Low-Level Windshear Alert Systems and Doppler Radar in Aircraft Terminal Operations

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As air travel increases, difficulties develop in avoiding severe weather, especially near terminals, while sharing crowded airspace and adhering to tight airline schedules. Several takeoff and landing accidents attributable to severe convective weather are discussed and related to new aids recently introduced and planned for terminal safety. Telemetered anemometric data, representing in situ observation of wind near the Earth's surface, and Doppler radar for remote detection of distributions of wind and precipitation are discussed critically. Surface anemometers have not been optimally placed for monitoring conditions along paths of final approach. Plans to provide precipitation and windshear data with a terminal Doppler radar operating at C-band are questioned.

I. Introduction

ACCIDENTS to jet aircraft at terminals in 1973, 1974, and 1975 marked a new trend wherein most encounters of aircraft with convective weather with resultant fatalities occurred in the terminal environment rather than en route. All of these and subsequent fatal convection-related accidents involving U.S. air carriers were associated with flight in heavy precipitation and significant wind variations. There is little question that the impacts of passenger aircraft with the ground in wrong places were due to inadequate adjustment of aircraft control surfaces and thrust during rapid and large excursions of lift and drag. Most of the changes of performance have been associated with changes of headwind, but a performance penalty is imposed by heavy precipitation also. Its magnitude remains somewhat uncertain at this writing and is being investigated.[1-3] In any event, response sufficiently fast to avoid an accident following a disturbance near the ground is more difficult to attain from modern jet aircraft than from aircraft with reciprocating engines and propellers.[4] Furthermore, effectiveness of pilot reaction in heavy precipitation is reduced by lack of visual clues, discussed by Connelly,[5] and by high levels of noise in the cockpit.[6]

Response to storm-related tragedies to aircraft has stimulated development of new systems to measure wind variations. Two innovations are discussed here. First, the low-level windshear alert system (LLWAS) consists of anemometers on towers several thousand feet from the centerfield anemometer, with systems for telemetry and for displays of processed wind data in the terminal controllers' cab. This program, whose first installation was in 1977, has produced fields of anemometers within and near the boundaries of more than 100 U.S. airports.[7]

The second technological approach involves Doppler radar, which I have also discussed elsewhere.[8] The focus on windshear has led to procurements and plans to deploy Doppler radar for automatic issuance of warnings on dangerous shears.

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II. Early Background

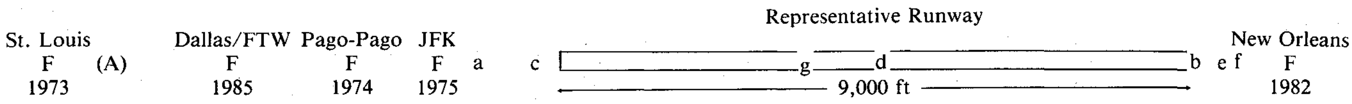
From 1964, when the National Oceanic and Atmospheric Administration's (NOAA) National Severe Storms Laboratory was first organized at Norman, Oklahoma, that laboratory, in cooperation with the Federal Aviation Administration (FAA), NASA, and USAF, continued to support a program that involved flights in thunderstorms by instrumented high-performance military aircraft. Simultaneous observation of the storms by calibrated radar provided data on correlations between reflectivity factors and turbulence, which were a partial basis for FAA advisory circulars on storm avoidance en route. The FAA advisory circulars and fear of storms appear to have contributed to a decline of en route accidents during the 1970s.[9-11]

A sense of accomplishment in weather safety matters was shaken in 1973 by the crash of a jet aircraft, with 38 fatalities, 2.3 n.mi. from the runway threshold at St. Louis, Missouri, after the aircraft entered areas of heavy rain and downdraft associated with a thunderstorm. In January 1974, during approach to landing at Pago Pago, American Samoa, a plane crashed short of the airfield, with 97 fatalities, when it approached the runway through a thunderstorm with heavy rain and shifting winds and downdrafts. These and other accidents have been summarized by Rudich[12] with a comprehensive list of references to the accident investigations; their touchdown points are illustrated schematically in Fig. 1, to which there is additional reference below.

