TORNADO DETECTION

ALGORITHM DESCRIPTION

NX-DR-03-039/01

1.0 PROLOGUE

1.1 FUNCTIONAL DESCRIPTION

1.1.1 Introduction

This document describes the Tornado Detection Algorithm (TDA). This introduction contains an overview of the algorithm. Then each subsequent subsection contains a more detailed description of the major functional parts of the algorithm. Much of the information contained in this document can also be found in Mitchell 1998. For more information about the performance of the algorithm, see Mitchell 1995.

The TDA uses radar data to identify intense 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 Tornadic Vortex Signature (ETVS) or Tornadic Vortex Signature (TVS) or not. Finally, the TVSs and ETVSs are associated with storm cells.

1.1.2 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 above radar level (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.

1.1.3 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 a azimuthal and range separation proximity thresholds and exceed the same differential velocity threshold. Multiple differential velocity threshold 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 vector 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, it's 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. 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.

1.1.4 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.

Once all potential 3D feature 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 it's 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. 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. it's 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 "??".

1.2 SOURCE

Brown, R.A., L.R. Lemon, D.W. Burgess, 1978: Tornado detection by pulsed Doppler radar. *Mon. Wea. Rev.*, 106, 29-38.

Mitchell, E.D., 1995: An enhanced NSSL Tornado Detection Algorithm. *27th Conference on Radar Meteorology*, Vail, Colorado, October 1995, Amer. Meteor. Soc.

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Next Generation Weather Radar (NEXRAD), 1985: Algorithm Report, NEXRAD Joint System Program Office, Washington, DC.

Sanger, S. S., 1994: An interactive Doppler radar and weather detection algorithm display system. Preprints, *Tenth Conference on Interactive Information and Processing Systems on Meteorology, Oceanography, and Hydrology*, Nashville, Amer. Meteor. Soc. 7-13.

Zrnic, D.S., R.J. Doviak, 1975: Velocity spectra of vortices scanned with a pulse-Doppler radar. *J. Appl. Meteor.*, 14, 1531-1539.

1.3 PROCESSING ENVIRONMENT

Base data used by this algorithm must be preprocessed to mitigate velocity aliasing, range folding, and ground clutter contamination. The TDA was developed for use on a Weather Surveillance Radar - 1988 Doppler (WSR-88D). As in the WSR-88D, this algorithm assumes that base data is collected and supplied in increasing azimuth (clockwise) and elevation angle. The TDA was developed and tested on National Severe Storm Laboratory's (NSSL's) Radar Analysis and Display Software (RADS) on a 32 bit UNIX based SUN Workstation which ingests live (wideband) or archived (Level II) radial data from a WSR-88D (Sanger 1994).

All radials of data are assumed to be adjacent and that there are no azimuthal gaps between the radials. Pattern vectors require gate to gate shear.

2.0 INPUTS

2.1 IDENTIFICATION

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 dBZe.
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°, range 0.0° to 4.0°.
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	=	The maximum horizontal radius used for

Radius1) 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.

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 ()RANGE(Slant)/)AZIMUTH) 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 = The maximum RANGE(Slant) at which pattern

Vector Range)	vectors are identified, in km; default 100 km, range 0 to 230 km.
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 # Vectors Per 2D Feature) =	The minimum number of Pattern Vectors 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°, range: 0.0° to 10.0°. Either height or ELEVATION criteria must be met to declare a TVS.
THRESHOLD(minimum TVS Base Height) =	The minimum height AGL 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).

2.2 ACQUISITION

AZIMUTH, ELEVATION, and RANGE(Slant) are directly measured by the radar's instantaneous position. The REFLECTIVITY FACTOR and VELOCITY of a sample volume are acquired by measurements by the radar hardware. The dimensions of RADIALs and SAMPLE VOLUMEs are a result of radar hardware and parameters at the time of the measurements. A radial is approximately 1 degree wide in azimuth. Each sample volume of reflectivity data is 1 km long, and each sample volume of velocity data is 0.25 km long. RADIUS (Earth) is a physical constant. All the thresholds are supplied as adaptable parameters whose values have been based on empirical studies and are adjustable by the operator/user. The Storm IDs, Azimuths, and Ranges are supplied by a storm cell identification and tracking algorithm.

3.0 PROCEDURE

3.1 ALGORITHM

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BEGIN ALGORITHM (TORNADO DETECTION)

DO FOR ALL (ELEVATIONs)
1.0 DO FOR ALL (RADIALs) while the # of Pattern Vectors in the ELEVATION is less than or equal to
    THRESHOLD(maximum # Pattern Vectors)
      DO FOR ALL (SAMPLE VOLUMEs)
         COMPUTE (Pattern Vector(Velocity Difference))
         IF [(Pattern Vector(Velocity Difference) is greater than or equal to THRESHOLD(Vector Velocity
         Difference)) AND (RANGE(Slant) less than or equal to THRESHOLD(maximum Pattern Vector Range)) AND
         (REFLECTIVITY FACTOR(Sample Volume) of the adjacent SAMPLE VOLUMEs in both radials are greater
         than or equal to THRESHOLD(minimum Reflectivity))]
            THEN
            COMPUTE (Pattern Vector(Height))
            IF (Pattern Vector(Height) is less than or equal to THRESHOLD(maximum Pattern Vector Height))
               THEN
               IDENTIFY a new Pattern Vector
               INCREMENT # of Pattern Vectors
               SET Pattern Vector(Range) to the RANGE(Slant)
               COMPUTE (Pattern Vector(Azimuth Difference))
               COMPUTE (Pattern Vector(beginning Azimuth))
               COMPUTE (Pattern Vector(ending Azimuth))
            END IF
         END IF
      END DO
   END DO

