CHAPTER 3

METEOROLOGICAL AND HYDROMETEOROLOGICAL ALGORITHMS

3.1 Introduction. The WSR-88D provides the operational meteorological community with state of-the-art automation for processing of Doppler weather radar data. The algorithmic processing derives explicit meteorological and hydrometeorological information and guidance from signal-processed data. This chapter provides information on many of these algorithms.

3.2 Hydrometeorological Processing Functions. The purpose of these functions is to collect data necessary for the mode selection function (described in Section 5.4), not precipitation accumulation (described in Section 3.3).

3.2.1 Precipitation Detection. The Precipitation Detection Function (PDF) processes each full volume reflectivity scan in order to perform several basic functions. It detects whether or not precipitation has occurred within a 230 km (124 nm) radius of the radar and assigns a Precipitation Category appropriate to the situation. It maintains a Precipitation Status Message (PSM) that indicates the Dates and Times of last precipitation occurrence and the previous and current Precipitation Categories. When precipitation is first detected, it changes the Weather Mode to 'Convective' which, in turn, will determine which default precipitation Volume Coverage Pattern (VCP), currently VCP 21, will be executed. If Auto PRF Selection is "On," it determines the Pulse Repetition Frequency (PRF) for insertion into the current VCP.

Precipitation is detected by comparing precipitation rates to threshold values contained in a site specific Precipitation Threshold Table (built with the same Z-R relationship as used in the Precipitation Rate algorithm). Each table row contains the precipitation rate threshold (in decibels of reflectivity, dBR, where dBR = 10 log [precipitation rate in mm/hr)]) for a given elevation angle (or range of elevation angles), the nominal clutter area (km^2), the precipitation area threshold (km^2), and the precipitation category. The values in the table are based on empirical studies and are site adaptable. Whenever the area covered by detected precipitation for a given rate at any elevation angle exceeds the combined value of the nominal clutter area and precipitation area thresholds, it is assumed that precipitation exists and the corresponding Precipitation Category is assigned. When substantial precipitation is occurring, Precipitation Category 1 (Significant) is assigned. Significant precipitation includes both high intensity events of small areal extent and widespread, low intensity events. When precipitation amounts and aerial extent are small, Precipitation Category 2 (Light) is assigned. A Precipitation Category remains in effect until a precipitation-free period of one hour occurs. Precipitation Category 1 takes precedence over Precipitation Category 2. When no precipitation is detected, the Precipitation Category is 0 (None).

The Nominal Clutter Area in each row in the table allows the performance of the function to be tuned to the clutter characteristics of individual WSR-88D sites, including the performance of any clutter filtering algorithm(s) applied to the Reflectivity Factor data before this function processes them.

3.2.1.1 Operational Parameters.

- Reflectivity Factor Data - Equivalent Reflectivity factor data (in units of dBZ, ranging from -32.0 to +94.5 in increments of 0.5) input to the PDF in reflectivity sample bins (of resolution 1 km (0.54 nm) x 1^o, ranging from 0 to 230 km (124 nm) in elevations -1^o to +45°).
- a--30 to 500; default, 300: Multiplicative coefficient in Z-R relationship.
- b--1.0 to 2.5; default, 1.4: Power coefficient in the Z-R relationship.
- Nominal Clutter Area--0 to 80,000 km^2 (0 to 23,324 nm^2); default, 80 km^2 (23 nm^2): Area assumed due to clutter with reflectivity factor equivalent to the precipitation rate threshold.
- Precipitation Area Threshold--0 to 80,000 km^2 (0 to 23,324 nm^2); default, 20 km^2 (6 nm^2): Minimum area assumed due to precipitation at the precipitation rate threshold.
- Precipitation Category--0 to 2: Precipitation category 0 = no precipitation; 1 = significant precipitation; 2 = light precipitation.
- Precipitation Rate Threshold--minus 10.0 to 10.0 dBR; default, minus 3.0 dBR: Minimum precipitation rate for tabulation of area (implemented in 0.1 dBR).
- Tilt Domain Minimum Angle--minus 1 to 45°; default, 0°: Elevation angle (implemented in 0.1°).
- Tilt Domain Maximum Angle--minus 1 to 45°; default, 4°: Elevation angle (implemented in 0.1°).
- The PSM maintained and output by this function contains the following elements:
  - Date/Time of last execution of PDF {modified Julian day; secs within day}.
  - Date/Time of last positive detection of precipitation {modified Julian day; secs within day}.
  - Current/Last Precipitation Category {0 – None; 1 – Significant; 2 – Light}.

3.2.1.2 Operational Considerations. If any operational mode fails to meet the requirements of Table 3-1, there can be no assurance that the PDF will detect precipitation; i.e., the WSR-88D may not be able to switch to the appropriate Operational Mode or use the appropriate VCP. (Note that with the implementation of the Enhanced Preprocessing Algorithm (EPRE), the Precipitation Processing Subsystem (PPS) is no longer dependent upon the PDF for determination of the precipitation condition; rather, it makes an internal determination of when to start/stop accumulating rainfall for the various precipitation products.)

Table 3-1
Minimal Scan Mode Requirements Necessary for Detecting Precipitation

Scan Characteristics	Minimal Requirements
Range	230 km (124 nm) or more
Range Resolution	2 km (1.1 nm) or less
Azimuthal Coverage	360°
Azimuthal Resolution	2° or less
Elevation Scans & Repetition	Lowest two elevation angles required at least every 10 minutes. Lowest elevation angles (below 4.0°) required at least every 30 minutes.

3.2.2 Rain Gage Data Acquisition. The Rain Gage Data Acquisition function maintains a "Rain Gage" Database that would support an infrastructure for a large collection of precipitation gage reports, ingested from an external system. However, its functionality has not been implemented operationally, having been effectively replaced by the ingestion of a Bias Table of Gage-Radar data by the Precipitation Adjustment Algorithm (Section 3.3.4). The function serves as a conduit for a category of data known as the PSM.

The Rain Gage database contains three sections: Precipitation Status Information; Rain Gage ID Information; and Rain Gage Reports. Only the Precipitation Status Information section is used. It is populated by the fields of the PSM, which are provided by the PDF (Section 3.2.1) every volume scan. On each instance when the PSM fields are ingested, they are written to the Precipitation Status Information section of the linear buffer containing the Rain Gage database, from which they are read by the EPRE algorithm (Section 3.3.1).

3.2.2.1 Operational Parameters. The PSM consists of several fields, but only the following are used:

- Date/Time of last execution of PDF {modified Julian day; secs within day}.
- Date/Time of last positive detection of precipitation {modified Julian day; secs within day}.
- Current/Last Precipitation Category {0 – None; 1 – Significant; 2 – Light}.

3.2.2.2 Operational Considerations. This function must follow the PDF in the execution sequence, in order for the Precipitation Status Information fields of the database to be updated properly.

3.3 Precipitation Processing Subsystem. The PPS is a set of hydrometeorological algorithms used to compute maps of 1-hour, 3-hour, storm total and user selectable precipitation accumulations. Functionally, this is done in five sequential steps:

Step 1. EPRE
Step 2. Precipitation Rate
Step 3. Precipitation Accumulation

Step 4. Precipitation Adjustment
Step 5. Precipitation Products.

These algorithms were designed to provide accurate, high-resolution precipitation measurements to be used as input to hydrologic river forecast models and for a variety of other applications. The algorithms contain significant quality control procedures designed to minimize ground clutter and anomalous propagation, improve range performance, eliminate outliers, and account for mean-field bias. The PPS is tuned to provide accumulations that are generally unbiased in terms of averages over the area of coverage. Smaller scales of precipitation accumulation are less accurate and single grid accumulations often vary significantly from coincidental rain gage values.

Although the WSR-88D provides high quality reflectivity data, other sources of error in the conversion of reflectivity to precipitation rate make it important to use data in real time from several automated rain gages to adjust the radar-derived precipitation fields to "ground truth." A source of potential error is in rain gage sampling. Non-representative sampling of the precipitation caused by an inadequate number of gages, poor placement of gages, an unfortunate distribution of precipitation patterns, or error in the gage estimates can affect the computation of the bias adjustment. To the extent possible, the Precipitation Adjustment algorithm described in Section 3.3.4 is designed to take these factors into account.

3.3.1 Enhanced Precipitation Preprocessing. The EPRE replaced the legacy Precipitation Preprocessing Algorithm. The advantages of the EPRE algorithm are to allow for precipitation processing with new VCPs and to update some processing logic. This new logic considers terrain blockage and clutter contamination on a point-by-point basis in building the Hybrid Scan. The EPRE algorithm affects how the reflectivity data are processed prior to converting to rainfall rate, such as which elevation is used for a particular range and azimuth. There are several operational impacts that affect product generation as well as the user interface, such as changes to adaptable parameters.

- New VCPs
- PDF and EPRE
- Exclusion Zones
- AP/Clutter Removal
- EPRE Effects on Precipitation Product Appearance

The EPRE algorithm provides the ability to accept new VCPs for precipitation processing. The legacy Precipitation Preprocessing Algorithm was dependent on the lowest four elevation angles of the legacy VCPs, which were the same. New VCPs (121 and 12) were introduced with Build 5. The EPRE algorithm accepts these new VCPs, which have elevation angles that differ from the legacy VCPs.

The EPRE algorithm is the first component of the PPS. The EPRE assembles a two-dimensional (230 km (124 nm) by 360 degrees) HYBRID SCAN (Reflectivity) Array from the volumetric reflectivity base data for use by the PPS and the Radar Coded Message (RCM). In the future, other algorithms may use the HYBRID SCAN (Reflectivity) Array.

The selection of reflectivity data is based on the functional philosophy of the original

Preprocessing Algorithm, i.e., that the volumetric reflectivity data that is most representative of ground precipitation is obtained from the lowest radar beam that is neither blocked nor contaminated by ground clutter. While preserving the philosophy of the Preprocessing Algorithm, the EPRE applies refined logic and new information to generate HYBRID SCAN (Reflectivity) arrays that are more representative of precipitation fields. In addition, the EPRE was designed to work with any WSR-88D VCP.

Specifically, the EPRE uses anomalous propagation (AP)/Clutter likelihood reflectivity (CLR) information from the Radar Echo Classifier (REC) Algorithm to more effectively and precisely remove ground clutter contamination from the HYBRID SCAN (Reflectivity) and uses high precision, high resolution radar beam blockage information from the Blockage Algorithm to smooth beam correction boundaries. See Figures 3-1 and 3-2 for an example of the difference in reflectivities the REC produces in creating a DHR product.

Exclusion Zones may be created to prevent known areas of persistent clutter residue (e.g., wind generator farms, highways) from contaminating the HYBRID SCAN (Reflectivity). These zones are used to remove residual clutter returns when the clutter filters are not able to remove the high power returns.

The EPRE maps input base reflectivity data to the whole degree HYBRID SCAN (Reflectivity) array if the input data meets the following criteria:

- The beam blockage must not exceed the BLOCKAGE THRESHOLD,
- The AP/Clutter likelihood must not exceed the CLUTTER THRESHOLD, and
- The data are not in an activated exclusion zone.

An input BASE REFLECTIVITY DATA bin that passes the above tests is corrected for any partial beam blockage and proportionally mapped to the nearest whole degree HYBRID SCAN (Reflectivity) bins. The proportionality is based on the overlap between the input radial azimuth angle and the whole degree azimuth angle of the HYBRID SCAN (Reflectivity). The overlap is used to weight the contribution of the input reflectivity data (in power) and the weights and weighted power are summed for each whole degree bin.

The average power for a whole degree bin is computed if the total input weighting for that bin exceeds the BIN WEIGHT THRESHOLD. The average reflectivity is computed and inserted into the HYBRID SCAN (Reflectivity) if that bin has not already been filled during a lower elevation tilt. For each HYBRID SCAN bin, the elevation angle of the BASE REFLECTIVITY DATA being used in the HYBRID SCAN (Reflectivity) is stored in the HYBRID SCAN (Elevation Angle) array.

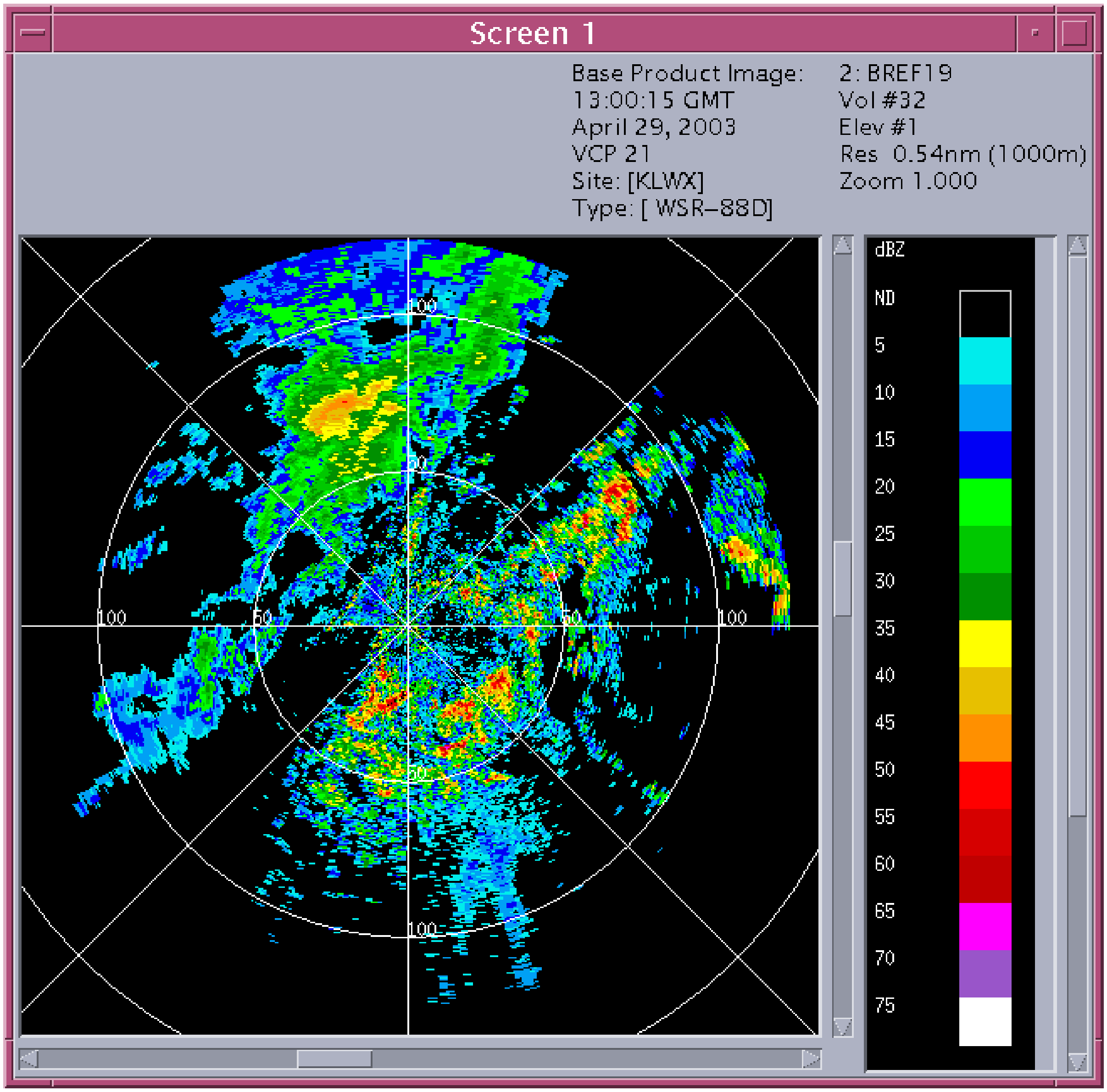

Figure 3-1
Reflectivity Product

This Reflectivity 0.5° elevation product is shown for comparison with the corresponding Digital Hybrid Scan Reflectivity (DHR) product in Figure 3-2 (CODE View graphic display). Note the high reflectivity values to the ENE through E to SW of the radar (Sterling, VA (KLWX).

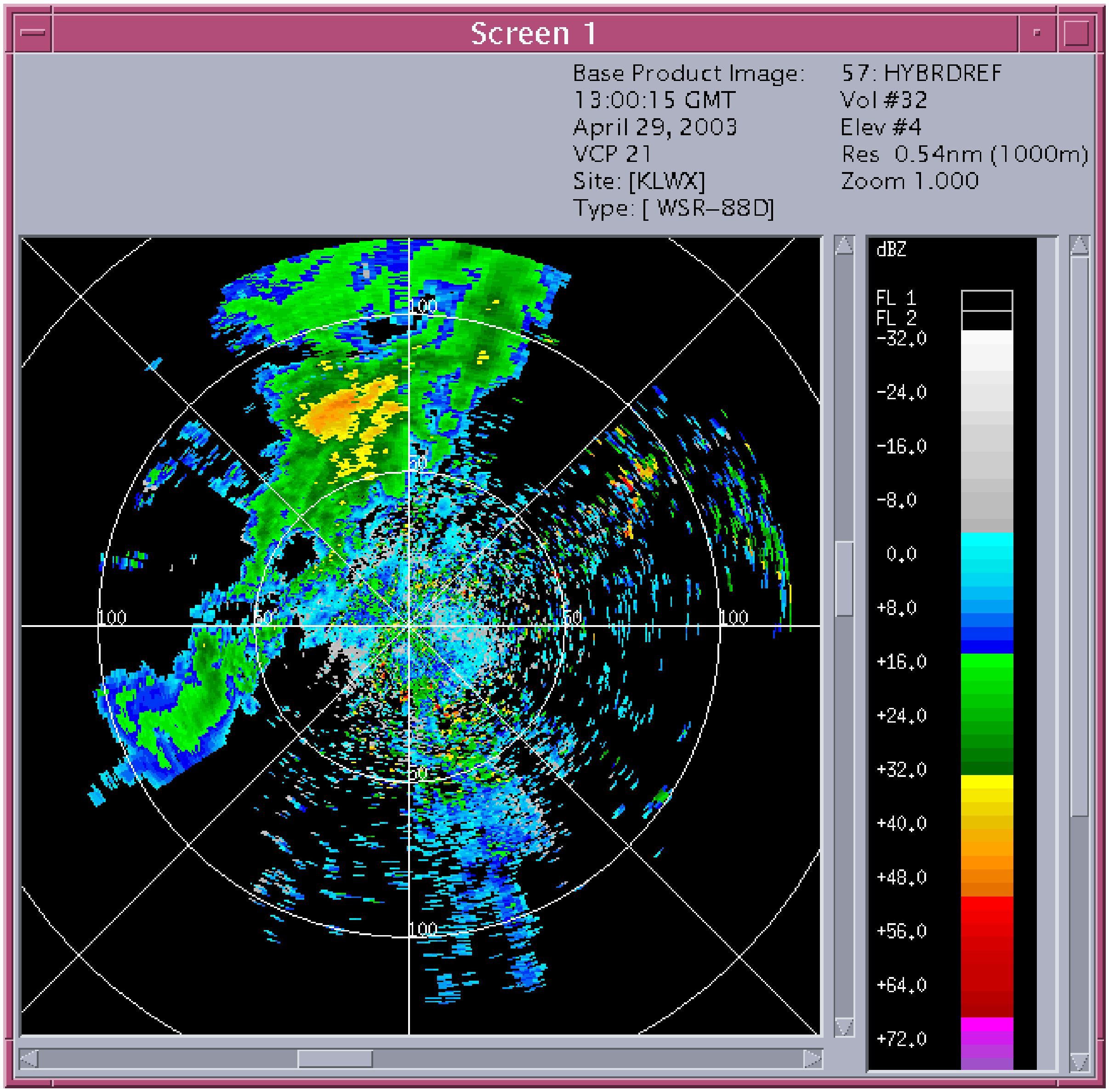

Figure 3-2
Digital Hybrid Scan Reflectivity Product

This DHR product is shown for comparison with the 0.5° Reflectivity product in Figure 3-1 to show how the Radar Echo Classifier removes clutter before processing to produce precipitation products (CODE View graphic display and generated by RPG Build 6 software). Note most of the high reflectivity values to the ENE through E to SW of the radar (Sterling, VA (KLWX)) have been removed. The DHR is used by the NWS Flash Flood Monitoring and Prediction (FFMP) Program.

The HYBRID SCAN (Reflectivity) array is considered to be filled when the portion of the array filled exceeds the FULL HYBRID SCAN THRESHOLD or when the next to highest elevation in the volume has been completed (whichever comes first). The "highest elevation" test is only applied to prevent the PPS volumetric processing from occurring at the end of the volume, thus preserving that period for processing other processor intensive algorithms. It is expected that very few HYBRID SCAN (Reflectivity) bins will not be filled because of this restriction.

When the HYBRID SCAN (Reflectivity) array is full, the EPRE computes the area of echo covered by reflectivity values exceeding RAIN DETECTION DBZ THRESHOLD. If the area is less than the RAIN DETECTION AREA THRESHOLD, the NO RAIN FLAG is set to notify further PPS algorithms to ignore the HYBRID SCAN (Reflectivity) data values. If the NO RAIN FLAG is continuously set for a time period equal to or exceeding RAIN DETECTION TIME THRESHOLD, the RESET PPS STORM TOTAL FLAG is set. Note, this logic replicates the PDF logic, but uses the HYBRID SCAN (Reflectivity).

3.3.1.1 Operational parameters.

- AP/CLUTTER ID: For each tilt, an array of bins identifying the likelihood of AP/Clutter for each BASE REFLECTIVITY DATA bin. Values range from 0 to 100 percent and the precision is at least 1 percent.
- BASE REFLECTIVITY DATA: Radar base reflectivity data. Accuracy is defined by the accuracy of the base data. Currently reflectivity values range from ~ -32 dBZ to +90 dBZ and the precision is 0.5 dBZ.
- BEAM BLOCKAGE: For each VCP for each tilt, an array of (3600 X 230) bins defining the portion of the radar beam blocked for each tenth of a degree azimuth and each whole kilometer in range. Values range from 0 to 100 percent and the precision is at least 1 percent.
- BEAM WIDTH: Width of the radar beam. Values may range from 0.88^o to 0.96^o, default is 0.90^o, and the precision is at least 0.01^o.
- BIN WEIGHT THRESHOLD: Bin weight required to compute average power value for HYBRID SCAN (Reflectivity). Expected values range from 0.0 to 100.0 percent, default is 50.0 percent, and the precision is 0.1 percent.
- BLOCKAGE THRESHOLD: Maximum portion of beam blocked to allow use of BASE REFLECTIVITY DATA in HYBRID SCAN (Reflectivity). Expected values range from 0 to 100 percent, default is 50 percent, and the precision is 1 percent.
- CLUTTER THRESHOLD - Maximum AP/CLUTTER ID value to allow use of BASE REFLECTIVITY DATA in HYBRID SCAN (Reflectivity). Expected values range from 0 to 100 percent, default is 50 percent, and the precision is 1 percent.
- DATE (BEGIN VOLUME) - Julian date at the beginning of volume. Precision 1 day.
- DATE (END OF REFLECTIVITY TILT) - Julian date at the end of the reflectivity tilt. Precision 1 day.

3.3.1.2 Strengths/Applications. See Section 3.3.5.2.

3.3.1.3 Limitations. See Section 3.3.5.3.

3.3.2 Precipitation Rate. The PRECIPITATION RATE Algorithm executes each time the PRECIPITATION PREPROCESSING Algorithm is completed. If the FLAG (Zero Hybrid) is on, the algorithm sets the FLAG (Zero Rate) and updates the reference values for the time continuity test. Otherwise, the PRECIPITATION RATE Algorithm uses preprocessed reflectivity factor (HYBRID SCAN) data from the PRECIPITATION PREPROCESSING Algorithm to estimate precipitation rates for 1° by 2 km (1.1 nm) sample volumes within a radius of 230 km (124 nm). The RATE SCAN is produced for input to the PRECIPITATION ACCUMULATION Algorithm. Also, three quality control related procedures are performed within the PRECIPITATION RATE Algorithm.

Precipitation rates are empirically determined from a relationship with reflectivity factor data. The precipitation rates from two adjacent 1° by 1 km (0.54 nm) volumes along the same radial are averaged to obtain values for the 1° by 2 km (1.1 nm) RATE SCAN. The RATE SCAN is comprised of 41,400 1° by 2 km (1.1 nm) sample volumes. The rate values are in dBR's.

Based on the time continuity of the total field volumetric precipitation rate on a scan-to-scan basis, a decision is made whether the current RATE SCAN should be used by the PRECIPITATION ACCUMULATION Algorithm or be discarded. This test is intended to identify those cases where the between scan increase/decrease of the total volumetric precipitation rate is greater than the increase/decrease expected from precipitation development/decay. These changes could occur as a result of spurious RF interference, transient system noise, or anomalous propagation. Echo areas from storms entering/leaving the scanning region between scans could also cause this parameter to suddenly increase/decrease.

To minimize the chance of rejecting scans because of echo movements into and out of the field of view, the total volumetric precipitation rate is examined for both the entire field of view and for an area with a radius somewhat less than 230 km (124 nm) (inner radius). The inner radius is computed from a climatological maximum speed for echo movement and the time between scans. This test is only considered valid if the time between the current and last good scan is less than a maximum difference at which time continuity is expected.

A range effect correction is then applied to all RATE SCAN values beyond a specified cut-off range. The correction function contains three coefficients which may vary from site to site and with the season. Inputs to the correction function are the range and precipitation rate. This procedure corrects for the effects of signal degradation due to beam losses and partial beam filling which, on the average, reduce the precipitation rate estimates at further ranges.

The area-averaged precipitation rates over each 1/4 LIMITED FINE MESH (LFM) rectangular grid box (approximately 40 km x 40 km (22 nm x 22 nm)) are computed for those boxes whose centers are located within 230 km (124 nm) of the radar. These are obtained by averaging the rates from all RATE SCAN sample volumes whose centers fall within each 1/4 LFM grid box. These data will be used further downstream at the regional/national processing level for important quality control applications and possibly for the construction of a National Radar Summary Chart.

Reflectivity factor data being used by this algorithm are assumed to have been pre-processed as described in the ENHANCED PRECIPITATION PREPROCESSING Algorithm.

The HYBRID SCAN (1° by 1 km (0.54 nm)) data have not been spatially averaged to obtain the 1° by 2 km (1.1 nm) resolution required for precipitation processing. A precipitation rate estimate based on the averaged reflectivity is not identical to the average of the precipitation rates based on the full resolution reflectivity data. Therefore, each pair of 1° x 1 km (0.54 nm) reflectivity values being used to estimate a 1° x 2 km (1.1 nm) precipitation rate are first converted from reflectivity to precipitation rate and then averaged to obtain a RATE SCAN (1° x 2 km (1.1 nm)) value.

The time continuity test checks whether scans are bad. Bad scans are rejected or discarded from further processing by the PRECIPITATION ACCUMULATION and subsequent algorithms. This information is saved so that the number of bad scans can be appended to some of the final precipitation products. The intent of this test is not to identify all cases where bad data may be present. It provides a simple means to remove scans which indicate sudden and unreasonable echo development/ decay.

The LFM grid is a rectangular grid based on a polar stereographic projection. An LFM grid box represents an area whose size and shape varies with latitude. Therefore the size and shape of the grid boxes will vary slightly over the area covered by the radar and even more from radar to radar (35 to 45 km^2 over the conterminous U.S. for the 1/4th LFM grid). The 1/4th LFM grid boxes used here are defined to have 1/4th LFM grid points as their centers and a mesh length of 47.625 km (25.72 nm) at the standard latitude (60° N). The information required to generate the grid are the latitude and longitude of the radar, the mesh length at 60° N latitude, and the standard longitude (105° W).

In order to cover the radar umbrella out to 230 km (124 nm), even at the lower latitudes of the conterminous United States, a 13 x 13 array of 1/4th LFM grid boxes will be required. This array will always be 13 x 13 regardless of the latitude of the site. This grid should be positioned in such a way that the radar site falls within grid box (7, 7). This array must be compacted (e.g., elimination of all 0 rows, run-length encoding of rows) to reduce storage and especially communications loadings. Compaction must be done in such a way that the source 13 x 13 array can be reconstructed with the use of nominal computer resources.

3.3.2.1 Operational Parameters.

- FLAG (Zero Hybrid) - A set or cleared flag indicating, if set, that no precipitation exists in the current scan.
- HYBRID SCAN - Reflectivity factor data on a 1° x 1 km (0.54 nm) polar grid from 1 to 230 km (124 nm), in dBZ_e. These data were composited from four elevation scans by the PRECIPITATION PREPROCESSING Algorithm. A precision of at least 1 dBZ_e is required.
- Average TIME (Scan) - The average scan time of the four elevation scans used to construct the HYBRID SCAN. This is a time of occurrence, not duration.
- Maximum SPEED (Storm) - The climatologically derived maximum expected storm SPEED (90.0), in km/hr.
- THRESHOLD (Max Time Difference) - Maximum time between scans allowed by the time continuity test. A precision of at least 0.01 hour is required.
- RANGE (Cut-Off) - The range beyond which a range effect correction must be applied in km.

- COEFFICIENTS (Range Effect) - Three coefficients used to specify the range effect correction function.
- BOX (1/4 LFM Grid) - Rectangular grid box which is 1/4th of the LFM grid. Consists of a file specifying the RATE SCAN data sample volumes whose centers fall within each of the 1/4th LFM grid boxes.
- COEFFICIENT (Multiplicative Z-R) - Multiplicative coefficient in the Z-R conversion equation.
- COEFFICIENT (Z-R Power) - Power coefficient in the Z-R conversion equation.
- RATE (Zero Precipitation) - Precipitation rate assumed to be zero precipitation, in mm hr^{-1}.
- PARAMETER (Time Continuity #1) - The allowable rate of change of the ratio of volumetric precipitation rates when the echo area is equal to minimum AREA (Time Continuity), in hr^{-1}.
- PARAMETER (Time Continuity #2) - The allowable rate of change of the ratio of volumetric precipitation rates when the echo area is equal to the full radar umbrella out to the 230 km (124 nm) range, in hr^{-1}.
- Minimum AREA (Time Continuity) - Minimum precipitation area to allow time continuity tests on volumetric precipitation rates, in km^2.
- Maximum RATE (Echo Area Change) - Maximum rate of change of echo area allowed to pass the time continuity test when the volumetric precipitation rate cannot be tested due to the minimum AREA (Time Continuity), in km^2/hr.
- PRECIPITATION STATUS MESSAGE - An alphanumeric message which includes the radar ID, TIME (Stamp), current radar status, current operational mode, current scan strategy, TIME (Last Precipitation Detected), CATEGORY (Precipitation), number of gages in data base, and time since last update to the gage data base.
- CATEGORY (Precipitation) - The precipitation category currently in effect.

CATEGORY	MEANING
0	No precipitation detected during last hour
1	Significant precipitation detected during the past hour
2	Light precipitation detected during the past hour

3.3.2.2 Strengths/Applications. See Section 3.3.5.2.

3.3.2.3 Limitations. See Section 3.3.5.3.

3.3.3 Precipitation Accumulation. The PRECIPITATION ACCUMULATION Algorithm uses the previous and current precipitation rate (RATE SCAN) data sets output by the PRECIPITATION RATE Algorithm to estimate the accumulation (mm) during all or parts of the scan-to-scan period. The period accumulation scan(s) generated during the current pass of this algorithm plus those produced within the hourly period under consideration are then used to estimate an hourly running total or a clock hour total accumulation scan. This hourly accumulation scan is input to the PRECIPITATION ADJUSTMENT Algorithm. The PRECIPITATION ACCUMULATION Algorithm also checks the hourly accumulations for suspect values and modifies these under certain conditions.

The technique used to estimate the accumulation during the scan-to-scan period depends upon the time between scans. If the time between scans is not too large, a simple average precipitation rate is computed for the scan-to-scan period. This average is computed for each of the 1° by 2 km (1.1 nm) sample volumes which make up the scan. These averages are then multiplied by the time between scans to construct a period accumulation scan with a 1° x 2 km (1.1 nm) resolution, which gives the estimated scan-to-scan accumulation. This scan is comprised of 41,400 1° x 2 km (1.1 nm) sample volumes.

If the time between scans is too large to use simple averaging (equivalent to linear interpolation), the precipitation rates for each scan are used separately to compute accumulations for the beginning and ending parts of the scan-to-scan period. The remainder of the scan-to-scan period, centered midway between the two scans, is flagged as a missing period. In this case, two 1° x 2 km (1.1 nm) resolution period accumulation scans are constructed.

Next, the beginning and ending times for the hourly accumulation period are established. Normally, this period extends backward from the current scan time to a time one hour earlier. However, if a clock hour was passed during the scan-to-scan period, these times coincide with the beginning and end of the most recently completed clock hour. The clock-hourly period coincides with that over which rain gage accumulations are tabulated and compared to radar-rainfall estimates in the Advanced Weather Interactive Processing System (AWIPS) application that determines gage-radar Bias corrections for ingest back into the PRECIPITATION ADJUSTMENT Algorithm. Indeed, the radar-rainfall estimates for this application are provided by the clock-hourly version of the DPA product.

Weighting each period accumulation scan by the fraction of it which falls in the hourly accumulation period, a 1° x 2 km (1.1 nm) resolution hourly accumulation scan for the specified hourly period is constructed. However, if too much of the specified hourly period is not covered by period accumulation scans (e.g., is missing), no hourly accumulations are constructed and the processing stream continues with the PRECIPITATION ADJUSTMENT Algorithm.

Finally, each hourly accumulation scan sample volume value is checked against a threshold to see if it is reasonable. If it is greater than the threshold, (i.e., an outlier) and the values of all neighboring sample volumes are below the threshold, an interpolated accumulation is computed. These changes are made in such a way that subsequent modifications to outliers are not affected by the changes to those previously identified.

This algorithm requires precipitation rate scans from both the previous and current outputs of the PRECIPITATION RATE Algorithm. Only scans flagged as good in the PRECIPITATION RATE Algorithm are used (i.e., previous scan means previous good scan). Zero rate scans (scans not actually generated, but assumed to be zero everywhere) can be good scans. The algorithm is sufficiently flexible so that it can provide accumulation information for as much of the scan-to-scan period as possible even when the time between scans is larger than 5 minutes. However, the error associated with the accumulation will grow rapidly as the time between scans increases. Therefore, in order to provide, to the maximum extent possible, an uninterrupted precipitation record, the method used to save the previous precipitation rate scan must be safe, even from temporary system shutdowns and restarts.

Whenever the current precipitation rate scan is the first scan in a new clock hour, clock hour accumulations are computed instead of running hourly accumulations (note: the only difference between clock hour and running hourly accumulations are the starting and ending times for the one hour accumulation period). Since the time between scans may be large if a system problem occurs, the clock hour accumulation period could be set to begin up to 2 hours before the current scan time. In addition, missing periods must be taken into account so that hourly integration criteria can be checked. Therefore, all scan-to-scan period accumulation scans for periods ending any time after 1 hour prior to the previous scan time must be saved. The previous scan time is the last good scan collected prior to the current scan. The method used to save these period accumulation scans must be safe, even from temporary system shutdowns and restarts.

3.3.3.1 Operational Parameters.

- RATE SCAN - Precipitation rate data on a 1° x 2 km (1.1 nm) polar grid from 1 to 230 km (124 nm), in mm/hr. A precision of at least 0.1 mm/hr and a dynamic range of at least 0 to 400 mm/hr are required (not generated for times when FLAG (Zero Rate) or when FLAG (Bad) are set).
- Average TIME (Scan) - The average scan time of the lower elevation scans used to construct the HYBRID SCAN. This is a time of occurrence, not duration.
- FLAG (Zero Rate) - A set or cleared flag for each average TIME (Scan) indicating, if set, that all precipitation rate values can be assumed to be zero.
- Maximum TIME (Interpolation) - The maximum period over which a period accumulation scan can be computed using two precipitation rate scans, in hours (approximately 0.5 hours).
- Minimum TIME (Period) - The minimum period of time during an hourly accumulation period for which ACCUMULATION SCAN (Period) data are required in order to estimate the hourly accumulation in hours (approximately 0.90 hours).
- ACCUMULATION SCAN (Period) - Interpolated or extrapolated period precipitation accumulation data on a 1° by 2 km (1.1 nm) polar grid from 1 to 230 km (124 nm), in mm.
- TIME (Last precipitation detected) - The time at which the Precipitation Detection Function last detected precipitation.
- PRECIPITATION STATUS MESSAGE - An alphanumeric message which includes the radar ID, TIME (Stamp), current radar status, current operational mode, current scan strategy, TIME (Last Precipitation Detected), and current and previous CATEGORY (Precipitation).
- THRESHOLD (Hourly Outlier) - The maximum hourly rainfall amount allowed in an hourly accumulation scan sample volume (400), in mm. A precision of at least 0.1 mm is required.
- Ending TIME (Gage accumulation) - The time, each hour, when hourly radar and gage accumulations are required by the PRECIPITATION ADJUSTMENT

Algorithm. Note: this time will always coincide with a clock-hour.

