The Integrated Terminal Weather System (ITWS)

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The Integrated Terminal Weather System (ITWS) is one of two major development projects sponsored by the FAA's Aviation Weather Development Program. Focused on the environment within the airport terminal area, ITWS integrates data from FAA and National Weather Service (NWS) sensors and systems to provide a suite of weather informational products for improving air terminal planning, capacity, and safety. This article provides an overview of the ITWS project, presenting the system concept, some of the design and engineering challenges, and plans for development that will lead to operational systems in the field.

INCLEMENT WEATHER in the airport terminal area is the major cause of flight delays as well as a principal reason for aircraft accidents. The deployment of systems such as the Terminal Doppler Weather Radar (TDWR), the Airport Surveillance Radar (ASR-9), the ASR-9 with a Wind Shear Processor (WSP) augmentation, and the enhanced Low Level Wind Shear Alert System (LLWAS) will significantly improve airport terminal safety. These systems acting individually, however, will not significantly reduce weather-induced delays. Furthermore, even a suite of the above systems cannot address a number of safety needs—for example, anticipating changes in the snowfall rate (which influence decisions about the need for deicing aircraft), predicting wind shear, and identifying hazardous storm cells. Finally, there is a growing need to reduce terminal controller work load, particularly during adverse weather conditions.

In this article, we discuss how weather data from various sources can be combined to obtain more accurate and detailed information of the weather in the airport terminal area. This improved weather information can then be used to reduce the frequency and severity of flight delays and improve the safety of air travel in adverse weather conditions. The Integrated Terminal Weather System (ITWS), being developed by Lincoln Laboratory's Weather Sensing Group under sponsorship of the FAA's Aviation Weather Development Program, will provide such improved weather information by integrating data from various FAA and National Weather Service (NWS) sensor and weather information systems. Figure 1 shows the major data sources for ITWS and some of the system's principal users.

Figure 1 emphasizes one of the important technological features of ITWS—the combining of knowledge from various sources to provide a suite of informational products on operationally significant weather in the airport terminal area. Historically, radar reflectivity from precipitation has been the principal source of information on storms in the terminal area, with information on airport surface winds, temperature, and humidity appearing on separate alphanumeric displays. However, thermodynamic factors (i.e., temperature and humidity), winds, and storm microphysical processes (e.g., the formation of ice crystals) are as important as radar reflectivity in determining the hazard level and time evolution of weather. Using the various data sources in a scientifically sound manner, ITWS can address the deficiencies discussed above by creating informational products that cannot be derived from the sensors individually.

ITWS will meet its primary objective, to reduce delays, in two ways: directly, by providing information to FAA supervisors and traffic managers so that they can work more actively to achieve an efficient

GLOSSARY OF ACRONYMS

ACARS Aircraft Communications Addressing and Reporting System

AGFS Aviation Gridded Forecast System

AP anomalous propagation

ARTCC Air Route Traffic Control Center

ASOS Automated Surface Observing System

ASR-9 Airport Surveillance Radar, 9th generation

ATC air traffic control

AWOS Automated Weather Observing System

C&V ceiling and visibility

CWSU Center Weather Service Unit

DFW three-letter designator for Dallas–Fort Worth International Airport

ETMS Enhanced Traffic Management System

FAA Federal Aviation Administration

FAATC FAA Technical Center

FSL Forecast Systems Laboratory

IFR instrument flight rules

IOC initial operational capability

ITWS Integrated Terminal Weather System

LLWAS Low Level Wind Shear Alert System

MAPS Mesoscale Analysis and Prediction System

MCO three-letter designator for Orlando International Airport

MDCRS Meteorological Data Collection and Reporting System

MSP three-letter designator for Minneapolis–St. Paul International Airport

NAPRS National Airspace Performance Reporting System

NEXRAD Next Generation Weather Radar

NOAA National Oceanic and Atmospheric Administration

NWS National Weather Service

RVR Runway Visual Range

TATCA Terminal Area Traffic Control Automation

TDWR Terminal Doppler Weather Radar

TMU Traffic Management Unit

TRACON Terminal Radar Approach Control

VAD velocity-azimuth display

VOR very high frequency (VHF) omnirange

WSP Wind Shear Processor

ZJX three-letter designator for the en route center (ARTCC) in Jacksonville, Florida and orderly flow of traffic during adverse weather, and, indirectly, by furnishing weather information to terminal automation systems (e.g., the Terminal Air Traffic Control Automation [TATCA] system) and wake-vortex advisory systems so that they can optimize usage of the available terminal routes and runways. Additional safety benefits will accrue from reduced controller work load as well as from better planning support. ITWS will further decrease controller work load and increase aircraft safety by transmitting tailored, timely information to pilots directly via data link and by reducing the need for controller interpretation of the provided information. Safety in the terminal area will also be improved by specific ITWS informational products that are tailored toward meeting one or more of the unfulfilled safety needs cited above.

In this article we first give examples of situations in which airport delays occur, to provide a background for the remainder of the article. Next, we describe how data from the various sensors are used to create the ITWS informational products. We then discuss the use of functional prototypes to acquire data for product development and to generate ITWS products in real time for operational evaluation. The design of the prototypes, which facilitates drop-in testing of a variety of product-generation algorithms, is discussed briefly. We then present the real-time evaluation of the informational products by air traffic controllers and managers, pilots,

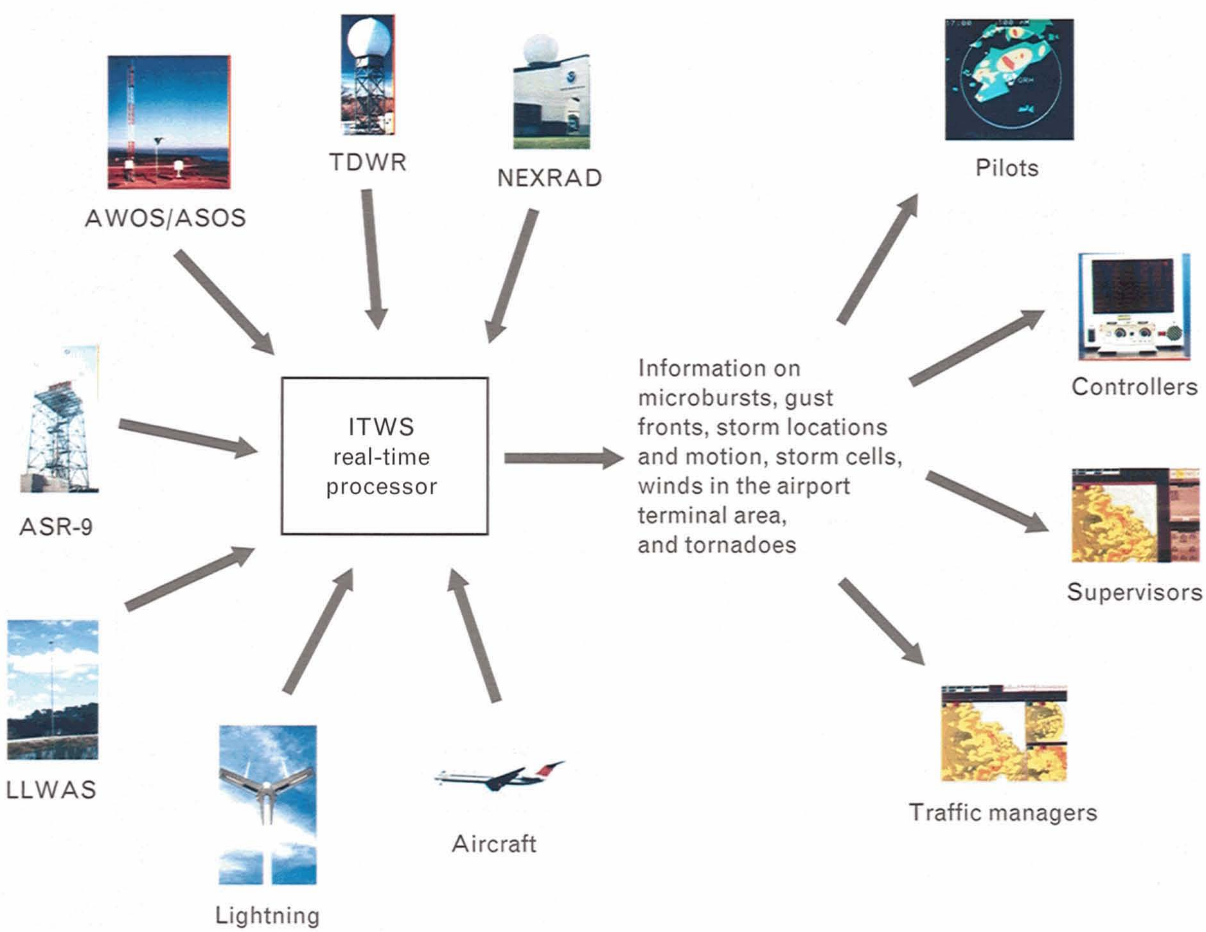

FIGURE 1. ITWS combines weather data from a variety of sources to provide a suite of informational products for improving airport terminal planning, capacity, and safety. For descriptions of the different sources, see Table 3 and the main text.

and airline flight operations users. This evaluation has been a key element of the development program and has provided helpful insights into user needs. In conclusion, we describe the near-term plans for further development of ITWS.

The Need for Improved Weather Information in the Airport Terminal Area

To understand how ITWS can reduce airport delays, we must first understand the interaction between adverse weather and delays at various points in the system. Preliminary studies of airport delay have been conducted with weather statistics and data that are available from the FAA performance-reporting systems. Table 1 shows an initial result obtained by M.E. Weber et al. [1] with data from the National Airspace Performance Reporting System (NAPRS). Using NAPRS data from O'Hare International Airport, Weber estimated the delay per aircraft for various types of weather, and then extrapolated the data to other airports by using the volume and frequency of the various types of weather. For the airports listed in Table 1, thunderstorms accounted for approximately 50% of the serious delays, low visibility accounted for 35%, and heavy fog the remainder. The results shown in Table 1, however, significantly underestimate the net effect of weather on delay because

1. NAPRS does not consider the duration of a gate hold at an originating airport (i.e., the airport where a flight originates) that results from adverse weather at the flight's destination, and
2. the system does not include *downstream effects,* whereby an aircraft may be delayed for several flight segments on a given day because of weather-induced delay on an earlier leg.

Using flight-delay data from major airlines at several large airports for a number of days with adverse weather, J.E. Evans and D.A. Clark [2] examined the applicability of the O'Hare data to other airports and investigated the effects of gate holds. From Table 2, which shows typical results, we see once again that thunderstorms are a principal cause of serious delays.