2.0DO FOR ALL (THRESHOLD(Differential Velocity) from largest to smallest)
      FLAG all Pattern Vectors as UNASSIGNED
2.1   DO FOR ALL (UNASSIGNED Pattern Vectors) while the # of 2D Features in the volume scan is less than
         or equal to THRESHOLD(maximum # 2D Features)
   2.1.1 IF (Pattern Vector(Velocity Difference) is greater than or equal to
         THRESHOLD(Differential Velocity))
            THEN
   2.1.1.1  DO UNTIL (Potential 2D Feature(# Vectors) is INCREMENTED)
   2.1.1.1.1   DO FOR ALL (Pattern Vectors already ASSIGNED to any Potential 2D Feature at this
               THRESHOLD(Differential Velocity))
                  COMPUTE (Vector Radial Distance)
                  COMPUTE (Vector Azimuthal Distance)
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   2.1.1.1.1.1    IF ((Vector Radial Distance is less than THRESHOLD(2D Vector Radial Distance)) AND
                  (Vector Azimuthal Distance is less than or equal to THRESHOLD(2D Vector Azimuthal
                  Distance)))
                     THEN
                     ASSIGN the Pattern Vector to the same Potential 2D Feature
                     COMPUTE (Potential 2D Feature(beginning Azimuth))
                     COMPUTE (Potential 2D Feature(ending Azimuth))
                     COMPUTE (Potential 2D Feature(beginning Range))
                     COMPUTE (Potential 2D Feature(ending Range))
                     INCREMENT (Potential 2D Feature(# Vectors))
                  END IF
               END DO
               IDENTIFY a new Potential 2D Feature
               ASSIGN Pattern Vector to the new Potential 2D Feature
               SET Potential 2D Feature(beginning Azimuth) to the Pattern Vector(beginning Azimuth)
               SET Potential 2D Feature(ending Azimuth) to the Pattern Vector(ending Azimuth)
               SET Potential 2D Feature(beginning Range) to the Pattern Vector(Range)
               SET Potential 2D Feature(ending Range) to the Pattern Vector(Range)
               INCREMENT (Potential 2D Feature(# Vectors))
            END DO
         END IF
      END DO
2.2   DO FOR ALL (Potential 2D Features at this THRESHOLD(Differential Velocity))
   2.2.1 SORT Pattern Vectors(Potential 2D Feature) by increasing Pattern Vector(Range) and secondly
         clockwise (in increasing Pattern Vector(Azimuth)))
   2.2.2 IF (Pattern Vector(Range) of the first pattern vector is equal to the Pattern Vector(Range) of
         the last pattern vector)
            THEN
   2.2.2.1  DO FOR ALL (Pattern Vectors(Potential 2D Feature))
   2.2.2.1.1   COMPUTE (Maximum Velocity Difference(Range))
   2.2.2.1.2   IF (Pattern Vector(Velocity Difference) is equal to Maximum Velocity Difference(Range))
                  THEN
   2.2.2.1.2.1    LABEL the Pattern Vector as the Reference Vector (for this range)
               END IF
            END DO
   2.2.2.2  SAVE Reference Vector (delete all others)
   2.2.2.3  SET Potential 2D Feature(# Vectors) equal to 1
   2.2.3 ELSE
   2.2.3.1  SET Reference Vector to the first Pattern Vector at the second range
   2.2.3.2  DO FOR ALL (Pattern Vectors at the first range)
   2.2.3.2.1   COMPUTE (Pattern Vector(Reference Azimuthal Difference))
   2.2.3.2.2   COMPUTE (Minimum Reference Azimuthal Difference) (for the Pattern Vectors at this range)
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2.2.3.2.3     IF (Pattern Vector(Reference Azimuthal Difference) is less than the Minimum Reference
              Azimuthal Difference)
                 THEN
2.2.3.2.3.1      LABEL the Pattern Vector as the Reference Vector at the 1st range
2.2.3.2.4     ELSE IF (Pattern Vector(Reference Azimuthal Difference) is equal to the Minimum
              Reference Azimuthal Difference)
                 THEN
2.2.3.2.4.1      COMPUTE (Maximum Velocity Difference(Range)) (for the Pattern Vectors at this range)
2.2.3.2.4.2      IF (Pattern Vector(Velocity Difference) is greater than or equal to the Maximum Velocity
                 Difference(Range))
                    THEN
2.2.3.2.4.2.1       LABEL the Pattern Vector as the Reference Vector at the 1st range
                 END IF
              END IF
           END DO
2.2.3.3    SAVE Reference Vector at the first range (delete all others at the first range)
2.2.3.4    INCREMENT Potential 2D Feature(# Vectors)
2.2.3.5    DO FOR ALL (ranges within the Potential 2D Feature)
2.2.3.5.1     DO FOR ALL (Pattern Vectors at the range after the Reference Vector)
2.2.3.5.1.1      COMPUTE (Pattern Vector(Reference Azimuthal Difference))
2.2.3.5.1.2      COMPUTE (Minimum Reference Azimuthal Difference) (for the Pattern Vectors at this range)
2.2.3.5.1.3      IF (Pattern Vector(Reference Azimuthal Difference) is less than the Minimum Reference
                 Azimuthal Difference)
                    THEN
2.2.3.5.1.3.1       LABEL the Pattern Vector as the Reference Vector (for the next range)
2.2.3.5.1.4      ELSE IF (Pattern Vector(Reference Azimuthal Difference) is equal to the Minimum Reference
                 Azimuthal Difference)
                    THEN
2.2.3.5.1.4.1       COMPUTE (Maximum Velocity Difference(Range) (for the Pattern Vectors at the next
                    range))
2.2.3.5.1.4.2       IF (Pattern Vector(Velocity Difference) is greater than or equal to the Maximum
                    Velocity Difference(Range))
                       THEN
2.2.3.5.1.4.2.1        LABEL the Pattern Vector as the Reference Vector (for the next range)
                    END IF
                 END IF
              END DO
2.2.3.5.2     SAVE Reference Vector at the next range (delete all others at the next range)
2.2.3.5.3     INCREMENT Potential 2D Feature(# Vectors)
           END DO
        END IF
2.2.4   IF (Potential 2D Feature(# Vectors) is greater than equal to THRESHOLD(minimum # Vectors Per
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      2D Feature))
         THEN
2.2.4.1  DO FOR ALL (Potential 2D Feature(# Vectors))
            COMPUTE (maximum Potential 2D Feature(Delta Velocity))
            COMPUTE (Pattern Vector(Momentum))
         END DO
         COMPUTE (Potential 2D Feature(Sum Momentum))
         COMPUTE (Potential 2D Feature(Sum Ranges))
         COMPUTE (Potential 2D Feature(Sum Middle Azimuths))
         COMPUTE (Potential 2D Feature(Sum Delta Azimuths))
         COMPUTE (Potential 2D Feature(Radial Diameter))
         COMPUTE (Potential 2D Feature(Azimuth))
         COMPUTE (Potential 2D Feature(Range))
         COMPUTE (maximum Potential 2D Feature(Shear))
         COMPUTE (Potential 2D Feature(X))
         COMPUTE (Potential 2D Feature(Y))
         COMPUTE (Potential 2D Feature(Average Elevation))
         COMPUTE (Potential 2D Feature(Height))
         COMPUTE (Potential 2D Feature(Azimuthal Diameter))
         COMPUTE (Potential 2D Feature(Aspect Ratio))
2.2.4.2  IF (Potential 2D Feature Aspect Ratio is less than THRESHOLD(maximum 2D Feature Aspect Ratio))
            THEN
            INITIALIZE Overlap Counter to Ø
2.2.4.2.1   DO FOR ALL (2D Features)[already found at this elevation scan]
               IF [(Potential 2D Feature(beginning Azimuth) is less than or equal to 2D
               Feature(beginning Azimuth) AND (Potential 2D Feature(ending Azimuth) is greater than or
               equal to 2D Feature (ending Azimuth) AND (Potential 2D Feature(beginning Range) is less
               than 2D Feature(beginning Range) AND (Potential 2D Feature(ending Range) is greater than
               or equal  2D Feature(ending Range) AND (Potential 2D Feature(Average Elevation) is equal
               to 2D Feature(Average Elevation))]
                  THEN
                  COMPUTE (Overlap Counter)
               END IF
            END DO
2.2.4.2.2   IF (Overlap Counter equals 1)
               THEN
               SET 2D Feature(Azimuth) to Potential 2D Feature(Azimuth)
               SET 2D Feature(Range) to Potential 2D Feature(Range)
               SET 2D Feature(Height) to Potential 2D Feature(Height)
               SET 2D Feature(X) to Potential 2D Feature(X)
               SET 2D Feature(Y) to Potential 2D Feature(Y)
               SET 2D Feature(beginning Azimuth) to Potential 2D Feature(beginning Azimuth)
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                    SET 2D Feature(ending Azimuth) to Potential 2D Feature(ending Azimuth)
                    SET 2D Feature(beginning Range) to Potential 2D Feature(beginning Range)
                    SET 2D Feature(ending Range) to Potential 2D Feature(ending Range)
  Note: REPLACE The attributes of the Saved 2D feature with these attributes of the Potential 2D Feature.
    2.2.4.2.3   ELSE IF (Overlap counter equals 0)
                    THEN
                    SAVE the Potential 2D Feature as a new 2D Feature
                    INCREMENT # of 2D Features
                    SET 2D Feature(Azimuth) to Potential 2D Feature(Azimuth)
                    SET 2D Feature(Range) to Potential 2D Feature(Range)
                    SET 2D Feature(Height) to Potential 2D Feature(Height)
                    SET 2D Feature(X) to Potential 2D Feature(X)
                    SET 2D Feature(Y) to Potential 2D Feature(Y)
                    SET 2D Feature(beginning Azimuth) to Potential 2D Feature(beginning Azimuth)
                    SET 2D Feature(ending Azimuth) to Potential 2D Feature(ending Azimuth)
                    SET 2D Feature(beginning Range) to Potential 2D Feature(beginning Range)
                    SET 2D Feature(ending Range) to Potential 2D Feature(ending Range)
                    SET maximum 2D Feature(Delta Velocity) to maximum Potential 2D Feature(Delta Velocity)
                    SET maximum 2D Feature(Shear) to maximum Potential 2D Feature(Shear)
    2.2.4.2.4   ELSE
                    DELETE the Potential 2D Feature
                  END IF
                END IF
              END IF
            END DO
          END DO (Differential Velocities)
        END DO