3.3.3.2 Strengths/Applications. See Section 3.3.5.2.

3.3.3.3 Limitations. See Section 3.3.5.3.

3.3.4 Precipitation Adjustment. The PRECIPITATION ADJUSTMENT Algorithm provides the capability to apply a mean-field, multiplicative correction to selected PPS accumulation products, based upon rain gage vs. radar comparison information contained in a "Bias Table" ingested periodically into the RPG from an external source (e.g., AWIPS).

Bias Tables are generated by the Weather Forecast Office (WFO) version of the AWIPS Multisensor Precipitation Estimator (MPE) function, based upon comparison of hourly rain gage reports against unbiased, radar-generated precipitation estimates. The gage reports are ingested into AWIPS from various collection networks while the precipitation estimates are provided by the DPA product received from the RPG. At co-located positions where both the radar and gage estimates are non-zero, the two types of reports are assembled into a vector of "gage-radar pairs". From these pairs, analyses are performed over various time periods ranging from short ("instantaneous") to mid (multi-hourly; daily; weekly) to long ("climatological") term in order to determine mean-field biases and auxiliary data. These data are assembled into rows in the Bias Table, arranged in ascending, temporal order (presently 10). Each row contains: the Bias (correction); the memory time span (in hours) over which the analysis was performed; the "effective sample size (a weighted estimate of the number of gage-radar pairs used in the analysis); the weighted-average gage-rainfall estimate; and the weighted-average radar-rainfall estimate, for that time span.

The tables are shipped from the AWIPS MPE function to all the radars associated with that WFO as part of a Bias Table Message, on an hourly basis. This is done at a specific time each hour, set via a cron job that allows the gage-radar pairs for the past clock-hour to be processed - typically about 25 minutes past the top of the hour. Tables may be sent more frequently, at operator discretion, if, for example, additional rain gage reports are received or suspect reports have been purged by QC procedures.

When the Bias Table arrives at the RPG, it is stored in a linear buffer, from which it is ingested by the Precipitation Adjustment Algorithm-task each time that task executes (i.e., every volume scan). If the table is recognized as new, based on date/time-of-generation comparison, it replaces the previous version internally (which, upon RPG start-up, is a default table of nominal values).

Then, the "Most Representative" Bias from among those determined over the various time spans of the table is extracted. This is done in a straightforward procedure in which, sequencing in ascending, temporal order, the bias in the first row whose Sample Size exceeds an adaptable parameter (Minimum No. Gage-Radar Pairs) is selected. The adaptable parameter (NGRPS) is found in the Hydromet Adjustment Algorithm adaptation data menu of the RPG Human Computer Interface (HCI); its default value is 10 and its range is 6 – 30. If the user wishes the selected bias to trend more toward the short term - i.e., based on the present precipitation, NGRPS may be lowered; whereas if the user wishes it to trend more toward the long term - i.e., seasonal or climatological, NGRPS may be raised. Note that this parameter will also be dependent on the density of reporting rain gages under the radar umbrella, and the user may wish to raise/lower the default in the presence of a dense/sparse network.

Once established, the Bias correction is either applied - or not applied - to selected PPS rainfall accumulation products, depending on whether or not the (adaptable) Bias Applied Flag is turned On or Off (default setting: False). (Note, while the Bias Flag is set in the Precipitation Adjustment Adaptable Parameters Menu at the HCI, biases are actually applied in the Precipitation Products task.) If the flag is Off, no biases are applied momentarily. If it is On, the present Bias is applied as one mean-field, multiplicative correction to all (non-zero; non-missing) grid points of the most recent period or hour of the OHP, THP, STP, USP, and DSP products.

Note that these products may not be completely unbiased if the Bias Flag is presently Off; nor is the present Bias correction necessarily applied through the duration of a product if the flag is On. Rather, only the most recent component portion of each product is affected by the present Bias value and flag setting. For THP and USP (whose constituent hours span clock-hourly periods), the Bias that was in effect at the end of each clock hour is either applied or not applied to that hour's accumulation, depending on the momentary setting of the Bias Applied Flag. For STP and DSP, the Bias in effect at each time is, likewise, either applied or not applied to each of the constituent (volume scan-to-volume scan) periods that comprise the storm-total duration. Only the OHP product is "pure" in the sense that the entire product will either be adjusted, or not adjusted, by the present Bias correction value.

It is thus recommended that, prior to the onset of precipitation, a determination (True/False) be made for the Bias Flag and then maintained through the duration of the event, unless it becomes obvious that the original choice was not the most prudent. Note that the Bias is most likely to fluctuate toward the beginning of an event (as it gets "established"), particularly if a long time has passed since the previous event or if meteorological conditions have changed significantly in the interim (e.g., from cool, stratiform rain to convective).

The only PPS accumulation product to which the mean-field Bias adjustment is never applied (regardless of the Flag setting) is the DPA. This is because that product is used, in its unadjusted form, in the AWIPS MPE application to determine the next Bias Table, by comparison to hourly rain gage reports. However, the selected Bias correction is contained in an appended alphanumeric "layer" of that product, along with the associated fields Sample Size, Memory Span, and Bias Applied Flag. A complete copy of the present Bias Table, itself, is also contained in this alphanumeric layer, along with the Date and Time the Bias was last updated locally.

The PPS reflectivity products (i.e., Hybrid Scan Reflectivity (HSR) and DHR) also never have a bias correction applied. However, similar to DPA, DHR contains the present Bias and its associated fields (as above) in an appended alphanumeric layer (though not the complete Bias Table).

Alphanumeric information about the Bias is also available in the paired alphanumeric products to OHP, THP and STP, which show the selected Bias and the associated fields (Effective) Sample Size and Memory Span (hours), as well as the setting of the Bias Applied Flag. The THP paired alpha product depicts these fields in tabular form, for each of the three hours comprising the product; while the OHP and STP paired alpha products show the most recent values of each.

USP does not have a paired alphanumeric product but, rather, a table across the top of the graphic product that depicts the Bias for each hour comprising the (variable-length) USP. That table contains up to three pages (eight hours per page) to depict the biases for up to the 24-hour maximum duration of the product.

Finally, the all-alphanumeric Supplemental Precipitation Data (SPD) product contains the Bias, its related fields (as above), and the Date and Time of its last update on its first page; and a listing of the complete Bias Table on its second page.

3.3.4.1 Operational parameters. The following is received from an external source (AWIPS) once per hour, automatically (or more frequently, upon manual intervention):

- Bias Table Message: a message containing a Header and a Bias Table, as follows:
- Header, consisting of the following:
  - AWIPS Site (origination) ID: 3-char (e.g., OUN)
  - NEXRAD Radar (destination) ID: 3-char (e.g., TLX)
  - Observation Date/Time: {yr;mo;da;hr;mn;sc} of gage & radar observations (end of clock hour)
  - Generation Date/Time: {yr;mo;da;hr;mn;sc} of message generation
  - No. Rows in ensuing table (2-12; default 10)
  - Bias Table: A table of gage and radar information analyzed over a number of aggregate time spans (corresponding to No. Rows) ranging from short ("instantaneous") to mid to long ("climatological") term, consisting of the following fields: (*note: all fields scaled by 1000):
  - Memory Span of analysis (range: 0.001 – $1x10^7$) (*actually presented as log before being scaled by 1000)
  - (Effective) No. of Gage-Radar Pairs (range: 0 – $1x10^5$) (*technically, Sigma Inverse of exponential analysis)
  - Average Gage Estimate (range: 0.00 – 254.00 mm): (Exponentially normalized)
  - Average Radar Estimate (range: 0.00 – 254.00 mm): (Exponentially normalized)
  - Mean-field Bias Correction (range: 0.01 – 100.00): (Gage/Radar Ratio).

The following fields are received from predecessor task PRECIPITATION ACCUMULATION:

- AVERAGE DATE/TIME (Scan): The average date/time of the elevation scans used to construct the present Hybrid Scan. Serves as the current Time Stamp and the ending time of the most recent accumulation period {modified Julian day; secs within day}.
- ACCUMULATION SCAN (Period): Precipitation accumulation data for most recent scan-to-scan period, on 1° x 2 km (1.1 nm) polar grid from 1 to 230 km (124 nm); units 0.1 mm.
- ACCUMULATION SCAN (Hourly): Precipitation accumulation data for most recent hour, on 1° x 2 km (1.1 nm) polar grid from 1 to 230 km (124 nm); units 0.1 mm.
- MAX VAL (Hourly): Maximum Hourly Accumulation value; units 0.1 mm.
- SCAN TYPE (Hourly): Indicator of whether Hourly Scan ends at present time (i.e., Average Date/Time (Scan), if zero) or at top of most recent clock-hour (if

non-zero).

- BEGINNING DATE/TIME (Hourly Accumulation): Beginning date/time of hourly accumulation period {modified Julian day; secs within day}.
- ENDING DATE/TIME (Hourly Accumulation): Ending date/time of hourly accumulation period {modified Julian day; secs within day}.
- FLAG (Zero Scan-to-Scan): Flag indicating, if set, that all locations in the current scan-to-scan period can be assumed of zero accumulation (in which case, Accumulation Scan (Period) not ingested nor generated).
- FLAG (Zero Hourly): Flag indicating, if set, that all locations in the current hour can be assumed of zero accumulation (in which case, Accumulation Scan (Hour) not ingested nor generated).
- FLAG (No Hourly): Flag indicating, if set, that no hourly accumulations could be generated, due to missing data (in which case, Accumulation Scan (Hour) not ingested nor generated).

The following fields are received from the RPG HCI adaptation data menu:

- Reset Bias: Value to which Bias is set upon initialization or if excessive time passes since new Bias Table received (range: 0.5 – 2.0; default: 1.0).
- Longest Lag: Longest time lag since last Bias Table received that still allows "Best Bias" to be extracted from that table (range: 100 – 1000 hrs; default: 168 hrs (i.e., one week)).
- Threshold # G-R Pairs: Threshold # of gage-radar pairs in a Bias Table row that must be exceeded for the "Best Bias" to be selected from that row (range: 6 – 30; default: 10).
- Bias Flag: True/False flag indicating whether the selected Bias will be applied to the PPS accumulation products (default: False).

The following fields are output by this task:

- BIAS (Current): "Best" G-R Bias value most recently selected from the Bias Table (range: 0.01 – 100.00).
- MEMSPAN (Current): Memory Span associated with the Bias most recently selected from Bias Table (i.e., from the same row) (range: 0.001 – $1x10^7$).
- G-R PAIR SIZE (Current): Effective Sample Size associated with the Bias most recently selected from Bias Table (i.e., from the same row) (range: 0 – $1x10^5$).
- DATE/TIME (Bias Calculation): Date & Time BIAS and associated fields most recently selected from Bias Table {modified Julian day; secs within day}.

3.3.4.2 Operational Considerations. If the Bias Table (expected at least once per hour) is late arriving, an adjustment is performed upon the most recently-received table (stored internally) whereby the "effective no. of gage-radar pairs" fields in all table rows are degraded in accordance with an exponential decay factor. That factor is determined as the exponential inverse of the ratio of the lag (in hours) since the last Bias Table was received to the Memory Span (also in hours) over which the analysis was performed for each table row. The effect of this procedure is to make it more likely that the "Most Representative" Bias will be extracted from a table row based upon a longer (more climatological) Memory Span.

If the Bias Table is so late arriving that the time lag exceeds another adaptable parameter - Longest Lag, the Bias reverts to a default value called the Reset Bias (also adaptable). The routine value of LGLAG is 168 hours (i.e., one week), with a range of 100 - 1000 hours, while RESBI has a default of 1.0 with a range of 0.5 to 2.0.

3.3.5 Precipitation Products. The PRECIPITATION PRODUCTS creates Hydro-meteorological products from hourly and scan-to-scan accumulations generated by the PRECIPITATION ACCUMULATION Algorithm and adjusted by the current BIAS computed by the PRECIPITATION ADJUSTMENT Algorithm if FLAG (apply BIAS) is set. Digital, graphical, and alphanumeric products are generated. The digital product is an hourly running total or clock hour accumulation mapped to a 1/40th LFM rectangular (approximately 4 km x 4 km (2.2nm x 2.2 nm)) grid. The graphical products are: (1) an hourly running total or clock hour accumulation, (2) a three hour total accumulation generated on the clock hour, and (3) a storm total accumulation. The graphical products are all displayed at a resolution of 2 km (1.1 nm) x 1°. The alphanumeric SPD product is displayed in ASCII format. The graphical and alphanumeric products are designed primarily for display systems while the digital product is designed for use on external computer systems. Other products pertaining to the PPS, including the DHR product (Figures 2-13 and 3-2), the DSP (Figure 2-38) product, and the USP product (Figure 2-48), are described in additional documents, including the Interface Control Document (ICD) for RPG/To Class 1 User and the ICD for Product Specification.

The hourly running totals or clock hour totals on the 1/40th LFM grid are obtained by determining the mean of all adjusted ACCUMULATION SCAN (Hourly) sample volumes whose polar coordinate centers fall within each 1/40th LFM grid box. At the far ranges where no sample volume centers fall inside a box, the sample volume value at the sample volume whose center is closest to the center of the grid box becomes the value at the grid box. Annotations are automatically added to identify the product and to provide information related to how the data used to generate this product were processed.

The hourly running totals or clock hour totals on the 2 km (1.1 nm) x 1^{o} grid are scaled to 16 levels for use as a display and annotations are added automatically to produce the PRODUCT (OHP, Figure 3-3).

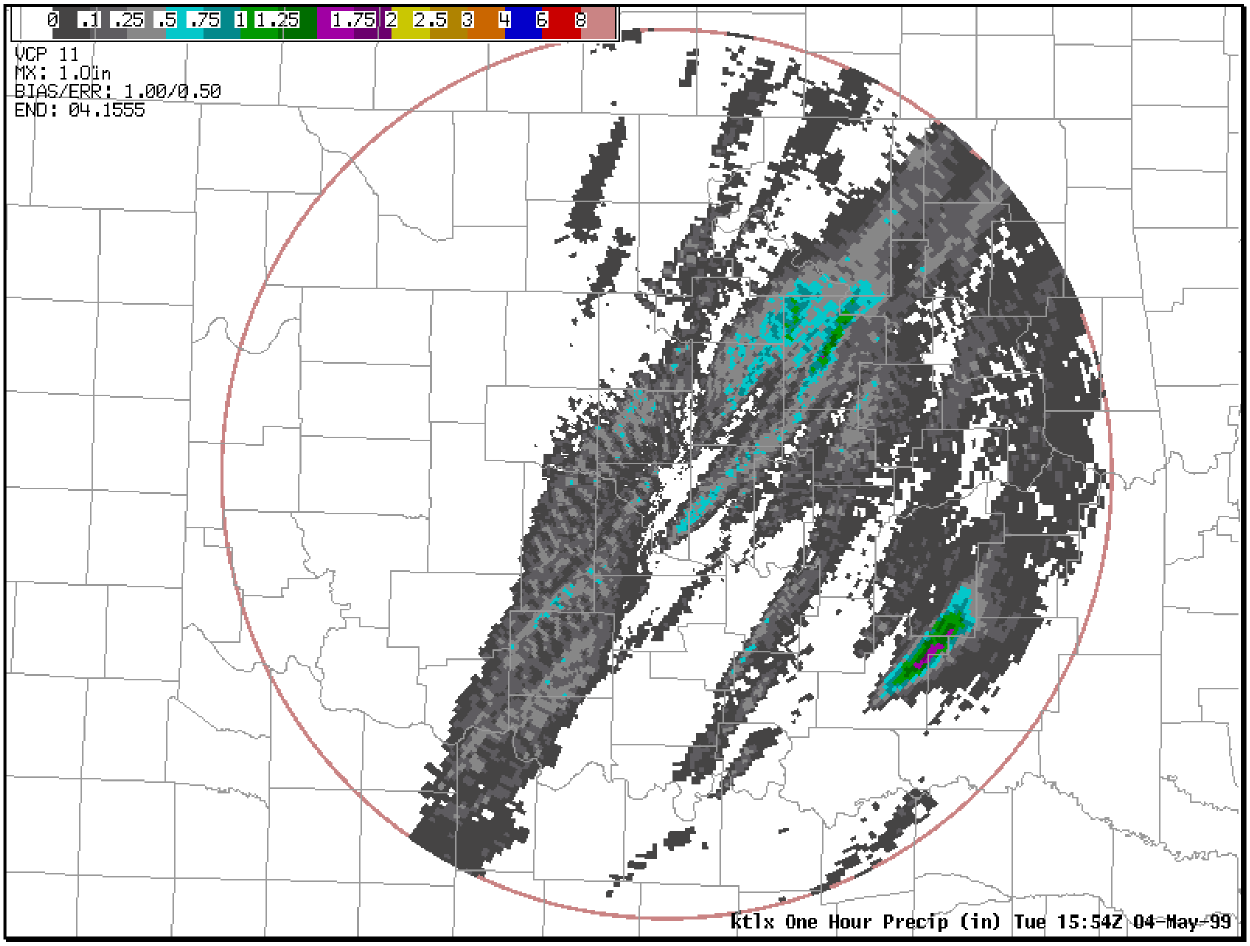

Figure 3-3
One-Hour Rainfall Accumulation Product

An OHP from the Oklahoma City, OK (KTLX) WSR-88D (AWIPS display).

The three clock hour totals are computed hourly by summing the available individual clock hour totals for the past three hours. At least two of the three hours of data must be available and missing periods should be noted. The data are then scaled to 16 accumulation levels for use as a display, and annotations are added automatically to produce the PRODUCT (THP).

The storm total (total precipitation since the last one hour break in significant precipitation) is generated whenever certain scan-to-scan accumulation parameters are exceeded. It is then updated using each ACCUMULATION SCAN (Scan-to-Scan) received until being reset after a one-hour break in significant precipitation. If FLAG (apply BIAS) is set, the ACCUMULATION SCAN (Scan-to-Scan) is adjusted using the computed BIAS. The data is then scaled to 16 levels for use as a display and annotations are added automatically to produce the PRODUCT (STP).

The ARRAY PRODUCT (Digital Precipitation) on the $1/40^{th}$ LFM grid provides hourly running total or clock hour total precipitation accumulation estimates in a digital array format to support hydrometeorological requirements for numerical use of precipitation data in computers external to the RPG. In addition to the precipitation array data, an extensive set of annotations (IDENTIFIER INFORMATION and SUPPLEMENTAL DATA) will be included automatically as part of this product. This information is intended for use in higher level (regional/national) processing to identify certain characteristics about the data up to that point in the processing stream. It will be used as part of the information for accomplishing more discriminating quality control functions at the higher level of processing.

In order to cover the radar umbrella out to 230 km (124 nm) even at the lower latitudes of the conterminous United States, a 131 by 131 array of $1/40^{th}$ LFM grid boxes will be required. This array will always be 131 by 131 regardless of the latitude of the site. This grid should be positioned in such a way that the radar site falls within the grid box (66, 66). The ARRAY PRODUCT (Digital Precipitation) must be compacted (e.g., elimination of all 0 rows, run length encoding of rows) to reduce storage and especially communications loadings. Compaction must be done in such a way that the source 131 by 131 array can be reconstructed with the use of nominal computer resources. The $1/4^{th}$ LFM area averaged precipitation rate data (8 coded precipitation rate levels) for each scan used to generate the ARRAY PRODUCT (Digital Precipitation) will be automatically included as part of the annotations (SUPPLEMENTAL DATA) to the ARRAY PRODUCT (Digital Precipitation). The values for the 13 by 13 $1/4^{th}$ LFM grid were computed by the PRECIPITATION RATE Algorithm. These must be compacted subject to the constraints specified above.

The PRODUCT (THP) uses the PRECIPITATION TOTALs (Hourly) for the last three clock hours. In order to provide these products on a consistent basis, the method used to save the PRECIPITATION TOTALs (Hourly) must be safe, even from temporary system shutdowns and restarts.

The PRODUCT (STP) uses the previous set of PRECIPITATION TOTAL (Storm). Again, the method used to save these data must be safe, even from temporary shutdowns and restarts.

3.3.5.1 Operational Parameters.

- FLAG (apply BIAS): A set or cleared flag indicating whether the bias should be applied.

- Current BIAS: The current BIAS generated by the PRECIPITATION ADJUSTMENT Algorithm.
- ACCUMULATION Scan (Hourly): The hourly radar precipitation accumulation SCAN (Hourly) data for an hourly running period or clock hour on a 1° x 2 km (1.1 nm) polar grid from 1 to 230 km (124 nm). A precision of at least 1 mm and a dynamic range of at least 0 to 1600 mm are required. Includes the beginning TIME (Accumulation) and ending TIME (Accumulation).
- ACCUMULATION SCAN (Scan-to-Scan): The total scan-to-scan accumulation data on a 1° x 2 km (1.1 nm) polar grid from 1 to 230 km (124 nm) for the period from the previous time to the current time. A precision of at least 0.1 mm and a dynamic range of at least 0 to 400 mm are required. Includes the previous average TIME (Scan) and current average TIME (Scan).
- CATEGORY (Precipitation): The precipitation category currently in effect.

CATEGORY	MEANING
0	No precipitation detected during the past hour
1	Significant precipitation detected during the past hour
2	Light precipitation detected during the past hour

- TIME (Stamp): The time at which the Precipitation Detection support function was last executed. A precision of at least 1/1200 hour is required.
- PRECIPITATION STATUS MESSAGE: An alphanumeric message which includes the radar.
- ID, TIME (Stamp), current radar status, current operational mode, current scan strategy, TIME (Last Precipitation Detected), CATEGORY (Precipitation), number of gages in data base, and time since last update to the gage data base.
- TIME (Last Precipitation Detected): The time at which the Precipitation Detection Function last detected precipitation. A precision of at least 1/1200 hour is required.
- FLAG (Zero Scan-to-Scan): A set or cleared flag indicating, if set, that all current ACCUMULATION SCAN (scan-to-Scan) values can be assumed to be equal to ACCUMULATION (Zero Interpolated).
- FLAG (Zero Hourly Accumulation): A set or cleared flag indicating, if set, that all current ACCUMULATION SCAN (Hourly) values can be assumed to be zero.
- BOX (1/40th LFM Grid): Rectangular grid box centered on 1/40th LFM grid points. At 60° N the mesh length is 4.7625 km (2.57 nm). Specifies the scan's sample volumes whose centers fall within each grid box. If none, the sample volume whose center is closest to the center of the grid box is specified. Grid boxes whose centers are more than 230 km (124 nm) from the radar are not assigned any sample volumes.

- RATE (1/4th LFM Grid Box): Area-average rate (8 level coded value) in each 1/4 LFM grid square. A 13 by 13 grid of values for each RATE SCAN used in constructing the hourly accumulations.
- FLAG (No Hourly Accumulation): A set or cleared flag indicating, if set, that no hourly accumulations were computed for the hour ending at the current ending TIME (Accumulation).
- SUPPLEMENTAL DATA: A set of varied data, determined during the execution of the precipitation processing series algorithms, which will be included as part of an alphanumeric, PUP-displayable product. Elements of the data will also be included as annotations to the other precipitation products.
- IDENTIFIER INFORMATION: Consists of annotations such as the radar I.D., product name, time (beginning and ending), date, and missing period times. The times must be in hours and minutes UTC.
- GAGE REPORTs (Accumulator): Reported values of accumulation in mm at each gage and time of occurrence (to the nearest 1/60 hour).
- GAGE REPORTs (Incremental): Reported values of incremental accumulation in mm, increment duration (hours to the nearest 1/60 hour) and time of occurrence (to the nearest 1/60 hour).
- GAGE-RADAR SET: Set of associated pairs of hourly radar and hourly rain gage accumulations.

3.3.5.2 Strengths/Applications.

- The PPS Algorithm creates hydrometeorological products from hourly and scan-to-scan accumulations generated by the algorithm and adjusted by the current BIAS. Digital, graphical, and alphanumeric products are generated.
- Significant quality controls are designed to produce better products by:
  - Minimizing overestimation due to ground return caused by anomalous propagation,
  - Eliminating reflectivity outliers and spurious noise, and
  - Reducing the effects of beam blockage.

3.3.5.3 Limitations. The PPS Algorithm does not provide sufficient information to distill and integrate heavy precipitation information into a flash flood alert map.

- Does not account for:
  - Below beam effects (wind, evaporation, coalescence)
  - Non-uniform Z-R relationships within the radar coverage area.
- Does not always account for:
  - Bright band contamination
  - Hail contamination
  - Inaccuracies due to radar outages
  - Inaccuracies due to Z-R limitations.

3.4 Storm Cell Identification and Tracking. The objective of the Storm Cell Identification and Tracking (SCIT) Algorithm is to identify, track, and forecast the movement of storm cells. The primary graphic product produced by this algorithm is Storm Track Information (STI). The STI product can display up to 100 cells identified by the SCIT Algorithm on a single product. It is also possible to display the actual past positions of the centroid on up to 13 (default 10) previous volume scans. Data developed by this algorithm are used extensively as input to several other products (i.e., HI, SS, SRM, SRR, M, TVS, RCM, CR Combined Attribute Table).

A storm cell is defined as a 3-dimensional region of significant reflectivity values above a specified threshold. It is assumed to be made up of reflectivity radial runs called segments and in turn 2-dimensional storm components composed of segment groups and occurring at different radar elevation angles. These components with calculated mass weighted centroids are then vertically correlated into a cell with an established centroid.

Therefore, the SCIT Algorithm consists of four sub-functions: Storm Cell Segments, Storm Cell Centroids, Storm Cell Tracking, and Storm Position Forecast (Figure 3-4). The Storm Cell Segments sub-function identifies the radial sequences of reflectivity (segments), and outputs information on these segments to the Storm Cell Centroids sub-function. The Storm Cell Centroids sub-function groups the segments into two-dimensional components, vertically correlates these components into three-dimensional cells, and calculates these cells' attributes. The cells and their attributes are output to Storm Cell Tracking and Storm Position Forecast. Storm Cell Tracking monitors the movement of the cells by matching cells found in the current volume scan to the cells from the previous volume scan. Storm Position Forecast predicts future centroid locations based on a history of the cell's movement.

The algorithm proceeds stepwise:

1. Storm Cell Segments - Identify segments along a radial of continuous reflectivity above the minimum reflectivity threshold and then identify reflectivity regions composed of adjacent segments by correlating the segments azimuthally.
2. Storm Centroids - Classify and rank vertically correlated reflectivity regions as storms.
3. Storm Tracking - Correlate storms from scan-to-scan to establish tracks.
4. Storm Position Forecast - Project the track forward in time.

Below, each of the sub-algorithms are discussed in their order of processing.

3.4.1 Storm Cell Segments. This algorithm defines a radial processing technique which identifies radial sequences of reflectivity, or segments, as part of the processing to identify storm cells. These segments are runs of contiguous sample volumes with reflectivity values greater than or equal to a specified threshold and have a combined length greater than a specified segment length threshold. Also, a segment may contain a specified number of contiguous sample volumes which are within a specified dropout reflectivity value below the reflectivity threshold.

The algorithm has multiple reflectivity thresholds (and a minimum segment length threshold for each reflectivity threshold). For each elevation scan the algorithm searches for segments using each of the reflectivity thresholds as a minimum value (Figure 3-5).

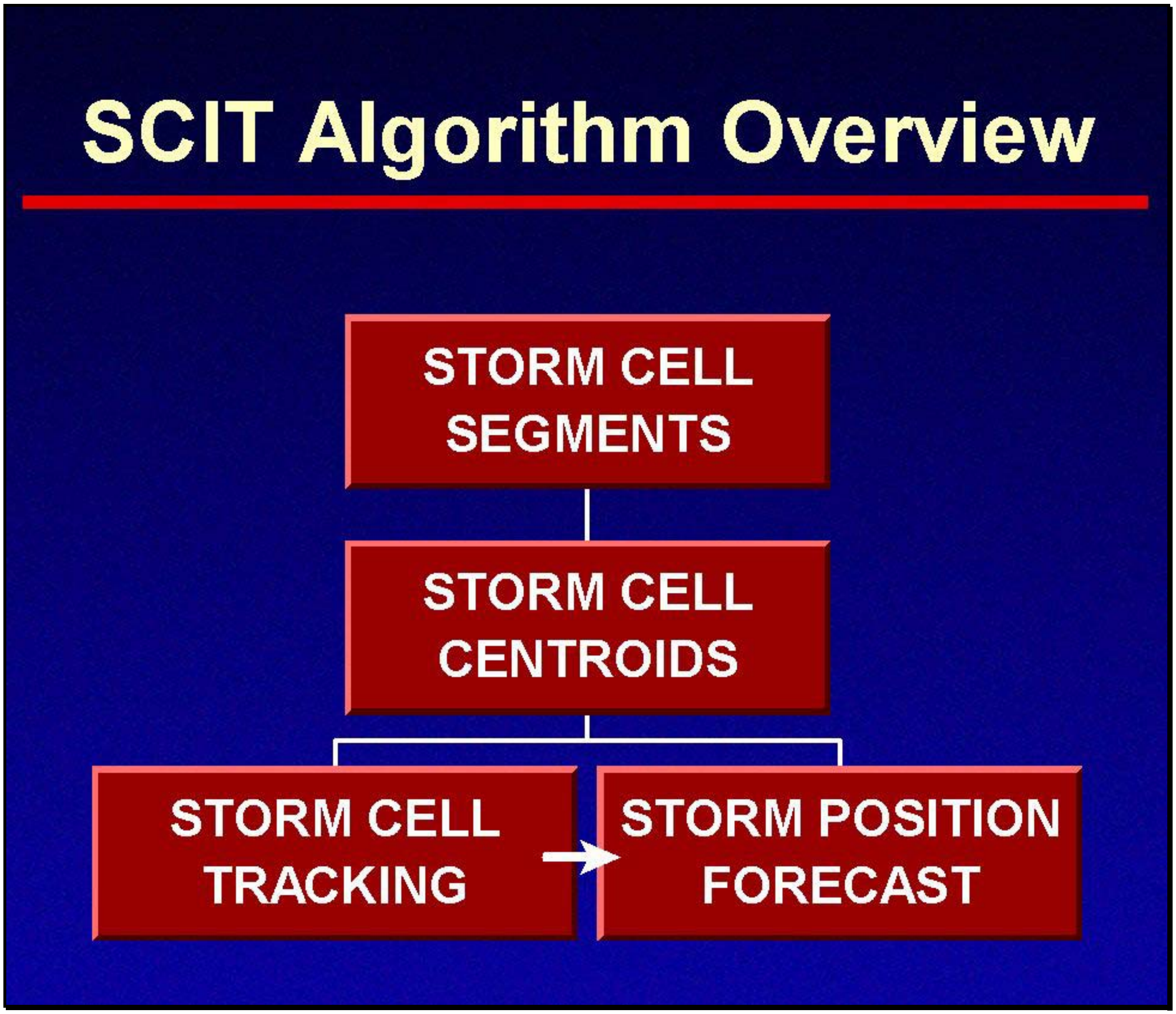

Figure 3-4
Storm Cell Identification and Tracking Algorithm Overview

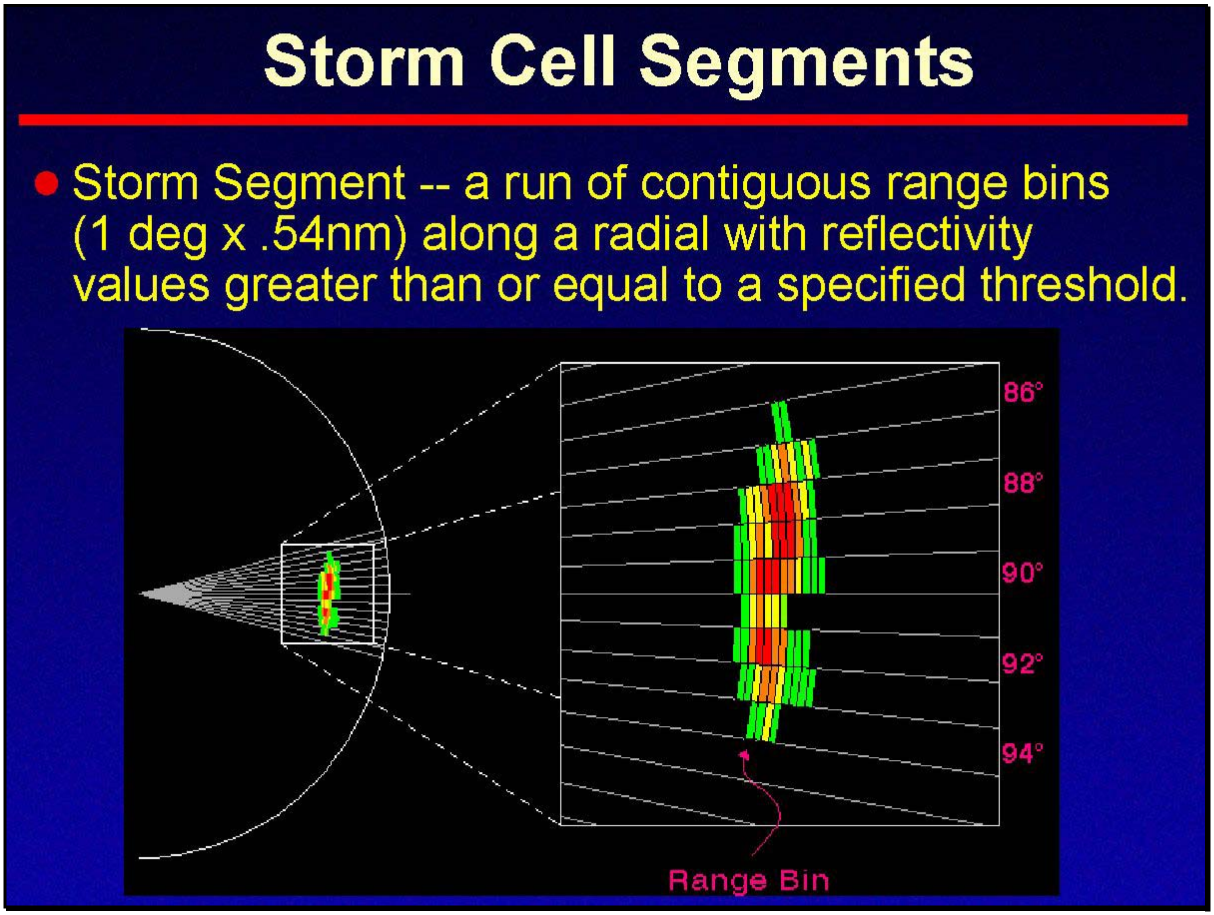

Figure 3-5
Storm Cell Segments Algorithm

Reflectivity information is quantified. The basic measurements of reflectivity are made in 1° x 0.54 nm (1 km) range bins. The function of this algorithm is to combine the individual range bins into storm segments along the radial. Note the segments along individual radials.

For each segment, the following attributes are calculated and saved: maximum reflectivity (using a three (adaptable) gate average), mass weighted length, and mass weighted length squared. In addition to those calculated attributes, the following attributes are saved for each segment: azimuth, reflectivity threshold, beginning range, and ending range. These attributes are used as inputs by the STORM CELL CENTROIDS Algorithm where radially adjacent segments are combined into storm components.

3.4.1.1 Operational Parameters.

- AZIMUTH: The azimuthal position of a radial or CELL SEGMENT, in degrees. Dropout Number Threshold--1 to 4; default, 2: The maximum number of sample volumes below the minimum reflectivity threshold and above the dropout reflectivity threshold that may be included in a storm segment.
- ELEVATION: The angle of the elevation scan, in degrees.
- MASS MULTIPLICATIVE FACTOR: multiplicative factor used in computing the PRECIPITATION INTENSITY for the MASS calculation (486), in $(mm^6/m^3)(hr/mm)$.
- MASS WEIGHTED FACTOR: A factor used in computing the MASS of a SAMPLE VOLUME (53×10^3), in $(hr)(kg)/(km^2m^2)$.
- PRECIPITATION INTENSITY EXPONENT: The power to which the PRECIPITATION INTENSITY is raised in calculating the effective REFLECTIVITY FACTOR (1.37), in dBZ_e.
- RANGE (Slant) Slant range to the center of a SAMPLE VOLUME, in km.
- REFLECTIVITY AVERAGING FACTOR: The number of SAMPLE VOLUMES used for computing a segment's maximum (average) REFLECTIVITY FACTOR (3).
- REFLECTIVITY FACTOR (Sample Volume): The effective radar reflectivity factor of a SAMPLE VOLUME, in dBZ_e.
- SAMPLE VOLUME: A data sample volume whose (half power) dimensions are 1 km (0.54 nm) in range (or length) and approximately 1^o in azimuth and depth (perpendicular to the radar beam).
- THRESHOLD (Dropout Count): The maximum number of contiguous SAMPLE VOLUMEs with a REFLECTIVITY FACTOR less than the THRESHOLD (Reflectivity) by less than or equal to the THRESHOLD (Dropout Reflectivity Difference) that may be included in a CELL SEGMENT (2).
- THRESHOLD (Dropout Reflectivity Difference): The difference below THRESHOLD (Reflectivity) in effective reflectivity that a SAMPLE VOLUME may still be included in a CELL SEGMENT (5), in dBZ_e.
- THRESHOLD (maximum Reflectivity Mass): The maximum REFLECTIVITY FACTOR used in the MASS WEIGHTED LENGTH and MASS WEIGHTED LENGTH SQUARED calculations (80), in dBZ_e.
- THRESHOLDS (Reflectivity): a set of minimum effective reflectivities which the REFLECTIVITY FACTOR of a SAMPLE VOLUME must meet or exceed to be included in a CELL SEGMENT. The REFLECTIVITY FACTOR of the SAMPLE VOLUMEs in a CELL SEGMENT of a THRESHOLD (Reflectivity) must meet or exceed the same THRESHOLD (Reflectivity) (60, 55, 50, 45, 40,

35, 30), in dBZ_e.

