Learning from Incidents – What the Machine Can Learn

Frances Sherertz, Ph.D. MO3461
United State Federal Aviation Administration
Dr. Sherertz is the Deputy Director of Weather for the Federal Aviation Administration, U.S.A, where she has worked since 1996. Previous assignments included duties in aviation security, anti-terrorism and counter-terrorism. She was employed from 1983 through 1989 as an aviation accident investigator with the NTSB. She holds a multi-engine airline transport pilot rating, and is an active member of ISASI, the American Academy of Forensic Science and the Airborne Law Enforcement Association.

John Farr
United States Federal Aviation Administration
Mr. Farr is the Federal Aviation Administration's senior technical officer for windshear and weather systems processors. He holds a degree in engineering, and was employed as an engineer in private industry for eight years. He has been in government service for sixteen years as a professional engineer and senior technical officer assigned to manage a number of complex equipment programs.

Mark Weber, Ph.D.
Massachusetts Institute of Technology Lincoln Laboratory

Dr. Weber is Group Leader of the Weather Sensing Group at Lincoln Laboratory (LL) where he has worked since 1984. He received a B.A. in Physics from Washington Univ. in St. Louis and a Ph.D. from the Space Physics and Astronomy Dept. at Rice Univ. His areas of research specialty include sonar and Doppler radar signal processing, atmospheric and ocean sound propagation and thundercloud electrification phenomena. Before coming to LL, Mark held postdoctoral appointments at Rice Univ., Columbia Univ. and worked at the U.S. Naval Research Laboratory.

I. Introduction

Aviation weather refers to any type of weather that can affect the operation of an aircraft – anything from a brief delay in departure to a catastrophic accident during flight. Wind shear and events associated with convective weather were recognized as an aviation hazard long before Dr. Theodore Fujita began publishing his now-famous treatises. On July 28, 1943, American Airlines Flight 63 from Cleveland, Ohio, USA to Nashville, Tennessee crashed after the pilot lost control of the Douglas DC3. The pilots and numerous passengers were fatally injured. The aircraft was destroyed by impact and post crash fire. The weather report at the time included warnings for storms, heavy rain, lightning and severe turbulence. The Civil Aeronautics Board found that the probable cause was a loss of control of the aircraft due to unusually severe turbulence and violent downdraft caused by a thunderstorm.

In the ten-year period from 1987 through 1996, 24% of all U.S. accidents were judged to be "weather related". For the twenty-year period 1976 to 1996 fully 43% of U.S. accidents were judged to have involved wind or wind shear, and 2.3 % thunderstorm, although the two data elements are not mutually exclusive. In the U.S., approximately 82% of accidents are general aviation; the rest are air carriers and commuters of various types. When general aviation accidents are negated, and only air carriers are considered, wind and wind shear issues account for 9.5% of accidents.

The Weather Systems Processor (WSP) has been developed to reduce the impact of severe weather conditions on air traffic by providing information concerning weather conditions in the airport terminal environment. WSP provides warnings to air traffic controllers and supervisors of hazardous wind shear and microburst events in the terminal area, forecasts the arrival of gust fronts, and tracks thunderstorms, providing a complete picture of current and future terminal area hazardous weather conditions that may impact runway and airport usage. Common weather situation awareness allows Terminal Approach, Tower Controllers and other traffic management personnel to jointly plan with confidence and safely manage more arrivals and departures with less delay. Knowledge of the location, severity and movement of hazardous weather allows dynamic adjustments to be made in routing aircraft to runways, approach and departure corridors, terminal arrival and departure transition areas (i.e. gate-posts) and other air routes.

