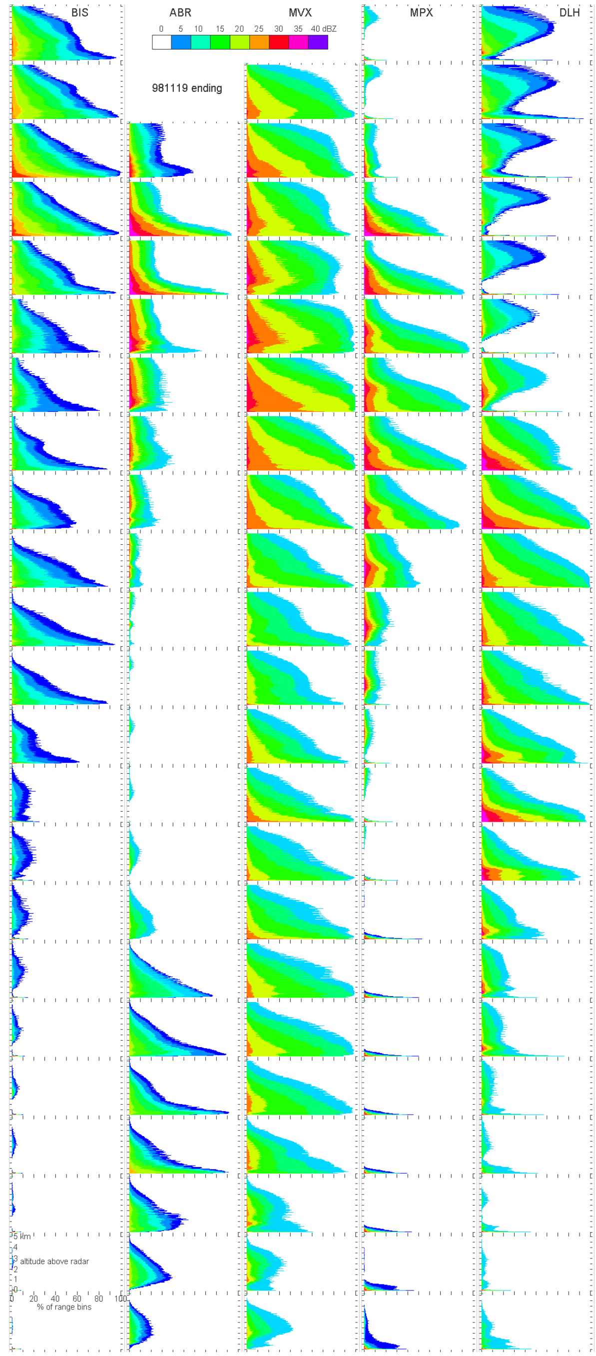

Figure 7e.—Vertical profiles for 19 November 1998.

The profiles for 16 November 1998, in figure 7c, show a period of virga at KBIS and KABR that covers only a minor portion of the radar view. The KMPX pattern indicates almost total virga; only trace amounts reach the surface. KMVX and KDLH start as virga and change to a precipitation gradient (increasing downward) before becoming weak echoes covering only minor portions of the radar view.

Figures 7d-e show that the storm of 18-19 November 1998, starts as virga at all five radars. Towards the end of the 18th, there is precipitation to the ground at the three more northern radars, KBIS, KMVX, and KDLH. On the 19th precipitation reaches the ground at all radars. KBIS changes to virga, as does KABR at the very end. At KDLH and KMPX the precipitation weakens to very light and scattered accumulations.

Our opinions about VPR were verified at the 11 June 1999 QPE workshop in Reno, Nevada. A presentation was made, based on a paper proposed by Dong-Jun Seo, J. Breidenbach, R. Fulton, D. Miller, and T. O'Bannon, that showed the utility of a VPR correction. The cases presented showed strong bright band effects, which were removed by the algorithm. Their algorithm appeared to be superior to what we had been considering for testing. Their algorithm would not only correct for bright band (warnings and corrections) but also correct for virga and underestimation with range. It appears that work should continue on efforts to incorporate the use of the VPR into the SAA.

The vertical profile graphs presented here (figures 1 and 7 a-e) could be the basis for a simpler VPR analysis, and therefore, the coding for generating them is presented in appendix A. It may be possible to analyze these hourly graphs within the SAA and generate decisions about virga presence, bright band presence, and the vertical profile of reflectivity. The latter might feed into a range correction scheme. These goals are beyond the scope of this project but could be investigated in the future.

7.4 Virga Removal

In addition to the vertical profile graphs, virga can be seen as echoes at far range, typically in a partial to full ring around the radar, with nothing at close range. Figure 8 gives an example of virga contamination on a 24-hr SAA product for 18 November, 1998, for KMPX. Virga produced rings of accumulation around the edges of the view while there was nothing accumulated at close ranges. The range correction (a factor of 3 increase at 230 km) accentuated the edge values. For major storms, the range correction appeared to be correct (see discussion for figures 6 a-e) out to far ranges, beyond ranges for which it was calibrated. Eliminating range correction was unacceptable for major storms. Without range correction, accumulations decreased markedly with range, producing a bull's eye pattern around the radar.