Tables 1 and 2 clearly show the strong relation between adverse weather and airport delay. We now examine specific cases to understand what information might help reduce such delays.

An Example of Significant Delays Caused by Thunderstorms

In general, when flights can be grouped tightly along standard routes, air traffic controllers can manage the flow efficiently and meet the scheduled demand. But when the flights deviate significantly from the standard routes, the controllers must interact much more with the aircraft, and thus each controller can handle fewer aircraft. If the controllers cannot handle the number of arrivals and departures that were planned, then delays will result.

Figure 2 illustrates two types of situations in which thunderstorms caused significant delays at Dallas–Fort Worth International Airport (DFW). In all four panels, weather reflectivity information from a NWS radar is shown along with flight tracks near DFW over a 15-min period centered on the time of the radar scan. Planes enter the terminal area through arrival transition areas (i.e., gates) located northeast ("BUJ"), southeast ("SCY"), southwest ("AQN"), and northwest ("BPF"), and land to the south at DFW airport. Departures leave the airport to the south and then turn to depart between the gates.

Figure 2(a) shows a 30-min period during which planes arriving at the DFW terminal area from the southeast encounter storm cells near the southeast arrival gate. We see that, for the first 15 min (time 14:45), most flight tracks travel very close to or through several high-reflectivity cells. In the next 15-min period (time 15:00), however, nearly all flow from the southeast gate has ended and there now are a variety of paths being used to approach and leave DFW. The key point to be made is that, in this 30-min period, there was a significant disruption to the terminal traffic flow even though there were no storms near the airport itself. Figure 2(a) illustrates the need to anticipate the movement of significant storms all the way out to the edges of the terminal area so that a safe and orderly traffic flow can be maintained.

Figure 2(b) shows a different 30-min period in which a storm is near the airport itself. We see that, for the first 15 min (time 17:45), aircraft are routed

Table 1. The Impact of Weather at Ten Large U.S. Airports (from Reference 1)

		Climatology (days per year)			Annual Delay (minutes X 1000) for Delays >15 min			
Airport	*Daily Operations*[1]	*Thunder-storms*	*Heavy Fog*	*Low Visibility*	*Thunder-storms*	*Heavy Fog*	*Low Visibility*	*Weather Delays*[2]
Chicago	2175	38	16	109	412	94	185	87%
Atlanta	2156	50	30	136	538	174	229	90%
Los Angeles	1589	3	44	121	24	188	150	83%
Dallas	1578	45	11	86	354	47	106	87%
Denver	1438	41	10	57	294	39	64	85%
San Francisco	1255	2	17	101	13	57	99	74%
St. Louis	1178	45	11	156	265	35	143	89%
Boston	1162	19	23	125	110	72	113	84%
Phoenix	1142	23	2	5	131	6	4	72%
Detroit	1137	33	22	121	187	67	107	87%

[1] Number of aircraft.
[2] Fraction of delays due to weather.

Table 2. Average Daily Airline Operations and Delay Minutes on Sample Days of Varying Weather Types (from Reference 2)

Airline	*Airport*	*Weather Day Type (number of days)*	*Daily Operations*		*Delay Minutes*[1]	
			Arrivals	*Departures*	*Arrivals*	*Departures*
A	Chicago	Baseline clear (1)[2]	381	393	0.6	< 0.1
B	Chicago	Baseline clear (1)[2]	315	316	3.3	4.4
C	Denver	Baseline clear (2)	194	195	0.5	0.4
D	Minneapolis–St. Paul	Baseline clear (1)	257	259	4.6	4.6
A	Chicago	Thunderstorm (4)[2]	392	387	8.7	5.1
B	Chicago	Thunderstorm (4)[2]	311	314	8.3	9.3
C	Denver	Thunderstorm (5)	193	193	6.1	2.0
D	Minneapolis–St. Paul	Thunderstorm (5)	273	272	16.8	16.3
A	Chicago	Heavy fog (4)[2]	359	356	13.0	3.4
B	Chicago	Heavy fog (4)[2]	296	297	13.4	11.3

[1] Average delay (in minutes) per operation.
[2] These data, subsets from two separate airlines (airlines *A* and *B*), represent operations and delays for a common set of weather days at Chicago.

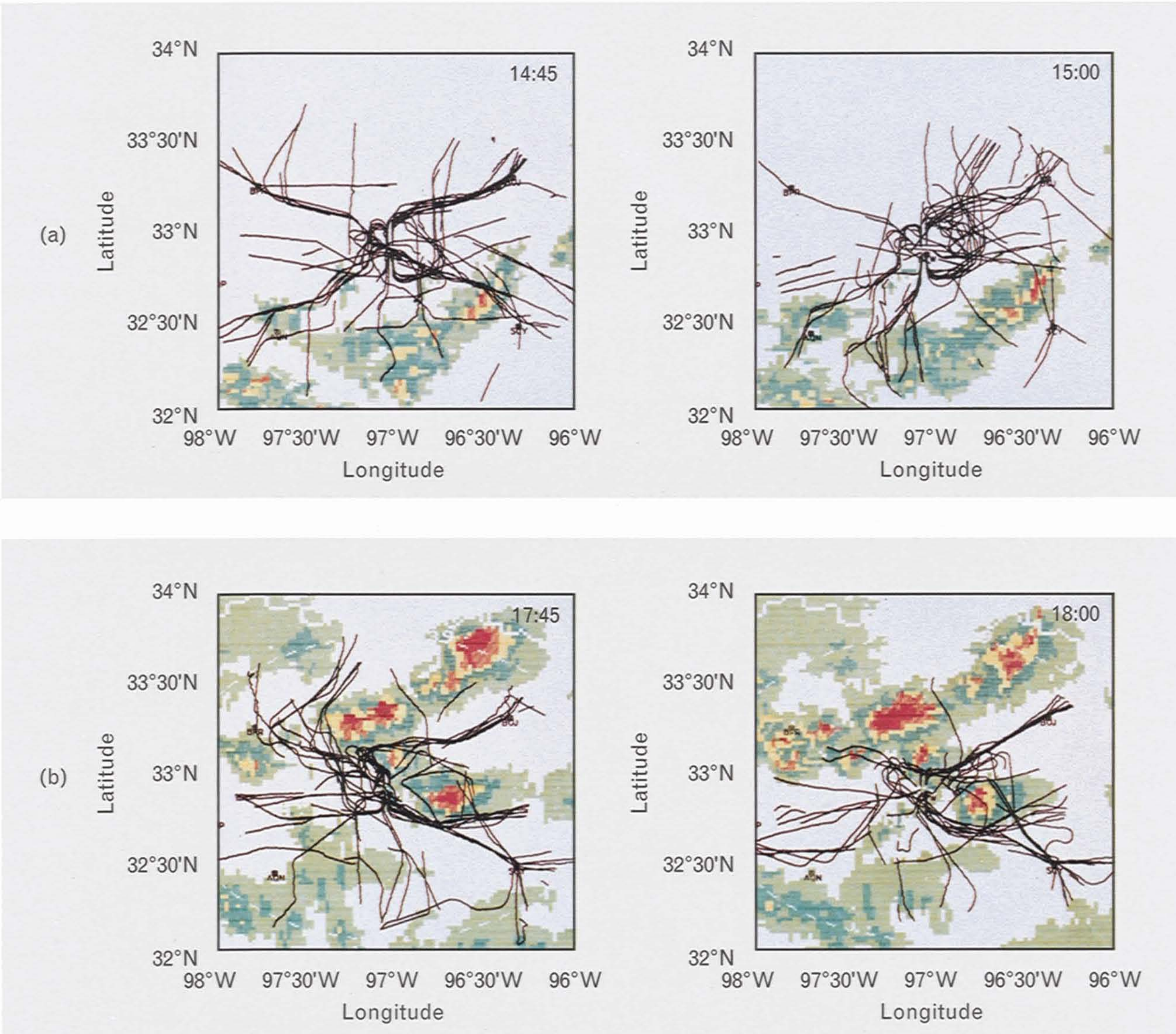

FIGURE 2. Example of the effects of a storm on a major airport for (a) a storm near an arrival gate, and (b) a storm near the airport itself. Weather reflectivity information from a National Weather Service (NWS) radar along with flight tracks are shown for Dallas–Fort Worth International Airport (DFW) on 2 August 1992 for 15-min intervals centered on the time indicated in the four panels (14:45, 15:00, 17:45, and 18:00). Planes enter the terminal area through arrival transition areas (i.e., gates) located northeast ("BUJ"), southeast ("SCY"), southwest ("AQN"), and northwest ("BPF"), and land to the south at DFW airport. Departures leave the airport to the south and then turn to depart between the gates. In part *a,* planes arriving at the DFW terminal area from the southeast encounter storm cells near the southeast arrival gate. For the first 15 min (time 14:45), most flight tracks travel very close to or through several high-reflectivity cells. In the next 15-min period (time 15:00), however, nearly all flow from the southeast gate has ended and there now are a variety of paths being used to approach and leave DFW. Note that there was a significant disruption to the terminal traffic flow even though there were no storms near the airport itself, thus illustrating the need to anticipate the movement of significant storms all the way out to the edges of the terminal area in order to maintain a safe and orderly traffic flow. In part *b,* a storm is near the airport itself. For the first 15 min (time 17:45), aircraft are routed around a storm cell to the north of the airport. During the next 15-min period (time 18:00), the preferred flight path has changed in that controllers are now routing aircraft between storm cells to the east and north of the airport by using a very short final segment, thus illustrating the need to have very accurate and timely information on storm locations around the airport and the importance of anticipating storm movement and growth in that area.

around a storm cell to the north of the airport. During the next 15-min period (time 18:00), the preferred flight path has changed in that controllers are now routing aircraft between storm cells to the east and north of the airport by using a very short final segment. In both cases, the flight paths are quite close (e.g., within two miles) to high-reflectivity regions. When the weather changes this quickly, determining usable routes by discussing the situation with pilots increases the controller work load significantly. Figure 2(b) illustrates the need to have very accurate and timely information on storm locations around the airport and the importance of anticipating storm movement and growth in that area.

This example from Dallas also illustrates the challenges that terminal automation systems will face in attempting to generate optimized traffic trajectories for terminal routes that must change quickly in response to evolving storms. Historically, the design of such automation systems has addressed path optimization and conflict resolution by typically assuming a time-stationary, fully understood set of flight paths. Accomplishing automation in storm situations such as those shown in Figure 2 will require very thorough knowledge of regions that aircraft must avoid as well as the capability to predict future storm locations.

