STATUS OF THE TERMINAL DOPPLER WEATHER RADAR ONE YEAR BEFORE DEPLOYMENT*

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1. INTRODUCTION

The Federal Aviation Administration (FAA) initiated the Terminal Doppler Weather Radar (TDWR) program in the mid-1980s in response to the need for improved real time hazardous weather (especially low altitude wind shear) detection in the terminal area. The program is designed to develop a reliable automated Doppler radar based system to detect terminal weather hazards and provide warnings that will help pilots successfully avoid these hazards.

Following the successful operational evaluation of the TDWR concept which was described at the last conference, [1] a production contract was awarded to the Raytheon Company, with the first deliveries scheduled for fall of 1992. This paper will describe the current status and deployment strategy for the operational systems and present recent results from the extensive testing of the radar system concept and weather information dissemination approach.

2. BACKGROUND

Improved air safety is the principal motivation for the system. Low altitude wind shear has been a major cause of U.S. air carrier fatalities in recent years. A 1983 National Research Council study identified low-altitude wind shear as the cause of 27 aircraft accidents and incidents, with a total of 488 fatalities between 1964 and 1982. Since that study, the National Transportation Safety Board has investigated at least three more wind shear incidents. One of these, the crash of Delta Flight 191 at Dallas/Ft. Worth on 2 August 1985, took another 137 lives.

The TDWR will also provide important benefits in the area of improved terminal area capacity and efficiency of operation. The system has the ability to track gust fronts and predict the time of their arrival at the airport as well as provide an estimate of the expected wind shift after the gust front passes. These predictions will enable airport supervisors to anticipate runway changes as opposed to reacting after a wind shift occurs. An estimate of the motion of storms is provided to further assist in minimizing the impact of weather on terminal area operations.

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

The need to improve wind shear detection capability has resulted in an overall "fast track" development program for the TDWR. As in the case of the Next Generation Weather Radar (NEXRAD) system, the government is supplying the meteorological algorithms, with the contractor providing the bulk of the signal processing algorithms. Testbed radars with "rapid prototyping" of key contractor systems and user interfaces have been used to address many of the issues normally assessed with a preproduction prototype system (including system operation in a variety of weather regimes). As a consequence, the Raytheon Company deliveries will commence with production systems.

3. TDWR SYSTEM FEATURES

The TDWR principal system requirements for initial deployment [2] are as follows:

1. Timely, reliable microburst detection including probability of detection (POD) > 90%, probability of an alarm being false (PFA) < 10%, and warnings to pilots at least one minute prior to an encounter.
2. Detection of gust fronts at the airport with 20-minute warning of gust front arrival. The direction of the wind after gust front passage should be accurate to $\pm 10°$ and ± 5 kts.
3. Location of precipitation regions corresponding to the 6 NWS levels out to 90 km.
4. Unattended, reliable operation with a system availability of 0.9967, mean time before critical failure (MTBCF) of 1500 hrs, no more than 6 critical failures and 10 routine maintenance actions per year, and remote maintenance monitoring (RMM).
5. Products provided automatically to ATC personnel with no need for meteorological interpretation. This would include integration of TDWR warnings with warnings from other wind shear systems (e.g., LLWAS)
6. Computational load < 50 % of computational capacity, three fold field expandability, and a government software modification facility to facilitate evolutionary upgrades and enhancements.

These basic requirements and the knowledge gained in a series of wind shear measurement programs were used to arrive at the technical characteristics summarized in the listing below. The rationale for this set of technical characteristics is discussed in. [3, 4]

1. C-band operation with 1.1 μs 250 kw pulses at Doppler mode PRFs from 1066–1930 Hz.
2. Pencil beam antenna with 0.5 degree beamwidth and sidelobes < -27 dB.
3. PPI volume scans over airport every 2.5 min, with surface scans every minute.
4. Clutter suppression by high pass filters as well as point target and ground clutter residue editing.
5. PRF selection to minimize data contamination near the airport by out of trip echos and editing of data which is contaminated by out of trip weather using low (325 Hz) PRF scan data.
6. Velocity unfolding using dual scans at different PRFs and two-dimensional continuity of velocity fields.
7. Extensive use of site adaptation parameters in microburst and gust front algorithms to facilitate performance optimization in a variety of environments.
8. Alphanumeric wind shear warning messages on "ribbon display" for local controllers to provide to pilots and color situation displays for terminal area planning by ATC supervisors.