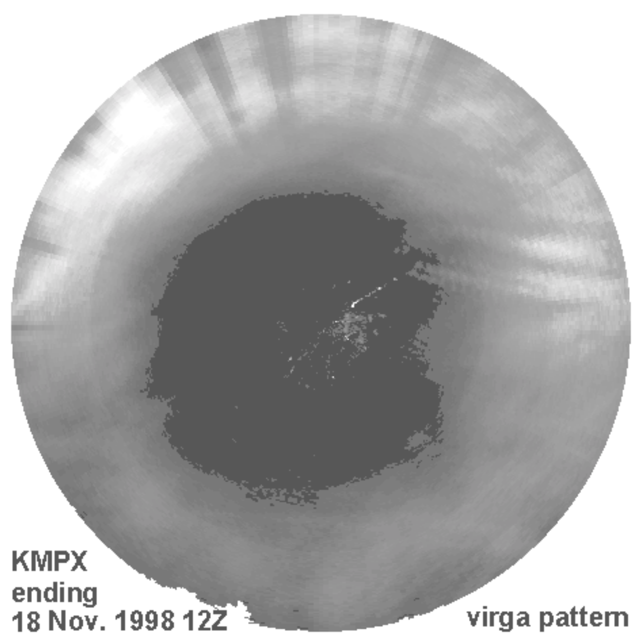

Figure 8.—Virga creates a donut pattern around the radar in the SAA products.

Increasing the minimum reflectivity threshold (DBZMIN) from 4 to 15 or 20 dBZ reduced much of the real precipitation yet did not fully solve the virga problem in the test cases, such as 18 November 1998 at KMPX. For several weeks, Reclamation used 10 dBZ, but that was too large for the arctic storm of 2-3 January 1999 (see section 3.2). In mid-January, DBZMIN was reset to 4 dBZ, the minimum threshold available in the NIDS data in clear air mode.

The profile diagrams provided an insight to the solution of the virga problem. A virga sensing cylindrical volume was defined in a new set of adaptable parameters: TOPIN, the top height - default 1.5 km above the radar; BOTIN, the bottom height - default 0.2 km above the radar; INSIDE, range - default 100 km; and FRACTION - default 0.05. The SAA operates normally throughout ranges out to the INSIDE range. When the fraction of radar bins within the cylinder, having a reflectivity of at least DBZMIN, is at least FRACTION, the SAA also accumulates S beyond the INSIDE range and applies the range correction there. Otherwise, beyond INSIDE, the SAA ignores all reflectivities. If the echoes cannot get down below the TOPIN altitude, it is likely that measurable snow is not be reaching the ground. This procedure may result in a sharp discontinuity in the S and SD products at the INSIDE range. Such a discontinuity should alert an analyst that virga was involved and that the results at farther range may be unreliable.

After the precipitation coverage within the cylinder has decreased to less than FRACTION, accumulations (with range correction) are allowed at ranges greater than INSIDE for a time, DURATION. Storms moving away from the radar can thereby continue to contribute to accumulations at ranges beyond INSIDE. No value is suggested for DURATION, although a value of 1 to 3 hours is reasonable. It is not possible to use the HINDSITE file to recover past potential accumulations for a similar time before the first qualification because that file contains only accumulations, not reflectivities.

The virga sensing cylinder was used on both intense storms and obvious virga for some November storms at KABR, KMVX, and KMPX. The suggested values (with DURATION = 0.0) produced no obvious change to major accumulations of snow over 24-hour periods. Virga was essentially eliminated in the other cases. There may be cases in which some far-range virga may be integrated because there are some real precipitating echoes within the qualifying cylinder. Such will often be detectable by a discontinuity in the accumulations at the range INSIDE. Therefore the algorithm change is not perfect. The coding has not been added to either version (Level II or Level III - NIDS) of the operational SAA because further testing (of this virga sensing cylinder and perhaps alternate schemes) should be pursued. The coding changes are given in Appendix C.

7.5 Reports and Publications

Arlin Super and I wrote a paper about the SAA, but it was not accepted for publication. It was patterned after the PPS Algorithm paper published by Fulton et al. (1998), and it was submitted to the same journal for publication. However, all three of the journal's reviewers wanted a different style, not a companion paper. Furthermore, they wanted a major evaluation program to justify the accuracy of the SAA, not recognizing that we were indeed presenting such calibrations from field studies at Denver, Albany, Cleveland, and Minneapolis. We expressed our regrets and did not revise our work.

Our SAA work was reported at a GCIP meeting at the University of Maryland (17-18 May 1999) and at QPE Workshops in Boulder, Colorado (14 April 1999), and Reno, Nevada (11 June 1999).

8. SUMMARY AND DISCUSSION

This extension of the previous work for the OSF produced a different style of field testing of the SAA under the GCIP program. The algorithm was modified to accept Level III data from NIDS providers in near real time for a series of five radars across the Dakotas and Minnesota. Products were provided via the Internet in the 4-km HRAP grid so as to be useful for forecast groups. Accumulations of S and SD were produced for a variety of time intervals up to 24-hours, ending at 12 UTC each day. The products of the five radars were combined in a mosaic to show regional accumulations.

Working with the NIDS data was generally successful. The mosaic process indicated that one or two radars appeared to be calibrated differently from the others, as shown by S and SD discontinuities across lines equidistant between the radars.

Virga was a persistent problem. An experimental procedure eliminated most virga without sacrificing the reliability of the algorithm in widespread, intense storms. That algorithm still needs further testing and adjustment before becoming part of the operational version of the SAA.

The SAA failed to match surface observations during a snowstorm in arctic air. An analysis indicated that the storm was shallow and had temperatures in the dendritic growth band for snow crystals. The radar beam generally was above the clouds, missing the rapid crystal growth close to the ground. Furthermore, dendritic crystals have the least density as snow on the ground. A change in a few adaptable parameters could have remedied the problem, but such was not possible in the routine production of products from the NIDS data stream.

