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GUST FRONT DETECTION ALGORITHM FOR THE TERMINAL DOPPLER WEATHER RADAR: PART 2, PERFORMANCE ASSESSMENT*

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1. INTRODUCTION

During the summer of 1988, the Terminal Doppler Weather Radar (TDWR) Operational Test and Evaluation (OT&E) was conducted near Denver, CO. One of the objectives of this test was to assess the performance of the Gust Front Detection and Wind Shift Algorithms (Gust Front Algorithm) to be used in the TDWR system. This paper presents an overview of the Gust Front Algorithm system from data collection to products displays and discusses the performance of the algorithm during the 1988 OT&E. Data editing, product generation, ground truth and scoring issues are addressed. Scoring results for the various products are presented and problems identified during the OT&E are discussed. The design of the Gust Front Algorithm is discussed in the companion paper (Part I: Current Status) numbered 1.6 in this preprint volume.

The Gust Front Algorithm serves two functions: warning and planning. Warnings are provided in alphanumeric messages on a "Ribbon Display Terminal". Wind shear warnings are issued when a gust front impacts the runways or within 3 miles of the ends of the runways. The planning function consists of alerting an Air Traffic Control Supervisor when a change in wind speed and/or direction due to a gust front at the airport will occur within 20 minutes. This planning information is displayed on a Geographic Situation Display (GSD).

2. MOTIVATION

A gust front is the leading edge of the cold air outflow from a thunderstorm. Wind shears and turbulence along the gust front may produce potentially hazardous conditions for an aircraft on takeoff or landing such that runway operations are significantly impacted. The Federal Aviation Administration (FAA) has therefore determined that the detection of gust fronts in the terminal environment be an integral part of the TDWR system. Detection of these shears by the algorithm permits the generation of warnings that can be issued to pilots on approach and departure. In addition to the detection capability, the algorithm provides an estimate of the wind speed and direction following the gust front (termed wind shift) and the forecasted location of the gust front up to 20 minutes before it impacts terminal operations. This has shown utility as a runway management tool, alerting runway supervisors to approaching wind shifts and the possible need to change runway configurations.

In order for the Gust Front Algorithm to be useful to Air Traffic Control (ATC) supervisors, controllers and pilots, it must detect gust fronts reliably and maintain a low Probability of False Alarm (PFA). The Gust Front Algorithm has been in existence since 1984 (Uyeda and Zrnic', 1986) and has been upgraded and improved continuously since that time. In 1987, a TDWR experiment was conducted in Denver that provided the opportunity to assess the performance of the 1987 version of the algorithm. This assessment indicated the the PFA was unacceptably large, the Probability of Detection (POD) was low, and the wind shift estimates algorithm was not functional. As a result, the Gust Front Algorithm Group, consisting of personnel from MIT/Lincoln Laboratory, the National Severe Storms Laboratory and the National Center for Atmospheric Research, were tasked to 1) reduce the PFA, 2) improve the POD for moderate or stronger gust fronts, and (3) improve wind shift estimates. The improved version of the algorithm was to be a part of the 1988 TDWR OT&E.

3. DATA EDITING

The 1987 performance evaluation highlighted a couple of data editing issues. The first concerned velocity dealiasing, which directly effected the algorithm's ability to compute an accurate wind shift estimate. During 1987, the velocity dealiasing preprocessor algorithm used radial continuity to unfold velocities (Uyeda and Zrnic', 1986). This scheme proved ineffective and the wind shift estimates based upon

*The work described here was sponsored by the Federal Aviation Administration. The United States Government assumes no liability for its content or use thereof.

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these erroneously-unfolded velocity data were completely unreliable.

An improved velocity dealiasing technique was introduced for the 1988 OT&E. This method uses radial and azimuthal continuity to unfold velocities (Eilts and Smith, 1989). The resultant wind shift estimates were drastically improved, as demonstrated subsequently.

Data editing was also an issue in the observed high PFA. The majority of false detections in 1987 were caused by environmental flow impinging on ridges and mountains. Ground clutter has a near-zero Doppler velocity which created an apparent radial convergence when ambient flow toward the radar encountered the clutter. In 1987, high pass digital filters (Evans, 1983) were used to reject clutter. However, this technique did not sufficiently remove all clutter from the data. Thus, in 1988 a clutter residue map (Mann, 1988) was used in addition to the high pass filters. This resulted in a drastic reduction of false detections. Other improvements made to the algorithm which did not involve data editing were described in Part I of this paper (Smith *et al*, 1989).