3.0 SORT 2D Features by MAXIMUM DELTA VELOCITY from largest to smallest

4.0 DO FOR ALL ELEVATIONS FROM LOWEST TO HIGHEST
   IF (the # of 2D Features on the current ELEVATION is greater than 0)
      THEN
      DO FOR ALL (2D Features on the current ELEVATION)
         THEN
         IF (the 2D Feature has not been ASSIGNED or DISCARDED)
            THEN
            ASSIGN 2D Feature on the current ELEVATION to the Potential 3D Feature
            IF (2D Feature(RANGE) is less than or equal to THRESHOLD(Circulation Radius(Range))
               THEN
               SET Circulation Radius to THRESHOLD(Circulation Radius1)
            ELSE
```

```
            SET Circulation Radius to THRESHOLD(Circulation Radius2)
         END IF (2D Feature(RANGE))
         DO FOR ALL (higher ELEVATIONs)
            IF (the # of 2D Features on the higher ELEVATION are greater than 0) AND (the number of
               ELEVATIONS between the current ELEVATION and the higher ELEVATION is less than or equal to
               one)
               THEN
               DO FOR ALL (2D Features the current ELEVATION)
                  IF (the next 2D Feature on the higher ELEVATION has not been ASSIGNED or DISCARDED)
                     THEN
                     COMPUTE (Potential 3D Feature to 2D Feature Distance)
                     IF (Potential 3D Feature to 2D Feature Distance is less than or equal to Circulation
                        Radius)
                        THEN
                        IF (a 2D Feature on the higher ELEVATION has already been ASSIGNED)
                           THEN
                           DISCARD 2D Feature found on the higher ELEVATION
                        ELSE
                           ASSIGN 2D Feature on the higher ELEVATION to the Potential 3D Feature
                           INCREMENT the # Of 2D Features(3D Feature)
                        END IF
                     END IF
                  END IF
               END DO
            END IF
         END DO
      END IF
   END DO
 END IF
END DO

5.0 SORT 2D Features by HEIGHT from smallest to largest

6.0 DO FOR ALL (Potential 3D Features)
      DO WHILE (the # of 3D Features is less than THRESHOLD(maximum # 3D Features))
         IF (# Of 2D Features(3D Feature) is greater than THRESHOLD(minimum # 2D Features (3D Feature)))
            THEN
            SAVE the Potential 3D Feature as a 3D Feature
            DO FOR ALL 2D Features(3D Feature) from lowest to highest
               IF (2D Feature is the lowest)
                  THEN
                  ASSIGN 2D Feature(Average Elevation) to 3D Feature(Base Elevaton)
```

```
                ASSIGN 2D Feature(Height) to 3D Feature(Base Height)
                ASSIGN 2D Feature(Delta Velocity)) to 3D Feature(Base Delta Velocity)
                ASSIGN 2D Feature(Range) to 3D Feature(Base Range)
                ASSIGN 2D Feature(Azimuth) to 3D Feature(Base Azimuth)
             ELSE IF (2D Feature is the highest)
                ASSIGN 2D Feature (Height) to 3D Feature(Top Height)
             END IF
             COMPUTE (3D Feature(Depth)
             COMPUTE (maximum 3D Feature(Delta Velocity))
             COMPUTE (HEIGHT maximum 3D Feature(Delta Velocity))
             COMPUTE (maximum 3D Feature(Shear))
             COMPUTE (HEIGHT maximum 3D Feature(Shear))
          END DO
          COMPUTE(Average Delta Velocity)
       END IF
    END DO
 END DO

7.0 DO FOR ALL (3D Features)
    IF ((3D Feature(Depth) is greater than or equal to THRESHOLD(minimum 3D Feature Depth))
       THEN
       IF (3D Feature(Base Height) is greater than THRESHOLD(minimum TVS Base Height)) AND (3D Feature (Base
       Average Elevation) is greater than THRESHOLD(minimum TVS Base Elevation))
          THEN
          IF Feature(Base Delta Velocity) is greater than or equal to THRESHOLD(minimum TVS Delta Velocity))
             THEN
             SAVE 3D Feature as an ETVS
          END IF
       ELSE IF (3D Feature(Base Delta Velocity) is greater than or equal to THRESHOLD(minimum 3D Feature Low
          Level Delta Velocity)) OR (maximum 3D Feature(Delta Velocity) is greater than THRESHOLD(TVS Delta
          Velocity))
          THEN
          SAVE 3D Feature as a TVS
       END IF
    END IF
    IF (3D was saved as a TVS or ETVS)
       THEN
       INCREMENT (# of TVSs/ETVSs)
       IF (TVS)
          THEN
          INCREMENT (# of TVSs)
          IF (the # of TVSs is greater than or equal to THRESHOLD(maximum # of TVSs)
```

```
            THEN
            SET (the # of TVSs equal to the THRESHOLD(maximum # of TVSs)
            DISCARD the TVS with the smallest TVS(Base Delta Velocity) and, secondly, the smallest maximum
               TVS(Delta Velocity)
         END IF
      ELSE
         INCREMENT (# of ETVS)
         IF (the # of ETVSs is greater than or equal to THRESHOLD(maximum # of ETVSs)
            THEN
            SET (the # of ETVSs equal to the THRESHOLD(maximum # of ETVSs)
            DISCARD the ETVS with the smallest TVS(Base Delta Velocity) and, secondly, the smallest maximum
               TVS(Delta Velocity)
         END IF
      END IF
      WRITE(TVS(Type)) Note: TVS or ETVS
      WRITE(TVS(Base Azimuth))
      WRITE(TVS(Base Range))
      WRITE(TVS(Base Elevation Angle)
      WRITE(TVS(Base Height))
      WRITE(TVS(Top Height))
      WRITE(TVS(Depth))
      WRITE(TVS(Base Delta Velocity))
      WRITE(maximum TVS(Delta Velocity))
      WRITE(HEIGHT TVS(maximum Delta Velocity))
      WRITE(Average Delta Velocity)
      WRITE(maximum TVS(Shear))
      WRITE(HEIGHT TVS(maximum Shear))
   END IF
END DO
WRITE(# of TVSs)
WRITE(# of ETVSs)
8.0 DO FOR ALL (TVS Features)
   INITIALIZE TVS(ID) to "??"
   DO FOR ALL (STORM CELLs)
      COMPUTE (Storm Association Distance)
      IF ((Storm Association Distance is less than the THRESHOLD(maximum Storm Association Distance) AND
         (Storm Association Distance is less than or equal to the minimum Storm Association Distance for
         this TVS Feature))
         THEN
         ASSIGN STORM CELL(ID) to the TVS(ID) (Note: Disassociate any previously associated STORM CELL)
         SET the minimum Storm Association Distance for this TVS Feature to the Storm Association Distance
      END IF
```