Though desired in the specifications for tasks, it was not possible to derive local parameters of alpha and beta for radars in Alaska, Washington, and Illinois. There was insufficient quality data for those sites. Analyses of the California (Sierra Nevada) data indicated that the radar beam was far above the snow growth zones, which resulted in small alpha values.

A separate program was written to combine many days of SAA files to produce composite accumulations for three partitions of area coverage: scattered, moderate, and widespread. The output gave guidance for adjusting the hybrid scan file for inadequate or excessive suppression of clutter. The same products using widespread storm data could be useful in determining adjustments in the occultation correction file.

As part of the virga investigations, experimental coding was produced to generate images of the vertical profile of reflectivities. The images gave insights into the changing vertical structure of the storms. Parts of the code could be used for producing a better algorithm that is sensitive to vertical gradients. There is potential for better performance with virga and bright band events and for a better range correction scheme.

In general, this extension of effort has shown that the original SAA tends to be robust in an operational mode. Therefore, no major modifications to the operational versions of the SAA were made. There are lingering blemishes to work on, such as virga and bright band effects, but for now, forecasters can be alerted to their effects by the natures of the patterns (rings and intense gradients) in the SAA output.

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APPENDIX A. TEMPORARY CODING TO CREATE VERTICAL PROFILE GRAPHS

In an effort to understand the variations in the vertical profile of reflectivity as a storm passes through an area, changing from virga to precipitation to virga, RADAR11.FOR was modified with additional coding, presented below. (The line numbers are from the experimental version of the program, but enough neighboring statements are included for location. All extra lines are commented out and many are identified with a $$$ identifier.)

```
(the following lines through 658 are from the main PROGRAM RADAR11)

(lines 50-52)

C   98/12 Ed: Temporary vertical profile of reflectivity for virga study.
C All commented out.  Can find it by looking for $$$ on single lines and
C within the PROFILE subroutine.

(lines 137-139)

C      COMMON/PROF/NSUM(101,41),NTOT(101),LINE(208),IMAG(108,208) ! $$$
C        BYTE LINE,IMAG ! $$$
       COMMON/RADIAL/ VAL(6), NUM(20), DBZ(0:459), IFLAG

(lines 210-212)

C      OPEN(1,FILE='PROFILE.BYT',STATUS='UNKNOWN',FORM='UNFORMATTED') ! $$$
C      CALL PROFINIT ! to initialize profile sums and image $$$
       CALL STARTUP

(lines 336-339)

*        22 Vol-scan starts were accepted.
C        CALL PROFDUMP ! $$$ and PROFINIT as well to output, initialize image
         STOP '(passing wanted end file)'
       ENDIF

(lines 656-658)

       CALL OCCULT            !! apply occult corrections
       CALL NOSPIKES          !! try removing lingering clutter & blemishes
C      CALL PROFILE           ! $$$ to make vertical profile image; temporary

(lines 1767-1864)

c      SUBROUTINE PROFILE  ! $$$ and following to END statement
C    makes an image of the vertical profile of reflectivity, contoured by
C    frequency of dBZ values at each height to 5.0 km
c      COMMON/ANGLES/ AZT(4,370), ELT(4), SECELT(4), JAT(4), TILTLAST
c      COMMON/CLOCK/ IDATE, ITIME, KDATE, KTIME, MDATE, MTIME,
c     ,  IDAT1, ITIM1, ITIM9, ITIMSC
c      COMMON/PROF/NSUM(101,41),NTOT(101),LINE(208),IMAG(108,208) ! $$$
c        BYTE LINE,IMAG ! $$$
c      COMMON/STORE/ ND05(370,230), ND15(370,230), ND25(370,230),
c     ,  ND35(370,230), NDN(5)
c        INTEGER*2 ND05, ND15, ND25, ND35, NDN5(370,920)
c        EQUIVALENCE (ND05,NDN5)
C    calculates altitude, km msl, of radar beam from range, R, elevation, E
c      BEAMHT(R,E)=R*SIND(E)+5.8869E-5*R*R*COSD(E)*COSD(E)
c      SIND(A)=SIN(A*.017453293)
c      COSD(A)=COS(A*.017453293)
C    Sum the reflectivity occurances
c      DO 40 N=1,4  !! tilt loop
c      DO 35 L=3,230  !! range loop
c      Z=BEAMHT(FLOAT(L),ELT(N))
c      IZ=1+NINT(20.*Z)
c      IF(IZ.LE.101)THEN ! 5.0 km limit for elevation consideration
c        DO 30 M=1,JAT(N) !! azimuth loop
C    Convert biased reflectivity to dBZ
C         DBZ = (NDBZ          -2)/2-32 was expectation, but Ra changed it:
C          ID=1+(NDN5(M,L+NDN(N))-2)/2-32
C    then dBz = (LV2128-8448)/256 elsewhere
c          ID=1+(NDN5(M,L+NDN(N))-8448)/256
c          IF(ID.LT.1)ID=1
c          IF(ID.GT.41)ID=41
c          NSUM(IZ,ID)=NSUM(IZ,ID)+1
```

```
c          NTOT(IZ)=NTOT(IZ)+1
c  30   CONTINUE     !! azimuth loop, M
c      ENDIF ! elevation limit test
c  35 CONTINUE     !! range loop, L
c  40 CONTINUE     !! tilt loop, N
c      RETURN
C
C   Output image
c      ENTRY PROFDUMP
C   Label the graph
c      IYR=IDATE/10000
c      IMAG(1,1)=IYR/100
c      IMAG(1,2)=MOD(IYR,100)
c      IMAG(1,3)=MOD(IDATE/100,100)
c      IMAG(1,4)=MOD(IDATE,100)
c      IMAG(1,6)=ITIME/10000
c      IMAG(1,7)=MOD(ITIME/100,100)
C   Fill the graph
c      DO 60 J=1,108 ! lines and heights
c      IF(J.GE.5.AND.J.LE.105)THEN ! in graph interior
c        IZ=106-J ! reverse order, prints from top to bottom in altitude
c        KSUM=0
c        LASTK=4
c        DO 45 ID=41,1,-1
c        KSUM=KSUM+NSUM(IZ,ID) ! cumulative sum
c        NK=4
c        IF(NTOT(IZ).GT.0)
c     +    NK=4+NINT(200.*(FLOAT(KSUM)/FLOAT(NTOT(IZ)))) ! cumulative percent *2
c        IF(NK.GT.204)NK=204 ! protection against array overflow
c        IF(LASTK.LT.NK)THEN
c          DO 42 I=LASTK+1,NK
c  42      IMAG(J,I)=ID-1 ! write dBZ values into image
c          LASTK=NK
c        ENDIF
c  45   CONTINUE ! dBZ loop, ID
c      ENDIF ! graph interior test
C   Output the graph
c      DO 55 I=1,208 ! columns
c  55 LINE(I)=IMAG(J,I)
c  60 WRITE(1)LINE
c
C   Initialize sums
c      ENTRY PROFINIT
c      DO 62 IZ=1,101
c      DO 61 ID=1,41
c  61 NSUM(IZ,ID)=0
c  62 NTOT(IZ)=0
C   Initialize upper and lower image edges
c      DO 65 J=1,4 ! lines
c      DO 63 I=1,208 ! columns
c      IMAG(104+J,I)=-1
c  63 IMAG(    J,I)=-1 ! or 255 white
c      DO 64 I=5,205,20
c      IMAG(104+J,I)=50 ! will color black
c  64 IMAG(    J,I)=50 ! cumulative percent tics at 10% intervals
c  65 CONTINUE ! then upper and lower edges finished
C   Initialize side image edges
c      DO 68 I=1,4 ! columns
c      DO 66 J=5,104 ! lines
c      IMAG(J,I+204)=-1
c  66 IMAG(J,I    )=-1 ! or 255 white
c      DO 67 J=4,104,10
c      IMAG(J,I+204)=50 ! will color black
c  67 IMAG(J,I    )=50 ! elevation tics at 0.5 km intervals
c  68 CONTINUE ! then right and left edges finished
c      RETURN
c      END      ! $$$ end of temporary addition
```