4. PRODUCT GENERATION AND DISPLAY FOR THE 1988 OT&E

Single Doppler radar data were collected by the TDWR testbed S-band radar. The data passed through the clutter filters and clutter residue maps and were dealiased using the scheme described by Eilts and Smith (1989). The data were then processed by the Gust Front Algorithm which detected gust fronts, computed wind shift estimates and stored appropriate information about each radial shear segment‡ that was associated with a given detection. This information was passed to the display software, where wind shear warnings were generated and sent to the Ribbon Display Terminal (RDT) located in the ATC tower. (The RDT is presents warnings to controllers in an alphanumeric format.)

When a gust front was detected on the runways or within 3 miles of the ends of the runways, a wind shear alert message was displayed on the RDT. This message, consisting of the type of hazard, the expected runway component gain in wind speed, and location of the shear (*e.g.* wind shear alert, 35 knot gain, one mile final), was then relayed by the Local Controller to arriving or departing pilots. The wind shear intensity was computed by averaging, over all associated radial shear segments, the peak one-kilometer shear and adding one standard deviation.

The gust front locations, forecasts, and wind shift estimates were displayed on the Geographic Situation Display (GSD; Figure 1). The current detection was indicated by a solid line. Forecasts of the gust front location for 10 and 20 minutes into the future were displayed as dashed lines. The winds behind the gust front were shown by a bold arrow located behind the detection and pointing along the direction of the wind. Wind speed (in knots) was given as a numerical value.

5. GROUND TRUTH

In order to score the various algorithm products (detections, forecasts, wind shift estimates, wind shear

‡ Shear segments are segments along radials that exhibit runs of decreasing Doppler velocities or radial convergence.

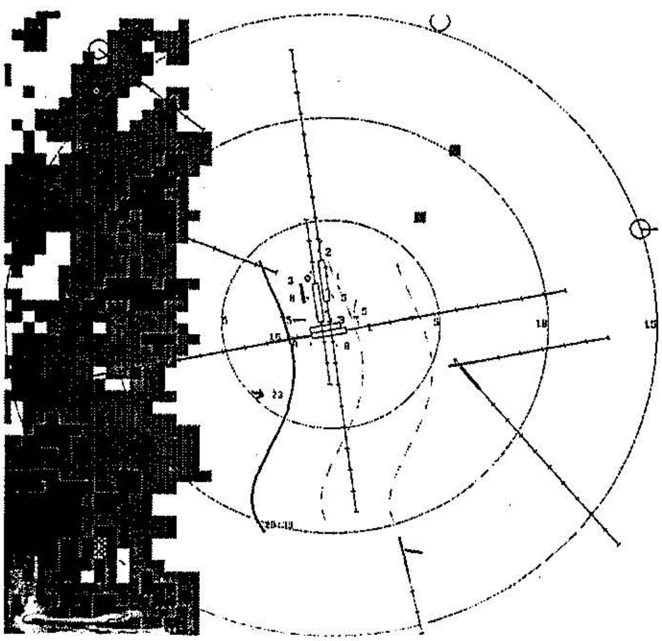

Figure 1. Black and white reproduction of the Geographic Situation Display (GSD). The heavy solid line is the gust front, the dashed lines are the 10 and 20 minute forecasts. The bold arrow is the wind direction behind the gust front and the wind speed (23) is in knots. Precipitation is contoured in gray scale (darkest is heavest). The figure is centered on the Stapleton runway complex.

alerts), it was necessary to generate a ground truth database. For the detections, forecasts and locations in the wind shear alerts, the true locations of all gust fronts were needed. This was accomplished by a group of experienced radar meteorologists who assessed the radar data for evidence of gust front signatures (*i.e.*, radial convergence, azimuthal shear, and reflectivity thin line). In establishing ground truth, the following rules were applied.

1.) A gust front had to have a length of at least 10 km.

2.) An outline consisting of points along the entire length of the gust front, as determined from convergence, azimuthal shear and/or the presence of a reflectivity thin line was entered into the truth files.

3.) The strength of the gust front (termed ΔV) was taken to be the average peak change in Doppler velocity perpendicular to and along the convergent portion of the gust front. Gust fronts were defined as weak (5 m/s $\leq \Delta V <$ 10 m/s), moderate (10 m/s $\leq \Delta V <$ 15 m/s), strong (15 m/s $\leq \Delta V <$ 25 m/s), and severe ($\Delta V \geq$ 25 m/s).