III. Discussion of Accidents

John F. Kennedy International Airport, June 24, 1975

The 1975 landing accident at John F. Kennedy Airport, New York, produced widespread and deep concern with aviation safety issues. In this case, the jet aircraft traversed a thunderstorm during its approach. Particularly distressing in the National Transportation Safety Board (NTSB) report on the accident were indications that controllers had relied solely on the centerfield anemometer to assess wind conditions and that judgments were not sufficiently influenced by visual observations of a dark cloud with heavy rain and lightning off the approach end of the active runway nor by adverse reports from pilots who had approached the active runway just before the crash.[13] It was plain that the aircraft had tried to land while there was a strong tail wind at and near the approach threshold of the active runway; standard practice, of course, has aircraft landing into the surface wind.



Nonfatal accidents at terminals indicated by letters above

a	Ldg	Chattanooga	Tennessee	Nov. 27, 1973
b	Tko	Denver	Colorado	Aug. 27, 1975
c	Ldg	Raleigh	North Carolina	Nov. 12, 1975
d	Ldg	Philadelphia	Pennsylvania	June 23, 1976
e	Tko	Tucson	Arizona	June 3, 1977
f	Tko	Denver	Colorado	May 31, 1984
g	Ldg	Detroit	Michigan	June 13, 1984

Fig. 1 Location of first contact with ground or object on the ground of aircraft involved in convection-related accidents since 1973.

New Orleans, July 9, 1982

A low-level windshear alert system with six anemometers was installed and operating at New Orleans when this accident occurred and was the source of a timely warning at 1603:33, approximately 4.5 min before the start of the takeoff roll. Takeoff of the jet aircraft, which was loaded to capacity, was toward a dark cloud with heavy rain at the departure end of the runway. An illustration in the report of the accident shows a divergent outflow (microburst) behind a gust front whose leading edge was depicted about 3000 ft beyond the departure end of the runway.[14] The weather analysis presented as a map in the NTSB report departs significantly from the report of the east LLWAS anemometer at the time. Thus, at 1609:03, the east sensor actually reported a wind from 310 deg and speed 6 kt, while the analysis for the same place and time (within a few seconds) shows a wind of approximately 20 kt and a conjectural nearby wind maximum in excess of 30 kt.[14]

Although some features of the wind analysis illustrated in this case lack credibility because they conflict with anemometric data, some important points can be made with confidence. Thus, the LLWAS at New Orleans did show significant wind changes, and a warning was issued. However, the peak wind speed reported to the pilot was only 23 kt. Precise values of wind changes were not mentioned with the report of windshear at 1603:33, and previous wind reports has indicated relatively small shears. Indeed, an NTSB finding was that the shear was theoretically manageable, but that effectiveness of pilot response had been reduced by heavy rain, poor visibility, and the need for great speed in reaction to entry into the shear zone.

It is not clear in this case that any different result would have been produced with additional on-airport anemometers because it is doubtful that such additional anemometers would have given any stronger indication of windshear than was actually provided. This is arguable, but it seems that this case presents a category of conditions that should have been avoided mainly on the basis of the radar reflectivity and visual observation. In other words, commercial aircraft should not be flown through convective storms with heavy precipitation, particularly during takeoff or landing, and especially when the LLWAS system indicates even moderate shear (see also Dietenberger et al.[15]).

Dallas/Ft. Worth, August 2, 1985

In this case, the jet aircraft was flown toward a landing from the north, passed through a thunderstorm on the approach, was seen emerging from heavy rain near the ground, and first touched ground approximately 6300 ft north of the approach end of the active runway.[16] Though the storm was clearly visible to controllers, it was not at all indicated by surface meteorological data at the time of the accident because the gust front or leading edge of the outflow had not yet arrived at any of the LLWAS anemometers, nor at any other in situ sensor. The LLWAS data were not recorded, but the record of the National Weather Service (NWS) anemometer at the airport, colocated with the LLWAS centerfield anemometer, shows that the gust front with winds of 35–45 kt arrived there approximately 4½ min after the accident. According to an analysis by Fujita,[17] the gust front probably arrived at the northeast LLWAS, located 3000 ft north of the threshold of runway 170, about 4 min earlier, or just 0.5 min after the accident.[17] The downdraft core, or microbust, from which the gust front evolved, was centered about 12,000 ft north of the runway threshold at the time of the crash.