- THRESHOLDS (Segment Length): A set of minimum lengths of a CELL SEGMENT for each reflectivity threshold (1.9), in km.

3.4.1.2 Strengths/Applications. See Section 3.4.5.

3.4.1.3 Limitations. See Section 3.4.6.

3.4.2 Storm Centroids. This algorithm identifies convective storm cells by grouping cell segments into components; computing the components' attributes; vertically correlating the components into cells; and computing the cells' attributes. A segment is a radial sequence of significant reflectivities; component is a two dimensional area of significant reflectivity; and a centroid is the mass weighted center of a three dimensional region of significant reflectivity. This algorithm identifies the individual high reflectivity cores or cells within convective storms.

First, to identify cells, the algorithm combines radially overlapping and azimuthally adjacent radial segments (from the STORM CELL SEGMENTS Algorithm) into two-dimensional potential components. Since there are multiple reflectivity thresholds used to find segments, only segments found on the same elevation scan with the same specified reflectivity threshold are combined. A potential component which has at least a specified number of segments and aerial extent becomes a component.

Next, a search is done for overlapping components of different reflectivity thresholds on the same elevation scan. If the center of a component found with a higher reflectivity threshold falls within the boundaries of another component, the component found with the higher reflectivity threshold is saved, and the other is discarded. In addition, the components on each elevation scan are sorted by decreasing mass (Figure 3-6).

Then the components are vertically correlated; when components are correlated, they are assigned to the same cell. The centers of mass of the components at adjacent elevation scans (starting at the lowest) are compared for proximity with respect to the x and y plane. For each component, the distance from the center of every component in the next highest elevation scan is compared until a component is found within a specified search radius. Since the components at each elevation scan are sorted by decreasing mass, the components with the largest masses will be compared first. If no match is found for a component, then the search radius is increased, and the comparison is done again. The comparison may be done up to three times with increasing search radii. If at least two components (on adjacent elevation scans) are vertically correlated, a cell is created and its centroid and attributes are calculated (Figure 3-7).

If two cells' centroids are within spatial proximity, the cells are merged. To merge two cells, their centroids must be within a specified horizontal distance, and their bases and tops must be within a specified vertical and angular separation. When merging two cells, one cell's components are added to the other cell, and a new centroid is calculated.

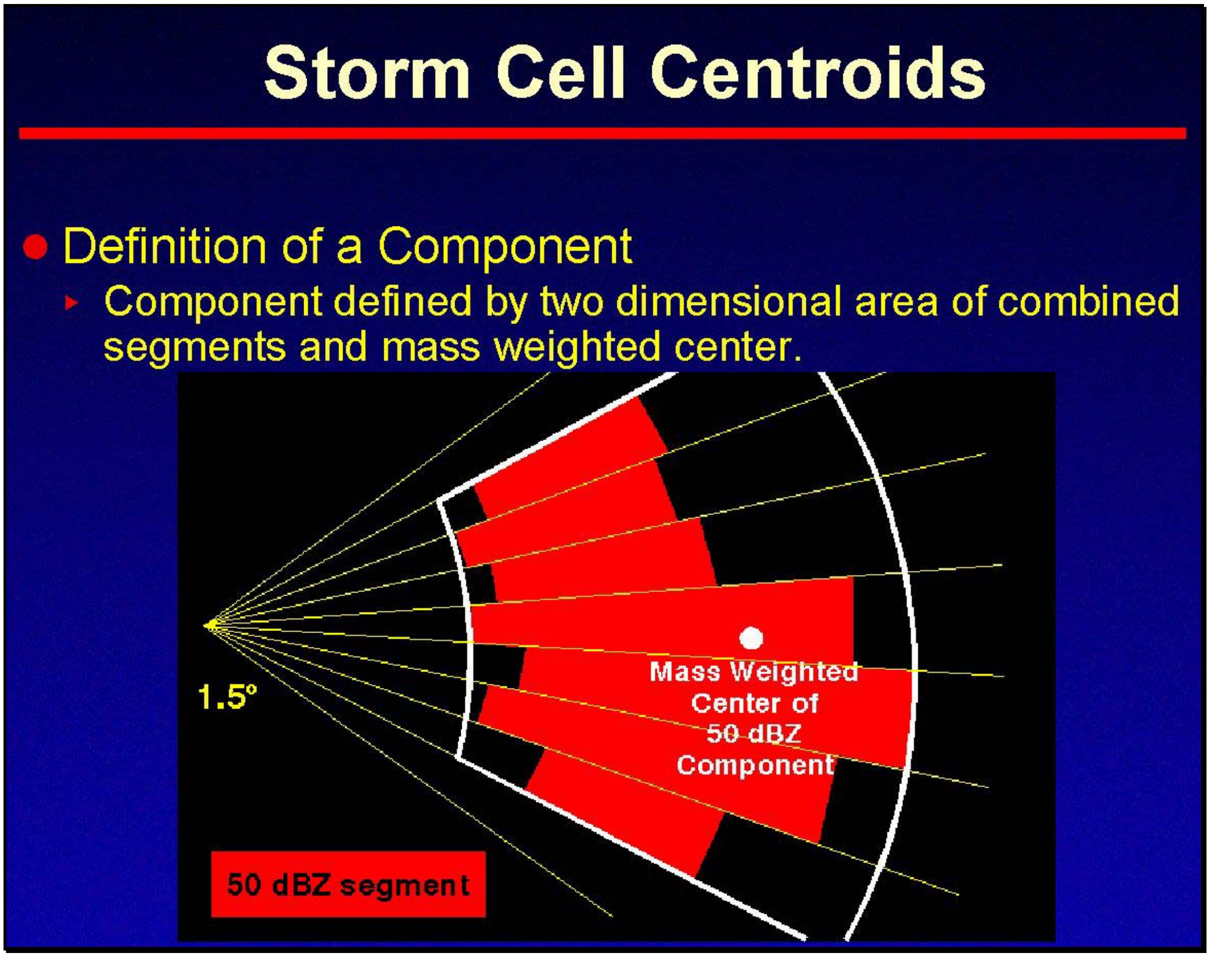

Figure 3-6
Component Development within Storm Cell Centroids Processing

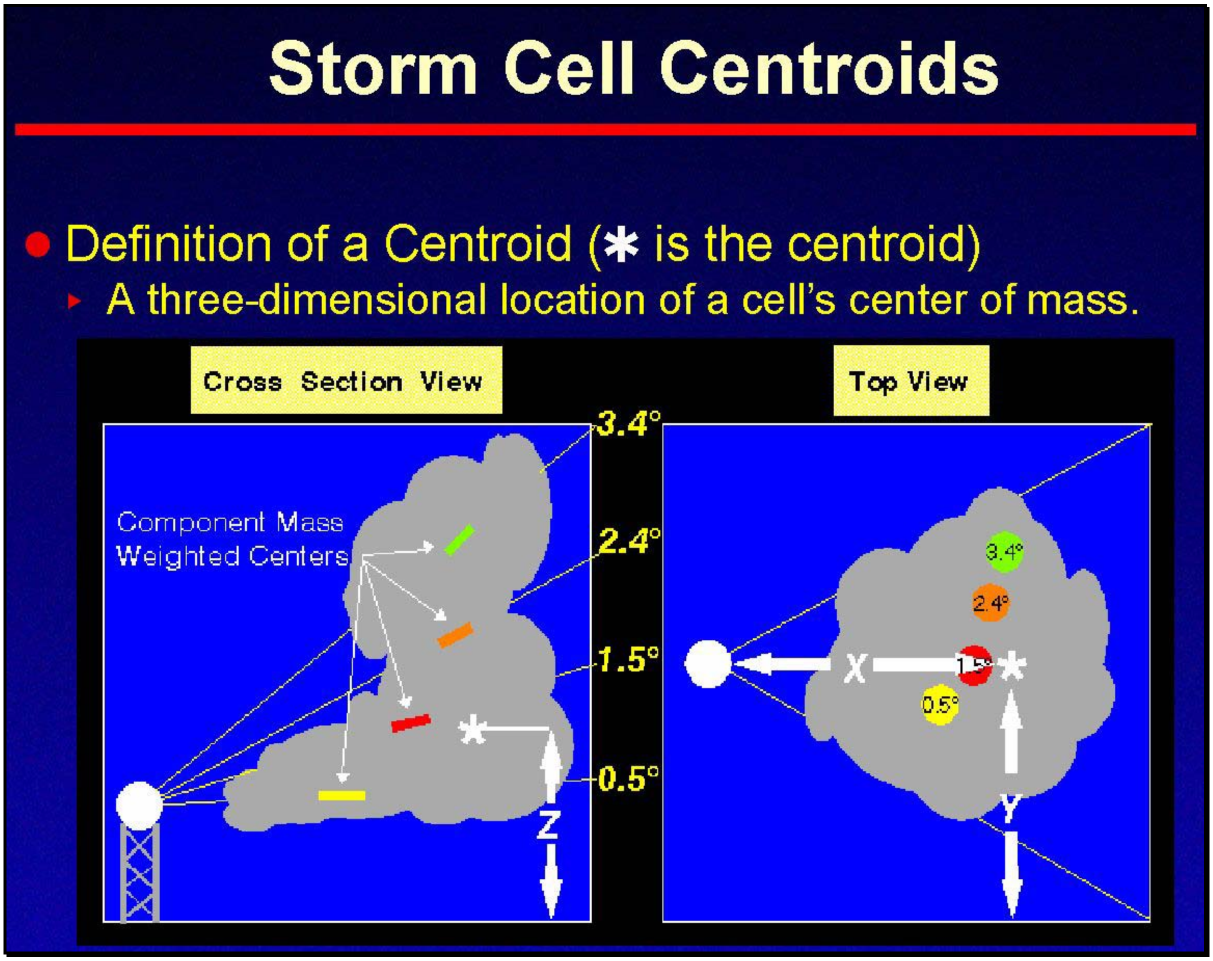

Figure 3-7
Storm Cell Centroid Locations

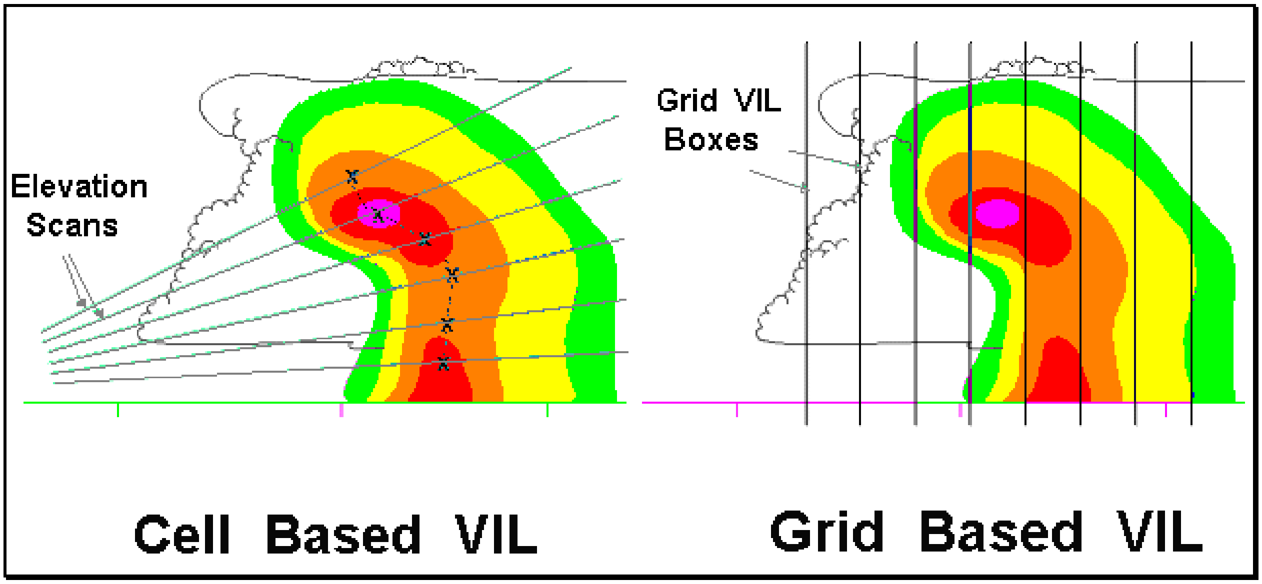

Figure 3-8
Cell-based vs. Grid-based VIL

The components (which compose the cells) are saved along with the following attributes: the elevation angle, mass weighted center (in Cartesian (x and y) and polar coordinates (azimuth and range)), height (AGL), mass, maximum reflectivity, and reflectivity threshold. In addition, the following cell attributes are calculated: centroid (in Cartesian (x and y) and polar coordinates (azimuth and range)), height, maximum reflectivity, height of the maximum reflectivity, top, base, Cell-based vertically integrated liquid (VIL), and number of components.

A calculation of VIL is made for each cell identified by Storm Cell Centroids by vertically integrating maximum reflectivity values of a cell's correlated components. This is a different calculation than the gridded VIL product (VIL). A fast-moving or highly tilted storm will usually have a higher Cell-based VIL than Grid-based VIL (Figure 3-8).

Next, to reduce the crowding, cells which are still within spatial proximity are deleted. If two cells are still within a specified horizontal distance and the difference in their cell depths is greater than a specified threshold, then the cell with the lesser Cell-based VIL is deleted.

Finally, the remaining cells are sorted by Cell-based VIL and secondly maximum reflectivity. The cells and components and their attributes are used as inputs to the HAIL CORE ALOFT, STORM CELL TRACKING, and STORM POSITION FORECAST Algorithms.

3.4.2.1 Operational parameters.

- Average DELTA AZIMUTH (Elevation): The average angular width of the radials in the ELEVATION scan, in degrees.
- AZIMUTH (Segment): The azimuthal position of a CELL SEGMENT, in degrees.
- BEAM WIDTH: The angular distance between half-power points on either side of the center of the radar beam, in degrees.
- Beginning RANGE (Segment): The slant range to the beginning (the front of the first sample volume) of a CELL SEGMENT, in km.
- CELL SEGMENT: A contiguous run of SAMPLE VOLUMES along a radial with reflectivity values above one of multiple reflectivity thresholds with the following attributes: AZIMUTH, beginning RANGE, ELEVATION angle, ending RANGE, MASS WEIGHTED LENGTH, MASS WEIGHTED LENGTH SQUARED, maximum REFLECTIVITY FACTOR, and THRESHOLD (Reflectivity).
- ELEVATION: Angle of the elevation scan, in degrees.
- Ending RANGE (Segment): The slant range to the end (the back of the last sample volume) of a CELL SEGMENT, in km.
- MASS WEIGHTED LENGTH (Segment): The mass density weighted length of a CELL SEGMENT, in kg/km.
- MASS WEIGHTED LENGTH SQUARED (Segment): The mass density weighted length squared of a CELL SEGMENT, in kg/km.
- Maximum REFLECTIVITY FACTOR (Segment): The maximum (average) reflectivity factor of a CELL SEGMENT, in dBZ_e.
- NUMBER OF SEGMENTS: The number of CELL SEGMENTS identified on each ELEVATION and THRESHOLD (Reflectivity).

- RANGE SAMPLE SPACING: The difference in slant range between two adjacent SAMPLE VOLUMEs along a radial, i.e., the length of a SAMPLE VOLUME (1), in km.
- THRESHOLD (Azimuthal Separation): The maximum azimuthal separation required for assigning CELL SEGMENTS into the same COMPONENT (1.5), in degrees.
- THRESHOLDS (Component Area): A set of required minimum areas for a COMPONENT. There is an area threshold for each reflectivity threshold used to find CELL SEGMENTs (10), in km^2.
- THRESHOLD (Depth Delete): The maximum difference in the depths of two STORM CELLs required to delete one of the STORM CELLs (4), in km.
- THRESHOLD (Elevation Merge): The maximum difference in the elevation angles between the top of one STORM CELL and the bottom of another STORM CELL required to merge the STORM CELLs (3.0), in degrees.
- THRESHOLD (Height Merge): The maximum difference in the height between the top of one STORM CELL and the bottom of another STORM CELL required to merge the STORM CELLs (4), in km.
- THRESHOLD (Horizontal Delete): The maximum horizontal distance between two centroids required to delete one of the STORM CELLs (5), in km.
- THRESHOLD (Horizontal Merge): The maximum horizontal distance between two centroids required to merge the STORM CELLs (10), in km.
- THRESHOLD (NUMBER OF SEGMENTS): The minimum number of CELL SEGMENTs required in a COMPONENT (2).
- THRESHOLDS (Reflectivity): A set of minimum effective reflectivities used to find CELL SEGMENTs and COMPONENTs and ordered from largest to smallest (60, 55, 50, 45, 40, 35, 30), in dBZe. The reflectivity factors of the sample volumes in a CELL SEGMENT must meet or exceed the same THRESHOLD (Reflectivity). And only CELL SEGMENTs which have been found using the same THRESHOLD (Reflectivity) can be assigned to the same COMPONENT.
- THRESHOLDS (Search Radii): A set of distances away from a COMPONENT's mass weighted center which a search is made for another COMPONENT's mass weighted center on the next elevation scan with which to correlate (5, 7.5, 10), in km.
- THRESHOLD (Segment Overlap): The minimum slant range overlap required for assigning CELL SEGMENTs to the same component (1.95), in km.

3.4.2.2 Strengths/Applications. See Section 3.4.5.

3.4.2.3 Limitations. See Section 3.4.6.

3.4.3 Storm Cell Tracking. The STORM CELL TRACKING Algorithm monitors the movement of storm cells by matching storms found in the current volume scan to the storm cells from the previous volume scan in time and space, through the use of a correlation table. The storm cells are matched as follows. Starting with the most intense cell (i.e., largest cell-based VIL value) in the current volume scan, the centroid position is compared to the projected centroid positions of cells from the previous volume scan. A cell's projected centroid position is its forecasted position for the current volume scan. The cell from the previous volume scan which is correlated is the cell with a projected centroid located within an adaptable range which is closest to the current cell. When a cell is correlated, it is considered the same cell and assigned the same storm cell ID. Then the next most intense cell in the current volume scan is compared to all uncorrelated cells in the previous volume scan, and so on until all cells in the current volume scan are processed. Once a cell from the previous volume scan is correlated, it is not compared to any more cells in the current volume scan. If no projected centroid positions are within the adaptable range of a cell's centroid position, the cell remains uncorrelated and is assigned a new storm cell ID. If more than a specified amount of time has passed between subsequent volume scans, then no matching is done, and all storm cells in the current volume scan are considered new. The centroid positions used are in a Cartesian coordinate system with the radar at the origin, and where the X-axis denotes east-west directions and the Y-axis denotes north-south directions. To complete the prediction process, the STORM POSITION FORECAST Algorithm must be used (Figure 3-9).

The ID assigned to a Cell consists of a letter-number combination (A0, B0, C0...Z0, A1, B1...Z1, A2, B2...Z9). This adds some value to the ID, such that storms with long lifetimes can be easily identified. The number has precedence over the letter in this scheme. The list of IDs will reset to begin with A0 when the RPG is rebooted, or when a threshold time interval has lapsed without cells.

The STI Attribute Table appears at the top of the STI product, and contains information on all identified cells. An STI Alphanumeric Product is received and stored in a text file along with every STI Graphic Product.

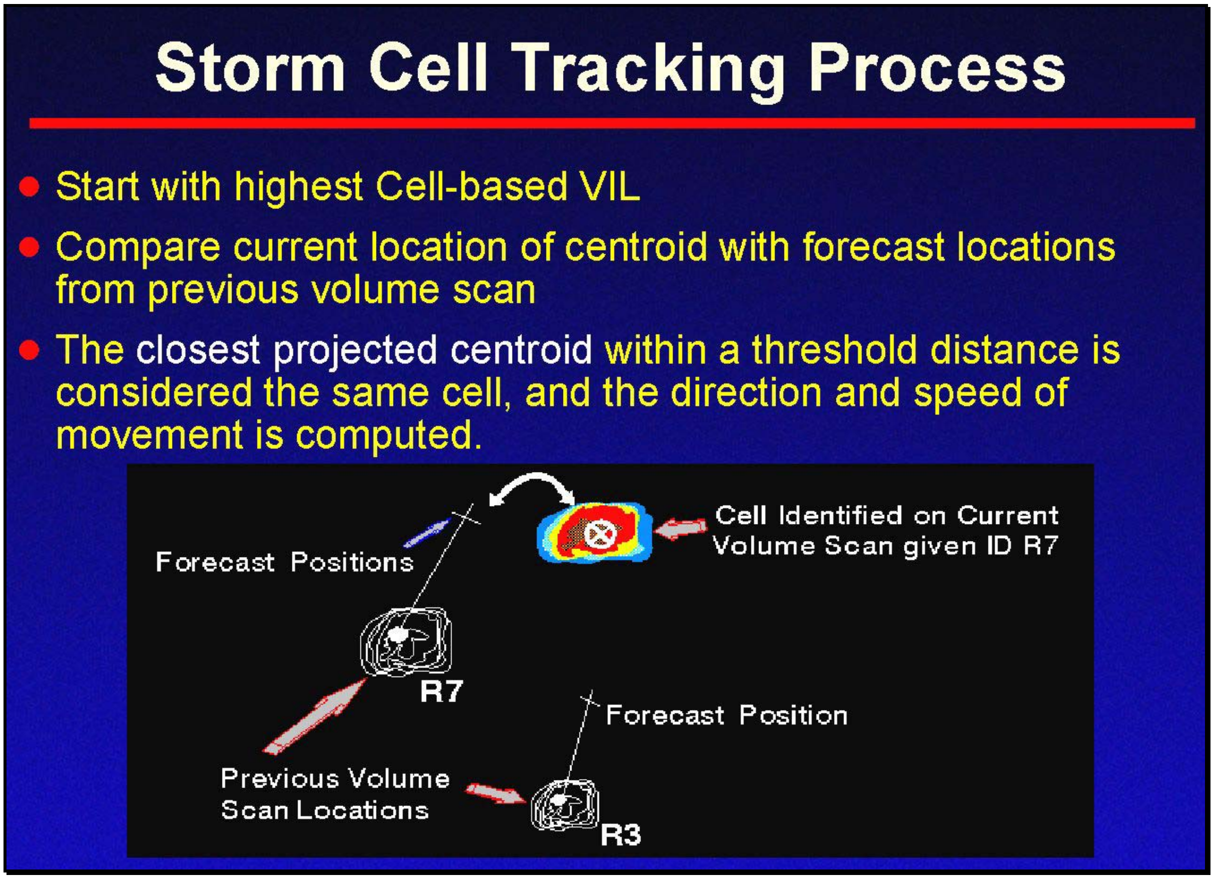

Figure 3-9
Storm Cell Tracking Process

Centroid location is compared with forecast location of centroids from the previous volume scan.

3.4.3.1 Operational Parameters.

- CORRELATION (Speed): Speed used to compute the CORRELATION (Distance), in km/hr.
- CORRELATION (Table): A data set used to keep track of the positions of correlated STORM CELLS.
- DIRECTION (Storm Cell): The direction from which a STORM CELL is moving, in degrees. Precise to 10^{-4} deg.
- ID: A unique label from a circular list assigned to a STORM CELL throughout its existence.
- SPEED (Storm Cell): Speed of a STORM CELL, in km/hr. Precise to 10^{-4} km/hr.
- STORM CELL: A three-dimensional region composed of COMPONENTs characterized by reflectivity values above a given threshold, ordered by cell-based VIL.
- TIME (Maximum): The maximum allowed TIME BETWEEN VOLUME scans (20), in minutes. Storm Correlation between the current and previous volume scans is not performed if the scan separation exceeds this value.
- TIME (Scan): The beginning time of a volume scan, in hours. Precise to 1/3600 hr.
- X-POSITION (Storm Cell): X-coordinate of the centroid (or center of mass weighted volume) of a STORM CELL, in km. Precise to 10^{-4} km.
- Y-POSITION (Storm Cell): Y-coordinate of the centroid (or center of mass weighted volume) of a STORM CELL, in km. Precise to 10^{-4} km.

3.4.3.2 Strengths/Application. See Section 3.4.5.

3.4.3.3 Limitations. See Section 3.4.6.

3.4.4 Storm Position Forecast. The purpose of the STORM POSITION FORECAST Algorithm is to predict the future centroid locations of storms (or storm cells) based on a history of their movement. The first volume scan a storm is detected, it is considered 'new', and the forecast movement used by the algorithm for processing purposes is either: a) the average movement of all identified cells, or b) if no other cells are identified, the default speed and direction as set at the Master System Control Function (MSCF). After the first volume scan a storm is detected, it is considered a 'continuing storm', and a forecast movement is computed based on a linear least squares extrapolation of the storm's previous positions. The linear least squares fits are for both X-position versus time and Y-position versus time. This process is continued for each consecutive volume scan that a storm is tracked.

Forecast positions are computed in equal time steps (0, 15, 30, 45, or 60 minutes) for each continuing storm. The number of forecast positions computed for a storm depends on the scaled forecast error and a permissible error. The scaled forecast error is the accuracy of the forecast from the previous volume scan for the storm, or forecast error, scaled by the ratio of a user specified error interval over the time between volume scans. The permissible error is a user specified allowable error scaled by the error interval over the length (in time) of the forecast. Basically, the poorer a forecast was for a cell for the past volume scan, the fewer the number of forecast positions. Each volume scan a vector-average storm motion is computed from all the continuing storms, and this average storm motion is assigned to any new storms.

The STORM POSITION FORECAST Algorithm is the final step in the storm identification and movement prediction process. It utilizes information output by the STORM CELL TRACKING and the STORM CELL CENTROIDS Algorithms. Therefore, it cannot be applied until the completion of that analysis, which requires a complete volume scan of data. Resulting products are then generated (Figures 3-10 and 3-11).

3.4.4.1 Operational Parameters.

- ALLOWABLE ERROR: The maximum acceptable error in the track of a STORM CELL allowed for the minimum forecast interval, in km (20).
- CORRELATION (Table): A data set used to keep track of the positions of correlated STORM CELLs.
- DEFAULT SPEED: A user-supplied speed at which storm cells are expected to move, in km/hr.
- DEFAULT DIRECTION: A user-supplied direction from which storm cells are expected to move, in degrees.
- ERROR INTERVAL: The amount of time upon which the ALLOWABLE ERROR was based, in hours (0.25).
- FORECAST INTERVAL: A set of time intervals for which STORM CELL positions may be projected into the future, in hours (0.25).

3.4.5 Strengths/Applications.

- The product works best with well-defined widely separated cells.
- A large number of past tracks, and/or four forecast positions signify a more reliable cell movement. Uneven spacing between past tracks, fewer than four forecast positions, and/or reidentification of cells indicate less reliable forecast positions.
- The STI product is useful as an overlay on volume products, but not limited to volume products.
- Cell motion is used in Storm Relative Velocity products (SRM, SRR).
- Cell attributes are critical inputs to the Hail Index product.

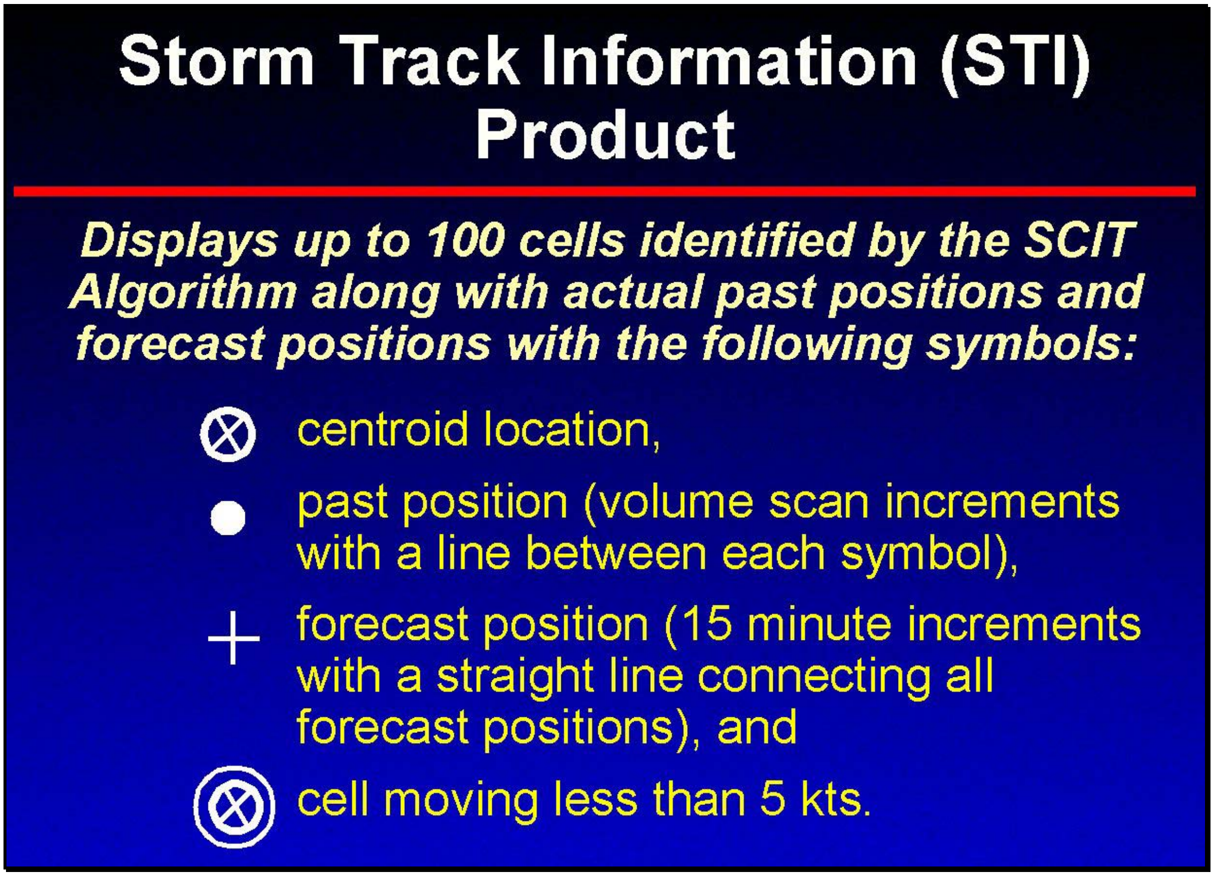

Figure 3-10
Storm Track Information Product Symbols

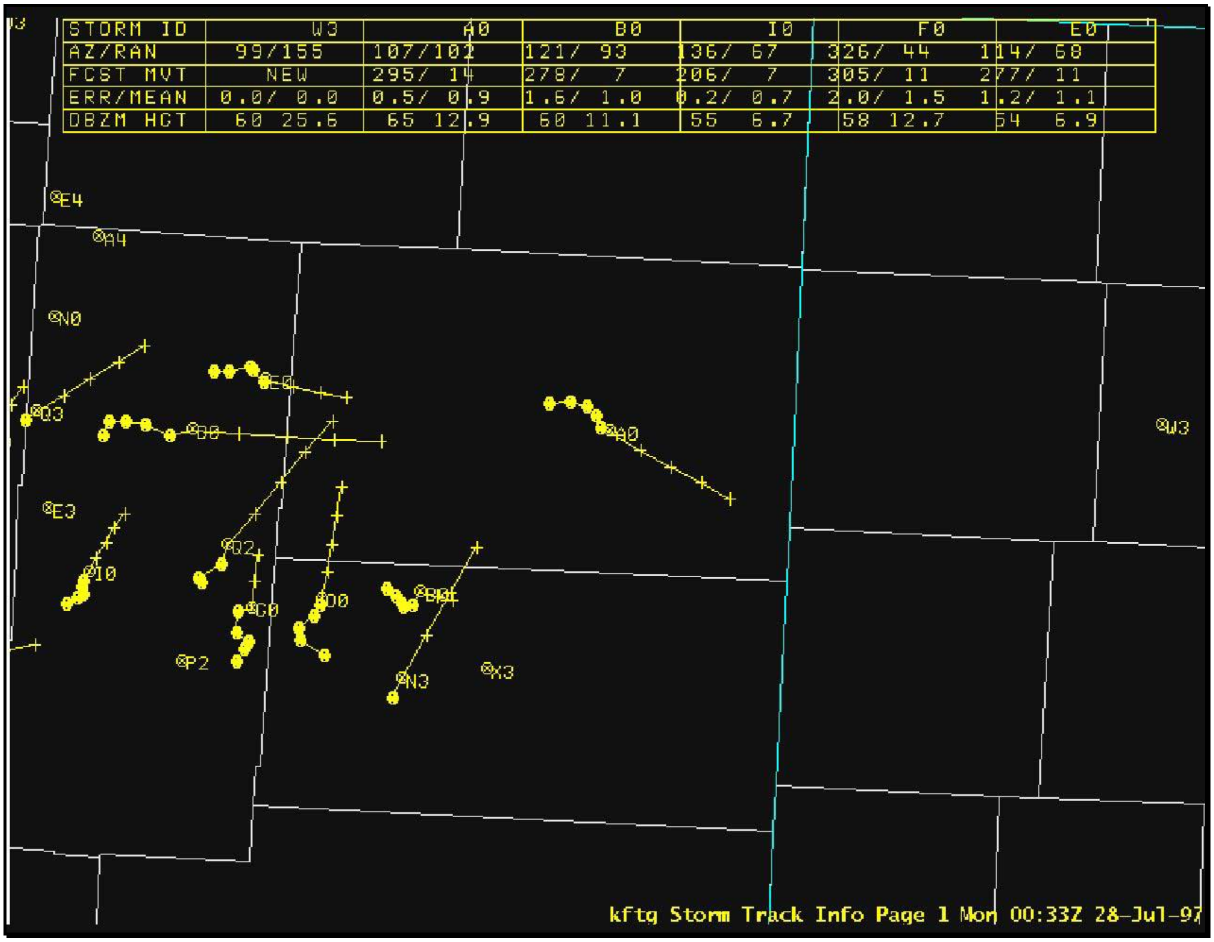

Figure 3-11
Storm Track Information Product

This STI example from the Denver, CO (KFTG) WSR-88D (AWIPS display) includes past positions of storms (yellow circles), 15-minute projected positions (yellow crosses), and the Combined Attribute Table of storm information.

3.4.6 Limitations.

- The algorithm does attempt to prevent non-meteorological targets (e.g., anomalous propagation or clutter) in the reflectivity data from being considered segments. Clutter filtering is being applied in the WSR-88D, but it is not always adequate or correctly applied. When non-meteorological targets are identified as segments, this may lead to falsely identified storm cells or parts of storm cells in the STORM CELL CENTROIDS Algorithm.
- At long ranges, only the lowest elevation scans of a volume scan will contain components. For example, at 120 nm, the bottom of radar beam at 0.5° is nearly 18 kft ARL. Components must be found on at least two consecutive elevation scans to be considered a storm cell. Storm cells at long ranges may not have enough vertical extent to be detected at even two elevation scans, and, therefore, will not be identified.
- Rarely, problems may arise in the vertical correlation process which will lead to improper identification of cells and/or computation of their attributes. When several cells are clustered closely together, the algorithm may combine separate components on an elevation scan into one component. Also, the algorithm may either falsely split a cell into two or more cells or combine a group of cells into one cell.
- The cell merging and deletion processes attempts to decrease the cluttered nature of cells. But deletion and merging of cells may decrease the performance of downstream algorithms using cell and component data.
- Alternatively (as studied and developed by the NSSL), this algorithm uses the Severe Hail Index (SHI) from the HAIL CORE ALOFT Algorithm (instead of Cell-based VIL) to sort cells and in the cell deletion process (which reduces crowding).
- This algorithm averages actual changes in cell movement and erratic movement due to centroid shifting which occurs in some storm cells.
- The forecast track is always a straight line.
- Because several volume scans are used for the forecast, a sudden shift in a centroid location will be damped out until the new track becomes established.
- The accuracy of the forecasted movement provided by this algorithm is limited by the accuracy of the tracking algorithm. For example, if the STORM CELL TRACKING Algorithm inaccurately matches storm cells between volume scans, then the forecasted movement of those cells will also be inaccurate.
- Errors may occur in the identification of cells and the calculation of cell attributes when cells are in close proximity.
- Large errors may occur in the attributes of cells close to the RDA, especially in VCP 21.
- Unrepresentative movements are possible due to propagational effects. Due to development or dissipation, the high reflectivity cores change location within an identified cell from one volume scan to the next, resulting in false representation of the movement of the cell.

