Weather Radar Development and Application Programs

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Weather phenomena such as microburst wind shear and severe thunderstorms are major concerns to the aviation industry. A number of significant airplane accidents have resulted from wind-shear encounters during takeoff and landing, and thunderstorms are a major contributor to airplane delay. Providing fully automated and timely warnings of these phenomena by radar is challenging because it requires rapid and accurate analysis of the three-dimensional storm structure in the presence of intense ground-clutter returns. For the last two decades, Lincoln Laboratory has been tackling this challenge by applying advanced radar signal- and image-processing techniques to weather radar data. The resulting technology is being deployed in radar-based weather information systems at major airports throughout the United States. We first discuss the salient meteorological factors that contribute to the formation of microburst wind shear, then we provide some general background on the use of pulse-Doppler radar for weather detection. We describe two specific Lincoln Laboratory programs that have generated deployed systems: the Terminal Doppler Weather Radar (TDWR) and the ASR-9 Weather Systems Processor (WSP). The article concludes with a discussion of future detection strategies that emphasizes the fusion of weather radar data by the Integrated Terminal Weather System (ITWS).

Adverse weather is the principal cause of aviation delays [1], and severe thunderstorms account for over half of the aviation delays due to weather [2]. Historically, the Federal Aviation Administration (FAA) air traffic control (ATC) system principally provided real-time separation of aircraft from other aircraft as opposed to separation of aircraft from adverse weather. However, as shown in Table 1, air-carrier fatal accidents due to thunderstorm-associated wind shear increased significantly in the period from 1975 through 1985. During that time, U.S. air-carrier accidents with fatalities due to wind shear exceeded those due to air-carrier collisions with other aircraft in controlled airspace. Although some wind-shear protection enhancements occurred after the 24 June 1975 accident at Kennedy International Airport in Jamaica, New York, a high degree of urgency in providing wind-shear protection did not occur until after the major fatal accidents in New Orleans, Louisiana (1982) and Dallas–Fort Worth, Texas (1985).

Radar detection of microburst wind shear is challenging because the spatial characteristics of wind shear vary rapidly. Furthermore, such a low cross-section target (sometimes equivalent to 0.0001 m^2 or –40 dBsm) must be detected at altitudes below 100 m in a high-level clutter environment close to the radar.

The Lincoln Laboratory weather radar program addresses detection and prediction of these aviation hazards in all phases of storm development. Lincoln Laboratory has shown that significant reductions in airplane accidents and weather-related delays can be achieved by predicting storm movements and winds in the terminal areas so that air traffic controllers can proactively route airplanes away from hazardous weather and optimize the use of airport runways.

Microburst Phenomena

A microburst is caused by storm downdrafts spreading out near the ground in short time periods of one to two minutes. Figure 1 shows the typical life cycle of a thunderstorm. Rising drafts of unstable air feed a developing column of rain and ice roughly five kilometers above sea level. This column grows vertically during the cumulus and mature phases of the thunderstorm. During these phases severe turbulence, heavy rain, and hail intensify. Relatively late in the thunderstorm's life cycle, during the mature and dissipating phases, gravitational and thermodynamic forces acting on the rain and ice column can produce a strong downdraft that extends to the earth's surface. The resulting surface outflows of air threaten the stability of aircraft at an airport on final approach or initial climb, as shown in Figure 2.

The basic model of a convective thunderstorm depicted in Figure 1 has been well understood ever since

Table 1. Passenger-Airline Accidents from 1975 to 1994 in the United States Attributed to Thunderstorm-Associated 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–Fort 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

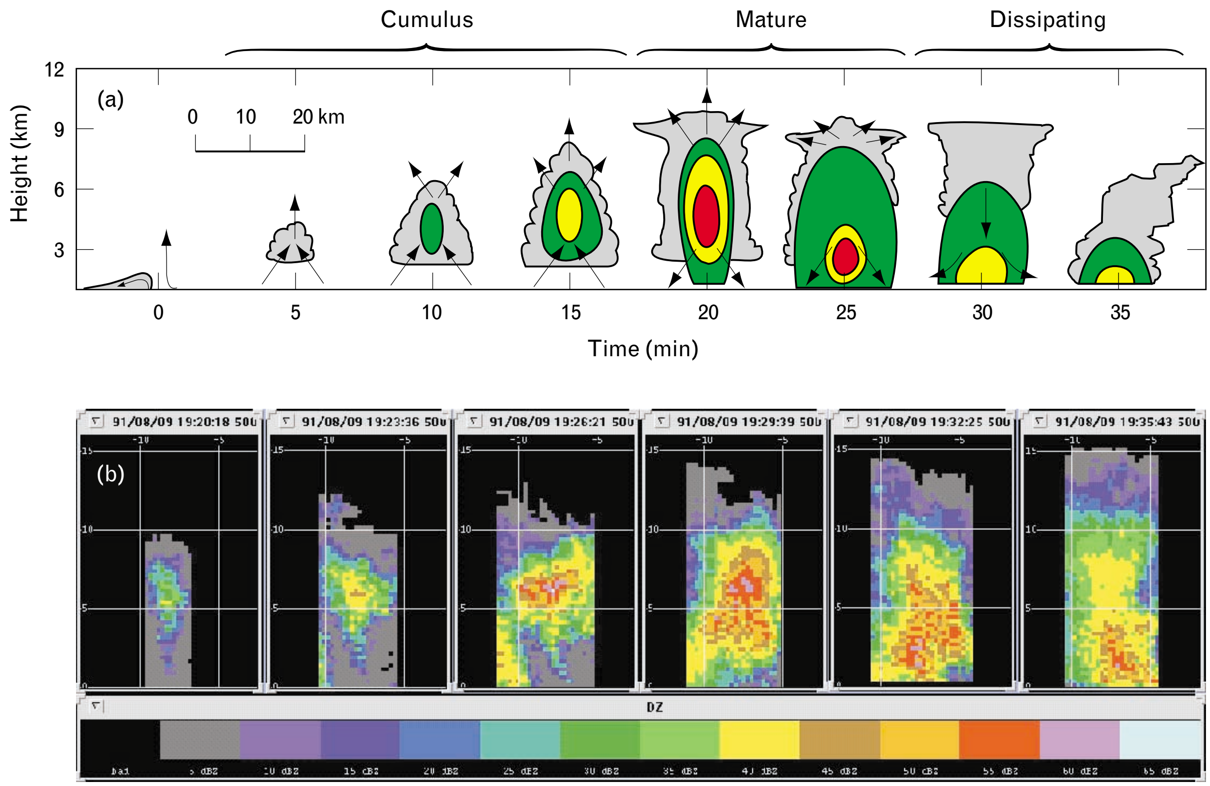


FIGURE 1. Phases of thunderstorm development and measured vertical cross sections of a storm in Orlando, Florida. (a) The upper panel shows the classical conceptual development of an air-mass thunderstorm. A gust front of colder air causes warm, moist air at the surface to be pushed aloft. The colder temperatures aloft cause the water vapor to condense into cloud droplets that release latent heat. The buoyancy created by the latent heat further increases the updraft while the cloud droplets coalesce into rain drops. In the mature phase, the downward force of water aloft exceeds the force of the updraft, allowing the rain-ice core to descend to the surface. Microbursts typically commence when the descending rain core reaches the surface. Further intensification of the downdraft can arise from melting ice or evaporative cooling. (b) The lower panel shows vertical cross sections for a convective cell observed with the Lincoln Laboratory Terminal Doppler Weather Radar (TDWR) prototype radar in Orlando in August 1991. The vertical and horizontal bars are 5 km apart, and the time difference between scans is about 3 minutes; hence about 15 minutes of observations are displayed. The storm first grew near the freezing level, which was about 5 km above ground. Dark blue corresponds to light rain, green corresponds to heavy rain, and red corresponds to very heavy rain possibly mixed with ice. A microburst occurred when the rain core descended to the surface. The rapid evolution of such storms requires weather radars to scan the storm rapidly.

