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AN IMPROVED GUST FRONT DETECTION ALGORITHM FOR THE TDWR*

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1. INTRODUCTION

Gust fronts are associated with potentially hazardous wind shears and cause sustained wind shifts after passage. Terminal Air Traffic Control (ATC) is concerned about the safety hazard associated with shear regions and prediction of the wind shift for runway reconfiguration. The Terminal Doppler Weather Radar (TDWR) system has a gust front detection algorithm which has provided an operationally useful capability for both safety and planning. However, this algorithm's performance is sensitive to the orientation of the gust front with respect to the radar radial. Due to this sensitivity, the algorithm is unable to detect about 50% of gust fronts that cross the airport. This paper describes a new algorithm which provides improved performance by using additional radar signatures of gust fronts.

The performance of the current TDWR gust front algorithm for the various operational demonstrations has been documented in Klingle-Wilson et al. (1989) and Evans (1990). These analyses highlighted deficiencies in the current algorithm, which is designed to detect radial convergent shears only. When gust fronts or portions of gust fronts become aligned nearly parallel to a radial, the radial component of the shear is not as readily evident. In addition, gust fronts that are near or over the radar exhibit little radial convergence along their lengths and ground clutter can obscure the gust front near the radar. Thus, special handling is needed for fronts that approach the radar.

Figure 1 illustrates the various components of a gust front as viewed by Doppler radar. The portion of the gust front in the figure labelled radial convergence is detectable with the current algorithm. Fronts, or portions of fronts, that are aligned along the radar radial and those that pass over the radar are examples of events which can exhibit little or no radial shear signature. These events are often detectable by variations in the radial velocities from azimuth to azimuth (i.e., azimuthal shear), and/or by radar reflectivity thin lines.

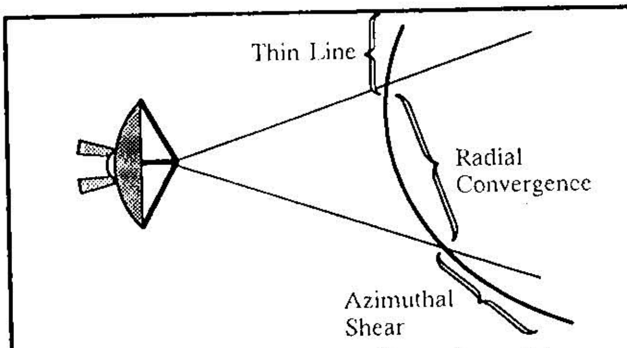

Figure 1. Schematic of a gust front illustrating radial convergence, azimuthal shear and reflectivity thin line.

The new algorithm improves the detection and prediction of gust fronts by merging radial convergence features with azimuthal shear features, thin line features, and the predicted locations of gust fronts which are passing over the radar. The next four sections of this paper describe the individual components of the improved algorithm. Section 6 describes the rule base used to combine detections from the four components into single gust front detections and Section 7 discusses the output of the algorithm.

2. RADIAL CONVERGENCE FEATURE DETECTION

The radial convergence feature detection algorithm used in the improved algorithm is an enhanced version of the current algorithm. The enhancements made were based on error analysis during the tests conducted during the summers of 1987-1989. The purposes of these improvements were to, a) increase the percent of length of gust front detection, b) increase the probability of detection, c) reduce the number of false detections, d) improve forecasting, and e) improve gust front representation (Hermes et al., 1990).

This section provides a brief overview of the algorithm's radial convergence feature detection capabilities. Sections 6 and 7 will discuss some of the other improvements that have been made since the last documentation of

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the base TDWR current algorithm (1988 Operational & Test Evaluation [OT&E] version). A more thorough description of the 1988 OT&E version of the current algorithm is provided by Smith et al. (1989).

2.1. Initial Radial Shear Feature Detection

The Doppler radar data are initially pre-processed to remove or correct ground clutter, velocity aliases, range folded echoes, and noisy data in areas of low signal-to-noise ratios. Data from both 0.5° and 1.0° constant elevation angle scans are used to determine if gust fronts are present.

The algorithm begins by smoothing data along a radial by computing a running average across a radial distance of approximately 1 km. The algorithm then searches along a radial for runs of decreasing Doppler velocity (radial convergence). If the run of radial convergence passes both minimum velocity difference and minimum peak shear thresholds it is saved as a shear segment. The minimum velocity difference threshold for saving shear segments is set at 7 m s^{-1} and 5 m s^{-1} for the lower and upper elevation scans respectively. The peak shear threshold is set at 2 m s^{-1} km^{-1} for both scans. A shear segment whose maximum velocity difference over 1 km is greater than it's beginning to ending velocity difference is discarded because it has been found empirically that most segments with this characteristic are caused by ground clutter.