```
   END DO
WRITE (TVS(ID))
END DO
```

3.2 COMPUTATION

3.2.1 NOTATION

#2D	=	# Of 2D Features(3D Feature), the number of 2D Features contained in a 3D Feature.
2DDVmax	=	2D Feature(Delta Velocity), the maximum velcocity difference of all 1D Pattern Vectors within a 2D Feature, in m/s.
2DHt	=	2D Feature(Height), the height (to the momentum weighted center) of a 2D Feature above radar level, in km.
2DShrmax	=	maximum 2D Feature(Shear), the maximum shear of all Pattern Vectors within a 2D Feature, in 1/s*E-03.
2DX	=	2D Feature(X), the X coordinate (to the momentum weighted center) of a 2D Feature being considered as part of a potential 3D Feature, in km.
2DY	=	2D Feature(Y), the Y coordinate (to the momentum weighted center) of a 2D Feature being considered as part of a potential 3D Feature, in km.
2D3DX	=	The X coordinate the 2D Feature that was last assigned to a Potential 3D Feature, in km.
2D3DY	=	The Y coordinate the 2D Feature that was last assigned to a Potential 3D Feature, in km.
3DDepth	=	3D Feature(Depth), the difference in height between the base and top of a 3D Feature, in km.
3DDVH	=	The HEIGHT maximum 3D Feature(Delta Velocity), the height (to the momentum weighted center) of the 2D Feature which contains the maximum delta velocity contained in a 3D Feature, in km.
3DDVmax	=	The maximum 3D Feature(Delta Velocity), the maximum delta velocity of a 3D Feature. The maximum gate-to-gate velocity difference of all the 1D Pattern Vectors in any of the 2D Features contained in a 3D Feature, in m/s.
3DSH	=	The HEIGHT maximum 3D Feature(Shear), the height (to the momentum weighted center) of the 2D Feature which contains the maximum shear contained in a 3D Feature, in km.
3DShrmax	=	The maximum 3D Feature(Shear), the maximum shear of a 3D Feature. The maximum shear of all Pattern Vectors in any of the 2D Features contained in a 3D Feature, in 1/s*E-03.
ADV	=	Average Delta Velocity (ADV), in a 3D Feature, a Summation of weighted 2D Feature Delta Velocities over the number of 2D Features, in m/s.
AveDelAz	=	The average difference between the beginning and ending azimuths of all radials in an elevation scan, in degrees.

AZ	=	AZIMUTH, the azimuthal position, in degrees.
BASEH	=	3D Feature(Base Height), the height (above radar level) of the lowest 2D Feature in a 3D Feature, in km.
Cell_Dis	=	The distance between a TVS Feature and a STORM CELL, in km.
Cell_X	=	X-coordinate (of the centroid) of a STORM CELL, in km.
Cell_Y	=	Y-coordinate (of the centroid) of a STORM CELL, in km.
DelAz	=	Delta Azimuth, the angle which the radials of the elevation scan encompass; usually ~ 360, in degrees.
EL	=	ELEVATION, the elevation angle of an elevation scan, in degrees.
f	=	An index for 2D Features.
IR	=	The index of refraction, or the factor by which the Earth's radius is multiplied to account for the refraction of the radar beam in a standard atmosphere (1.21).
MaxVD	=	Maximum Velocity Difference(Range), the maximum velocity difference of all the Pattern Vectors (compared) at the same range within a Potential 2D Feature, in m/s. (Not all Pattern Vectors at the same range within Potential 2D Feature will be compared.)
MinAD	=	Minimum Reference Azimuthal Difference, the Pattern Vector with the Minimum Reference Azimuthal Difference (at any one range within a Potential 2D Feature) is the closest in azimuth to the Reference Vector, in degrees.
Momentum	=	Pattern Vector(Momentum), the momentum of a Pattern Vector in a Potential 2D Feature, in deg*m/s.
n	=	An index for Pattern Vectors assigned to a Potential 2D Feature.
OverCount	=	Overlap Counter, the number of overlapping 2D Features.
P2DAspectRatio	=	Potential 2D Feature(Aspect Ratio), the ratio of a Potential 2D Feature's radial diameter over it's azimuthal diameter.
P2DAveElev	=	Potential 2D Feature(Average Elevation), the average ELEVATION of all radials in a Potential 2D Feature, in degrees.
P2DAz	=	Potential 2D Feature(Azimuth), the azimuth of the (momentum weighted) center of a Potential 2D Feature, in degrees.
P2DAzDia	=	Potential 2D Feature(Azimuthal Diameter), the azimuthal diameter of a Potential 2D Feature weighted by momentum, in degrees.
P2DBegAz	=	Potential 2D Feature(beginning Azimuth), the beginning or most couter-clockwise AZIMUTH of a Potential 2D Feature, in degrees.

P2DBegRng = Potential 2D Feature(beginning Range), the beginning or closest RANGE(SLANT) of a Potential 2D Feature, in km.

P2DDVmax = maximum Potential 2D Feature(Delta Velocity), the maximum velocity difference of all Pattern Vectors within a potential 2D Feature, in m/s.

P2DEndAz = Potential 2D Feature(ending Azimuth), the ending or most clockwise AZIMUTH of a potential 2D Feature, in degrees.