(lines 2091-2098, in SUBROUTINE HINDSUM)

```
          IF (0.LT.ITOP) CALL TOPHOUR  !! if doing any top-of-hour files
C       CALL PROFDUMP ! $$$ and PROFINIT as well to output, initialize image
        ENDIF
        IYMDHB4 = NDATSTRT*100+NEWHR
        IF (0.LT.IENDSUM) RETURN       !! special HENDSUM call at end
      ENDIF
C update the storm and 3-hr and 1-hr totals
      DO 25 M=1,360          !! azimuth loop
```

APPENDIX B. RESIDUAL GROUND CLUTTER AND OCCULTATION BLEMISHES

The following FORTRAN code provides an aid for hand modification of the hybrid scan and possibly the occultation files. The program reads from a list of *.STP files (daily storm totals) that is created by a sorted directory listing written to a file. It then opens each *.STP file and determines the number of range bins with non-zero values. The operator selects a classification criterion: 1 = 0 to 20,000 bins (scattered precipitation), 2 = 20,000 to 50,000 bins (moderate precipitation) , 3 = 50,000 to 82,800 bins (widespread precipitation), or 4 = any number of bins. If the *.STP file matches the selected criterion, then for each bin the program determines the count of non-zero daily totals, the mean and standard deviation of the totals, and the minimum and maximum values. Those numbers are output to an I*2 array for examination in an image processor.

Examination of the resulting images can reveal bins that are almost always non-zero, even in clear air; bins that are excessively suppressed in widespread precipitation; and radials that have uncorrected occultation. The hybrid scan file can be edited to rise higher above residual ground clutter or sink lower above “holes” in the *.STP output. New SAA products with the corrected hybrid scan file can be run through this program to note any improvements or degradations.