Reducing Delays That Result from Low Ceilings and Visibility (C&V)

Clouds and/or fog that results in low ceilings and visibility (C&V) can significantly reduce the rate at which planes may land at an airport. The majority of C&V events occur early in the morning or evening, with the morning events being particularly disruptive because they create delays that propagate throughout the day. From 60% to 90% (depending on location) of C&V events last less than two hours [3].

There are two means of recovering the reductions in effective airport capacity that are caused by C&V events:

1. maximize the instrument flight rules (IFR) capacity of the runways by using terminal automation and wake-vortex advisory systems to achieve more nearly optimal aircraft sequences and spacings, and
2. help anticipate the onset and cessation of C&V events so that traffic flow into the terminal area can be matched more appropriately to the available capacity.

Each of these approaches has different requirements for weather information. We first consider the type of weather information that is needed to maximize the IFR capacity of runways.

The use of terminal automation systems to improve the effective capacity of a runway has been discussed previously by D.A. Spencer et al. [4] and H. Vandevenne and M.A. Lippert [5]. In the essential computation, flight times are determined for various possible trajectories so that the aircraft arrive at merge points and at the final approach fix to within an inter-aircraft timing tolerance of approximately five seconds. Meeting this constraint requires very accurate and detailed knowledge of the wind field.

Figure 3 compares flight times for typical DFW traffic merging with and without winds aloft. From the figure, we see that we must consider the winds aloft to meet the terminal-automation objectives of increased runway utilization. Obtaining an accurate wind field, however, can be very difficult for certain weather situations, e.g., the coastal storms that move up the East Coast, producing windy, low C&V events. For such storms, the winds can vary significantly over periods as short as a half hour as a front passes. Furthermore, the winds can also vary dramatically with altitude.

The separation between successive aircraft landing on a runway or on an adjacent runway during IFR conditions is governed by worst-case wake-vortex-protection considerations. These considerations, however, are excessively conservative for much of the time, either because the wind may blow the vortices away or because turbulence may cause the vortices to dissipate. By predicting the winds and turbulence phenomena that will occur during an aircraft's final approach, ITWS can facilitate the deployment of an effective wake-vortex advisory service [6, 7].

To make the best use of airport capacity, aircraft must be available and ready to take off or land as soon as conditions permit. Thus we need to anticipate the onset and cessation of C&V events accurately. The current FAA policy is to hold some of the aircraft at the departure airport when adverse weather is projected for the destination airport at the expected time of arrival. Thus uncertainty in the start time of a C&V event may result either in a holding pattern at the destination (if the C&V event occurs sooner than expected because more planes arrive than can be landed immediately) or unnecessary delays (if the C&V event occurs later than expected) [8]. Uncertainty in the stop time of a C&V event often leads to planes being held at the departure airport until the weather clears at the destination. Because the duration of the majority of domestic airline flights in the United States ranges from one to two hours, the net effect is that an uncertainty in stop time can increase the effective impact of a short-duration C&V event by 50% to 100% [9].

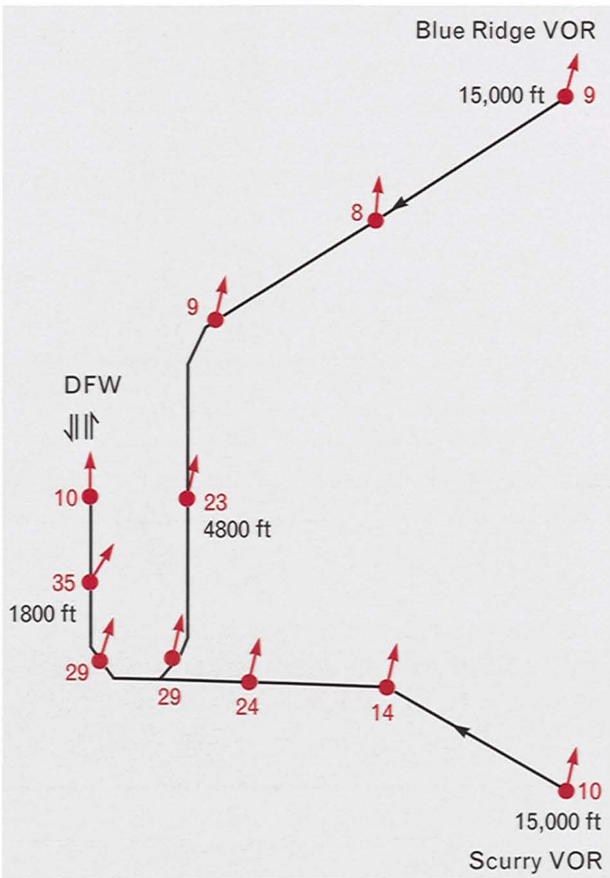

FIGURE 3. Flight paths to DFW and corresponding wind field in knots (shown in red) from 1993 ITWS data. For a flight from the northeast to the runway, the time of flight with the wind field indicated is 24 min 13 sec. (With no winds, the time of flight would be 23 min 47 sec.) For a flight from the southeast to the runway, the time of flight with the wind field indicated is 15 min 42 sec. (With no winds, the time of flight would be 16 min 30 sec.) At the merge point of the two flight paths, the error in the time difference between the two flights would be 1 min 14 sec (2.9 nmi) if the wind field indicated had not been considered in the calculations. This error is much greater than the desired inter-aircraft timing tolerance of approximately 5 sec.

Generating ITWS Informational Products

In this section, we describe the salient features of several ITWS informational products to illustrate how the use of data from several sources can take advantage of the complementary nature of the various sensors involved to provide capabilities not possible with any single sensor. The strategy used has been to introduce ITWS products in a series of steps. For obtaining early operational benefits, the first step calls for the release of products (called initial operational capability [IOC] products) that are relatively mature from the viewpoint of current meteorological knowledge. The IOC products will

1. increase the effective airport capacity during adverse weather by predicting the weather's impact on terminal routes (such as occurred in the DFW examples) and the wind shifts that may dictate runway changes, and by providing weather information for the TATCA system,
2. address urgent safety needs such as the prediction of microburst wind shear and the identification of particularly hazardous storm cells, and
3. reduce controller work load and improve pilot awareness of weather conditions by providing tailored information for direct data-link transmission to pilots.

The second step of ITWS product development will focus on providing products that can better anticipate changes in the airport arrival and departure rates. Applied research continues on these products, which will provide, e.g., short-term predictions of changes in C&V and storm growth and decay.

Weather Sensors in the Terminal Area

To understand the ITWS informational products, we first need to be familiar with the available sensor data. Table 3 [10] describes salient features of the principal ITWS sources:

- As described by M.W. Merritt et al. [11], TDWR is scanned over a 120° sector to provide a very-high-resolution view, in both space and time, of the airspace near the airport (e.g., within 10 km of the airport center). Because TDWR focuses on the airspace immediately around the airport, the radar typically provides volumetric coverage over only about one-third of the terminal airspace.

- Functionally similar to TDWR, the Next Generation Weather Radar (NEXRAD) is a pencil-beam pulsed Doppler weather radar. In addition to providing aviation weather information to en route facilities, NEXRAD is also a principal severe-weather data source for NWS forecast offices. Because NEXRAD typically covers the full terminal area with 360° scans, the radar takes more than twice as long as TDWR to complete a full-coverage scan even though NEXRAD scans fewer elevation angles and to a lower maximum angle. The end result is that the interval between the time NEXRAD makes a measurement in a specific location and the

Table 3. Principal FAA and National Weather Service (NWS) Sensors Used for Aviation in the Airport Terminal Area (from Reference 10)

Sensor	*Type*	*Distance from Airport* [1]	*Informational Products*	*Update Interval*	*Comments*
TDWR	Pencil-beam Doppler radar	15 km	Microburst, gust fronts, wind-shifts reflectivity, and radial-velocity storm motion	1 min at surface; 2.5 min aloft	Volume scan over 120° sector centered on airport; color and alphanumeric displays
NEXRAD	Pencil-beam Doppler radar	10–80 km	Mesocyclone, tornado, hail, echo tops, radial-velocity reflectivity, velocity-azimuth display (VAD), and storm track	6 min	Color display at CWSU
ASR-9	Fan-beam Doppler radar	0 km	Vertically integrated reflectivity	30 sec	On controller displays
LLWAS	Anemometers	0 km	Microburst and gust fronts	30 sec	Alphanumeric displays only
Lightning	Air-to-ground VHF receivers	>100 km	Air-to-ground lightning-stroke locations	5 min	National network; locates strokes by time of arrival
MDCRS	On-board aircraft measurements	0–80 km	Temperature and winds	7 min per aircraft	Downlink via ACARS
ASOS	Several types	0 km	Automated station observations	1 min	Thunderstorm-report sensor under study
RVR [2]	Optical	0 km	Horizontal visibility	10 sec	

[1] Airport distances are typical. A distance of 0 km indicates on or very near the airport location.
[2] The Runway Visual Range (RVR) data will not be used by ITWS until the second phase of development.

time at which ITWS must still treat the measurement as "current" information can be quite long relative to thunderstorm growth times.

- The ASR-9, which provides the main source of reflectivity information to terminal controllers, uses a fan beam in elevation and a 2° azimuth beam scanning at 90° per sec. The weather reflectivity information is smoothed with respect to time to yield an effective update time of 30 sec. By judicious choice of range weighting parameters [12], the ASR-9 does a reasonable job of estimating storm reflectivity. There have been significant operational problems, however, as a result of ground clutter induced by anomalous propagation (AP). This effect is discussed in the following subsection.
- LLWAS is a set of anemometers located near the approach corridors at a number of major airports.
- Lightning information is provided by a national network of VHF receivers that locate cloud-to-ground lightning by the differential time of arrival at various locations.
- Airline aircraft that have been suitably equipped measure and record the atmospheric temperature and wind velocity during a flight. The information is then transmitted to the ground via a data link and stored and made available by the Meteorological Data Collection and Reporting System (MDCRS).
- ASOS is an automated ground-based system that provides information on surface temperature, humidity, wind speed, C&V, and precipitation type at many locations throughout the United States.
- Lastly, the Aviation Gridded Forecast System (AGFS), a major system not shown in Table 3, is a new analysis of global weather data coupled to numerical weather-prediction models. With relatively high space/time resolution, AGFS provides background winds, humidities, and temperature for the ITWS analyses.

ITWS Initial Operational Capability (IOC) Products

We focus first on the ITWS products that provide reliable information on storm location and severity. For some of these products that have not been described in a publication before, this subsection provides the relevant technical discussion. We then highlight some of the remaining IOC products, which either are described in other articles in this issue (e.g., the products for storm motion, microburst detection and prediction, and terminal wind) or have been presented elsewhere (e.g., the gust-front product).

