Project Report
ATC-332

Analysis of Operational Alternatives to the Terminal Doppler Weather Radar (TDWR)

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26 February 2007

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Prepared for the Federal Aviation Administration,
Washington, D.C. 20591

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Springfield, Virginia 22161

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. ATC-332	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Analysis of Operational Alternatives to the Terminal Doppler Weather Radar (TDWR)		5. Report Date 26 February 2007 6. Performing Organization Code
7. Author(s) Mark E. Weber, John Y. Cho, Michael Robinson, and James E. Evans		8. Performing Organization Report No. ATC-332
9. Performing Organization Name and Address MIT Lincoln Laboratory 244 Wood Street Lexington, MA 02420-9108		10. Work Unit No. (TRAIS) 11. Contract or Grant No. FA8721-05-C-0002
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration 800 Independence Ave., S.W. Washington, DC 20591		13. Type of Report and Period Covered Project Report 14. Sponsoring Agency Code

15. Supplementary Notes

This report is based on studies performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, under Air Force Contract FA8721-05-C-0002.

16. Abstract

Possible alternatives to the Terminal Doppler Weather Radar (TDWR) are assessed. We consider both the low altitude wind shear detection service provided by TDWR and its role in reducing weather-related airport delays through its input to the Integrated Terminal Weather System (ITWS). Airborne predictive wind shear (PWS) radars do not provide an acceptable alternative because many commercial aircraft and practically all general aviation and business aircraft are not equipped. Further, the PWS radars have limited range and scan-angle capability and cannot provide the broad area situational awareness needed to proactively reroute aircraft away from the affected runways. We considered in detail the alternative of using the ASR-9 Weather Systems Processor (WSP) and NEXRAD in lieu of TDWR. An objective metric for wind shear detection capability was calculated for each of these radars at all TDWR equipped airports. TDWR was uniformly superior by this metric, and at a number of the airports, the ASR-9/NEXRAD alternative scored so low as to raise questions whether it would be operationally acceptable. To assess airport weather delay reduction impact, we compared the accuracy of the high-benefit ITWS "Terminal Winds" product with and without TDWR input. Removal of the TDWR data would have increased the mean estimate error by a factor of 3 near the surface.

17. Key Words TDWR — ITWS Terminal Winds wind shear — WSP	18. Distribution Statement This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	66	

FORM DOT F 1700.7 (8-72) Reproduction of completed page authorized

ABSTRACT

The Terminal Doppler Weather Radar (TDWR) was developed in response to a series of commercial aircraft wind shear accidents in the 1970s and 1980s. In parallel, improved versions of the Low Level Wind Shear Alert System (LLWAS) and a Weather Systems Processor (WSP) modification for existing Airport Surveillance Radars (ASR-9) were developed to detect wind shear at smaller airports. On-board wind shear detection equipment was mandated for Part 121 aircraft, and more effective training for pilots and air traffic controllers was instituted. As a result of these steps, there has not been a commercial aircraft accident attributed to wind shear since 1994.

Because of the substantial costs associated with operating and maintaining the U.S. network of 45 operational TDWRs, the FAA has requested that Lincoln Laboratory assess the technical and operational viability of alternative approaches to the low-altitude wind shear hazard. Airborne predictive wind shear (PWS) radars do not provide an acceptable alternative because many commercial aircraft, and practically all general aviation and business aircraft, are not equipped. Further, the PWS radars have limited range and scan-angle capability and cannot provide the broad area situational awareness needed to proactively reroute aircraft away from wind shear. We considered in detail the alternative of substituting ASR-9 WSP and NEXRAD derived wind shear detections for those currently provided by the TDWR. An objective metric for wind shear detection capability was calculated for each of these radars at all TDWR-equipped airports. TDWR was uniformly superior by this metric, and at more than 10 of the airports, the ASR-9/NEXRAD alternative scored sufficiently low as to raise questions whether the alternative would be operationally acceptable. Results from field measurement programs are presented that are consistent with this analysis. Finally we interviewed ATC personnel at both TDWR and ASR-9 WSP equipped airports. Although both systems were regarded as providing operationally acceptable performance, the responses indicated a generally higher level of confidence in the wind shear products at TDWR-equipped airports, and higher usage of the gust front planning product.

Because of its near-airport siting and high-resolution antenna beam, TDWR provides a unique capability to observe low-altitude wind and precipitation conditions affecting airport operations. We evaluated the associated operational benefits by focusing on the Integrated Terminal Weather System (ITWS) "Terminal Winds" product which has been shown to substantially reduce delays during adverse wind conditions at high-density airports. Analysis and case studies show clearly that removal of TDWR input from ITWS would substantially degrade the accuracy of this product.

Finally, we considered the role of TDWR in supporting future terminal weather capabilities including wind-dependent wake vortex separation procedures and hazardous low-altitude turbulence detection. Our assessment clearly indicates that the superior low-altitude coverage and near-airport resolution of TDWR will provide higher capability than could be achieved with the alternative ground-based system.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
(Continued)

LIST OF TABLES

1. INTRODUCTION

The Terminal Doppler Weather Radar (TDWR) was developed in response to a series of commercial aircraft wind shear accidents in the 1970s and 1980s (Table 1). In aggregate, these resulted in over 400 fatalities and pressure on the FAA to develop effective warning technologies. An aggressive development and implementation program led to operational deployment of the TDWR at 45 airports during the 1990s. In parallel, improved versions of the Low Level Wind Shear Alert System (LLWAS) and a Weather Systems Processor (WSP) modification for existing Airport Surveillance Radars (ASR-9) were developed to provide similar warning services at smaller airports.

To date, there has not been a wind shear related accident at an airport where one of these modern wind shear detection systems is in operation. Most experts believe that this reflects a combination of circumstances including, but not confined to, deployment of the ground-based warning systems. Improved pilot awareness of the meteorological conditions in which wind shear occurs and associated visual cues, as well as extensive pilot training on recovery procedures are clearly factors. All Part 121 aircraft are now equipped with either "reactive" or "predictive" on-board wind shear detection equipment. These either assist the pilot in recovery when wind shear is encountered, or provide short lead-time warnings that the aircraft is approaching wind shear. Finally, deployment of the ground-based systems and associated training have enhanced air traffic controller awareness of wind shear and their ability to provide pro-active advisories to pilots.

While weather-related accidents have decreased in frequency, flight delays caused by adverse weather are growing rapidly. Figure 1, which depicts monthly OPSNET delays for the last decade, emphasizes that delays have grown with demand—maximizing in 2000 and again in 2005/2006—and increase markedly during the summer when thunderstorms disrupt the orderly flow of traffic in terminal and en route airspace. The Integrated Terminal Weather System (ITWS) was developed to provide a common, high-quality depiction of operationally important weather conditions in terminal airspace including thunderstorms, wind shear, lightning and non-hazardous, but operationally significant, wind and winter precipitation conditions. FAA and airline Traffic Flow Management (TFM) specialists have realized substantial flight delay reductions by exploiting ITWS products to proactively adjust traffic flows to minimize the adverse weather's impact (Allan et al., 2001; Allan and Evans, 2005). TDWR is a key input to ITWS owing to its unique capability to accurately measure precipitation and winds in critical, low-altitude airspace near airports.

TABLE 1

Passenger-Airline Accidents From 1975 to 1994 in the United States Attributed To Low Altitude Wind Shear

Date	Location	Aircraft	Fatalities	Injuries	Uninjured
24 June 1975	Jamaica, NY	Boeing 727	112	12	0
7 Aug. 1975	Denver, CO	Boeing 727	0	15	119
23 June 1976	Philadelphia, PA	McDonnell-Douglas DC-9	0	86	20
3 June 1977	Tucson, AZ	Boeing 727	0	0	91
21 May 1982	Dayton, OH	BAC 1-11	0	0	48
9 July 1982	New Orleans, LA	Boeing 727	153	9	7
28 July 1982	Flushing, NY	Boeing 727	0	0	129
31 May 1984	Denver, CO	Boeing 727	0	0	105
13 June 1984	Detroit, MI	McDonnell-Douglas DC-9	0	10	46
2 Aug. 1985	Dallas/Ft. Worth, TX	Lockheed L-1011	135	28	2
11 July 1987	Washington, DC	Boeing 727	0	0	87
15 Sept. 1987	Tulsa, OK	Boeing 727	0	0	62
3 Nov. 1987	Orlando, FL	Lear Jet 35A	0	0	5
1 June 1988	Jamaica, NY	Boeing 747	0	0	157
26 Apr. 1989	Mt. Zion, IL	Cessna 208A	0	1	0
22 Nov. 1989	Beaumont, TX	Saab-Fairchild 340A	0	0	37
18 Feb. 1991	Thornton, TX	Cessna 172N	1	0	0
14 Feb. 1992	Lanai, HI	Beech D-18H	0	0	1
7 Jan. 1993	Akutan, AK	Grumman G-21A	0	0	8
26 Apr. 1993	Denver, CO	McDonnell-Douglas DC-9	0	0	90
2 July 1994	Charlotte, NC	McDonnell-Douglas DC-9	37	20	0

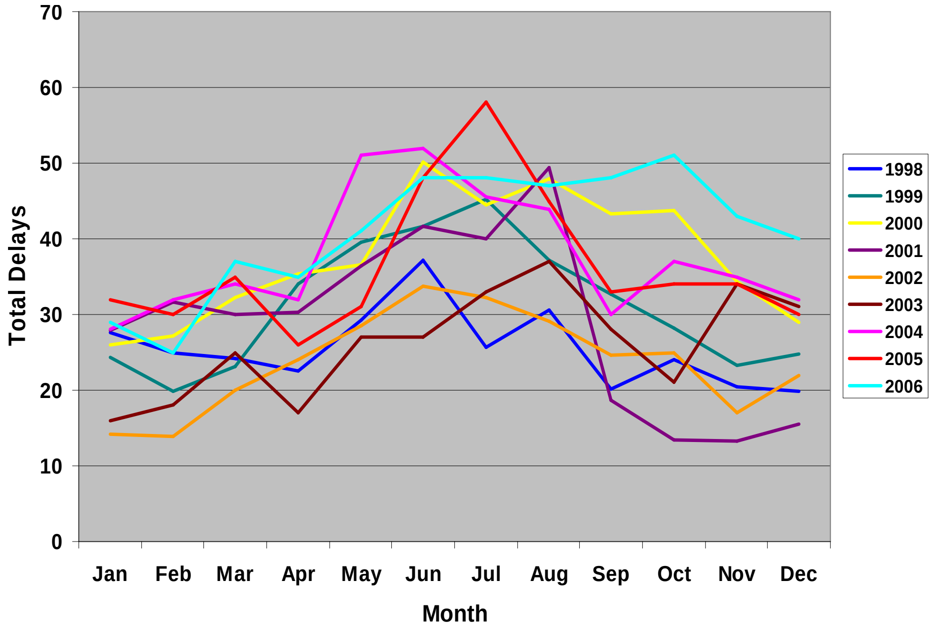


Figure 1. OPSNET delays (thousands of aircraft) by month for the period 1998–2006.

The costs of operating, maintaining and upgrading the dedicated TDWR are high, however. In addition to recurring costs associated with site- and second-level engineering support, substantial non-recurring costs accrue from hardware, processor and software upgrades which are necessary to assure long-term TDWR operational availability. The FAA is currently executing a multi-year Service Life Extension Program (SLEP) for TDWR that addresses many of its major subsystems, including the antenna drive mechanism, signal- and data-processing computers and user displays.

In this report, we examine the technical and operational impacts of a potential cost-saving strategy that would utilize existing national radar networks—specifically, the ASR-9 augmented with the Weather Systems Processor (WSP) and NEXRAD—in lieu of TDWR to provide terminal weather services at large U.S. airports. Where appropriate, we discuss the economic value of services provided by TDWR. This report does not, however, provide a comprehensive "cost-benefit" analysis. Rather our goal is to articulate the operational benefits that result from TDWR unique technical parameters and to project the operational capability "delta's" that would result from the removal of these radars.

Section 2 discusses relevant technical and operational changes that have occurred since the decision to deploy TDWR was made over 20 years ago. This includes a discussion of relevant technologies (ground-based and airborne wind shear detection systems, ITWS) and of evolution in operational needs—particularly at congested, "pacing" airports. In Section 3, we summarize a technical analysis of the alternative strategy discussed above for providing terminal weather services at large airports. Section 4 discusses our findings from interviews on terminal weather system operational usage at 20 medium-to-large U.S. airports equipped with WSP, TDWR or TDWR/ITWS. A brief discussion of potential future terminal weather applications where the availability of TDWR data would have a performance impact is presented in Section 5. We summarize our findings and recommendations in Section 6.

2. OPERATIONAL ENVIRONMENT EVOLUTION

The decision to deploy TDWR took place at a time when three major wind shear related accidents had occurred in the preceding decade. At that time, the only ground-based wind shear detection system – the six station Low Level Wind Shear Alert System (LLWAS-2)—was essentially useless for the detection of the most hazardous wind shear phenomena, the microburst, and no effective on-board wind shear detection or recovery systems were deployed. The pilot and air traffic controller community was largely untrained in recognizing and responding to wind shear—indeed, scientific understanding of wind shear phenomena was based largely on a small number of field programs at two sites (Denver and the upper Midwest). Finally, U.S. commercial aviation operations rates were approximately 1/3 lower than they are today and weather-related delay was not considered to be a major problem.

In the intervening 20 years, all of these circumstances have changed significantly. In this section, we provide background information on changes that are relevant to the operational role of TDWR.

2.1 GROUND-BASED WIND SHEAR SYSTEMS

Today, approximately 120 U.S. commercial airports subject to thunderstorm wind shear conditions are equipped with an effective ground-based warning system (Figure 2). As a complement to TDWR, the ASR-9 Weather Systems Processor (WSP) was developed by the FAA, Lincoln Laboratory and Northrop Grumman Corporation and deployed at 34 medium density airports during the period 2002-2005. Although the ASR-9 does not have the high-resolution “pencil beam” antenna pattern characteristic of weather radars, when augmented with the WSP it has been shown to provide operationally effective wind shear detection capability at short ranges (less than about 15 nmi), as well as the capability to measure thunderstorm locations, intensity and movement over the full 60 nmi instrumented range of the ASR-9. Metrics for the wind shear detection capability of the WSP, based on field measurement programs, are discussed in detail in Weber et al. (1996) and Weber (2007). Subsequent sections of this report provide direct technical comparisons of WSP and TDWR for wind shear detection capability. Results of an assessment of the terminal delay aversion benefits of WSP are presented by Rhoda and Weber [1996].

The Low Level Wind Shear Alert System’s anemometer network design, sensor siting criteria and processing algorithms were extensively reworked in the 1980’s and early 1990’s in order to provide effective detection of both microburst and gust front wind shear occurring within the network (Wilson and Gramzow, 1991). This work led to the LLWAS relocation and sustainment (LLWAS-RS) procurement from Climatronics for 40 small to medium density airports as shown in Figure 2. LLWAS-RS provides excellent detection of wind shear occurring within its network, as long as all anemometers are working properly. In contrast to the radar-based systems which provide wind shear coverage over the entire area in which planes are at risk (i.e., 3 miles beyond the runway thresholds), cost and land-acquisition issues typically limit LLWAS network coverage to the runways and perhaps the 1-mile approach/departure zones beyond the runway thresholds.