IV. Discussion of Other Important Accidents

The touch-down points of all convection-related accidents involving U.S. air carriers at and near terminals since 1973 are depicted in Fig. 1, where the fatal accident locations are indicated by "F" and nonfatal accidents bear a letter designation in lower case that is identified in the accompanying table. Actual runway lengths varied somewhat from the 9000 ft depicted, but distances shown are scaled correctly with respect to the nearer approach or departure threshold. These data, though sparse, because crashes are infrequent, suggest several important relationships. First, all fatal accidents occurred off the runways; four of the five were landing accidents and only that at New Orleans occurred on takeoff. Perhaps there are more accidents at landing than at takeoff because a greater sense of urgency attends completion of an approach to land than the start of a takeoff. Note also that the fatal landings are spread across more than 2 miles in advance of the runway, while the one fatal and three nonfatal episodes on takeoff are comparatively near the runway. This may reflect the comparatively shallow glide slope on descent, usually near 3.5 deg, which has the aircraft at altitudes vulnerable to effects of storms for at least twice as long as the 7.5-deg ascent slope of aircraft typical of takeoffs. Furthermore, aircraft on takeoff usually leave the ground well before the departure threshold is attained, and are operating nearly at full power, which itself provides an important margin of safety.

Of the seven nonfatal accidents, three occurred on the runway and four near the runway. All nonfatal accidents were nearer the runway than all of those with fatalities. This is not surprising because fatalities were associated with large obstructions that are not present on and near airport runways.

All fatal accidents and all landing accidents involved both heavy precipitation and wind changes, but three nonfatal accidents on takeoff encountered wind changes only. Both Fig. 1 and reports of the NTSB indicate that all of the landing accidents were a result of weather phenomena along the approach path but off the airport. Absence of precipitation and windshears about the runways is not a reliable indication of safety along the approach path, where encounters with convective phenomena may lead to a short or otherwise improper landing. On the other hand, the takeoff episodes were influ-

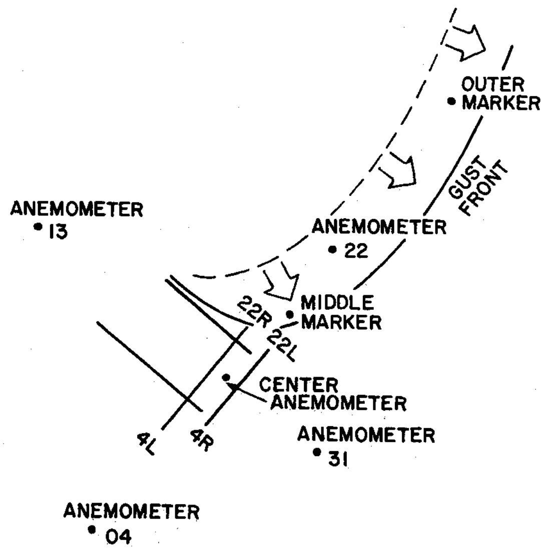


Fig. 2 Proposed configuration of anemometers for JFK; outer and middle markers are shown for runway 22L.[18]

enced most directly by phenomena at the airport, with the possible exception of the accident at New Orleans. These observations imply that the highest priority objective for remedial technology should be to facilitate avoidance of heavy precipitation and shifting winds along the final approach corridor.

V. Origin and Development of LLWAS

Study of the 1975 Kennedy Airport accident, with some attention to reports about preceding accidents and consideration of technical means for providing additional wind information, led to a memorandum to the director of the Wind Shear Program office in the FAA signed by the directors of NOAA's National Severe Storms Laboratory and Wave Propagation Laboratory. The memorandum suggested that anemometers be placed "about halfway between the outer markers and the touch down points of the associated runways, (about 2 miles from touch down)" to provide controllers with an objective indication of surface wind and its variations along the path of approaching and departing aircraft.[18] An illustration from this memorandum is presented here as Fig. 2. Also note the designation (A) in Fig. 1, which indicates a location 2 miles in front of the approach threshold.