Storm Location and Severity. Table 4 shows the three sources of storm reflectivity information and lists the weaknesses of each of the different radar sensors. Because of their distinct characteristics and weaknesses, these three sensors provide differing depictions of the same situation to air traffic users (i.e., terminal controllers, terminal supervisors/traffic managers, en route traffic managers, and airlines), thus sometimes making the efficient coordination between users difficult. Such coordination is essential, however, to achieve orderly and efficient traffic flow. Consequently, ITWS seeks to supply a single product that provides reliable integrated reflectivity and storm information to all users.

In a recent study of storms in Denver and Florida, the reflectivity of a number of storms increased by approximately thirty decibels (from a level close to the reflectivity of clear air to a level that many pilots will avoid) in a time interval as short as eight minutes [13]. Because a storm's reflectivity can change so quickly and because aircraft may fly in very close proximity to storms in the terminal area, it was essential that the sensor responsible for the reflectivity data have as high an update rate as possible and provide coverage throughout the terminal area. These considerations virtually dictated the use of the ASR-9.

Data from the ASR-9 weather channel are often contaminated by AP clutter. In the standard atmosphere, a radar beam typically travels in a slightly curved path whose radius of curvature is greater than the earth's radius. Under super-refraction conditions, however, *ducting* may occur in which the path of the beam becomes more highly curved and energy is diverted toward the ground, thus illuminating targets below the radar horizon. Radar returns from these targets are referred to as AP clutter. Because of the spatial and temporal smoothing performed by the ASR-9 weather-channel processing, a user looking at

Table 4. Weaknesses of the Three Radar Sensors Used to Obtain Storm Reflectivity Information

Radar Sensor	*Deficiencies in Precipitation Representation*	*Deficiencies in Operational System Tracking and Extrapolation*
TDWR	• Misses cells aloft • Does not provide product in high-attenuation regions (e.g., in and beyond heavy-rain regions) • Underestimates reflectivity due to attenuation • Has slow update rate beyond 5 nmi	• Errors due to reflectivity-core descent • No extrapolated positions
ASR-9	• AP ground clutter can contaminate data • Quality of display is poor • Only two of six levels are displayed • Supervisors and traffic managers do not have displays	• No tracking or extrapolation (manual option is available, but it is *very* work-load intensive)
NEXRAD	• Slow update rate • Data-processing and transfer delays • Available only on Enhanced Traffic Management System (ETMS) at terminal facility	• Erratic tracking • No extrapolated positions

a display has difficulty distinguishing AP clutter from real weather signals.

The atmospheric conditions that cause AP are temperature inversions (temperature increasing with altitude) and moisture gradients (moisture decreasing with altitude). During a nocturnal inversion, radar returns that look very similar to weather returns will appear on the ASR-9 displays even when the sky is free of clouds. As the inversion strengthens throughout the night, the AP clutter increases in spatial extent and intensity.

In addition to nocturnal inversions, the passage of a cold thunderstorm outflow over or near the ASR-9 site sets up an inversion condition that may cause ducting. In such a situation, valid weather returns coexist with, and may even be contaminated by, AP clutter.

ITWS identifies AP clutter by comparing ASR-9 data to a NEXRAD reflectivity product. Basically, returns in the ASR-9 data that do not have corresponding returns in the NEXRAD product are assumed to be AP clutter [14]. (Note: The use of TDWR data in the comparison is being investigated.)

To compare the ASR-9 data with the NEXRAD data, we must first consider the different characteristics of the two radars. The ASR-9 fan beam provides a near-instantaneous vertical integration of the weather. The NEXRAD product represents the maximum reflectivity (in the column above a grid point) of the data collected during a series of non-overlapping scans at different elevation angles. Because the ASR-9 update time of thirty seconds is substantially less than the NEXRAD product update time of five to six minutes, adverse weather can develop and be detected by the ASR-9 before it even appears in the NEXRAD product. Under such circumstances, the adverse weather in the ASR-9 data can be misidentified as AP clutter because of the lack of sufficient confirmation in the NEXRAD data. To prevent such errors, ITWS compares the NEXRAD product to an ASR-9 measurement near to the middle of the NEXRAD measurement interval.

Furthermore, because of the dynamic nature of weather, the possibility exists that a storm may move into an area that was previously occupied by AP clutter. In such situations, valid weather returns will be edited unless corrective action is taken. Thus the AP-identification process must account for storm motion, which is discussed below.

Figure 4 provides an example of AP clutter in the presence of thunderstorms at Memphis International Airport on 8 June 1994. On that day, a line of strong thunderstorms moved from west to east across the airport, leaving a pool of cool air near the ground. The cool air resulted in a ducting condition that generated AP clutter. Figure 4(a) shows the raw ASR-9 returns, which suggest strong storms 70 km west and 100 km northwest of the airport. Figure 4(b) shows the corresponding NEXRAD data, which indicate no significant reflectivity in those areas. By comparing these two data sources, ITWS determined that the ASR-9 returns west and northwest of the airport were from AP clutter. Figure 4(c) shows the locations of AP clutter in black, and Figure 4(d) shows the edited precipitation map as it might appear on the ITWS product display. Similar AP-induced false weather echoes have been observed during thunderstorms at both Orlando, Florida [15], and Dallas.

Reflectivity is not the only attribute related to storm severity. Other common characteristics include

1. storm reflectivity regions with high tops (such tops require strong updrafts, which are an indication of storm vigor),
2. lightning activity (both a direct hazard to airframes and an indicator of strong updrafts above the freezing level), and
3. storm structures indicative of hail and/or tornadic storms.

NEXRAD is used to provide estimates of the storm echo tops and hail/tornadic storm structures while the national lightning network provides lightning data.

The ITWS Storm Cell Information Algorithm [16] associates the above meteorological parameters with defined storm-cell regions. First, the algorithm defines storm cells by contouring NWS levels 3 and higher on the ITWS precipitation map created with the AP-clutter-removal process described earlier. Next, each meteorological characteristic is gridded (i.e., converted from polar to Cartesian coordinates) and standardized in orientation, resolution, origin, and time to the most recent ITWS precipitation map. Information on storm motion is used to translate the grids by an amount corresponding to the time differential with respect to the ITWS precipitation map. In the resulting array of gridded storm-cell characteristics, the algorithm finds cell contours that correspond to the highest nested reflectivity levels for areas exceeding a minimum size; i.e., the local maxima in the gridded array are located. For each storm cell found, the ITWS Storm Cell Information Algorithm generates text to describe the cell: the maximum echo-top value within the contour is displayed and the maximum probability of severe hail and the maximum lightning flash rate are given if they exceed their respective threshold levels. An example message, which is displayed for a particular storm in response to a user request, appears in the lower right corner of Figure 5. In this example, the ITWS algorithm indicates the presence of hail, wind circulations, cloud-to-ground lightning, and echo tops of 58,000 ft, all of which are indicative of a severe storm.

Storm Motion. From our earlier discussion, information on storm motion is clearly essential in associating measurements made by different sensors. The ITWS Storm Motion Algorithm, discussed in the article "Automated Storm Tracking for Terminal Air Traffic Control" by E.S. Chornoboy et al. in this issue [17], has a dual role of providing planning information directly to ITWS users as well as assisting ITWS algorithms that combine location-specific data from different sensors in the data-association process.

The ITWS Storm Motion Algorithm translates the smoothed representations of storm leading edges to obtain the storm extrapolated positions (SEP). These positions represent the first steps in estimating the future locations of storms. The ITWS Storm Motion Algorithm is also viewed as the principal means of estimating the future locations of snow regions to assist in estimating the future snowfall rate at an airport. In Figure 5, the leading edge of the storm and the extrapolations for 10 and 20 min in the future are represented by light-blue lines.

Microburst Detection and Prediction. As noted in the article "Supporting the Deployment of the Terminal Doppler Weather Radar (TDWR)" by J.E. Evans and D.M. Bernella in this issue [18], the identification of regions of significant wind shear is a key step