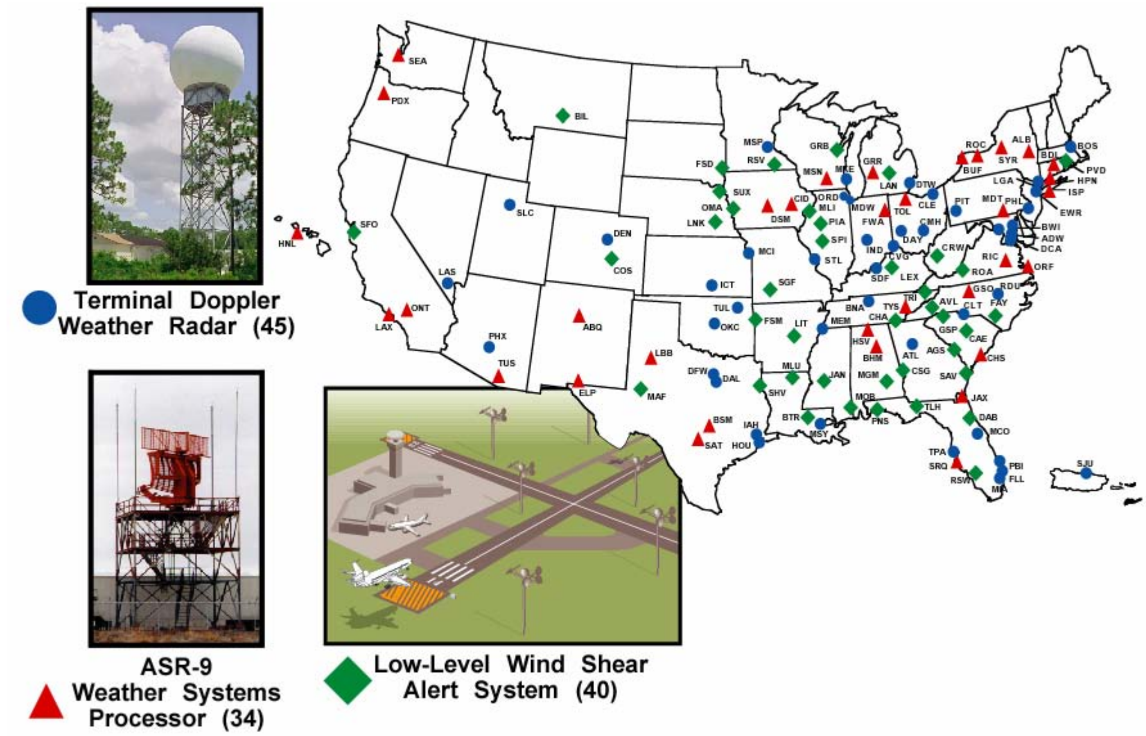


Figure 2. U.S. ground-based wind shear detection systems.

Finally, nine of the TDWR equipped airports also have a large LLWAS that is integrated with the radar system. This “network expansion” LLWAS (LLWAS-NE) assists in the detection of very dry wind shear at one such airport (Denver) and at the remaining sites is valuable in detecting events whose strongest velocities are not aligned with the radar line of site (Miller et al., 2002).

2.2 AIRBORNE WIND SHEAR DETECTION SYSTEMS

Federal Acquisition Rule (FAR) 121.358, issued on 9 May 1990, required that all Part 121 aircraft be equipped with either a “reactive” wind shear warning and flight guidance system or a “predictive” wind shear (PWS) radar. The reactive system technology was developed in the mid-1980’s by Boeing and Sperry and certified by the FAA in November 1985 as an enhancement to onboard Performance Management Systems (PMS). Primary inputs are true airspeed, angle of attack, longitudinal acceleration, normal acceleration and pitch. Performance was certified using computer models representing documented wind shear conditions. Figure 3 illustrates this systems response to a notional wind shear encounter, as well as the flight-deck indicators activated by the system.

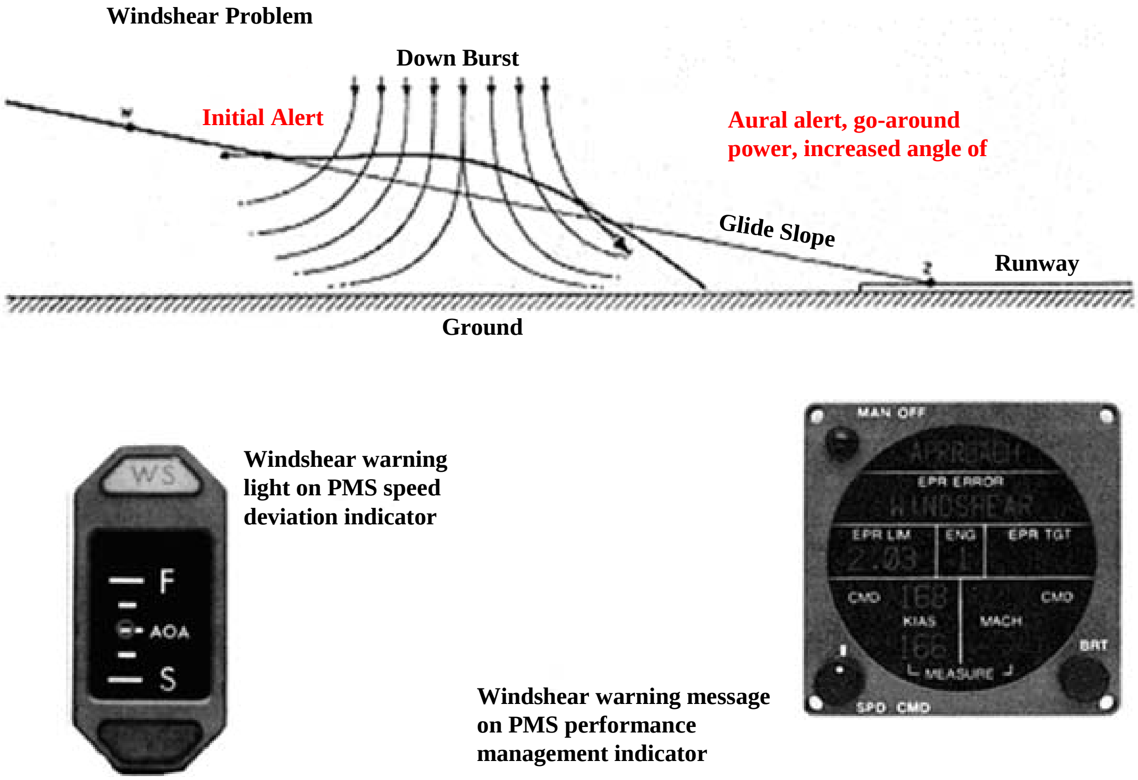


Figure 3. Notional "reactive system" wind shear encounter scenario and associated warning messages on PMS indicators.

Predictive wind shear warning systems were developed in the early 1990s by NASA Langley Research Center. Microwave radar, lidar and passive infrared detection systems were evaluated through simulations and flight testing in conjunction with FAA prototype testing of TDWR in Denver, CO, and Orlando, FL. The first microwave PWS radar was certified by FAA in September 1994 and today several systems are available for Part 121 aircraft (e.g., the Rockwell-Collins WXR-700 and the Honeywell, RDR-4B). PWS radars compatible with regional jet size constraints are not available at present. Figure 4 illustrates a wind shear encounter timeline for a PWS. Note that the warning horizon with these systems is extended to many 10's of seconds.

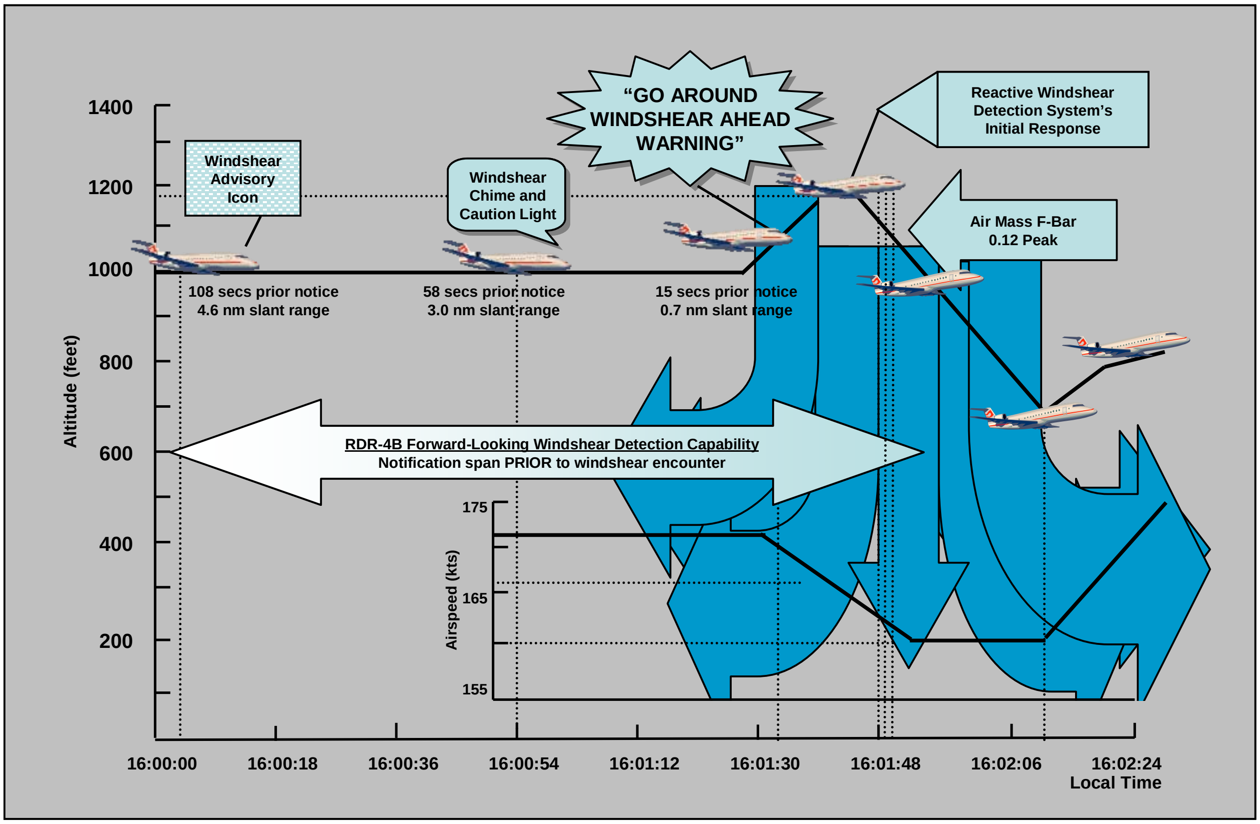


Figure 4. Notional PWS radar wind shear encounter scenario.

At the request of the FAA's Terminal Business Service organization, the lead author poled airline industry and PWS manufacturer personnel to estimate the percentage of the commercial fleet currently equipped with PWS radars, and to obtain feedback on the operational value of both reactive systems and PWS radars. Table 2 shows that approximately ½ of the U.S. commercial part 121 fleet was equipped with PWS radars at the time of this survey (September 2005). The equipage rate is increasing at a moderate pace as older aircraft are replaced by PWS-equipped new Boeing or Airbus aircraft. Although manufacturers are evaluating the option to develop RJ-compatible PWS systems, there is no guarantee that this will be feasible given radar antenna-size constraints for this aircraft class.

The authors note that field validation of the reactive wind shear systems and PWS radars has not been nearly as extensive as was accomplished for the FAA ground-based warning systems. Manufacturers continue to do some flight testing, but certification has been accomplished entirely through computer simulated microburst penetration data. The airline users we spoke with generally felt that the PWS radars were useful, but they uniformly emphasized that these were not a substitute for the ground-based systems. Broad-area situational awareness of wind shear—not attainable with the limited range, on-board systems—was felt to be essential for minimizing encounter risk. The reactive windshear systems were stated to be ineffective by those users who commented on their performance.

TABLE 2

U.S. Part 121 Fleet Equipage Percentages For PWS Radars, Based on a Telephone Poll of Industry Representatives in September 2005

Carrier	Total Fleet Size	Fleet with PWS	% Equipped
American	840	122	15
Delta	490	286	58
United*	494	250	51
Northwest	441	41	9
Southwest	429	215	50
Continental	348	348	100
USAirways	266	266	100
AirTran	93	93	100
Jet Blue	77	77	100
Totals	3478	1698	49

2.3 INTEGRATED TERMINAL WEATHER SYSTEM

During operational prototype testing of the Terminal Doppler Weather Radar, researchers recognized that thunderstorm situational awareness provided by the radar's broad area surveillance allowed terminal air traffic controllers to improve decision making relative to openings/closings of runways, arrival and departure fixes and other critical airspace assets. These insights spurred development of the Integrated Terminal Weather System (Evans and Ducot, 1994) which was originally tested at moderate density airports in the southern U.S. such as Orlando, FL and Memphis, TN. At these airports, thunderstorms are a dominant cause for delay and the primary operational benefits of ITWS resulted from its depiction and forecasts of their location, intensity and movement. TDWR data are the basis for the wind shear products provided by ITWS; additional thunderstorm related products (e.g., current locations, movement and 0–1 hour forecasts) are derived from ASR-9 and NEXRAD precipitation reflectivity measurements.

Subsequent ITWS prototype operations at New York City's airports provided the opportunity to assess the delay issues associated with weather impacts on highly congested airspace in the northeastern U.S. (Allan et al., 2001). From both a meteorological and operational perspective, the New York City airports are representative of many of the high value terminal areas served by ITWS and TDWR (e.g., ORD, BOS, PHL, Washington, DC airports). Figure 5, showing annual airport delays at major U.S. airports over the period 2000–2005, indicates that 7 of the 10 most delayed airports are in the northeastern quadrant of the U.S.

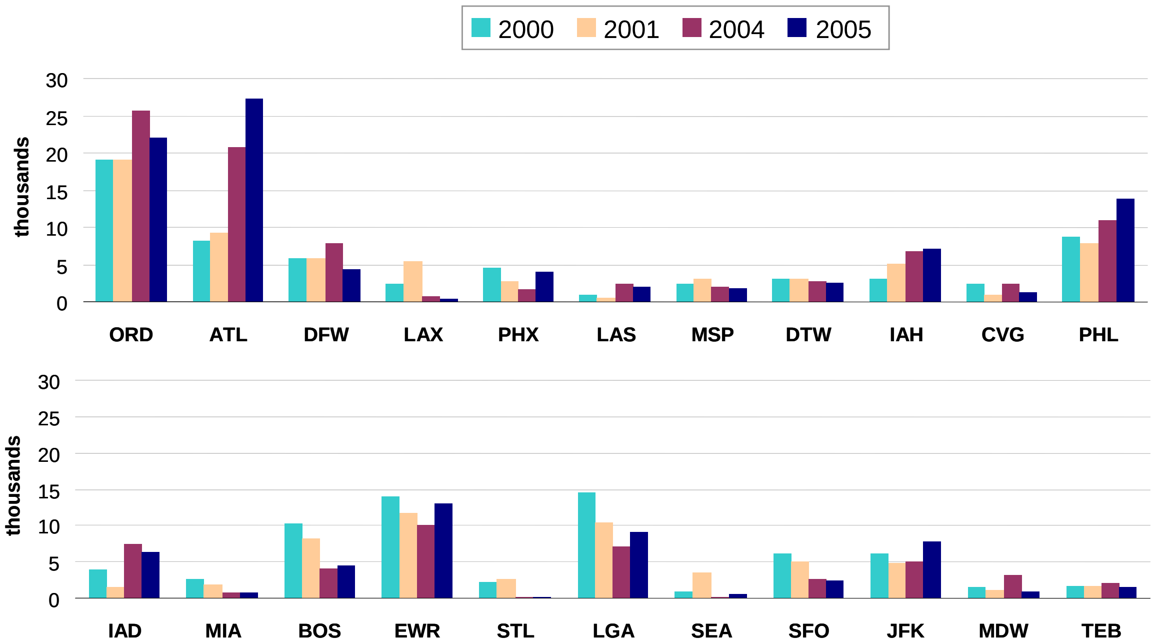


Figure 5. Annual airport delays (thousands of aircraft) at major U.S. airports, ordered by airport total operations. From Lamon (Nextor Workshop, 2006).

Allan's et al. (2001) evaluation of weather delay causality at Newark airport (EWR) is summarized in Figure 6. Although local and en route thunderstorms are major contributors, non-convective weather impacts (reduced ceiling and visibility, high winds, sharp vertical variations in wind, and winter precipitation) are also significant. Airport ceiling and visibility restrictions in the northeastern U.S. are often associated with large-scale, winter storm systems and associated precipitation. High winds, often varying rapidly with altitude make it difficult to maintain precise separation between aircraft in approach streams. This can result in significant reductions in terminal arrival rates, particularly when wind direction at the surface prevents use of efficient runway configurations.