P2DEndRng = Potential 2D Feature(ending Range), the ending or farthest RANGE(SLANT) of a Potential 2D Feature, in km.

P2DHt = Potential 2D Feature(Height), the height above the radar of the (momentum weighted) center of a Potential 2D Feature, in km.

P2DRadDia = Potential 2D Feature(Radial Diameter), the radial diameter of a Potential 2D Feature, in km.

P2DRng = Potential 2D Feature(Range), the slant range to the (momentum weighted) center of a Potential 2D Feature, in km.

P2DShrmax = maximum Potential 2D Feature(Shear), the maximum shear of all Pattern Vectors within a potential 2D Feature, in 1/s*E-03.

P2DX = Potential 2D Feature(X), the X-coordinate of the (momentum weighted) center of a Potential 2D Feature, in km.

P2DY = Potential 2D Feature(Y), the Y-coordinate of the (momentum weighted) center of a Potential 2D Feature, in km.

P3D_2D_Dist = Potential 3D Feature to 2D Feature Distance, the X-Y distance between the 2D Feature being considered and the last assigned 2D Feature of the Potential 3D feature being built, in km.

r = An index for RADIALs.

RE = RADIUS(Earth), the redius of the Earth (6371), in km.

REF = An index to the REFERENCE Vector.

RS = RANGE(Slant), the slant range to the center of a SAMPLE VOLUME, in km.

S = Summation of weighted 2D Feature(Delta Velocities) in a 3D Feature - used in the computation of ADV, in m/s.

SumDeltaAzMom = Potential 2D Feature(Sum Delta Azimuths), a summation of the delta Azimuths of the Pattern Vectors in a Potential 2D Feature weighted by momentum.

SumMidAzMom = Potential 2D Feature(Sum Middle Azimuths), a summation of the middle azimuths of the Pattern Vectors in a Potential 2D Feature weighted by momentum.

SumMom	=	Potential 2D Feature(Sum Momentum), a summation of the Momentum of the Pattern Vectors in a Potential 2D Feature.
SumRngMom	=	Potential 2D Feature(Sum Ranges) = a summation of the RANGEs(Slant) of the Pattern Vectors in a Potential 2D Feature weighted by momentum.
TOPH	=	3D Feature(Top Height), the height (above radar level) of the highest 2D Feature in a 3D Feature, in km.
TVS_Az	=	The azimuth (of the base) of a TVS Feature, in deg.
TVS_El	=	The elevation (of the base) of a TVS Feature, in deg.
TVS_Ran	=	The slant range (of the base) of a TVS Feature, in km.
TVS_X	=	The X-coordinate (of the base) of a TVS Feature, in km.
TVS_Y	=	The Y-coordinate (of the base) of a TVS Feature, in km.
V	=	VELOCITY(Sample Volume), the mean radial velocity of a SAMPLE VOLUME, in m/s.
VectAD	=	Patten Vector(Azimuth Difference), the difference in AZIMUTH between 2 radials being processed, in degrees.
VectBegAz	=	Pattern Vector(beginning Azimuth), beginning AZIMUTH of a Pattern Vector, in degrees.
VectEndAz	=	Pattern Vector(ending Azimuth), ending AZIMUTH of a Pattern Vector, in degrees.
VectHt	=	Pattern Vector(Height), height of a Pattern Vector, above radar level, in km.
VectRefAD	=	Pattern Vector(Reference Azimuthal Difference), the difference in AZIMUTH between the beginning azimuths of two Pattern Vectors of different ranges within a Potential 2D Feature, in degrees. One of the Pattern Vectors is at the current range, and the other Pattern Vector is either at the next or previous range in the feature. If the current range is the Potential 2D Feature(beginning Range), then the Reference Vector is at the next range. Otherwise, the Reference Vector is at the previous range.
VectRng	=	Pattern Vector(Range), the range to a Pattern Vector, in km.
VectVD	=	Pattern Vector(Velocity Difference), the difference in VELOCITY between a pair of sample volumes at the same range from 2 adjacent radials, in m/s.
VAD	=	Vector Azimuthal Distance, the azmuthal distance between an unassigned Pattern Vector and a Pattern Vector assigned to a Potential 2D Feature, in degrees.
VRD	=	Vector Radial Distance, the radial distance between an unassigned Pattern Vector and a Pattern Vector assigned to a Potential 2D Feature, in km.

WT	=	Weighting function for the 2D Feature(Delta Velocity) used in the computation of ADV; it is based on the 2D Feature(Height).

3.2.2 SYMBOLIC FORMULAS

COMPUTE (Pattern Vector(Velocity Difference))

$VectVD = V_{RS,r} - V_{RS,r+1}$

COMPUTE (Pattern Vector(Height))

$VectHt = SIN(EL)(RS) + (RS)^2/(2(IR)(RE))$

where SIN is the sine function

COMPUTE (Pattern Vector(Azimuth Difference))

$VectAD = ABS(AZ_r - AZ_{r+1})$,

if VectAD > 180, then VectAD = 360 - VectAD

where ABS is the absolute value function

COMPUTE (Pattern Vector(beginning Azimuth))

$VectBegAz = AZ_r$

COMPUTE (Pattern Vector(ending Azimuth))

$VectEndAz = AZ_{r+1}$

COMPUTE (Vector Radial Distance)

$VRD = ABS(VectRng - VectRng_f)$

COMPUTE (Vector Azimuthal Distance)

$$VAD = ABS\left(\left[\frac{VectAD}{2} + VectBegAz\right] - \left[\frac{VectAD_f}{2} + VectBegAz_f\right]\right)$$