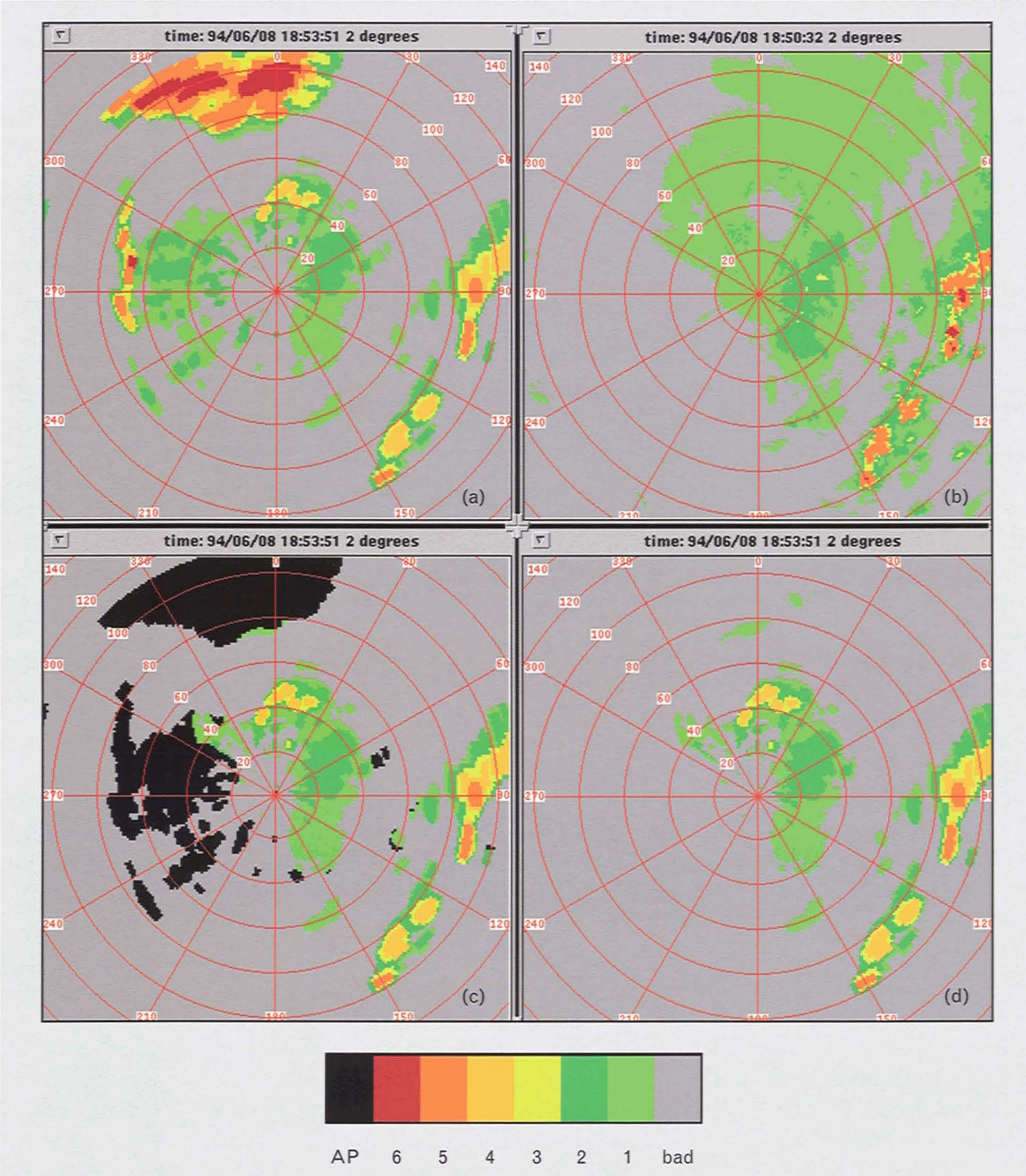

FIGURE 4. Removal of anomalous propagation (AP) clutter in the presence of thunderstorms at Memphis International Airport on 8 June 1994: (a) raw Airport Surveillance Radar-9 (ASR-9) data contaminated with returns from AP clutter, (b) corresponding Next Generation Weather Radar (NEXRAD) reflectivity data, (c) areas (shown in black) identified as AP clutter, and (d) the edited image with AP clutter removed. For part *c*, ITWS determined the AP-clutter regions by comparing the overlapping areas of images *a* and *b*. (Note: In the color bar, levels 1 through 6 correspond to the standard NWS levels.)

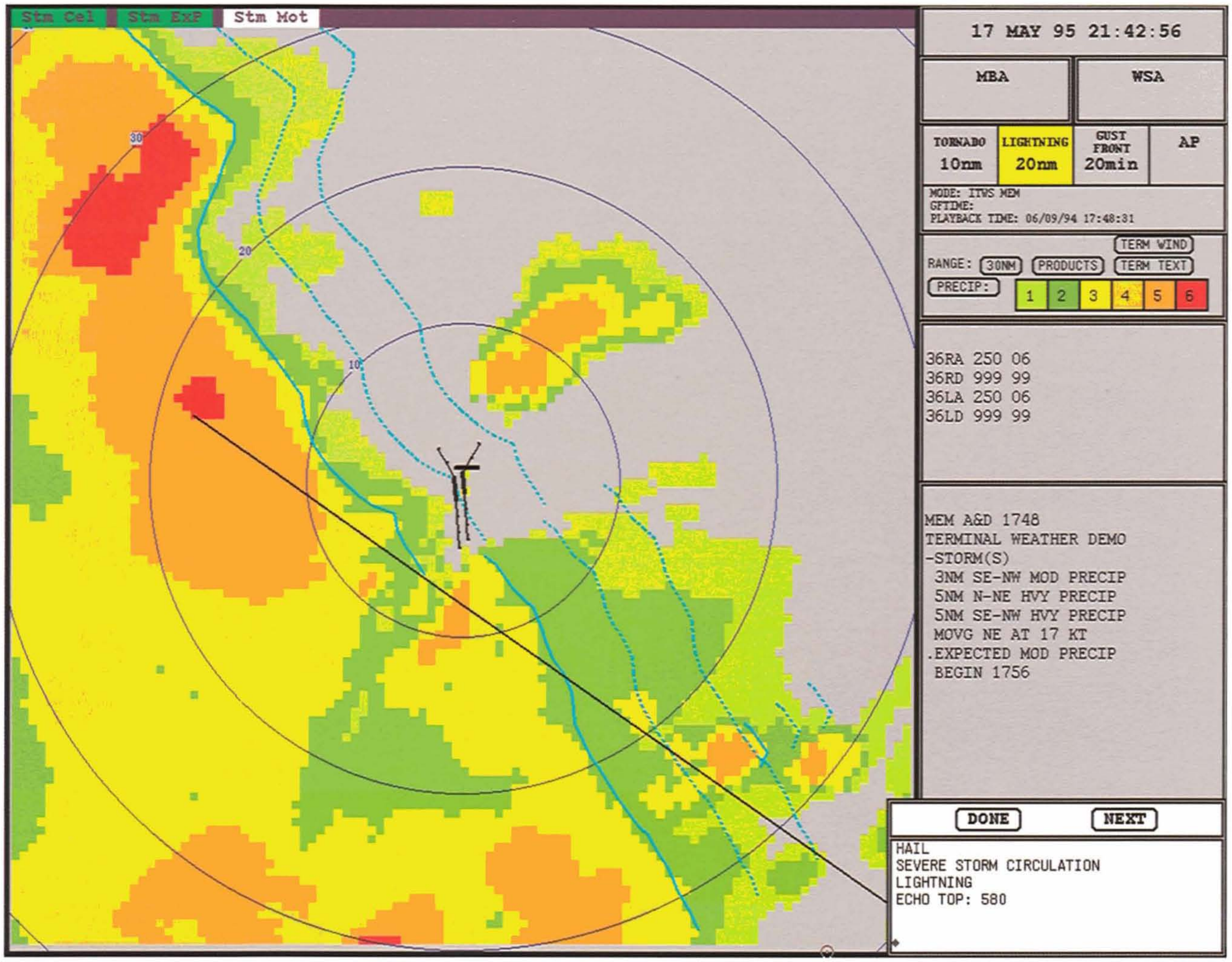

FIGURE 5. Example of ITWS storm-cell information feature for a severe storm that recently occurred at Memphis airport. The storm-cell information box is shown at the bottom right corner, and the ITWS pilot terminal text message is shown above that box.

in determining whether a pilot receives a wind-shear warning for a specific approach or departure region. The alerts generated by ITWS are made more meaningful by a combination of techniques: one that provides better localization of the shear and another that gives advance warning of the onset of a wind-shear event.

The ITWS Microburst Detection Algorithm focuses on estimating regions of strong shear [19]. The resulting regions are typically more compact than those provided by TDWR and will more closely match those supplied by airborne systems for detecting wind shear.

The ITWS Microburst Prediction Algorithm, described in the article "Automated Microburst Wind-Shear Prediction" by M.M. Wolfson et al. in this issue [20], uses thermodynamic information coupled with radar reflectivity data to estimate the strength of a downdraft from a descending storm core, thus predicting the onset of wind-shear events. Here, again, information on storm motion is essential for ascertaining vertical changes in a storm that is moving horizontally. Because many microburst predictions occur for storm cells that are in close proximity to a storm that is already producing microbursts, accurate estimates of the spatial regions associated with existing microbursts are crucial. Such accurate estimates can be obtained from the ITWS Microburst Detection Algorithm.

Gridded Terminal Winds. Estimation of the horizontal winds on a three-dimensional grid is currently required for terminal automation and will also be required for wake-vortex advisory systems [6]. Additionally, knowledge of the wind field will be important in the future for estimating storm growth and decay, whether the estimation is accomplished by rule sets or by explicit numerical models.

The development of a wind-estimation algorithm poses a number of challenges. First, the algorithm must take into account differences in the nature of the available measurements: e.g., aircraft and LLWAS measurements provide vector winds at discrete points; Doppler radar data supply the radial component of the wind over wide regions. In addition, the algorithm must also account for the different spatial and time resolutions of the available data: e.g., the national model data arrive infrequently and cover a large three-dimensional area; the aircraft measurements, which, although sparse, are the principal source of data at upper altitudes in the descent and initial approach regions; and the Doppler measurements provide data of high spatial/time resolution at lower altitudes. The article "The Integrated Terminal Weather System Terminal Winds Product" by R.E. Cole and F.W. Wilson in this issue [21] describes an approach that uses a cascade-of-scales analysis consisting of nested grids. Each of the nested analyses provides a uniform level of refinement, incorporating at each stage information appropriate to the scale in question.

Gust-Front Detection and Wind-Shift Estimation. An enhanced gust-front detection algorithm has been developed for both the ASR-9 and TDWR [11]. The new algorithm, which has many features not found in the current TDWR gust-front algorithm, is much better than the previous TDWR algorithm at detecting gust fronts that have weak shear and/or unfavorable viewing angles [22]. Estimating the winds behind a gust front, however, continues to be a challenging task.

Knowledge of gust-front winds is important for ATC planning. If the winds behind a gust front can be estimated accurately before the front crosses an airport, air traffic supervisors can position aircraft to accomplish runway changes with minimal disruption. At major airports, approximately fifteen to twenty minutes are typically required to change the direction of traffic on a particular runway.

Currently, with TDWR alone, a least-squares uniform wind field is fitted to the radial velocities in an area behind the detected gust front. For best accuracy, the azimuth and range extent of this area needs to be relatively large. Unfortunately, a uniform field may not be a good model of the winds behind a gust front. To obtain much more precise estimates of the winds behind a gust front, the ITWS IOC Gust Front Detection and Wind Estimation Algorithm combines information from LLWAS with TDWR information. The use of information from multiple TDWR systems and the ITWS gridded terminal winds product will be investigated as a preplanned product improvement to IOC ITWS.

Text Products for Data-Link Transfer to Pilots. S.D. Campbell [23] has demonstrated the value of using existing text data-link displays in aircraft to provide pilots with important weather information. A principal challenge here has been to develop algorithms that can provide reliable short-term predictions of weather events, such as heavy precipitation or wind shear, that will affect airport operations. Typically, pilot data-link users require weather information while they are still some distance away from the airport, thus making heads-up anticipatory information essential.

ITWS generates these anticipatory pilot text products by using the underlying storm-motion gridded-field estimates together with regions of heavy precipitation and wind shear. A challenge in constructing the format for the weather summary has been the determination of priorities for reporting various phenomena. This prioritization has been accomplished by a group of pilots from the major airlines, who have substantial flying experience and a good understanding of aviation meteorology. An example of an ITWS text message appears in Figure 5.

Preplanned Product Improvements

To improve terminal safety and reduce delays as quickly as possible, the FAA will deploy the system with only the initial set of products described above. For the initial system, a cutoff date was established and only those operationally useful products which were relatively mature from a scientific and engineering viewpoint were included. There were a number of areas where very substantial further improvements in safety and delay reduction could have been achieved by accurate short-term predictions, but the scientific/engineering knowledge was too immature to be a part of the initial system.

Research is currently under way in three areas to enable adding the desired enhancements to the system. Predicting convective storm growth and decay will permit the extrapolated-storm-position product to be more useful as a tool for traffic planning. The Microburst Prediction Algorithm has a rudimentary storm growth and decay detection capability that may be useful in achieving accurate estimates of the future spatial extent of storms.