Similar findings for Atlanta are reported by Allan and Evans (2005). Terminal and en route thunderstorms are a dominant cause for delay during the spring and summer months (May–September). During the cool season, ceiling and visibility restrictions, high surface winds and sharp vertical shear in the horizontal winds have significant impact.

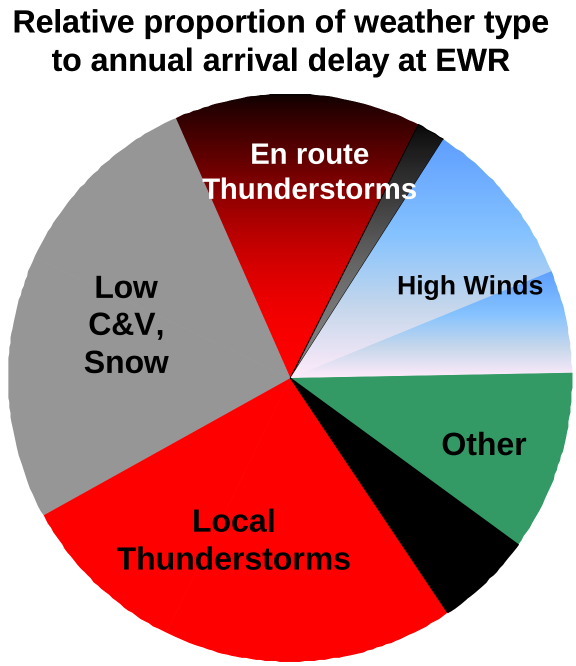


Figure 6. Causality of delay at Newark International Airport.

It is important to note that detection and forecasting of many of these meteorological phenomena requires observations at very low altitudes. Low altitude wind shears and runway wind shifts caused by thunderstorms can result in large disruptions to terminal operations. These are small in scale, and observable only within approximately 1000 feet of the surface. Operationally significant airport visibility restrictions can be inferred in many cases through the detection and tracking of areas of drizzle or snow. (Clark 2006). Likewise, winter weather impacts on airport operations (de-icing, snow removal) can be forecast by tracking the movement of areas of snow. Cloud bases for winter systems responsible for ceiling, visibility and snow impacts at eastern U.S. airports are typically 2000'.

In the context of ITWS, a key benefit of TDWR has been its ability to provide precisely the type of accurate, low-altitude observations needed to observe and forecast these high-impact phenomena. An example ITWS product that relies heavily on TDWR data is "Terminal Winds (TWINDS)." A three-dimensional (3D) gridded wind-field product for the region around the airport, TWINDS optimally combines data from a numerical weather prediction model, Doppler weather radars, ground stations, and aircraft reports. Current operational usage of TWINDS is discussed in Allan et al. (2001) and in Section 4 of this report. In the future, TWINDS may also be used for weather adaptive adjustments of wake turbulence separation requirements, to generate aircraft-path-based alerts of strong shear/turbulence segments, and to provide improved wind-field analysis input for gust-front/wind shift detection at airports. The annual estimated operational benefit of TWINDS for the New York City region (including direct operational costs and passenger time savings) is $62 million (Allan et al., 2001). For Atlanta, the figure is $3 million (Allan and Evans 2005). Benefits appropriately scaled from these two studies for some other high-delay airports are shown in Table 3. The total annual TWINDS cost benefit for just these airports is over $130 million.

TABLE 3

Estimated TWINDS Annual Benefit At Major U.S. Airports

Airport	Delay Savings (hrs)	Cost Savings ($M)
EWR, JFK, LGA	18,000	62
ORD	5,400	29
BOS	3,200	17
PHL	3,200	17
DFW	540	3
ATL	540	3

3. TECHNICAL COMPARISON OF TDWR WITH ALTERNATIVES

In this section, we provide a technical comparison of TDWR with the proposed alternative sensor configuration involving ASR-9 (augmented with WSP) and NEXRAD. Where suitably sited, NEXRAD could potentially provide airport wind shear detection services. A gust front detection algorithm has been implemented in NEXRAD (Smalley et al., 2005) and in principal a microburst detection algorithm could also be inserted. The latter would require that NEXRADs scan strategy be modified to include more frequent (~1 minute) surface scan strategies.

TDWRs two critical operational missions are treated: (1) low-altitude wind-shear detection; and (2) as an input to the Integrated Terminal Weather System (ITWS). For the second mission, we focus on the Terminal Winds (TWINDS) product as this is representative of current (or potential future) high-value ITWS products that utilize TDWRs high-quality, low-altitude wind and precipitation measurements. Details of the analysis and airport specific findings are presented in the companion report by Cho and Martin (2007).

3.1 AIRPORT VIEWING GEOMETRY

TDWR is typically sited 10 to 20 km from the airport it protects. This provides an appropriate compromise between low altitude coverage near the airport, mitigation of “radar cone of silence” issues and the ability to measure the headwind/tailwind shear experienced by aircraft flying along principal extended runway centerlines. Although the TDWR produces base data out to a range of 90 km from the radar, its microburst and gust-front products only extend to 60 km from the airport, and wind-shear alerts are only generated within an approximately 10 km region around the airport. While the alert region is most critical for flight safety, the longer-range products (e.g., approaching wind shifts) are very useful for planning that can lead to delay reduction. We will divide our analysis results into near- (0–10 km) and far-range (10–60 km) categories.

Wind-shear phenomena hazardous to aircraft that are landing at and taking off from an airport are at low altitude, especially microburst outflows. Therefore, there must be a requirement for minimum observable height above the airport. The further the radar is from the airport, the less it will be able to see near the ground due to the earth’s curvature. TDWRs can see at least down to 400 ft AGL at all associated airports (Figure 7).

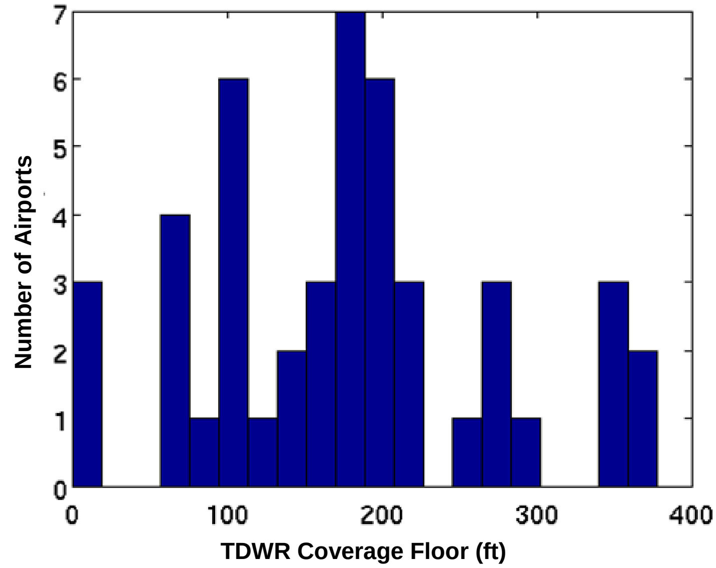


Figure 7. Histogram of minimum observable height above the airport ground level for all TDWRs.

Figure 8 shows corresponding minimum observable heights for the ASR-9 and NEXRAD that is nearest to each TDWR airport. The red and blue lines indicate the 400-ft height requirement. Of the 46 airports considered, two (West Palm Beach and San Juan) have neither an ASR-9 nor a NEXRAD close enough to provide the necessary low-altitude coverage. Of the remaining airports, 26 have alert-region coverage by an ASR-9 only and 18 have coverage by both ASR-9 and NEXRAD.

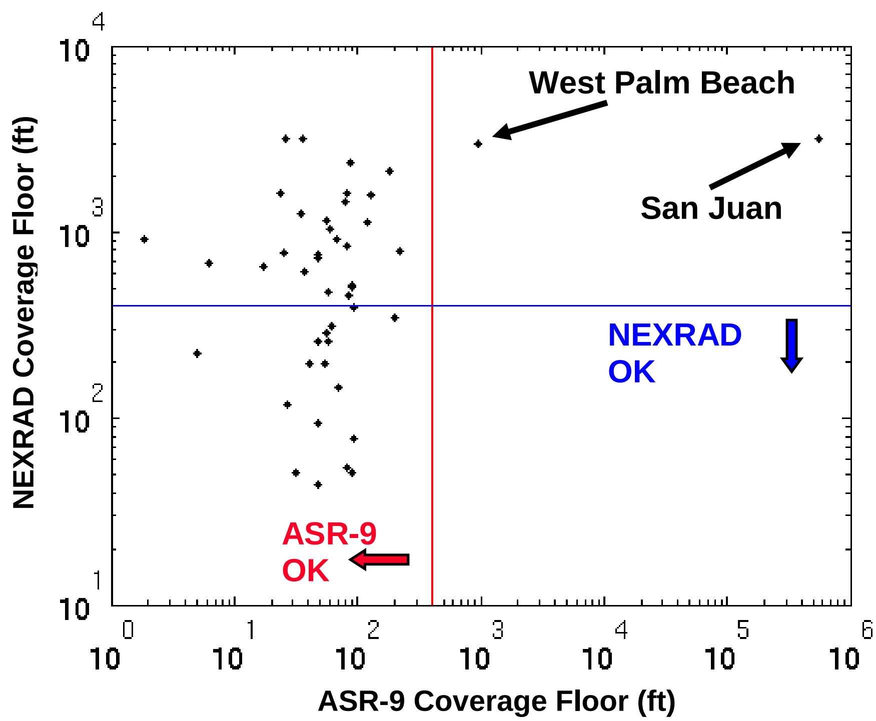


Figure 8. Minimum observable height above the airport ground level for the closest ASR-9 and NEXRAD to each TDWR airport.

Cho and Martin (2007) also evaluated terrain blockage for each TDWR and the corresponding ASR-9 and NEXRAD. Of the 46 airports, only 16 had any blockage for any radar, and in no cases was blockage of the safety-critical runways and approach/departure corridors significant.

We conclude that, with the exception of two current TDWR airports, existing ASR-9 and/or NEXRADs would provide acceptable line-of sight measurements at low altitudes.

3.2 MICROBURST AND GUST-FRONT VISIBILITY

We next assess the "visibility" of low altitude wind shear to each of these radars. We define visibility as the probability that the radar return from the wind-shear event is high enough in amplitude to be distinguished from noise and clutter. Visibility is different from probability of detection (P_d) in that the P_d is measured at the output of a signature recognition algorithm that must be able to distinguish the wind-shear signature from all other signals visible to the radar, while keeping the false-alarm rate at an acceptable level. Thus, wind-shear visibility is an upper bound for wind-shear P_d.

To calculate wind shear visibility for each airport, we compared measured distributions of wind shear radar reflectivity with the TDWR, ASR-9 or NEXRAD parameters that determine the sensitivity of each radar. The signal-to-noise ratio for wind shear depends on range so radar location must be taken into account. The calculated visibility is averaged over the specified near- and far-range airport coverage areas. At times, ground clutter is the main hindrance to visibility rather than the receiver noise. To account for these cases, a separate calculation was performed using measured distributions of airport ground clutter intensity and the radars' clutter suppression capabilities. Finally, a joint visibility value was calculated for the noise-limited and the clutter-limited cases. The technical details of the procedure are presented in Cho and Martin (2007).

The radar system characteristics are listed in Table 4. The "bottom line" is weather sensitivity, which is computed as $P\tau G^2\Delta\theta\Delta\phi/\lambda^2$, where P is the peak transmitter power, τ is the pulse length, G is the antenna gain, $\Delta\theta$ is the elevation beamwidth, $\Delta\phi$ is the azimuthal beamwidth, and λ is the wavelength. The ASR-9 is nearly 20 dB less sensitive than the TDWR, while the NEXRAD is only 4 dB less sensitive. However, this metric does not include other factors that make the ASR-9 WSP and NEXRAD (especially the former) even less sensitive to low-altitude wind-shear events than the TDWR. A wider elevation beam means that phenomena confined near the ground (like microbursts and gust fronts) will fill a smaller fraction the beam, which makes the classical weather sensitivity metric an overestimate. Also, a weaker clutter suppression capability leads to lower visibility in clutter-limited environments. And a smaller number of pulses per coherent processing interval (CPI) results in increased base data variance. All of these factors are taken into account in computing visibility.

TABLE 4

Radar System Parameters

Parameter	TDWR	ASR-9 WSP	NEXRAD
Peak Power (kW)	250	1120	750
Pulse Length (µs)	1.1	1	1.6
Antenna Gain (dB)	50	34	45.5
Beamwidth (Az x El)	0.55° × 0.55°	1.4° × 4.8°	0.925° × 0.925°
Wavelength (cm)	5.4	11	10.5
Max. Clutter Suppression (dB)	60*	48	50
Rotation Rate (°/s)	~ 20	75	~ 20
CPI Pulses	~ 80	26	~ 50
Weather Sensitivity (dB)	115	96	111

*After radar data acquisition (RDA) system upgrade (Cho et al., 2005).

The resulting airport wind-shear average visibilities are sorted according to whether or not the airport is subject to frequent low radar reflectivity, "dry" microbursts, and whether or not the closest NEXRAD provides necessary low-altitude coverage for the airport alert region (near-range). The median values for each of the airport categories are tabulated in Tables 5 through 8. West Palm Beach and San Juan data were not included in these medians, since these airports do not have low-altitude alert region coverage by an ASR-9 or a NEXRAD. We have somewhat arbitrarily assigned a color coding scheme of green (>90%), yellow (80–90%), and red (<80%) to the alert-area results based on the FAA goal of 90% P_d for wind-shear events within this region (FAA 1987). (In practice, this "requirement" has only been applied to microburst detection and not gust-front detection, but for the purposes of this report we will reference this figure as a target for both wind-shear categories in the alert region.) In fact, a visibility of well above 90% would be needed, since the visibility is only an upper bound for the P_d.

As expected, the TDWR microburst and gust-front visibility is high in the 0–10 km range alert region. These are the categories most vital for safety concerns. It also does extremely well for gust-front visibility at far ranges for wet sites. For dry sites at far range, the numbers are down significantly due to the extensive terrain blockage at those sites. Gust-front tracking throughout all ranges is most useful for traffic management, i.e., for delay reduction. Microburst detection beyond the near-range alert area is not an FAA requirement, so those numbers are not as important.

TABLE 5

Visibility for Wet Sites Without NEXRAD Alert Region Coverage (23 Sites)

Shear Type	Radius Around Airport					
	0 – 10 km			10 – 60 km		
	TDWR	ASR-9	NEXRAD	TDWR	ASR-9	NEXRAD
Microburst	100	93	0	68	27	28
Gust Front	98	88	80	97	3	50

TABLE 6

Visibility for Wet Sites With NEXRAD Alert Region Coverage (17 Sites)

Shear Type	Radius Around Airport					
	0 – 10 km			10 – 60 km		
	TDWR	ASR-9	NEXRAD	TDWR	ASR-9	NEXRAD
Microburst	100	93	99	68	28	63
Gust Front	98	89	99	97	3	85

TABLE 7

Visibility for Dry Sites Without NEXRAD Alert Region Coverage (3 Sites)

Shear Type	Radius Around Airport					
	0 – 10 km			10 – 60 km		
	TDWR	ASR-9	NEXRAD	TDWR	ASR-9	NEXRAD
Microburst	91	38	0	19	0	0
Gust Front	91	81	0	28	0	0

TABLE 8

Visibility for Dry Sites With NEXRAD Alert Region Coverage (1 Site)

Shear Type	Radius Around Airport					
	0 – 10 km			10 – 60 km		
	TDWR	ASR-9	NEXRAD	TDWR	ASR-9	NEXRAD
Microburst	95	41	93	31	0	40
Gust Front	99	87	95	80	3	82

At wet sites, ASR-9 WSP visibility for microbursts and gust fronts over the airport is also good, although lower than is the case for the other radars. At longer ranges, and at all ranges at "dry sites," the ASR-9's suboptimal parameters reduce the average visibility for wind shear events to values much lower than for the other radars.