4. PRODUCTION CONTRACT STATUS

The TDWR production contract for 47 systems is progressing on schedule at this time, with testing of the engineering model presently underway in Norwood, MA. The first deliveries for operation will be to Memphis, TN and Houston, TX in the fall of 1992, with deliveries of three per month commencing in March 1993. The software development, a major risk item, is being conducted under DOD specification 2167A. This approach results in much greater effort and documentation in the design phase, but appears to be providing significant benefits in the software integration phase. The testing of software that implements the government-supplied algorithms is accomplished by an independent verification contractor and by comparison of numerical results for measured base data from testbed experiments with the results obtained by the algorithm developers for those same data sets.[1]

1. A major issue in the overall TDWR production system verification was whether there should be an acceptance test demonstrating wind shear detection with a production system. This was viewed as unnecessary given the very extensive testing with functionally equivalent testbeds and the use of actual recorded data sets to verify implementation of the detection algorithms.

Figure 1 shows the currently planned locations for the TDWR system. The principal criteria used for choosing the sites is the product of expected microbursts and emplanements so as to maximize the benefit from improved safety. The actual site at a given airport is chosen based on the desired distance from the airport (approximately 15 km), the runway orientation (it is preferable to place the system along the extension of runway centerline for the principal IFR runway), ground clutter, visibility to 100 m above the runway surface, and land availability. Instrumented vans are making detailed clutter and visibility surveys of candidate sites to assist in the site selection.

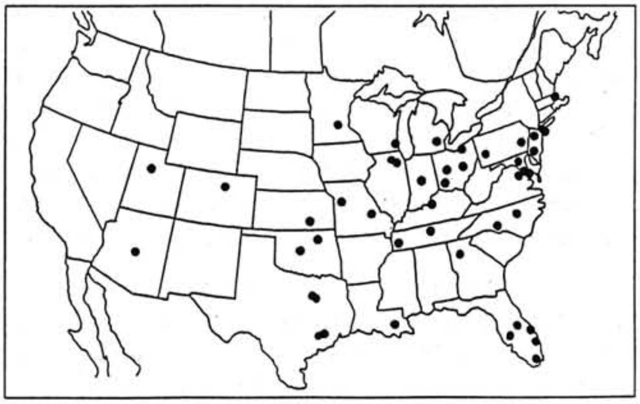

Figure 1. Planned locations of the initial 47 Terminal Doppler Weather Radars.

An important issue in a computer/software-intensive system such as the TDWR is the ongoing support for the system. Commercial off-the-shelf computer systems (COTS) are being used, with the suppliers providing maintenance for the COTS hardware. The government will assume long-term responsibility for software maintenance and upgrades using a Program Support Facility (PSF) which includes the main product generation and display computer systems. The PSF will also have principal responsibility for optimizing system performance at particular sites by adjustment of the algorithm site adaptation constants.

5. TECHNICAL INVESTIGATIONS

Experimental investigations of the TDWR, using two testbed systems, have continued since the production system award. The objective of these experiments is to reduce the overall development risk and facilitate rapid commissioning by addressing issues such as C-band radar performance, adaptation to a variety of weather environments, microburst asymmetry, and integration with the Low Level Wind Shear Alert System (LLWAS). Salient results in each of these areas are discussed below.

5.1. C-band Operations

The bulk of the TDWR testbed experiments were conducted at S-band, with simulations and analyses used to estimate C-band performance. The principal concern at

C-band was with velocity folding and/or wind shear signature obscuration by out-of-trip weather. Another concern was rain attenuation (based on difficulties with long-range weather detection at C-band).

In 1989, a contract was let to the Westinghouse Corporation to modify an ASR-9 transmitter to work at C-band. This transmitter was used to convert the testbed used for earlier TDWR experiments [5] to C-band. The existing reflector was retained so that the beamwidth would be 0.5 degrees. The radiated waveforms and signal processing (including velocity dealiasing) algorithms proposed by Raytheon were rapidly implemented and used for operational testing at Orlando, FL in 1990. A collaborative working relationship between the Raytheon system designers and the M.I.T. Lincoln Laboratory developers/operators of the TDWR testbed achieved a rapid implementation of the Raytheon algorithms, validation of the software, and analysis of performance deficiencies. The results to date [6, 7] are very encouraging in that velocity folding has not resulted in any missed microbursts and has contributed to very few false alarms, while out-of-trip echos have not prevented the detection of any microbursts near the airport.