Changes in C&V or runway winds can cause major changes in effective airport capacities. Anticipating such changes is essential for the efficient management of aircraft traffic flow. Initial experiments in predicting C&V changes will commence in 1995 at San Francisco International Airport. Research is also under way to predict changes in runway winds. Anticipating changes in runway winds will also be very important for dynamically adjusting aircraft spacings on approach to maximize capacity while maintaining a safe margin against wake-vortex encounters [6].

Real-Time Prototype Systems

The objectives outlined in the previous sections—to reduce flight delays caused by adverse weather and to improve airport safety (both directly, by providing improved information on the nature of the weather hazards, and indirectly, by reducing the work load of those individuals responsible for ensuring that safety)—are principal objectives of the overall U.S. aviation system. Given the analyses provided in numerous articles, the technical validity of the individual ITWS algorithms is evident. Nonetheless, technical validation of the ITWS approach, although necessary to ensure the ultimate success of the development project, is not sufficient. We do not have to look far to find instances of systems that were laudable in theory but were exorbitant to develop, late to deliver, and, when commissioned, not what the users wanted or needed. Thus, no matter how promising the concepts of a system like ITWS might appear, we must address at least two key areas of concern before proceeding to full-scale development:

1. Can ITWS generate its informational products in real time by using a reasonable level of computing resources? Can a production version of the system be deployed at multiple airports without prohibitive cost or long delays?
2. Will users find the ITWS products operationally useful? Can the weather information be delivered in a format that does not increase the user work load?

Our approach, which has proven extremely successful in previous development programs at Lincoln Laboratory [24], was to use a functional prototype of the system to generate products in real time for operational assessment by potential users. Real-time demonstrations early in the development process were preferred over off-line simulations because of the difficulty involved in simulating the weather environment so that the visual observations of both pilots and controllers are included and enough operational fidelity is provided to permit a legitimate evaluation.

When we began to consider the real-time functional prototype as part of the evaluation and development process for the ITWS project, we discovered a number of significant challenges that we had not faced to such an extent in prior projects. The first challenge was the diversity of the ITWS data sources, which, in many cases, did not (and currently do not) provide real-time access to the data required by the ITWS algorithms. The second challenge was the number of different ITWS users: air traffic personnel in both the primary airport and en route centers, pilots, airline operations personnel, and NWS users. We had to consider the needs of all of these users to obtain a meaningful evaluation of the products. The third challenge was a result of the extremely ambitious project schedule and the desire for quickly incorporating feedback from the users into either the product content or presentation. Finally, mechanisms to allow continuous monitoring of the system were required because air traffic personnel and pilots would be using the experimental ITWS products to make decisions in real time.

We translated these challenges into a set of design considerations for the system. The prototype had to

1. be flexible so that additional users, data sources, products, and/or alternative versions of algorithms to generate a given product could be added,
2. enable the rapid transition from off-line development to real-time usage of the software, and
3. provide for additional displays, alerts, and other tools for representing status information to support the real-time analysis of product algorithms by safety monitors.

Figure 6 contains a high-level depiction of the architecture of the ITWS functional prototype that was used for real-time testing in Memphis in 1994. In the figure, only the product-generation nodes and user displays are shown; specifics of the communications systems, monitoring displays, and system control have been omitted.

The prototype can best be described as one that provides the flexibility normally associated with a research and development activity, and not with an operational service. The prototype consists of a wide-area network that connects a variable number of commercially available reduced-instruction-set computer (RISC) workstations, which execute the product-generation algorithms. The network permits the addition of machines as needed because our configuration is well within the network's theoretical performance limits. The underlying infrastructure that connects these workstations into a single virtual system is designed to allow binary compatibility between the real-time and off-line worlds. This feature permits algorithm developers to execute their development software in the real-time system without having to re-engineer or even relink their code, thus providing the shortest cycle time between new algorithms (or algorithm corrections) and real-time deployment. Because the algorithms must be developed quickly, individual workstations (or sets of workstations for the computationally intensive products) are allocated on a per-product basis. This procedure achieves maximum product isolation and allows algorithm developers to feel confident that their product generators, which they can test individually off line without having to share computing resources with other products, will meet the performance requirements when the generators are operated in real-time in the context of the rest of the system.

In the architecture of the prototype, a backbone Ethernet is used to send ITWS products, intermediate test results, product-quality-monitoring information, and archival information to product-generation workstations, monitoring displays, and recording systems. The backbone Ethernet also handles network management and control functions. High-bandwidth data, i.e., the unprocessed data from TDWR and NEXRAD, are kept isolated from the backbone Ethernet by two additional Ethernets, one dedicated to TDWR and the other to NEXRAD.

RISC workstations have also been used for the individual user displays. Via point-to-point protocol, the display workstations connect through the network to the product-generation workstations. Because a number of data processing functions reside in the displays, users can quickly customize the information presented without adding to the network load, thus allowing connections of relatively low bandwidth (typically 19.2-kbaud digital phone lines) between the displays and the product-generation system.

The requirement for continuous system monitoring is a burden on a lightly staffed field site, not only because the weather is unpredictable, requiring the system to run for long periods of time, but also because of the complexity of the system and the failure modes that can occur as a result of this complexity. Therefore, we have split the processing load between those workstations running remotely at a field site and those running locally at a Lincoln Laboratory facility in Lexington, Massachusetts. High-bandwidth communication links connect the remote and local operations such that the real-time system, which resides at both locations, appears to be a single logical entity that can be operated and monitored from either of the locations. By allowing some of the monitoring functions to be performed at the Lincoln Laboratory site in Lexington, this structure will have additional benefits as the number of field sites that require monitoring increases. The mechanisms that move data through the system allow new destinations to be added in real time, thus enabling additional spot monitoring when problems are suspected.

To achieve the flexibility described above, we have

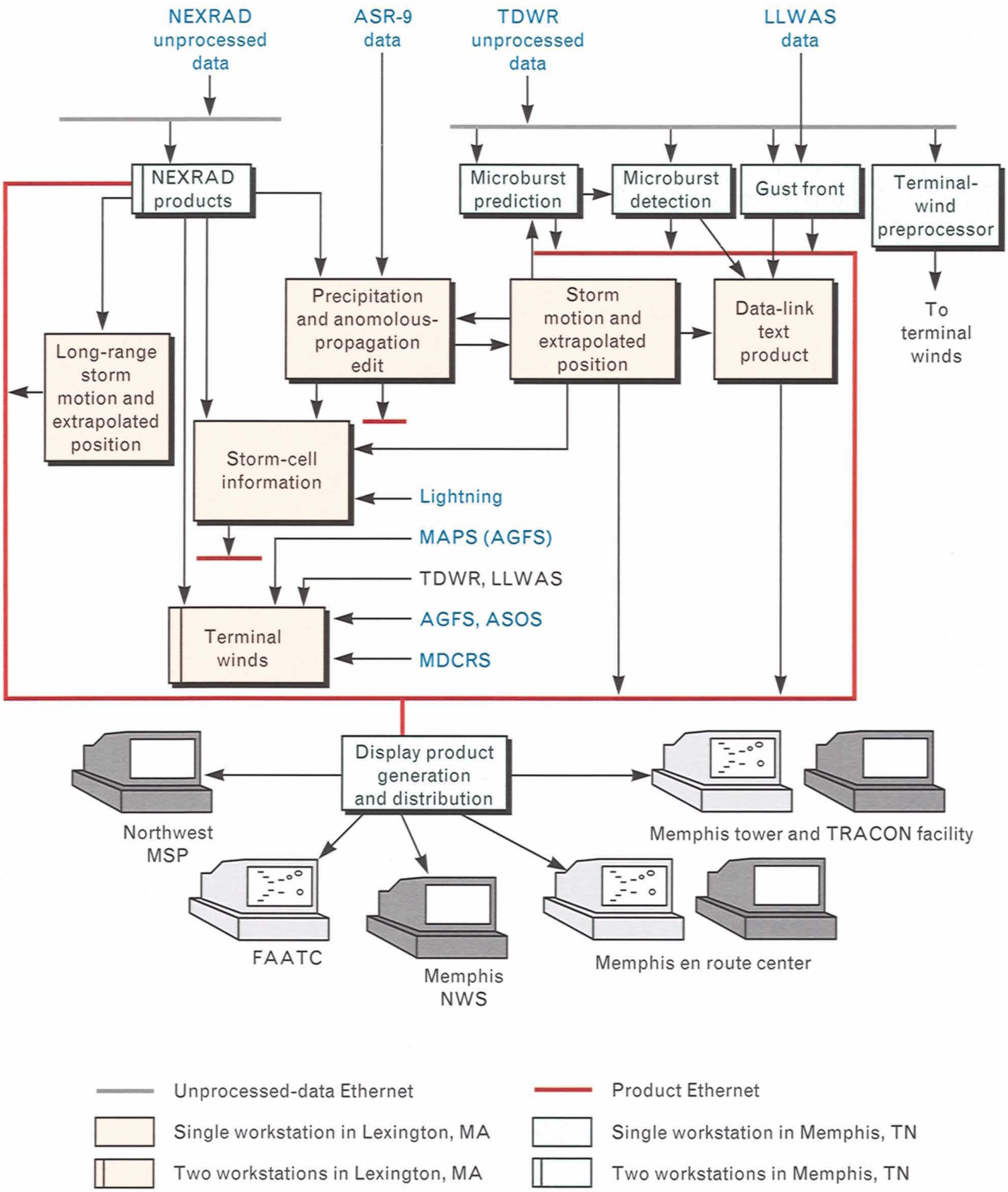

FIGURE 6. Real-time system architecture used for demonstrating ITWS in Memphis, Tennessee, in 1994. Green and red boxes represent workstations that were resident in Memphis and Lexington, Massachusetts, respectively. Data sources are indicated in blue.

made a number of compromises that would not have been made in deploying an operational system. For example, the flexibility noted in the product-isolation approach incurs greater overall processor costs, a heavier load on the overall network administration, and somewhat lower overall system reliability than would be the case with a less distributed system. The overhead (in terms of data movement and processing), which is substantial in our functional prototype, would also be reduced in a production version of ITWS. Likewise, the substantial system overhead inherent in our requirement for continuous human monitoring of product quality (e.g., the need for additional diagnostic displays) would be eliminated. Finally, the extra system overhead that results from the deployment of research code, with the mechanisms and data structures for debugging and monitoring still in place, would not be present in a formal fielded system.