NEXRAD, which is comparable in sensitivity to TDWR, has wind-shear visibility values that vary mainly with distance to the airport. If it is close enough, it has visibility that is similar to the TDWR, although at far ranges the additional beam-filling loss associated with its wider elevation beam degrades its performance relative to the TDWR. Note that even though its visibility in the alert region can be excellent, NEXRAD volume scan patterns would need to be modified to provide more frequent near-surface scans for microburst detection.

Cho and Martin (2007) present the airport-by-airport average wind shear visibilities that are summarized in Tables 5–8. For the TDWR, all near-airport microburst visibilities are above 90%, except at SLC (85%). In fact, case studies by scientists at the FAA's TDWR Program Support Facility (PSF) have shown that the microburst P_d at SLC is about 83%. This lower-than-desired figure, resulting from frequent "dry" wind shear phenomena and difficult terrain clutter and blockage, has generated much discussion about how to improve it.

Cho and Martin (2007) use the 90% visibility threshold as a means of picking out airports that could be left with unsatisfactory microburst alert capability if the TDWRs were decommissioned. If only the ASR-9 WSP is considered as an alternative to TDWR, then the following airports would not have 90% or greater average microburst visibility in the alert region: BOS, DAL, DCA, DEN, EWR, LAS, LGA, MDW, PBI, PHX, SDF, SJU, and SLC. If we assume that NEXRAD scan strategies could be modified to support airport microburst detection, then DEN, MDW and SDF would not be on this list. Included in these lists are 7 of the top 20 busiest airports in the United States in traffic movements (Airports Council International 2006): LAS (#5), DEN (#7), PHX (#8), SLC (#15), EWR (#16), BOS (#18), and LGA (#19). Note also that 2 out of 3 New York City area airports are on the list as well as the primary airport serving the nation's capital. Thus, even though these airports constitute a minority of the 46 airports served by TDWR, the overall negative impact on flight safety would be quite significant.

For gust-front/wind-shift detection and tracking at 10–60 km, the TDWR provides good visibility (>80%) at 38 airports. Assuming that NEXRAD data could be used for this task, only 15 airports would retain the same or better level of visibility, which is a reduction of 61% in the number of airports with high quality, long-range gust-front products.

3.3 IMPACT ON ITWS ALGORITHMS

As noted, the ITWS terminal winds product (TWINDS) provides a substantial delay reduction benefit and is representative of terminal area weather services that benefit from the TDWR low-altitude coverage and good vertical resolution in the airport region. In this section we summarize our assessment of the impact of removing TDWR as an input to TWINDS. The reader is again referred to Cho and Martin (2007) for details.

TWINDS assimilates data from the Rapid Update Cycle (RUC) numerical weather prediction model, TDWR, NEXRAD, aircraft weather reports, and ground observation sensors to produce a high-resolution gridded wind field in the terminal area (Cole and Wilson 1994). The errors in the output winds are dependent on the errors of the input data combined with geometric factors and displacement errors.

Figure 9 illustrates the impact of TDWR data on TWINDS accuracy for the New York City terminal region. Figure 9 shows the vector wind estimate error for the 360-ft level with (right) and without (left) TDWR data as an input to TWINDS. Without the TDWR data input the vector wind error is mostly pegged to the RUC input error of ~7 ms^{-1}. One can see the influence of the closest NEXRADs barely coming into view from the southwest and east. However, without dual-Doppler overlap, the improvement is not great. With the TDWR data the errors are reduced to ~1 ms^{-1} in the near-terminal area. The overlap in coverage of the two TDWRs yields dual-Doppler information, which makes this dramatic improvement in vector wind error possible.

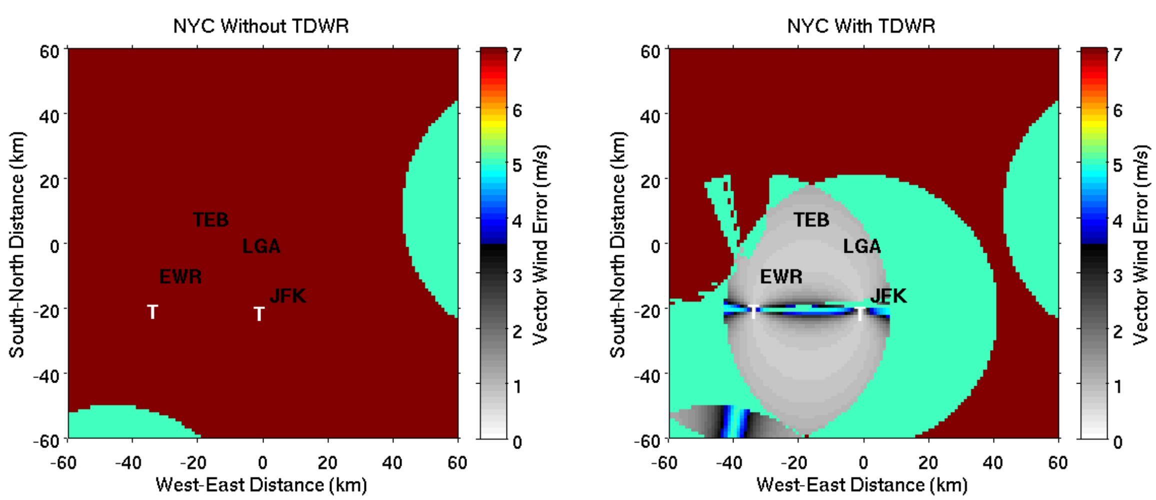


Figure 9. Vector wind error for the New York City region for the 1000-mb (360 ft MSL) level: (top left) without TDWR data, (top right) with TDWR data. TDWR locations are indicated by the "T"s.

The distribution of TWINDS vector wind errors averaged over an area around each of the TDWR airport are summarized in Figure 10. Again the difference between having and not having TDWR data as input to TWINDS is clear and substantial. Note that TWINDS does not currently ingest ASR-9 WSP data. This is due to the poor vertical resolution of the ASR-9 radar. There may be a limited contribution that WSP could make to TWINDS at very short range, but it cannot be expected to replace much of the coverage lost if TDWRs were to be eliminated.

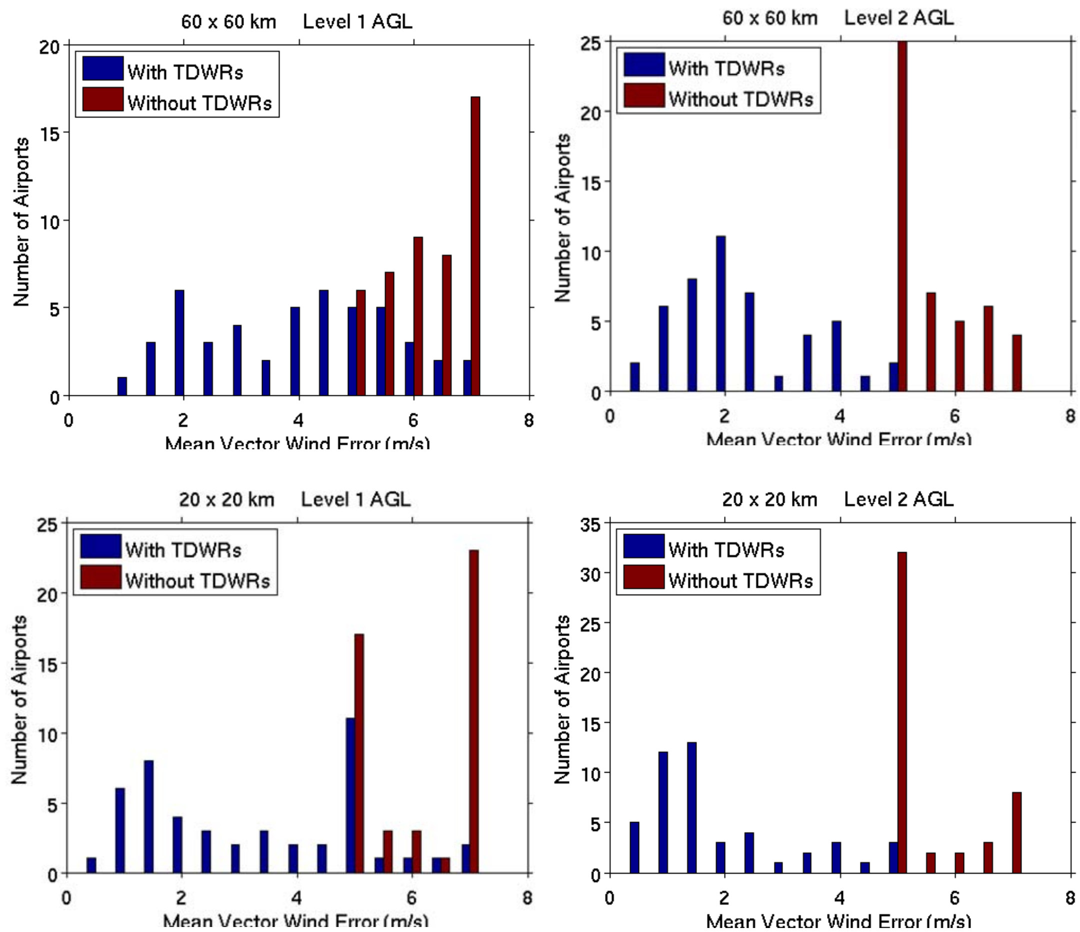


Figure 10. Vector wind errors averaged over a 60 × 60 km (top) and 20 × 20 km (bottom) domain around each TDWR airport for 360 ft (left) and 1000 ft (right) heights above the airport ground level.

Average TWINDS errors, with and without TDWR for all covered airports are listed in Cho and Martin (2007). The greatest loss in TWINDS accuracy is experienced at airports that are within ITWS domains that utilize data from multiple TDWRs: Chicago, Dallas, Houston, Miami, New York, and Washington, DC. These domains also include some of the highest delay-reduction benefit airports for TWINDS (see Table 3).

At higher altitudes, the NEXRADs that are located far away from the airport terminal area will be able to contribute more information to the TWINDS domain. However, even if the data from the maximum Doppler range are assumed to be available, the impact of losing TDWR data is substantial. This is because the addition of TDWR data allows the near-terminal domain to have extensive multi-Doppler coverage, which dramatically improves vector wind estimates. Figure 11 is a simple illustration of the effect removing TDWRs would have on multi-Doppler TWINDS coverage at selected major airports. Images are color coded by the number of radars that provide coverage (for maximum Doppler range) in a given geographical area. Notice the large reduction in multi-Doppler coverage that would occur in the near-terminal area without the TDWR. The situation is, of course, much worse at low altitudes, where the visibility range of the radars become much shorter than their maximum range. At the major hubs of New York City, Washington, DC, and Chicago, much of the multi-Doppler wind retrieval would only be facilitated by distant NEXRADs, providing little improvement in wind estimates over the RUC input at critical low altitudes. This reduction is most prevalent in the DC area, where four TDWRs are positioned inside the fine-analysis domain. The bottom line is that NEXRADs are spaced too far apart to provide adequate multi-Doppler coverage in the terminal area at most TDWR airports.

Cho and Martin (2007) examine three actual wind-shear cases and compare the TWINDS output with and without TDWR input data. The examples consist of a convective event in the Dallas area and two wind-shear events over the New York City airports. Results show that eliminating TDWR data input to the algorithm significantly reduces the TWINDS ability to properly resolve wind-shear events, especially at critical near-terminal low altitudes. Poor resolution of these types of near-terminal wind events can lead to an increase in operational costs as well as pose the risk of reducing a controller's ability to conduct safe operations.

3.4 FIELD MEASUREMENT PROGRAM RESULTS

Table 9 summarizes microburst and gust front detection performance metrics for real wind shear events. The TDWR statistics (Evans and Weber, 2000; Troxel et al., 1996) used data collected from operational TDWRs. Experienced radar meteorologists at Lincoln Laboratory and the FAA's TDWR Program Support Facility (PSF) manually examined the reflectivity and Doppler velocity imagery from the TDWRs to determine "truth"—that is, the presence and location of microburst or gust front events on a scan-by-scan basis. In some cases, the meteorologists could also use data from anemometer arrays and other Doppler weather radars to more accurately determine the location and severity of wind shear events. Probability of detection (P_d) is the scan-by-scan probability—updated every minute—that the TDWR microburst or gust front detection algorithm declared an event when one was determined to be present. Probability of false-alarm (P_{fa}) is the scan-by-scan tabulation of the probability that an alert is generated when a wind shear event is not present.

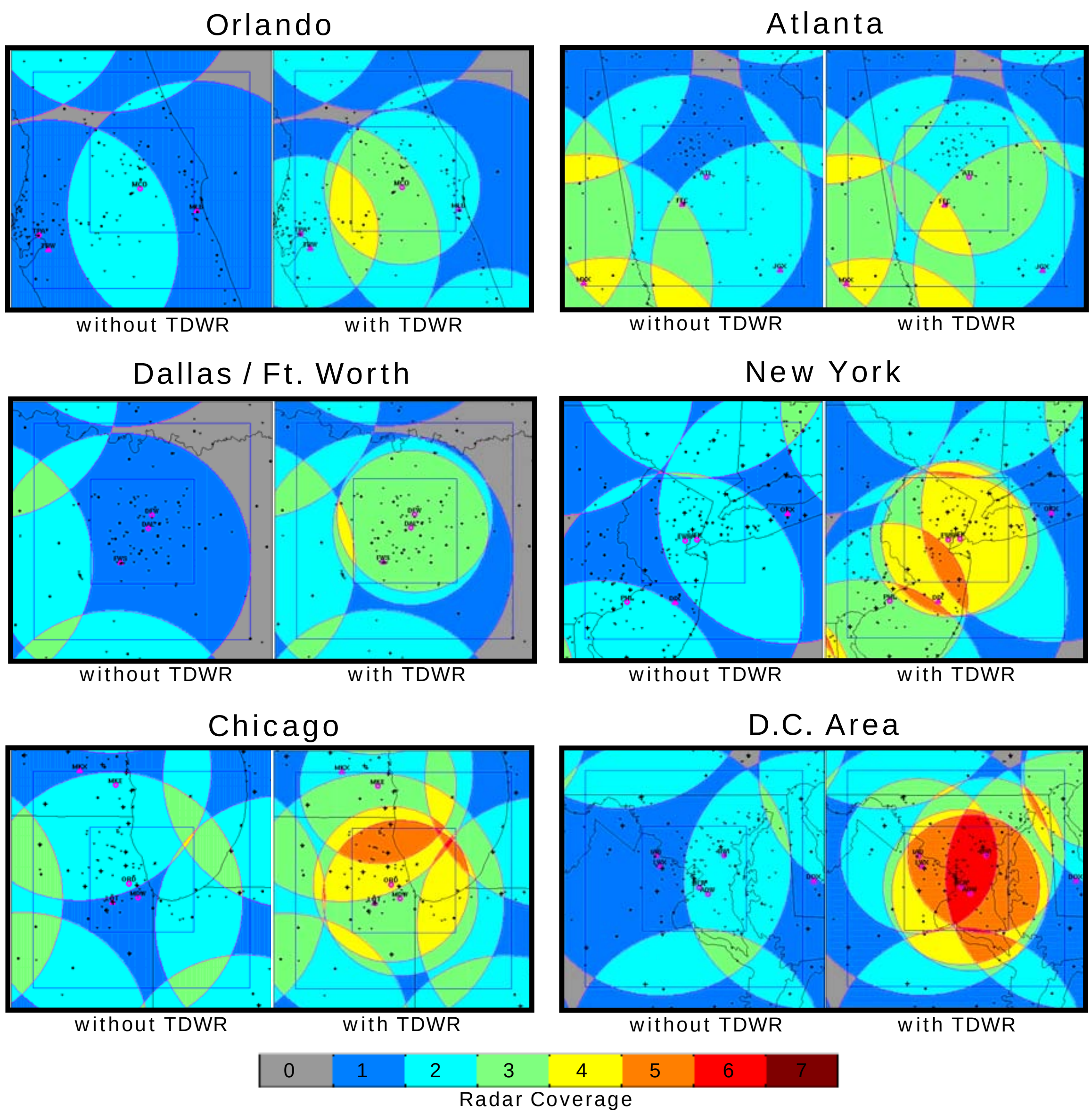


Figure 11. Radar coverage reduction that results from the exclusion of TDWRs. Maximum Doppler range is assumed. The color scale shows the number of radars providing coverage for a particular region. Left-side images of each comparison set show the reduction of coverage that result when only NEXRADs provide data input. Right-side images of the comparison sets include both NEXRADs and TDWRs.