A. Hazardous Convective Weather Phenomena

Figure 1 illustrates the low-altitude wind shear (LAWS) phenomena against which the WSP is targeted. A microburst occurs when the thunderstorm downdraft reaches the ground and is diverted horizontally, as shown, to produce a strongly divergent outflow wind pattern. Penetrating aircraft encounter in rapid succession a headwind (lift increasing), followed by a downdraft and tailwind (lift decreasing). This sequence has led to a number of fatal commercial aircraft accidents [1]. Most microbursts, as shown in the photograph, are associated with intense precipitation although in arid environments, strong divergent outflows may occur in the absence of heavy rain at the ground. Gust fronts form on the leading edge of thunderstorm outflows and may propagate tens of kilometers away from the generating storm. Aircraft penetrating a gust front experience an increase in headwind and may encounter turbulence or crosswinds that effect controllability. Gust fronts may also require that the direction of landings and takeoff at an airport change owing to the sustained wind speed and direction shift that may occur behind the front.

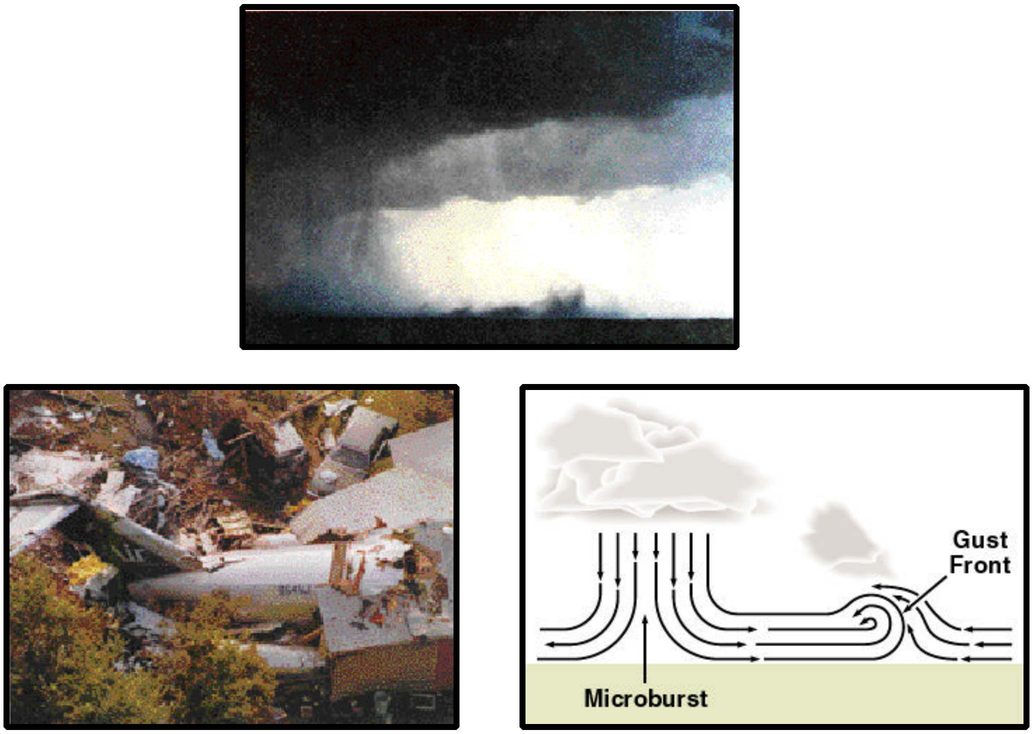


Figure 1. Low Altitude Wind Shear phenomena and their possible consequences for aviation.

Detailed understanding of the safety and airport-operations related aspects of these phenomena have been obtained from a series of accident and incident investigations [2,3], scientific field programs [4,5] and aviation working group meetings [6]. These have established the following key facts:

(i) LAWS is hazardous primarily at altitudes below 330 m AGL. Given commercial aviation landing and takeoff practices, this translates to corridors that extend 3 nmi beyond the runway thresholds for approaching aircraft and 2 nmi on departure;

(ii) wind shear producing an integrated airspeed loss or gain exceeding 15 to 20 kts over a distance of 4 km or less is deemed strong enough to warrant notification to the aircrew. A loss-producing event (i.e. a microburst) whose total wind speed change exceeds 30 kts should not be penetrated at low altitude. Recent work by scientists at NASA have suggested refined metrics for the wind shear intensity that involve spatial derivatives of the flight-path oriented wind component and an estimate of the associated downdraft [7];

(iii) microbursts are much more prevalent, particularly in small-scale “air mass” thunderstorms, than previously recognized. This recognition has prompted redesign of the anemometer network initially deployed to combat LAWS and fielding of additional systems based on Doppler weather radar technology.