detailed radar observations of thunderstorms were carried out in Florida just after the end of World War II [3]. However, major controversy existed over the cause of wind shear that led to the accidents from 1975 through 1982 shown in Table 1. Researchers first thought that the accidents arose from gust fronts induced by long-lasting thunderstorms with sustained downdrafts. Thus, in the late 1970s, the FAA deployed an anemometer-based system, the Low Level Wind Shear Alert System (LLWAS), to provide warnings on gust fronts.

Concurrently, T. Fujita of the University of Chicago had been studying tornadic storms and other severe weather for many years by analyzing the pattern of damage to structures, farm fields, and woods. (Fujita was also the developer of the F-scale for tornado severity.) He noticed that in a number of cases the resulting patterns of toppled corn stalks and trees appeared to be due to surface winds emanating from a central point as if there had been an intense, short-lived downdraft focused on the region. Fujita concluded that on the basis of flight-recorder data, the

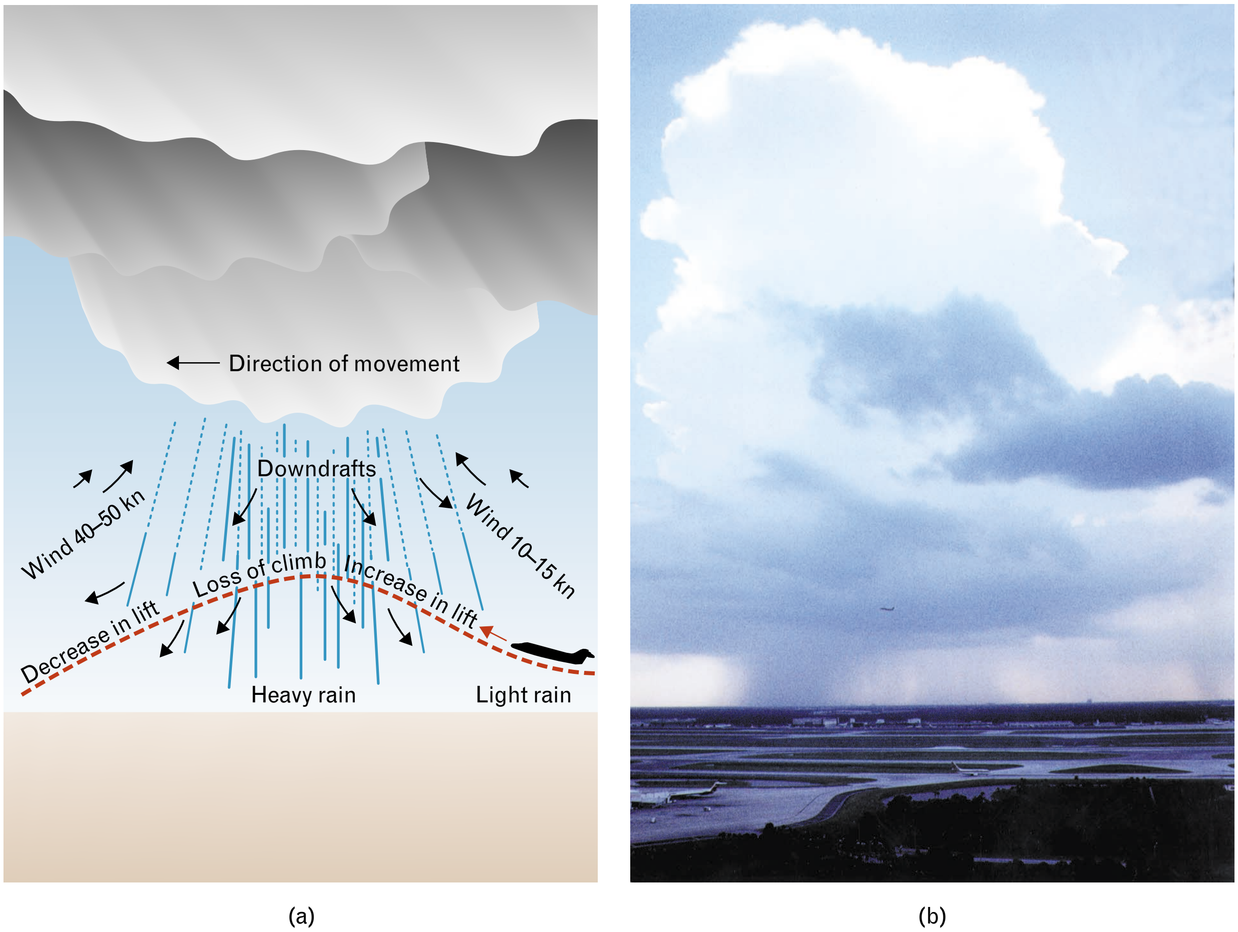


FIGURE 2. Hazardous downdrafts from a thunderstorm: (a) schematic of an aircraft taking off in a microburst, and (b) photograph of a microburst-producing thunderstorm in Orlando. The pilot first encounters a head wind (increase in lift), then a downdraft (loss of climb), and, finally, a tail wind (decrease in lift), which causes the airplane to lose airspeed.

1975 airplane accident at Kennedy International Airport had resulted from an intense, compact, short-lived downdraft that he termed a downburst [4].

Fujita's hypothesis was received with great skepticism by the thunderstorm research community. In 1982, an initial scientific weather radar experiment near Chicago, Illinois, to detect microbursts was inconclusive. In retrospect this study, called Project NIMROD for Northern Illinois Meteorological Research on Downbursts, could have been inconclusive because it had focused on the large, organized storms that produce tornadoes or hail rather than the more benign storms that produce microbursts.

Validation for Fujita's downburst hypothesis, however, came in a 1984 Joint Airport Weather Studies (JAWS) experiment near Denver, Colorado, which was led by Fujita and J. McCarthy of the National Center for Atmospheric Research (NCAR). This study unequivocally established the existence and key characteristics of microbursts [5, 6].