3.5 <u>Hail</u>. The purpose of the Hail Core Aloft Algorithm (HDA) is to provide for each storm cell the following three estimates:

- The Probability of Hail (POH) of any size,
- The Probability of Severe Hail (POSH) (or hail ¾" in diameter), and

- The Maximum Expected Hail Size (MEHS).

Based on drop-size/hailstone distribution and empirical studies, the algorithm assumes that large reflectivity values observed aloft (above the freezing level (0°C)) are most likely hail in the midst of large concentrations of supercooled liquid water.

This algorithm analyzes storm cell and environmental data available in a specific format. The STORM CELL CENTROIDS Algorithm provides storm cell data as input to this algorithm. The SCIT Algorithm identifies individual cells within a convective storm instead of the entire storm. A storm cell is defined as a core of a three dimensional region of significant reflectivity values. Each storm cell is made up of two-dimensional components in horizontal proximity at adjacent elevation angles of radar observation. A component is a minimum aerial extent of reflectivity values greater than or equal to a specific reflectivity threshold at one elevation. The algorithm's inputs are environmental data and storm cell components' maximum reflectivity and height ARL (of the mass weighted center (or centroid)). The environmental data is the height above mean sea level (MSL) of the 0°C and -20°C environmental temperatures (which is usually derived from a nearby sounding).

To determine the POH of any size for each storm cell, the height of the highest component with a large maximum reflectivity value (of at least a threshold value) which is above the freezing level is used in an empirical relationship. The higher the component is above the freezing level, the greater the POH.

To determine the POSH and MEHS for each storm cell, the algorithm uses a relationship between reflectivity and the Hailfall Kinetic Energy (E). E is the flux of kinetic energy of hailstones. E is calculated from components with large maximum reflectivity values (of at least a threshold value) above the freezing level. The larger the components' maximum reflectivity values, the larger their E. A height and reflectivity weighted vertical integration of the E is done for all components within a storm cell (which meet the relative height and reflectivity criteria). The vertical integration of E is weighted toward components with very large (of at least a threshold value) maximum reflectivity values above the height of the -20°C environmental temperature (Figure 3-12). The vertical integration results in a parameter called the Severe Hail Index (SHI). The greater the collective depth of components in a storm cell with large E values and the higher those components are (above the freezing level), the larger a storm cell's SHI value. The POSH is calculated from SHI and a threshold which is a function of the height of the freezing level. The MEHS for each storm cell is computed using SHI in an empirical formula. The algorithm is designed to work independent of cell type, tilt, and overhang. The primary product produced by the algorithm is Hail Index (HI) which can be useful in identifying cells that have the potential to produce hail. The Hail Index Attribute Table will be available at the top of the product which lists the Cell ID, Azimuth and Range, POSH or POH, the MEHS, and the last line in the table identifies the altitudes of the temperatures and the date/time at which the information was last updated (See Figure 3-13). If the cell is beyond the hail processing range of 230 km (124 nm), then the hail estimates are labeled as UNKNOWN in the Attribute Table.

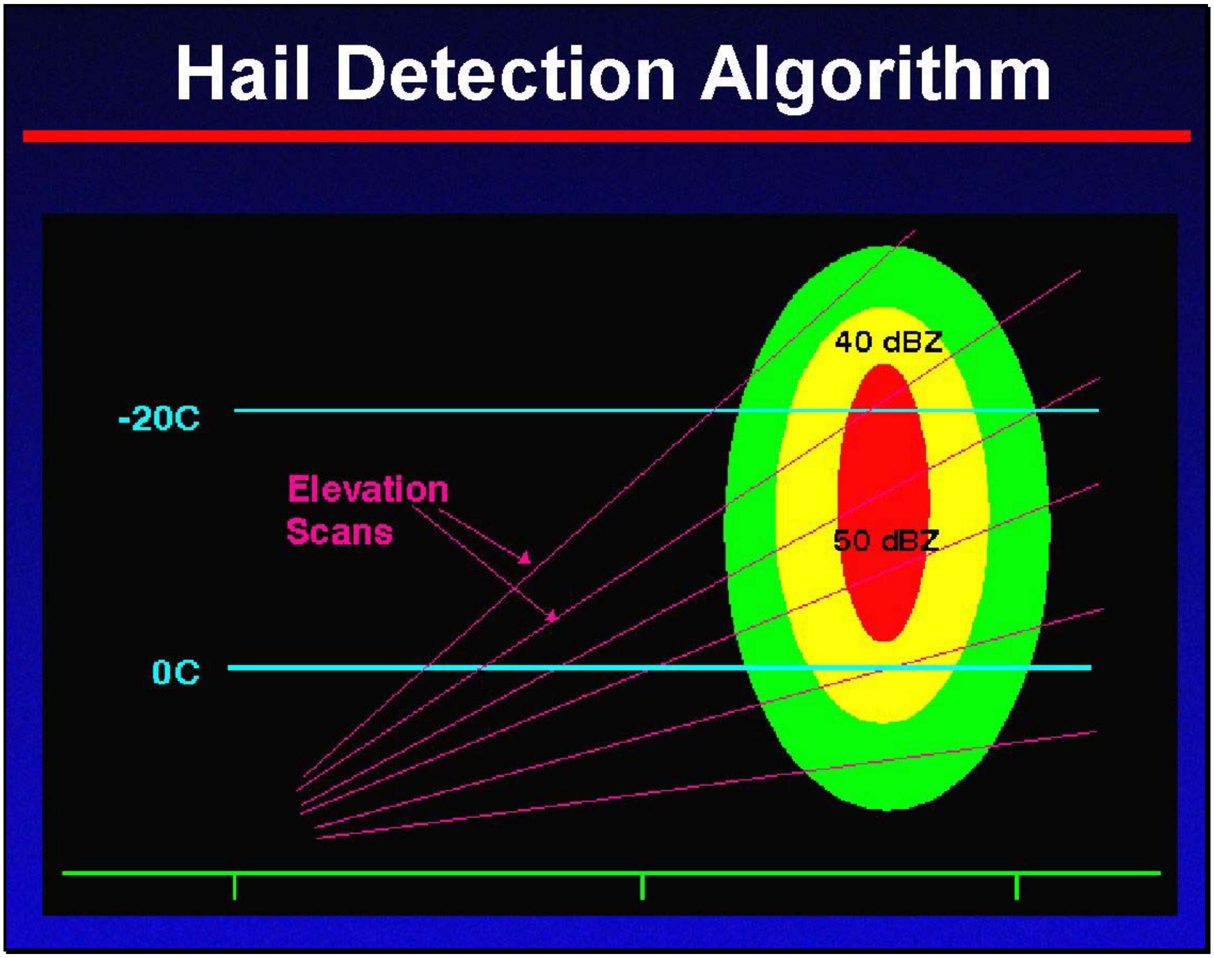

Figure 3-12
Hail Detection Algorithm Process

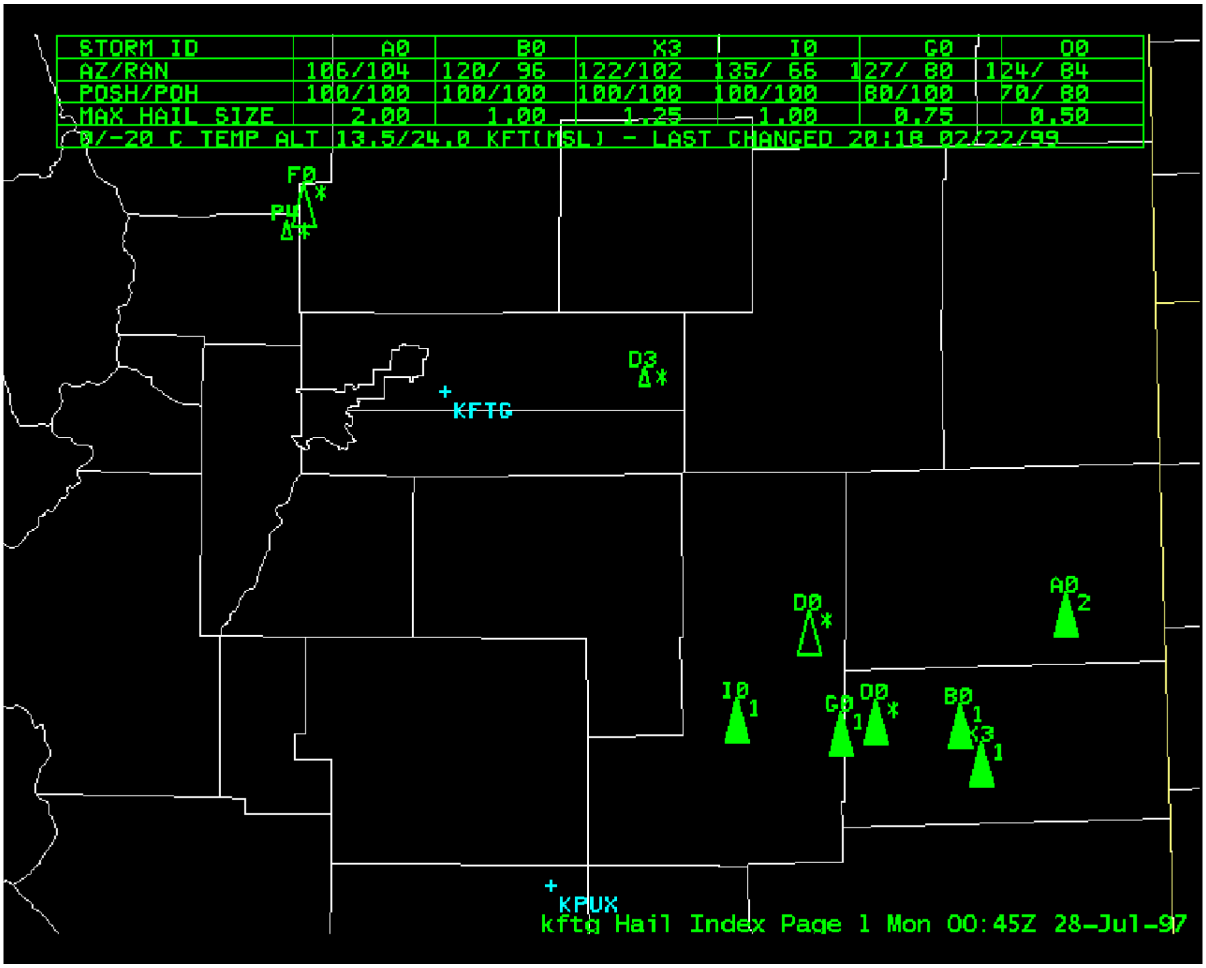

Figure 3-13
Hail Index Product

This HI example from the Denver, CO (KFTG) WSR-88D (AWIPS display) includes identification numbers for identified storms. The hail symbol is a green isosceles triangle, filled or unfilled depending on adaptable probabilities of severe hail and probabilities of hail. In addition, the maximum expected hail size rounded to the nearest inch is displayed in the middle of the triangle. The Combined Attribute Table provides alphanumeric storm information.

3.5.1 Operational Parameters.

- HEIGHT (0^{o} C): The height of the 0^{o} C environmental temperature (or freezing level), in km AGL.
- HEIGHT (-20^{o} C): The height of the -20^{o} C environmental temperature, in km AGL.
- HEIGHT (Component): The height of the center of mass of a component, in km AGL.
- HKE COEFFICIENT #1: A multiplicative factor used in computing the Hailfall Kinetic Energy ($5x10^{-4}$).
- HKE COEFFICIENT #2: A multiplicative exponential factor used in computing the Hailfall Kinetic Energy ($8.4x10^{-2}$).
- HKE COEFFICIENT #3: An operand factor used in computing the Hailfall Kinetic Energy (10).
- Maximum REFLECTIVITY (Component): Maximum (averaged) reflectivity value detected in an individual COMPONENT, in dBZ_e.
- POSH COEFFICIENT: A multiplicative factor used in computing the POSH from the SHI (29).
- POSH OFFSET: An offset used in computing the POSH from the SHI (50), in percent.
- SHI HAIL SIZE COEFFICIENT: A multiplicative factor used in calculating the MEHS from the SHI (0.1).
- SHI HAIL SIZE EXPONENT: The power to which the SHI is raised in calculating the Maximum Expected Hail Size from the SHI (0.5).
- STORM CELL: A STORM CELL is a three dimensional region composed of COMPONENTs characterized by reflectivity values above a given threshold.
- COMPONENT (Storm Cell): A COMPONENT is a two dimensional region of a STORM CELL which meets reflectivity and area thresholds, ordered from lowest to highest for each STORM CELL.
- THRESHOLD (HKE Reflectivity Weighting Lower Limit): The lower limit of reflectivity values used in the reflectivity weighting function for the POSH calculation (40), in dBZ_e.
- THRESHOLD (HKE Reflectivity Weighting Upper Limit): The upper limit of reflectivity values used in the reflectivity weighting function for the POSH calculation (50), in dBZ_e.
- THRESHOLD (minimum Reflectivity POH): Minimum maximum REFLECTIVITY (Component) used in the calculation of the POH (45), in dBZ_e.
- THRESHOLD (POH Height Difference #1): Maximum height difference which correlates to 0% POH (1.625), in km.
- THRESHOLD (POH Height Difference #2): Maximum height difference which correlates to 10% POH (1.875), in km.
- THRESHOLD (POH Height Difference #3): Maximum height difference which correlates to 20% POH (2.125), in km.
- THRESHOLD (POH Height Difference #4): Maximum height difference which correlates to 30% POH (2.375), in km.
- THRESHOLD (POH Height Difference #5): Maximum height difference which correlates to 40% POH (2.625), in km.
- THRESHOLD (POH Height Difference #6): Maximum height difference which correlates to 50% POH (2.925), in km.

- THRESHOLD (POH Height Difference #7): Maximum height difference which correlates to 60% POH (3.3), in km.
- THRESHOLD (POH Height Difference #8): Maximum height difference which correlates to 70% POH (3.75), in km.
- THRESHOLD (POH Height Difference #9): Maximum height difference which correlates to 80% POH (4.5), in km.
- THRESHOLD (POH Height Difference #10): Maximum height difference which correlates to 90% POH (5.5), in km.
- WARNING THRESHOLD SELECTION MODEL COEFFICIENT: A factor multiplied by the HEIGHT (0^{o}C) in the Warning Threshold Selection Model ($57.5x10^{2}$), in J $m^{-2}s^{-1}$.
- WARNING THRESHOLD SELECTION MODEL OFFSET: An offset used in the Warning Threshold Selection Model ($-121x10^{5}$), in J $m^{-1}s^{-1}$.

3.5.2 Strengths/Applications.

- In operational use, the MEHS parameter has provided a useful rough estimate of the maximum hail size.
- The HDA has shown a very high probability of detection in cells that contain severe hail, especially greater than one-inch diameter hail. A POSH of 50% or greater has shown skill as a warning threshold.

3.5.3 Limitations.

- The HDA needs as input, accurate and timely measurements of the MSL altitudes for the 0°C and -20°C levels. Failure to update this information will degrade the algorithm’s performance.
- Values of POH, POSH, and MEHS will fluctuate at close ranges, especially in VCP 21, due to gaps in coverage at higher elevation slices.
- The values for POH, POSH, and MEHS may fluctuate at longer ranges from the radar due to the limited number of slices through the cell.
- The maximum hail processing range is 230 km (124 nm). For cells beyond 230 km (124 nm), hail will be identified as UNKNOWN.
- POSH and MEHS tend to overestimate the chances and size of hail in weak wind and tropical environments where freezing levels are higher and more melting during descent occurs. The accuracy of the hail estimates partially depends upon the accuracy of cell (component) information. MEHS is an estimation of the largest hail in the cell, and often times, most of the hail from a cell is smaller.

3.6 <u>Legacy Mesocyclone Detection</u>. The legacy Mesocyclone Detection Algorithm (M) uses a pattern recognition technique to detect mesocyclones. This technique defines a process used for searching through Doppler velocity data for symmetric regions of large azimuthal shear. The Mesocyclone Detection Algorithm is based on the extraction of significant attributes that characterize mesocyclones. The first step is to search for a consistent increase of Doppler velocity in the azimuthal direction at a constant range with clockwise antenna rotation. (A consistent decrease of Doppler velocity is required for counterclockwise antenna rotation.) A "pattern vector" is formed when a series of azimuthally adjacent sample volumes of increasing or decreasing Doppler velocity ends. A pattern vector contains seven components: the slant range, the azimuth angles at both ends of the series, the Doppler velocities that correspond to those azimuth angles at the slant range, and the tangential shear and angular momentum. A pattern vector that does not have the magnitudes of angular momentum and azimuthal shear typical of mesocyclones is discarded. The remaining pattern vectors are consolidated to form "features." A "feature" is a set of pattern vectors in close proximity. If a feature is too small it is discarded. If a feature is sufficiently large, but not symmetrical, it is classified as a shear region. Sufficiently large, symmetrical shear regions are characteristic of mesocyclones. If these regions are in close vertical proximity, a mesocyclone is identified. Lesser shear regions in close vertical proximity identify 3-dimensional shear regions. The remaining features characterize uncorrelated shear.

3.6.1 Operational Parameters.

- AZIMUTH: Azimuthal position, in radians.
- ELEVATION: Elevation angle, in radians.
- RADIUS (Earth): The radius of the Earth (6371), in km.
- RANGE (Slant): The slant range to the center of a SAMPLE VOLUME, in km.
- SAMPLE VOLUME: A data sample volume whose dimensions are 1 degree in azimuth, 0.25 km in range, and 1 degree in depth (perpendicular to the radar beam).
- THRESHOLD (Feature Height): A value that represents the maximum height of possible mesocyclone FEATUREs (8), in km.
- THRESHOLD (High Momentum): A value which represents the minimum magnitude of angular momentum expected in a mesocyclone in the presence of low shear (540.0), in km^2/hr.
- THRESHOLD (Radial Distance): A value which represents the maximum distance in the radial direction between PATTERN VECTORs within the same FEATURE (0.75), in km.
- THRESHOLD (Meso cyclone-High Shear): A value which represents the minimum magnitude of shear expected in a mesocyclone in the presence of low angular momentum (14.4), in 1/hr.
- THRESHOLD (Low Momentum): A value which represents the minimum magnitude of angular momentum in a mesocyclone (180.0), in km^2/hr.
- THRESHOLD (Meso Shear): A value which represents the minimum cyclone Low magnitude of shear expected in a mesocyclone (7.2), in 1/hr.
- THRESHOLD (Meso Azimuth): A value that represents the maximum cyclone tangential separation of PATTERN VECTORs to be considered part of the same FEATURE (0.034), in radians.
- THRESHOLD (Pattern Vector): A value which represents the minimum number of PATTERN VECTORs required to build a FEATURE (10.0).
- THRESHOLD (Far Ratio): A maximum value which represents the Maximum upper bound of a range of values related to the ratio of radial and azimuthal diameters of a FEATURE at ranges further than THRESHOLD (Range) (4.0).
- THRESHOLD (Far Minimum Ratio): A minimum value which represents the lower bound of a range of values related to the ratio of radial and azimuthal diameters of a FEATURE at ranges further than THRESHOLD (Range) (1.6).

- THRESHOLD (Maximum Ratio): A maximum value which represents the upper bound of a range of values related to the ratio of radial and azimuthal diameters of a FEATURE at ranges closer than THRESHOLD (Range) (2.0).
- THRESHOLD (Minimum Ratio): A minimum value which represents the lower bound of a range of values related to the ratio of radial and azimuthal diameters of a FEATURE at ranges closer than THRESHOLD (Range) (0.5).
- THRESHOLD (Range): A variable that represents the range at which long-range symmetry criteria take effect, in km (140.0 km).
- VELOCITY (Doppler): Doppler velocities in a SAMPLE VOLUME, in km/hr.

3.6.2 Strengths/Applications.

- The algorithm automatically processes 3-dimensional velocity data to identify regions that may contain operationally significant mesocyclones.
- A mid-level mesocyclone that lowers toward the surface may indicate a tornado is developing.

3.6.3 Limitations.

- The operator should use the algorithm as a safety net and manually examine reflectivity, velocity/SRM to verify the existence of operationally significant mesocyclones.
- Algorithm does not consider time continuity; consequently, transient, operationally insignificant circulations are identified.
- The radar horizon and cone-of-silence can prevent the radar from detecting circulations at times.
- Velocity signatures may be obscured or degraded where there are improperly dealiased velocity data or where data are obscured by range-folded echoes.
- The algorithm only requires two vertically linked elevation angles. No storm depth criteria are applied. Operationally insignificant circulations are identified.
- The algorithm only detects cyclonic rotations, not anticyclonic rotations.
- Identification is influenced by aspect ratio.
- Don't know which elevation angle to examine shear. - Attribute Table and mesocyclone Alphanumeric Product only give height.
- Range thresholds may discard or improperly classify mesocyclones. No data within 10 km (5.4 nm) is processed by the Mesocyclone Algorithm.
- The Mesocyclone Algorithm uses no reflectivity structures (BWER, Hook Echo, etc.) to identify tornadic circulations.
- Shear thresholds are not continuously variable with range, rather they are step-wise which introduces a nonrealistic effect. Because of averaging across the beam that spreads with increasing range, real shears between inbound and outbound velocity maxima do continuously decrease with range. More elaborate shear thresholds would perform better. However, there is an inherent distance limitation for signature recognition, due to spreading of the beam versus signature size.
- Algorithm default values adapted for classic supercells.
- Various operational parameters need to be optimized for best performance.

3.7 <u>Mesocyclone Detection Algorithm</u>. This section describes the primary modules 1D, 2D, and 3D processing steps of the MDA. For completeness, this section also includes a brief overview of other MDA modules; tracking, and trending. The major steps in MDA are as follows: 1) threshold velocity data by reflectivity value; 2) identify MDA 1D Features; 3) identify MDA 2D Features; 4) identify MDA 3D Features; 5) classify MDA 3D Features; 6) track MDA 3D Features; 7) trend MDA 3D Features.

3.7.1 MDA Overview. The MDA uses pattern recognition techniques to detect mesocyclones. These techniques define a process used for searching through Doppler velocity data for symmetric regions of large azimuthal shear. The MDA is based on the extraction of significant attributes which characterize mesocyclones.

The MDA locates mesocyclones where a mesocyclone is defined as a three-dimensional region in a storm which rotates (usually cyclonically), and is closely correlated with severe weather. The MDA uses the systematic procedure described below.

The MDA uses radial velocity and reflectivity data to detect storm-scale (1 - 10 km (0.54 – 5.4 nm)) cyclonic vortex signatures and diagnose the attributes of the detected signatures to determine if they are associated with tornadoes and/or damaging wind. The algorithm starts by identifying one-dimensional (1D) shear segments (pattern vectors) from mean radial velocity data. To help limit the search for circulations to those associated with storm cells, the algorithm only searches velocity data from sample volumes that have reflectivities above THRESHOLD (minimum Reflectivity) and are below THRESHOLD (maximum Shear Segment Height). Shear segments (pattern vectors) are an azimuthal run of velocities whose gate-to-gate shear is continuously cyclonic. Gate-to-gate means the sample volumes are from adjacent radials and at the same range. A look-ahead function, that is range dependent, mitigates problems with small perturbations in shear during shear segment construction. All shear segments must also pass strength and length criteria.

Shear segments on each elevation scan in azimuthal and radial proximity are combined into potential two-dimensional (2D) features. Using multiple strength rank thresholds, 2D vortex cores of different strength rank are isolated from broader regions of 2D azimuthal shear. Strength rank is a function of rotational velocity, shear, and range. If a potential 2D feature still has enough shear segments and meets an aspect ratio criteria, it is checked for overlap with all previously saved 2D features on the elevation scan. If weaker features overlap stronger features, the weaker features are discarded.

2D features from adjacent elevation scans are vertically correlated into potential three-dimensional (3D) features. The mesocyclone 3D features are associated with storm cells and their attributes are computed and saved.

After all 3D mesocyclone features have been identified, features are time associated. A first guess location is made, using a motion vector from the previous volume scan. 3D features within a certain radius of the first guess point become association candidates. Additional 3D features are also added as potential candidates for association as radii are increased around the first guess point. The best candidate for time association is found by sorting the candidates within each distance threshold first by strength rank and then by circulation type. The 4D detections are classified by vortex type (e.g., Mesocyclones, Low-core mesocyclones) and the classifications are saved for display purposes. Attributes of 4D detections are used to calculate time trends. Trend and time-height information of tracked 4D detection attributes are saved for display purposes.

At the display device, 4D detection attributes, their classifications, and characteristics are presented in an attribute table. Graphical overlays communicate vortex type (e.g., Mesocyclones, Low-core mesocyclones), location, and strength to forecasters. Feature strength can be used by forecasters to remove weaker detections from overlay displays that become too cluttered.

3.7.2 One-Dimensional (1D) Features. Shear segments, 1D features, are identified on each elevation scan from velocity data in azimuthally adjacent radials. It is assumed the radar rotates clockwise, and the radials are approximately 1 degree in azimuthal width with no gaps between radials. The counter-clockwise velocity difference is computed for each pair of sample volumes (from adjacent radials) that are constant in range, closer than THRESHOLD (maximum Shear Segment Distance), below THRESHOLD (maximum Shear Segment Height) ARL, and coincide with reflectivity values above THRESHOLD (minimum Reflectivity). If a pair of sample volumes has a positive velocity difference (cyclonic shear) or the first (most counter clockwise) velocity value is valid and the second is missing, then a shear segment is started. If the first or both velocity values are range folded or missing, a shear segment is not started. If subsequent velocity data at the same range exhibits anticyclonic shear with respect to the first velocity value in the shear segment, the shear segment is ended at the last velocity value exhibiting cyclonic shear, including look-ahead radials. When subsequent negative or neutral azimuthal shear is computed or missing or range folded data is found, the algorithm looks ahead a number of radials which varies with range. If the next non-missing, non-range folded velocity value exhibits cyclonic shear with respect to the last non-missing, non-range folded velocity value, look-ahead mode is canceled and cyclonic shear is again searched for and the shear vector becomes larger. If the number of look-ahead radials is exceeded, the vector is ended with the last velocity value exhibiting cyclonic shear.

All 360 radials in a sweep are processed as shear vectors are identified. At the end of the 360-degree sweep, processing continues until all 1D features that are open are closed. This overlap processing allows 1D features to overlap the beginning / ending radial so that all shear regions around the beginning radial can be identified. If the number of 1D features in the volume scan meets or exceeds THRESHOLD (maximum # 1D Features), then processing immediately skips over the remainder of the 1D identification step and proceeds to the 1D attribute identification.

For each shear segment the following information is computed: beginning Az (azimuth), ending Az, beginning velocity, ending velocity, shear segment delta V (Ending velocity - beginning velocity), length of the shear segment (distance between beg Az and end Az), shear (delta V / length of the shear segment), max gate-to-gate delta V of any two adjacent radials, azimuth of the max gate-to-gate delta V, range, and strength rank.

One-Dimension feature strength ranks are selected from a look-up table of range dependent values of velocity difference and shear. Each entry is scanned from lowest to highest strength rank. The shear segment strength rank is the largest rank in which 1) the shear segment Gate-to-Gate delta velocity is above THRESHOLD (minimum Velocity Difference), a range dependent threshold or 2) the shear segment velocity difference is greater than THRESHOLD (minimum Velocity Difference) and shear segment shear is greater than THRESHOLD (minimum Shear), a range-dependent threshold. If the computed strength rank is less than 1, then the shear segment is discarded.

If the length of a shear segment exceeds THRESHOLD (maximum Shear Segment Length), then the shear segment is considered to be too long. The algorithm searches within the shear segment, beginning with the first velocity, to see if an embedded vector is present that passes the strength thresholds for the next larger strength rank than the original "long" shear segment. If a next larger strength rank vector is found, the Cartesian length of the core shear segment that was found is computed. If the length of the core shear segment is more than THRESHOLD (maximum Core Shear Segment Length) then the strength rank is increased by one and a new core shear segment is sought. This process is repeated until the Cartesian length of the core shear segment is less than or equal to THRESHOLD (maximum Core Shear Segment Length). At this point the shear-segment attributes of the core shear segment are re-computed, and the shear segment is saved. If a core shear segment cannot be found whose length is less than or equal to THRESHOLD (maximum Core Shear Segment Length), the entire original "long" shear segment is discarded.

The final output of the 1D analysis is a list of shear segments and 11 of their attributes.

3.7.3 Two-Dimensional (2D) Features. Once all shear segments have been identified on an elevation scan, they are combined into potential two-dimensional (2D) features. Processing begins with the first available shear segment that has a maximum strength rank. If any other shear segment with the same strength rank as the first segment overlaps in azimuth and is separated in range by no more than THRESHOLD (maximum 2D Construction Radial Distance) from the original segment, then the shear segment is added to the 2D feature. Once all shear segments that have maximum strength rank are checked for proximity, another 2D feature is started by selecting an unused shear segment that has the maximum strength rank. A search is conducted for other shear segments that meet azimuth and distance criteria. This process continues until all possible 2D features of maximum strength rank are found. If the total number of shear segments in a 2D feature is less than THRESHOLD (minimum # Shear Segments) or if any feature extends less than THRESHOLD (minimum 2D Radial Diameter) in the radial direction, the 2D feature is discarded.

Each potential 2D feature at the initial, maximum, strength rank is examined for overlapping shear segments. If any shear segments within a feature have the same range, then their combined length is calculated. If the combined shear segment has a length greater than THRESHOLD (maximum Shear Segment Length), then the weaker (based on the shear-segment rotational velocity) is discarded. If both shear segments used to produce the combined shear segment are the same strength and the maximum shear-segment length has been exceeded, then the entire shear segment is discarded. Otherwise, the two shear segments are combined into one and the shear-segment attributes are re-computed.

The algorithm then computes the potential 2D feature aspect ratio. If the 2D feature aspect ratio (radial distance / azimuthal distance) is greater than or equal to THRESHOLD (maximum Aspect Ratio) or less than or equal to THRESHOLD (minimum Aspect Ratio), the 2D feature is discarded. 2D features having a total number of segments less THRESHOLD (minimum # Shear Segments) or a diameter greater than or equal to THRESHOLD (maximum 2D Diameter) are discarded. Two-dimensional features that have an azimuth of the maximum inbound velocity which is greater than the azimuth of the maximum outbound velocity are also discarded.

The next step is to build a list of potential 2D features by grouping shear segments that have the next smaller rank with those that have the maximum strength rank. Processing is the same, as described above. All 2D features are checked for overlapping shear segments, appropriate aspect ratios, total number of shear segments, threshold radius, and azimuth of maximum inbound and outbound velocities. Two-dimensional features are built for each of the strength rank categories from maximum to minimum rank. Each iteration includes shear segments from the current and all higher ranks. Shear segments are reused in different features. All unused shear segments are discarded.

If and when the number of 2D features in the volume scan meets or exceeds THRESHOLD (maximum # 2D Features), then processing immediately skips over the remainder of the 2D identification step and proceeds to the 2D classification step.

Attributes for each potential 2D feature are computed, including 2D feature strength rank. If certain thresholds and criteria are not met, the potential 2D feature is discarded.

The Az/Ran of max v and Az/Ran of min v for each 2D feature are computed. A running average of max v and min v across 3 shear segments within each 2D feature are also computed. The result is a smooth max v and smooth min v for the 2D feature. The following attributes are computed for all 2D features: rotational velocity = abs (smooth max v - smooth min v)/ 2, shear = rotational velocity divided by the distance between max v and min v, centroid location = Az/Ran of the midpoint of the line between max v and min v, centroid height, diameter = the distance between max v and min v, maximum GTGDV for all shear segments in the 2D feature, max and min azimuth and range bounded by the max v and min v points, and elevation angle. The 2D feature attributes and strength rank are saved.

The next step is to extract azimuthal shear cores on an elevation slice. This analysis begins by comparing locations of 2D features of highest strength rank with those having the next lower strength rank. If a feature with lower rank does not contain, within its azimuth and range boundaries, a 2D feature of next higher rank, then the 2D feature and its attributes including its strength rank is retained. If any shear segments are shared between a 2D feature of smaller strength rank and a feature of higher strength rank or if a centroid of a feature of larger strength rank is within the maximum range and azimuthal extent of another feature of lesser strength rank, then the lower strength rank feature is retained. If a lower strength rank feature overlaps more than one feature of higher strength rank, then the lower strength rank feature is discarded and the higher strength rank features are retained as individual 2D features. Feature core extraction is repeated comparing features with highest strength rank values with features of all smaller strength rank values. Comparisons continue in a double loop structure where all features of higher strength rank value are compared to all features with smaller strength rank values. The last iteration compares all rank 2 features with all rank 1 features.

By extracting the feature cores and reconstructing 2D features from features of different strength rank, as described above, some 2D features may contain new values for max v, min v, max GTGDV, and shear. This processing leads to a change in the 2D feature strength rank; therefore, strength rank needs to be re-computed for each 2D feature.

At the end of 2D processing, 23 attributes are saved for each 2D feature.

3.7.4 Vertically-Associated 3-Dimensional (3D) Features. Once all of the 2D features have been constructed and saved for the second two tilts, the algorithm vertically correlates the 2D features from different elevation scans into vertically-associated 3D features. Processing begins with any 2D feature on the first tilt. A list is assembled of all 2D features on the second tilt whose center is within THRESHOLD (minimum 2D Association Distance) of the 2D feature on the first tilt. If there are more than one, the list of second tilt candidates is sorted first by strength rank and then by distance. Next, all of the 2D features on the second tilt are found that are within a specified annulus size of the center of the 2D feature on the first tilt. If more than one candidate exists, second tilt candidates are sorted first by strength rank and then by distance. Then, the second tilt candidates from the specified annulus are added to the bottom of the list of candidate that were in the second search area. The algorithm repeats this process until the search radius annulus equals THRESHOLD (maximum 2D Association Distance). All the previous 3D processing steps are repeated for all 2D features on the first tilt. In the end, each 2D feature on the first tilt has a list of sorted candidates associated with it.

Next, the algorithm guarantees that each 2D feature on the higher elevation is used only once or not at all. A check is made to see if any 2D features on the higher elevation appear first in the candidate list of more than one lower elevation 2D feature. If so, the first higher elevation 2D feature on the list of a lower elevation 2D feature whose center is closer is retained as the first element in its list. The higher elevation 2D feature at the top of the list of the lower elevation 2D feature whose center is farther away is removed from the candidate list and the second candidate 2D feature is promoted to the top in the list. This process continues until each 2D feature on the higher elevation is uniquely associated (first on the list of candidates) with one 2D feature on the lower elevation. If any feature from the higher elevation scan cannot be vertically associated with another lower elevation 2D feature because it is first on the candidate list, or if the higher elevation feature becomes unassociated from all lower 2D features, the higher elevation 2D feature remains un-associated, possibly becoming a candidate for association with a 2D feature on the next higher elevation. In the end, each 2D feature on the lower elevation is associated with the first candidate from the list of 2D features on the higher elevation. These associations result in 3D features. Each 2D feature on the first tilt is used only once or not at all.

The algorithm then creates candidate lists for all the 2D features on the third tilt from those on the second tilt and makes sure that 2D features on the second tilt are used only once or not at all. This process progresses up through the volume scan stopping when the top elevation scan is reached and all 3D features have been identified.

If and when the number of 3D features in the volume scan meets or exceeds THRESHOLD (maximum # 3D Features), then processing immediately skips over the remainder of the 3D identification process and proceeds with the 3D classification process.

All unused 2D features are discarded. Several calculated attributes are now described.

A mesocyclone strength index (MSI) is calculated for each 3D feature. Strength ranks of all 2D feature components are multiplied by 1000, weighted by the average air density in a standard atmosphere, and integrated vertically across the half-power beam width depth at the height of the 2D feature. Integration is done from the feature's base (plus the half-beam width depth) to its top (plus half-beam width depth) or THRESHOLD (maximum 3D Couplet Core Top), whichever is lower in altitude. The integrated value is divided by the total depth (with half-power beam width added).

An MSI rank is calculated for each 3D feature. The algorithm vertically integrates rotational velocity, shear, and gate-to-gate delta V in the same manner as strength ranks were integrated in the calculation of MSI. An MSI rank is assigned to each 3D feature by looking up rank values associated with integrated values of rotational velocity, shear, and gate-to-gate delta V in a table.