Individual shear segments are combined into features based on spatial proximity of the peak shear locations within the segments. Site-adaptable thresholds for building features are a maximum azimuthal separation of 2.2° and maximum range separation of 2 km. Features comprised of fewer than five segments or having lengths (the distance between end points of the feature) less than a threshold (4 km) are discarded. Features can be split if there are two or more shear segments with the same azimuth (usually caused by ground clutter or small microburst outflows). Finally, two features from the same elevation scan are combined if the end points of the features are within a specified distance (5 km).

3. COMBINED SHEAR FEATURE DETECTION

Since a single-Doppler radar is only capable of resolving the component of velocities along the radar beam, velocity features which have components perpendicular to the beam are not easily observed. If shears are aligned across an azimuth, they often can be observed as an azimuthal variation of the wind field rather than as a radial variation. The combined shear feature detection component of the improved algorithm attempts to use the information contained in azimuthal variations in Doppler velocity to augment estimates of radial convergence. An estimate of the azimuthal shear component is only made if the radial convergence is not strong enough to pass a threshold.

The algorithm initially smoothes the velocity data using a two-dimensional median filter. The filter size is 7 range gates long by 3 radials wide. The spacing between radials gets very narrow close to the radar, so a fixed-azimuth-width filter covers a small physical distance close to the radar.

To generate the radial shear estimate at a gate, a least-squares line is fit to the smoothed velocity data along the radial, centered at the gate where the shear estimate is to be made. The slope of the line is used as the estimate of the radial shear at that point (Figure 2).

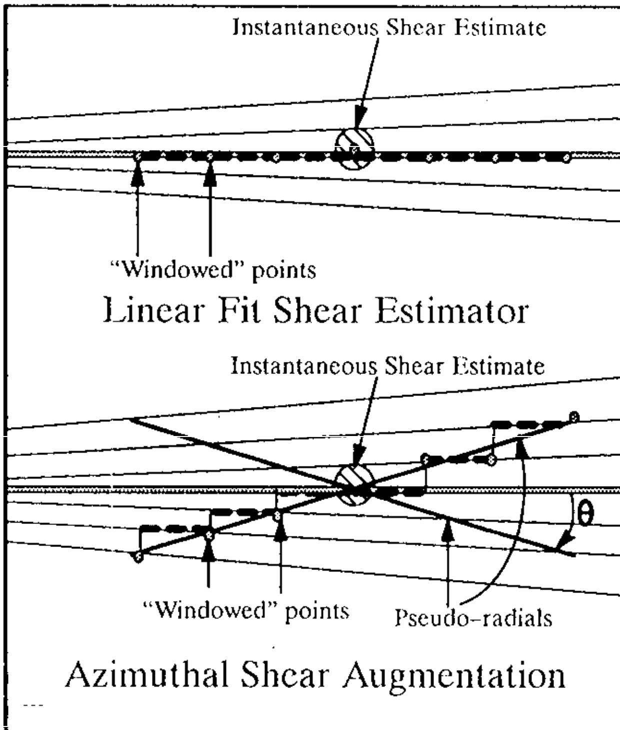

Figure 2. Instantaneous Shear Estimation. Radial shear and Pseudo-radial techniques.

To generate a shear estimate that has both radial and azimuthal components (combined shear), "pseudo-radials" of velocity data are built at an angle from the actual radial. These pseudo-radials pass through the estimate point at a skewed angle to the radial and have an orientation angle and length as specified by site-adaptable parameters (Figure 2). The location in space of the gates along the pseudo-radials are calculated and the value of the real gate closest to these gates are used to make up the value at the pseudo-radial gates. Shear is estimated along this pseudo-radial using the same least-squares line fitting technique. If the shear is still not strong enough, then a second skewed shear estimate is calculated on another pseudo-radial whose orientation angle is directly opposite the first pseudo-radial. The value of the combined shear at a gate is then the strongest of the three convergence estimates.

The procedure which produces features from the field of combined shear is similar to the procedure for creating thin line features from the field of reflectivity data, and is described within Section 4.