The FAA has fielded three complementary LAWS detection systems which will cover close to 150 U.S. airports. As mentioned, an anemometer network – the Low Level Wind Shear Alerting System (LLWAS) – is being refined to provide reliable detection of microburst and gust front wind shear over the area it covers [8]. Typical LLWAS networks extend ½ to 1 nmi beyond the principal runway thresholds although a few larger networks have been deployed at major U.S. airports. FAA will deploy 40 of the small enhanced networks (LLWAS-RS) and has already deployed 9 of the large networks (LLWAS-NE). The Terminal Doppler Weather Radar (TDWR) is a high-resolution, three dimensional radar-based detection system deployed to 45 major U.S. terminals [9]. The ASR-9 WSP will provide radar-based wind shear detection at an additional 34 airports. With the exception of the 9 LLWAS-NE installations which are deployed in an integrated mode with a co-located TDWR, these wind shear detection systems are deployed to different airports based on the facility's operations mode and exposure to LAWS.

The operational procedures that exploit these systems to reduce the risk of a LAWS-related accident were developed in the 1980's by a "TDWR/LLWAS Users Group" [6]. A runway-specific LAWS alert message is generated automatically based on the overlap of a detected event and an airport's runways or approach/departure corridors. This message captures the type of wind shear (loss or gain), its intensity and the location of first encounter relative to the intended flight path. These messages are read verbatim by tower local controllers to the crew of affected aircraft.

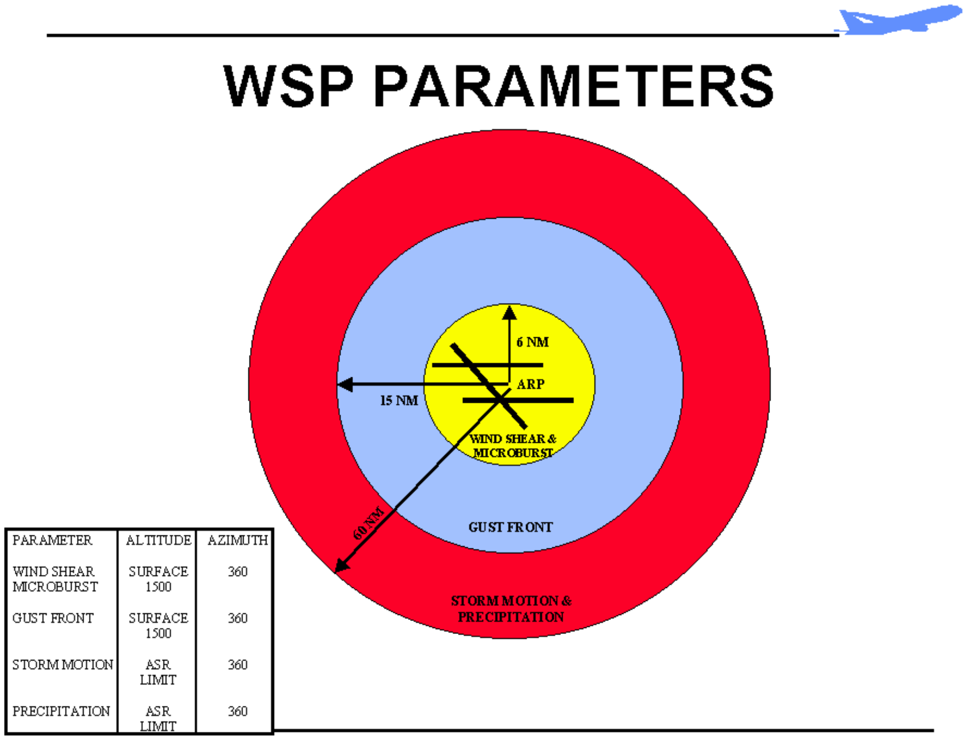
The radar-based technologies (TDWR and WSP) also support generation of broad-area information on the location and movement of thunderstorms in terminal airspace and forecasts of impending wind-shifts based on the tracking of approaching gust fronts. A Situation Display (see Figure 3) presents this information graphically in relation to terminal air routes and runways. Operational experience with TDWR and WSP indicate that this ancillary information significantly enhances the efficiency and safety of terminal operations by reducing the likelihood that aircraft will be routed into areas of thunderstorm activity.