An important element in the minimal impact of out-of-trip echos in Orlando is the relatively high reflectivities (nearly all are greater than +10 dBZ) associated with microburst outflows. These high reflectivities result in an outflow signal-to-noise ratio (SNR) greater than + 25 dB over much of the airport region. Attenuation by the heavy rains that occur in Orlando would not be expected to reduce such a high SNR to the current +10 dB threshold and in fact there have been no microburst events missed to date due to rain attenuation.

5.2. Performance in a Variety of Environments

The rapid pace at which TDWR systems will be deployed in 1993-1994 and the fully automated operations make it highly desirable to have substantive experience at site- specific optimization in a full variety of wind shear environments. The TDWR testbed was moved to Kansas City, MO in 1989 for testing in a highly sheared midwest environment [8] and was then moved to Orlando, FL in 1990 for testing in a heavy rain, subtropical environment. Tables 3 through 5 compare the system performance at these sites with that from earlier testing in Denver and Huntsville, AL.

The Kansas City microburst detection performance was substantially better than in Denver due to the higher reflectivity of the Kansas City outflows (median of approximately + 35 dBZ, 95 percent with reflectivities greater than +5 dBZ).[2] However, the false alarm probability slightly exceeded the requirements when site adaptation parameters from Denver were used. Investigation showed a significant number of false alarms occurred in clear air conditions with high surface winds. These were significantly reduced by setting site adaptation parameters so that reflectivity aloft was used to validate the surface microburst detections. The Kansas City gust front performance was poorer than in Denver due to an unfavorable viewing angle geometry and false alarms due to vertical wind shear. Work is underway to develop a gust front algorithm that will be less sensitive to viewing angle geometry based on the use of additional radar observable features. [9, 10]

2. By contrast, Denver outflow median reflectivities are +9 dBZ, with 95 percent of the outflows having a reflectivity greater than -8 dBZ.

Table 3.
Microburst (MB) Detection Performance

	Pobs	Prec	Pd	Pfa
Huntsville 1986				
strong MB	1.00	1.0	1.0	
all MB	.98	.91	.89	.05
Denver 1987-1988				
strong MB	.99	.98	.98	
all MB	.95	.90	.86	.04
Kansas City 1989				
strong MB	TBD	.99	TBD	.01
all MB	TBD	.94	TBD	.09
Orlando 1990				
strong MB	TBD	1.00	TBD	.00
all MB	TBD	.95	TBD	.02

strong: $\Delta V \geq 15$ m/s; all: $\Delta V \geq 10$ m/s
ΔV: wind change across the microburst
Pobs: probability that a microburst was observable by radar meteorologist analysis of single Doppler radar data.
Prec: probability that an observable microburst is recognized by algorithm
Pd: probability of detection= Pobs Prec
Pfa: probability of false alarm
TBD: to be determined. The Pobs for Kansas City and Orlando are believed to be comparable to that for Huntsville.

Table 4.
Gust Front Detection Performance as a Function of Gust Front Strength

	Probability of Detection			
	Gust Front Strength			
	Moderate	Strong	Severe	PFA
Within 60 km of radar				
Denver 1988	.73	.91	1.00	.02
Kansas City	.72	.81	.92	.13
Orlando 1990	.75	.84	1.00	.06

Table 4. (Continued)

At airport				
Denver 1988	.64	.86		.00
Kansas City 1989	.29	.68	.40	.40
Orlando 1990	.60	.50		.00

moderate:	$10 \leq \Delta V < 15$
strong:	$15 \leq \Delta V < 25$
severe:	$\Delta V \geq 25$
ΔV:	wind change across gust front in m/s
PFA:	probability of false alarm

Table 5.
Gust Front/Wind Shift Planning Product Performance

	Denver	Kansas City	Orlando
Ff	.45	.50	.56
10–Minute Forecast			
Pcf	.97	.97	.95
Pff	.11	.18	.13
20–Minute Forecast			
Pcf	.83	.94	.75
Pff	.18	.21	.30
Wind Shift Estimate			
Ve(m/s)	3	3	2
Ae(°)	30	30	15

Ff:	fraction forecasted
Pf:	probability of correct forecast
Pff:	probability of false forecast
Ve:	mean absolute velocity error (m/s)
Ae:	mean absolute direction error (deg)

The Orlando microburst detection performance was the best to date, while the gust front detection performance was similar to that of Kansas City (again due to unfavorable viewing geometry). More stringent values for the microburst outflow site adaptation parameters were used in Orlando than in Kansas City (e.g., the SNR threshold was increased from + 8 dB to + 10 dB and the core reflectivity threshold was increased from 54 dBZ to 57 dBZ).