Two kinds of microburst occur—wet and dry—and each kind is caused by different storm mechanisms. A wet microburst occurs with heavy rain in a humid subcloud environment. The strength of the downdraft depends on water loading and the thermodynamic profile of the subcloud air. A dry microburst occurs when rain falls into a dry subcloud environment and evaporates before reaching the ground. Evaporation cools the downdraft during descent, thereby increasing its density relative to the surrounding air. In this case, the rain rate (and radar cross section) at the surface of the downdraft can be low. Pilots have difficulty identifying dry microbursts because the visual indicators of a surface outflow, which are shown in Figure 2, are not always available.

Researchers learned that a microburst might be only 2 to 6 km across with peak outflow velocities occurring in a surface layer only 100 to 200 m thick. The lifetime of the operationally significant wind outflow could be as little as ten minutes.

Given the short lifetime and compact physical size of the microburst phenomenon, it became clear why the combination of pilot reports from a preceding aircraft and an LLWAS system with sensor spacing on the order of 5 to 6 km could not reliably warn of hazardous microbursts.

Pulse-Doppler Radar for Weather Sensing

Pulse-Doppler radar is the preferred approach for detecting and predicting the thunderstorm phenomena discussed above. Point-measurement systems (e.g., anemometers, surface weather-sensing systems, and meteorological sensing balloons) cannot rapidly measure the three-dimensional structure of the storms. Satellite sensors cannot explicitly measure the winds or resolve the internal structure of the thunderstorms.

Pulse-Doppler-radar weather sensing for aviation by ground sensors is currently accomplished by two types of radar: (1) dedicated, mechanically scanned pencil-beam weather radars operating at S-, C- or X-band with beamwidths of 0.5° to 2.0°, and (2) air-surveillance radars operating at L- or S-band with azimuth beamwidths of about 1.5° and two or more broad fan beams in the elevation-angle plane. Both types of radar typically have pulse durations of about 1 μsec and peak powers on the order of 1 MW.

A wind-shear detection radar is sited to measure the low-altitude winds in the critical region from three miles before the runway threshold to two miles beyond the departure end of the runway. The microburst winds are measured via radar reflections from atmospheric particles, or wind tracers, such as rain drops, dust, or insects. Because the wind tracers are a three-dimensional distributed scatterer, the effective radar cross section depends on the radar resolution volume V and the tracer-volume-scattering density η (in m^2 per m^3). A wind-tracer cross section ($V \times \eta$) for dry microburst-outflow detection is typically on the order of –50 dBsm, while a wet microburst-outflow effective cross section is on the order of –20 dBsm. In comparison, typical urban clutter has many point targets of 1 m^2 or greater emerging from a distributed clutter background of typically –40 dBsm radar cross section per resolution element. Detecting low-cross-section microbursts just above such high urban clutter is a significant challenge to the radar system designer.

In the remainder of this article, we discuss the principal areas where Lincoln Laboratory has developed weather radar technology to address aviation weather needs. Included are descriptions of associated technology developments such as radar-signal processing and data-quality editing, fully automated generation of products via advanced digital processing techniques, and the integration of Doppler-weather radar data with other meteorological sensors.

Terminal Doppler Weather Radar

The FAA charged the Laboratory to develop a robust, fully automated pencil-beam Doppler-radar-based detection system for detecting microbursts, which was called the Terminal Doppler Weather Radar (TDWR). Three factors contributed to the difficulty of developing the TDWR. First, the data from meteorological-research radars used for the scientific experiments were of only limited value for developing fully automated detection algorithms, since the radars had no clutter filters. The data obtained with such radars required highly sophisticated interpretation by experienced radar meteorologists to determine microburst locations and features. Second, the pattern-recognition approaches used by the radar meteorologists were not appropriate for automation. Third, the FAA could obtain a frequency allocation for the TDWR only in the 5-cm wavelength region (C-band) instead of the preferred 10-cm wavelength region (S-band).

Two problems were associated with C-band operations. First, C-band was more susceptible than S-band to rain attenuation. Second, C-band suffered more problems with second-time-around, or out-of-trip, weather returns. Because the unambiguous range R_a and unambiguous Doppler velocity V_a for a pulse-Doppler radar are related by the equation $R_a V_a = c\lambda/8$, where c is the speed of light and λ is the wavelength of the propagated energy, a C-band TDWR would have a greater problem in achieving operationally acceptable values of R_a and V_a than would have been the case at S-band. Out-of-trip weather returns are a major concern because the received power from these storms drops off only as $1/R^2$.

The interclutter visibility scheme used by the Laboratory was a clutter-residue-editing map that flags range cells whose measured power does not exceed a threshold based on the fair-weather clutter-residue power [7]. Moving targets like single birds and aircraft could largely be eliminated by use of a point-target editor that ignored gates with reflectivities much higher than the local spatial average.

Some locations such as major roads that were directly illuminated by the radar beam had to be masked out under all circumstances due to the enormous range of clutter residue that was encountered at various times of the day. The impact of out-of-trip weather returns was significantly reduced by using a waveform that was unambiguous in the range domain but highly ambiguous in the velocity domain to measure the locations of storms producing these returns. The range-ambiguous Doppler-measurement waveforms were chosen to minimize the likelihood of distant weather returns being range-aliased into the central region near the airport runways.

These interference-suppression approaches have proven effective—typically fewer than 2% of the microbursts near the runway are missed due to either ground-clutter returns or range-aliased returns.

TDWR Test Bed

Achieving the desired TDWR wind-shear detection capability required antenna scanning, ground-clutter suppression, automated data-quality editing, and automated wind-shear detection capabilities that exceeded those used for the National Weather Service Doppler weather radars. To demonstrate that these capabilities were achievable, Lincoln Laboratory conducted an aggressive field-test program at five different U.S. locations, using a Laboratory-built TDWR prototype.

The prototype initially operated in the FAA-authorized S-band (2700 to 3000 MHz). The transmitter from an Airport Surveillance Radar (ASR-8) was modified to achieve zero-velocity clutter suppression in excess of 50 dB by increasing its stability. Lincoln Laboratory designed and built the receiver and digital preprocessors, continuously upgrading them as the scope of the TDWR test-bed radar evolved. The antenna pedestal came from an earlier FAA project, and the antenna reflector was built to Lincoln Laboratory's specification by Hayes and Walsh of Cohasset, Massachusetts.

The TDWR test-bed radar was deployed in 1984 near Memphis, Tennessee, for data collection in a decidedly wet microburst wind-shear environment. Figure 3 shows the test-bed radar at this site. During 1985, the major air-carrier accident at the Dallas–Fort Worth Airport in Texas further accentuated the need for rapid deployment of an operationally effective wind-shear detection capability [8].

It was also necessary to carefully assess the ability of a single Doppler radar to detect microbursts. Of particular concern was the possibility that a microburst outflow would not be observable in the radial Doppler field of a single radar. To address these concerns, the test-bed radar was accompanied by one or two additional Doppler radars (sited to provide orthogonal viewing angles of wind-shear events in a specified coverage area) plus more than twenty-five anemometers on tall poles.