TABLE 9

Field Measurements of Wind Shear Detection Performance for TDWR and WSP

The statistics are grouped according to the part of the U.S. in which data were analyzed. Summertime (*) and wintertime (+) statistics are shown separately for the Austin WSP data set.

Location/Date	TDWR Microburst P_d/P_{fa}	TDWR Gust Front P_d/P_{fa}	WSP Microburst P_d/P_{fa}	WSP Gust Front P_d/P_{fa}
Northeast				
Washington, DC (DCA)	.92/.10	–	–	–
Southern	.			
Orlando, FL (MCO)	.95/.06	.84/.03	.91/.06	.67/.11
Houston, TX (IAH)	.95/.05	–	–	–
Dallas, TX (DFW)	–	.94/.06	–	–
Austin, TX (AUS)	–	–	–	69/.03* .46/.35+
Atlanta, GA (ATL)	.94/.03	–	–	–
Midwest				
Memphis, TN (MEM)	.94/.07	–	–	–
Kansas City, KS (MCI)	–	–	.87/.15	–
High Plains				
Denver, CO (DEN)	.87/.03	–	–	–
Albuquerque, NM (ABQ)	–	–	.78/.18	.59/.14

The ASR-9 WSP statistics are derived partly from Lincoln Laboratory prototype operations in the southeast U.S. (Huntsville and Orlando) and the Midwest (Kansas City). Results from Austin (south-central U.S.) and from Albuquerque (high-plains) were obtained using data collected during operation of production WSPs at these "key sites." In all cases, the WSP alerts were scored against "truth" determined by human interpretation of data from independent sensors (pencil-beam Doppler weather radars and/or airport anemometer networks). It is important to note that the WSP microburst results apply only to "microburst strength" alerts (loss > 30 kts) whereas the TDWR results include scoring of divergent wind shear events with losses as low as 20 kts. This difference results in a favorable "high bias" for WSP P_d estimates.

In order to capture performance differences that may result from geographic differences in the characteristics of wind shear, these metrics are grouped according to the part of the U.S in which the data were collected. Thunderstorms in the midwestern and high-plains U.S. for example, are often "tilted" by environmental wind shear. As discussed by Weber (2006), in this situation the ASR-9's fan-shaped elevation beam may convolve vertical shear in the horizontal wind to produce erroneous wind shear signatures that increase the WSP false alarm rate. Microbursts in the high-plains may exhibit very low radar cross-sections. This circumstance is problematic for both TDWR and WSP.

Overall, these results track our "visibility" analysis. For a given environment, WSP wind shear detection probabilities are lower than those of TDWR (particularly when the differences in the minimum velocity thresholds for microburst scoring are considered). The performance difference clearly results from the sub-optimal sensitivity, antenna elevation beam shape and short coherent processing intervals of the ASR-9. It is important to note that the false alarm probability associated with WSP wind shear detections was consistently higher than for the TDWR. This is the result of the more aggressive detection algorithm parameter settings needed to maintain a comparable P_d, and situations where "contamination" from winds aloft produced erroneous wind shear signatures in the base data. False alarms are operationally problematic because they reduce controller confidence in the validity of true wind shear alerts.

4. OPERATIONAL ASSESSMENT

4.1 ATC FACILITY INTERVIEWS

To document user perspectives on the performance of these systems, we conducted structured interviews with air traffic controllers and supervisors at 5 airports equipped with TDWR, 4 airports with TDWR and ITWS, and 5 airports that utilize WSP (see Figure 12). All user interviews were conducted voluntarily, and each respondent was free to decline to answer any questions they wished. The same questions were asked of all operational ATC personnel interviewed, though some questions were specific to facilities using ITWS (i.e., inquiries pertaining to the ITWS Terminal Winds product, which is not available with the WSP or TDWR-only tools). A total of 14 to 18 ATC personnel were interviewed for each of these three facility-types.

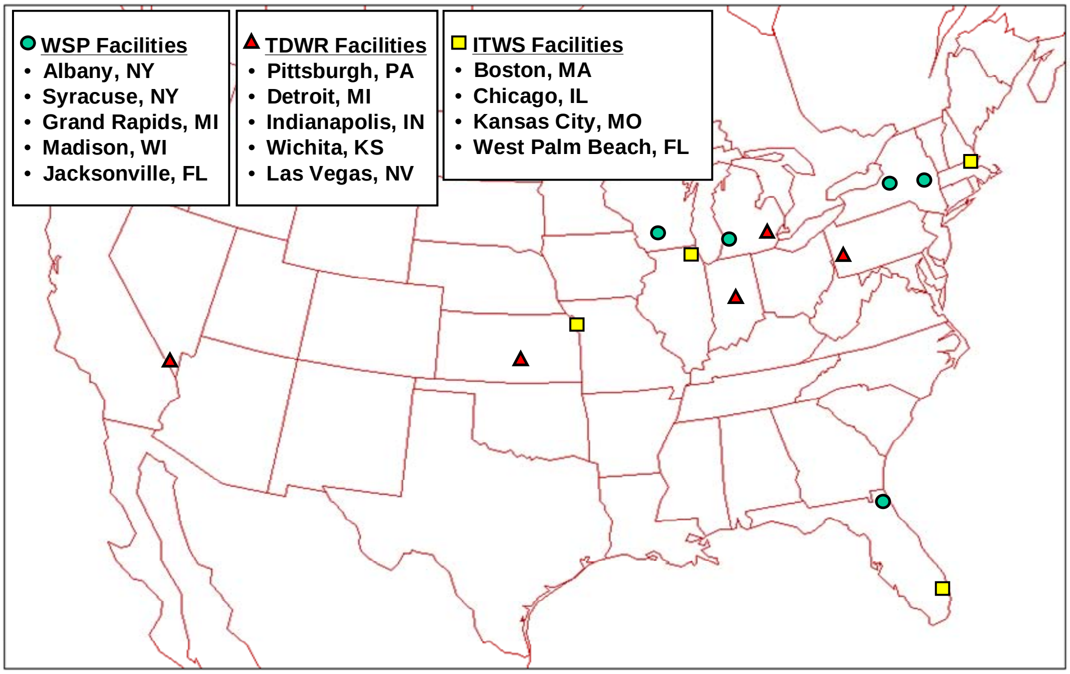


Figure 12. FAA facilities at which ATC user interviews, pertaining to WSP, TDWR, or ITWS usage and performance, were conducted.

The questions covered 5 specific areas:

1. Utility and performance of wind shear products (microburst and wind shear alerts and gust front forecasts);
2. Utility and performance of storm motion products;
3. Utility and performance of precipitation intensity products;
4. Utility and performance of the ITWS Terminal Winds product; and
5. User training.

Given the relatively small sample size of interviews conducted, and the wide range of additional variables present at individual facilities that affected user perceptions, the results should be considered in a general, qualitative sense.

4.1.1 Wind Shear Products

Air traffic controllers and traffic managers at each facility were all asked the following questions:

- What fraction of days on which the specific wind hazard occurred in your airspace do you estimate microburst/wind shear alerts or gust front forecasts provided by WSP/TDWR/ITWS were sufficient?

- What fraction of microburst/wind shear alerts or gust front forecasts issued by WSP/TDWR/ITWS would you estimate were false alarms?

In answering these questions, interview respondents were offered choices of: near 0%, 20%, 40%, 60%, 80%, and near 100%. The distribution of total user responses for each system is presented in Figure 13.

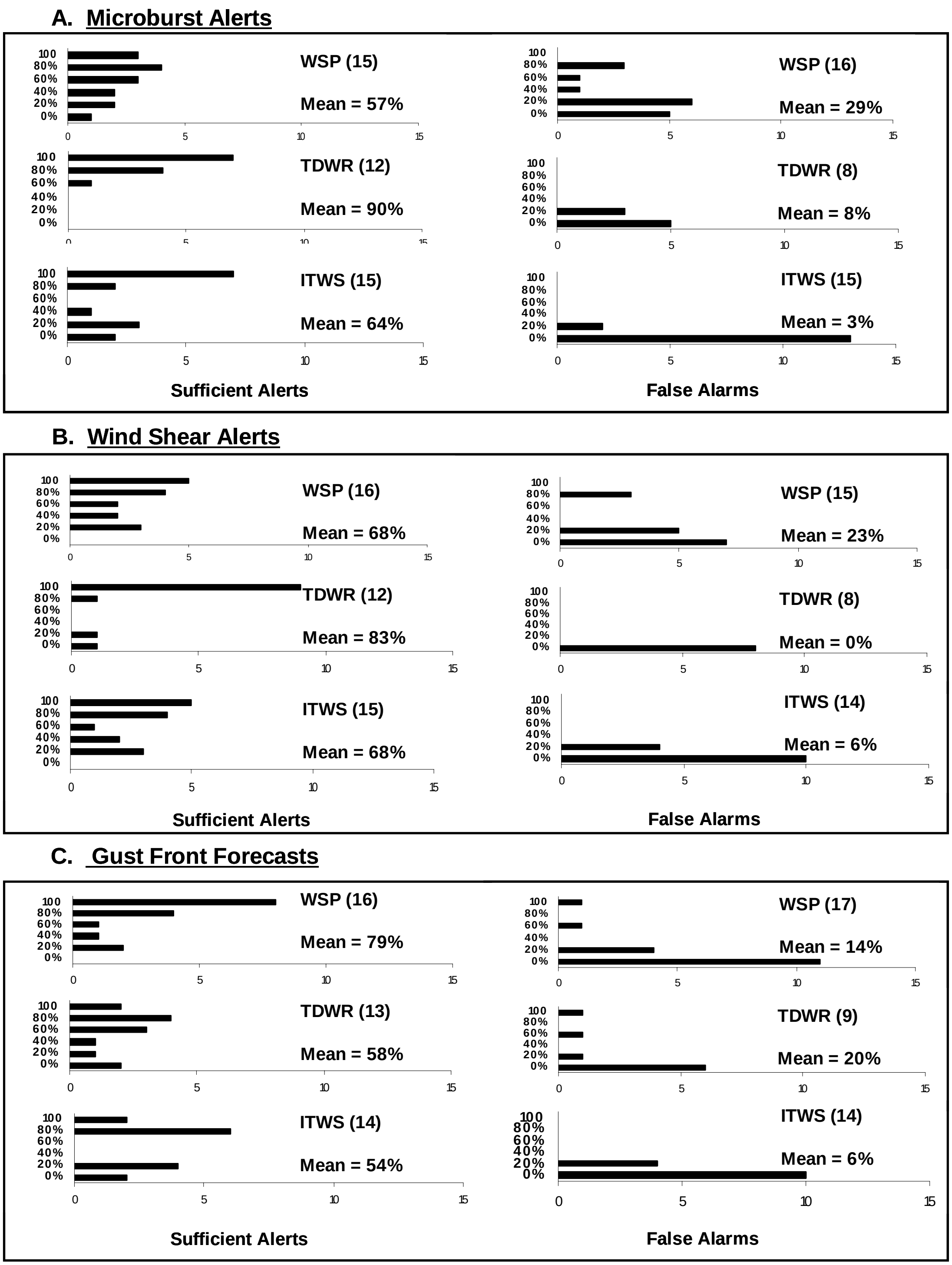


Figure 13. Distribution of user responses at facilities with access to WSP, TDWR, or ITWS, when asked to characterize the frequency of (A) microburst alerts, (B) wind shear alerts, and (C) gust front forecasts considered "sufficient" or "false alarms." The numbers in parentheses indicate the number of responses for each question at collective facilities with access to a specific tool. Variability in the number of responses for a specific tool (e.g., TDWR) indicates the inability or unwillingness of some respondents to answer specific questions. The mean of the responses for each wind shear product are shown.

For microburst and wind shear alerts ("wind shear" in this context refers to alerts associated with losses less than 30 kts and all gains) these results track the technical analysis in Section 3, showing higher user confidence in wind shear products at TDWR or TDWR/ITWS airports than at those facilities using the ASR-9 WSP. At some WSP sites (e.g., Syracuse and Grand Rapids), users noted that prior to the installation of a software patch, the false alarm rate for microburst and wind shear alerts generally exceeded 60-80% of all issued alerts. These false alarms resulted in extra workload for not only air traffic controllers, who are required to pass all wind hazard alerts to pilots on approach, but also for pilots, who are obligated to "go around" and make another pass on final approach when alerted of wind hazards by ATC. These requirements had to be fulfilled even when the alerts occurred "in clear skies and calm winds in the middle of the night," as did happen according to controllers at the Syracuse Tower. After the WSP software was upgraded, users at affected facilities noted that occurrences of microburst and wind shear false alarms declined significantly. One controller from Syracuse cited the frequency of pre/post-upgrade false alarm rates for microbursts and wind shear as 80/<20% and 80/0%, respectively.

Users at WSP, TDWR, or ITWS facilities that considered microburst or wind shear alerts less than 100% "sufficient" often cited missed alerts. A supervisor at Las Vegas Tower said he witnessed a dry microburst on 23 August 2006. He noted that dust was swirling at the surface but no wind shear alerts were issued by their TDWR display. At Albany Tower, one controller asked if WSP was initially developed in "flat-land" regions, because in his opinion the complex topography around Albany may prove problematic for the ASR-9 radar to identify wind hazards. He specifically noted that wind shear off the end of runway 28 occurs often, and WSP usually fails to provide an alert. Until it was removed, he said he was made aware of these wind shear episodes by the Low Level Wind Shear Alert System (LLWAS). Controllers at Albany (WSP) and Indianapolis (TDWR) noted that their respective displays frequently "go down" (no data displayed, screen shows only a large 'X') when weather or strong winds are present, and this has resulted in some missed alerts (Albany controllers note that this is currently the biggest problem with their WSP). A traffic manager at Boston TRACON said that on one occasion he recalls that LLWAS was showing a microburst alert but none was visible on ITWS. He later realized that the ITWS display was zoomed out beyond the TRACON-view and microburst alerts are not graphically displayed in the far-range view. (This account demonstrates that training plays an important role in realizing effective product usage). Additionally, ATC personnel at Syracuse (WSP) and Boston (ITWS) feel that some wind shear alerts are "missed" because they are not triggered when weaker than 15 knots. A traffic manager at Boston said that pilots report wind shear less than 15 knots. When this occurs, Land and Hold Short Operations (LAHSO) at Boston Logan airport must be suspended. Therefore, information on the occurrence of weak wind shear events would be operationally useful.

Surprisingly, results for questions pertaining to the performance of gust front forecasts do not follow the results for microburst and wind shear alerts. For this product, responses from WSP facilities were most favorable, followed by TDWR and ITWS. Supporting comments suggest some potential reasons for the inconsistency. Two controllers at Pittsburgh TRACON (TDWR) stated that the gust front forecast product is difficult to decipher, especially when multiple gust fronts are moving through the airspace in different directions. They admit that the increased complexity of the product renders it "less sufficient" because it is more difficult to apply.

Traffic managers at Chicago and Boston TRACONs both noted that the ITWS gust front product has a difficult time diagnosing and predicting wind shifts associated with sea breeze fronts. Unanticipated wind shifts associated with the sea breeze passage through the terminal precludes proactive runway management and suspends LAHSO programs at these two airports, resulting in increased ATC complexity and workload. Sea breeze concerns were only noted at these two ITWS sites, and at no WSP or TDWR sites.

Finally, we suspect that the performance of decision support tools are more closely scrutinized when either applied more often to operational decisions or applied to decisions with more operational significance. TDWR and ITWS are deployed at larger airports with higher traffic volumes and greater needs for proactive decision-making. Figure 14 shows the distribution of user responses when asked:

- What percentage of days when wind shifts occurred in the terminal were gust front forecasts used to proactively modify runway configurations?