```
IF (VAD > 180)
   THEN
   VAD = 360 - VAD
ENDIF
```

(i.e. subtract the average AZIMUTH of the unassigned Pattern Vector and the Pattern Vector already assigned to a Potential 2D Feature being compared.

Note: the variables with subscript f are attributes of a pattern vector which has already been assigned to a 2D Feature.

COMPUTE (Potential 2D Feature(beginning Azimuth))

```
IF (ABS(VectBegAz - P2DBegAz) < 180)
   THEN
   IF VectBegAz < P2DBegAz)
      THEN
      P2DBegAz = VectBegAz
```

```
   ENDIF
ELSE IF (VectBegAz > P2DBegAz)
   THEN
      P2DBegAz = VectBegAz
ENDIF
```

(Redlines added to correct for zero crossing)

COMPUTE (Potential 2D Feature(ending Azimuth))

```
IF VectEndAz > P2DEndAz, P2DEndAz = VectEndAz

IF (ABS(VectEndAz - P2DEndAz) < 180)
   THEN
   IF VectEndAz > P2DEndAz)
      THEN
      P2DEndAz = VectEndAz
   ENDIF
ELSE IF (VectEndAz < P2DEndAz)
   THEN
      P2DEndAz = VectEndAz
ENDIF
```

(Redlines added to correct for zero crossing)

COMPUTE (Potential 2D Feature(beginning Range))