Ground truth for the Wind Shift Algorithm was derived from surface wind measurements that were made at 38 locations around the airport (termed mesonet). It was determined that since winds ahead of the gust front were available to ATC (via LLWAS), only the wind estimate behind the gust front would be displayed and scored. Since mesonet data constituted ground truth, only those wind shifts associated with gust fronts that passed through the mesonet were scored. To determine which mesonet stations were behind a gust front, the location of the gust front from single Doppler radar data was superimposed on the plotted mesonet data. Those stations that had experienced a change in wind speed and/or direction were used for analysis. The wind direction computed by the algorithm was compared to the average wind direction from the mesonet. The algorithm-computed wind speed was compared to the average of the peak mesonet wind speeds that occurred during a one minute interval. Ground truth for the wind shear alert intensities was pilot reports as recorded by observers located in the tower.

6. SCORING DEFINITIONS, RULES AND RESULTS

It was determined that simply representing the gust front ground truth outline by a straight line introduced errors into the representation of the gust front location. The gust front is a transition zone that is often not well-represented by a line. The difficulty inherent in identifying the precise location of the peak shear, and the use of straight line segments rather than curves to connect the points also introduces errors. To compensate, truth was represented by a box that was 5 km wide and centered on the straight line segments. Figure 2 illustrates a truth box.

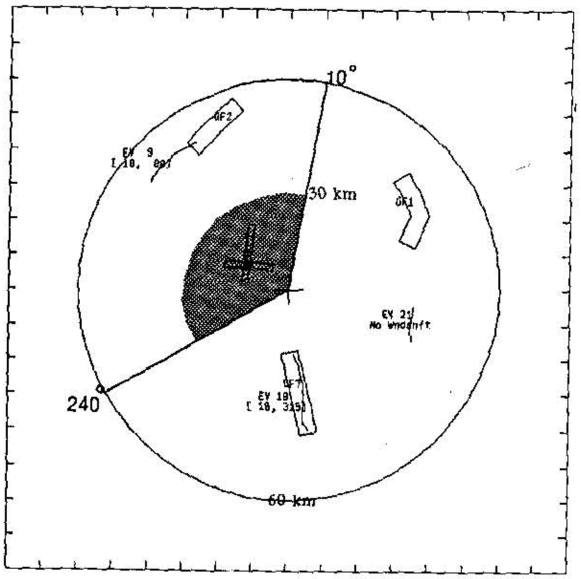

Figure 2. Diagram illustrating truth, detections and false alarms. Ground truth is represented by the boxes whose widths are 5 km, detections are solid lines. GF1 is an example of a missed gust front (truth with no associated detection. EV 21 is an example of a false alarm (detection not associated with truth). The stippled area is the airport sector. The values in square brackets are estimates of wind speed and direction behind the front.

Algorithm performance is measured by the Probability of Detection (POD), which is defined as the number of true detections divided by the number of gust fronts. A true detection is declared when **any part** of a gust front is detected. The POD, as a function of gust front strength, for 1988 is shown in Table 1. The 1987 data are provided for comparison to show the overall improvement in algorithm detection capability.

The Probability of False Alarm (PFA) is defined as the number of false detections divided by the total number of detections (true plus false). For 1987 and 1988, the PFA is 37/84 (44.0%) and 27/1146 (2.4%) respectively. None of the 1988 false alarms occurred in the airport sector, defined as the area bounded by the

Table 1: Probability of Detection

	MODERATE	STRONG	SEVERE	ALL
1987	$\frac{90}{167} = 0.539$	$\frac{35}{48} = 0.729$	-	$\frac{125}{215} = 0.581$
1988	$\frac{783}{1073} = 0.730$	$\frac{321}{352} = 0.912$	$\frac{1}{1} = 1.000$	$\frac{1105}{1426} = 0.775$

azimuths 240° and 10° and the ranges 0 to 30 km from TDWR testbed radar (shown in Figure 2).

The POD does not indicate how **well** a gust front is detected. Figure 2 shows an example of a valid detection that may not be considered a "good" detection. A portion of the detection labeled EV9 is located within the truth box representing a gust front identified as GF2. A valid detection is declared, but less than 10% of the total length of the gust front is detected by the algorithm. It is possible to apply a minimum Percent of Length Detected (%L) threshold ($\%L_{min}$) such that %L must exceed the threshold before a valid detection is declared. POD as a function of $\%L_{min}$ is plotted in Figure 3. The average Percent of Length Detected as a function of gust front strength is given in Table 2.