As noted by Goff and Gramzow,[7] the FAA responded to this suggestion with the low-level windshear alert system; the first test system was in place in 1977, and by mid-1978 eight operational prototype systems had been installed. However, the system as implemented differs from the memorandum's recommendation in that the anemometers are not placed well before the touch-down points (about halfway between outer markers and touchdown) but near and within the airport boundaries.

The New Orleans accident stimulated an important study of all storm-related accidents and incidents to that date; a recommendation of this study was that LLWAS be improved.[19] This was followed by FAA funding for a project of research and system development at Denver, Colorado,[20] and by increased provision of anemometers on airports rather than on installation of anemometers well beyond airport boundaries where the wind shifts associated with fatalities usually had occurred. The FAA has not been inclined to attempt to place anemometers outside of airports and has cited nonrepresentative winds in the vicinity of structures, vandalism of surface sites, and administrative difficulties in dealing with private property owners. Thus, in congressional testimony on at least two occasions, FAA spokespersons indicated that LLWAS was perceived as an on-airport sensing system.[21-22] On the other hand, the National Severe Storms Laboratory (NSSL) deployed several tens of complete surface stations on private property for 15 or more successive years at nominal cost. (The typical cost was $100 for annual rental of 900 ft^2 fenced by NSSL staff and equipped with a weather station to measure all standard meteorological parameters.) Furthermore, the wind atop an ordinary structure does not differ significantly in direction from that in the free stream, though wind speed does increase with elevation. For example, the official U.S. Weather Bureau anemometer at Oklahoma City Airport was maintained atop the administration building at a height of 70 ft above the ground from 1932 to 1954. It has been shown that the average wind speed at that height at Oklahoma City Airport is about 3.4 mph greater than at the current anemometer elevation of 20 ft.[23] It seems that the FAA could negotiate contracts for otherwise unused space atop nearby tall structures where vandalism would not be a problem. Off-airport anemometry is scheduled for deployment as phase III of the LLWAS system.[7]

In search for understanding of FAA program directions, we note that some conditions at Denver, Colorado, favored establishment there of a major program of system development. These conditions include a very busy air terminal, a higher frequency of intense downdraft-outflow (microburst) events than is common in the Mississippi Valley and further east, the large and capable meteorological community at the National Center for Atmospheric Research and NOAA laboratories in nearby Boulder, Colorado, and a number of serious though nonfatal accidents at Denver caused by windshear. Especially notable at Denver were the crash of a Boeing 727 near the departure end of the runway on August 7, 1975 and an encounter of another Boeing 727 with the ILS localizer antenna 1,074 ft beyond the end of the runway during takeoff on May 31, 1984 (see Fig. 1). Perhaps these incidents were not worse because good visibility accompanied the dangerous shears, and in this important respect, conditions at Denver tend to be atypical of the environment that has accompanied convection-related fatalities in aviation.

The LLWAS project at Denver has involved 11 anemometers near the airport runways and has developed means for reducing telemetered data to simple real-time messages on headwind changes along approach and departure paths. It is unfortunate that the introduction of off-airport anemometry has been so long delayed, but it is now planned to install anemometers up to 3 miles from runway thresholds. When such installations are complete, the system in general application should provide protection in important situations where strong wind shifts lie along paths of final approach and immediate departure and where heavy precipitation itself is not a factor. Of course, the discussion of Sec. II indicates that information about precipitation along paths of approach and departure is also essential to the terminal weather system.

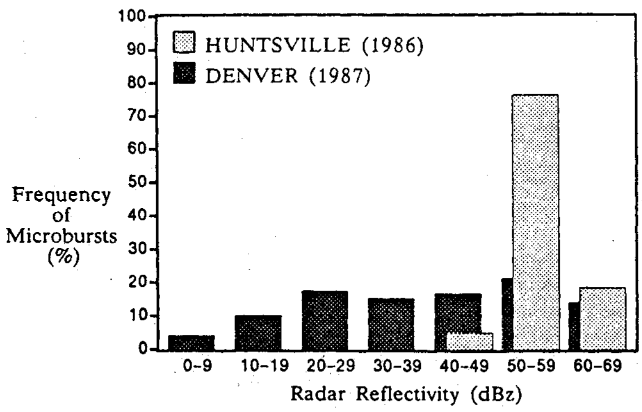


Fig. 3 Distribution of the maximum surface radar reflectivity factor in cells that produced microbursts.[26]

