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# GUST FRONT DETECTION ALGORITHM FOR THE TERMINAL DOPPLER WEATHER RADAR

## PART I: CURRENT STATUS

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### 1. INTRODUCTION

The gust front detection and wind shift algorithm is one of the two main algorithms developed for the Terminal Doppler Weather Radar (TDWR) program. This two-part paper documents some recent enhancements to, and the current status of, the algorithm (Part 1) and presents some results from recent testing of the algorithm during the TDWR Operational Test and Evaluation (OT&E) (Part 2: Klinge-Wilson et al., 1989).

### 2. BACKGROUND

A gust front is the region of rapid wind increase or shear at the leading edge of the cold air outflow from a thunderstorm. Wind shears and turbulence along the gust front are potentially hazardous to landing or departing aircraft. Because of this, the detection of gust fronts in the terminal environment is an integral part of the Federal Aviation Administration's (FAA) TDWR system.

The change of wind speed and direction in the terminal area associated with gust fronts and synoptic fronts also cause significant air traffic delays and excess fuel consumption due to time-costly runway configuration changes. During the Classify, Locate, and Avoid Wind Shear (CLAWS) project (McCarthy et al., 1986) it was determined that a 20 minute forecast of a wind shift at the airport was a useful product for air traffic management. This gives controllers time to redirect air traffic without significantly affecting airport operations.

The Gust Front Detection and Wind Shift Algorithm (here after called the Gust Front Algorithm) addresses both of these problems. When a wind shift is expected to occur at the airport within 20 minutes, a 10 and 20-minute forecasted location, as well as the expected wind vector behind the front is given to air traffic control so that plans for changing the approach and departure runways can be started if needed. When a gust front wind shift line is detected on or within 3 miles of the end of the runway, wind shear warnings are generated.

### 3. ALGORITHM DEVELOPMENT

The initial design and development of the Gust Front Algorithm was done by Uyeda and Zrnic (1985,1986). This algorithm has the capability of detecting, within a field of Doppler radar velocities, the radial convergence lines that characterize gust fronts. With limited testing, Uyeda and Zrnic showed that the algorithm could locate and track strong gust fronts that commonly occur in Oklahoma in the Spring. During the past three years, the algorithm was changed from its semi-automatic research state to that of a fully automated algorithm for operational use.

Enhancements added prior to real-time testing during the 1987 TDWR experiment in Denver, Colorado, included the vertical association of gust front signatures using two low-altitude elevation scans to reduce false alarms, as well as a technique to supply horizontal wind estimates ahead and behind detected gust fronts. The report by Witt and Smith (1987) highlights these enhancements and documents other refinements to the algorithm, such as proper threshold selection.

Another iteration of algorithm development followed field tests of the algorithm in the Denver area during 1987. Enhancements included a sophisticated velocity dealiasing scheme (Eilts and Smith, 1988), a technique to mitigate some ground clutter induced errors, better representation of the gust front, and error checking of the wind estimates along with a perpendicular wind estimate as an alternative when uniform wind estimates were not possible.

In this paper the principles of the algorithm are outlined, and those aspects that have not been previously documented are discussed in more detail. The intent is to give the reader a better understanding and appreciation of the algorithm.



#### 4. PATTERN RECOGNITION

The Gust Front Algorithm uses pattern recognition techniques that identify gust front attributes possessed in Doppler velocity fields, i.e., lines of radial convergence. Data artifacts such as ground clutter, velocity aliases, and data in areas of low weather signal to receiver noise ratios must be either corrected or removed for the algorithm to perform properly. The algorithm uses two low-elevation angle scans (0.5° and 1.0°) of data to determine if gust fronts are present.

The algorithm begins by computing a nine-point (seven point if the range gate spacing is greater than 200 m) running average to smooth the velocity data in range. Using the smoothed data, the algorithm searches along radials for shear segments (runs of decreasing velocity which represent radial convergence). However, there is often substantial point-to-point variation of velocity in range. Therefore, when searching for segments, a seven-point (five if the range gate spacing is greater than 200 m) look ahead capability that allows for comparison of a particular valid velocity with the seven adjacent velocities in range is used. The algorithm accepts the velocity within the group of seven which is closest but less than or equal to the velocity in question. If radial convergence is detected, the next iteration compares the chosen velocity with the next seven values in range. If there is an increase in radial velocity over seven consecutive points in range, a segment terminates. Figure 1 shows the radial velocities through a gust front and the beginning and ending locations of the shear segment found.