A procedure for adjusting the occultation file, based on radials that are significantly less than their neighbors, was pondered but not created. While the amount of correction needed at far ranges can be calculated, it is difficult to note the range at which the correction should begin.

```
$debug
      PROGRAM RESIDUAL
C   Adds up many days of radar *.STP files for a radar site.  Counts number
C   of non-zero days at each radar bin, average of non-zero precip and
C   standard deviation, minimum and maximum values.  The results should give
C   guidance on reducing residual ground clutter.  There may also be helps
C   for adjusting the occultation file.
C   Writes image array of 1800 lines by 232 I*2 columns.  The final two
C   columns give the partition style, as does a digit in the file name.
C   Updated 23 March 1999 by Ed Holroyd
      INTEGER*1 LN(460)
      INTEGER*2 LINE(230)
    EQUIVALENCE (LN,LINE)
      CHARACTER NSTA*3,LISTFILE*12,INFILE*12,OUTFILE*12,OUTFILE0*12(4)
    +,MY*1
      COMMON/SUMS/SX(360,230),SX2(360,230),NX(360,230),MINX(360,230)
     +,MAXX(360,230)
    INTEGER*2 NX
      DATA LISTFILE/'printer.NNN '/
    DATA OUTFILE0/'summary1.NNN','summary2.NNN','summary3.NNN'
    +,'summary4.NNN'/
C
   10 WRITE(6,*)' Type 3 letter station name'
      READ(5,11)NSTA
   11 FORMAT(A3)
      LISTFILE(9:11)=NSTA
      OPEN(1,FILE=LISTFILE,STATUS='OLD')
C   initialize sums, extremes
      DO 12 L=1,360
      DO 12 KM=1,230
      SX(L,KM)=0.
      SX2(L,KM)=0.
      NX(L,KM)=0.
      MINX(L,KM)=100000
      MAXX(L,KM)=0
   12 CONTINUE
C   select partition style
      WRITE(6,13)
   13 FORMAT(' Which partition style for echo coverage:'/
     +,      ' 1 = 0 to 20,000 bins (scattered)'/
    +,      ' 2 = 20,000 to 50,000 bins (moderate)'/
    +,      ' 3 = 50,000 to 82,800 bins (widespread)'/
     +,      ' 4 = all')
```

```
      READ(5,*)IP
      OUTFILE=OUTFILE0(IP)
        OUTFILE(10:12)=NSTA
        OPEN(3,FILE=OUTFILE,STATUS='UNKNOWN',RECL=464,FORM='UNFORMATTED'
       +,ACCESS='DIRECT')
      REWIND 1
C     date recycle point
   15 READ(1,16,ERR=50)INFILE
   16 FORMAT(39X,A12)
        WRITE(6,*)INFILE,IP
      CLOSE (2)
        OPEN(2,FILE=INFILE,STATUS='OLD',RECL=460,FORM='UNFORMATTED'
      +,IOSTAT=IER,ACCESS='DIRECT')
      IF(IER.NE.0)WRITE(6,*)IER,': can not open ',INFILE
C     initial scan for echo coverage
        JP=4
        IF(IP.LT.4)THEN
        KNT=0
        DO 18 L=1,360
          READ(2,REC=L,ERR=15)LN ! entire radial
        DO 18 KM=1,230
        K=2*KM-1
        L1=LN(K)
        IF(L1.LT.0)L1=L1+256
        L2=LN(K+1)
        IF(L2.LT.0)L2=L2+256
          LIN=L1*256+L2 ! reverse byte order
        IF(LIN.GT.0)KNT=KNT+1
   18     CONTINUE
          IF(KNT.LT.20000)JP=1
        IF(KNT.GE.20000.AND.KNT.LT.50000)JP=2
        IF(KNT.GE.50000)JP=3
        ENDIF ! for coverage partitioning
      IF(JP.NE.IP)GOTO 15 ! for a different date; wrong partition
C     get precip echo characteristics
        DO 30 L=1,360
        READ(2,REC=L,ERR=15)LN ! entire radial
        DO 20 KM=1,230 ! ranges
      K=2*KM-1
      L1=LN(K)
      IF(L1.LT.0)L1=L1+256
      L2=LN(K+1)
      IF(L2.LT.0)L2=L2+256
        LIN=L1*256+L2 ! reverse byte order
      IF(LIN.EQ.0)MINX(L,KM)=0
        IF(LIN.GT.0)THEN
        X=LIN
          SX(L,KM)=SX(L,KM)+X ! sum of non-zero values
          SX2(L,KM)=SX2(L,KM)+X*X ! sum of squares
          NX(L,KM)=NX(L,KM)+1
          MINX(L,KM)=MIN0(MINX(L,KM),LIN)
          MAXX(L,KM)=MAX0(MAXX(L,KM),LIN)
        ENDIF
   20 CONTINUE ! range loop
   30 CONTINUE ! azimuth loop
        GOTO 15  ! for another date
C     summary after last file
   50 DO 59 L=1,360
        DO 58 KM=1,230
   58 LINE(KM)=NX(L,KM) ! counts
   59 WRITE(3,REC=L)LINE,JP
        DO 53 L=1,360
        DO 52 KM=1,230
   52 LINE(KM)=MINX(L,KM) ! minima
   53 WRITE(3,REC=360+L)LINE,JP
        DO 56 L=1,360
        DO 55 KM=1,230
   55 LINE(KM)=MAXX(L,KM) ! maxima
   56 WRITE(3,REC=720+L)LINE,JP
        DO 62 L=1,360
        DO 61 KM=1,230
        AVE=0.
        IF(NX(L,KM).GT.0)AVE=SX(L,KM)/FLOAT(NX(L,KM))
   61 LINE(KM)=AVE ! averages
   62 WRITE(3,REC=1080+L)LINE,JP
        DO 65 L=1,360
        DO 64 KM=1,230
        STD=0.
        IF(NX(L,KM).GT.1)THEN
          S=SX(L,KM)
          S2=SX2(L,KM)
```

```
      T=NX(L,KM)
      STD=SQRT((S2-S*S/T)/(T-1.))
    ENDIF
64 LINE(KM)=STD ! standard deviations
65 WRITE(3,REC=1440+L)LINE,JP
    WRITE(6,*)' Do you want another station or partition?'
    READ(5,71)MY
71 FORMAT(A1)
    IF(MY.EQ.'Y'.OR.MY.EQ.'y')THEN
   CLOSE (3
   GOTO 10 ! for next station
 ENDIF
    WRITE(6,*)' Normal stop'
    STOP
    END
```

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APPENDIX C. TEMPORARY CODING TO REMOVE VIRGA FROM SAA PRODUCTS

In an effort to remove virga from SAA products, RADAR11.FOR was modified with additional coding, presented below. (The line numbers are from the experimental version of the program, but enough neighboring statements are included for location to show the context so that such lines can be inserted in the correct locations. All extra lines are identified with a @@@ identifier. Some lines deal only with a simple range restriction.)