```
IF VectRng < P2DBegRng, P2DBegRng = VectRng
```

COMPUTE (Potential 2D Feature(ending Azimuth))

```
IF VectRng > P2DEndRng, P2DEndRng = VectRng
```

COMPUTE (Pattern Vector(Reference Azimuthal Difference))

$VectRefAD_{RS} = ABS(VectBegAz_{REF} - VectBegAz_{RS})$

where $VectBegAz_{REF}$ is the beginning azimuth of the Reference Vector and $VectBegAz_{RS}$ is the beginning azimuth of the Pattern Vector at the current RANGE(Slant). If the current RANGE(Slant) is the same as the Potential 2D Feature(beginning Range), then the Reference Vector will be the first next Pattern Vector (in the sorted list) with a RANGE(Slant) greater than Pattern Vector(Range). Otherwise, the Reference Vector will be the last previous Pattern Vector (in the sorted list) with a RANGE(Slant) less than Pattern Vector(Range).

COMPUTE (Minimum Reference Azimuthal Difference)

IF VectRefAD < $MinAD_{RS}$, $MinAD_{RS}$ = VectRefAD

Note: MinAD should be reinitialized whenever the Reference Vector changes.

COMPUTE (Maximum Velocity Difference(Range))

IF (VectVD > $MaxVD_{RS}$), $MaxVD_{RS}$ = VectVD

COMPUTE (maximum Potential 2D Feature(Delta Velocity))

IF (VectVD > $P2DDVmax_f$), $P2DDVmax_f$ = VectVD

COMPUTE (Pattern Vector(Momentum))

Momentum = ABS(VectAD * VectVD)

COMPUTE (Potential 2D Feature(Sum Momentum))

$$SumMom = \sum_{n} (Momentum)$$

COMPUTE (Potential 2D Feature(Sum Ranges))

$$SumRngMom = \sum_{n} (VectRng)_n * (Momentum)_n$$

COMPUTE (Potential 2D Feature(Sum Middle Azimuths))

$$SumMidAzMom = \sum_{n} (Centroid\ Az)_n * (Momentum)_n$$

where,

$$Centroid\ Az = \left(\frac{VectAD}{2}\right) + MIN(VectBegAz, VectEndAz)$$

```
IF (ABS(VectBegAz - VectEndAz) >180)
   THEN
```

$$Centroid\ Az = \left(\frac{VectAD}{2}\right) + MAX(VectBegAz, VectEndAz)$$

```
   IF (Centroid Az > 360)
      THEN
      Centroid Az =  Centroid Az - 360
   ENDIF
ENDIF
```

COMPUTE (Potential 2D Feature(Sum Delta Azimuths))

$$SumDeltaAzMom = \sum_{n} (VectAD)_n * (Momentum)_n$$

COMPUTE (Potential 2D Feature(Radial Diameter))

P2DRadDia = ABS(P2DEndRng - P2DBegRng)

COMPUTE (Potential 2D Feature(Azimuth))

P2DAz = SumMidAzMom / SumMom

COMPUTE (Potential 2D Feature(Range))

P2DRng = SumRngMom / SumMom

COMPUTE (maximum Potential 2D Feature(Shear))

$P2DShrmax_f = P2DDVmax_f/(P2DRng_f * 2 * SIN(AveDelAz/2))$,

where AveDelAz = DelAz/((# of radials for the elevation scan) - 1)

where DelAz = ABS(Az(last radial) - Az(first radial))

```
IF (# of radials > 180) THEN
   IF (DelAz <= 180) THEN
      DelAz = 360 - DelAz
   END IF
ELSE
   IF (DelAz > 180) THEN
      DelAz = 360 - DelAz
   END IF
END IF
```

COMPUTE (Potential 2D Feature(X))

P2DX = P2DRng * sin(P2DAz)

COMPUTE (Potential 2D Feature(Y))

P2DY = P2DRng * cos(P2DAz)

COMPUTE (Potential 2D Feature(Average Elevation))

$$P2DAvgElev = \frac{1}{n} * \sum_n (Elevation\ Angle\ of\ Radial)_n$$

COMPUTE (Potential 2D Feature(Height))

$$P2DHt = (P2DRng * \sin(P2DAvgElev)) + \frac{P2DRng^2}{(2*IR*RE)}$$

COMPUTE (Potential 2D Feature(Azimuthal Diameter))

P2DAzDia =

$$SumDeltaAzMom * P2DRng * \frac{(3B^2)}{(8 * 180 * SumMom}$$

COMPUTE (Potential 2D Feature(AspectRatio))

P2DAspectRatio = P2DRadDia / P2DAzDia

COMPUTE (Overlap Counter)

OverCount = OverCount + 1

COMPUTE (Potential 3D Feature to 2D Feature Distance)

P3D_2D_Dist =

$$\sqrt{(2DX - 2D3DX)^2 + (2DY - 2D3DY)^2}$$

COMPUTE (maximum 3D Feature(Delta Velocity))

3DDVmax = 2DDVmax, if 2DDVmax ≥ 3DDVmax

COMPUTE (HEIGHT maximum 3D Feature(Delta Velocity))

3DDVH = 2DHt, when 3DDVmax = 2DDVmax for the heightest 2D Feature

COMPUTE (maximum 3D Feature(Shear))

3DShrmax = 2DShrmax, if 2DShrmax ≥ 3DShrmax

COMPUTE (HEIGHT maximum 3D Feature(Shear))

3DSH = 2DHt, when 3DShrmax = 2DShrmax for the heightest 2D Feature

COMPUTE (Average Delta Velocity)

ADV = S/(#2D + 1)

where, $S = \sum_{f} WT_f * 2DDVmax_f$

where,