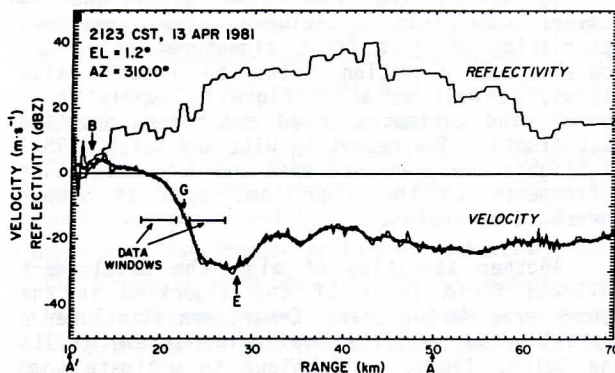


Figure 1. Radial Velocity and Reflectivity factor along a radial which cuts through a gust front. "B" and "E" denote the beginning and ending range of a valid shear segment. "G" is the detected position of the gust front. The "data windows" are the location of data that are used to make wind estimates.

The peak radial shear and difference between the beginning and ending velocity,  $\Delta V$ , are compared to minimum thresholds to determine valid shear segments. Thresholds for  $\Delta V$  are presently set at  $7 \text{ ms}^{-1}$  for the 0.5° elevation angle 360° scan and  $5 \text{ ms}^{-1}$  for the 1.0° elevation angle scan. These thresholds appear to maximize the detection of gust fronts with  $\Delta V > 10 \text{ ms}^{-1}$ . A

minimum peak shear threshold of  $2 \text{ ms}^{-1} \text{ km}^{-1}$  (same at both scans) is used. Test results have also shown that when the maximum velocity difference, over a distance of  $\sim 1 \text{ km}$  (seven or five range gates) within the shear segment, is greater than the beginning to ending velocity difference, the shear segment is usually associated with ground clutter or noisy data. Therefore, a shear segment whose maximum velocity difference over  $\sim 1 \text{ km}$  is greater than its beginning to ending velocity difference is discarded.

#### 5. FEATURE EXTRACTION

Typically, a single elevation scan can have 200 or more valid shear segments. Individual shear segments are combined into features based on spatial proximity. Features are groups of shear segments that may later be combined into gust fronts. Shear segments are sorted into a common feature if they are separated in azimuth by  $< 2.2^\circ$  and if the locations of the peak shears are within 2 km in range. If, after sorting, there are fewer than five segments in any one feature, or if the feature length (end point to end point) is  $< 5 \text{ km}$ , that feature is discarded. The minimum number of shear segments per feature, five, and the length threshold, 5 km, are those recommended by Witt and Smith (1987) for the Denver environment. Features in close proximity to each other are combined using an end point to end point search radius of 5 km.

Combining shear segments into features and feature connecting are performed for each of the two low-level scans. The next step is to use vertical continuity to associate detections between the two scans.

#### 6. VERTICAL CONTINUITY

In order to reduce the number of false alarms, potential gust fronts are subjected to a vertical continuity check using data from two low-level scans ( $\sim 0.5^\circ, 1.0^\circ$ ). In order for two features detected at different elevation scans to satisfy the vertical continuity requirement, the center of one feature must be within a rectangle which loosely describes the location of the second feature (Figure 2). Testing showed a large reduction in false alarms after vertical continuity checks were added to the algorithm (Witt and Smith, 1987). Potential gust fronts are thresholded after vertical continuity using a 10 km minimum length threshold.

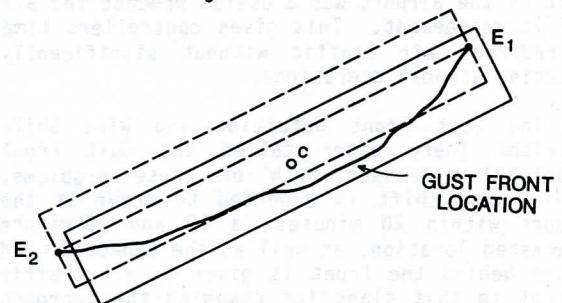


Figure 2. Geometry of the vertical continuity box. The uppercase "E"s denote the endpoints of the detected gust front and the lowercase "c" denotes the centroid position. Initially determined size and location is dashed and the solid line box is its final location centered over the gust front.



## 7. POLYNOMIAL CURVE FITTING

After completing the vertical continuity check the gust front location is represented either by a third or fifth order polynomial fit to the peak shear locations depending on whether the gust front length is less than or greater than 20 km. A recent addition to the curve fitting procedure combines features from both low-level scans to be used in estimating the polynomial coefficients. The displayed results are relatively smooth but still represent the true locations of the peak shear quite well.