The test-bed radar, with its supporting sensors, was then moved to Huntsville, Alabama, in 1986 to take advantage of additional meteorological sensors there.

FIGURE 3. Illustrated cutaway of radome revealing the Lincoln Laboratory TDWR at Memphis, Tennessee, in 1985.

In 1987, the radar was moved to Denver for testing on dry microbursts and refining the automatic microburst and gust-front detection algorithms. At that time, the Laboratory generated a technical specification for the TDWR, based on the technology developed and demonstrated by using the prototype.

In 1988, the test-bed radar was used for an operational real-time demonstration of automated microburst and gust-front detection (a discussion of this demonstration appears in the section on microburst detection). In 1989, the test-bed radar was moved to Kansas City, Kansas, to test the algorithms in an environment characterized by squall lines and clutter from moving cars, trucks, and trains.

In 1990, the test-bed radar was moved to Orlando, Florida. The S-band transmitter was replaced with a C-band transmitter to verify that acceptable performance could be achieved at the higher operating frequency specified for the production system. When the transmitter operated at C-band, the resulting beamwidth was 0.5° with maximum antenna sidelobes 25 dB down (one way) from the peak. These antenna characteristics supported the requirement of avoiding main-lobe illumination of ground scatterers while detecting returns from wind-shear phenomena extending only a few hundred meters up from the surface.

The test-bed radar operated at Orlando until the production system was installed in 1993. The test-bed radar was then used for scientific experiments by a meteorological research group.

Clutter Suppression for the TDWR

Achieving adequate suppression of clutter from fixed and moving clutter sources proved challenging. The extended nature of the weather targets (e.g., microburst outflows 2 to 6 km in diameter) meant that there could be a number of range-azimuth cells within the target region for which the residual clutter exceeded the weather returns. Also, major airports have moving clutter associated with roadways in the immediate vicinity.

The first obstacle was establishing adequate clutter suppression on clutter from fixed objects. Continuous-wave waveforms could not be applied because of the extended nature of the weather target. Pulse-compression waveforms would have difficulties from weather returned in the range sidelobes (especially when measurements are made of low-reflectivity gust fronts preceding a high-reflectivity squall line). Hence designers of the TDWR opted for a more or less standard pulse-Doppler waveform with approximately 1-μsec pulse and peak power of about 250 kW (corresponding to commercial-off-the-shelf klystron technology circa 1988). The principal problem encountered in achieving an effective 50-dB subclutter visibility over a wide variety of clutter levels was the limitation induced by the dynamic range of the analog-to-digital converter. This dynamic-range problem was addressed by using a fast-acting automatic gain control followed by digital compensation.

However, 50-dB suppression alone did not permit effective detections of low-reflectivity microbursts in high-clutter environments. Fortunately, the extended nature of the targets meant that we could take advantage of interclutter visibility (that is, in many cases we did not have to cope with the high amplitude "tails" of the clutter-intensity distribution).

Microburst Detection Algorithm

As measured by a single Doppler weather radar, the divergent outflow from a microburst produces a pattern of increasing Doppler velocity with range. This pattern is detected by using pattern-search algorithms that identify the trend of radial velocities across the outflow. For ease of implementation, the search is performed first along individual radials to produce shear segments, which are then grouped azimuthally and subjected to scan-to-scan continuity tests to detect potential outflow-regions [9].

Post-detection processing verifies the outflow-region detections by establishing that the candidate microbursts are physically plausible [10]. This process confirms that the outflow coexists with adequately intense precipitation and that storm structural and temporal features are consistent with the processes known to give rise to microburst outflows.

Table 2 quantifies the performance achieved by the TDWR algorithm. The statistics were obtained by an experienced radar meteorologist comparing the results of an off-line analysis of base data from the prototype radar with the automatic-detection algorithm

Table 2. TDWR Microburst Detection Performance by Site

Location–Year	*Probability of Detection*	*Probability of False Alarm*
Washington National (DCA)–1994	0.92	0.1
Orlando International (MCO)–1994	0.95	0.06
Memphis International (MEM)–1994	0.94	0.07
Houston Inter-Continental (IAH)–1996	0.95	0.05
Atlanta Hartsfield (ATL)–1996	0.94	0.03
Denver International (DEN)–1996	0.87	0.03

results. Probability of detection is the scan-by-scan probability, updated every minute, of the algorithm declaring a microburst that is present. Probability of false alarm is the probability of the system declaring a microburst that is not present. For both probabilities, the "truth" is measured as the determination by a trained radar meteorologist that a microburst was present on the basis of a manual examination of the radar images. In some coverage regions the radar meteorologist could also use data from the anemometer arrays and other Doppler weather radars to more accurately determine the location and severity of microburst events.

The first operational demonstration of fully automated microburst detection was carried out by using the Lincoln Laboratory TDWR test-bed radar together with a display developed by NCAR at the Stapleton Airport in Denver in 1988 [10]. A highlight for this demonstration occurred on 11 July, when the TDWR system warned five approaching United Airlines aircraft of a severe microburst that had associated airspeed losses of 40 to 80 knots [11]. Pilots flying into Denver that day reported various effects that included (1) an airspeed loss of 10 knots in 1 sec; (2) a 400-to-500-ft altitude drop with an airspeed increase from 150 knots to 210 knots within 7 sec; and (3) no airspeed or altitude losses but an inability to slow the airplane down.

The successful performance of the TDWR system during this operational period convinced the FAA to develop a network of TDWR systems at major airports throughout the country. Additional operational demonstrations of the microburst-detection algorithm were carried out from 1989 to 1993 at Kansas City and Orlando. As a result of these demonstrations, a number of improvements were made to the microburst detection algorithm to reduce false alarms and biases in the estimate of the microburst severity [12].

Gust-Front Detection Algorithm

Achieving an adequate detection capability for gust fronts that are long, narrow targets—often greater than 10 km in length—proved to be much more difficult than microburst detection. We faced a special challenge when the wind shear associated with the gust front was orthogonal to the radar line of sight (i.e., not observable in the radial velocity field).

Lincoln Laboratory's strong background in automated target detection by radar was critical in addressing the gust-front detection problem. Specifically, the following machine-intelligence approach was employed that was similar to an approach suggested by classic radar detection theory:

1. Various linear and nonlinear spatial filters (termed "functional templates") were convolved with the radar images to generate a set of interest images that are analogous to log-likelihood ratios.
2. The various interest values at each point were summed to create a net interest level analogous to summing log-likelihood ratios.

3. Similar functional templates for each phenomenon causing false alarms were used to generate negative interest values, which were summed with the positive interest values (analogous to a log-likelihood-ratio test) to create a net interest.
4. The net interest field was searched for linear features, which had the time dynamics associated with gust fronts [13]. Time continuity generated positive interest values.

Figure 4 shows the block diagram of the resulting machine-intelligent gust-front algorithm (MIGFA). The MIGFA approach provided a significant improvement in gust-front detection over the initial approach used in the TDWR: the probability of detection nearly doubled from 30% to 65% while the probability of false detection declined by 75% from 40% to less than 10%.