5.3. Microburst Asymmetry Investigations

The current TDWR microburst detection and alarm generation algorithms basically assume that microburst outflows are symmetrical. Dual Doppler studies show that a substantial fraction of Denver microbursts are in fact asymmetrical in the sense that the measured velocity change across the microburst outflow depends on the viewing angle. [11] Based on the comparison of single radar detections with anemometer array data [3] and limited dual Doppler analysis, [12] it was concluded that three to five percent of Denver microbursts might not be observable by a single radar due to asymmetry. [2] Recent calculations suggest that a greater fraction of low reflectivity microbursts might not be observable, although no operationally significant missed events (e.g., those which elicited a pilot report) occurred in three years of testing in Denver, Kansas City, and Orlando. The impact of asymmetry on performance will be addressed in the coming year by extensive performance analysis using dual Doppler derived "truth" data sets.

5.4. TDWR/LLWAS Integration

The FAA Air Traffic service has requested that the TDWR alarms be integrated with those produced by the improved LLWAS [13] to provide a single, integrated alarm message at airports where both systems are installed. A second TDWR testbed[3] (derived from the Raytheon NEXRAD prototype radar) was deployed to Denver in 1989 to develop and validate a TDWR/LLWAS integration algorithm using data from the Denver enhanced LLWAS. An initial algorithm was developed and tested in 1989, and a more refined algorithm was tested in 1990. The recommended algorithm [14] reports the union of strong microburst warnings from either system and uses the TDWR reflectivity aloft data to assist in the validation of weak LLWAS microburst alerts that may be caused by spurious winds. Gust front warnings are generated by LLWAS within the LLWAS coverage and by TDWR outside the LLWAS coverage region. Analysis of the 1990 Denver data suggests an overall microburst probability of detection (POD) greater than 95 percent and a probability of false alarm (PFA) less than 6 percent, albeit quantitative scoring was hampered by the lack of dual Doppler "truth" data. In 1991 additional operational testing will occur in Denver, and dual Doppler data will be obtained in Orlando to make off-line performance analyses.

6. USER INTERFACE/SYSTEM OPERATIONAL UTILIZATION

A key component of the TDWR test program since 1988 has been testing and refinement of the user interface and operational concept.

6.1. Display/User Interface

The basic TDWR ATC controller interface consisting of an alphanumeric "ribbon" display (RD) and a color geographical situation display (GSD) was successfully used at the TDWR testbed in Denver, 1988 and has continued to be well received in subsequent Mile-High Radar (MHR) testing. A functional emulation of the Raytheon GSD was developed and used successfully in the Orlando 1990 tests. Several features (e.g., user selection of the runway messages to be displayed on a given RD and the use of menus) are

3. This system, known as the Mile-High Radar (MHR), is being operated and upgraded for the FAA by the National Center for Atmospheric Research.

being re- examined based on the test results. The production RD, as well as possible refinements to the current Raytheon GSD, will be evaluated in the 1991 Orlando tests.

6.2. Operational Utility in a Variety of Environments

The TDWR products were well received by the users in Kansas City, although the overall impact of weather on operations was lessened during the test period by reduced air traffic[4] and less convective weather than normally occurs during the severe storm portion of the summer. The storms that did occur advected quickly, so airport operations were not impacted significantly by the wind shear alerts.

The Orlando testing proved very useful for assessing and refining the TDWR alerting strategy. Orlando is characterized by frequent heavy rain thunderstorms during most afternoons in the summer, with many of these producing microburst outflows. Since the storms were also slow moving (90 percent of microburst–producing storms moved less than 0.25 nmi/min), wind shear alerts issued for a runway often continued for an extended period of time. This slow movement, coupled with the close proximity of the two (both north–south oriented) runways at Orlando, meant that airport operations would be impacted significantly by wind shear alerts.

The current TDWR alerting strategy [3] is very conservative. Hence, there were a number of occasions in which the airport operation was adversely impacted when there was no significant shear along the runway centerline. Some pilots responded by taking evasive actions[5] based on visual observations of the rain regions as opposed to not taking off or landing. Although this avoidance approach, based on visible rain regions, is usually (but not always) safe in Orlando, such an approach would have a much higher likelihood of leading to inadvertent wind shear encounters in other regions (e.g., Denver or Kansas City) where microburst outflows with little or no rain occur more frequently. Consequently, approaches are being investigated for providing warnings that better reflect the wind shear that would be encountered on the nominal flight path.