## 8. HORIZONTAL WIND ESTIMATION ON BOTH SIDES OF A DETECTED GUST FRONT

A technique to estimate the horizontal wind ahead of and behind the gust front using least-squares techniques has been incorporated into the Gust Front Algorithm (Witt and Smith, 1987). This technique is very similar to the Next Generation Weather Radar (NEXRAD) Sectorized Uniform Wind algorithm (Smith, 1986). Initial testing of this portion of the algorithm began during the 1987 TDWR experiment in Denver.

Using data from the  $0.5^\circ$  elevation angle scans, the windshift portion of the algorithm assumes a uniform, horizontal wind within specified spatial sectors. For each detected gust front, sectors are offset by  $\delta r$  in range from the front ( $\sim 2$  km) and extend in range by an amount  $\Delta r$  ( $\sim 2$  km). The azimuthal width of the sectors is  $\Delta\theta > 30^\circ$  (Figure 3).

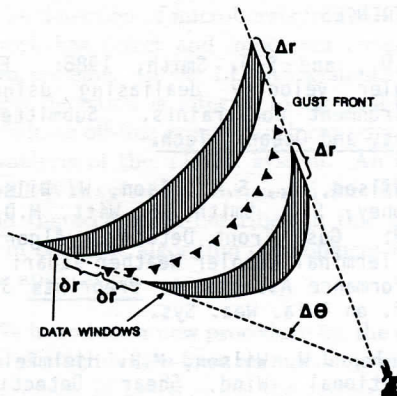


Figure 3. Schematic showing detected gust front and the two data windows over which we estimate the horizontal wind. The adjustable parameters are:  $\Delta r$  is the range extent of the window;  $\Delta\theta$  is the azimuthal extent of the window; and  $\delta r$  is the range offset of the window from the detected front.

The relationship between the radial velocity,  $v_r$ , and the wind components ( $u_0, v_0$ ) for a uniform, horizontal wind is

$$v_r = u_0 \sin\theta \cos\phi + v_0 \cos\theta \cos\phi + \epsilon \quad (1)$$

where  $u_0$  is positive eastward,  $v_0$  is positive northward,  $\theta$  is azimuth angle from north,  $\phi$  is radar elevation angle, and  $\epsilon$  is a small but unknown error. For low elevation angles ( $\phi < 2^\circ$ ),  $\cos\phi \approx 1$  so the elevation dependence can be neglected in (1) without serious conse-

quences. Estimates of the wind components,  $(u_0, v_0)$ , are obtained from regressing the smoothed Doppler velocities within each data sector onto the functions  $\sin\theta$  and  $\cos\theta$  and minimizing the sum of the squared errors,  $\epsilon^2$ , between the measurement and the fitted values. Details of the linear regression can be found in Smith (1986).

There is uncertainty in  $(u_0, v_0)$  owing to Doppler velocity measurement uncertainty, that increases as the sector's azimuthal width,  $\Delta\theta$ , decreases. Thus a lower limit on the sector width of  $30^\circ$  is used. At this width the uncertainty in the wind estimates nearly equals that of the individual Doppler velocity measurements.

For gust fronts of azimuthal extent less than  $30^\circ$  or when uniform wind estimates for longer gust fronts are not reasonable, the horizontal wind direction behind the front is considered to be perpendicular to the gust front orientation angle. The orientation angle is the angle from east subtended by the straight line connecting the end points of the detected gust front. For outflow perpendicular to the gust front orientation, the Doppler velocity,  $v_r$ , and the horizontal wind speed,  $|V|$ , are related:

$$v_r = |V| \cos\psi + \epsilon \quad (2a)$$

where the angle  $\psi$  is the difference between the radar azimuth and the angle perpendicular to the gust front orientation. Using linear regression techniques, the estimate of the wind speed behind the gust front,  $|V|$ , is

$$|\hat{V}| = \frac{\sum_{i=1}^N v_{ri} \cos\psi_i}{\sum_{i=1}^N \cos^2\psi_i} \quad (2b)$$

where the summations are over all  $N$  data points within the sector. Hence, the wind speed estimate is a weighted average, in a least-squares sense, of the wind component perpendicular to the front.

The gust front tracking and orientation information is used to determine which side of the gust front is the outflow side (behind) and also for quality control of the horizontal wind estimates. On occasion, significant non-uniformities in the wind field behind gust fronts can occur. As a result, wind estimates with directions that are quasi-parallel to the gust front orientation may be produced. Such wind estimates are rejected if their directions are less than  $25^\circ$  from the orientation direction. Wind direction estimates for both long and short gust fronts are also checked against the gust front propagation direction. Estimates with a component opposite the propagation direction are rejected. Wind estimates with extreme magnitudes ( $> 40 \text{ m s}^{-1}$  for Denver) are also rejected by the algorithm. Wind estimates for the longer gust fronts that fail these error checks are replaced with the perpendicular wind estimate.