Deploying the TDWR to the Nation's Airports

On the basis of the successful operational demonstration of wind-shear detection capability in Denver in 1988, the FAA proceeded with the construction and deployment of the TDWR using a Lincoln Laboratory-generated technical specification for the wind-

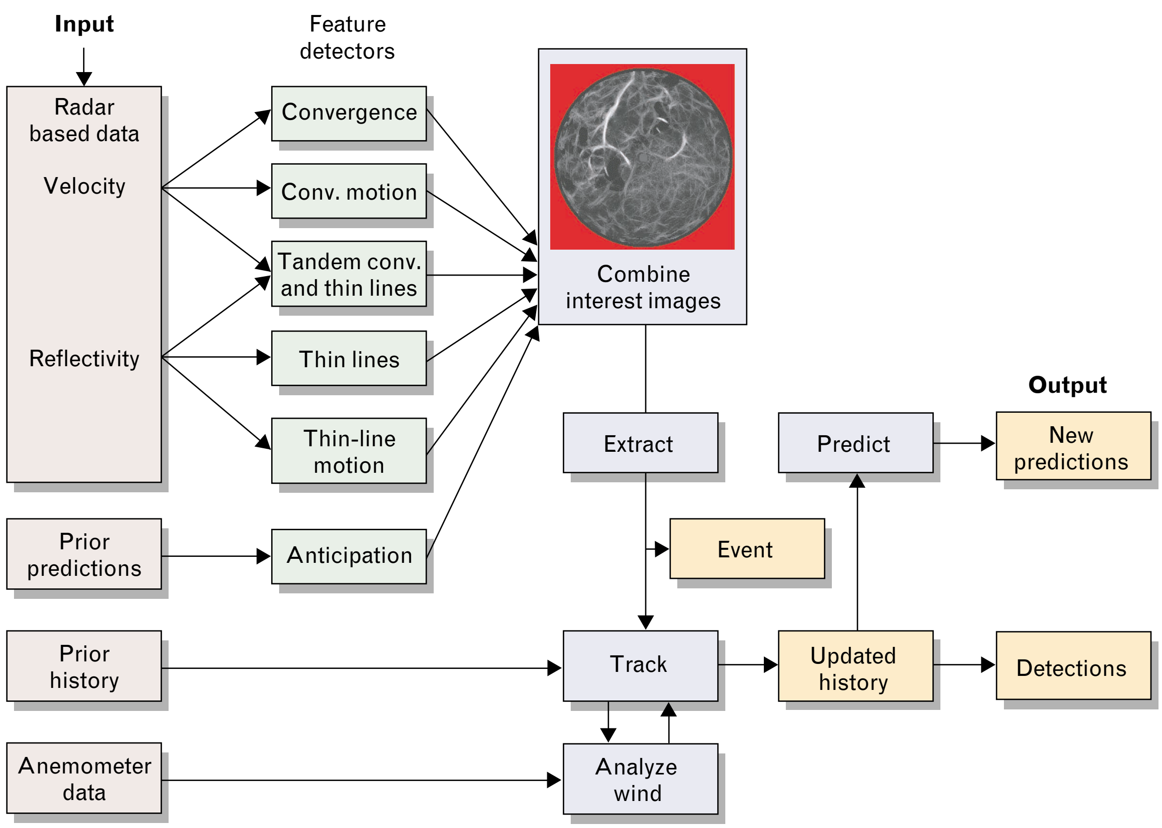


FIGURE 4. Block diagram of the machine-intelligent gust-front algorithm (MIGFA). Reflectivity and Doppler velocity data are input to a series of feature detectors that employ functional template correlation as a pattern-matching filter to identify gust-front signatures, including velocity convergence boundaries, reflectivity thin lines, and motion of these features. Each feature detector outputs an interest image indicating the probability that the particular feature being sought is present at each location in the image. Negative interest images are generated by additional feature detectors (not shown) that are designed to identify phenomena that can cause false alarms. Interest values output from each of the feature detectors are combined (e.g., by performing a pixel-wise weighted average) to produce a combined interest image (similar to that shown) from which gust-front chains are extracted by thresholding. The extracted gust-front chains are correlated with prior detections in the algorithm's event history to generate updated tracking statistics that are used to generate predictions of future gust-front locations. Estimates of the winds associated with each detected gust front are computed by applying a variety of estimation techniques, including Doppler-wind field analysis and measurements from a nearby anemometer.

FIGURE 5. The TDWR system at the Memphis International Airport in Tennessee.

shear detection algorithms. Raytheon won the competition for the operational system deployment. The Laboratory provided technical support to the FAA throughout the TDWR production-system development and initial deployment. After the deployment commenced, the Laboratory provided the MIGFA enhancements to TDWR algorithms to improve gust-front detection and the terminal weather information for pilots (TWIP) algorithm to generate data-link products for pilots [12].

Delivery of the TDWR to forty-five airports started in 1993 and will be completed in May of 2001. Figure 5 shows the TDWR located in Memphis, Tennessee.

ASR-9 Weather Systems Processor

The TDWR, despite its success, proved too costly to deploy at small- and medium-density airports. During the course of TDWR development, researchers realized that more limited but still useful microburst-wind-shear detection capability could be achieved by using the ASR-9.

Approximately 130 ASR-9s are deployed in the United States primarily at medium- to high-density airports. The radars operate at a 10-cm wavelength and transmit an uncoded 1-MW, 1-μsec pulse. The ASR antenna pattern is narrow in azimuth (1.4°) but broad in elevation angle (5°) to detect aircraft from the surface to 20,000 ft. The antenna is scanned in azimuth at a rate of 12 revolutions per minute.

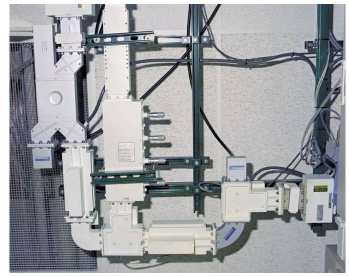
The ASR-9 was deployed with a processor that measures and displays six calibrated levels of weather reflectivity (rain intensity). This "weather channel" provides terminal radar controllers valuable information on the location and intensity of storms. It does not, however, provide information on low-altitude wind shear and is subject to ground-clutter breakthrough caused by anomalous propagation.

To extend the radar-based wind-shear detection capability to airports not equipped with a TDWR, the FAA asked Lincoln Laboratory to develop technology that would allow the ASR-9 to measure Doppler wind fields and automatically provide controllers and pilots with information on hazardous wind shear. The resulting Weather Systems Processor (WSP) consists of microwave and digital interfaces to the ASR-9, an add-on receive chain and data processor, and dedicated air-traffic-controller displays that are patterned closely after those developed for the TDWR.