VI. Weather Radar

Radar Reflectivity

As noted in Sec. II, the use of weather radar and instrumented high-performance aircraft in a multiagency experimental program in the 1960s led to criteria for the avoidance of severe storms by commercial aircraft. These criteria were based on radar reflectivity, and observance of the guidance provided in FAA advisory circulars appears to have resulted in marked reduction of accidents attributable to convective weather during en route stages of commercial flights. Use of these same criteria during terminal portions of flights has lagged. Airborne radar is less effective at low altitudes, and real-time reflectivity data from radars at the Earth's surface have not been routinely provided to controllers of the terminal phases of flight. Radar information comes to the terminal controllers as interpreted by meteorologists and with delays of some tens of minutes. This condition persists today, although technology for provision of easily readable displays of reflectivity in essentially real time at locations remote from a radar has been available since the mid-1970s.[8]

The case for improved use of reflectivity data is compelling. As noted with the flight simulator data gathered and discussed by Connelly,[5] the loss of visual clues in heavy precipitation and clouds makes otherwise moderate windshear a hazardous phenomenon. This finding is reinforced by experience. To the date of this writing, all convection-related fatalities aboard U.S. air carriers have resulted from encounters with windshear and heavy precipitation in combination and not with windshear alone. Low altitude windshear and precipitation are, of course, physically intertwined, and heavy convective precipitation is easily recognized by conventional radar. In the United States, outside of the high plains and desert areas, avoiding convective precipitation means avoiding dangerous winds also. Thus, although distributions of microburst intensity at Huntsville, Alabama, and Denver, Colorado, are similar, there is a remarkable difference in the distributions of precipitation intensity accompanying storm downdrafts in the Huntsville and Boulder areas, as illustrated in Fig. 3, from a paper by Biron and Isaminger.[24] Furthermore, storm microburst characteristics at Kansas City are quite similar to those at Huntsville, and the microbursts accompanied by low reflectivity values at both Kansas City and Huntsville were invariably observed to be relatively weak.[25] (During the 1989 field program at Kansas City, from March 27 to September 9, only 1 of 390 observed microbursts accompanied reflectivity less than 35 dB. Its velocity differential was 22 m/s.[25])

Reflectivity data provided in real time to controllers concerned with relatively unforgiving flight in the terminal area and relayed promptly to pilots would be a basis for avoiding both heavy precipitation and dangerous windshears in the regions where fatal accidents have occurred. Evaluation of associated procedures would facilitate orderly development of the aviation weather system. But, as noted, the terminal weather system has not used technologies of radar reflectivity and digital communication of weather radar data that have been available since the 1970s.

Doppler Radar

The radial component of wind can be measured by Doppler radar. Important practical applications of Doppler radar were clearly demonstrated in the Joint Doppler Operational Project,[26] and Doppler radar technology has been the principal focus of FAA-sponsored experiments and plans during the last decade. The strong focus of the FAA interest is indicated by the statement of Turnbull et al.[27]: "Wind shear has caused more U.S. air-carrier fatalities than any other weather hazard. A 1983 National Research Council ... study ... identified low-altitude wind shear as the cause of 27 aircraft accidents and incidents between 1964 and 1982." Turnbull et al. hardly mention the corollary role of precipitation, and such omission has similarly characterized other FAA treatments of aircraft accidents related to convective weather. (Similar bias is evident in a long-range plan for the aviation weather system developed under FAA auspices at the National Center for Atmospheric Research.[28])

The FAA is oriented toward provision of a highly automated aviation weather system in which radar and LLWAS products are combined for use in terminal areas.[27-29] This could be a fine objective, provided the resulting system can be effective and reasonably cost beneficial. (I do not attempt quantitative analysis of cost and benefits; this is usually difficult and controversial when human lives enter the equations.)