A 3D strength rank, core base, core top, and core depth are calculated for all 3D features. The 3D strength rank is defined as the strongest continuous core of 2D features of a given strength rank that is at least 3 km (1.6 nm) of half-beam width in depth. The base of the core must be below 5 km and the top of the core must be at or below 8 km (4.3 nm). The 3D strength rank, core base, core top, and core depth are associated with each 3D feature.

Fifty-seven attributes, some derived from 3D features themselves and some calculated, are saved for later use. Ten attributes and their height values from 2D features that are components of 3D features are saved for time-height cross-sections.

3.7.5 Rapid Update. Rapid update allows MDA to output 3D feature information at the end of every tilt, beginning with the first tilt, rather than at the end of the volume scan. As 3D features are built, 3D feature information is updated so that forecasters can see if 3D features are increasing in intensity. Rapid update increases algorithm output lead-time, allowing forecasters more time to view algorithm output and issue severe weather warnings.

After 2D features have been identified on the first tilt of a new volume scan, their locations are compared to forecast locations of 3D features from the previous volume scan. This comparison is described in the time association step of the MDA tracking module. The time association information defines 3D feature tracks. After time association, before MDA processes data from the second tilt, the direction and speed of each detection is computed and the position of severe weather feature icons and table attribute information on the display are updated for the current volume scan. Low-level attributes of the 2D feature on the current volume scan; low-level diameter, low-level rotational velocity, low-level shear, and low-level gate-to-gate velocity difference; are assigned and the rest of the attributes (e.g., circulation type, mesocyclone strength index, maximum rotational velocity, maximum shear) are inherited from time associated 3D features detected on the previous volume scan.

The 3D features that are not time associated with 2D features found on the new volume scan are identified as “extrapolated” features. If 3D features from the previous volume scan are associated with features on the current volume scan, their classification is changed from extrapolated to matched. Extrapolated features that are not matched by the time the radar beam reaches three km over the previously detected feature base height are removed from the product.

When the RDA provides radar data from higher tilts, 1D and 2D features are identified by MDA. New 2D features are vertically associated with adjacent-tilt 2D features, 3D features, or retained as potential bases of new 3D features. Feature attributes are updated when: 1) a new 3D feature is identified during the current volume scan; 2) feature attributes indicate a mesocyclone is increasing in severity; or 3) all information has been obtained for a mesocyclone (i.e., the feature is topped).

At the end of the volume scan MDA computes an average motion and speed of all 3D features and computes forecast positions for all 3D features and the resulting product is generated (Figures 3-14 and 3-15).

3.7.6 External Interfaces. MDA interfaces with the SCIT [Centroids] Algorithm to obtain an average storm depth of the 10 strongest storm cells. Storm cell strength is based on SHI and maximum reflectivity. The average storm depth is used to determine if a 3D velocity feature meets criteria to classify the MDA detection as a low-core circulation.

MDA also uses SCIT information to associate each 3D velocity feature with a storm cell. This association information can be used in the storm attribute table to let the user know that a storm cell has a mesocyclone associated with it.

3.7.7 Adaptable Parameters. The MDA has many adaptable parameters to allow maximum flexibility in fine-tuning algorithm performance. The vast majority of the parameters are intended for ROC use only, not for users to change during operations.

Users are allowed to activate or deactivate a display filter and to specify a minimum strength rank value, below which 3D features are marked for non-display. Users are also allowed to activate or deactivate a switch that allows forecasters to define their own mesocyclone criteria. By default, MDA requires mesocyclones to have predefined values for minimum strength rank, maximum base height, and minimum depth.

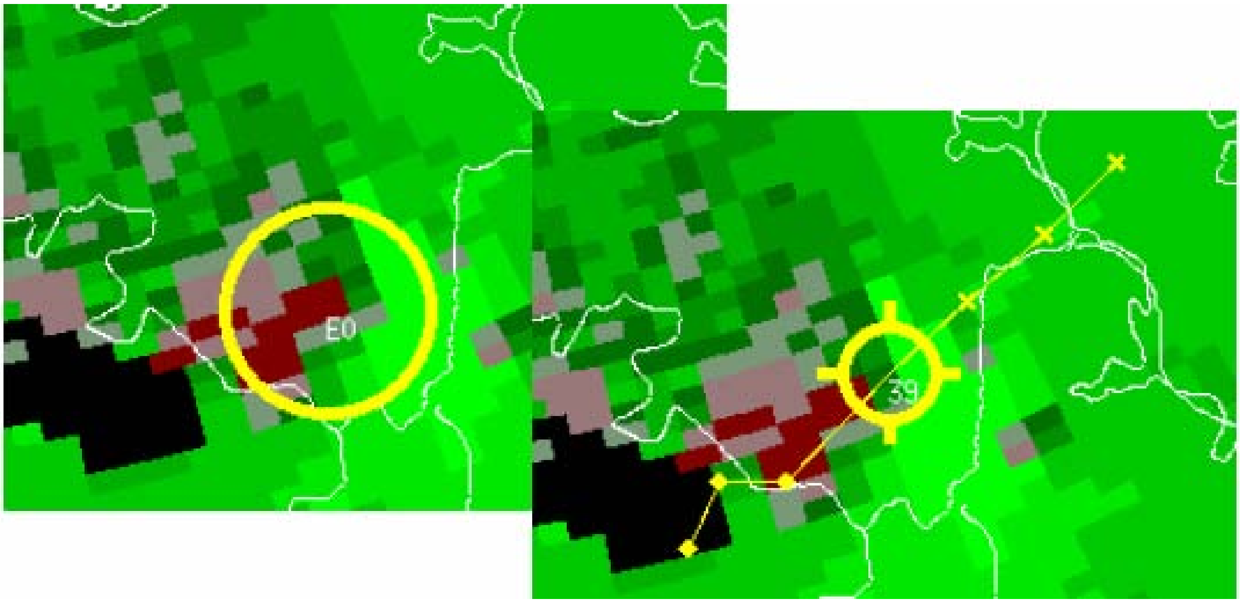

Figure 3-14
Mesocyclone Product Comparison

Legacy Mesocyclone (M) (upper left) versus MD (lower right) product difference in circulation depiction. MD detections with spikes indicate that the circulation was detected on the lowest radar elevation tilt. The MD detections without spikes, regular circles, indicate that the circulation was detected aloft.

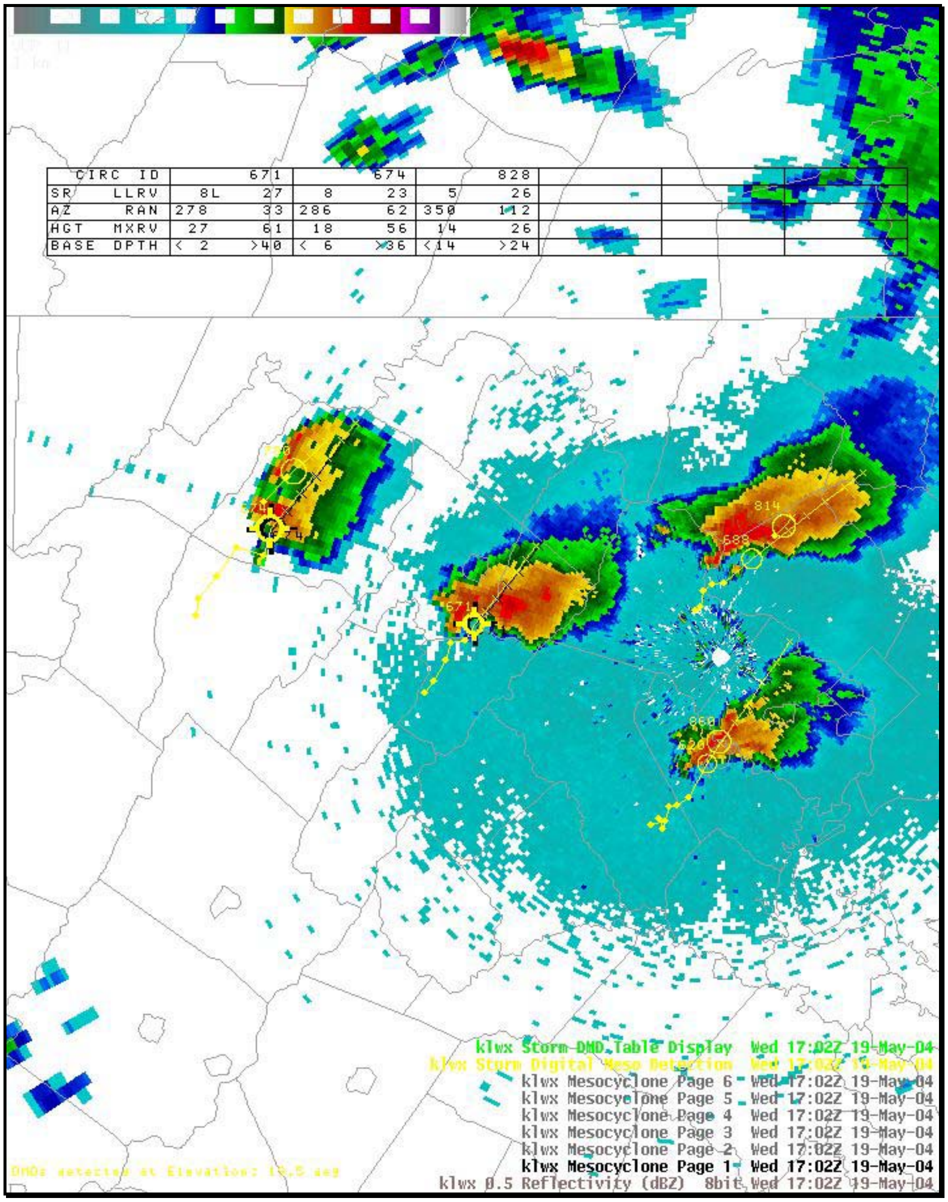

Figure 3-15
Mesocyclone Detection Product Overlaid on a Reflectivity Product

This MDA example (AWIPS display) includes identification numbers for identified storms. The yellow symbols are related to the circulation strength rank for the cell (less than 5 is a thin, yellow, open circle; greater than or equal to 5 is a thick open circle), the diameter of the circle is based on the diameter of the circulation. Past position symbols are indicated by solid diamonds. Forecast position symbols are indicated by Xs. The Combined Attribute Table provides alphanumeric storm information.

3.7.8 Operational Parameters.

- AZIMUTH: Azimuthal position, in radians.
- ELEVATION: Elevation angle, in radians.
- RADAR (Beam Width): Width of the radar beam. Values may range from 0.0 to 10.0 degrees and the precision is at least 0.1 degree.
- RADAR (Height): Height of the RDA in km.
- RADIAL: The set of sample volumes, only one at each RANGE (Slant), along a constant AZIMUTH and ELEVATION.
- RADIUS (Earth): The radius of the Earth (6371), in km.
- RANGE (Slant): The slant range to the center of a SAMPLE VOLUME, in km.
- REFLECTIVITY FACTOR: The effective radar reflectivity factor (SAMPLE VOLUME) assigned to a (velocity) SAMPLE VOLUME, in dBZ_e.
- SAMPLE VOLUME: A data sample volume along a radial whose (half power) dimensions are described by the azimuthal and vertical beam widths and the RANGE (Slant) sampling interval. These dimensions are approximately 1 degree in azimuthal and vertical width (perpendicular to the beam) and 0.25 km (0.13 nm) in RANGE (Slant) (or length) for Velocity sample volumes and 1.0 km (0.54 nm) in RANGE (Slant) for Reflectivity (Factor) sample volumes.
- VELOCITY (Sample Volume): The mean radial velocity of a SAMPLE VOLUME, in m/s.
- STANDARD ATMOSPHERE AIR DENSITY LOOK-UP TABLE VALUES: The Standard Atmosphere Air Density is used to calculate the 3D Feature (MSI). The Standard Atmosphere Air Density is interpolated from a table of look-up values.
- THRESHOLD (minimum Reflectivity): Minimum reflectivity (dBZ) needed to process radial velocity data; default 0 dBZ, range = -25 dBZ_e (process all data) to 35 dBZ_e (process precipitation data only), precision: 1 dBZ_e. This adaptable parameter should have URC level of change authority.
- THRESHOLD (maximum Shear Segment Height): The height above which shear segments are not identified; default 15 km (8.1 nm), range 1 to 15 km, precision: 1 km (0.54 nm). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum Shear Segment Distance): The Range (Slant) beyond which shear segments are not identified; default 230 km (124 nm), range 0 to 230 km (124 nm), precision: 1 km (0.54 nm). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum # 1D Features): Maximum number of 1D Features the algorithm can process per elevation scan; default 5000, range 2000 to 5000, precision: 1. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum # 2D Features): Maximum number of 2D Features the algorithm can process per elevation scan; default 500, range 400 to 1000, precision: 1. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum # 3D Features): Maximum total number of 3D Features the algorithm can process per volume scan; default 500, range 100 to 500, precision: 1. This configuration parameter can be used to change MDA's functionality.

- THRESHOLD (minimum # Shear Segments): Minimum number of 1D shear segments needed to declare a group of segments a 2D shear feature. For example, if you want a minimum diameter of 1 km (0.54 nm) for the 2D features, then divide diameter (1 km (0.54 nm)) by the gate spacing (250 m (0.13 nm)) to get the minimum number of shear segments per 2D feature equal to 4; default 4, range 3 to 8, precision: 1. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (minimum Strength Rank): Minimum strength rank to locate shear segments, rank 2D features, and rank 3D features; default 1, range 1 to 5, precision: 1. Value must be less than or equal to maximum Strength Rank. See Table 1 in Appendix A. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum Strength Rank): Maximum strength rank to locate shear segments, rank 2D features, and rank 3D features; default 25, range 5 to 25, precision: 1. Value must be greater than or equal to minimum Strength Rank. See Table 1 in Appendix A. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (minimum Velocity Difference): Minimum velocity difference (ms^{-1}) needed to save 1D azimuthal shear segments. This value is also used as the minimum gate-to-gate velocity difference (ms^{-1}) needed to save 1D azimuthal shear segments. The parameter is also part of an array, from 1 to 25, corresponding to the thresholds for strength ranks of 1 to 25; default is range dependent, See Table 1 in Appendix A, range 7.5 to 130.0 ms^{-1}, precision: 0.5 $m\ s^{-1}$. This parameter is RANGE (Slant)-dependent. Values given in Table 1 in Appendix A are applied to RANGE (Slant) from 0 to THRESHOLD (beginning range Linear Reduction). If the RANGE (Slant) to the shear segment is between THRESHOLD (beginning Range Linear Reduction) and THRESHOLD (ending Range Linear Reduction), the velocity difference values in Table 1 in Appendix A are modified so that their values at THRESHOLD (beginning Range Linear Reduction) are as given in Table 1 in Appendix A, at THRESHOLD (ending Range Linear Reduction) the velocity difference values in Table 1 in Appendix A are reduced by 75%, and at intermediate RANGES (Slant), the velocity difference values are interpolated linearly between the THRESHOLD (beginning Range Linear Reduction) and THRESHOLD (ending Range Linear Reduction) values. Beyond THRESHOLD (ending Range Linear Reduction), the minimum velocity difference is kept at 75% of the original values shown in Table 1 in Appendix A. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (minimum Shear): Minimum shear ($ms^{-1}\ km^{-1}$) needed to save 1D azimuthal shear segments. The parameter is also part of an array, from 1 to 25, corresponding to the thresholds for strength ranks of 1 to 25; default See Table 1 in Appendix A, range 1.75 to 21.00 $ms^{-1}\ km^{-1}$, precision: 0.25 $ms^{-1}\ km^{-1}$. This parameter is RANGE (Slant)-dependent. Values given in a table are applied to RANGES (Slant) from 0 to THRESHOLD (beginning Range Linear Reduction). If the RANGE (Slant) to the shear segment is between THRESHOLD (beginning Range Linear Reduction) and THRESHOLD (ending Range Linear Reduction), the shear values in Table 1 in Appendix A are modified so that their values at THRESHOLD (beginning Range Linear Reduction) are as given in Table 1 in Appendix A, at THRESHOLD (ending Range Linear Reduction) the shear values in the table are reduced by 50%, and at intermediate RANGES (Slant), the shear values are interpolated linearly between the THRESHOLD (beginning Range Linear Reduction) and THRESHOLD (ending Range Linear Reduction) values. Beyond THRESHOLD (ending Range Linear Reduction), the minimum shear is kept at 50% of the original values in the table. This configuration

parameter can be used to change MDA's functionality.

- THRESHOLD (beginning Range Linear Reduction): The beginning RANGE (Slant) at which the velocity difference and shear thresholds start to drop off linearly. Used in conjunction with Table 1 in Appendix A; default 100 km (54 nm), range 0 to 230 km (124 nm), precision: 1 km (0.54 nm). Value must be less than THRESHOLD (ending Range Linear Reduction). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (ending Range Linear Reduction): The ending RANGE (Slant) at which the velocity difference and shear thresholds start to drop off linearly. Used in conjunction with Table 1 in Appendix A; default 200 km (108 nm), range 0 to 230 km (124 nm), precision: 1 km (0.54 nm). Value must be greater than THRESHOLD (beginning Range Linear Reduction.) This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum Shear Segment Length): Maximum length (km) allowed for a shear segment. This assumes that a stronger "core" shear segment does not exist within the shear segment under consideration; default 10 km (5.4 nm), range 5 to 15 km (2.7 to 8.1 nm), precision: 1 km (0.54 nm). The THRESHOLD (maximum Shear Segment Length) must be greater than or equal to THRESHOLD (maximum Core Shear Segment Length). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum Core Shear Segment Length): Maximum length (km) allowed for a shear segment whose "core" region is used in lieu of the full length of the actual shear segment because the original shear segment is more than THRESHOLD (maximum Shear Segment Length). Shear segments whose core region is larger than THRESHOLD (maximum Core Shear Segment Length) are discarded; default 10 km (5.4 nm), range 5 to 15 km (2.7 to 8.1 nm), precision: 1 km (0.54 nm). THRESHOLD (maximum Core Shear Segment Length) must be less than or equal to THRESHOLD (maximum Shear Segment Length.) This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum # Shear Segments): The maximum number of shear segments allowed per 2D feature, default 200 shear segments, range 50 to 200, precision: 1. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum Aspect Ratio): The maximum aspect ratio (RANGE (Slant) divided by AZIMUTH) allowed for a 2D feature; default 2.0, range 1.0 to 4.0, precision: 0.5. The THRESHOLD (maximum aspect ratio) must be greater than THRESHOLD (minimum Aspect Ratio). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (minimum Aspect Ratio): The minimum aspect ratio (RANGE (Slant) to AZIMUTH) allowed for a 2D feature; default 0.0, range 0.0 to 2.0, precision: 0.5. The THRESHOLD (minimum aspect ratio) must be less than THRESHOLD (maximum Aspect Ratio). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum 2D Feature Height): Maximum allowable height (km) to build 2D features. No 2D features will be saved above this height; default 12 km (6.5 nm); range 6 to 12 km (3.2 to 6.5 nm), precision: 1 km (0.54 nm). This configuration parameter can be used to change MDA's functionality.

- THRESHOLD (minimum 2D Radial Diameter): Minimum radial diameter (km) of a 2D feature (or the RANGE (Slant). Difference between shear segments having the minimum and maximum center RANGES (Slant)); default 1.00 km (0.54 nm), range 0.75 to 2.50 km (0.4 to 1.3 nm), precision: 0.05 km. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum 2D Diameter): Maximum diameter (km) of a 2D Feature. Distance between min and max velocities in a 2D Feature; default 15 km (8.1 nm), range 10 to 20 km (5.4 to 10.8 nm), precision: 1 km (0.54 nm). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum 2D Distance): Maximum allowable radial distance (km) Construction Radial between shear segments for segments to become associated into 2D features; default 1.00 km (0.54 nm), range 0.25 (sample volume size) to 2.00 km (0.4 to 1.3 nm), precision: 0.25 km (0.13 nm). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (2D Feature minimum Range): Minimum range from the radar allowed for a 2D Feature; default 5 km (2.7 nm), range 0 to 15 km (0 to 8.1 nm), precision: 1 km (0.54 nm). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (minimum 2D Association Distance): The minimum search radius distance used to associate 2D features into 3D features; default 2 km (1.1 nm), range 2 to 10 km (1.1 to 5.4 nm), precision: 1 km (0.54 nm). (This parameter must be less than THRESHOLD (maximum 2D Association Distance.) This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum 2D Association Distance): The maximum search radius distance used to associate 2D features into 3D features; default 8 km; range 5 to 10 km, precision: 1 km. (This parameter must be greater than THRESHOLD (minimum 2D Association Distance.) This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum 3D Couplet Core Base): Maximum allowable base altitude (km) of a 3D couplet of a particular 3D Strength Rank "core". All 3D couplets whose base is above this level are discarded; default 5 km; range 2 to 5 km, precision: 1 km. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (minimum 3D Couplet Core Depth): Minimum allowable half-beamwidth depth (km) of a 3D circulation couplet of a particular 3D Strength Rank core. All 3D couplets less than this depth are discarded; default 3 km, range 2 to 5 km, precision: 1 km. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum 3D Couplet Core Top): Maximum allowable top (km) of a 3D couplet core". All 3D couplets whose "core top" is above this level are adjusted so that the core top is set to THRESHOLD (maximum 3D Couplet Core Top). Also, MSI integration does not exceed this level; default 8 km, range 8 to 12 km, precision: 1 km. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum Parm Height): Maximum height (km) at which the values for maximum rotational velocity, shear, and gate-to-gate velocity difference are taken from 2D features for each 3D feature; default 12 km, range 6 to 12 km, precision: 1 km. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (minimum Low-Core Mesocyclone Depth Fraction): The minimum storm-relative depth fraction allowed to classify 3D features as low-core mesocyclones;

default 0.25 (which is 25%, range 0.10 to 0.50, precision: 0.05. This configuration parameter can be used to change MDA's functionality.

- THRESHOLD (maximum Low-Core Mesocyclone Depth): The maximum absolute depth (km) allowed to classify 3D features as low-core mesocyclones; default 3 km, range 0 to 5 km, precision: 1 km. This value must be less than or equal to the depth that results from the multiplication of the mesocyclone depth by the THRESHOLD (minimum Low-Core mesocyclone Depth Fraction). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (maximum Altitude Low-Core Mesocyclone Base): The maximum circulation base altitude (km) allowed to classify 3D features as low-core mesocyclones; default 3 km, range 0 to 5 km, precision: 1 km. This value must be less than or equal to THRESHOLD (maximum 3D Couplet Core Base). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (Convergence Look Ahead): Maximum number of sample volumes allowed for the "look-ahead" feature when building radial convergence pattern vectors; default 4 sample volumes, range 3 to 6, precision: 1. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (Convergence minimum Length): Minimum distance required between min and max velocity values within a Convergence Vector; default 1.0, range 1.0 to 2.0 km, precision: 0.5 km. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (Convergence Delta Velocity): Minimum velocity difference allowed for saving radial convergence pattern vectors; default 5 ms^{-1}; range 4 to 8 ms^{-1}, precision: 1 ms^{-1}. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (Convergence maximum Height): Maximum height allowed for saving radial convergence pattern vectors; default 8 km, range 4 to 8 km, precision: 1 km. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (Convergence Shear): Minimum Shear required before convergence vectors need to be searched for a shear core; default 1.0 ms^{-1} km^{-1} range 0.5 to 2.0 ms^{-1} km^{-1}, precision: 0.5 ms^{-1} km^{-1}. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (Convergence Buffer Zone): Buffer zone outside the diameter of a 2D feature within which radial convergence pattern vectors are to be associated with the 2D feature for convergence calculations; default 2 km, range 0 to 4 km, precision: 1 km. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (3D Feature Low Level Convergence Height): The maximum altitude for calculating low-level convergence for 3D features; default 2 km, range 1 to 3 km, precision: 1 km. This value must be less than THRESHOLD (3D Feature Mid Level Convergence Height1). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (3D Feature Mid Level Convergence Height1): The minimum altitude for calculating mid-level convergence for 3D features; default 2 km, range 2 to 4 km, precision: 1 km. This value must be greater than THRESHOLD (3D Feature Low Level Convergence Height). This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (3D Feature Mid Level Convergence Height2): The maximum altitude for calculating mid-level convergence for 3D features; default 4 km, range 3 to 6 km,

precision: 1 km. This value must be greater than THRESHOLD (3D Feature Mid Level Convergence Height1). This configuration parameter can be used to change MDA's functionality.

- THRESHOLD (max number of elevations in 3D Feature): The maximum number of elevations allowed in a 3D Feature; default 22, range 5 to 25 elevation slices, precision: 1. This parameter should equal the maximum number of elevations of the WSR-88D VCP's. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (min Rank LT): Minimum strength rank for a low core mini-supercell and NSSL defined Mesocyclone; default 5, range 3 to 7, precision: 1 This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (Shallow Allowed): Boolean flag indicating that MDA is allowed to identify and classify shallow circulations; default TRUE; range TRUE - FALSE. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (Meso min Rank Shallow): Minimum strength rank for a shallow circulation; default 5, range 2 to 5, precision: 1. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (Meso min Depth Shallow): Minimum depth for a shallow circulation; default 1.0, range 0.5 to 1.5 km, precision: 0.5 km. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (Meso max Top Shallow): Maximum top for a shallow circulation; default 3 km, range 1 to 3 km, precision: 1 km. This configuration parameter can be used to change MDA's functionality.
- THRESHOLD (Overlap Display Filter): Boolean value that allows a user to turn on the algorithm based overlap display filter. The overlap display filter eliminates the display of 3D features that overlap lower elevation features; default TRUE, range TRUE to FALSE. This adaptable parameter should have URC level of change authority.
- THRESHOLD (minimum Display Filter Rank): The minimum strength rank below which 3D Features are marked not to be displayed; default 5, range 1 to 5, precision: 1. This adaptable parameter should have URC level of change authority.
- THRESHOLD (Use Near Storm Environment (NSE)): Boolean value that allows a user to turn on the algorithm's use of NSE data.

3.7.9 Strengths/Applications.

- The algorithm automatically processes 3-dimensional velocity data to identify regions that resemble mesocyclones.
- A mid-level mesocyclone that lowers toward the surface may indicate a tornado is developing.
- The strength of MDA is that the algorithm allows for the detection of an entire spectrum of storm-scale circulations with different strength and spatial characteristics. These circulations are then classified using a variety of definitions.
- The detection techniques have been made much more robust than in earlier versions of mesocyclone detection. Individual forecasters/users can take advantage of the algorithm's robustness by adjusting a display filter to meet their needs.
- The MDA includes time association routines to provide tracking and trend data for the rapid synthesis of many data points from a number of elevations and volume scans into single-parameter trends.

- Time-Height trends provide useful guidance information that cannot be easily calculated in the short amount of time to make warning decisions.

3.7.10 Limitations.

- The algorithm only detects cyclonic rotations, not anticyclonic rotations.
- Identification is influenced by aspect ratio.
- Range thresholds may discard or improperly classify mesocyclones. No data within 5 km (2.7 nm) is processed by the mesocyclone algorithm. – the operator must search base products for evidence mesocyclones.
- The operator must examine reflectivity, velocity/SRM to verify existence of operationally significant mesocyclones.
- The radar horizon and cone-of-silence can prevent the radar from detecting circulations at times.
- Velocity signatures may be obscured or degraded where there are improperly dealiased velocity data or where data are obscured by range-folded echoes.
- While MDA uses a minimum reflectivity threshold to confine the search for shear segments typically associated with storms, MDA uses no reflectivity structures (BWER, Hook Echo, etc.) to identify tornadic circulations.
- The algorithm may falsely identify shear segments and 3D features in areas of higher reflectivity and high spectrum width such as ground clutter, sea breezes, gust fronts, close to the RDA, and at the edge of the first trip.
- The shear segment image is sized to hold 5000 shear segments. Additionally the total number of 2D and 3D features are set to 800 and 200 respectively. If any of these array limits are exceeded, processing stops and potentially tornadic storms may go undetected.
- Squall line often produce numerous, transient, operationally insignificant circulations along their leading edge.
- MDA will perform best on isolated supercell storms.

3.8 <u>Tornado Detection Algorithm</u>. Much of the information contained in this section can be found in Mitchell et al 1998. For more information about the performance of the algorithm, see Mitchell 1995.

The TDA uses radar data to identify intense, small circulations that are producing or are likely to produce tornadoes. The algorithm starts by identifying one-dimensional (1D) pattern vectors from (mean radial) velocity data. To help limit the search of circulations to those associated with the low-levels of storm cells, the algorithm only searches velocity data from sample volumes that 1) have reflectivities above a specified threshold, 2) are within a threshold range, and 3) are below a threshold height. Pattern vectors are gate-to-gate velocity differences that exceed a specified velocity difference threshold. Gate-to-gate means the sample volumes are from adjacent radials and at the same range. Next, for six (by default) differential velocity thresholds, the pattern vectors on each elevation scan that are in azimuthal and horizontal proximity and exceed the same differential velocity threshold are combined into potential two-dimensional (2D) features. Then, the potential 2D features are trimmed such that only one pattern vector remains at any range within the feature. Afterward, if a potential 2D still has enough pattern vectors and has a below threshold aspect ratio, it is checked for overlap with all previously saved 2D features on the elevation scan. If the potential 2D feature overlaps no other 2D features, it is saved as a new 2D feature. Next, the 2D features from adjacent elevation scans are vertically correlated into potential three-dimensional (3D) features. Potential 3D features with enough 2D features are saved as 3D features. Lastly in the identification process, each 3D feature is compared against thresholds to determine if it is an Elevated Tornado Vortex Signature (ETVS) or TVS or not. Finally, the TVSs and ETVSs are associated with storm cells.

3.8.1 Pattern Vectors. Pattern vectors are identified on each elevation scan from velocity data from azimuthally adjacent radials. (It is assumed that radials are approximately 1 degree in azimuthal width and have no gaps between them.) The counter-clockwise velocity difference is computed for each pair of sample volumes (from the adjacent radials) that are constant in range that are below a threshold height ARL and within a maximum processing range. If the sample volumes have a velocity difference above a minimum threshold and their corresponding reflectivities are at least a minimum threshold, then the pair is saved as a pattern vector. For each pattern vector the following information is then computed: the range, azimuthal difference (between the radials), and the beginning and ending radials' azimuths. If the number of pattern vectors found on an elevation scan ever exceeds a specified maximum number allowed, the search for pattern vectors stops for the elevation scan.

3.8.2 2D Features. Once all the pattern vectors have been identified on an elevation scan, they are combined into potential 2D features. In order for two pattern vectors to be correlated to the same potential 2D feature, they must be within an azimuthal and range separation proximity thresholds and exceed the same differential velocity threshold. Multiple differential velocity thresholds are used to isolate core (i.e., stronger) circulations imbedded within long azimuthal shear regions (e.g., radially oriented gust fronts). By default, six differential velocity thresholds are used to construct potential 2D features. All the pattern vectors on an elevation scan are processed once for each differential velocity threshold, starting with the greatest.

As the potential 2D features are built using each of the differential velocity thresholds, each of the potential 2D features have their associated pattern vectors sorted by increasing range and then trimmed. The trimming results in only one pattern vector for any range within the potential 2D feature and is accomplished in the following manner. Each potential 2D feature is processed from beginning to ending range. At each range within the feature, the pattern vector retained at the next range is the one that is closest in azimuth to a reference (pattern) vector, and all others are trimmed (or not saved). If multiple pattern vectors are equally close in azimuth to the reference vector, then the one with the greatest velocity difference is selected. The reference vector changes for each new range within the feature. For the first range, the reference vector is at the second range; otherwise, the reference vector is the pattern vector retained at the previous (lesser) range. For the first range, the reference vector is the pattern vector on the second range that is closest to the first pattern vector (at the first range).

Next, the 2D features are determined from the potential 2D features. First, the following potential 2D feature attributes are calculated: azimuth, range, height, X-coordinate, Y-coordinate, beginning azimuth, ending azimuth, beginning range, ending range, # of pattern vectors, maximum velocity difference, average elevation, maximum shear, azimuthal diameter, radial diameter, and the aspect ratio. If a potential 2D feature's aspect ratio is less than a specified threshold value, then the feature is compared for overlap with all previously saved 2D features on that elevation scan. When a feature overlaps another, its boundaries (i.e., beginning and ending azimuths and ranges) exceed those of the other feature. If the potential 2D feature overlaps no other 2D features, it is saved as a new 2D feature. If the potential 2D feature overlaps one 2D feature, the 2D feature acquires many of the potential 2D features attributes, e.g., range, azimuth, height, etc. If the potential 2D feature overlaps more than one 2D feature, it is deleted (i.e., not saved as a 2D feature). Finally, after all the 2D features are found on the elevation scan, they are sorted by decreasing maximum delta velocity (See Figure 3-16). If and when the number of 2D features in the volume scan meets or exceeds the threshold maximum number allowed in the volume scan, then processing immediately skip over the remainder of the 2D functionality to the 3D functionality.

3.8.3 3D Features, TVSs, and ETVSs. Once all of the 2D feature have been constructed and saved for the volume scan, the algorithm vertically correlates the 2D features from different elevation scans into 3D features. Starting with the lowest elevation scan, for each remaining 2D feature, a new potential 3D feature is started with the 2D feature. Then, all other 2D features on the elevation scan within the circulation radius are discarded from future 3D processing. Remember, the 2D features on each elevation are sorted by decreasing maximum delta velocity; so the first 2D feature found always has the strongest maximum delta velocity. Also, once a 2D feature is assigned to a potential 3D feature it is removed from future consideration in other potential 3D features. Then, the 2D features on the next elevation scan are searched until one is found within the circulation radius of the last 2D feature assigned to the potential 3D feature. The first 2D feature found is vertically correlated into the same potential 3D feature. And, all other 2D features on that elevation scan within the circulation radius are discarded. If no 2D features are found at the next elevation scan within the circulation radius, then that elevation scan is skipped, and the following elevation scan is similarly searched for a 2D feature to vertically correlate. Only one elevation scan can be skipped in the vertical stack of 2D features. This one elevation scan gap provides some flexibility to allow for 2D features that should be part of the potential 3D feature but were missed possibly because of range aliasing or improper velocity dealiasing. Once all elevation scans are processed for that 3D feature, the entire vertical correlation process is repeated starting with the next undiscarded and uncorrelated 2D feature on the lowest elevation scan.

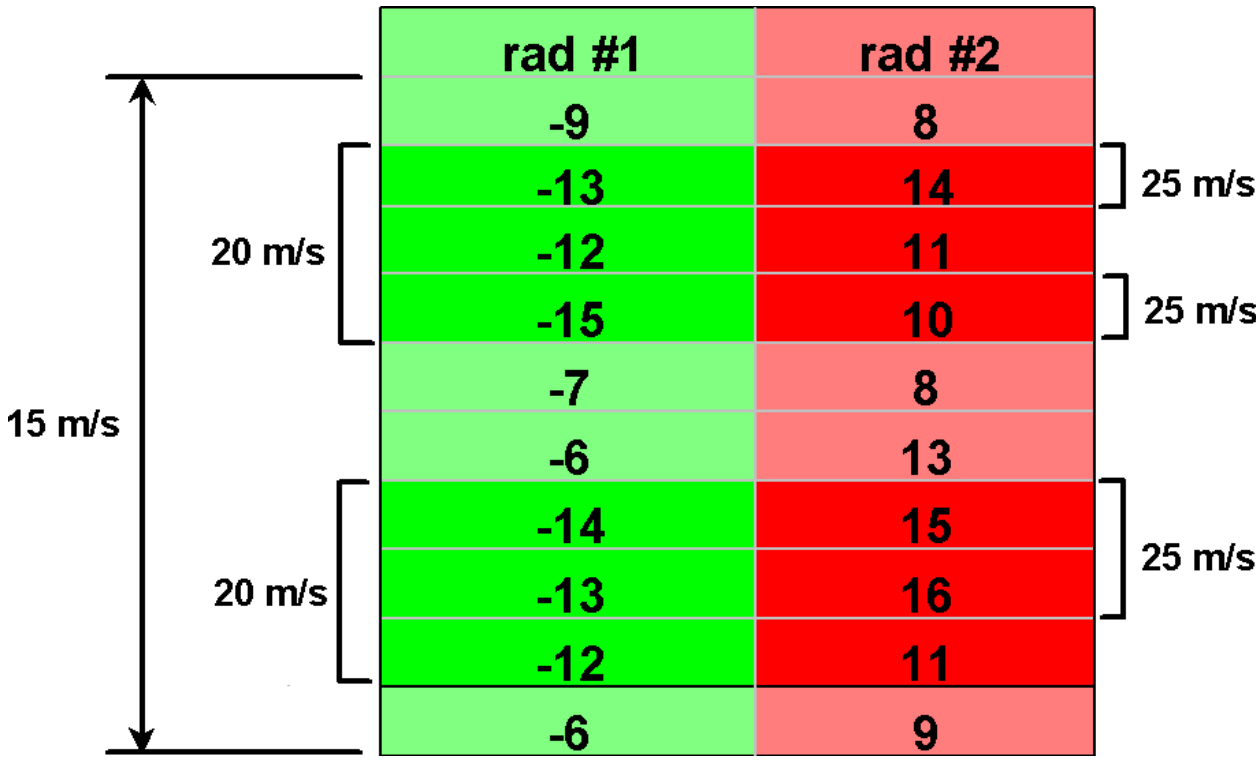

Figure 3-16
Two-Dimensional Features

Multiple velocity thresholds used to identify stronger shear embedded within weaker shear.