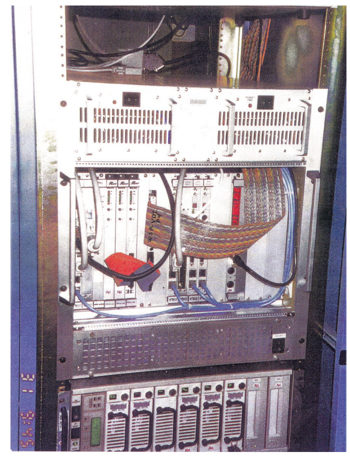
The WSP was developed and validated by using a test bed established in Huntsville in 1987. The test bed was moved in 1989 to Kansas City to evaluate the data-processing algorithms in a midwestern U.S. storm environment. In 1990, the test bed was relocated to Orlando, where an ongoing series of operational demonstrations of the WSP commenced. The WSP algorithms for rejection of ground clutter, measurement of the low-altitude Doppler wind field, and detection of microburst and gust-front wind shears were successfully used to output wind-shear warnings and thunderstorm-movement forecasts to tower and radar-approach controllers. Details of this WSP design and test program are reported by M.E. Weber and M.L. Stone [14].

In 1998, Lincoln Laboratory developed robust, second-generation WSP prototypes to operate at Albuquerque, New Mexico, and the Austin International Airport in Texas. Figure 6 depicts the WSP prototype at Austin. The compact commercial processors were hosted by the FAA-commissioned ASR-9s at these two airports and operated on an around-the-clock, seven-days-per-week basis. This robust processing configuration and the associated software were provided to the WSP production contractor as a technical exhibit, thereby significantly reducing the amount of engineering design required for the production WSP.

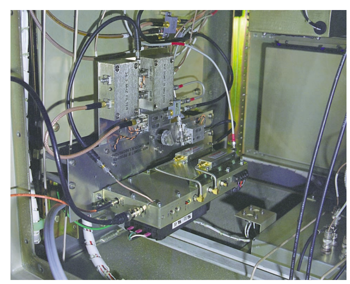
FIGURE 6. ASR-9 (above) at Austin International Airport in Texas, and components of the Lincoln Laboratory Weather Systems Processor (WSP) prototype (right). The WSP extracts microwave and timing signals from the ASR-9. A direct-down-conversion receiver and VME-based data processor provided fully automated detection of wind shear and storm tracking. Products are displayed to controllers in the tower cab and at the radar-approach control room.

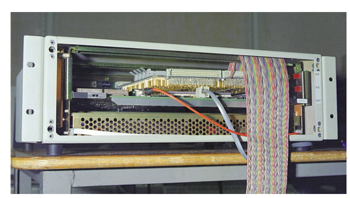


Microwave switches and couplers

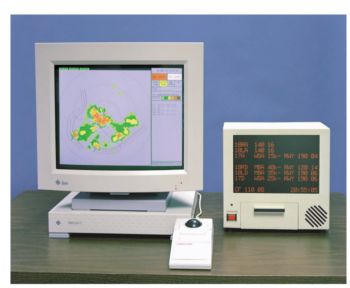


Data processor





Intermediate frequency receiver and radar interface module



Air traffic controller display

As a result of this successful development and test program, the FAA is procuring thirty-five WSP systems to be deployed on selected ASR-9s. Northrop Grumman was awarded a production contract in 1998, and three limited production systems are deployed and operating at Albuquerque, Austin, and Norfolk, Virginia. Deployment of the remaining thirty-two operational WSPs is scheduled to comment in spring 2001, following completion of the FAA's operational test and evaluation program

Integrated Terminal Weather System

Delays in the aviation system, which have been growing for the past decade, will increase rapidly in the next decade if recent trends in air traffic growth continue [15]. Because weather contributes significantly to aviation delays at major airports, the FAA urgently needs to improve the weather information provided to FAA and airline decision makers in the aviation

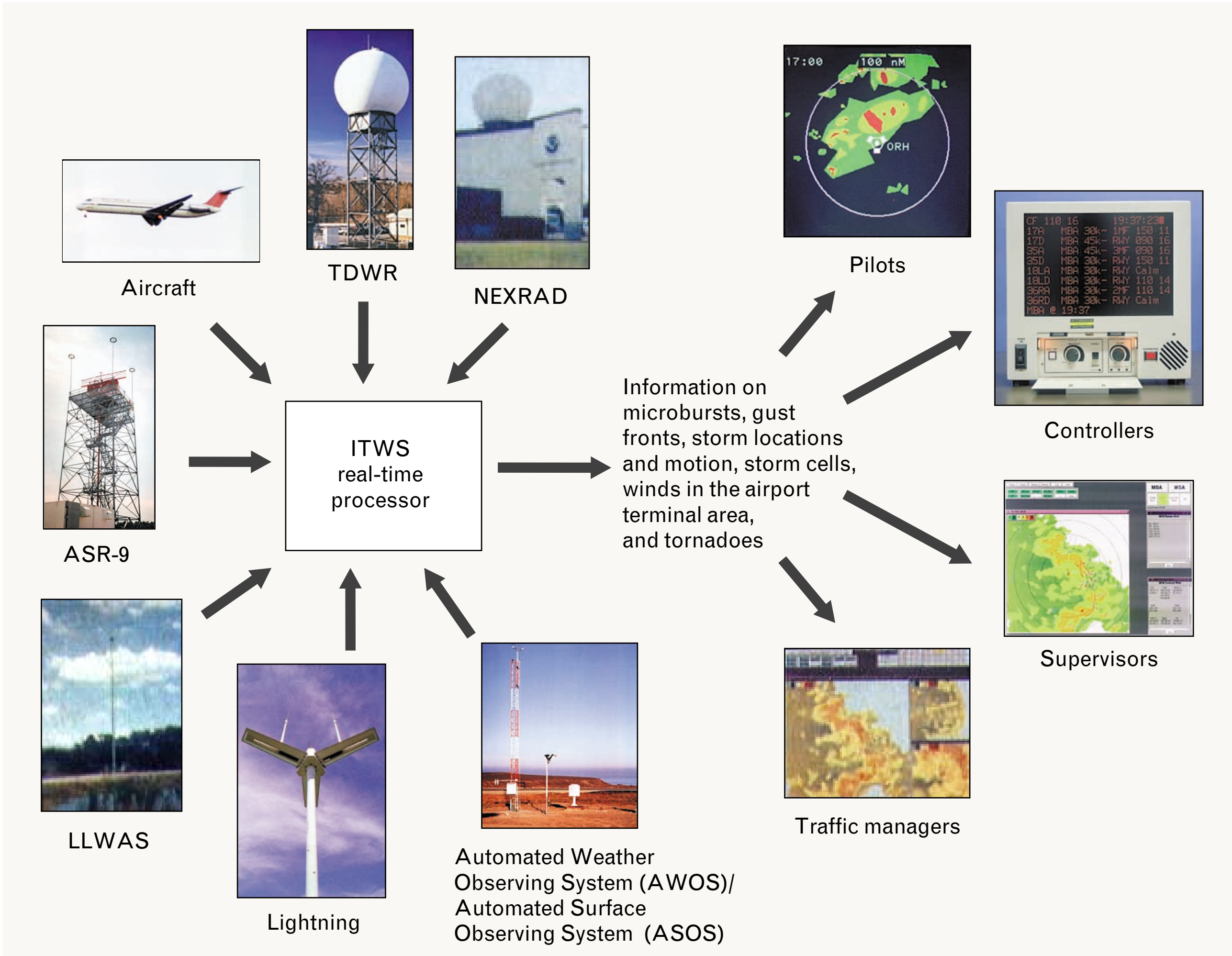


FIGURE 7. Integrated Terminal Weather System (ITWS). The ITWS combines data from a variety of sources to provide a suite of informational products for improving airport terminal planning, capacity, and safety.