Though interview results showed ITWS gust front forecasts were considered least "sufficient" (Figure 14), the answers to this question suggest that ITWS gust front forecasts are used 2–4 times more often to proactively plan for modified runway configurations than at the TDWR-only or WSP airports. Users at the smaller airports interviewed in this study stated that they have little need for proactive runway configuration planning given that aggressive traffic management is largely unnecessary with such limited traffic demand. At the larger ITWS airports, ATC personnel stated that gust front forecasts are "critical" to the proactive traffic management decisions they must make in an effort to mitigate delay. The greater scrutiny they apply to the gust front/wind shift forecasts is a likely contributor to their assessment of the accuracy of the product. It is also worth noting that, when asked about the effectiveness of the wind shift product in forecasting specific meteorological phenomena (e.g., cold front passages or thunderstorm outflows) the responses indicated approximately equal confidence for users of the different systems.

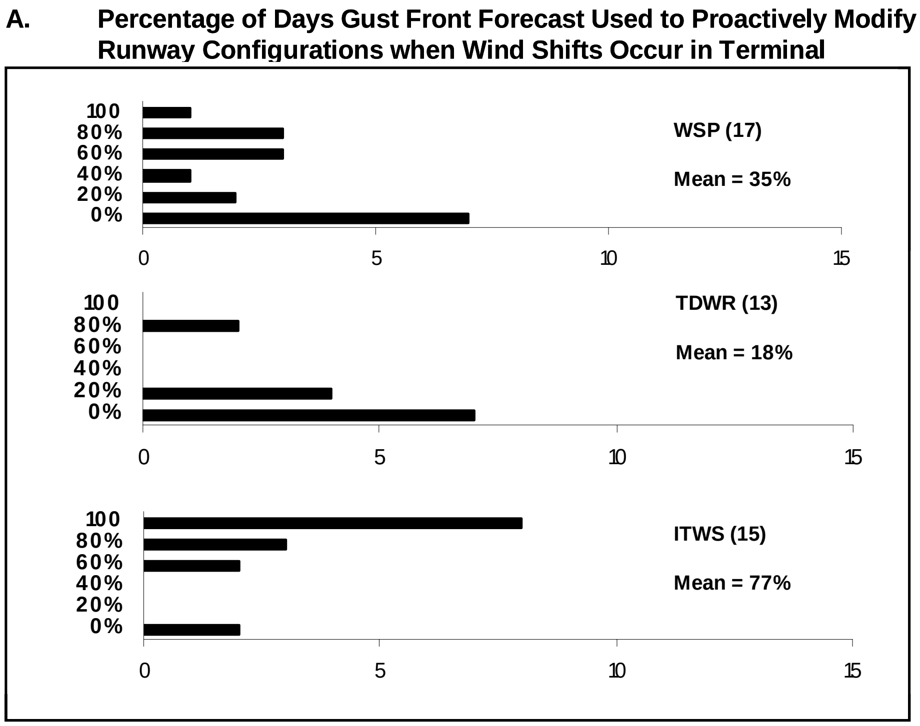


Figure 14. Distribution of user responses at facilities with access to WSP, TDWR, or ITWS, when asked to estimate how often the gust front forecast product is used to proactively plan for modified runway configurations. Response percentages per WSP, TDWR, and ITWS site where users classified gust front forecast effectiveness in depicting cold fronts and thunderstorm outflow boundaries as either "good" or "excellent" are shown in (B) and (C), respectively.

4.1.2 Storm Motion Products

Air traffic controllers and traffic managers were asked to estimate the fraction of thunderstorm impact days on which WSP, TDWR, or ITWS storm motion information was consulted, how frequently they had concerns about the accuracy of this product and how frequently they used the product for proactive planning of terminal operations. Their responses are tabulated in Figure 15.

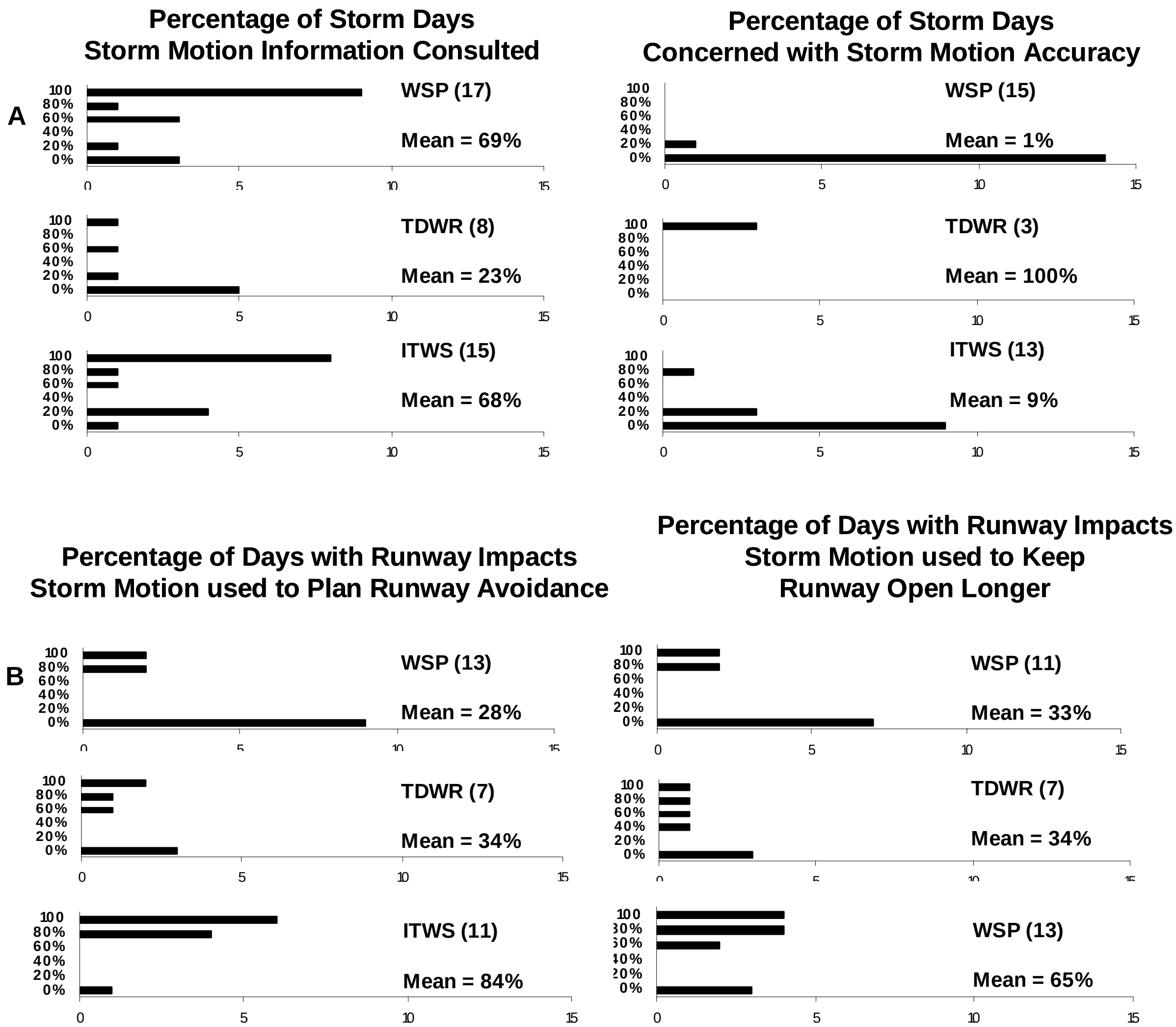


Figure 15. Distribution of user responses, when asked to estimate how often the WSP, TDWR, or ITWS storm motion information is (A) consulted on days with thunderstorms, and (B) used to proactively plan for either runway avoidance by pilots or to keep runways open longer.

The marked difference in TDWR-user responses and users of WSP and ITWS is not surprising given that the WSP and ITWS storm motion products are presented as vectors tagged directly to individual storms depicted on the situation display. TDWR presents storm motion information only as a text message on the display. Based upon the user interview results, the TDWR storm motion information may either not be clearly visible or air traffic controllers may not have time to read and decipher storm motion text messages during busy storm impacts.

In terms of applying storm motion information for proactive runway planning, use at ITWS sites is much more frequent than at either WSP or TDWR sites. Again, as with use of the gust front forecasts, the greater *need* for proactive planning and aggressive traffic flow management at high volume airports where ITWS is installed is the likely explanation. When asked to describe general benefits achieved through use of storm motion information, users at WSP and ITWS sites cited:

- Enhanced situational awareness;
- Improved safety information to relay to pilots;
- Providing pilots with information on possible routes;
- Estimating when storms will impact the airport;
- Runway taxi planning – getting aircraft off before storm impacts occur;
- Vector efficiency – determining which final approach would be clear of weather;
- Modifying runway configurations;
- Determining when to stop using a runway for final approach;
- Identifying runway availability; and
- Planning for impacts at arrival fixes.

Some users at TDWR-only sites also noted some operational usages of the storm motion text messages. However, several traffic managers at facilities equipped with TDWR displays stated that they were unaware of what the storm motion text message meant until it was discussed during the interviews. Three traffic managers at Pittsburgh TRACON stated that storm motion vectors provided by the Corridor Integrated Weather System (CIWS) are preferred over the TDWR storm motion text message. These comments again suggest that storm motion information is applied more frequently at WSP and ITWS sites because the data disseminated as vectors on the precipitation display are more readily visible and easier to use. This finding suggests that it would be operationally beneficial to include a graphical storm motion product on the TDWR situation display.

4.1.3 Precipitation Products

Air traffic controllers and traffic managers were asked a series of yes or no questions as to whether they were satisfied with WSP, TDWR, or ITWS precipitation depictions during convective weather and where applicable, snow events. Responses are shown in Table 10.

TABLE 10

User Responses When Asked if Satisfied With Precipitation Depictions

	YES		NO	
WSP				
Satisfied with Precip Depictions for Storm Severity	✓✓✓✓✓✓✓✓✓✓✓✓	12	✓	1
Witnessed Precipitation Over/Under-Estimates	✓✓✓✓✓	5	✓✓✓✓✓✓✓✓	8
Satisfied with Snow Depictions	✓✓✓✓✓✓✓✓✓	9	✓✓✓✓	4
Satisfied with Depictions of Snow Onset	✓✓✓✓✓✓✓✓✓✓	10	✓✓	2
Satisfied with Depictions of Heavier Snow Bands	✓✓✓✓✓✓✓✓✓✓	10	✓	1
TDWR				
Satisfied with Precip Depictions for Storm Severity	✓✓✓✓✓✓✓✓✓✓✓✓	12	✓✓✓	3
Witnessed Precipitation Over/Under-Estimates	✓	1	✓✓✓✓✓✓✓✓✓✓✓	11
Satisfied with Snow Depictions	✓✓	2	✓✓✓✓✓	5
Satisfied with Depictions of Snow Onset	✓✓	2	✓✓✓✓	4
Satisfied with Depictions of Heavier Snow Bands	✓✓✓✓✓✓	6	✓	1
ITWS				
Satisfied with Precip Depictions for Storm Severity	✓✓✓✓✓✓✓✓✓✓✓✓	2	✓✓	2
Witnessed Precipitation Over/Under-Estimates	✓✓✓	3	✓✓✓✓✓✓✓✓✓✓✓	11
Satisfied with Snow Depictions	✓✓ ✓✓✓✓✓✓✓✓	10	✓✓✓	3
Satisfied with Depictions of Snow Onset	✓✓✓✓✓✓✓✓✓	9	✓	1
Satisfied with Depictions of Heavier Snow Bands	✓✓✓✓✓✓✓✓	8	✓✓✓	3

In general, almost all were satisfied with depictions of convective activity. Several controllers at facilities with WSP and TDWR stated that representations of VIP level 3+ convection appeared to compare well with thunderstorm regions through which pilots were unwilling to fly. A traffic manager at Las Vegas said that the TDWR precipitation matched up well with precipitation seen on STARS, ETMS, and their NEXRAD display.

More users at WSP sites than TDWR or ITWS sites noted occurrences where the precipitation either over or under-estimated thunderstorm intensity. Despite overwhelming satisfaction with the product, some controllers at WSP sites noted:

- Storm intensity overestimations (Grand Rapids)
- Aircraft flying through level 3 precipitation, raising controller concern for WSP intensity accuracy (Albany)
- Significant level 3+ AP contamination at night (Madison)

One traffic supervisor at Indianapolis Tower (TDWR facility) stated that when he compares TDWR and ASR-9 precipitation the differences are slight, but only TDWR is used as a guideline for informing pilots of weather impacts. Another traffic supervisor at Kansas City TRACON (ITWS facility) noted that distant storms (near the TBA arrival fix) sometimes are shown at different locations when comparing NEXRAD and ASR-9 precipitation depictions.

Operational users were also asked about the performance of precipitation products during snow events. Snow is much less reflective than liquid precipitation and known to be difficult to represent in radar weather depictions. The majority of user responses from WSP, TDWR, and ITWS facilities all generally agreed though that depictions of snow, snow onset in the terminal, and heavier snow bands were satisfactory. Some controllers and traffic managers however did cite some limitations associated with using precipitation products during snow events:

1. WSP
    - Difficult to measure actual snowfall and snowfall rates (Grand Rapids)
    - Weather depiction fails to capture true areal extent of regions where snow is falling (Grand Rapids)
    - Does not depict lake effect snow very well; lake effect snow is too light and dry (Syracuse)
    - Snow can be hard to see (Madison)

2. TDWR
    - Snow saturates the level 1 intensity level; resolution is not ideal (Indianapolis)
    - Never thought of using TDWR during snow (Indianapolis)
    - Light snow does not show up (Pittsburgh)
    - Will miss the start of snow falling in the terminal (Pittsburgh)

3. ITWS
    - Snow precipitation is sometimes not accurate (Kansas City)
    - Can not differentiate precipitation type – snow, rain, or mixed (Boston)
    - Prefer CIWS, which shows precipitation-type (Chicago)

Despite these identified issues, most users still considered representations for snow “satisfactory” because impacts on air traffic operations, compared to summertime thunderstorms, are relatively minimal. However, as was the case with gust front forecasts, high traffic terminals with appreciable snow impacts (e.g., Chicago and Boston, both with ITWS) were more vocal in describing their need for winter weather information. Conversely, controllers at Syracuse Tower, which receives in excess of 100 inches of snow per season, stated that impacts during winter weather events were minimal, and current weather displays available for snow events were adequate.

4.1.4 ITWS Terminal Winds Product

Controllers and traffic managers at the three of the facilities with access to ITWS (Chicago, Boston, and Kansas City) were asked about the use and performance of the Terminal Winds product. The following questions were presented[1]:

- What percentage best indicates the fraction of days during which you use the ITWS Terminal Winds product in some way?
- What percentage best represents how often ITWS Terminal Winds is consulted to assist with runway configuration changes? *(Tower personnel only)*
- What percentage best represents how often ITWS Terminal Winds is consulted to assist with spacing aircraft? *(TRACON personnel only)*
- What percentage best represents how often you are satisfied with the accuracy of the ITWS Terminal Winds product (for instance when compared to actual winds as reported by pilots)?
- What percentage best describes the possible increase in air traffic benefits that could be potentially realized if Terminal Winds were to cover more airspace?

Responses to these questions (Figure 16) show that the ITWS Terminal Winds product is viewed very favorably. It is used, on average, 7 out of every 10 days during operations and there are virtually no concerns with the accuracy of the product. In fact, one traffic manager at Boston TRACON stated that the accuracy of ITWS Terminal Winds is so good that it often matches wind reports from PIREPs to within one degree in wind direction.

ATC personnel at Chicago O'Hare Tower, Chicago TRACON, and Boston and Kansas City TRACONs noted that ITWS Terminal Winds information is very beneficial when thunderstorms are present in their airspace. Traffic managers at Boston TRACON said that Terminal Winds is "always consulted" during weather events with winds persistently out of the northeast (e.g., classic coastal precipitation events that move up the East Coast in the winter). During these events, the runway configuration for arrivals at Boston Logan airport and the overriding synoptic weather situation result in strong tailwinds for aircraft on approach. Terminal Winds is used to help manage compression and set arrival acceptance rates. In fact, each traffic manager interviewed at all three ITWS TRACONS stated that the Terminal Winds product is routinely consulted to help manage compression and/or set arrival acceptance rates.