As we operate our current prototype under a variety of weather scenarios, we will refine our estimates of the system's load and throughput capacity requirements, and will increase our understanding of the interactions between processes in terms of system resources. We expect that this experience will not only affect the evolution of our own functional ITWS prototype, but will also provide useful insight to a contractor in developing a more streamlined (albeit probably less flexible) system architecture without sacrificing product performance.

We plan to make a number of changes so that our current functional prototype product generator can evolve into a next-generation prototype system. From now until the deployment of operational ITWSs, we will most likely be required to support a number of additional field sites. As the number of field sites grows, so does the incentive to make the system easier to deploy and manage. Such improvement might be accomplished by sacrificing some of the flexibility that we had held onto throughout the demonstration of the ITWS IOC products. Making ITWS easier to deploy and manage provides challenges to develop new strategies for system monitoring as well as for load sharing between algorithms.

At the same time, we will be engineering a new display system. By the spring of 1994, when the full set of user requests had been articulated, we realized that the current real-time product display system (which originally had not been designed for the type of product presentation that emerged) was going to have difficulty performing all of its real-time functions. Compromises had to be made. In some cases, users were promised that, in the future, certain products would have specific response times. Furthermore, we realized that some of the product concepts that arise in a multi-airport context (e.g., the capability to switch airport displays, depending on conditions at various airports) could not be supported by mere enhancements to our current software. These requirements, which are part of the design for the IOC ITWS, have not yet been evaluated operationally. Because early operational assessment of the concepts is considered important in ensuring that the fielded system will meet user needs, developing a new display subsystem that incorporates all user requests has become a high-priority enhancement of the ITWS prototype.

Regardless of the excesses or limitations associated with our current functional prototype, the following should be considered in assessing the feasibility of the ITWS program: a functional prototype exists and that prototype can (1) generate products reliably in real time at multiple sites without requiring extraordinary computing resources, and (2) deliver those products to users in a timely fashion and useful form. Thus the prototype reduces at least one of the major risks (discussed at the beginning of this section) in bringing a system from concept to reality. The second area of concern—suitability of products—is addressed in the following section.

Results of the ITWS Testing To Date

In operational demonstrations at the Dallas–Fort Worth (DFW), Orlando (MCO), and Memphis (MEM) airports, we used the real-time ITWS functional prototype described earlier to evaluate the effectiveness and suitability of the ITWS products. The demonstrations assessed the site-specific performance and operational utility of individual products, as well as the overall system effectiveness in reducing delays and achieving efficient air-system operations. In this section, we describe the salient findings that were obtained from these initial demonstrations.

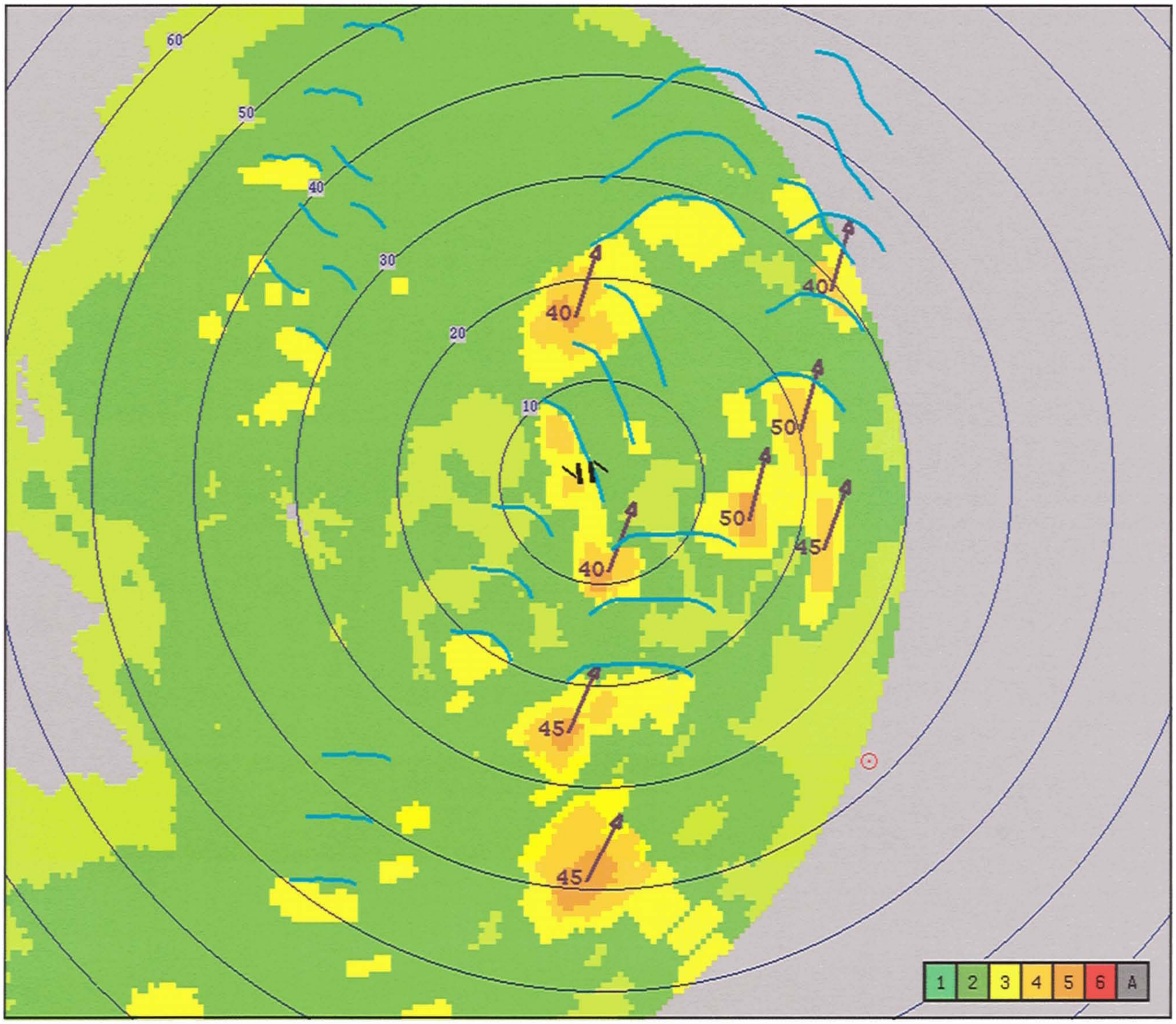

FIGURE 7. ITWS precipitation at the time an American Airlines DC-10 was landing at DFW on 14 April 1993. Right at touchdown, the DC-10 encountered heavy rain and the pilot could not keep the plane from running off the runway. The nose wheel of the DC-10 collapsed on the grass and the engine caught on fire, resulting in major damage to the aircraft's frame. In addition, several passengers were injured in the evacuation.

The first test of ITWS products was performed at DFW from May through September 1993. The test used the ASR-9, a pencil-beam radar operated by the University of North Dakota, as a surrogate NEXRAD; gridded winds data furnished by NOAA's Forecast Systems Laboratory (FSL) as a substitute for AGFS model data; and ASOS and MDCRS data relayed in real time from FSL to Lexington. The ASR-9 precipitation, storm motion/extrapolated position, and storm-cell information were provided to the DFW tower and TRACON facility, to the Fort Worth en route center Traffic Management Unit (TMU) and Center Weather Service Unit (CWSU), and to American Airlines operations personnel. The gridded winds data were supplied to a TATCA prototype that was being tested off line at Lincoln Laboratory.

The DFW weather environment presented a number of challenges. In the DFW tests, storms moved horizontally much more rapidly than in the Orlando tests that had been used for initial product development. The AP ground-clutter environment was also

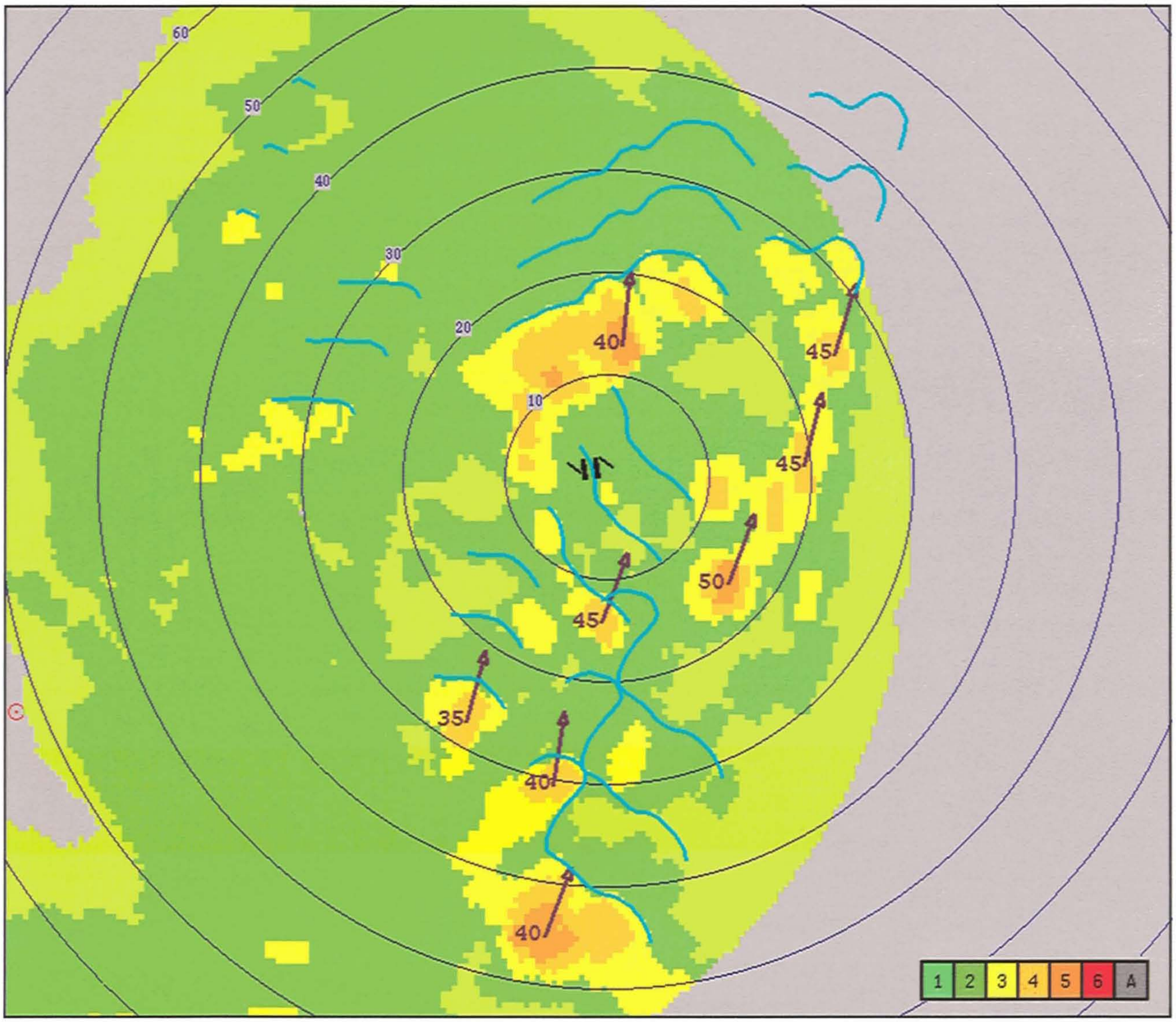

FIGURE 8. ITWS precipitation and storm extrapolated position computed for the American Airlines DC-10 touchdown at DFW on 14 April 1993. The storm extrapolated position was computed about ten minutes prior to the DC-10's touchdown, i.e., at a time when the pilot was making a decision whether to continue the approach. Note how the storm extrapolated contour lies across the runways with much the same orientation as that of Figure 7.

found to be much more severe than that observed in Orlando. As a result, we made changes to the association logic used by ITWS to combine various data sources. In addition to prompting these changes, the DFW tests also highlighted the importance of route-planning aids.