network. Lincoln Laboratory studies show that the following strategies reduce weather-related delays at major U.S. airports:

1. Communicate current and predicted storm locations throughout the terminal area and the en route airspace that surrounds major terminals so that air traffic planners can route airplanes around hazardous storms.
2. Provide weather information that will enable the terminal controllers to optimize the use of the available runways. Specific needs include accurate predictions of the start and stop of weather disruptions on the runways, and information on three-dimensional winds.

These weather information strategies cannot be achieved solely with TDWR data, because the TDWR scanning antenna pattern does not cover much of the airspace of concern and cannot determine the three-dimensional winds aloft. Consequently, Lincoln Laboratory used additional existing weather-sensing radars (specifically, the ASR-9 and the National Weather Service Next Generation Weather Radar [NEXRAD] radars) to augment the radar coverage provided by the TDWR. Also, Lincoln Laboratory developed algorithms to integrate radar sensor data with numerical forecast models and other types of sensor data, including wind and temperature measurements from airplanes, and surface anemometer measurements. The resulting Integrated Terminal Weather System (ITWS) will provide this data-fusion

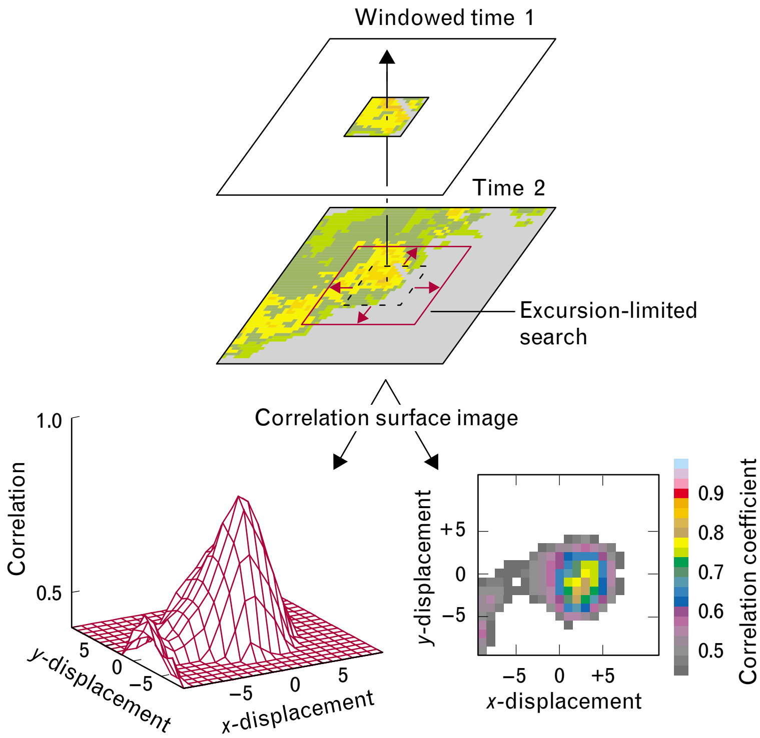


FIGURE 8. Storm tracking via cross-correlation of successive weather radar reflectivity images. The top half illustrates how the radar reflectivity measured at time 1 is shifted in position to determine the best match to the radar reflectivity at time 2. The degree of goodness is measured by the spatial cross-correlation of the two images. The bottom two panels illustrate the spatial cross-correlation results. The displacement vectors associated with the largest cross-correlations between corresponding subimages estimate the local motion of thunderstorm cells.

function at forty-five major US airports. Figure 7 shows the major data sources for the ITWS and some of the principal products and users.

A critical component of predicting future storm locations is estimating storm movement. Because a storm changes shape and size as it moves, conventional radar point-target tracking approaches suitable for following aircraft movement cannot be used. Lincoln Laboratory took the approach of computing spatial correlations between the radar weather images measured at successive times, as illustrated in Figure 8. The spatial displacement that maximizes the correlation function is used to estimate the motion of the storm.

FAA air traffic planners receive a depiction of the storm motion and extrapolated position. These storm-predictive products in conjunction with improved integrity of the ASR-9 weather depiction have proven very successful at simultaneously reducing delays and controller work load at major terminals. According to the results of real-time testing with Lincoln Laboratory ITWS prototypes at Memphis, Orlando, and Dallas, the combined savings in passenger time and airline operating expenses from these products are expected to exceed $500 million per year when the ITWS is fully deployed.

A significant element of traffic merging and sequencing is the process of making accurate estimates of the time of flight for the airplanes, which in turn requires accurate estimates of the winds aloft. The desired spatial resolution is on the order of 1 to 2 km horizontally and 500 to 2000 m vertically.

Doppler weather radars such as the TDWR can sense the radial component of the winds aloft only when there is precipitation. The ITWS solution to this problem has been to accomplish real-time fusion of the radial-wind estimates from the available radars. Because the weather radars cannot measure the winds aloft under many conditions, aircraft reports and wind predictions from numerical-forecast models must be utilized to augment the radar estimates. The fusion of data from these various sensors is accomplished by statistical-estimation techniques that use the assumed error-covariance matrix of the various measurements to address issues such as lack of time coincidence and/or spatial coincidence between the various measurements. Details of this approach and the associated algorithms appear in Reference 16.

Lincoln Laboratory conducted a successful demonstration of the initial ITWS capabilities in Memphis and Orlando in 1994 with Laboratory-developed prototypes. Following this demonstration, Raytheon won the production contract. To facilitate development at Raytheon, Lincoln Laboratory detailed the ITWS radar-processing algorithms and provided a complete description of the prototype software. Raytheon expects to begin delivery in 2001. Meanwhile, Lincoln Laboratory ITWS prototypes are operating at Memphis, Orlando, Dallas, and New York to refine the initial product and to test new radar-derived storm-prediction products.

The Future

Future efforts in this research area will refine the technological advances discussed above and take advantage of related technological developments at Lincoln Laboratory. These developments include

1. improving weather reflectivity and velocity data from weather-sensing radars though the application of advanced signal processing techniques that provide simultaneous estimation of range-ambiguous multitrip storm returns and improved Doppler-ambiguity resolution;
2. improving processors for other point-target-detection-pulse-Doppler radars, such as the long-range Air-Route Surveillance Radar 4 (ARSR-4), that will, for example, both heighten point-target-detection capability and provide weather-sensing capabilities;
3. integrating thermodynamic and lightning information with radar data for convective-storm-growth/decay prediction and ceiling/visibility prediction;
4. relating storm features as sensed by ground-based weather radars to pilot decision making; and
5. providing radar-derived products to address safety concerns such as wake vortices and turbulence (including low-altitude wind shear from gravity waves [17]).