4. REFLECTIVITY THIN LINE FEATURE DETECTION

Reflectivity thin lines are often evident in association with gust fronts. Unlike Doppler velocities, reflectivity is invariant with viewing direction, thus, a reflectivity thin line can be seen independent of the viewing angle. Detecting reflectivity thin lines will give important information on the location of gust fronts, especially when the gust fronts are orientated so that radial convergence is not readily observed. However, there are four difficulties when using reflectivity thin line features as a means of identifying gust fronts: 1) not all gust fronts have thin lines; 2) the reflectivities in the thin line signatures are usually not much larger than the background reflectivities and the linear patterns are difficult for the algorithm to identify, even when they are quite apparent to a human; 3) the appearance of a thin line does not indicate the strength of the convergent boundary that causes it and 4) some meteorological phenomena (e.g., cloud streets) and radar data artifacts (e.g., range folding) that are not gust fronts are associated with reflectivity thin lines.

The thin line feature detection algorithm described here was developed to enhance the performance of the current TDWR algorithm, but has recently served as the primary component of the new Airport Surveillance Radar–Wind Shear Processor (ASR–WSP) gust front algorithm (Noyes et al., 1990).

The reflectivity thin line feature detection algorithm initially subjects the reflectivity data to the same median filtering technique applied to the velocity data when calculating combined shear. The procedure for segment finding, segment association, feature formation, and feature interpretation for the reflectivity field is similar to that of the combined shear field. Thus the following discussion, slanted to thin line feature detection, describes the technique used both for combined shear feature and thin line feature detection.

The core idea of the thin line feature detection algorithm is the use of multi-thresholding and shape analysis to try to isolate thin lines from the reflectivity field. To find segments of a thin line along radials, the algorithm searches along the radial, finding runs of reflectivity values that are above one or more thresholds. These thresholds are currently set at 0, 2.5, 5, 7.5, 10, 12.5, and 15 dBZ. All threshold values are processed in parallel, thus any given reflectivity datum may be a part of several segments at once. This leads to the situation where a single "hump" is found to contain segments at several threshold levels (Figure 3).

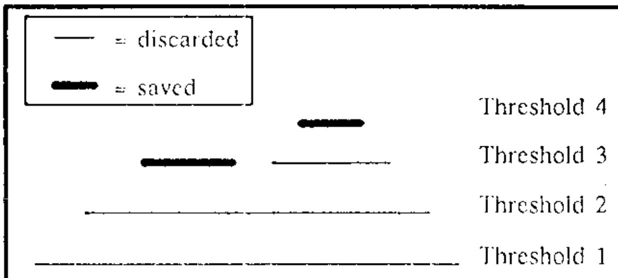

Figure 3: Overlapping segments generated at four threshold levels.

Segments are constrained to have a minimum (1–1.5 km) and a maximum (about 4 km) allowed length. Potentially, many segments could be found through a storm cell, but they are all removed because they are too long. This helps to cut down on incorrect associations. An additional feature of the algorithm is the ability to skip over a radial that contains no nearby segments. It is not unusual for even a strong thin line to have a few individual radials where the algorithm fails to detect a valid segment. This ability to skip a segment is helpful in reducing the fragmentation of the detected thin line.

After segments are grouped together, reflectivity thin line features are constructed. A feature is represented by a sequence of points that are chosen by taking the peak reflectivity point of each segment in the feature. A secondary task is to compute properties of the features such as length, area, maximum dBZ, minimum dBZ, and average dBZ. These are used by later stages of the improved algorithm to help discriminate against false features. Using these attributes, the improved algorithm attempts to remove spurious features caused by sources such as range folding and velocity folding.

5. OVERHEAD TRACKING OF GUST FRONTS

As a gust front propagates toward the radar, the portion of the front having significant radial convergence decreases. For a front with a uniform velocity difference of 10 m s^{-1} and length of 50 km, the decrease in algorithm detection capability as a function of radar range is given in Figure 4. For this simple representation, as the radar range decreases from 15 to 5 km, the maximum detectable length (bold curve) decreases to 10 km. The detection of close-in gust fronts may be even further degraded by non-uniform intensity, different orientations or curvatures, and/or different propagation directions, along with data artifacts produced by ground clutter removal and beam blockage (Hermes et al., 1990).

The objectives of the overhead tracking technique are to maintain the length and accuracy of front detections as long-lived gust fronts pass over and near the radar. Thus, time continuity constraints, orientation checks, and spatial proximity checks, are used to ensure accurate detections.