[1] Options for answers to these questions were: (a) near 0%, (b) 20%, (c) 40%, (d) 60%, (e) 80 %, (f) near 100%, or (g) can't estimate.

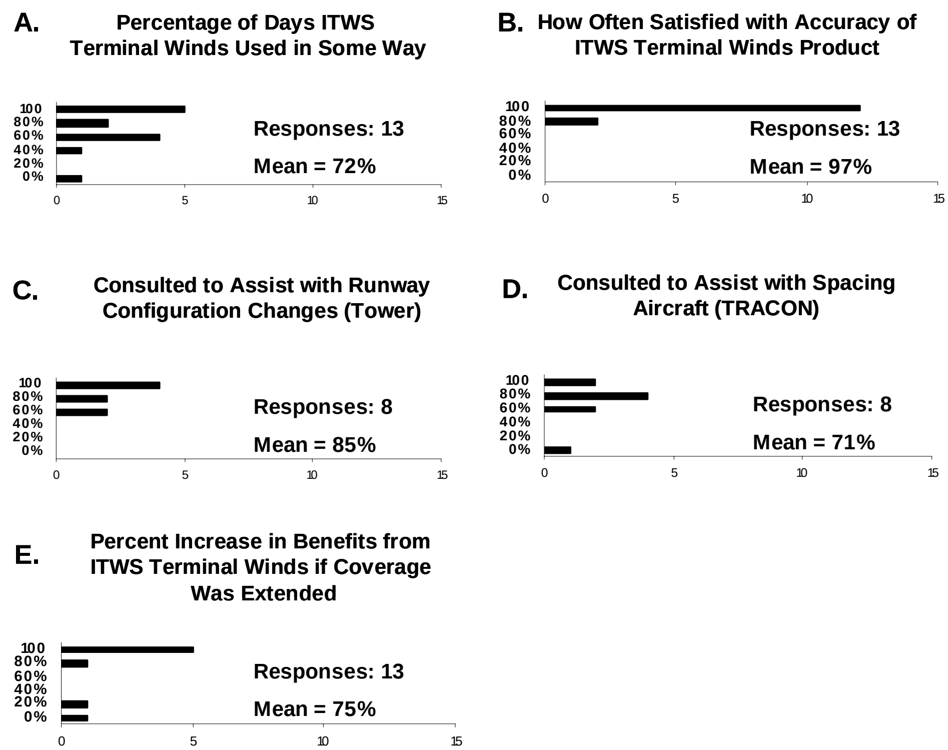


Figure 16. Distribution of ITWS user responses (and mean response) when asked to estimate the percentage of days the Terminal Winds product is (A) used by them in some way, (B) considered accurate, (C), used in the Tower to assist with runway configuration changes, and (D) used in the TRACON to assist with aircraft spacing. The user-estimated percent increase in realized benefits from Terminal Winds if the product covered more airspace is shown in (E).

4.1.5 User Training

As part of each interview, each user was asked to share any comments they may have had regarding WSP, TDWR, or ITWS training. Comments about training for specific products or general comments about the tools as a whole were welcome. Some results and specific user responses presented in previous sections demonstrate that some of the variability in perceived performance between ASR-9 and TDWR weather information can be explained by the varying levels of user experience and training.

Most users interviewed stated that the initial CBI training for WSP, TDWR, or ITWS was “sufficient” or “satisfactory.” Some stated that the CBI training was excellent and users went back to watch it again. Almost all agreed that yearly “refresher” training is necessary to stay current on the capabilities of these tools and their specific products.

However, some controllers and traffic managers (7 TDWR users, 2 WSP users) stated that they did not recall receiving any training. One traffic manager at Pittsburgh TRACON stated that the initial CBI training for TDWR was “years ago” and there has been no refresher training. Similarly, a controller at Grand Rapids Tower (WSP) stated that there was “a larger break” between the initial CBI training and when the WSP became operational, adding that training would have been better if conducted closer to when the system became available. Some users at Indianapolis (TDWR), Syracuse (WSP), Albany (WSP), and Kansas City (ITWS) said they would benefit from more training. Users at many facilities (WSP, TDWR, and ITWS) stated that training may be more valuable if conducted with a live person, rather than through the CBI module. Finally, ITWS users at Kansas City and Boston stated that refresher training would be most beneficial if conducted twice per year: at the start of the convective weather and winter weather seasons.

5. FUTURE TERMINAL WEATHER SERVICES

This section briefly discusses recommended future terminal weather services that would be significantly impacted by a decision to remove TDWR from the terminal area. The common denominator is that these services rely on high quality, high resolution measurements of weather phenomena close to the airport and at low altitude. Although FAA has not established implementation programs for these services, we believe they have potentially high operational value based on input from key users.

5.1 TERMINAL LOW ALTITUDE TURBULENCE

Bieringer et al. (2004) describe a class of low-altitude, organized "turbulent" phenomena they dubbed terminal low altitude turbulence or TLAT. TLAT can occur as a result of buoyancy waves propagating along the stable, boundary between cool surface air and warmer air aloft (see Figure 17), compensating divergence behind a strong gust front, or lines of divergence associated with decaying convection. Although readily observable by TDWR, the radar signatures associated with TLAT are sufficiently different from those of microbursts that the phenomena is not detected by current TDWR or ITWS wind shear detection algorithms.

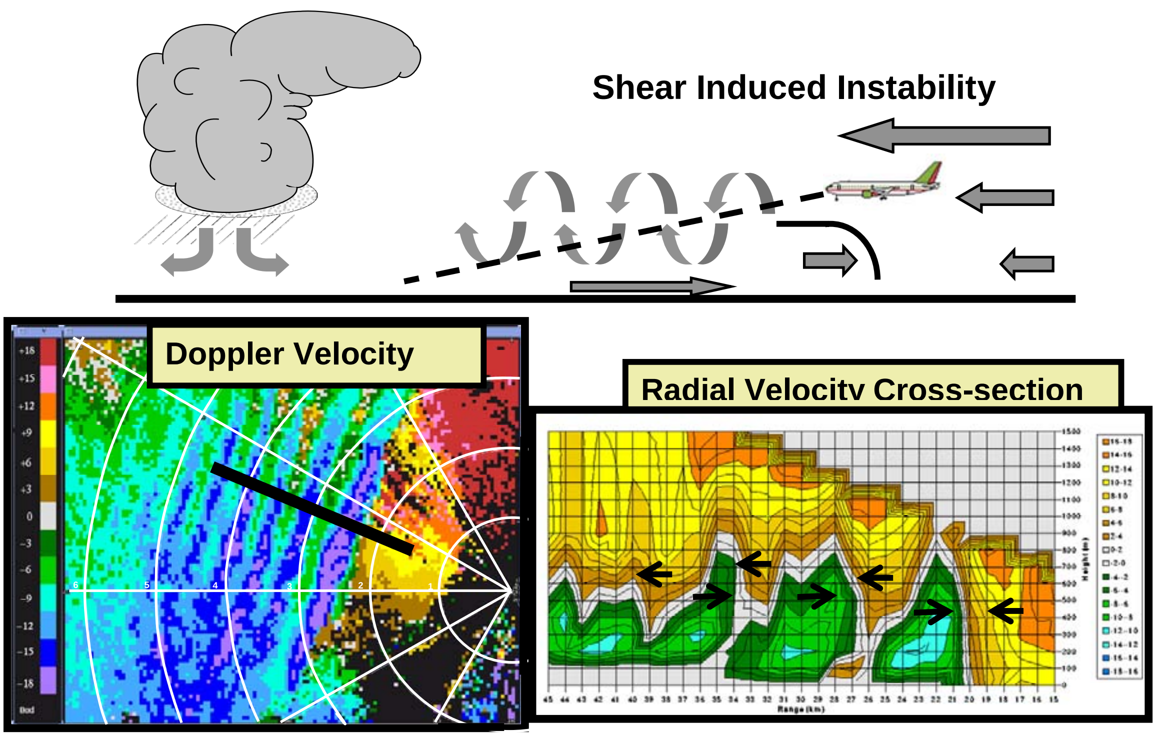


Figure 17. Illustration of terminal low altitude turbulence caused by gravity waves propagating along a stable boundary. The Doppler velocity images are from the TDWR at Memphis.

Table 11 is a list of aircraft accidents and incidents attributed to TLATS. This represents events that occurred at Lincoln Laboratory operated ITWS prototype sites or, in one case, an accident where National Transportation Safety Board (NTSB) personnel requested our assistance in evaluating the associated meteorological conditions. Our ITWS site personnel have estimated that over one-half of the divergent wind shear phenomena observed at these sites are associated with TLAT as opposed to microbursts. The NTSB continues to notify of us of potential TLAT-related aircraft incidences.

TABLE 11

Terminal Low Altitude Turbulence (TLAT) Incidents/Accidents Documented By Lincoln Laboratory Site Personnel.

Place	Date	Aircraft	Description
Dallas-Ft. Worth International Airport	12 April 1996	MD 80	Severe turbulence reported. Aircraft diverted to Tulsa for damage inspection
Orlando International Airport	12 December 1997	Commercial jet. Type not documented	50 kts losses and gains reported
Norman, Oklahoma	6 December 1998	Beech Baron	Fatal GA accident
John F. Kennedy International Airport	29 April 2002	Boeing 767	Uncontrolled descent from 1500'-400' on final
Dallas-Ft. Worth International Airport	30 April 2002	MD 80	Significant accelerations and loss in airspeed and altitude
John F. Kennedy International Airport	29 August 2002	Boeing 757	After takeoff, lost 60 kts airspeed in 16 seconds at 700'.

As with microburst and gust front wind shear, the radar signatures associated with TLAT are confined to a shallow layer near the surface and thus require a near-airport radar to protect aircraft at risk during take-off and landing. TLAT phenomena are typically not embedded in strong convection and as a result, the associated radar reflectivity may be low. TDWR has demonstrated capability to measure the radar signatures associated with TLAT and, with suitable modifications to its wind shear detection algorithms, could likely serve as the basis for a reliable warning system. We do not have a sufficient number of TLAT observations to reliably assess expected detection performance for an ASR-9 based warning system. However, the reduced ASR-9 sensitivity (see Table 4) and its poorer vertical resolution will undoubtedly degrade detection performance. If we use the 400 foot minimum height threshold over the airport, NEXRAD would provide adequate low altitude coverage for TLAT at only 18 of the TDWR equipped airports.

5.2 WIND DEPENDENT WAKE VORTEX PROCEDURES

NASA and the FAA are developing procedures and technologies to reduce the airport capacity constraints imposed by current wake turbulence separation standards. Wind dependent wake separation requirements for closely spaced parallel runways (CSPR) departures are the focus of near- to mid-term development efforts. As illustrated in Figure 18, when a persistent cross wind component is present, aircraft on the upwind CSPR can be launched independent of wake constraints from the downwind runway. A MITRE study (Cooper, 2003) estimates that delay-reduction benefits exceeding $3 M per year can be realized at a single, congested U.S. airport (BOS) using these wind dependent wake turbulence departure rules. Demonstrations of the procedure are planned at St. Louis and Houston Intercontinental airports and an FAA acquisition program for critical technology implementation may be approved in 2007.

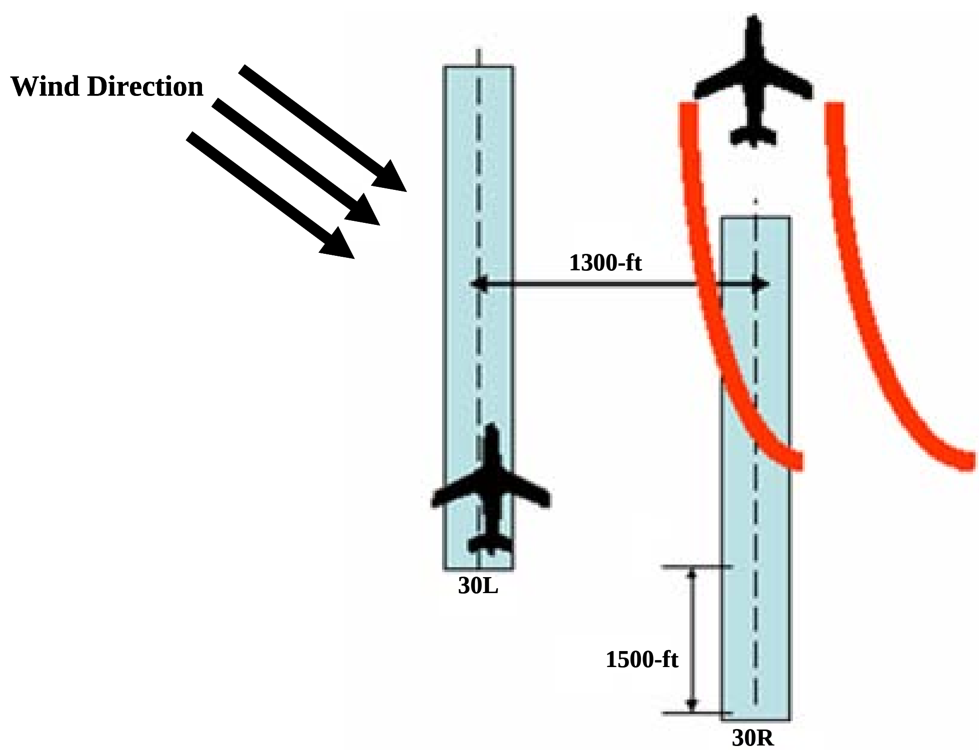


Figure 18. Illustration of closely spaced parallel runway wind dependent departure procedure at St. Louis Lambert International Airport.

The key technology component for wind dependent, CSPR wake turbulence separation rules is a robust Wind Forecasting Algorithm or WFA (Lang et al., 2005). The WFA is currently under development at Lincoln Laboratory. The primary inputs to the WFA are airport surface wind data from the airport Automated Surface Observing System (ASOS), and wind profiles aloft from the Rapid Update Cycle (RUC) operational numerical weather prediction model. Simplistically, the output of WFA is a "green- or red-light" condition indicating whether or not the cross-wind at the airport will support safe use of the wind-dependent wake separation standards on the upwind runway for the next 5 minutes.

Table 12 summarizes the results of a WFA validation exercise involving 70,000 minutes of wind data for runway 12R at STL. This “contingency” table shows minute-by-minute tabulations of the four possibilities: forecast green, actual green (upper left); forecast green, actual red (upper right); forecast red, actual green (lower left); forecast red, actual red (lower right). To maintain a very high level of safety, the WFA is tuned to produce very few “Type 1” errors where the forecast erroneously predicts winds favorable to the procedure. For this data set, the probability of a Type 1 error is 0.001. Because of the very conservative algorithm parameters needed to maintain this high level of safety, a significant fraction of the actual “green” periods are not forecast as available for utilization of the procedure (lower left table cell). This significantly reduces the operational benefit that can be realized from utilization of the wind-dependent procedure.

TABLE 12

Minute-by-Minute Scoring of the Wind Forecast Algorithm Used To Determine That Wind-Dependent Wake Vortex Separation Standards are Safe. Data are from STL for the Period February – December 2004.

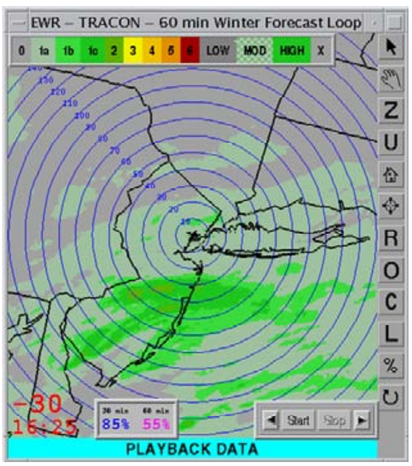
	Validation Green	Validation Red
Forecast Green	9799	10 (“Type 1 Error”)
Forecast Red	28089	31355

Evaluation of the causes of “Type 1” failures has shown that they are almost always due to sudden airport wind shifts caused by synoptic fronts or thunderstorm outflows (Lang et al., 2005). If additional sensor data and processing can be used to detect the presence of these organized wind shifts, then the WFA parameters can be relaxed to allow for “green light” forecasts during a much larger portion of the available benefits periods. Various options are being considered including the use of NEXRAD storm products to identify the presence of convection in the airport area. The most robust solution, however, would include the use of TDWR-derived low altitude wind information—specifically gust front/wind shift detections and/or front-detection processing applied to the gridded TWINDS data. Detailed evaluation of the technical efficacy and associated operational benefits of utilizing TDWR as a component of the WFA is planned during Fiscal Year 2007.