(lines 52-60, main program comments section)

```
C   98/12 Ed: Range limit added, reducing view from 230 to perhaps 200 km.
C Look for @@@.
C   98/12 Ed: Virga restrictions added to /RESTRICT/, also noted with @@@.
C If there is enough precip within the "virga box" (shallow disc close to
C ground and at relatively near range) then range correction is applied
C beyond the box edge.  Otherwise the echoes are not boosted out there and
C their contributions are greatly reduced.  That will let intense echoes
C contribute somewhat to the precip accumulation, but virga contributions
C should be minimized.  A discontinuity may be seen where confidence drops.
```

(SUBROUTINE STARTUP: lines 693-703)

```
C             /RESTRICT/ variables for virga reductions:                 @@@
C LIMITVUE       I*4  Maximum range for precip accumulations             @@@
C INSIDE         I*4  Range within which significant echo must occur     @@@
C TOPIN          R*4  Altitude (km) above radar for top of qualifying box @@@
C BOTIN          R*4  Altitude (km) above radar for bottom of qualif. box @@@
C INSUM          I*4  Range bin count of echoes >=10 dBZ within box      @@@
C INTOT          I*4  Range bin count of all data within qualifying box  @@@
C INFLAG         I*4  0, else 1 if enough bright echoes inside box       @@@
C INQUALIF       I*4  Last qualifying time, hhmmss                       @@@
C DURATION       R*4  Duration, fract. hrs, allowed since last INFLAG=1  @@@
C FRACTION       R*4  Qualifying fraction, INSUM/INTOT, to set INFLAG    @@@
```

(SUBROUTINE STARTUP: lines 710-711)

```
      COMMON/RESTRICT/LIMITVUE,INSIDE,TOPIN,BOTIN,INSUM,INTOT,INFLAG,  ! @@@
     ,  INQUALIF,DURATION,FRACTION                                     ! @@@
```

(SUBROUTINE STARTUP: lines 721-729)

```
      DATA LIMITVUE/200/ ! range, km, for limit of precip accumulation   @@@
      DATA INSIDE  /125/ ! range, km, for edge of virga box              @@@
      DATA TOPIN   /1.5/ ! altitude, km, for top of virga box            @@@
      DATA BOTIN   /0.5/ ! altitude, km, for bottom of virga box         @@@
      DATA DURATION/1.0/ ! elapsed time from last qualifying virga in box@@@
      DATA FRACTION/.05/ ! qualifying fraction of precip bins in box     @@@
      DATA INFLAG  /0/   ! qualifying flag, 0 or 1                       @@@
      DATA INQUALIF/-200000/ ! fictitious clock time                     @@@
      DATA INSUM,INTOT/2*0/  ! initial sums                              @@@
```

(SUBROUTINE STARTUP: lines 805-822, note the new list of parameters)

```
C read in SAA adaptation data (only those used by snow algorithm)
      READ(2,*, IOSTAT=IER) CZM       !! Z-S mult. coef. for snow, 150.
      IF (IER.NE.0) READ(2,*) CZM     !! if was a column heading line
      READ(2,*) CZP         !! Z-S power coef. for snow, 2.0
      READ(2,*) MAXSPEKL    !! dBZ*2 noise tolerance, else 0
      READ(2,*) MAXNOISE    !! percent precip noise tolerance, else 0
      WRITE(6,'(I5,"=MAXSPEKL,",I5,"=MAXNOISE")') MAXSPEKL,MAXNOISE
      READ(2,*) DBZMIN      !! trace snow threshold (dBZ), 10.
      READ(2,*) DBZMAX      !! outlier bin threshold (dBZ), 40.
      READ(2,*) LIMITVUE    !! range beyond which data are not trusted  @@@
      READ(2,*) INSIDE      !! range edge for virga box                 @@@
      READ(2,*) TOPIN       !! altitude, km, of top of virga box        @@@
      READ(2,*) BOTIN       !! altitude, km, of bottom of virga box     @@@
      READ(2,*) DURATION    !! duration, frac.hr., after last qualify   @@@
      READ(2,*) FRACTION    !! fraction of range bins with precip in box@@@
      READ(2,*, IOSTAT=IER) KLEAIR
C 1 (0) if (not) restricting accum. to VCP 11 & 21
      CLOSE(2)
```

(SUBROUTINE HINDZERO: lines 947-948)

```
      COMMON/RESTRICT/LIMITVUE,INSIDE,TOPIN,BOTIN,INSUM,INTOT,INFLAG,  ! @@@
     ,  INQUALIF,DURATION,FRACTION                                     ! @@@
```

(SUBROUTINE HINDZERO: lines 970-973)

```
      DO 10 L=1,230
      PTOT(L) = 0  !! zero the precip total at all ranges
      IF(L.GT.LIMITVUE)PTOT(L)=-1 ! no confidence in results @@@
   10 CONTINUE
```