6.3. Integrated System Characteristics

The ribbon display and message format for the integrated system was identical to that for TDWR or LLWAS alone, and the user had no knowledge as to which system generated a given alert. Since the integrated system did not provide a substantially greater number of alarms than either system alone, it was not surprising that no user interface issues have arisen to date.

The desire to provide overall wind shear planning information on the GSD required some changes since this information was not provided by a stand–alone LLWAS. Two LLWAS–derived elements were added to the GSD for the Denver tests:

1. Vectors showing the winds at each LLWAS sensor to assist in overall airport weather assessment and,
2. Divergence region shapes (similar to those generated by TDWR) computed from gridded LLWAS divergence information so that the GSD would show a set of circles or "band–aids" corresponding to regions of LLWAS microburst detections.

The LLWAS runway alerting strategy was then modified to use the shape intersections with runway boxes analogous to the TDWR. This provided a uniform alerting strategy and correspondence between the GSD and RD for microbursts, which was well received by the Denver controllers.

It was not possible to derive a satisfactory representation of gust front locations from LLWAS data, although the runway shear messages from LLWAS were found to be more accurate than those from the TDWR. Thus, the GSD depicted the current and predicted locations of gust fronts from TDWR data. The runway alerts for the GSD and the RD used the integration algorithm discussed earlier. In contrast to microburst detection, there was not always a correspondence between the graphical representation of a gust front and the runway alerts. However, the LLWAS wind vectors provided some visual confirmation for the LLWAS–generated runway alerts, and the overall approach was viewed by the controllers [14] as satisfactory.

7. SYSTEM ENHANCEMENTS/FUTURE DEVELOPMENTS

A number of enhancements to the baseline TDWR design are being tested and may be implemented in the near future. The correlation tracker–based storm motion estimator has been well received in testing to date and will become part of the baseline design in the very near future. As noted above, an improved gust front algorithm is being developed to reduce the current performance sensitivity to gust front orientation relative to the radar. It has been shown that microburst occurrence can be predicted a significant fraction of the time using current precursor features. [15] Tornado vortices have been recognized with a high degree of reliability using data from Denver, Oklahoma, and Kansas City. [16]

Additional improvements in the safety and efficiency of terminal ATC operations will become possible when TDWR data is used in conjunction with other terminal sensors via the Integrated Terminal Weather System. [17] Wolfson [18] has suggested using storm reflectivity structure together with (sounding) thermodynamic data to predict the strength of microburst outflows. TDWR will also play an important role in providing wind change information to support terminal automation and wake vortex advisory systems.

4. An airline running a "hub" operation at Kansas City significantly reduced its operations during the summer.

5. For example, turning sharply after takeoff when an alert was issued for a microburst two miles off the departure end of the runway.

8. SUMMARY

The TDWR program is continuing to meet a very challenging "fast track" schedule and expects to commence deliveries to operational sites in the fall of 1992. Key elements in maintaining this schedule have been the extensive validation of the basic system concept, "rapid prototype" testing of key production system features using TDWR testbeds, and a good working relationship with the system contractor. Considerable operationally-oriented testing has occurred since the production award to refine and extend the system capability, and this will continue, at least until system deliveries. A number of important new capabilities have reached an advanced state of testing, and we see the TDWR playing a key role in providing improved terminal area efficiency and safety via integration with other terminal weather sensors in the coming years.

9. ACKNOWLEDGMENTS

The rapid development of the TDWR has been facilitated by the continued effort of a talented group of researchers (from Lincoln Laboratory, the National Severe Storms Laboratory, and the National Center for Atmospheric Research) and the FAA System Integration Contractor (Martin Marietta) staff under the leadership of Don Turnbull and A. Hansen of the FAA. The testbed system developers and operators at Lincoln Laboratory (directed by D. Bernella) and NCAR (directed by J. Moore) have played a key role in the ongoing system testing and refinement. The Orlando microburst and gust front performance results and comments on the paper were provided by S. Campbell and D. Klingle-Wilson, respectively. D. Turnbull also provided comments on the paper. L. Mahn very ably edited and formatted the paper.

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