The procurement of 10-cm next-generation radars (NEXRAD) has begun and will lead to deployment of approximately 150 of these systems across the United States. An update interval of approximately 6 min is planned for these radars; they will depict distributions of wind and reflectivity within a range of 200 km but generally will not provide windshear assessments along approach and departure corridors.[30] Although the update rate is a marked improvement to current practice, these specifications have been deemed somewhat inadequate, and so the FAA has decided to develop a terminal Doppler weather radar system (TDWR) dedicated to windshear detection in the vicinity of airports. This involves initial procurement of 47 TDWR systems operating at C-band, but "because of the pressing need for windshear detection at major air-carrier terminals, the FAA plans to divert 16 NEXRAD systems for use at airports until TDWR systems are delivered".[27] There is also a longer range plan to combine a reflectivity product from the forthcoming ASR-9 radar with the TDWR velocity products and with LLWAS.[31] The ASR-9 can identify heavy precipitation quite well, and Doppler processing with the ASR-9 can identify significant windshear.[32]

When heavy precipitation is present, avoidance must be the norm, regardless of the shear indication. Even moderate shear becomes hazardous in heavy precipitation because lack of visual clues and loud cockpit noise reduce pilot performance, and perhaps also because of reduced aircraft performance caused by water on the airfoils. Furthermore, strong reflectivities can be associated with damaging hail and electrical activity, and engine flameouts have occurred when aircraft have entered heavy precipitation. (The accident to Southern Airways on April 4, 1977, was partly a result of engine flameouts in heavy precipitation. More recently, however, Boeing 737 flameouts occurred on August 21, 1987, May 24, 1988, and July 26, 1988, all at altitudes above 8000 ft and all in heavy rain or hail and turbulence only moderate or less.[33-35] None of the recent incidents involved an airplane crash or fatalities, but such a favorable outcome is less likely to attend flameout at low altitude.) Thus, the reflectivity mapping radars already available or planned could serve alone to vector aircraft, and the TDWR system will unnecessarily complicate the aviation weather system in the areas where convection-related accidents have occurred. The use of reflectivity products from the NEXRAD and ASR-9 radars should be the strongest focus of the radar program at this writing.

Note further that weather-related accidents at intervals as long as several years have been the motive for the massive effort discussed here toward improving the aviation weather system. Therefore, rare situations that produce extreme attenuation at C-band are cause for concern. Choice of C-Band (rather than S-Band) for the TDWR was forced by considerations of frequency allocation,[31] but use of C-band in heavy precipitation may prove hazardous. Turnbull et al.[27] wrote, "[the NEXRAD qualities are] not needed for the 50-mile radius to be covered by the TDWR". But two-way attenuation at 5 cm is approximately 0.2 dB/km with a reflectivity factor of 10^5 mm^6/m^3 (50 dB) and temperature of 18°C; attenuation is twice larger at 0°C and larger still when it is raining on the radome.[36,37] These are very common conditions in moderate to severe thunderstorms. Thus, at a 25-mile (40-km) range, two-way attenuation along a squall line could be in the range 8-20 dB with a C-Band system, and a 50-dB echo at that distance then would be perceived as a moderate value, in the range 30–42 dBZ. (This allows up to 4 dB for wet radome attenuation, which depends on the transmitted wavelength, condition of the radome surface, radome size, and local accumulations of rainwater on the structure that can be induced by wind forces.[37,38]) While such a case can be somewhat adjusted with a correction algorithm, note that with very intense precipitation, the radar reflectivity factor can attain much larger values, even above 10^6 mm^6/m^3. Spatial extension of such values is usually quite limited, as shown by studies undertaken at the Bell Telephone Laboratories,[39] for example, but typical conditions are occasionally exceeded substantially. Furthermore, extreme attenuation cannot be well corrected, though attenuating regions can be flagged, and this is planned. Special care must be taken when no echo or weak echo is a result of attenuation because aircraft might be directed to extremely hazardous airspace when such radar data are misinterpreted. An example of severe C-Band attenuation in a situation of practical interest has been presented by Allen at al.[40]

Finally, problems of ambiguities in range and velocity determinations during severe weather with extended precipitation echoes are at least twice as serious at C-band than at the S-band wavelength.[36] Another problem arises with any Doppler radar in that the wind component transverse to the beam is not measured directly but must be deduced by a process that involves considerable uncertainty.