```
IF (2DHt_f ≤ THRESHOLD(Average Delta Velocity Height)
   THEN
   WT_f = 1
ELSE
   WT_f = (-.14285 * 2DHt_f) + 1.4285
   IF (WT_f < 0)
      THEN
         WT_f = 0
   END IF
END IF
```

COMPUTE (3D Feature(Depth))

3DDepth = TOPH - BASEH

COMPUTE (Storm Association Distance)

Cell_Dis = SQRT((Cell_X - TVS_X)^2 + (Cell_Y = TVS_Y)^2)

where TVS_X = TVS_Ran * SIN(TVS_Az) * COS(TVS_El)

TVS_Y = TVS_Ran * COS(TVS_Az) * COS(TVS_El)

4.0 OUTPUTS

4.1 IDENTIFICATION

For each vortex (TVS or ETVS) found by this algorithm, the following are outputted:

- Vortex Type: TVS or ETVS,
- Base Azimuth,
- Base Range,
- Base Height,
- Top Height,
- Depth,
- Base Elevation,
- Base Delta Velocity,
- Average Delta Velocity,
- Maximum Delta Velocity,
- Height of the Maximum Delta Velocity,
- Maximum Shear, and
- Height of the Maximum Shear.
- Storm Cell ID

In addition, each volume scan, the algorithm outputs the number of TVSs and the number of ETVSs identified.

4.2 DISTRIBUTION

The output from the algorithm are intended for display. It is also possible for the output to be input to tracking/trending algorithms.

5.0 INFERENCES

5.1 STRENGTHS AND LIMITATIONS

a. 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.

b. The algorithm uses velocity data. Therefore, improperly dealiased velocity data will degrade the algorithm performance. Also, discarded velocity bins (possible during with dealiasing techniques) can degrade algorithm performance.

c. Range folded echoes often obscure the velocity data making the detection of pattern vectors (and, hence, circulations) impossible.

d. While the TDA uses a Minimum Reflectivity Threshold to confines 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.

e. The algorithm may falsely identify pattern vectors in areas of higher reflectivity such as ground clutter, sea breezes, gust fronts.

f. The algorithm only detects pattern vectors, and thus TVSs, with cyclonic shear.

g. The shared pattern vector image is sized to hold 3000 pattern vectors and 400 radials per elevation scan (i.e. each half of the image). An adaptable threshold may further limit the number of pattern vectors.

h. At the beginning of the elevation scan, if the shared pattern vector image (i.e. the half to be used) is not unlocked, then the task is aborted for the elevation scan. And, the entire elevation scan is missed.

i. Many of the adaptable parameters allow the TDA to become more sensitive, i.e. identify more circulations. However, this will also increase the processing load.

j. Because of the radar sampling limitations, (i.e. the relative size and height of the radar beam to those of a tornado), the radar (and hence, the algorithms) can not actually detect a tornado (except in rare cases). Instead, the TDA attempts to identify intense circulations usually associate with tornados. But, as range increases, the radar beam gets even larger and higher. Therefore, at far ranges the TDA may detect mesocyclones, and small tornadic circulations may be smoothed and unidentifiable by the algorithm.

k. Also, 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 .

l. Squall line events present a challenge to the TDA because numerous, transient, non-tornadic circulations may develop along the leading edge. This is especially true when the squall-line is aligned along a radial creating near zero radial velocities.

m. 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.

n. The algorithm logic assumes that within the volume scan, each new elevation scan is at a higher elevation angle than the last.

In the following discussion, any comparisons made are between this algorithm and the TVS [026/10] algorithm (NEXRAD Algorithm Report 1985). The TDA is based on the paradigm that the circulation 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. Also, 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. Also, 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. landspouts in the High Plains region) and storms that contain undetected mesocyclones. Currently, the TDA has a higher POD than the TVS Algorithm and performs best during events characterized by isolated supercells. More testing and data analysis is required to determine more accurately how the TDA performs in various weather scenarios.

Note that tornado detection is a function of the beam width, the circulation radius, and the distance between the beam and circulation centers. Obviously, we do not know the spatial dimensions of a tornado unambiguously in realtime. Thus, one limiting factor to tornado detection is caused by the sampling limitations of the radar when observing phonemena of unknown a spatial dimensions. These sampling limitations are related to the range dependence of the sample volume size, the radar horizon, and the proximity of the beam center to the center of the circulation. For example, tornado signatures at far ranges may be severely smoothed. Another limiting factor includes the improper dealiasing of velocity data which is critical to the success of tornado detection. Additionally, range folded echoes may obscure the velocity data. False alarms may also result from noisy data within ground clutter near the radar. Tornadoes at near ranges (< 20 km) may go unidentified by the TDA since a circulation may actually span three or more azimuths. Furthermore, squall line events present a challenge to the TDA because numerous, transient, non-tornadic circulations may develop along the leading edge. Currently, the TDA uses no reflectivity data (BWER, Hook Echo, etc.) to identify tornadic circulations. Finally, the TDA does not use range dependent velocity difference thresholds. Thus, circulations are given equal weight regardless of range.

5.2 FUTURE DEVELOPMENTS

Adaptable parameter studies are on-going by the Operational Support Facility, the NSSL, and NWS Forecast Offices to optimize the parameters for different storm regimes, e.g. low-topped super-cells. Time association techniques have been developed for tracking TVSs and ETVSs and trending their attributes. It is anticipated that these will be added to the TDA.

Currently, NSSL is working on a number of ways to improve the TDA. The TDA will be combined with the Mesocyclone Detection Algorithm (MDA) into a Vortex Detection Algorithm (VDA). A neural network will be used within the VDA to classify circulations and provide probability functions. The probability function will determine the probability of severe weather, for example, whether a tornado may be expected within the next 20 minutes.