## 9. GUST FRONT TRACKING AND FORECASTING

If one or more gust fronts are detected on two consecutive radar volume scans, an attempt is made to establish time continuity between the gust fronts. Starting with the largest fronts first, the distance between the centers of the fronts from the current and previous radar volume scans are calculated. If two gust front centroids are within a distance threshold, time continuity is established. If there is more than one association in time, the algorithm chooses the closest gust front.

The original version of the algorithm used a simple center-point to center-point method for determining the propagation vector for use in tracking and forecasting the future positions of gust fronts. Testing of this method showed large errors, where fronts were often forecast to move long distances almost parallel to their orientation. In order to alleviate this problem, the propagation vector is calculated by using the component of the center-point to center-point motion that is perpendicular to the line connecting the end points of the gust front. This method was found to work much better than the previous method.

## 10. SUMMARY AND CONCLUSIONS

Over the past two years work has continued on Gust Front Algorithm development and testing. In addition to improvements in the preprocessing of radar data (ground clutter suppression and reliable velocity dealiasing), numerous enhancements were made to the algorithm. Algorithm detection and tracking performance has benefited by inclusion of 1) maximum velocity difference thresholding; 2) variable thresholds for the two elevation scans; 3) connection of nearby shear features (convergence lines) into a single shear feature; 4) fifth-order polynomial fit to the radial convergence lines to allow more representative positioning of the gust front; and 5) normal velocity component for tracking and forecasting. Improvements in the wind estimation technique include: 1) velocity data outlier rejection scheme; 2) redefinition of the data processing sector; 3) perpendicular wind estimation technique for use with short gust fronts and as a replacement estimate when uniform wind model estimates fail error checks; and 4) error checking of wind estimates using gust front orientation and tracking information.

The performance evaluation of the current version of the gust front algorithm is shown in Part 2 of this paper. The most notable results, related to the algorithm improvements, are the high tilt-by-tilt Probability of Detection (78%) and low False Alarm Ratio (2.4%). Wind estimates behind the fronts also compare well with surface wind measurements.

A concerted effort by the authors of Parts 1 and 2 of this paper has led to demonstrated improvements in algorithm performance. With support of the FAA, further refinements are

possible. Other pattern recognition techniques could be implemented after the radial convergent part of a gust front is detected. Inclusion of techniques to detect reflectivity thin lines and azimuthal shear along with lowering radial convergence thresholds at gust front edges, should help increase the length of detected fronts. Intermittent detections of gust fronts have also been an occasional problem. Time consistency of gust front detections will be enhanced by maintaining gust front detections and wind shift information for one scan at the five minute predicted location.

Although several improvements to the gust front algorithm are planned, the algorithm currently provides reliable information of both wind shears and wind shifts associated with significant gust fronts. In its present form, the gust front algorithm has successfully exploited its ability to detect patterns of radial convergence from Doppler radar velocities such that is a useful algorithm for air traffic management.

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## 11. REFERENCES

- Eilts, M.D., and S.D. Smith, 1988: Efficient Doppler velocity dealiasing using local environment constraints. Submitted to J. Atmos. and Oceanic Tech.
- Klinge-Wilson, D., S.H. Olson, W. Wilson, W.P. Mahoney, S.D. Smith, A. Witt, M.D. Eilts, 1989: Gust Front Detection Algorithm for the Terminal Doppler Weather Radar: Part 2, Performance Assessment, Preprints 3rd Int'l Conf. on Avia. Wea. Sys.
- McCarthy J., J.W. Wilson, M.R. Hjelmfelt, 1986: Operational Wind Shear Detection and Warning: The "CLAWS" Experience at Denver and Future Objectives. Preprints, 23rd Conf. on Radar Meteor., 22-26 Sept. 1986, Snowmass, CO, AMS, Boston, MA.
- Smith, S.D., 1986: Sectorized uniform wind algorithms. NEXRAD Joint Systems Program Office Report, September, 25 pp.
- Uyeda, H. and D.S. Zrnic', 1985: Automatic detection of gust fronts. FAA Report No. DOT/FAA/PM-85/11.
- Uyeda, H. and D.S. Zrnic', 1986: Automatic detection of gust fronts", J. Atmos. Oceanic Tech., 3, 36-50.
- Witt, A., and S.D. Smith, 1987: Development and testing of the gust front algorithm. FAA Report No. DOT/FAA/PS-87/4.