Once all potential 3D features have been found, they are thresholded to determine if they are 3D features, TVSs, or ETVSs. First, the 2D features within each potential 3D feature are sorted by increasing height. Then, if a potential 3D feature contains at least a minimum threshold number of 2D features and the number of 3D features is less than a threshold number, it is saved as a 3D feature, and its attributes (e.g., base height, shear, and maximum delta velocity) are computed. Next, each 3D feature is checked to determine whether it is a TVS Feature; a TVS Feature is a TVS or ETVS (Figures 3-17 and 3-18). If a 3D feature has at least a minimum threshold depth and a minimum threshold velocity difference and if its base is above a minimum elevation angle and height thresholds (i.e., its base is not on the lowest elevation angle or below a certain height), the 3D feature is saved as an ETVS. Otherwise, if the 3D feature has at least a minimum threshold depth and if it's base maximum delta velocity or maximum delta velocity is above threshold, the 3D feature is saved as a TVS. When saving a TVS Feature, if the number of TVSs or ETVSs meets or exceeds the threshold maximum number allowed, the features (TVSs or ETVSs) are sorted and the one with the smallest TVS (Base Delta Velocity) and, secondly, the smallest maximum TVS (Delta Velocity) is discarded. Lastly, each TVS Feature is associated with the nearest storm cell that is within a threshold maximum association distance. When a TVS Feature is associated with a storm cell it is assigned the same ID. If a TVS Feature is not within the threshold distance from any storm cell, it has an ID of "??".

3.8.4 Rapid Update. In a fashion similar to the Legacy Mesocyclone Algorithm Rapid Update, in the TDA Rapid Update features are updated with each elevation angle. Rapid update allows TDA to output 3D feature information at the end of every tilt, beginning with the first tilt, rather than only at the end of the volume scan. As 3D features are built, 3D feature information is updated so that forecasters can see if 3D features are increasing in intensity. Rapid update increases algorithm output lead-time, allowing forecasters more time to view algorithm output and issue severe weather warnings.

After 2D features have been identified on the first tilt of a new volume scan, their locations are compared to forecast locations of 3D features from the previous volume scan. This comparison is described in the time association step of the TDA tracking module. The time association information defines 3D feature tracks. However, in contrast to the Legacy Mesocyclone Algorithm the TDA requires 3 contiguous elevations of 2D couplets before combining them into a 3D TVS.

After time association, before TDA processes data from the second tilt, the direction and speed of each detection is computed and the position of severe weather feature icons and table attribute information on the display are updated for the current volume scan. Low-level attributes of the 2D feature on the current volume scan; low-level characteristics such as shear and gate-to-gate velocity difference; are assigned and the rest of the attributes are inherited from time associated 3D features detected on the previous volume scan.

The 3D features that are not time associated with 2D features found on the new volume scan are identified as “extrapolated” features. If 3D features from the previous volume scan are associated with features on the current volume scan, their classification is changed from extrapolated to matched. Extrapolated features that are not matched on the current elevation scan or the next are removed from the product.

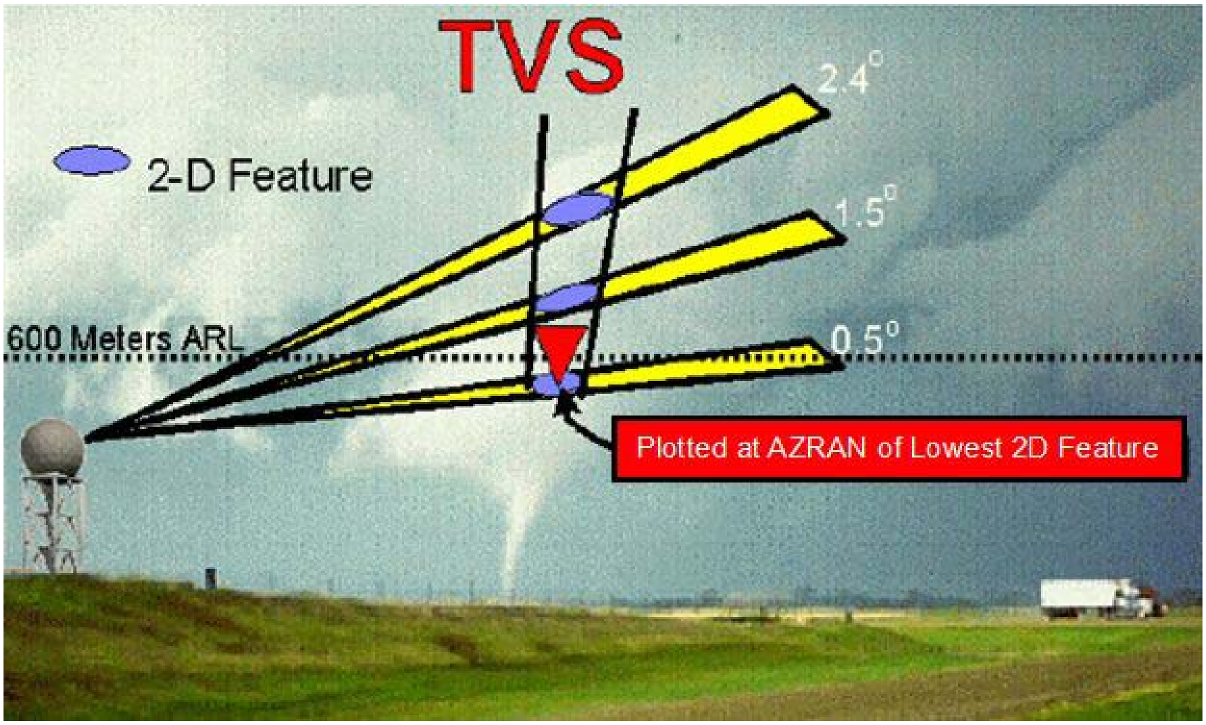

Figure 3-17
TVS Definition

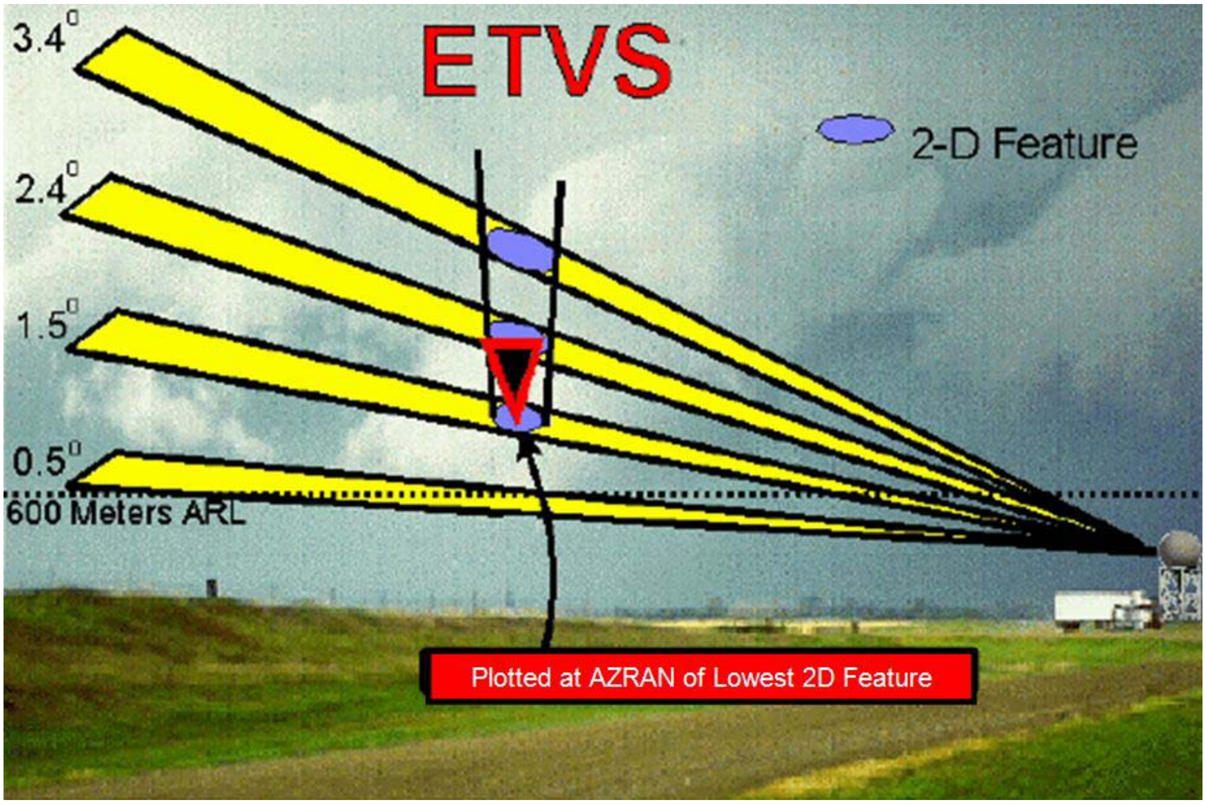

Figure 3-18
ETVS Definition

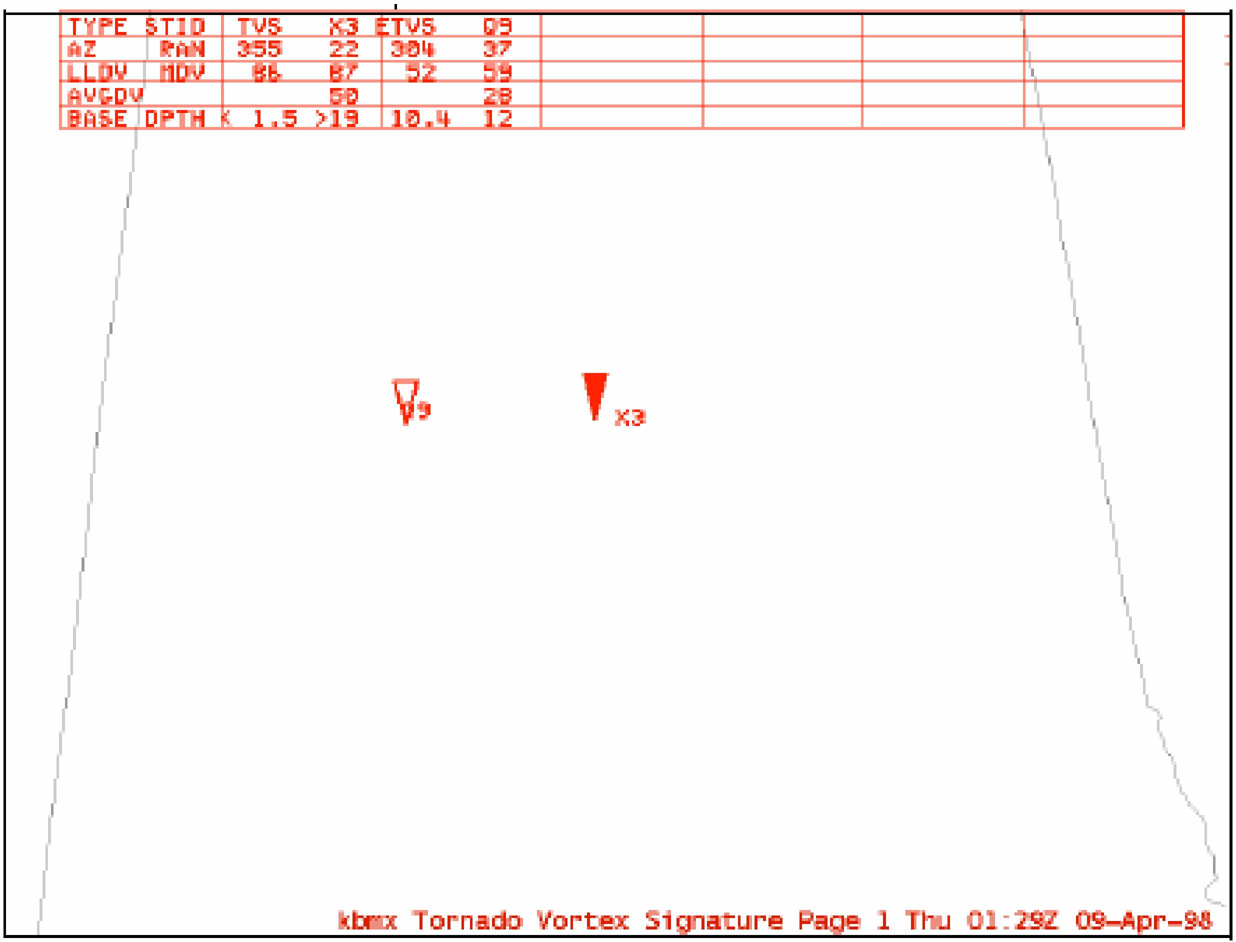

Figure 3-19
TVS Graphic Product

This TVS example (AWIPS display) includes identification numbers for identified storms. The isosceles red triangles indicate the position of the calculated TVS. The Combined Attribute Table provides alphanumeric storm information.

When the RDA provides radar data from higher tilts, 1D and 2D features are identified by TDA. New 2D features are vertically associated with adjacent-tilt 2D features, 3D features, or retained as potential bases of new 3D features. Feature attributes are updated when: 1) a new 3D feature is identified during the current volume scan; 2) feature attributes indicate a TVS is increasing in severity; or 3) all information has been obtained for a TVS (i.e., the feature is topped).

At the end of the volume scan TDA computes an average motion and speed of all 3D features and computes forecast positions for all 3D features and the resulting product generated (See Figure 3-19).

3.8.5 Operational Parameters.

- AZIMUTH: The azimuthal position of a radial in degrees.
- ELEVATION: The elevation angle of the radial or scan, in degrees.
- RADIAL: The set of sample volumes, only one at each RANGE (Slant), along a constant AZIMUTH and ELEVATION.
- RADIUS (Earth): The radius of the Earth (6371), in km.
- RANGE (Slant): The slant range to the center of a SAMPLE VOLUME, in km.
- REFLECTIVITY FACTOR (Sample Volume): The effective radar reflectivity factor assigned to a (velocity) SAMPLE VOLUME, in dBZ_e.
- SAMPLE VOLUME: A data sample volume along a radial whose (half power) dimensions are described by the azimuthal and vertical beam widths and the range sampling interval. These dimensions are approximately 1 degree in azimuthal and vertical width (perpendicular to the beam) and 0.25 km in range (or length) for Velocity sample volumes and 1.0 km in range for Reflectivity (Factor) sample volumes.
- STORM CELL (ID): IDs are a set of unique labels for algorithm identified storm cells.
- STORM CELL (X-coord): The set of x-coordinates for algorithm identified storm cells, in deg.
- STORM CELL (Y-coord): The set of y-coordinates for algorithm identified storm cells, in deg.
- VELOCITY (Sample Volume): The mean radial velocity of a SAMPLE VOLUME, in m/s.
- THRESHOLD (2D Vector Azimuthal Distance): The maximum AZIMUTH distance allowed for two Pattern Vectors to be associated into the same 2D Feature, in degrees; default 1.5^o, range 0.0^o to 4.0^o.
- THRESHOLD (2D Vector Radial Distance): The maximum radial distance allowed between two Pattern Vectors to be associated into the same 2D Feature, in km; default 0.5 km, range 0.0 km to 3.0 km.
- THRESHOLD (Average Delta Velocity Height): The minimum height below which all 2D Features comprising a 3D Feature are assigned an equal weighting of 1, in km; default 3.0 km, range 0.0 km - 10.0 km.
- THRESHOLD (Circulation Radius1): The maximum horizontal radius used for searching for 2D Features on adjacent or the same ELEVATION scans in building a 3D Feature. This radius is used when the RANGE (Slant) of an assigned 2D Feature is less than or equal to THRESHOLD (Circulation Radius (Range)), in km; default 2.5 km, range 0.0 - 10.0 km.

- THRESHOLD (Circulation Radius2): The maximum horizontal radius used for searching for 2D Features on adjacent or the same ELEVATION scans in building a 3D Feature. This radius is used when the RANGE (Slant) of an assigned 2D Feature s greater than THRESHOLD (Circulation Radius (Range)), in km; default 4.0 km, range THRESHOLD (Circulation Radius1) - 10.0 km.
- THRESHOLD (Circulation Radius (Range): The RANGE (Slant) beyond which THRESHOLD (Circulation Radius2) is invoked, other wise THRESHOLD (Circulation Radius1) is used, in km; default 80 km, range 0 - 230 km (124 nm).
- THRESHOLD (Differential Velocity): Six velocity difference thresholds used as criteria for building 2D Features, in m/s; defaults 11, 15, 20, 25, 30, 35 m/s; ranges 10 to 75, 15 to 80, 20 to 85, 25 to 90, 30 to 95 and 35 to 100 m/s. Note: 1) The first threshold should be equal to Vector Velocity Difference; 2) Threshold values should increase from smallest to largest; 3) It is recommended that the difference between successive threshold values not exceed 5 m/s (e.g., 20,25,30,35,40,45 m/s).
- THRESHOLD (maximum # 2D Features): Maximum number of 2D Features the algorithm can process per volume scan; default 600, range 600-800.
- THRESHOLD (maximum # 3D Features): Max total number of 3D Features the algorithm can process per volume scan; default 35, range 30 - 50.
- THRESHOLD (maximum # ETVS): Maximum number of Elevated TVS's the algorithm can process per volume scan; default 20, range 15-25.
- THRESHOLD (maximum # Pattern Vectors): Maximum number of Pattern Vectors the algorithm can process per elevation scan; default 2500, range 1500-3000.
- THRESHOLD (maximum # TVS): Maximum number of TVS's the algorithm can process per volume scan; default 15, range 15-25.
- THRESHOLD (maximum 2D Feature Aspect Ratio): The maximum allowable aspect ratio (ΔRANGE (Slant)/ΔAZIMUTH) for a 2D Feature, in km/km; default 4.0, range 1.0 to 10.0 km/km.
- THRESHOLD (maximum Pattern Vector Height): The maximum height at which Pattern Vectors are identified, in km; default 10.0 km, range: 1.0 - 15.0 km.
- THRESHOLD (maximum Pattern Vector Range): The maximum RANGE (Slant) at which pattern vectors are identified, in km; default 100 km, range 0 to 230 km (124 nm).
- THRESHOLD (maximum Storm Association Distance): The maximum distance from a storm within which to associate TVS and ETVS detections with storm cell detections. Association is not required to declare a TVS or ETVS detection, in km; default 20.0 km, range 0.0 to 20.0 km.
- THRESHOLD (minimum # 2D Features Per 3D Feature): The minimum number of 2D Features needed to make a 3D Feature (TVS or ETVS); default 3, range 1 to 10.
- THRESHOLD (minimum # of Pattern Vectors Vectors Per 2D Feature): The minimum number required to declare a 2D Feature; default 3, range 1 to 10.
- THRESHOLD (minimum 3D Feature Depth): The minimum depth required to declare a TVS or an ETVS, in km; default 1.5 km, range 0.0 to 5.0 km.
- THRESHOLD (minimum 3D Feature Low Level Delta Velocity): The minimum radial velocity difference at the base ELEVATION scan required to declare a TVS or ETVS, in m/s; default 25 m/s, range 0 to 100 m/s.
- THRESHOLD (minimum Reflectivity): The minimum reflectivity value required in a SAMPLE VOLUME for it to be used in a Pattern Vector, in dBZ; default 0 dBZ, range

-20 to 20 dBZ.

- THRESHOLD (minimum TVS Base Elevation): The lowest ELEVATION angle to which the base of a 3D Feature must extend to declare a TVS, in degrees; default 1.0^o, range: 0.0^o to 10.0^o. Either height or ELEVATION criteria must be met to declare a TVS.
- THRESHOLD (minimum TVS Base Height): The minimum height ARL to which the base of a 3D circulation must extend to be declared a TVS, in km; default 0.6 km, range 0. - 10.0 km. Either height or ELEVATION criteria must be met to declare a TVS.
- THRESHOLD (minimum TVS Delta Velocity): The minimum radial velocity difference of the maximum 3D Feature delta velocity required to declare a TVS detection, in m/s; default 36 m/s, range 0 to 100 m/s.
- THRESHOLD (Vector Velocity Difference): The minimum required gate-to gate velocity difference required for Pattern Vectors, in m/s; default 11 m/s, range 10 to 75 m/s. This threshold should be equal to the first THRESHOLD (Differential Velocity).

3.8.6 Strengths/Applications.

- The algorithm searches for gate-to-gate shear and detects TVSs, which are related to tornadic circulations.
- Multiple velocity-difference thresholds make it possible to isolate small regions of shear within broader regions and allow performance tuning through adaptable parameter changes.
- A distinction is made between different types of shears (TVS vs. ETVS, delta velocity calculations), and more information is provided about the base and depth of circulations.
- The TDA vector velocity threshold is not range dependent. Thus, pattern vectors, and thus circulations in TDA 2D and 3D processing, are given equal weight regardless of range.
- Many of the adaptable parameters allow the TDA to become more sensitive, i.e., identify more circulations.
- The TDA is based on the paradigm that TVSs associated with tornadoes may be sampled by adjacent radar beams (Doviak and Zrnic 1975, Brown et al 1978). Ideally, though, it is desired that each beam be centered on the velocity peaks of the circulation. As a result, less stringent Differential Velocities are used in the TDA which affords a greater number of detections.
- A more robust vertical association scheme is employed to help avoid false detections. In light of modern computing, the TDA has been designed to allow a greater amount of information to be processed.
- The TDA operates independently of any mesocyclone detection algorithm. Therefore, the TDA is allowed the freedom to identify tornadic circulations within storms that do not contain mesocyclones (e.g., non-supercell tornadoes) and storms that contain undetected mesocyclones.
- Currently, the TDA has a higher Probability of Detection (POD) than the previous TVS Algorithm and performs best during events characterized by isolated supercells.

3.8.7 Limitations.

- Adaptable parameters need more research. Parameters which work well in one type of meteorological setting may not be as effective in other situations.
- High false alarm rates especially in squall lines and tropical cyclones. A high False Alarm Ratio (FAR) with TDA may result in over-warning, or desensitizing forecasters. False alarms have also been caused by vehicle traffic during clear, cold, inversion conditions.
- Little research has been done to date relating the occurrence of tornadoes to ETVSs. Forecasters should use ETVS output with caution until they develop a better understanding of its utility.
- Beyond 80 km (50 nm) TDA most likely detects strong mesocyclones. No circulations are identified beyond approximately 100 km (62 nm).
- Doppler radar's ability to measure thunderstorm mesocyclones and tornadoes is primarily dependent on the relationship between the vortex size and the size of the radar sample volume.
- Discrete azmuthal sampling may or may not coincide with the peak rotational velocities in the TVS.
- Signature position in relation to storm structure should be used to filter false detections.
- Time and range continuity must be considered.
- Classification as INC (increasing) or persistent (PER) may be the result of sampling issues versus an actual change of the feature.
- The TRU graphical attribute table and alphanumeric product contain attributes from both the previous and current volume scan.
- Feature matching ability is dependent on the motion supplied by the SCIT Algorithm.
- There is no functionality within the 3D processing that filters multiple circulations in close horizontal proximity. Therefore, multiple TVSs and ETVSs can be detected very close to each other.
- Improperly dealiased velocity data will degrade the algorithm performance.
- Discarded velocity bins (possible with some dealiasing techniques) can degrade algorithm performance.
- More testing and data analysis is required to determine more accurately how the TDA performs in various weather scenarios.
- Range folded echoes often obscure the velocity data making the detection of pattern vectors (and, hence, circulations) impossible.
- While the TDA uses a Minimum Reflectivity Threshold to confine the search for pattern vectors within the higher reflectivities typically associated with storms, the TDA uses no reflectivity structures (BWER, Hook Echo, etc.) to identify tornadic circulations.
- The algorithm may falsely identify pattern vectors in areas of higher reflectivity such as ground clutter, sea breezes, gust fronts.
- The algorithm only detects pattern vectors, and thus TVSs, with cyclonic shear.
- Because of sampling limitations at very close ranges, large tornadic circulations may span several radials. In the middle of these circulations there may be very little shear observable in the radial velocity data. Therefore, in these cases, the TDA may miss this type of circulation (i.e., not identify it as a TVS) or identify two circulations.
- Squall line events present a challenge to the TDA because numerous, transient, TVSs are often detected along the leading edge. This is especially true when the squall line is

aligned along a radial creating near zero radial velocities.

- The TDA does not use range dependent velocity difference thresholds. Thus, TVSs are given equal weight regardless of range.

3.9 Echo Tops. The Echo Tops Algorithm only requires reflectivity data. The reflectivity data values for each sample volume are assigned a number representing fifteen categories. If the return power is less than a threshold (defaulted to 18.5 dBZ_e) it is assigned a value of zero. The data are also filtered to remove any spurious data. A data point must have at least two adjacent points with a category value of at least one, otherwise the isolated point is removed. That is, at least two of the four possible sample volumes at a particular elevation with adjoining sides to the sample volume in question must be in category one or above. This final data set is the one used as input to the Echo Tops Algorithm.

The Echo Tops Algorithm itself estimates the maximum echo top height for each 4 x 4 km (2.2 x 2.2 nm) grid box in an array covering a radius of 230 km (124 nm) from the radar. For each elevation scan, the algorithm checks each reflectivity factor value against a "Minimum Significant Reflectivity" threshold. For those sample volumes meeting this threshold, an echo top height is calculated from sea level to the center of the beam and mapped to the appropriate grid box. The final value of each grid box is the maximum echo top height mapped onto it.

3.9.1 Operational Parameters.

- AZIMUTH: Azimuthal position, in radians. Precise to 10^{-3} radians.
- BEAM WIDTH: The angular width of the radar beam between the half-power points (0.017), in radians.
- SAMPLE VOLUME: A data sample volume whose dimensions are 1 degree in azimuth, 1.0 km in range, and 1 degree in depth (perpendicular to the radar beam).
- CATEGORIES: Categorized effective reflectivity factor data for each SAMPLE VOLUME.
- ELEVATION: Elevation angle, in radians.
- RANGE (Slant): The slant range to the center of a SAMPLE VOLUME, in km.
- BOX (4 km x 4 km (2.2 nm x 2.2 nm)): Square grid boxes which are 4 km on a side and cover ranges from 0 to 230 km (124 nm). The intersection of 4 boxes is centered on the radar location.
- Minimum Significant Reflectivity: The minimum reflectivity considered to be non-zero for the purpose of determining the echo top; ranges from -33.0 to 94.0 dBZ_e; default, 18.3 dBZ_e.

3.9.2 Strengths/Applications.

- The Echo Tops Algorithm estimates of the Echo Top heights for each 4 x 4 km (2.2 x 2.2 nm)grid box.
- Quick estimation of the most intense convection; higher echo tops.
- Assist in differentiating non-precipitation echoes from real storms.

- Aids in identification of storm structure features such as tilt, updraft flank, max top over strong low level reflectivity gradient, etc.
- May detect mid-level echoes before low-level echoes are detected.

3.9.3 Limitations.

- The precision for measuring the height decreases with range because of beam broadening. At a range of 230 km (124 nm), the one-half power beam width is 1980 m (6,500 ft).
- The algorithm does not correct for data contamination from side lobes. The height of echo tops could be overestimated from this effect.
- Tops will be underestimated close to the radar due to the cone of silence.
- Due to the lack of vertical extrapolation and gaps between beam placements, all tops are along the beam resulting in a “stair-step” appearance, at times concentric rings, and often considerable underestimates of the actual echo tops.
- No upward extrapolation from the last elevation angle where precipitation was detected.
- Difficult to locate the highest echo top in a storm due to lack of upward vertical extrapolation and heights are displayed in 5000 ft increments.
- Echo top heights from this algorithm do not have enough precision to be used reliably for severe weather warnings.

3.10 Vertically Integrated Liquid Water. The VIL Algorithm only requires reflectivity data. The reflectivity data values for each sample volume are assigned a number representing 15 display categories. If the return power is less than a threshold (defaulted to 18.5 dBZ_e) it is assigned a value of zero. If the return power is greater than or equal to 56 dBZ, the corresponding liquid water value is assigned a value of 5.4 gm^{-3}. The categorization of the data is performed using a look-up table to arrive at liquid water values. The filtering routine removes any spurious data. A data point must have at least two adjacent points with a category value of at least one, otherwise the isolated point is removed. That is, at least two of the four possible sample volumes at a particular elevation with adjoining sides to the sample volume in question must be in category one or above. This final data set is the one used as input to the VIL Algorithm.

The VIL Algorithm converts weather radar reflectivity factor data into liquid-water content values based on theoretical studies of drop-size distributions and empirical studies of the relationship between reflectivity factor and liquid-water content. The algorithm described uses an equation that relates reflectivity factor to liquid water content for one such relationship:

$$M = 3.44 \times 10^{-3} Z^{4/7}$$

where M = liquid water content ($g\ m^{-2}$) Z = radar reflectivity ($mm^6\ m^{-3}$).

The values are derived for each 4 x 4 km (2.2 x 2.2 nm) grid box; then vertically integrated. VIL values are output in units of mass per area ($kg\ m^{-2}$). The algorithm assumes reflectivity returns are from liquid water.

For each elevation angle, each 4 x 4 km (2.2 x 2.2 nm) grid box is assigned the largest liquid water value of all the sample volumes located within the grid box. However, a liquid water value may not exceed 5.4 gm^{-3} (or equivalently, reflectivity values are capped at 56 dBZ.) All other liquid-water values in each grid box are ignored. This attempts to compensate for the fact that the storm may be tilted and moving during the time required for a complete volume scan. These partial liquid-water content values are then integrated vertically to arrive at VIL values for each grid box. If the VIL value for a grid box exceeds 80 kg m^{-2} it is adjusted to 80 kg m^{-2} to mitigate the large reflectivity values associated with hail.

3.10.1 Operational Parameters.

- AZIMUTH: Azimuthal position, in radians. Precise to 10^{-3} radians.
- BEAM WIDTH: The angular width of the radar beam between the half-power points (0.017), in radians.
- SAMPLE VOLUME: A data sample volume whose dimensions are 1 degree in azimuth, 1.0 km in range, and 1 degree in depth (perpendicular to the radar beam).
- RANGE (Slant): The slant range to the center of a SAMPLE VOLUME, in km.
- BOX (4 km x 4 km (2.2 nm x 2.2 nm)): Square grid boxes which are 4 km on a side and cover ranges from 0 to 230 km (124 nm).
- REFLECTIVITY FACTOR (ZE): The effective radar reflectivity factor of a SAMPLE VOLUME, in mm^6/m^3. (Maximum value of 56 dBZ.)
- Maximum Liquid Water Threshold--1 to 200 kg m^{-2}; default, 80 kg m^{-2}: Threshold against which liquid water (integrated) is tested. Maximum allowable computed VIL value.

3.10.2 Strengths/Applications.

- A set of VIL values corresponding to the BOXes (4 km x 4 km (2.2 nm x 2.2 nm) Grid) is output by this algorithm.
- Locate the most significant storms. (Best used when comparing storms located at about the same range). High VIL values correspond to deep areas of high reflectivity indicative of strong updrafts. VIL Density (VIL divided by Echo Tops) has also shown some skill indicating significant storms.
- Useful for distinguishing storms with large hail once threshold values have been established. Establishing a VIL of the Day using climatological data and/or sounding data can be of some limited use for initial development, but better skill can be achieved by real-time comparison between VIL values and spotter reports.
- Persistent high VIL values are associated with supercells. Rapid decrease in VIL values may signify the onset of wind damage. (Use caution with this technique because gaps in the current VCP 21 can create abrupt decreases in VIL values.)

3.10.3 Limitations.

- Hail can produce fictitious values of liquid water due to enhanced reflectivity values. Therefore, a maximum value of 80 kg $m\text{-}^{2}$ is set as a ceiling of the display to mitigate this effect.
- Except for the lowest tilt, the current implementation has no earth curvature correction, i.e., the earth is considered flat when mapping data in polar coordinates to the rectilinear

coordinates. The values obtained at distant ranges may be misleading because liquid water below the radar beam is not sensed.

- At long ranges, errors may be due to large radar sample volumes.
- Values for warnings may change daily and across the warning area. Values are air mass dependent. An important consideration is the need to quantify the regional, seasonal, diurnal, and air mass variations in VIL magnitude versus severe weather. Under differing meteorological conditions, the minimum VIL associated with severe weather may vary considerably. Warm, moist environments tend to require higher VIL values for severe weather occurrences than do cool, dry conditions.
- Values are range dependent. Values within 40 km (20 nm) of the radar are underestimated. This is due to the cone of silence.
- Values at longer ranges are occasionally unreliable. The reflectivity value at 0.5° is integrated down to the ground. At distant ranges the beam may be cutting through the highly reflective hail cores in the mid levels of a storm producing an overestimation of VIL. With very low- topped convection VIL values may be underestimated at long ranges.
- Cell-Based VIL values are computed from the vertical component of an identified cell. Consequently, the Grid-based VIL values will differ from Cell-based VIL values, in shear situations where the cells are tilted in the vertical.
- VIL values for a strongly tilted or a fast moving storm will be lower than if the storm was vertical or moving slower. The upper portion of the storm may extend into another grid box.
- May be contaminated by non-precipitation echoes.
- More VIL fluctuation with VCP 21 than VCP 11 and VCP 12. There are fewer gaps in VCP 11 and VCP 12. This is mainly within 60 nm of the radar. An example of this phenomenon is shown in Figure 3-20.

3.11 Severe Weather Probability. Severe Weather Probability (SWP) Algorithm estimates the probability that a given cell will produce severe weather. The algorithm defines cells from the VIL grid by associating with each VIL maximum (>10 x 10^6 kg km^{-2}) a specified number of VIL grid values surrounding that maximum. The center of one cell may not be part of any other cell, but the edges of two cells may overlap. For a given cell, the VIL values are used to calculate parameters related to the size of the cell and to the area of the cell with VIL values exceeding certain thresholds. These parameters are then used to solve an equation (developed by statistically relating archived VIL data to concurrent reports of severe weather) to estimate the SWP for that cell. Both the number of VIL grid boxes used to constitute a cell and the equation coefficients are site adaptable parameters. The default cell size is 28 x 28 km (15.1 x 15.1 nm) and the default coefficients are those derived from Oklahoma data. This algorithm has not been updated since its introduction into the WSR-88D.

3.11.1 Operational Parameters.

- LIQUID WATER (Integrated): The integrated liquid water values (per grid box), for a column within a STORM, in kg/km^2.
- SEVERE WEATHER COEFFICIENTS*: The set of coefficients (SW1...SW6) of a regression equation that determines the severe weather probability. The default values

are SW1 = 6.90, SW2 = 7.39, SW3 = 0.22, SW4 = 3.67, SW5 = 0.01 and SW6 = 2.55.

- Box (4 km x 4 km (2.2 nm x 2.2 nm) Grid): Square grid boxes which are 4 km on a side and cover ranges from 0 to 230 km (124 nm).
- Box (SWP): A box composed of a square array of BOXes (4 km x 4 km (2.2 nm x 2.2 nm) Grid).
- SWP BOX SIZE: The size of the SWP analysis area, in odd numbered multiples of 4 x 4 kilometer boxes (e.g., 28 x 28, 36 x 36, 44 x 44...etc.) The default size is 44 x 44 km (23.8 nm x 23.8 nm).

* Note that these coefficients will vary substantially with the quality of the severe weather ground-truth information, size of the data set, with the radar, and with the location. Therefore these are essentially examples.

3.11.2 Strengths/Applications. Locate the most significant storms.

3.11.3 Limitations.

- SWP is biased on VIL and ground truth records of severe weather occurrence only.
- An accurate estimate of severe weather probability at any location requires a large climatological radar data set and accurate severe weather ground-truth data set for that radar site. The required climatology of VIL and severe weather occurrence data does not exist for any site at this time.
- As with any empirical, statistical technique, there is the possibility that the statistical sample does not reflect the true population. How much of the variance in the true population is explained by this equation is not known; in the dependent sample, 24% of the variance was explained.
- The lack of earth curvature correction described in the limitations section of the VIL Algorithm apply.