Overhead tracking is initiated when a gust front's centroid is within an site-adaptable range threshold (20 km) and it is propagating towards the radar with a speed greater than an site-adaptable speed threshold (4 m s^{-1}). In addition, the front must have been detected on the two previous

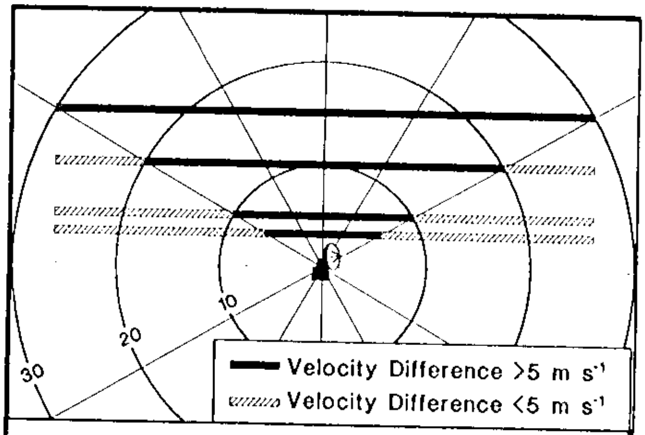

Figure 4. An example of how algorithm detection capability is reduced as a front (uniform velocity difference of 10 ms^{-1} and length of 50 km) approaches the radar site. The solid (hatched) curve indicates convergence areas where velocity difference is greater (less) than 5 ms^{-1} (an algorithm threshold).

volume scans, to help ensure that the front is not a transient phenomenon.

Once a front is chosen to be overhead tracked, special rules are used which try to maintain the detection and its length as it passes over the radar. The algorithm attempts to match the front chosen for overhead tracking with detections from subsequent volume scans. A match is established if the two fronts are time associated (see Section 7). If a match is found, the forecasted locations, available at one minute intervals, are examined to see which is the nearest to the current detection. With the goal of maintaining length, the selected forecast is merged with the current detection. A final representation is obtained by smoothing these locations using a polynomial of the appropriate order (third or fifth).

If no time association is established between the overhead tracked front and a detection from the next scan, "coasting" is used to generate the gust front product. The coasted location is determined by the front's propagation speed, the time difference between scans (approximately 5 minutes), and the location from the previous scan.

The overhead tracking process is aborted if, 1) the overhead tracked front moves outside of the range threshold (20 km), 2) the front's propagation speed decreases to 2 m s^{-1} below the threshold speed, 3) coasting persists for more than 12 consecutive volume scans (site-adaptable threshold), or 4) detections are time associated but do not have similar orientation.

Once overhead tracking is initiated, the wind shear hazard estimates and the wind estimates behind the front, for the current detection, are set to those estimates from the overhead tracked front. If a detection is generated by coasting for more than 3 scans, its wind shear hazard estimate is set to zero.

The overhead tracking technique was tested on a subset of 203 scans of Doppler velocity data. The algorithm with overhead tracking detected 87% (176/203) of the fronts, without it only 70% were detected. The probability of false alarm (12%) did not change.

6. METHODOLOGY FOR COMBINING DISSIMILAR FEATURES

Because of the past success of the radial convergence feature detection algorithm, especially the low false alarm ratio, it is used as the starting point for the multiple feature association.

On a given tilt, an attempt is made to associate features from the combined shear and reflectivity thin line algorithms with features from the radial convergence algorithm. These features are joined using an endpoint proximity check. If either endpoint of the two features are within 5 km of each other they are joined. To ensure that the features are a good match their orientation must also differ by less than 30 degrees. All possible combinations of features on a tilt are joined together. Only features that have one radial convergence feature as part of the combination are considered candidate gust fronts and are used for further association checks. Overhead tracked front detections are treated as if they are radial convergence detections.

In the future more sophisticated checks will be incorporated into this methodology, but at the present time we are taking a conservative approach to ensure that the number of false alarms is kept at a minimum.

6.1. Vertical Association

In order to minimize the number of false alarms, features from the two elevation scans are required to be vertically associated for a gust front detection to be declared. The 1988 OT&E current algorithm's vertical association method has been improved. The old method required that the centroid of a feature on one elevation tilt be located within a rectangle which loosely described the location of the second feature on the other tilt. This technique worked well when gust fronts were nearly straight, but frequently failed on curved fronts. The upgraded technique compares feature endpoints with the peak shear locations of all features on the other tilt. If the endpoint of one feature is within 2 km of any point on another feature on the opposite tilt, the two features become vertically associated. All possible combinations of features from the two tilts are then put together to determine the total gust front. This new technique resulted in an overall improvement to 16% of the gust fronts detected and reduced the false alarms by 5% over the old version of the algorithm (Hermes et al., 1990).