II. WSP Description

The WSP consists of radar interface hardware, distributed processing/display computers and recording devices that obtain radar data from a host Airport Surveillance Radar Model 9 (ASR-9) and use these to generate weather related products. Specific products generated by WSP include:

(i) detection of wind shear and microburst events along approach and departure corridors as well as detection of similar nearby events that may impact flight paths in the near future;
(ii) detection of gust fronts and estimates of their time of airport impact and associated wind shift;
(iii) thunderstorm cell location and movement;
(iv) forecasts of future thunderstorm cell position;
(v) improved mapping of precipitation intensity through detection and censoring of ground clutter breakthrough caused by ducting or anomalous propagation.

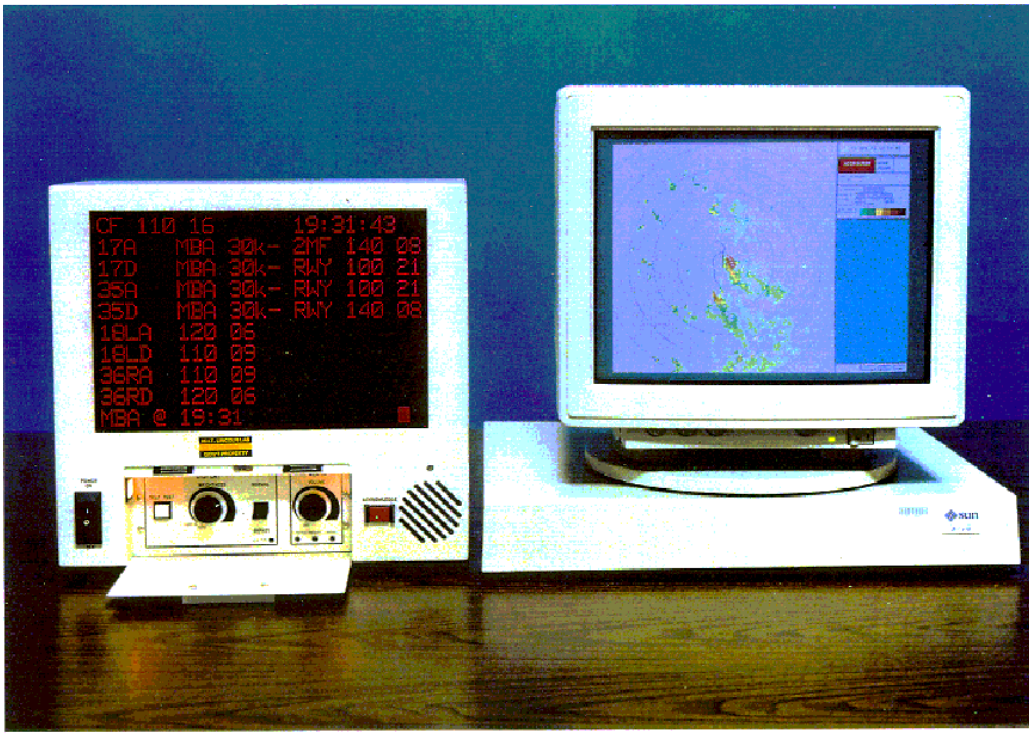
Figure 2 illustrates the different WSP products, their altitude and azimuth parameters, and the distances from the airport over which they are generated.