(SUBROUTINE NOSPIKES: lines 1586-1587)

```
      COMMON/RESTRICT/LIMITVUE,INSIDE,TOPIN,BOTIN,INSUM,INTOT,INFLAG,  ! @@@
     ,  INQUALIF,DURATION,FRACTION                                     ! @@@
```

(SUBROUTINE NOSPIKES: lines 1606-1608, top of executables)

```
C   Set virga detection parameters                                      @@@
      INSUM=0                                                         ! @@@
      INTOT=0                                                         ! @@@
```

(SUBROUTINE NOSPIKES: lines 1616-1629)

```
      DO 80 N=1,4            !! step thru all four tilts (if present)
        IF (JAT(N).EQ.0) GOTO 80       !! skip if no data for tilt N
C   Do a virga check                                                    @@@
        DO 5 IBIN=2,INSIDE   !! for nearly all bins within virga box    @@@
        Z=BEAMHT(FLOAT(IBIN),ELT(N))                                    @@@
        IF(Z.GE.BOTIN.AND.Z.LE.TOPIN)THEN ! inside virga box            @@@
          DO 3 M=1,JAT(N)                ! all azimuths at tilt N       @@@
          INTOT=INTOT+1                  ! sum all bins in box          @@@
          NDBZ = NDN5(M,IBIN+NDN(N))     ! get bin reflectivity         @@@
          IF (ISHFT(NDBZ,-7).GE.NMIN) INSUM=INSUM+1 ! sum precip bins   @@@
    3     CONTINUE ! end of azimuth loop                                @@@
        ENDIF ! altitude limit check                                    @@@
    5   CONTINUE ! end of range loop                                    @@@
C Isolation testing
```

(SUBROUTINE NOSPIKES: lines 1755-1765)

```
   80 CONTINUE     !! tilt loop, N
C   Evaluate virga box contents                                         @@@
      IF(INTOT.GT.0)THEN                                              ! @@@
        F=FLOAT(INSUM)/FLOAT(INTOT) ! fraction of precip echoes in box  @@@
        IF(F.GE.FRACTION)THEN ! found precip within virga box           @@@
          INFLAG=1                                                    ! @@@
          INQUALIF=IENDSCAN ! end time of this volume scan              @@@
        ENDIF ! qualifying test                                         @@@
      ENDIF ! zero-divide protection                                    @@@
      RETURN
      END
```

(SUBROUTINE PRECIP: lines 1874-1886)

```
C             /RESTRICT/ variables for virga reductions:                 @@@
C LIMITVUE       I*4  Maximum range for precip accumulations             @@@
C INSIDE         I*4  Range within which significant echo must occur     @@@
C TOPIN          R*4  Altitude (km) above radar for top of qualifying box @@@
C BOTIN          R*4  Altitude (km) above radar for bottom of qualif. box @@@
C INSUM          I*4  Range bin count of echoes >=10 dBZ within box      @@@
C INTOT          I*4  Range bin count of all data within qualifying box  @@@
C INFLAG         I*4  0, else 1 if enough precip echoes inside box       @@@
C INQUALIF       I*4  Last qualifying time, hhmmss                       @@@
C DURATION       R*4  Duration, fract. hrs, allowed since last INFLAG=1  @@@
C FRACTION       R*4  Qualifying fraction, INSUM/INTOT, to set INFLAG    @@@
      COMMON/RESTRICT/LIMITVUE,INSIDE,TOPIN,BOTIN,INSUM,INTOT,INFLAG,  ! @@@
     ,  INQUALIF,DURATION,FRACTION                                     ! @@@
```

(SUBROUTINE PRECIP: lines 1933-1939)

```
      CALL TIMESPAN(JTIMSTRT,JDATSTRT,JTIMSTOP,JDATSTOP,SPANT) ! time period
C   Test elapsed time for last non-virga in virga box                   @@@
      V0 = IHMS2S(INQUALIF)/3600.      !! last time INFLAG set          @@@
      VT=T2-V0  ! fractional hours                                      @@@
      IF(VT.LT.0)VT=VT+24.                                            ! @@@
      IF(VT.GT.DURATION)INFLAG=0 ! no precip in virga box; stop accum.  @@@
C increment volume scan index: IVS is 0 to 39
```

(SUBROUTINE PRECIP: lines 1968-1987)

```
C calculate precipitation contribution, IP
```

```
C       DO 30 L=4,230      ! radius loop; avoid first 3 (was 2) km from radar
        DO 30 L=4,LIMITVUE ! radius loop; avoid first 3 (was 2) km from radar @@@
          IP = 0   !! 97/9 -Ra: Dr. Super said for nids change from L=3,230
          N = HYBRD(L)
          IF (JAN(N).EQ.-99.) GOTO 29  !! skip vacant azimuths
C next line would be .GT.1 but Ra scaled *128 for fine adjustment
          IF (NDN5(JAN(N),L+NDN(N)).GT.128 .AND. L.LE.NDN(N+1)-NDN(N))
     ,      IP = RATE_TABLE(ISHFT(NDN5(JAN(N),L+NDN(N)),-7))
   29     FP = FLOAT(IP)*SUMT          !! mm * 100
C apply range correction: default RC1=1, RC2=RC3=0 for no range cor.
          IF (FP.GT.0. .AND. RC4.LE.FLOAT(L)) THEN ! cor. for RC4 <= range
            IF(INFLAG.EQ.1.OR.L.LE.INSIDE)THEN ! minimal virga hazard       @@@
              FP=FP*(RC1+RC2*FLOAT(L)+RC3*FLOAT(L*L))
            ELSE                                                          ! @@@
              FP=0. ! zero it beyond virga box edge if little precip inside @@@
            ENDIF                                                         ! @@@
          ENDIF
          PPI2(L) = NINT(FP) !! now save nearest integer result
   30   CONTINUE             !! end of radius loop, range L
```