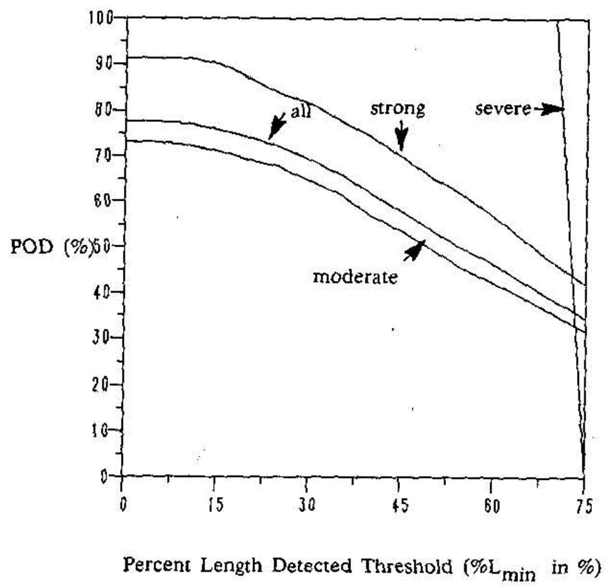

Figure 3. Probability of Detection (POD) as a function of Percent Length Detected Threshold ($\%L_{min}$) for moderate, strong, severe and all gust fronts.

Table 2: Average Percent of Length Detected

MODERATE	STRONG	SEVERE	ALL
66.5	68.5	73.1	67.1

The wind shear warning is composed of two parts, the location of the wind shear and the intensity. Location is scored by computing the number of wind shear alerts **issued** at the airport divided by the number of wind shear alerts that **should have been** issued. The results of this analysis, termed the Probability of Correctly Locating Wind Shear are shown in Table 3. The Probability of False Warning (PFW) is defined as the number of false alarms issued divided by the total

Table 3: Probability of Correctly Locating Wind Shear

MODERATE	STRONG	ALL
$\frac{93}{146} = 0.637$	$\frac{53}{62} = 0.855$	$\frac{146}{208} = 0.702$

number of alarms issued (3/206 or 1.5%). In these three instances, gust fronts were in the airport vicinity but the detections did not agree well with the truth and warnings were generated unnecessarily. At no time was there a detection in the airport sector where no gust front existed.

Wind shear intensity is scored by comparing the intensity expressed in the wind shear alert message to pilot reports as logged by observers in the tower. The average absolute difference between pilot reports and alerts is about 10 kts, with alerts overestimating wind shear relative to pilot reports.

An aircraft that encounters a gust front should always experience a gain in wind speed. As the airplane flies into the gust front, it encounters an increasing headwind. As the plane flies out of a gust front, it experiences a decreasing tailwind. Both flight paths result in a performance gain. Therefore, wind shear associated with a gust front is always reported as a gain. In some instances, pilots reported a wind speed loss. This resulted in a large wind speed difference in the wind speed error analysis. If these pilot reports are removed from the analysis, the average absolute difference between pilot reports and alerts is about 5 kts. Cases in which pilots reported a loss need to be studied further to determine why there was an inconsistency between the reported and estimated shears.

Effective runway management is achieved by alerting an ATC Supervisor when, within 20 minutes, a wind shift is expected at the airport (forecasted location) and to what velocity the winds will change with its passage (wind shift estimate). The forecasted location is scored by determining if a forecast falls within the truth region for the time at which the forecast is valid. If so, a valid forecast is declared. If the forecast falls outside the truth box, the forecast is considered a miss. A false forecast is declared if the gust front dissipates before the validation time. The Probability of Correct Forecast (PCF) is given by the number of valid forecasts divided by the number of gust fronts for which forecasts were made. The Probability of False Forecast (PFF) is the number of false forecasts divided by the number of gust fronts for which forecasts were made plus false forecasts. When the algorithm is able to generate a forecast, forecasts are made for 10 and 20 minutes into the future. PCF, as a function of gust front strength, is given in Table 4. The PFF for the 10 and 20 minute

Table 4: Probability of Correct Forecast

	MODERATE	STRONG	SEVERE	ALL
10	$\frac{447}{474} = 0.943$	$\frac{236}{246} = 0.959$	$\frac{1}{1} = 1.000$	$\frac{684}{721} = 0.949$
20	$\frac{333}{404} = 0.824$	$\frac{183}{219} = 0.836$	$\frac{0}{1} = 0.000$	$\frac{516}{624} = 0.827$

forecasts is 11.0% (63/571) and 18.4% (99/538), respectively. However, the algorithm was able to produce forecasts for only about 45% of the approximately 270 gust fronts and convergence boundaries that occurred during the 1988 OT&E.