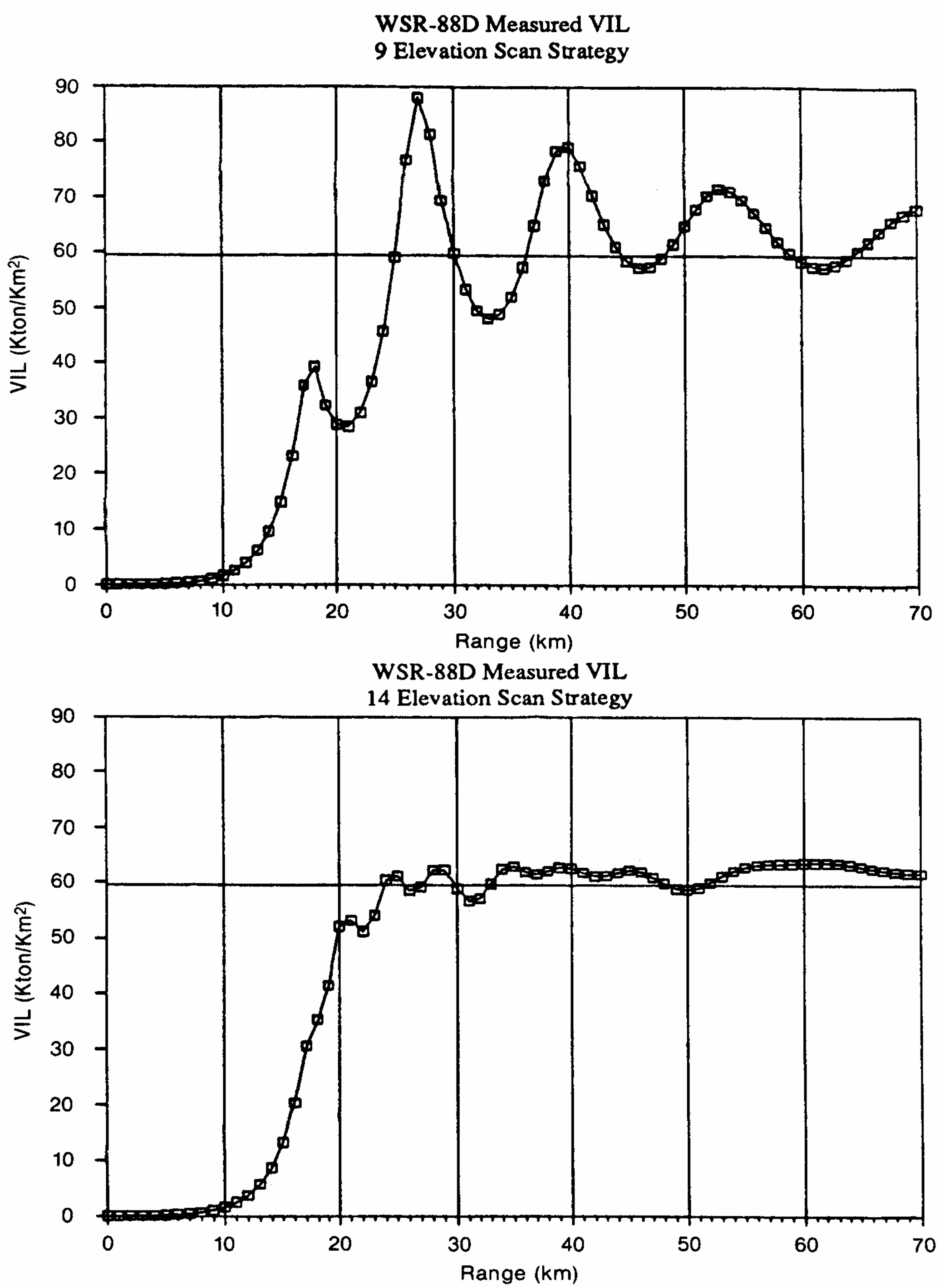

Figure 3-20
VIL Values for a Single Storm as a Function of Range and Volume Coverage Pattern Elevation Samples

(Mahoney, 1987)

3.12 <u>Velocity Azimuth Display</u>. The Velocity Azimuth Display (VAD) Algorithm is used to obtain the vertical profile of horizontal wind speed, direction, divergence and vertical velocity for the region of the atmosphere surrounding a Doppler radar. Velocity data at different azimuths collected from a Doppler radar scanning the atmosphere at a constant elevation angle about a vertical axis is used. This algorithm performs a harmonic analysis along with a best-fit test on the Doppler velocities around the circumference of a circle at a specified slant range to obtain these parameters (Figure 3-21). The vertical wind velocity is obtained through a series of steps involving the relationship between horizontal wind speed and conservation of mass through a constant elevation surface above the radar.

As mentioned above, for each horizontal wind estimate, the VAD Algorithm performs a harmonic analysis, i.e., calculates the best fit sine wave regression equation, along with a best fit test on the Doppler velocities around the circumference of a circle between the beginning and ending azimuths at a specified slant range and elevation angle. This process is done for a specific slant range, range and altitude when a specific VAD product is requested (Figure 3-21). Areas of significant blockage are not used. The best-fit test uses the calculated RMS velocity to identify outliers, and eliminates them from the regression analysis. As a final check on the quality of the wind estimates produced, tests are made on the minimum number of data points used, fit symmetry, and Root Means Square (RMS) velocity. If any one of these tests fails, the computed wind is displayed as "no data" on the VAD Wind Profile product (Figure 3-22). Chapter 6 of Part B of this Handbook describes the general technique and geometry that is implemented in this algorithm.

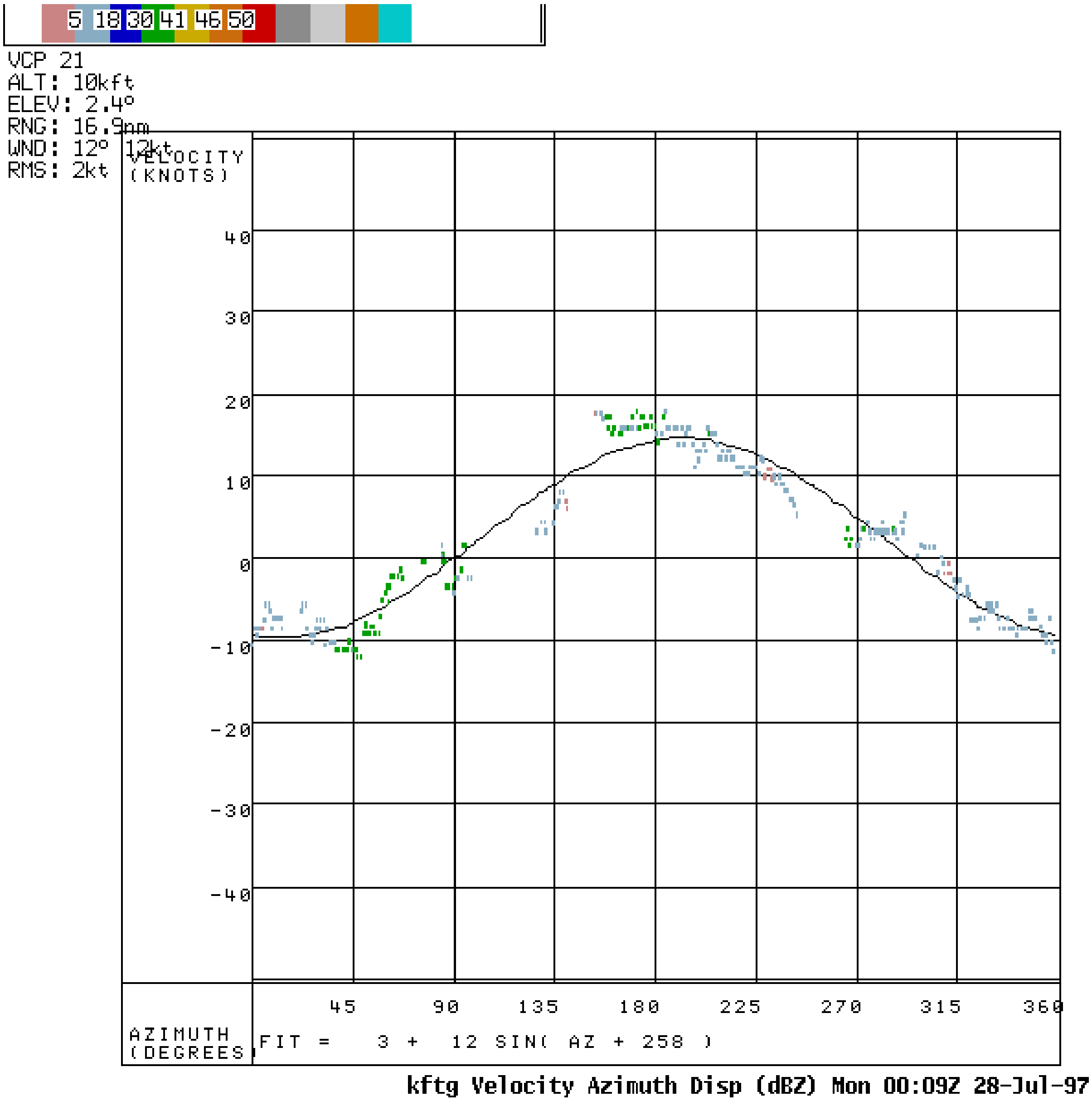

Figure 3-21
Velocity Azimuth Display Product

This example of a VAD Product (AWIPS display) shows the fit of radial winds measured at a 2.4° scan with respect to the theoretical sine wave curve.

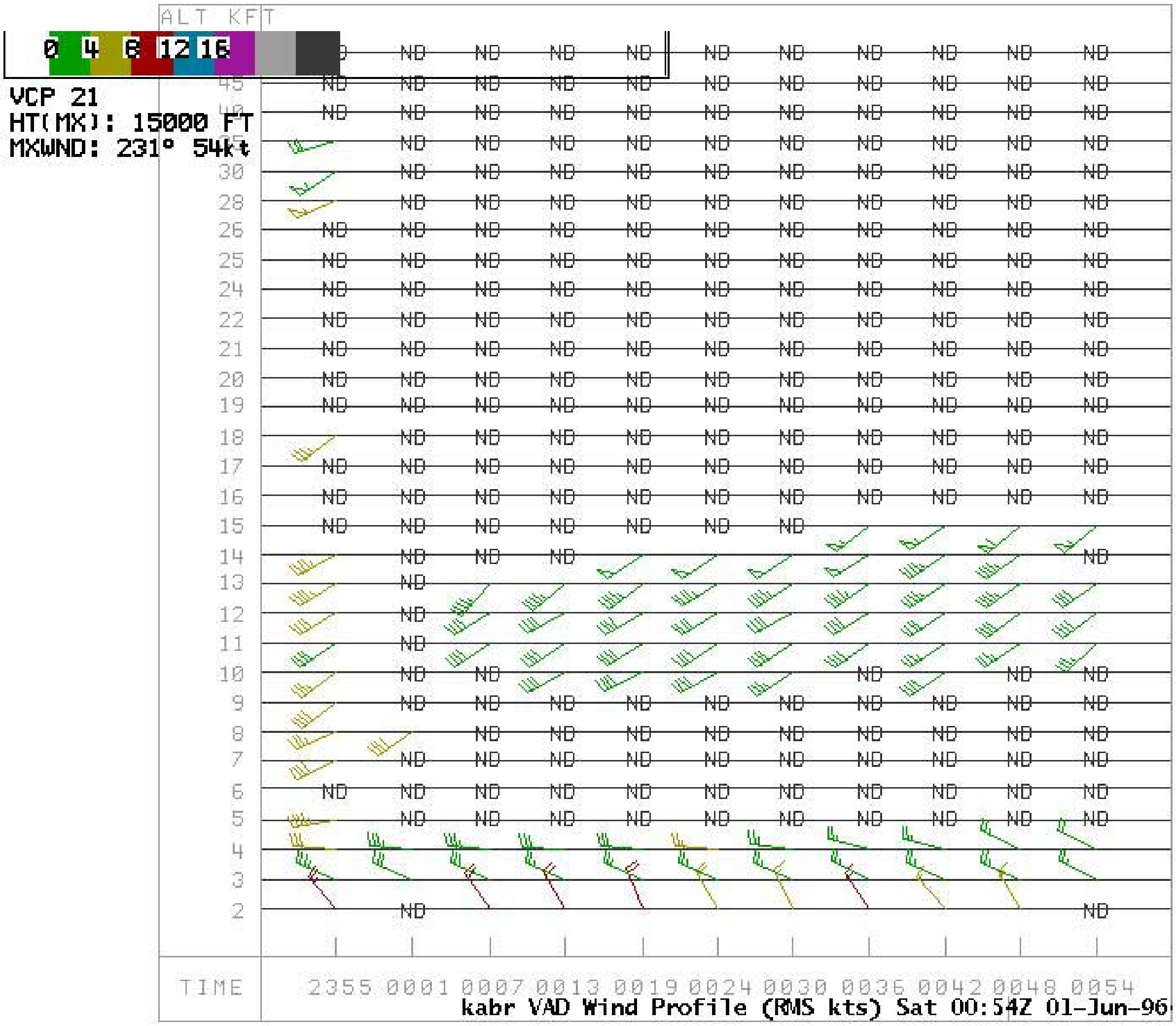

Figure 3-22
Velocity Azimuth Display Wind Profile Product

This example of a VWP Product (AWIPS display) shows the wind estimates produced in the vertical for the last 11 volume scans. “ND” indicates levels where the algorithm was not able to produce a reliable wind estimate.

3.12.1 Operational Parameters.

- AZIMUTH: Azimuthal position, in radians.
- HEIGHT (Radar): The radar height above sea level, in km.
- DENSITY (Atmospheric): A set of density values for each altitude, in kg/km^3.
- DENSITY (Atmospheric Gradient): A set of density gradient values at each altitude, in kg/km^4.
- ELEVATION: Elevation angle, in radians.
- FIT TESTS: The number of times the fit test procedure is to be run (2).
- REFLECTIVITY FACTOR (ZE): The effective radar reflectivity factor of a SAMPLE VOLUME, in mm^6/m^3.
- THRESHOLD (Begin in Azimuth): Starting azimuth for VAD analysis, radians.
- THRESHOLD (Data Points): The minimum number of data points allowed for the Fourier least squares fitting, dimensionless (25).
- THRESHOLD (End Azimuth): Ending azimuth for VAD analysis, in radians.
- THRESHOLD (Symmetry): A value for determining symmetry, in km/hr (25.2).
- THRESHOLD (Velocity): A RMS velocity threshold (18), in km/hr.
- TIME (Scan): The beginning time of a scan, in hours. Precise to 1/3600 hr.
- VAD (Analysis Ranges): The set of specific slant range(s) for each elevation angle at which horizontal wind estimates are computed. The VAD Range is included in the VAD Analysis Ranges, in 1/4 km.
- VAD RANGE: The subset of VAD (Analysis Ranges) used to compute estimates of vertical velocity and divergence, in 1/4 km.
- VELOCITY (Doppler): Doppler velocities in a SAMPLE VOLUME, in km/hr.

3.12.2 Strengths/Applications.

- Using the velocity and reflectivity data points, the velocity Azimuth Display Algorithm attempts to calculate the wind direction and speed at an operator selected height at a selectable but nearby radius from the radar.
- VAD Winds are available in clear air or precipitation mode. Generally speaking, the wind estimates will be slightly better in clear air mode since the radar antenna rotation is slower.
- The VAD Algorithm does not require 360 degrees of data. The algorithm only requires 25 (adaptable) data points (a sample from 25 degrees of azimuth), and they don't have to be contiguous. It is possible to only sample a certain sector to produce the VAD winds e.g., 135° to 225° to get an estimate of the winds ahead of a front. The "Beginning" and "Ending" azimuth is set at the RPG HCI (under Unit Radar Committee (URC) Control).
- Update Environmental Winds Table. The VAD winds are fed into the Environmental Winds Table for use in the velocity dealiasing algorithm. This helps minimize dealiasing errors.
- VAD winds are included on the Radar Coded Message (RCM).

3.12.3 Limitations.

- Needs sufficient data points - Clear, cold, dry air often lacks scatterers. No sine wave will be plotted unless there are at least 25 data points (default parameter).

- May be unreliable in disturbed environments. The algorithm does not account for deformation but assumes horizontal uniformity of the wind field. If there is a front or boundary near the RDA, the data will often fail either RMS or symmetry thresholds.
- Available for preestablished altitudes only. As designated at the RPG HCI for the VAD Wind Profile.
- Large flocks of migrating birds may produce anomalous wind data. The averaging of the motion of birds in conjunction with the motion of the wind, can lead to erroneous wind data. Birds can cause the speed to be off by several knots and the direction to be off by several degrees. Typical symptoms include an "explosion of reflectivity returns in an expanding "donut" pattern centered on the RDA just after sunset.

3.13 <u>Combined Shear</u>. This algorithm computes combined shear of the radial velocities at a single elevation within a volume scan. This combined shear is related, but not equivalent to the total shear of the horizontal wind field.

On an azimuth-by-azimuth basis, the algorithm performs the following calculations:

- Computes the running averages of Doppler velocity over a specified number of sample volumes. Only those data values with corresponding received power levels greater than the velocity power threshold are included in the averages.
- Computes the running differences of the radially averaged Doppler velocities. These differences are taken over a radial distance equal to the averaging distance. For final processing, the differences are assigned to Cartesian grid points.
- Computes the azimuthal differences of the radially averaged Doppler velocities. These differences are taken between adjacent azimuths at a constant range. These differences are divided by the distances between the effective sample volume centers, with the quotients then assigned to Cartesian grid points.

Once all azimuths have been processed, the following are performed sequentially within the rectangular Cartesian grid:

- Computes the average radial and azimuthal differences at each grid point.
- Filters the difference fields using a centered, two-dimensional filter.
- Combines the shear of the radial velocities at each grid point by squaring the radial and azimuthal shears, adding, and taking the square root.
- Thresholds the combined shears, keeping only those values above the combined shear threshold.

This process yields a field of shear values that are displayed in the Combined Shear (CS) product.

3.13.1 Operational Parameters.

- Combined Shear Threshold--0.0 to 5.0 x 10-3 s^{-1}; default, 2.0 x 10-3 s^{-1}: The minimum combined shear value allowed for acceptance in the final shear field.

- Domain Resolution--0.5 to 4.0 km (0.27 to 2.2 nm); default, l km (0.54 nm): The spatial resolution of shear data after mapping onto the Cartesian grid; the effective resolution of the products.
- Domain X Minimum--minus 116 to 0 km (-63 to 0 nm); default, minus 116 km (-63 nm): The lower left X (W-E) coordinate relative to the radar for the rectangular Cartesian grid for the interpolated shears.
- Domain X Size--0 to 232 km (0 to 125 nm); default, 232 km (125 nm): The length of west-east side of Cartesian grid box (the radar is on the intersection of the grid boxes).
- Domain Y Minimum--minus 116 to 0 km (-63 to 0 nm); default, minus 116 km (-63 nm): The lower left Y (N-S) coordinate relative to the radar for the rectangular Cartesian grid for the interpolated shears.
- Domain Y Size--0 to 232 km (0 to 125 nm); default, 232 km (125 nm): The length of north-south side of the Cartesian grid box (the radar is at the intersection of the grid boxes).
- Maximum Number of Radial Samples--650 to 660; default, 660: The maximum number of samples in one radial.
- Number of Filter Points--1 to 25; default, 9: The number of data points used in the uniform filter applied to the mean shear (azimuthal) and mean shear (radial) fields.
- Number Threshold--0.25 to 0.75; default, 0.75: The minimum fraction of radial and azimuthal differences.
- Radial Shear Flag Value--minus 999.9 to -1.0; default, -999.9: The default value for filtered radial and azimuthal and combined shear.
- Sample Volume Number--1 to 5; default, 3: The number of contiguous sample volumes to be averaged to produce each estimate of average radial velocity.
- Velocity Power Threshold--0 to 10 dB; default, 5 dB: The received power above which velocities will be processed.

3.13.2 Strengths/Applications. Radial shear and azimuthal shear are combined into a single field of values. In this way separate products are not required.

3.13.3 Limitations.

- Extensive filtering is done in order to reduce the noisiness of the shear data. Radial and azimuthal shears are combined in order to get a shear value of some magnitude regardless of the viewing aspect of the radar. The extensive filtering will reduce small-scale shears.
- Comprehensive research has not been done to investigate the capabilities and weaknesses with the algorithm and product.

3.14 <u>Radar Echo Classifier</u>. The Radar Echo Classifier (REC) Algorithm is a real-time software package that processes base radar data through a "fuzzy" logic process to determine the likelihood that the radar is detecting a specific category of target. The likelihood is defined for each base reflectivity and Doppler (velocity and spectrum width) bin for each elevation. Initially, the REC was designed to determine the likelihood that the radar is detecting AP/ground clutter. Future plans are to refine the determining process to identify other specific target categories (precipitation, large hail, biological, clutter residue, etc.) and to help discriminate between different phenomena (rain/snow, convective/stratiform, etc.).

The REC output includes digital arrays that contain the bin-by-bin likelihood (in percent) that the specific target category has been identified. The digital files are intended for use by other real-time algorithms (for instance, PRECIPITATION PREPROCESSING, COMPOSITE REFLECTIVITY, etc.) that need to make decisions based on the target identification. The REC output also includes graphic products that depict the likelihood of target identification. The graphic products are intended to assist users in making operational and maintenance decisions and to increase operator confidence in REC identifications.

The REC identification is based on a comparison of the pattern of the base radar data over a small bounded area with the expected patterns of specific targets. These bounded PATTERN CHARACTERISTICS have been selected based on their ability to discriminate between different target categories.

The first major component of the REC Algorithm computes PATTERN CHARACTERISTIC values for each base data radar bin. The PATTERN CHARACTERISTIC value is computed using the highest resolution, accuracy, and precision of the base radar data.

The second major component of the REC applies the TARGET CATEGORY SCALING FUNCTIONS to each PATTERN CHARACTERISTIC value to generate a set of SCALED CHARACTERISTIC values. For each radar bin and each PATTERN CHARACTERISTIC, the SCALED CHARACTERISTIC value represents the likelihood that the PATTERN CHARACTERISTIC value indicates the selected target.

The third major component of the REC defines the TARGET LIKELIHOOD by weighting the SCALED CHARACTERISTIC values using the TARGET PROBABILITY WEIGHTS and then summing the weighted SCALED CHARACTERISTIC values. For each radar bin, the TARGET LIKELIHOOD expresses the likelihood that the radar information from that bin is a member of the target class.

The RADAR ECHO CLASSIFIER processing will be performed in real time. The resulting digital output will be provided for use by the Precipitation Processing Subsystem (PPS) Preprocessing Algorithm and other algorithms as needed. In addition, graphical depictions of the REC output will be made available for visual analysis.

3.14.1 Operational Parameters.

- BASE REFLECTIVITY: Base reflectivity data. Accuracy is defined by the accuracy of the base radar data, currently 0.5 dBZ for the WSR-88D.
- BASE VELOCITY: Base Doppler velocity data. Accuracy is defined by the accuracy of the base radar data, currently 0.5 ms^{-1} for the WSR-88D.
- BASE SPECTRUM WIDTH: Base spectrum width data. Accuracy is defined by the accuracy of the base radar data, currently 0.5 ms^{-1} for the WSR-88D.
- REFLECTIVITY AZIMUTH ANGLE: Azimuthal position information for the BASE REFLECTIVITY radial. Accuracy of at least 0.1 degree.
- DOPPLER AZIMUTH ANGLE: Azimuthal position information for the BASE VELOCITY radial. Accuracy of at least 0.1 degree.

- TARGET CATEGORY SCALING FUNCTIONS: Predetermined functions for each TARGET CATEGORY and each PATTERN CHARACTERISTIC used to scale the PATTERN CHARACTERISTIC value to the SCALED CHARACTERISTIC value, generates a likelihood ranging from 0 to 1.
- TARGET CATEGORY PROBABILITY WEIGHTS: Probability weighting values for each TARGET CATEGORY which are multiplied to the SCALED CHARACTERISTIC value to derive the TARGET LIKELIHOOD.
- SPIN CHANGE THRESHOLD: Difference in reflectivity between successive range gates to be considered significant "spin". Accuracy of at least 0.5 dBZ.
- SPIN REFLECTIVITY THRESHOLD: Reflectivity value below which no "spin" is computed. Accuracy of at least 0.5 dBZ.
- RADIAL_EXTENT: The number of radials (+/-) used to define the region for computing ZTXTR, ZSIGN, and VSTDV. Accurate to one radial.
- Z_RANGE_EXTENT: The number of reflectivity range bins (+/-) used to define the region for computing ZTXTR and ZSIGN. Accurate to one reflectivity range bin.
- D_RANGE_EXTENT: The number of Doppler range bins (+/-) used to define the region for computing VSTDV. Accurate to one Doppler range bin.

3.14.2 Strengths/Applications.

- The algorithm produces a digital output, the Target Likelihood Array that is provided for use by the PPS. The Target Likelihood Array expressed the likelihood that a target is AP or clutter.
- This algorithm assists in the identification of clutter, AP echo, and thus, precipitation.

3.14.3 Limitations.

- Because the PATTERN CHARACTERISTICS of different targets may be similar at times, the REC will not likely generate a unique and specific identification at each location.
- This Algorithm description assumes the azimuthal resolution/spacing of the reflectivity information is the same as the Doppler azimuthal resolution. In addition, this description assumes a Doppler range resolution of 250 m (0.13 nm) and a reflectivity range resolution of 1000 m (0.54 nm). This may be changed in time.
- The REC presents the identification as a probability (likelihood) and requires that the user of the information (whether human or algorithm) determine a level of confidence and tolerance in the decision process.
- The algorithm cannot now assign a likelihood that a target is biological in nature.
- The REC clutter likelihood percentage values tend to be biased toward higher values in areas of range overlaid data.

3.15 Snow Accumulation Algorithm. The purpose of the Snow Accumulation Algorithm (SAA) is to provide estimates of accumulated snow water equivalent (S) and snow fall (SD). The algorithm was developed for use during dry snow, or snow that is not melting while falling or on the ground. Therefore, the adaptable parameters have been optimized for dry snow. Like the PPS for rain, SAA uses a Z-S relationship to convert reflectivity to a rate of S. Rates of S are also converted to rates of SD using a user adaptable snow water ratio. SAA converts the rates to accumulations of S and SD for a storm total accumulation and over different accumulation periods (such as one-hour and three-hour).

For some SAA adaptable parameters, optimum settings were derived for different regions of the CONUS using data from one representative site within that region.

Ideally, input reflectivity data for the SAA should come from as close to the ground as possible without ground (clutter) contamination. In this version of SAA, the algorithm uses data from the EPRE. The EPRE uses beam blockage information from the Blockage Algorithm and AP/Clutter likelihood from the REC Algorithm to construct a HYBRID SCAN array of uncontaminated, unblocked reflectivity data from the volume of base radar reflectivity data. If the beam blockage or likelihood of AP/Clutter exceeds adaptable thresholds, reflectivity information from a higher elevation is used. The EPRE also adjusts (or adds) power for partial beam blockage. In addition, EPRE stores the elevation angle from which the reflectivity data is obtained for each HYBRID SCAN bin and outputs the elevation angle information in an HYBRID SCAN Elevation Angle array for use by the SAA and other algorithms.

Whenever a HYBRID SCAN of reflectivity data is available from the EPRE, SAA processes the data. (See Figure 3-23 for an overview of the SAA). During periods of no observed snow at the surface, the algorithm accumulates bogus snow totals returns that are only aloft. SAA relies on the user to reset accumulations when snow has started to reach the ground.

Before converting reflectivities to rates, SAA filters incoming reflectivity data to further mitigate contamination from isolated sample volumes that are likely not dry snow (such as residual clutter). Reflectivities below an adaptable minimum reflectivity threshold are not considered snow and are ignored. Algorithm developers recognized that sometimes light snow can result in reflectivities below the minimum reflectivity threshold, but accumulation rates observed with below threshold reflectivities are extremely light. A sample volume with reflectivities above an adaptable maximum reflectivity threshold are either set 1) to no data if the sample volume is isolated or 2) to the reflectivity corresponding to the average rate of its neighbors if the sample volume is not isolated.

Next, reflectivities from the hybrid scan are converted to rates of S using a Z-S relationship in the form of $Z = \alpha S^{\beta}$, where α and β are the adaptable Z-S multiplicative and power coefficients, respectively.

Once rates of S are computed, SAA applies a simple range / height correction. Above a minimum threshold height, S is multiplied by a range / height correction factor to mitigate underestimation caused when the radar beam begins to overshoot the precipitation. The range / height correction increases with height and is computed from a second order polynomial. The development version of SAA used range (vs. height) as the dependent variable.

Snow Accumulation Algorithm

Algorithm Functional Overview

- Provides Snow Water Equivalent (SWE) and Snow Depth (SD) estimates over various periods of time, including one-hour, user selectable, and storm total
- Uses reflectivity from Enhanced Preprocessing (EPRE)
- Filters incoming data for
  - Isolated bins - above min. ref. threshold, but no neighbors
  - Outlier bins – above the max. ref. Threshold
- Converts reflectivity to SWE rate using Z-S; there is no averaging. Unless there is a gap in the data, the rate is applied since last scan
- Applies range / height correction – For now only a static correction is applied/available.
- Converts to SD

06 Nov 03 Snow Accumulation Algorithm, DAR 3

Figure 3-23
Snow Accumulation Algorithm Overview

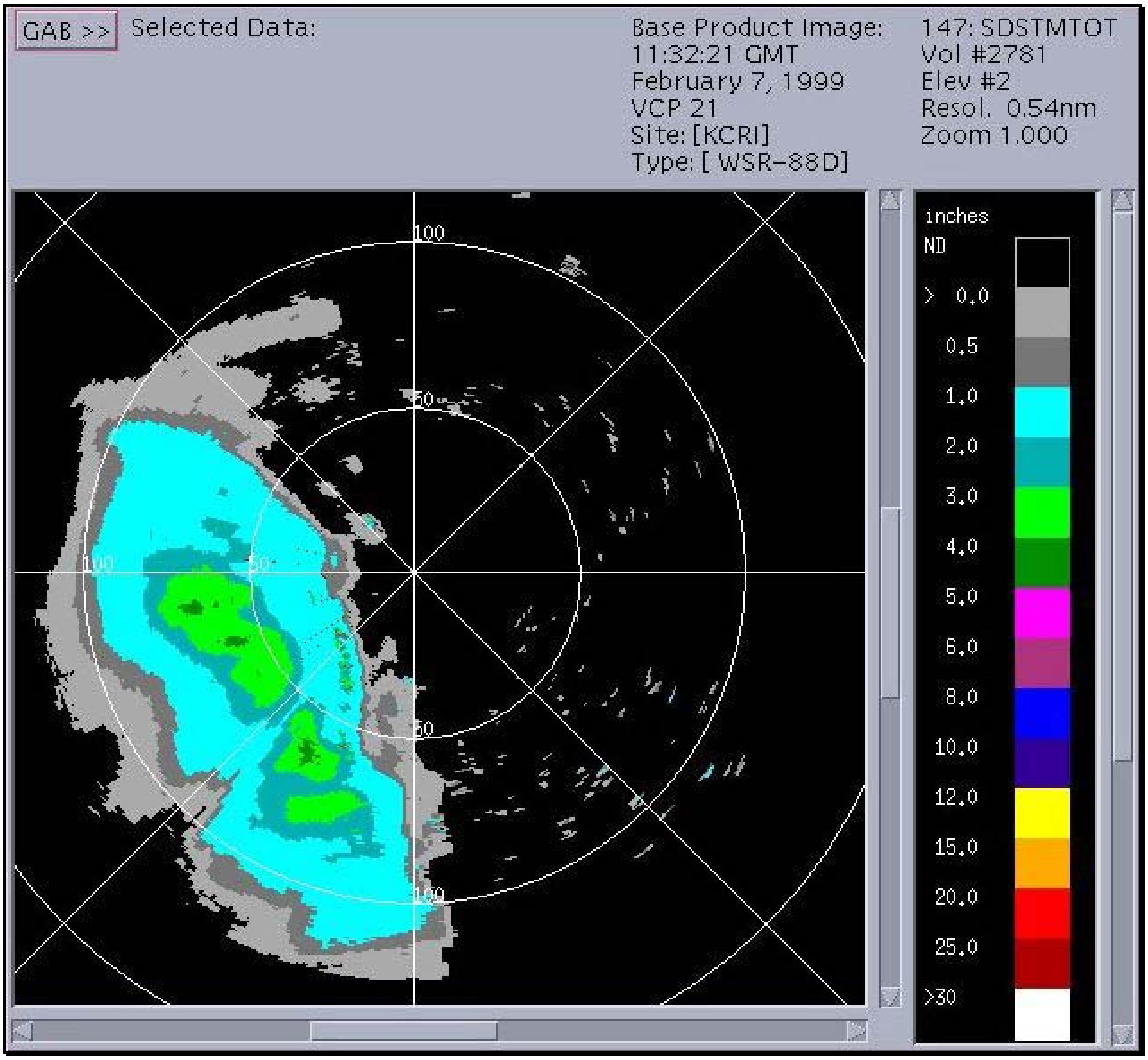

Figure 3-24
Storm-Total Snow Depth Accumulation Product

An example of a SSD product (CODE View graphics).

The SAA computes SD values by multiplying S by an adaptable snow ratio. To compute accumulations, each volume scan S and SD rates are multiplied by the time span between volume scans producing a scan to scan accumulation for both S and SD. For the first volume scan after an accumulation reset, the time span is from the beginning to the end of the hybrid scan. Otherwise, the time span is from the end of the previous hybrid scan to the end of the current hybrid scan. As time progresses, S and SD scan to scan accumulations are accrued to the S and SD storm total accumulations, respectively. For different accumulation periods (such as storm total), the scan-to-scan accumulations over the accumulation period are summed (See Figure 3-24 for a product example). For an hour-long accumulation period, scan-to-scan accumulations must exist for an adaptable minimum time threshold. Therefore, after an accumulation reset, accumulations will not be available for a specific accumulation period until the minimum time threshold has passed for that accumulation period. For all accumulations no extrapolation is done over missing time periods.

The SAA will be preformed in real-time after the EPRE has run. The EPRE is typically run near the middle of the volume scan, but could be run as late as after the second-to-last elevation scan in the volume scan.

3.15.1 Operational Parameters.

- ACCUMULATION PERIODS: Time periods over which accumulations are to be computed, such as 1-hr and 3-hr, in hrs.
- ACCUMULATION RESET FLAG: Flag indicating that all accumulations should be reset to zero; units: none, range of values: True or False, precision: n/a.
- BASE ELEVATION: Elevation angle of the lowest elevation scan in the volume scan; units: degrees, range of values: 0.1 to 2.0, precision: at least 0.1 degrees.
- DATE (END HYBRID SCAN): Date of the last radial used in the hybrid scan, in Julian Days since 01 January 1970.
- DATE (START HYBRID SCAN): Date of the first radial used in the hybrid scan, in Julian Days since 01 January 1970.
- HYBRID SCAN: Preprocessed reflectivity data mapped to a polar grid from 0 (due north) to 359 in whole degrees in azimuth and 0 to 229 km in range. Resolution of the grid is 1 degree in azimuth and 1 km in range. In addition, for each grid point, the hybrid scan must retain its elevation angle; units: dBZ_e, range of values: -32 to 95, precision: 0.5.
- HYBRID SCAN Elevation Angles: For each bin in the HYBRID SCAN array, the elevation angle of the base reflectivity data used, units: degrees, range of values: 0.0 to 20.0, precision: at least 0.1.
- MAXIMUM REFLECTIVITY THRESHOLD: Maximum reflectivity to convert to S, default value: 40.0, units: dBZ_e, range of values: 30.0 to 55.0, precision: 0.5.
- MINIMUM HEIGHT CORRECTION THRESHOLD: Minimum height (ARL) to apply the range/height correction, default value: see Appendix A, units: km, range of values: 0.01 to 20.00, precision: 0.01.
- MINIMUM REFLECTIVITY THRESHOLD: Minimum reflectivity to convert to S, default value: 5.0, units: dBZ_e, range of values: -10.0 to 25.0, precision: 0.5.