5.3 AIRPORT SNOW FORECASTING AND DE-ICING DECISION SUPPORT

Rasmussen et al. (2001) describe the Winter Storm and Deicing Decision Support (WSDDM) system that has been utilized at large U.S. airports (DEN, ORD, JFK, EWR, LGA) to improve airport ground operations during snowstorms. WSDDM correlates radar returns from winter storms with surface snow gauges to develop an adaptive relation between surface snow rate and radar reflectivity, then forecasts airport snow timing and intensity based on tracking of the radar echoes. WSDDM products are utilized to assist in the staging of aircraft deicing and snow removal operations, and in decision making on which aircraft deicing chemicals should be employed.

The Lincoln NYC ITWS prototype precipitation forecast algorithm was modified to include a winter storm forecast that tracks and forecasts wintertime precipitation, and estimates whether the precipitation is rain, snow or sleet (Wolfson and Clark 2006). The Corridor Integrated Weather System (CIWS) forecast algorithm likewise now includes a winter forecast mode. A key operational benefit is the capability to more proactively respond to the impact of winter storms on airport visibility, runway conditions and associated operations rates. Figure 19 summarizes the operational benefit realized by this product during a single winter storm in New York City in 2003. Because the ITWS winter precipitation forecast allowed Traffic Flow Management personnel to determine that heavy snow entering the area would stay to the south of the NYC airports, a planned ground delay program was cancelled. Using a queuing model to estimate the delay that would have been incurred from the scheduled ground delay program, NYC TFM personnel determined that their decision to cancel the program resulted in $1.5 M savings in airline direct operating costs.



	With Scheduled Delay Program	After Delay Program Cancellation
Est. Cost* of Delay	**$1,751,250**	**$204,500**
Savings		**$1,546,570**

*** Direct Operating Cost only ($3000/hr), no downstream delay included**

Figure 19. Lincoln prototype ITWS display of NYC snowstorm on 10 February 2003 and operational benefits realized as a result of a decision to cancel a scheduled ground delay program for LGA, JFK and EWR.

Winter snow storms are typically comprised of low stratus clouds (bases 2000–3000 feet). There is often significant vertical variation in the amount and phase of the precipitation at lower altitudes as the snow clumps, melts or blows horizontally. Radar measurements of snow must be made as close as possible to the ground to accurately reflect the intensity of snow at the surface. Although WSDDM and the CIWS forecast can use NEXRAD data, their accuracy where the NEXRADs are far from the airport will be degraded. Because of the ASR-9's much lower intrinsic sensitivity and the large beamfilling loss associated with shallow snow storms, this radar may fail to detect light snow or may significantly underestimate its intensity. TDWR's near-airport siting and high-resolution beam assure that it will accurately measure the near-surface distribution and intensity of the winter precipitation.

5.4 AIRPORT LIGHTNING DETECTION

Current airline procedures require that ground operations (e.g., baggage loading and refueling) be suspended when there is a threat of lightning. The airlines and airport operators would benefit significantly through improved management of ground-operations halts during thunderstorms. This improved ground operations management would in turn lead to National Airspace System (NAS) capacity enhancements that align with Operational Evolution Plan (OEP) “Airport Capacity” goals. The Executive Vice President at Dallas-Ft. Worth airport has asked Lincoln Laboratory to develop a proposal for ITWS augmentations that would support improved lightning warning capabilities, and the Transportation Research Board has awarded a study contract to evaluate various technology options.

Figure 20 illustrates the potential operational benefit through analysis of two thunderstorm impact days at DFW where significant ground operations halts occurred. We carefully reviewed all available meteorological data associated with these cases and estimated that a more effective lightning warning system could have reduced the durations of the ground operations halts by 10 to 20 minutes. Assuming that this translates into a corresponding reduction in the period of airport arrival/departure halts and surface ground delays, the associated cost savings for just these two episodes at DFW would have been close to $400 K. (This analysis used a queuing model and cost analysis similar to that employed for the Atlanta ITWS benefits study [Allan and Evans, 2005].) Extapolated to a year-round, national basis the potential capacity benefits at pacing airports are very large.

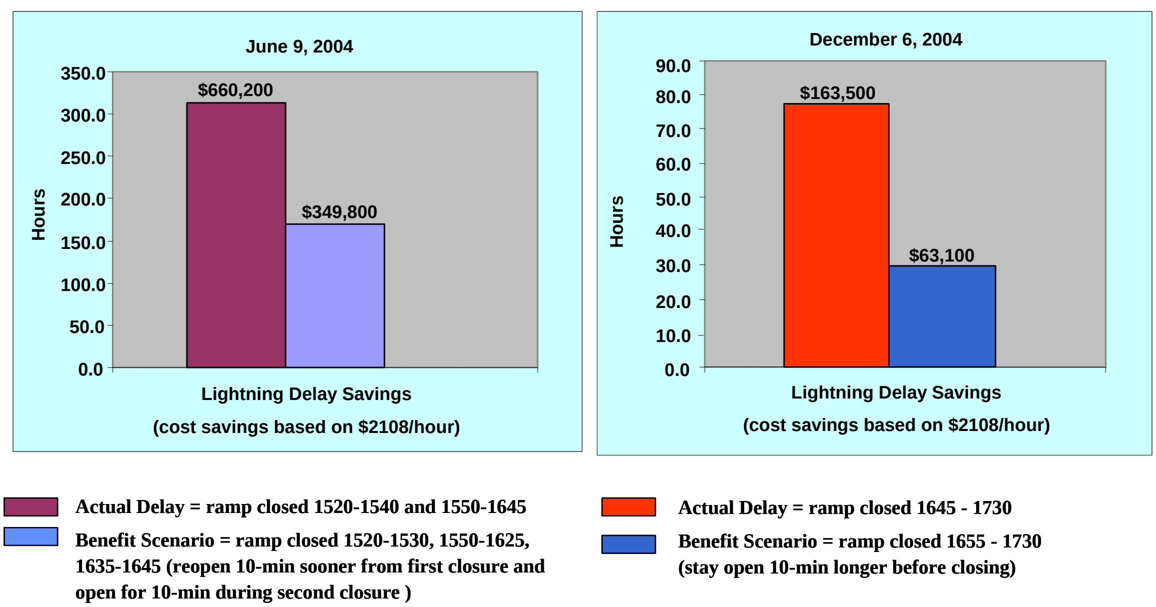


Figure 20. Benefits estimates for two thunderstorm days at DFW where ground operations halt due to lightning caused significant delay.

Current airport lightning warning systems are commercially built and typically utilize:

(i) electrostatic field measurements to infer the presence of electric charge accumulations in nearby clouds that may result in lightning; and

(ii) detection and position locating of cloud-to-ground lightning strokes.

While useful, these measurements do not provide a capability to precisely localize the area affected by a current lightning threat condition, nor do they allow for forecasting of the onset or cessation of the lightning threat. As a result, the operational performance of the current warning system has not been satisfactory.

Utilization of the high-quality, three-dimensional weather radar data provided by the TDWR would allow for a much more precise measurement of the areas where thunderstorm electric charge accumulations may exist, and for tracking and forecasting of the movement of these areas. The Doppler wind measurements provided by the radar allow for inference of electric-charge "blow-offs" that may result in lightning threats in areas not coincident with thunderstorm cores. In combination with the direct electrical measurement systems described above, TDWR data and associated ITWS products could be used to accurately define the current location, extent and future positions of "lightning activity areas." From these, criteria and procedures for suspending and resuming ground operations activities could be developed that are much more efficient than current procedures.

In contrast to the other meteorological phenomena discussed in this report, lightning and the thunderstorm charge accumulations that produce it are not fundamentally low altitude phenomena. NEXRAD and ASR-9 could certainly provide very useful measurements of thunderstorm intensity, movement and (in the case of NEXRAD) 3-D structure. However, TDWR would be expected to provide superior measurements in that it's near-airport location and 1/2° beam would support better resolution of the storm structures (e.g., bright bands) and flow-patterns that are important in determining that lightning is probable.

6. SUMMARY AND RECOMMENDATIONS

Although the circumstances that led to deployment of the TDWR have since evolved significantly, our analysis indicates that the radar continues to provide extremely high-value services, particularly at pacing airports where mitigation of delay during adverse weather is essential. Even the very partial tabulation of operational benefits presented here far exceeds the operations, maintenance and upgrade costs required to keep TDWR in service.

We compared the wind shear detection services provided by TDWR to both airborne predictive wind shear (PWS) radars and alternative ground-sensor configurations. Airborne predictive wind shear radars do not provide an acceptable alternative because many commercial, and practically all general aviation and business aircraft are not equipped. Further the PWS radars have limited range and scan-angle capability and cannot provide the broad area situational awareness needed to proactively reroute aircraft away from wind shear.

We considered in detail the alternative of substituting ASR-9 WSP and NEXRAD derived wind shear detections for those currently provided by TDWR. A technical analysis compared radar siting, terrain blockage, radar sensitivity and ground clutter suppression capabilities amongst these radars. An objective performance metric based on these parameters—"wind shear visibility"—was tabulated for each of these radars at all TDWR-equipped airports. TDWR was uniformly superior by this metric, and at more than 10 of the airports, the "visibility" metrics for the ASR-9/NEXRAD alternative was sufficiently low as to raise questions whether the alternative would be operationally acceptable. Performance metrics from field measurement programs likewise show that TDWR wind shear detection performance is superior to that provided by the ASR-9 WSP. Finally, we interviewed ATC personnel at both TDWR and ASR-9 WSP equipped airports. Although both systems were regarded as providing operationally acceptable performance at the facilities they support, the responses indicated generally higher level of confidence in the wind shear products, and higher usage of the gust front planning product at the TDWR and TDWR/ITWS equipped airports.

To assess the terminal delay aversion benefits associated with TDWR observations, we analyzed the contribution of this radar to the Terminal Winds (TWINDS) product provided by ITWS. Because of its near-airport siting and high-resolution antenna beam, TDWR provides a unique capability to observe low-altitude wind conditions affecting airport operations. Analysis and case studies show clearly that removal of this input from TWINDS would significantly degrade the accuracy of the product. Operational benefits estimates for TWINDS expose very large delay cost aversions at pacing airports such as LGA, JFK, EWR, BOS, ORD, and ATL. The majority of these benefits accrue at low-altitude during landing and take-off operations. Thus it is reasonable to project that removal of TDWR input to the TWINDS algorithm would have substantial negative impact on the efficiency of terminal operations.

Finally, we considered the role of TDWR in supporting potential future terminal weather services including low-altitude turbulence detection, wind-dependent wake vortex separation procedures, decision support for winter-storm deicing and airport operations, and airport lightning warnings. Although qualitative, these discussions clearly indicate that the superior low-altitude coverage and near-airport resolution of TDWR will provide higher capability that could be achieved with the alternative ground-based systems.

Following are three recommendations based on our analysis:

Recommendation 1: Based on this analysis, we believe it would be imprudent to remove TDWR from operational service in favor of currently available alternatives. To the contrary, we recommend that the FAA seek to increase the already high operational benefit provided by this radar by continuing to improve its availability, the quality of its precipitation and wind measurements and the end-user services to which it contributes. The TDWR Service Life Extension Program, if appropriately funded, will address availability and data quality through replacement of aging subsystems and enhancements to the radar processing algorithms. Corresponding programs to improve end user services are not adequately developed. In this report we enumerated a number of significant terminal-area capability enhancements to which TDWR would contribute substantially:

(1) safety warnings for organized, low-altitude turbulent phenomena (TLAT) not currently detected by ground-based wind shear detection systems;

(2) improved utilization of the ITWS Terminal Winds product, for example in depicting approach path segments where aircraft experience spacing compression due to vertical shear in the horizontal wind;

(3) improved detection of airport wind shifts by fusing data from multiple TDWRs (present at several pacing airports) and other sensors;

(4) wind-dependent CSPR wake turbulence procedures;

(5) decision support for operations during winter storms; and

(6) airport lightning detection.

While TDWR is a critical input in realizing these enhanced user capabilities, the terminal weather processing architecture (currently represented by ITWS) must be modernized to allow for insertion of new sensor data, efficient implementation of new algorithms, and easy interface to Traffic Flow Management Decision Support tools. Requirements for the enhanced user services must be established and adequate funding for their implementation provided.

Recommendation 2: The FAA should more actively monitor system performance and more frequently "refresh" user training at airports equipped with WSP, TDWR and TDWR/ITWS. User concerns with the accuracy of wind shear reports or planning products from these systems need to be understood and, where possible, mitigated. At one WSP facility, persistent microburst false-alarms were clearly related to a site-specific performance problem (ground clutter breakthrough) that existed in the operational environment for an extended period of time. The lead author is aware of analogous issues at several other WSP sites. In addition, significant enhancements to the WSP gust front algorithm, developed in response to performance issues identified during key site testing should be fielded nationally as soon as possible.

Whatever wind shear detection system an airport is equipped with, effort should be invested in more clearly understanding the circumstances that lead to reduced user confidence. As an example, during WSP key site testing, ATC reports of missed wind shear events turned out to be due to pilot reports of "wind shear" during gusty, high wind conditions completely devoid of the organized wind shear the WSP is designed to detect. Follow-on user interactions exposed this issue and, via education of the workforce, mitigated the perceived performance problem. The authors' speculate that some of the performance concerns raised at western U.S. TDWR sites may likewise be the result of gusty, turbulent conditions which, while operationally problematic, are not the type of organized wind shear that TDWR was deployed to protect against.

Recommendation 3: The FAA should begin serious evaluation of options for next generation weather (and non-cooperative aircraft) surveillance. The current strategy is best characterized as "wait and see," based on the assumptions that a shift to all-cooperative aircraft surveillance (ADS-B) may reduce the need for primary ATC radars, and that the continued absence of wind-shear accidents may obviate the need for an airport weather radar such as TDWR. Our analysis, however, indicates that high-quality, ground-based weather radar measurements are critical for robust operations at congested, pacing airports in today's NAS. As "super-density" operations expand in the next-generation airspace system, the numbers of such radars required can only be expected to increase. The TDWR system parameters need not be duplicated exactly for such services. Analysis needs to be conducted to determine whether smaller, lower-cost "commercial grade" weather radars could provide the requisite capabilities. Alternatively, if primary aircraft surveillance around airports is to be maintained as a backup to ADS-B, low-cost multi-mission radars (Weber et al., 2007) may provide a cost-effective alternative to today's single-function systems. In any event, if at least modest investments in analyzing and developing alternatives to today's ground-based radars are not commenced in the near term, the FAA may have no choice in the next decade other than to continue to expend funds to maintain an aging, non-optimized ground radar network.

GLOSSARY

ASR-9	Airport Surveillance Radar-9
ATC	Air Traffic Control
CIWS	Corridor Integrated Weather System
FAA	Federal Aviation Administration
FAR	Federal Acquisition Rule
ITWS	Integrated Terminal Weather System
LGA	LaGuardia
LLWAS	Low Level Wind Shear Alert System
NAS	National Airspace System
NEXRAD	Next Generation Weather Radar
OEP	Operational Evolution Plan
P_d	probability of detection
P_{fa}	probability of false-alarm
PMS	Performance Management Systems
PSF	Program Support Facility
PWS	predicitive wind shear
RUC	Rapid Update Cycle
SLEP	Service Life Extension Program
TDWR	Terminal Doppler Weather Radar
TEB	Teterboro
TFM	Traffic Flow Management
TWINDS	Terminal Winds
WSP	Weather Systems Processor

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