PARAMETER	ALTITUDE	AZIMUTH
WIND SHEAR MICROBURST	SURFACE 1500	360
GUST FRONT	SURFACE 1500	360
STORM MOTION	ASR LIMIT	360
PRECIPITATION	ASR LIMIT	360

Figure 2. Coverage volumes for ASR-9 WSP products.

WSP provides users with two types of displays. An alphanumeric Ribbon Display Terminal (RDT) provides runway-specific readout of the location, type, and intensity of wind shear/microburst that is hazardous to aircraft near terminal approach and departure corridors and on airport runways. A Graphical Situation Display (GSD) depicts the location, movement, and future position of precipitation cells and gust fronts, the location and intensity of wind shears and microbursts, and provides an estimate of the wind shift behind a front. Figure 3 shows the RDT and GSD with typical information displays.



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CF 110 16          19:31:43
17A    MBA 30k- 2MF 140 08
17D    MBA 30k- RWY 100 21
35A    MBA 30k- RWY 100 21
35D    MBA 30k- RWY 140 08
18LA   120 06
18LD   110 09
36RA   110 09
36RD   120 06
MBA @ 19:31
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Figure 3. WSP Ribbon Display Terminal (RDT) and Situation Display (SD).

WSP performs additional processing of precipitation data to produce a six-level reflectivity weather map that is free of false weather reports caused by anomalous propagation (AP). This improved precipitation map data replaces that from the current ASR-9 weather channel on terminal controller displays. The weather channel data are operationally important in that they are overlaid with the terminal aircraft surveillance data and provide important information about the location of storm cells relative to flight routes.

A. Airport Surveillance Radar

The ASR-9 is a two dimensional, S-band, klystron based, primary radar that includes both a target channel used for aircraft surveillance and a separate weather channel for reflectivity data. The current ASR-9 weather channel provides valuable storm reflectivity information but does not detect hazardous wind shear conditions on the runways or approach/departure corridors. Advance warning of wind shifts associated with gust fronts is not provided, precluding the opportunity to anticipate these shifts and change runway usage in an orderly and efficient manner. Explicit information on storm movement is not provided by this weather channel, thus reducing its value for efficient planning of terminal area flight route planning during thunderstorm activity. A significant operational problem has been identified with the ASR-9 six-level weather channel - false weather contours caused by ground clutter breakthrough during AP conditions. The Doppler processing utilized by WSP allows for detection and elimination of this AP-induced breakthrough. Finally, the displays for ASR-9 six-level weather reflectivity are monochrome and do not allow for viewing at one time of more than two of the six weather intensity levels provided.

B. Background and Development History

WSP has evolved over a ten year development period including seven years of successful field testing of the functional prototype WSP in Huntsville, Alabama, Kansas City, Missouri, Orlando, Florida, Albuquerque, New Mexico and Austin, Texas. A radar test-bed was deployed near Huntsville in 1986 to assess the capability to reliably measure the Doppler velocity and reflectivity signatures of low-altitude wind shear. Off-line analysis demonstrated that an ASR radar could measure the Doppler velocity and reflectivity signatures associated with microbursts and gust fronts in an area extending 10 to 15 nautical miles from the radar.