VII. Concluding Remarks

The aviation weather system implemented by the FAA has a number of features that do not follow well from findings of the related science. Thus, with indications that the most frequent and serious airplane crashes associated with stormy weather occurred after passage through thunderstorms on the approach path, the responsive LLWAS system is comprised of anemometers on airports rather than in the environment of airports. The accidents at St. Louis and Pago Pago would not have benefited from LLWAS as subsequently installed, and the system at Dallas/Ft. Worth may have contributed to the accident there, since the lack of windshear indication from the ground stations was a motive for operations as usual. Anemometers placed further from the runways probably would have been effective in all of these cases. In the Kennedy and New Orleans accidents the present LLWAS system or that contemplated in field trials at Denver would have provided or did provide an indication of a storm on or near the airport, though storms on the airport were not the cause of the Kennedy crash and may not have been the immediate cause of the New Orleans crash. The present plan to extend anemometry beyond airport boundaries should be implemented vigorously.

In spite of the fact that heavy precipitation has been a factor in every fatal, convection-related accident, the FAA has tended to downgrade radar reflectivity in its considerations of improved weather services in the terminal area, and the NWS has not vigorously promoted better processing and communication of reflectivity data to controllers. If the technology of the 1970s were implemented, terminal controllers would be responsible for oral relay of reflectivity data to pilots, and the NWS would be responsible for the accuracy and reliability of data from those NWS radars committed to providing reflectivity displays to controllers. The FAA's stated position has been that "transmission of hazardous weather information by controllers interferes with their other duties,"[27] but why controllers are deemed to have time for LLWAS data and not for weather radar data has not been discussed or explained in the technical literature. Controllers in the terminal area have been best placed to provide timely and reliable information to pilots on significant convective events along approach and departure paths.

The projected use of Doppler radar for warning of low-altitude windshear in and near airports is questioned. The C-band TDWR systems now being procured should have some utility in the high plains and in desert regions, but their use must confront the realization that thunderstorm-related accidents to U.S. air carriers in these regions have been extremely rare and none have been fatal. In contrast, the several accidents with fatalities in the Mississippi Valley and eastward all have been associated with heavy precipitation as well as windshear. It seems likely that windshear indications in these regions will be redundant because strong reflectivity must be avoided in and of itself. Avoidance of high-reflectivity regions would associate with avoidance of associated strong shear as well, but any C-band weather radar is subject to attenuation by heavy precipitation and cannot be relied on to provide accurate reflectivity indications in rare extreme situations of greatest concern. Nor would shear indications be wholly reliable, since only the radial component of the wind is measured directly by Doppler radar. Shear indications of an extended LLWAS system with reflectivity data from existing radars, to be replaced with ASR-9 and/or NEXRAD radars, should suffice to keep aircraft from dangerous encounters with both precipitation and shear.

There have been no fatal convection-related accidents in U.S. commercial aviation since 1985, probably owing to increased awareness of weather hazards by pilots and controllers, and the present system has been comprised of essentially the same aids available during the period of all of the accidents discussed in this paper. But now we confront the possibility that aircraft on rare occasions may continue an approach into precipitation that constitutes a hazard irrespective of associated shear. Misinformation about the severity of precipitating weather systems may lead to accidents that could be avoided with use of 10-cm radar systems already in place or planned. Finally, the complexity implied by the algorithms needed to identify windshear and to correct attenuated data, or by supplemental use of a nonattenuating radar during heavy precipitation, is cause for concern since complexity increases possibilities for failure.[41] I believe that the next configuration of the aviation weather system would be safer as well as less costly without the proposed TDWR radar.

The FAA program has provided significant employment in the meteorological research community and to some equipment manufacturers. Research results with implications for future good have been forthcoming.[42] But there has been significant delay in implementation of means to allay important weather-related problems, means that have been available since the 1970s without extensive research. The author hopes that attention to detail in design of the aviation weather systems will prevent tragedies attributable to inappropriate expectations and use of new equipment.

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