(SUBROUTINE HINDSUM: lines 2009-2010)

```
      COMMON/RESTRICT/LIMITVUE,INSIDE,TOPIN,BOTIN,INSUM,INTOT,INFLAG,  ! @@@
     ,  INQUALIF,DURATION,FRACTION                                     ! @@@
```

(SUBROUTINE HINDSUM: lines 2097-2119, range restriction)

```
C update the storm and 3-hr and 1-hr totals
      DO 25 M=1,360          !! azimuth loop
C all 230 km, precip in interval, mm*100
        READ(9, REC=NVS+M) PPI2
        READ(10, REC=M) PTEMP          !! read storm total precip
C       DO L=1,230                     !! radius loop, calculate depths
        DO L=1,LIMITVUE                !! radius loop, calculate depths @@@
          PTEMP(L) = PTEMP(L)+PPI2(L)  !! add to storm total precip
          DPI2(L) = NINT(FLOAT(PPI2(L))*FLUFFN/10.)
        ENDDO      !! depth in interval, mm*10
        WRITE(10, REC=M) PTEMP         !! write storm total precip
        IF (SNSTD.NE.' ') THEN         !! if want snow depth files
          READ(11, REC=M) DTEMP        !! storm total depth
C         DO L=1,230                   !! add to storm total depth
          DO L=1,LIMITVUE              !! add to storm total depth @@@
            DTEMP(L) = DTEMP(L)+DPI2(L)
          ENDDO
          WRITE(11, REC=M) DTEMP       !! write storm total depth
        ENDIF
        READ(9, REC=K3P+M) PTEMP       !! read 3-hr precip
        READ(9, REC=K3D+M) DTEMP       !! read 3-hr depth
C       DO 22 L=1,230                  !!
        DO 22 L=1,LIMITVUE             !! @@@
```

(SUBROUTINE HINDSUM: lines 2026-2127, another range limit)

```
C       DO 23 L=1,230                  !!
        DO 23 L=1,LIMITVUE             !! @@@
```

(SUBROUTINE HINDSUM: lines 2222-2223, another range limit)

```
C           DO 30 L=1,230      ! radius loop
            DO 30 L=1,LIMITVUE ! radius loop @@@
```

(SUBROUTINE HINDSUM: lines 2262-2263, another range limit)

```
C             DO 40 L=1,230       !! radius loop
              DO 40 L=1,LIMITVUE  !! radius loop @@@
```

(SUBROUTINE FULLHOUR, lines 2443-2444)

```
      COMMON/RESTRICT/LIMITVUE,INSIDE,TOPIN,BOTIN,INSUM,INTOT,INFLAG,  ! @@@
     ,  INQUALIF,DURATION,FRACTION                                     ! @@@
```

(SUBROUTINE FULLHOUR, lines 2487-2508, two more range restrictions)

```
      IF (1.LT.ITOP) THEN    !! if want 3-hr files
        DO M=1,360 !! all azimuths
          READ(9, REC=K3P+M) PPI2      !! all 230 km
C         DO L=1,230                   !! all ranges
          DO L=1,LIMITVUE              !! all ranges @@@
C extrap. to full 3-hour period, precip
            PPI2(L) = NINT(F*FLOAT(PPI2(L)))
          ENDDO
          WRITE(16, REC=M) PPI2        !! all 230 km
```

```
        ENDDO
        IF (SNSTD.NE.' ') THEN          !! if want snow depth files
          DO M=1,360 ! all azimuths
            READ(9, REC=K3D+M) DPI2     !! all 230 km
C           DO L=1,230                  !! all ranges
            DO L=1,LIMITVUE             !! all ranges @@@
C extrap. to full 3-hour period, depth
              DPI2(L) = NINT(F*FLOAT(DPI2(L)))
            ENDDO
            WRITE(17,REC=M)DPI2         !! all 230 km
          ENDDO
        ENDIF
      ENDIF
```

(SUBROUTINE FULLHOUR, lines 2529-2549, two more range restrictions)

```
      DO M=1,360             !! all azimuths
        READ(9, REC=K1P+M) PPI2         !! all 230 km
C       DO L=1,230                      !! all ranges
        DO L=1,LIMITVUE                 !! all ranges @@@
C extrap. to full 1-hour period, precip
          PPI2(L) = NINT(F*FLOAT(PPI2(L)))
        ENDDO
        WRITE(18,REC=M) PPI2 !! all 230 km
      ENDDO
      IF (SNSTD.EQ.' ') RETURN          !! if no snow depth files wanted
      DO M=1,360             !! all azimuths
        READ(9, REC=K1D+M) DPI2         !! all 230 km
C       DO L=1,230                      !! all ranges
        DO L=1,LIMITVUE                 !! all ranges @@@
C extrap. to full 1-hour period, depth
          DPI2(L) = NINT(F*FLOAT(DPI2(L)))
        ENDDO
        WRITE(19,REC=M) DPI2 !! all 230 km
      ENDDO
      RETURN
      END
```