There is a special case where vertical association is not required for a gust front detection to be declared. If a radial convergent feature and a thin line feature are associated on one tilt and the features total length is greater than 15 km, then it is allowed to be declared a gust front. It is believed that the co-location of these two different types of features allow a safe declaration of a gust front.

7. ALGORITHM OUTPUT

The final product of the gust front algorithm is a smooth curve representing the location of the gust front, 10- and 20- minute forecasts of gust front location, an estimate of the speed and direction of the wind behind the gust front, and an estimate of the wind shear hazard.

7.1. Gust Front Representation

The gust front detection that results from the merging of the various features is not a smooth curve. The smooth curve representing the gust front is generated by least-squares fitting a polynomial (in x,y) to the peak shear locations in the features that have been vertically associated. A number of modifications to this technique have been made since the 1988 OT&E version of the current algorithm. These include an endpoint "smoother", a new coordinate system transformation scheme, and a technique to fit multiple polynomials to long, irregularly curved fronts.

A third-order polynomial is used for the gust front representation when the front length is less than or equal to 20 km. For fronts whose length is greater than 20 km, a fifth-order polynomial is used, however the endpoints (last 4 km) are replaced with points from a third-order fit. This merged set of polynomial points is then fit with a new fifth-order polynomial. This method of merging a lower-order polynomial results in a smoother representation of the endpoints of many long fronts. The coordinate system used for the polynomial fitting is determined by fitting a straight line to all the peak shear locations.

The method of fitting a single polynomial to the peak shear locations occasionally fails for long and/or highly curved fronts or for fronts that contained splitting features. These problem fronts can be identified as having a large root mean square error between the original peak shear locations and the fitted curve. To mitigate these problems, these fronts are split in half and both halves are fit with a polynomial. This splitting and fitting continues until each segment can be fit such that the polynomial used to represent the segment has a root mean square error, when compared to the peak shear locations, below a critical threshold. The adjacent ends of the polynomial segments are then joined and smoothed to eliminate discontinuities.

7.2. Time Association and Forecasting

If a gust front is detected on two consecutive scans, an attempt is made to establish time continuity between the pair of detections. The 1988 OT&E version of this technique compared the location of the centroids of the two fronts. This sometimes caused time association to fail when fronts were highly curved or when fronts split. The present technique uses 1 km sections along the front to determine the association of old and new fronts. If a sufficient percentage of old front sections are within some critical distance (along a perpendicular line) of the new front, the old and new fronts are time associated. A secondary technique, used in cases where the other technique fails, bases time association on the overall gust front orientation angle and the distance between midpoints. This technique is designed to time associate front pairs which have similar shapes. Overall, the new time association technique has increased the amount of correct time associations by 12 percent.

The time-associated gust front's speed and direction of movement are forecasted. The propagation speed of the gust front is determined by averaging the distance along 1 km sections between the current gust front and its time associated partner from the previous scan. Those distances which lie more than 2 standard deviations from the mean are rejected, and a new average is calculated with the remaining values. The polynomial representation of the current front is then propagated forward, in the direction of the average perpendicular vector between the two fronts, the average speed determined from the average distance. Forecasts are generally produced for 10- and 20-minute periods. This technique differs from the 1988 OT&E version of the algorithm, which used the centroid to determine the speed and direction of movement. This technique significantly improved approximately 15% of the forecast estimates.

7.3. Wind and Wind Shear Estimation

Once gust fronts are time-associated, the computation of horizontal wind estimates ahead of and behind the gust front is attempted. The wind estimates are made using a least-squares technique to estimate the wind speed and direction in geometric sectors defined ahead of and behind gust fronts (Smith et al., 1989). Comparison of wind estimates made by this technique, with those observed at the surface, are on average within 3 $m\ s^{-1}$ in speed and 30° in direction.

Finally, an estimate of the wind shear hazard that an aircraft might experience upon encountering the gust front is computed. This hazard estimate is the sum of the mean plus one standard deviation of the peak shear values for every segment within the gust front. Wind shear hazard warnings are issued only if the estimate is greater than 7.5 $m\ s^{-1}$.

8. SUMMARY

The detection of potentially hazardous wind shears and the prediction of wind shifts associated with gust fronts is important for aircraft safety and runway management. The current gust front algorithm products have proven to be very useful and accurate, but are not produced as reliably as desired. The improved gust front algorithm uses additional features (thin lines and azimuthal shears) and enhanced association techniques to improve algorithm performance. Scoring of the improved algorithm against previously recorded data from Denver, Kansas City and Orlando is underway. The TDWR gust front algorithm will be upgraded if the expected performance improvement is demonstrated.

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