One of the potential values of ITWS is evident from analyzing an accident that occurred at DFW on 14 April 1993, when the prototype was operating in real time but was not yet providing informational products to the FAA and American Airlines users. On that day, an American Airlines DC-10 arriving non-stop from Honolulu elected to land at DFW just as storms were affecting the runway, as shown in Figure 7. Right at touchdown, the DC-10 encountered heavy rain and the pilot could not keep the airplane from running off the runway. The nose wheel of the DC-10 collapsed on the grass and the engine caught on fire, resulting in major damage to the aircraft's frame. In addition, several passengers were injured in the evacuation.

Figure 8 shows the ITWS precipitation map about ten minutes prior to the DC-10's touchdown, i.e., at a time when the pilot was making a decision whether to continue the approach. Note that, even though there were numerous storms in the terminal area, the storm of concern was located nearly ten miles away from the airport and the airport was experiencing only light rain at that time. Determining the ground speed of the storm and the storm's expected position at touchdown—information that can be estimated by ITWS—would have been difficult for any pilot of an aircraft flying at 140 mph. In Figure 8, note that the ten-minute storm extrapolation contour from ITWS lies across the runways with much the same orientation as that of Figure 7. By using a data link to transmit such information to pilots, ITWS could mitigate the effects of storms because pilots who are well informed of adverse weather conditions will be able to anticipate potential problems and respond accordingly.

The American Airlines accident at DFW also illustrates the difficulty faced by air traffic supervisors and managers who have to determine usable terminal routes by inspecting just the current precipitation information. Although we can only speculate about how useful ITWS would have been in the DFW accident, further testing at Memphis demonstrated that ITWS can be used to maintain high rates of operations in terminal areas affected by thunderstorms.

This capability was dramatically demonstrated by a severe storm that occurred midday at the Memphis airport on 9 June 1994. The storm brought near-tornado-like winds, causing considerable damage to neighborhoods around the airport. Prior to the storm's arrival, air traffic personnel in the Memphis tower had no visual clues suggesting that a severe storm with strong winds was approaching. Despite the lack of visual cues, the ITWS gust-front product had predicted a 60-kn wind 10 min prior to the storm's impact at the airport. The actual recorded gust-front winds were 63 kn, which forced the controllers to evacuate the tower. (Note: J. Evans, a coauthor of this article, was one of the people in the Memphis tower.)

The storm arrived at a particularly busy time—during the midday hub operations of Northwest Airlines. On that day, approximately seventy-five Northwest planes were scheduled to arrive and depart between 12:30 p.m. and 2:30 p.m. Northwest airline dispatchers as well as personnel at the FAA en route center, the Memphis tower, and TRACON facility had access to the same ITWS product on their displays so that they could coordinate their actions among themselves in an effective manner as the inclement weather moved within 50 nmi of the airport. The situation was particularly complicated because a storm that had spawned locally southwest of the airport was overrun by another rapidly moving storm from the west. By continually referring to ITWS's frequently updated (every 30 sec) current storm locations and 10- and 20-min extrapolated locations, the users estimated that they were able to land an additional 15 to 20 aircraft before the severe weather forced the airport to close. Furthermore, Northwest was able to make an early decision to divert 17 aircraft to alternative airports. Also, air traffic controllers using ITWS were able to determine a suitable location for holding 6 aircraft that were unable to land before the storm so that the planes could be brought safely around to the rear of the storm and be landed as soon as the storm had cleared the airport.

The major surprise in the 1993–1994 tests was the utility of ITWS to *non*-terminal users such as the personnel at the en route centers and the airlines. These users have a special need to anticipate the start and stop times of disruptions at airport terminals. Although previous TDWR and ASR-9 Wind Shear Processor (WSP) [25] testing at Orlando [24] had suggested the potential benefit of ITWS for tower/TRACON users, the Orlando TDWR and WSP testing had not considered en route or airline usage of terminal products.

Another interesting result was that the characteristics of the weather at a specific site could substantially influence the degree to which users found ITWS beneficial. For example, benefits analyses based on user comments at the end of the demonstrations in Orlando suggested that the use of ITWS in the ZJX en route center was more instrumental in reducing delays than the use of ITWS in the tower/TRACON facility. The difference can be explained by the weather characteristics in the Orlando area. Orlando summer storms move rather slowly, which allows the Orlando tower and TRACON users to anticipate the very near term (e.g., five minute) impacts by using just the locations of the current storm and wind shear. By contrast, the en route facilities, which need to anticipate the onset and cessation of weather impacts on the airport and TRACON facility so that they can better plan traffic flows and holding patterns, must rely on additional information (such as that provided by the ITWS storm-motion/extrapolated-position and storm-cell information) to make effective decisions.

A similar result was obtained by the airlines that used ITWS—the local operations offices for United Airlines and Delta Air Lines in Orlando and the systems operations center for Delta in Atlanta. The largest monetary benefits from using ITWS can be achieved at system operations centers such as Delta's in Atlanta because the bulk of the decisions on flight diversions and cancellations are made at those centers. For example, in the summer of 1993 Delta made a decision, based on the ITWS products, to continue a wide-body flight to Orlando that would otherwise have been diverted. A Delta representative later estimated that the cost of the diversion, had it occurred, would have exceeded $100,000.

Similarly, the pilot data-link text messages did not appear to be a significant factor in a pilot's deciding whether to fly through a particular storm cell or whether to continue an approach along a runway [23]. The text messages, however, did provide very useful information regarding the overall weather situation in the terminal area. For example, when wind shear had been reported on the data link with about a 15-min forewarning, pilots were more cautious in attempting low-altitude penetrations into a storm. The ability to obtain very current information on the weather near the airport proved particularly useful in reducing air-to-ground conversations (and controller work load) in situations in which severe weather had essentially halted airport operations.

The anecdotes cited above were part of valuable user feedback that helped refine ITWS. The FAA Technical Center evaluation of the ITWS 1994 demonstration made the more formal conclusions that

1. ATC personnel could use and understand the ITWS products easily; that is, meteorological interpretations of the information were not required;
2. ITWS enhanced traffic management and planning in general, and made specific improve-

Table 5. Projected ITWS Benefits for Initial Capability Products Installed at 45 TDWR Airports

User-Identified Payoff Area	*Annual Benefit* (millions of dollars)*
Higher effective airport capacity during thunderstorms	7
Anticipation of arrival- and departure-area closures/reopenings	51
Anticipation of runway impacts and shifts	36
Better terminal-area traffic patterns	3
Optimization of traffic flows	39
Reduction of downstream delays	80
Optimization of airline operations (including fuel, connections, and ramp operations)	19
Total	235

* Based on 1993–1994 demonstrations at Memphis, Orlando, and Dallas–Fort Worth

ments in traffic-route planning; and

3. during major weather incidents at both Memphis and Orlando, ITWS enabled significant improvements in operations, as documented by users at both sites.

Based on the 1993–1994 demonstrations, Table 5 summarizes the preliminary results of the ITWS benefits assessment. We see that many of the benefits are associated with traffic management use of the ITWS products to anticipate changes in terminal-area traffic flows. Originally, ITWS displays were planned for only the airport towers and terminal radar rooms. As a result of the 1993–1994 demonstrations, however, the FAA has expanded the ITWS operational concept to include ITWS displays at the en route centers as well.

Summary

Our studies indicate that inclement weather in the airport terminal area is the principal cause of delays, a significant fraction of which can be avoided by providing tailored weather information to terminal air traffic facilities, automation systems, pilots, and non-terminal users (especially air traffic management units and airline flight dispatchers) who control the flow of aircraft into and out of the terminal area. The needs of these various users cannot be addressed adequately by any single terminal sensor; rather, information from a variety of different sensors and systems must be combined.

The practical feasibility of integrating terminal sensors and systems and some sense of the benefits of such integration were demonstrated in 1993 by initial operational tests at Orlando, Florida, and Dallas, Texas, and further confirmed in the formal demonstration of the initial operational capability (IOC) ITWS products during the summer of 1994 at Memphis, Tennessee, and Orlando. In all demonstrations, the Lincoln Laboratory real-time functional prototype systems were used as a part of the FAA test and evaluation process associated with the transition of the ITWS program to full-scale development.

If the ITWS program does proceed to full-scale development in 1995 as planned, production systems are expected to be deployed at major airports by the year 2000. Meanwhile, additional demonstrations of the IOC ITWS products will take place at Memphis, Orlando, and Dallas–Fort Worth airports for further validation of ITWS's capability to deal with site-specific meteorological and operational issues. Also, research work will continue to expand the functionality of ITWS to address important needs that have yet to be met—for example, the ability to predict the growth and decay of thunderstorms and the start/stop times for events in which airport visibility is low because of clouds or fog.

Acknowledgments

Virtually every member of the Lincoln Laboratory Weather Sensing Group, which currently consists of approximately sixty people, has contributed to the ITWS development described in this article.

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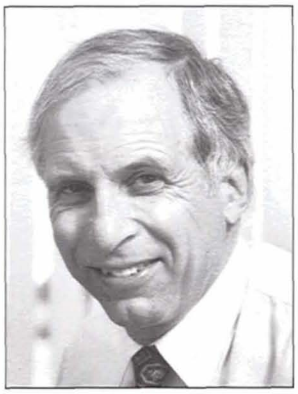

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