Summary

In its aviation-weather research program, Lincoln Laboratory has developed radar-based techniques for the automatic detection and short-term prediction of the location and intensity of severe convective weather phenomena. These techniques are embodied in several operational systems, especially the Terminal Doppler Weather Radar (TDWR), the ASR-9 Weather System Processor (WSP), and the Integrated Terminal Weather System (ITWS).

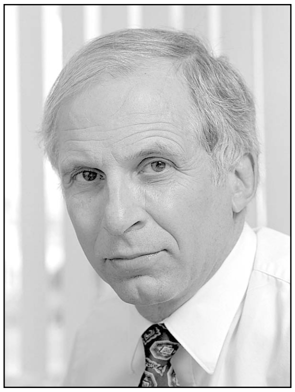
Technology developed by Lincoln Laboratory has helped achieve a dramatic reduction in air-carrier accidents: no air-carrier accidents due to thunderstorm-induced wind shear have occurred to date at the forty-six airports that are currently utilizing radar wind-shear detection systems with the Lincoln-developed wind-shear detection algorithms. When the ITWS is deployed to the TDWR airports starting in 2001, delays due to thunderstorms and adverse winds will be reduced significantly in relationship to the cost of the ITWS. The cost savings associated per year (over $500 million) from the expected delay reduction achieved with the ITWS will exceed the entire life-cycle cost of the ITWS.

Acknowledgments

We would like to acknowledge the hard work, creative problem solving, and dedication of the numerous staff members in the Weather Sensing group who made these programs successful. In addition, we acknowledge our sponsors in the FAA's Research and Acquisitions Division. Their steadfast support of the Laboratory's work and their guidance were instrumental in the successful fielding of TDWR, WSP, and ITWS.

REFERENCES

1. "1999 Aviation Capacity Enhancement Plan and Airport Database," FAA Office of System Capacity, Dec. 1999, http://www.faa.gov/ats/asc/Pubs.html>.
2. M.E. Weber, M.M. Wolfson, D.A. Clark, S.W. Troxel, A.N. Madiwale, and J.W. Andrews, "Weather Information Requirements for Terminal Air Traffic Control Automation," *4th Int. Conf. on Aviation Weather Systems, Paris, 24–28 June 1991,* pp. 208–214.
3. H.R. Byers and R.R. Broscoe, "The Thunderstorm," Report of the Thunderstorm Project (a joint project of four U.S. Government Agencies: Air Force, Navy, National Advisory Committee for Aeronautics, and Weather Bureau), (U.S. Govt. Printing Office, Washington, 1949).
4. T.T. Fujita and H.R. Byers, "Spearhead Echo and Downburst in the Crash of an Airliner," *Mon. Weather Rev.* **105,** Feb. 1977, pp. 129–146.
5. T.T. Fujita and R.M. Wakimoto, "Microbursts in JAWS Depicted by Doppler Radars, PAM, and Aerial Photographs," *21st Conf. on Radar Meteorology, Edmonton, Canada, 19–23 Sept. 1983,* pp. 638–645.
6. T.T. Fujita, *The Downburst: Microburst and Macroburst* (University of Chicago, Chicago, 1985).
7. D.R. Mann, "TDWR Clutter Residue Map Generation and Usage," *Project Report ATC-148*, Lincoln Laboratory (29 Jan. 1988), DTIC #AD-191148/6.
8. T.T. Fujita, *DFW (Dallas-Fort Worth) Microburst on August 2, 1985* (University of Chicago, Chicago, 1986).
9. M.W. Merritt, "Automated Detection of Microburst Windshear for Terminal Doppler Weather Radar," *SPIE* **846,** 1987, pp. 61–68.
10. M.W. Merritt, D.L. Klingle-Wilson, and S.D. Campbell, "Wind Shear Detection with Pencil-Beam Radars," *Linc. Lab. J.* **2** (3), 1989, pp. 483–510.
11. H.W. Schlickenmaier, "Windshear Case Study: Denver, Colorado, July 11, 1988," Federal Aviation Administration, Advanced System Design Service (Nov. 1989), DOT/FAA/DS-89/19.
12. J.E. Evans and D.M. Bernella, "Supporting the Deployment of the Terminal Doppler Weather Radar (TDWR)," *Linc. Lab. J.* 7 (2), 1994, pp. 379–398.
13. R.L. Delanoy and S.W. Troxel, "Machine Intelligent Gust Front Detection," *Linc. Lab. J.* **6** (1), 1993, pp. 187–212.
14. M.E. Weber and M.L. Stone, "Low Altitude Wind Shear Detection Using Airport Surveillance Radars," *IEEE Aerosp. Electron. Syst. Mag.* **10** (6), 1995, pp. 3–9.
15. J. Ott, "Welcome to Gridlock, All Flights Delayed," *Aviat. Week & Space Technol.* **151** (17), 25 Oct. 1999, pp. 42–44.
16. R.E. Cole and F.W. Wilson, "The Integrated Terminal Weather System Terminal Winds Product," *Linc. Lab. J.* 7 (2), 1994, pp. 475-501.
17. D.W. Miller, "Thunderstorm Induced Gravity Waves as a Potential Hazard to Commercial Aircraft," *Am. Meteorological Soc. Proc. 8th Conf. on Aviation, Range and Aerospace, Dallas, 11–15 Jan. 1999,* pp. 225–229.



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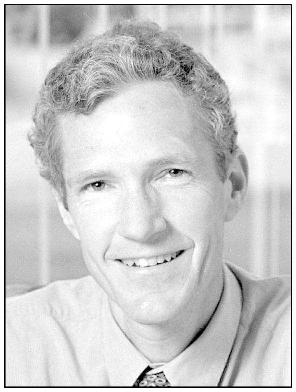

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leads the Weather Sensing group, which develops systems that exploit weather-sensor processing, data integration, and automated forecast technology to improve the safety and efficiency of civil aviation operations. Mark's current technical interests include the development of augmented weather-processing capability for the FAA's network of over 400 Doppler surveillance radars (Terminal Doppler Weather Radars, Airport Surveillance Radars, and Air Route Surveillance Radars). Operational results of this work include the ASR-9 Weather Systems Processor (WSP), currently being deployed to enhance wind-shear detection capability at thirty-five U.S. airports, and substantial ongoing enhancements to the weather reflectivity processor in the ASR-11. Mark received a B.A. degree in physics from Washington University in St. Louis and a Ph.D. degree in geophysics from Rice University. Before joining Lincoln Laboratory in 1984, he worked at Columbia University's Lamont-Doherty Geological Observatory and the U.S. Naval Research Laboratory.