The accuracy of the wind shift estimate is determined by comparing the wind shift estimate to the mesonet data. The average absolute difference in wind speed and direction between the wind shift estimate and the mesonet data is 3 m/s and 30°, respectively. The wind shift speed is, on the average, about 1.5 m/s larger than that determined from the mesonet data (which may be explained by the difference in height of the measurements (Eilts, 1987) and the wind shift direction is about 5° counterclockwise of the mesonet wind direction.

7. FUTURE ENHANCEMENTS

Observations of the Gust Front Algorithm used during the 1988 OT&E suggested further enhancements. The Gust Front Algorithm detected convergence in the radial direction only. However, gust fronts often were not aligned with respect to the radar such that the convergence across the front could be detected along their entire lengths. There were cases in which the portion of the gust front that was not detected was the portion that impacted the airport and therefore no warnings were issued. The accuracy of forecasts was also affected by this incomplete detection of the gust front length. Forecasts were generated by taking the detection and propagating it for 10 and 20 minutes. At times, the undetected portion of the gust front passed over the airport, thus a forecast was not given to the ATC Supervisor. The 1988 algorithm detected about 70% of the total gust front length. However, with further enhancements to the algorithm (such as the ability to detect reflectivity thin lines and/or azimuthal shears) it will be able to detection of a higher percentage of the total length.

Intermittent detections and tracking errors were also observed during the OT&E. In order for either a forecast or the determination of the wind shift **behind** the gust front to be made, it was necessary to know the speed and direction of gust front propagation. Propagation was assessed by tracking the gust front on two consecutive scans. Intermittent detections precluded tracking and made the calculation of propagation impossible. Thus, the algorithm could not make a forecast nor did it know which side of the gust front was behind.

Tracking was performed by comparing the location of the detection centroid from scan to scan. The centroid location was heavily influenced by the length of the gust front that was detected. If the detected length changed considerably from scan to scan, the gust front appeared to move in the wrong direction, resulting in bad forecasts and estimates for winds that were in reality **ahead** of the gust front. This occurred most often in association with slow-moving or stationary gust fronts, which were typically weak or marginally moderate, or associated with the leading edge of microburst outflows. The solution rests in improving detection and tracking and improving time continuity by maintaining detections for one scan at the five minute predicted location.

In order to reduce false alarms but allow detection of significant gust fronts, the algorithm searched the Doppler data for convergences on larger spatial scales than those associated with microbursts. This resulted in missed wind shear lines produced by microbursts. To be able to detect microburst-induced gust fronts, it may be necessary to design an interface algorithm between the gust front and microburst algorithms.

The current algorithm was run on two low-elevation angle scans that were updated every 5 minutes. The OT&E has shown that in order to make the algorithm more useful to ATC, it will be necessary to use a faster update rate, especially when a gust front is in the immediate airport environment. It may be possible to alter the algorithm to run on the lowest microburst scan, which is collected every minute.

It should be noted that some apparent problems observed during the OT&E were caused by the evolution, collisions and mergers of the gust fronts. This can not be attributed directly to deficiencies in the algorithm.

8. CONCLUSIONS

Drastic improvements were made in the Gust Front Algorithm between the TDWR Experiment of 1987 and the OT&E of 1988. The Probability of False Alarm was reduced and the algorithm's detection capability for gust fronts whose strengths are moderate or greater was improved. The emphasis of the work was to keep false alarms to a minimum, even at the expense of detection capability.

The next step in the development of the algorithm is to improve the detection capability (both in terms of detecting previous misses and detecting a greater percent of the total gust front length) while maintaining the low PFA. Experience gained during the OT&E has suggested additional improvements to the basic convergence detection algorithm. Work needs to be done to improve tracking and efforts to add enhancements such as thin line and azimuthal shear are needed.

ACKNOWLEDGEMENTS

The authors wish to express their sincere thanks to Chuck Curtis, Stan Dajnak, Nat Fischer, and Mark Isaminger who ran and maintained the TDWR testbed radar at Denver throughout the OT&E. Thanks also to Laurie Hermes, Steve Vasiloff and Kevin Thomas for supplying some of the ground truth.

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