- MINIMUM TIME THRESHOLD (Period): The minimum length of time for which scan to scan accumulations are required to estimate accumulations over a one-hour period of time, default value: 54, units: minutes, range of values: 0 to 60, precision: 1.
- RANGE / HEIGHT CORRECTION COEFFICIENT #1: Coefficient #1 in the equation used to range/height correct estimates, default value: see Appendix A, units: dimensionless, range of values: -5.0 to 5.0, precision: 0.0001.
- MINIMUM HEIGHT CORRECTION THRESHOLD: Minimum height (ARL) to apply the range/height correction, default value: see Appendix A, units: km, range of values: 0.01 to 20.00, precision: 0.01.
- RANGE / HEIGHT CORRECTION COEFFICIENT #2: Coefficient #2 in the equation used to range/height correct estimates, default value: see Appendix A, units: km^{-1}, range of values: -0.5 to 0.5, precision: 0.0001.
- RANGE / HEIGHT CORRECTION COEFFICIENT #3: Coefficient #3 in the equation used to range/height correct estimates, default value: see Appendix A, units: km^{-2}, range of values: -0.001 to 0.001, precision: 0.0001.
- SNOW WATER RATIO: The ratio of SD to S, default value: see Appendix A, units: in (snow depth) /in (snow water equivalent), range of values: 4.0 to 100.0, precision: 0.1 in/in.
- TIME (END HYBRID SCAN): Time of the last radial used in the hybrid scan, in fractional hours since midnight.
- TIME (START HYBRID SCAN): Time of the first radial used in the hybrid scan, in fractional hours since midnight.
- TIME SPAN THRESHOLD: Maximum time allowed between the end of the previous hybrid scan and the beginning of the current hybrid scan, default value: 11, units: minutes, range of values: 3 to 30, precision: 1.
- Z-S MULTIPLICATIVE COEFFICIENT: Multiplicative coefficient in the Z-S relationship; also referred to as alpha, default value: see Appendix A, units: n/a, range of values: 10 to 1000, precision: 1.
- Z-S POWER COEFFICIENT: Exponential (power) coefficient in the Z-S relationship; also referred to as beta, default value: see Appendix A, units: n/a, range of values: 1.00 to 3.00, precision: 0.01.

3.15.2 Strengths/Applications.

- This algorithm is designed to estimate both the snowfall accumulation and the equivalent liquid water accumulation.
- The SAA's adaptable parameters were optimized for different WSR-88Ds around the CONUS. During development, the WSR-88Ds for SAA optimization were chosen so there would be at least one site within each geographic area which normally receives widespread snow storms.
- SAA's adaptable parameters were optimized for best overall performance throughout a winter season.
- SAA's Z-S relationships were primarily optimized from high quality hourly snow measurements. Measurement locations were also verified using the Global Positioning System.
- The maximum reflectivity threshold is used to filter reflectivities which usually are not producing dry snow.

3.15.3 Limitations.

- The SAA tends to overestimate SD when compared to snowfall that was subject to melting below the radar beam, including on the ground.
- With "wet snow" occurring with low-level temperatures of > ~ 30° F, the SAA will tend to overestimate snowfall.
- When comparing SAA estimates with snow measurements, low quality measurements should be used with caution. At WSR-88Ds where the adaptable parameters were not optimized, it is likely SAA performance will be diminished by an unknown amount, especially for situations where there are large geographical differences between the study WSR-88Ds and other WSR-88Ds. For example, large difference in radar heights will likely result in different range / height corrections.
- During SAA development and in other work, a high degree of variability has been observed with snow - radar measurements in shorter time intervals (such as Z-S relationships within an hour). Accordingly, SAA performance at small time intervals (such as 1-hour) is not as good as longer time intervals (such as storm totals).
- Since the snow ratio can vary greatly in time and space, SAA users should use caution in changing the snow ratio during a snowstorm based on in situ measurements. Algorithm developers found hourly snow ratios varied greatly and were a poor forecast of the next hour's snow ratio.
- Due to the low-topped nature of snowstorms, the SAA is subject to underestimation that becomes substantial beyond 70 km (at an elevation angle of 0.5° and increases with range). The simple range / height correction scheme extends the useful range to at most 150 km when the hybrid scan is using the lowest elevation scan. For areas where the lowest elevation scan is blocked at close range and for mountain top radars, the SAA's effective range will be less.
- SAA cannot discriminate between reflectivities representing dry snow reaching the ground and representing other targets. Therefore, the other targets will be included in SAA estimates resulting in overestimates or bogus estimates. Some common examples are virga, rain, birds, and chaff. In order to eliminate these bogus accumulations and have realistic storm total accumulations, the user must reset SAA accumulations when snow starts reaching the ground. However, a hybrid scan can contain reflectivities representing both snow reaching the ground and representing other targets at the same time. For example, snow does not start reaching the ground at the same time throughout the radar umbrella. After an accumulation reset, areas where snow has not yet reached the ground may be having virga which SAA will add to accumulation estimates.
- SAA cannot discriminate between snow and other types of precipitation. A common example is when snow and rain are falling under a radar umbrella at the same time but in different areas. If the areas of snow and rain did not change location, it would be relatively easy to keep track of which area contained snow and have useful SAA estimates. However, if the areas of rain and snow are changing, it would be unrealistic to keep track of the areas containing snow, and SAA estimates should only be used with caution.
- In rare cases, reflectivities greater than the maximum reflectivity threshold have been observed with heavy snow. In these cases, SAA tended to underestimate snow.

- SAA was developed to be used for dry snow, or snow that is not encountering temperatures of ~ 30°F or higher.
- When and where a bright band occurs, SAA tends to overestimate.

3.16 <u>Multiple Pulse Repetition Frequency (PRF) Dealiasing Algorithm</u>. The MPDA scanning strategy collects sequential scans at the same antenna elevation angle using different Nyquist velocities (PRFs). These are then range dealiased, aligned, and processed to produce a final dealiased velocity field based on the combined scans. The actual unambiguous ranges and corresponding Nyquist velocities depend on the operating frequency of the radar and may be expressed as follows:

$$R_a V_a = c^2/(8f)$$

where c is the speed of light, f is frequency, Ra is the Unambiguous range and Va is the Nyquist velocity. Typical single PRFs, Nyquist velocities, and unambiguous ranges are shown in Table 5-7 of this Handbook.

The MPDA requires VCP 121 (Table 5-4 of this Handbook). It requires three Doppler scans, besides the surveillance scan, at both 0.5 and 1.5 degrees elevation. It requires two additional Doppler Scans in addition to the Batch mode scans at 2.4 and 3.3 degrees elevation. Lastly, it adds one additional Doppler scan at 4.3° elevation. Above 4.3° elevation, the VCP is identical to VCP21.

Because the current RDA processor does not range unfold the second and third Doppler scans at the same elevation, the MPDA incorporates a range-unfolding algorithm similar to the one implemented in the WSR-88D RDA. The VCP is designed so that the data with the highest Nyquist velocity are collected first. This ensures the most intense range dealiasing will occur within the RDA.

The MPDA dealiasing scheme is a multi-step process that arrives at a final dealiased velocity solution at each radar gate. Throughout the processing steps described below, "seed" velocities are used to check the gate-by-gate MPDA results for consistency. These seeds can be single previously dealiased velocity solutions along the same radial, averages of previously dealiased gates, or estimates from the Environmental Wind Table (EWT).

3.16.1 Dealiasing Steps.

The main dealiasing steps are:

1. Solutions from Velocity Triplets (tight constraint)

This first step considers only gates at which three velocity estimates are present (See Figure 3-25 for differing solutions for velocity products based on the three PRFs). The three estimates must be dealiased within a small velocity difference of each other and within a threshold velocity difference of a seed velocity as previously defined for a final solution to be accepted. In general, this processing accounts for about 57% of the final dealiased field.

2. Solutions from Velocity Triplets (relaxed constraint)

The second step considers only gates at which three velocity estimates are present. The three estimates and a seed velocity must be dealiased within a larger velocity difference than step (a).

3. Solutions from Pairs within Triplets

The algorithm next attempts to dealias velocity pairs that did not pass the dealiasing tests in steps a and b. The use of velocity pairs may be due to there being only two estimates at a particular location in space or due to the failure to find a solution using triplets. In the case where triplets are present three solutions are possible. However, the first pair that provides an acceptable solution is retained. Note that at 4.3^{o} elevation, where only two velocity cuts are obtained, MPDA processing begins with this step.

4. Solutions from Single Estimates

At this point the remaining solutions are derived from the single velocity estimates that exist within the unsolved triplets and pairs, and those locations in space that only contained only one estimate. The single estimates are dealiased using seed values from the previous steps and increasingly relaxed thresholds. Once this processing is complete, more than 99.99% of the gates contain a final dealiased velocity value.

5. Use original velocity estimates

The remaining gates are assigned one of the three original velocity estimates that are closest to an average of the surrounding dealiased gates.

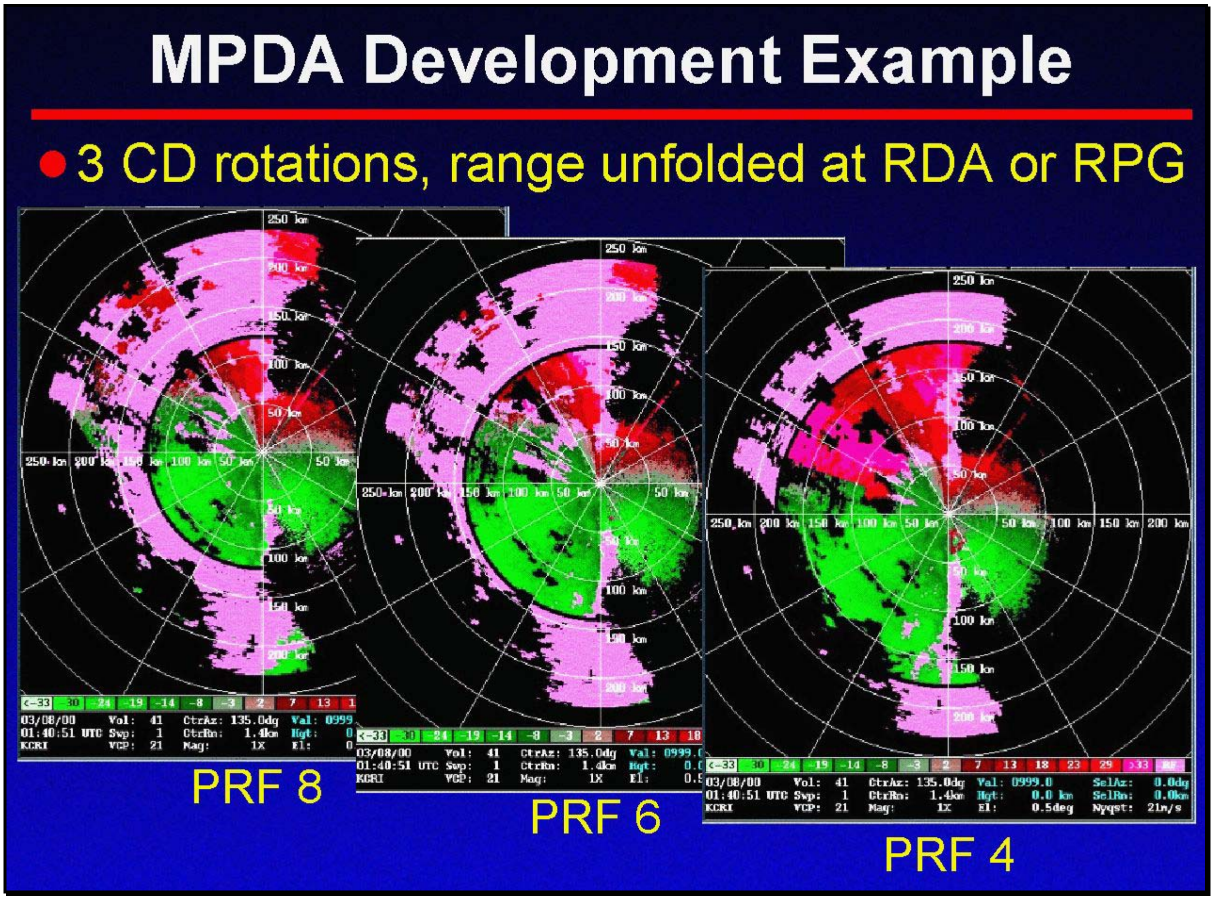

Figure 3-25
Multiple Pulse Repetition Frequency Dealiasing Algorithm Development

This sequence of Mean Radial Velocity products (AWIPS displays) demonstrates the varying range resolution of velocities the MPDA obtained during of three scans with differing PRFs.

3.16.2. Error Mitigation Schemes

After each of the steps described in Section 3.16.1, error mitigation is applied to check for outliers and for azimuthal and radial inconsistencies in the dealiased field.

1. Despeckling

A despeckling function is applied after each processing step. This routine check for single velocity gates whose solutions differ significantly from surrounding gates. Several averages of surrounding gates are checked against the gate in question. If the gate can be dealiased within a strict threshold of one of the averages, it is assigned a value. Otherwise, it is set to missing.

2. Azimuthal Error Correction

This routine searches for runs of gates along radials that differ significantly when compared to adjacent azimuthal values. Adjacent azimuths on both sides of the azimuth in question are considered in the checking. If the azimuth in question can be dealiased within a strict threshold of its adjacent azimuths, values are assigned to it. Otherwise, the gates on the radial are set to missing.

3. Radial Error Correction

This routine searches for large gate-to-gate jumps along radials. If a jump is encountered, an attempt is made to dealias it into the correct Nyquist interval based on averages of other radially adjacent gates within a strict threshold. If the gates in question can be dealiased, new values are assigned, otherwise the gates are set to missing.

3.16.3 Operational Parameters.

- Threshold (Range Unfold Power Difference): Minimum power difference (in dB) between the first and second trip echoes in order to assign unambiguously a range to velocities. (Default is 5 dB.) This parameter is used to range unfold the second and third velocity fields for the MPDA and is entirely equivalent to TOVER used by the RDA.
- Threshold (Fix Trip Minimum Bin) and Threshold (Fix Trip Maximum Bin): These two parameters define a narrow annulus at the end of each trip of Doppler data the MPDA uses to clear out noisy velocity data. The default value is -7 bins for the first parameter and -3 bins for the second parameter; range is +/- bins relative to the last bin of each trip.

3.16.4 Strengths/Applications. The MPDA has been increasingly used by operational sites to reduce “purple haze,” especially in hurricane and tornado environments (Figure 3-26).

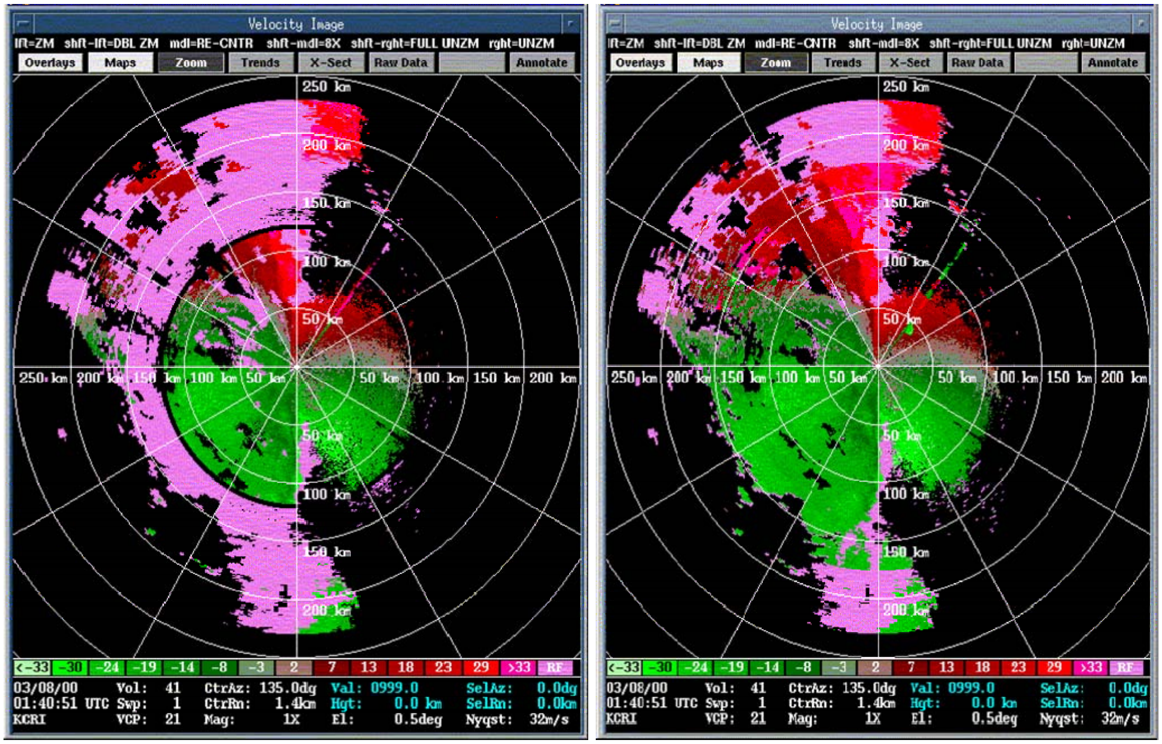

Figure 3-26
Multiple Pulse Repetition Frequency Dealiasing Algorithm Velocity Product Comparison

Velocity product produced using PRF8 (left) compared with a product produced by the MPDA (right) for the same situation. Notice that the range folding, represented by the solid purple color, is much less for the MPDA-produced velocities.

3.16.5 Limitations.

- In situations with very strong extensive echoes, range folding may be present in all input velocity fields despite having different PRFs. Under those conditions, the MPDA will also have extensive range folding.
- In locations where there is only velocity data from the lowest PRF, the velocity data may be dealiased incorrectly.
- Because the MPDA requires two extra sweeps of Doppler data, the time between elevations is somewhat greater for its VCP than for normal precipitation mode VCPs.
- Algorithms that rely on vertical continuity may not perform as well with the MPDA because of the translation and/or morphology of features.
- Because data are combined from three different sweeps, shear features near the radar may become distorted or have weakened gradients. This could have a negative impact on the Tornado Detection Algorithm. Users should exercise caution if the MPDA is used when there are tornadic storms near the radar.

3.17 Data Quality Assurance Algorithm. The Data Quality Assurance Algorithm (DQA) provides an alternate source of reflectivity factor data to WSR-88D algorithms internal to the RPG. This algorithm does not yield a product that is available to external systems. The DQA identifies and removes radials contaminated with constant power function signatures as well as regions of anomalous propagation clutter from the reflectivity factor data. This is the only such edited reflectivity factor data available. Upon completion of each elevation cut of the radar volume, the DQA passes the processed reflectivity factor data to receiving algorithms as an elevation cut. The original radar volume's elevation cut spatial integrity is maintained. The reflectivity factor data provided after DQA processing are not quantized. The original resolution of the reflectivity factor data is maintained. While DQA returns edited reflectivity factor data, it requires for analysis the original three moments of radar data for the elevation tilt plane. Both the EET Algorithm and the DVL Algorithm require the DQA data as input.

The DQA produces an intermediate, elevation cut product internal to the RPG of 1^{o} x 0.54 nm (1 km) original polar grid resolution to a range of 460 km (248 nm). This is the identical elevation cut of reflectivity factor data except for the removal of identified data contaminants. The DQA first independently analyzes every radial for the presence of a constant power function signature. This radial signature is represented by a steady increase in reflectivity factor with distance from the radar following the inverse range-squared relationship. That is, reflectivity factor increases with distance as a function of the inverse of range squared for equal returned power along the length of the radial. Figure 3-27 illustrates the contrast between individual radials – one with weather, the other with a constant power function signature. Identified constant power function radials have their original reflectivity factor replaced with the "no data" value.

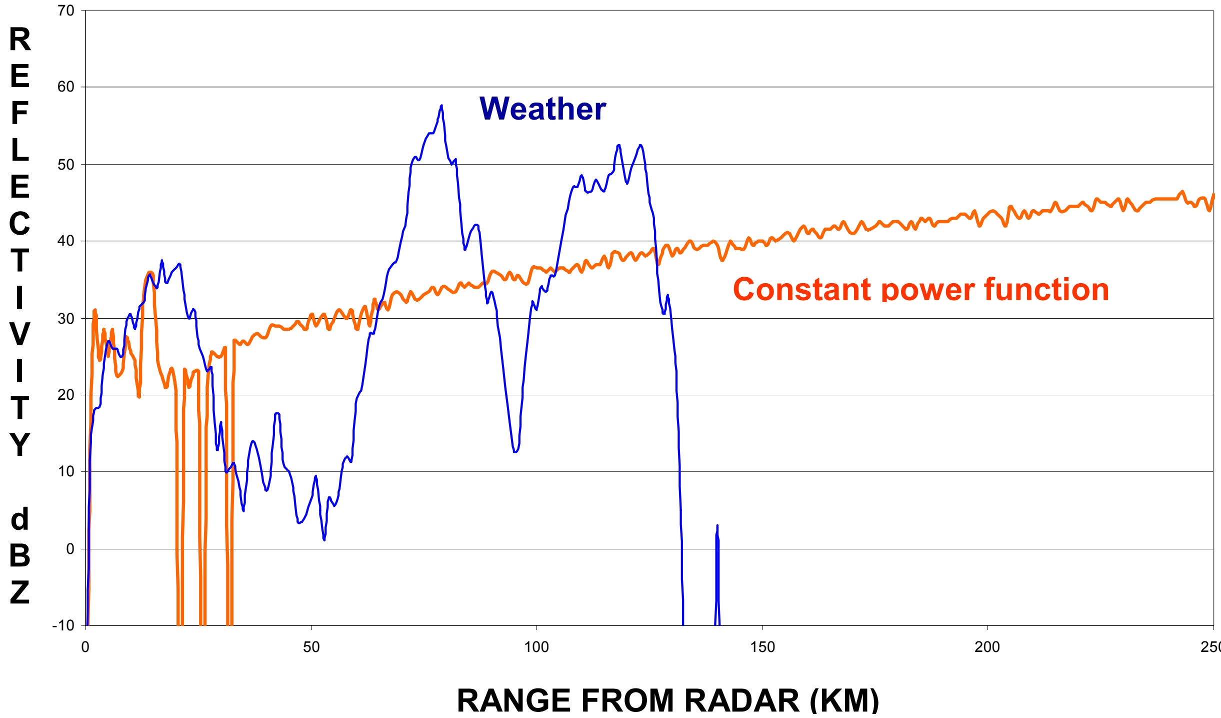

Figure 3-27
Reflectivity Factor Signatures

Sample radials depicting typical reflectivity factor signatures for a radial involving weather echo (blue) and a radial with a constant power function (orange).

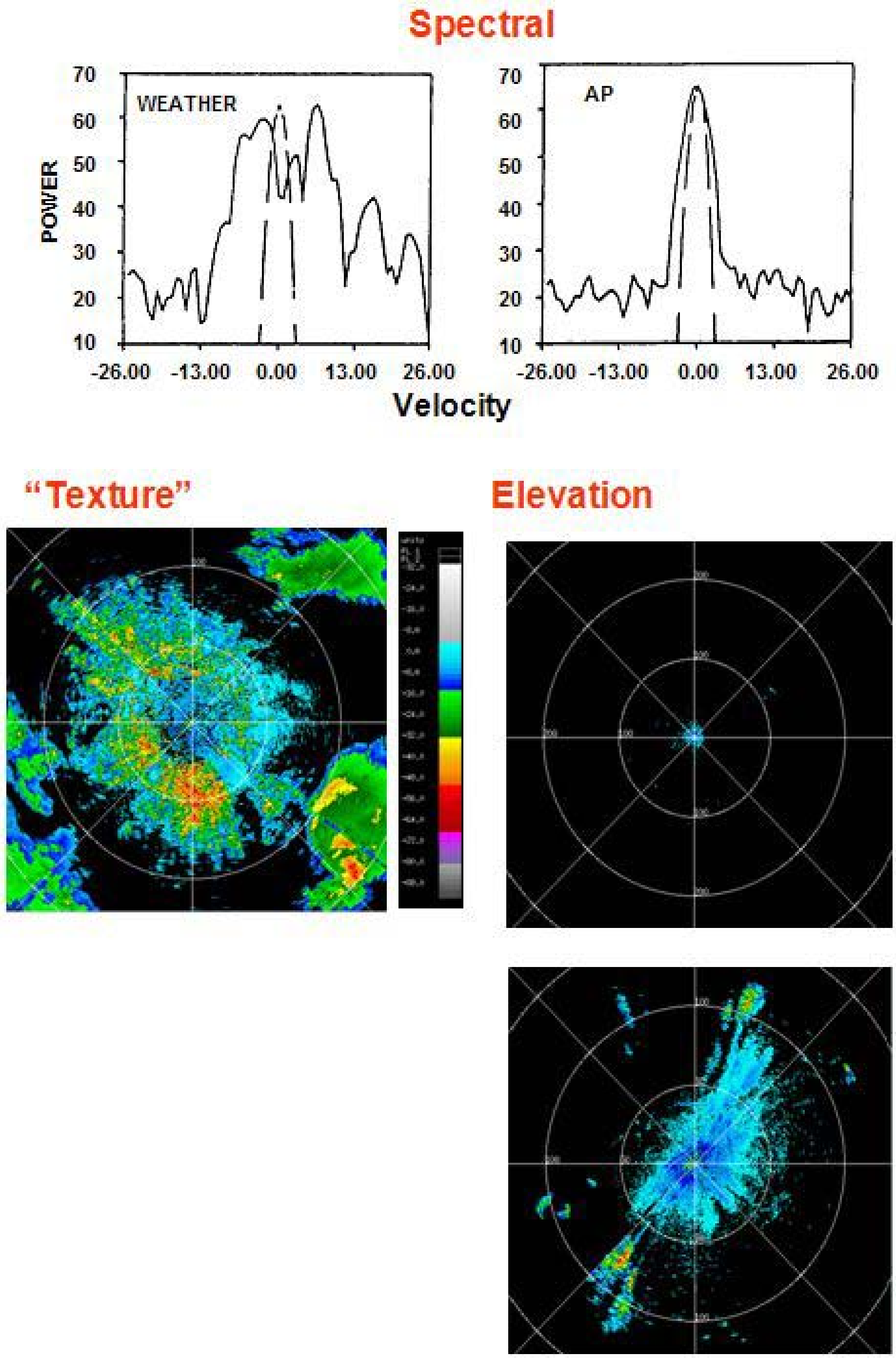

Figure 3-28
Radar Product Discriminations

The three general concepts for the AP editor portion of the DQA Algorithm are shown.

DQA follows the constant power function radial analysis with an analysis to identify and remove AP clutter in the elevation tilt plane. The identification of AP uses three concepts applied in one and two dimensions as shown in Figure 3-28. The spectral signature of AP differs from that of weather. The AP is typified by high reflectivity factor data coincident with near zero Doppler moment values. The AP typically is observed at low elevations nearer the radar; thus, DQA uses elevation discrimination to identify areas of AP. Thirdly, DQA exploits the observation that AP often has a visual texture of greater variability in the reflectivity factor data as compared to areas of weather when viewed in two dimensions. The identified AP have their original reflectivity factor replaced with the NEXRAD "no data" value.

3.17.1 Operational Parameters. None

3.17.2 Strengths/Applications

- Combined removal of AP, clutter and constant power function radials.
- Provides an alternate source of reflectivity factor data to WSR-88D algorithms.
- Identified problematic data removed from reflectivity factor; no additional editing required.
- Removes "bulls-eye" and "starburst" full volume constant power function phenomenon often associated with a WSR-88D radar in maintenance mode or suffering a hardware failure.

3.17.3 Limitations.

- Identified problematic data removed from reflectivity factor; no ability to recover those original values in DQA product.
- Constant power functions remain in the presence of weather signature.
- Actual weather signatures can be erroneously removed.
- The AP editor will not analyze areas lacking Doppler moment data.

3.18 <u>High Resolution Enhanced Echo Tops Algorithm</u>. The High Resolution Enhanced Echo Tops Algorithm (EET) ingests processed reflectivity factor data from the DQA Algorithm. The DQA Algorithm identifies and removes radials contaminated with constant power function signatures as well as regions of anomalous propagation clutter from the reflectivity factor data. Upon completion of each elevation cut of the radar volume, the DQA passes the processed data to receiving algorithms as an elevation cut. The original radar volume's elevation cut spatial integrity is maintained. The reflectivity factor data provided after DQA processing are not quantized. The original resolution of the reflectivity factor data is maintained.

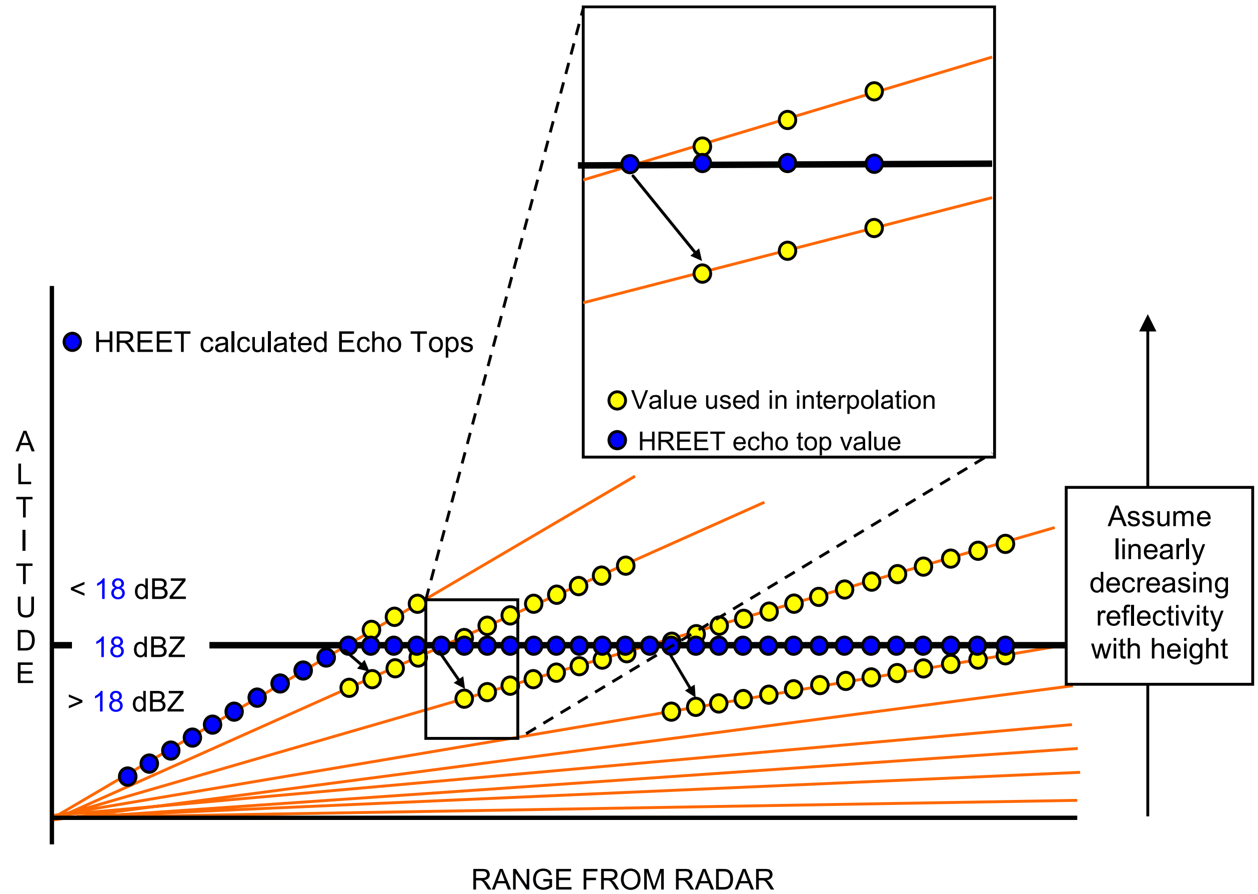

Figure 3-29
Enhanced Echo Tops Algorithm

The EET determines the proper echo top height (blue circles) within the radar volume by selecting a range gate along a radial or interpolating in the vertical between two on adjacent elevation tilt planes that bisect the threshold level.

The EET produces an output product of estimated echo top heights on a 1° x 0.54 nm (1 km) polar grid resolution to a range of 186 nm (345 km). Each point of the EET product represents processing through a vertical column of the radar volume. Each column is populated by range gate sample volumes from the intersected elevation tilt planes of the radar volume. The EET determines the altitudes along the elevation tilt plane for range gate sample volumes whose reflectivity factor equals or exceeds the reflectivity factor threshold. The EET analyzes vertically upwards through successive elevation tilt planes in this manner. For any vertical column, altitude is determined through vertical linear interpolation between successive elevation tilt planes when the reflectivity factor threshold is exceeded for the lower plane and not exceeded for the upper plane. This processing functionality mitigates the computationally-introduced "stair-step" artifact of the ET product.

Figure 3-29 illustrates the method used by EET to determine the echo top height. An echo top deck (dark line) of constant altitude defined by the 18 dBZ threshold is modeled with higher reflectivity factor below and lesser reflectivity factor above. The orange lines represent individual elevation tilt planes within the radar volume. Circles along the tilt planes represent (not to scale) sections of individual range gate sample volumes comprising the radial. The blue circles represent the echo top height determined by the EET Algorithm for this case. In the highlight box, the EET echo top height is indicated with the blue circles based on vertical linear interpolation between the higher reflectivity factor sample volumes on the lower elevation angle tilt plane and the lower reflectivity factor sample volumes on the higher elevation angle tilt plane. The diagonally downward pointing arrow from the left-most blue circle to the left-most yellow circle on the lower angle elevation tilt plane is provided to contrast EET with the "stair-step" altitude selection methodology of the ET product.

The EET provides the echo top height in 1 kft resolution along with a flag value to indicate if the echo top height is "topped". A "topped" echo top occurs when the last elevation tilt plane has range gate sample volumes with reflectivity factor that meets or exceeds the threshold. In the case of the Figure 3-29, the "topped" EET echo top heights are all along the left-most elevation tilt plane below the actual modeled echo top height. This region is the "cone-of-silence" for the radar and typically will have "topped" echo top heights during significant convection in close proximity to the radar. The EET product can be provided as a bzip2 compressed product for external user systems.

3.18.1 Operational Parameters. None.

3.18.2 Strengths/Applications.

- A vertical linear interpolation technique is utilized to estimate echo top heights between elevation tilt planes.
- An indicator if an echo top height is "topped".
- High spatial resolution of 1° x 0.54 nm (1 km).
- Data resolution of 1 kft.

3.18.3 Limitations.

- The precision for measuring the height decreases with range because of beam broadening. At a range of 230 km (124 nm) the half-power beam width is 4040 meters.
- The algorithm does not correct for data contamination from side lobes. The height of echo tops could be overestimated from this effect.
- The echo tops may be undetectable by the radar at close range with a limited range of elevations.
- The vertical change of reflectivity factor may not be linear.
- No adaptable parameters are available.

3.19 Digital High Resolution Vertically Integrated Liquid Water. The Digital High Resolution Vertically Integrated Liquid Water Algorithm (DVL) ingests processed reflectivity factor data from the DQA Algorithm. The DQA Algorithm identifies and removes radials contaminated with constant power function signatures as well as regions of anomalous propagation clutter from the reflectivity factor data. Upon completion of each elevation cut of the radar volume, the DQA passes the processed data to receiving algorithms as an elevation cut. The original radar volume's elevation cut spatial integrity is maintained. The reflectivity factor data provided after DQA processing are not quantized. The original resolution of the reflectivity factor data is maintained.

The DVL produces an output product of a digitally encoded estimate of VIL on a 1° x 0.54 nm (1 km) polar grid resolution to a range of 460 km (248 nm). Each point of the DVL product represents processing through a vertical column of the radar volume. Each column is populated by a set of range gate sample volumes from each intersected elevation tilt plane of the radar volume. The DVL determines the partial VIL contribution from each intersected elevation tilt plane of the column by selecting the range gate sample volume with the largest reflectivity factor, converting it to equivalent liquid water, and vertically integrating through the depth of the range gate sample volume. The calculation of the partial VIL is the same as that done for the VIL Algorithm except that DVL uses non-quantized reflectivity factor data and includes the conversion to VIL of reflectivity factor below 18 dBZ threshold. Any range gate sample volume used with a reflectivity factor greater than 56 dBZ provides a partial VIL based on 56 dBZ.

At completion of the last elevation tilt plane, DVL tallies the partial VIL contributions in each column to arrive at the column total VIL in kg m^{-2}. The total VIL value is capped at 80 kg m^{-2} if exceeded. The resolution of DVL varies due to the digital encoding. The DVL digitally encodes the data using a linear scale for VIL less than 0.19 kg m^{-2} and a log scale thereafter up to the cap threshold. The DVL product can be provided as a bzip2 compressed product for external user systems.

3.19.1 Operational Parameters. None

3.19.2 Strengths.

- High spatial resolution of 1^o x 0.54 nm (1 km).
- Inclusion of reflectivity factor below 18 dBZ heightens depiction of incipient development of convective weather.

- Provides fine scale depiction of VIL at levels below that depicted by the minimum threshold of the original VIL product.

3.19.3 Limitations.

- This algorithm has a bias towards larger drop sizes. Clouds containing a large number of small precipitation drops produce very small values.
- The values obtained at distant ranges may is often misleading because liquid water below the radar beam is not measured.
- At long ranges, errors may be due to large radar sample volumes.
- There are no adaptable parameters.

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