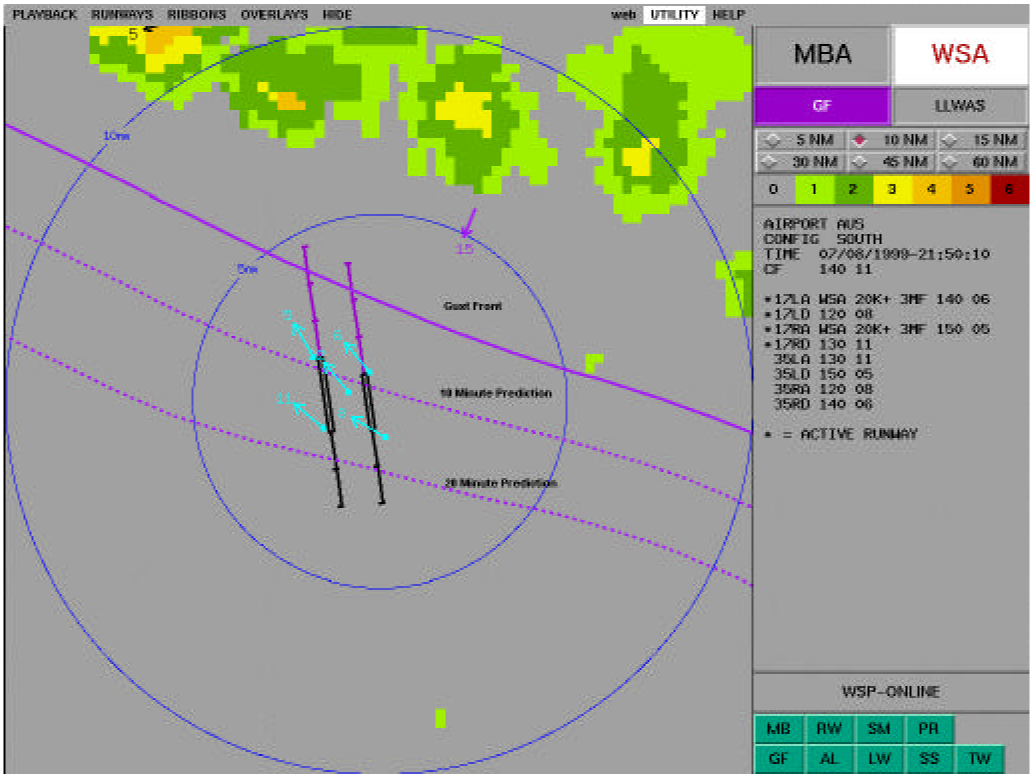
The signal processing algorithms and the wind shear signature recognition algorithms were then tested operationally to verify that a high-confidence automated detection system for Air Traffic controllers was possible. These algorithms were tested in parallel with a prototype of the Terminal Doppler Weather Radar in Orlando and were validated as being effective. Additional testing at Albuquerque since 1993 through the present has verified the WSP performance in the high plains areas. Since 1999, a prototype has also operated at Austin, Texas. Invaluable feedback for refinement of the system hardware and algorithms has been provided, resulting in numerous upgrades. Reports from the prototype sites have validated the system’s intended benefits in both air traffic management and safety. The formal WSP Operational Test and Evaluation (OT&E) is scheduled for this year, to be followed by full-scale production and delivery of systems to 34 airports nationally.

C. How WSP Is Used

The intended operational use of the WSP RDT is to generate air traffic advisories for immediate voice relay to pilots. WSP wind shear and microburst alerts specific to active runways are to be read from the RDT without interpretation by controllers to the pilots who then decide on approach, go-around, and departure action. WSP improves aviation safety by providing air traffic controllers the ability to detect, track and warn pilots of terminal area hazardous wind shear and microburst events in order to avoid them. Low altitude wind shear and microbursts usually occur in thunderstorms during periods of restricted visibility. Pilot recognition of wind shear by visual means may be difficult, especially in darkness and/or instrument meteorological conditions and with the distractions of landing preparation. Therefore, avoidance is aided significantly by means of externally generated wind shear information for pilots.

The intended operational use of the WSP GSD is to provide an accurate, current and predicted, local severe weather picture, matched to the aircraft surveillance picture. These data are used to assess near term severe weather impact on terminal area operations and to provide the means for advanced, coordinated, and informed planning between TRACON approach control, traffic management, and ATCT control. WSP increases capacity of terminal operations by providing information supporting more efficient usage of arrival/departure transition area, terminal area flight routes, and runways under thunderstorm conditions.

Figures 4 and 5 illustrate the way in which the WSP information is used by the controllers in a gust front condition. Figure 4 is an actual display from Austin, Texas, showing a gust front moving toward the airport runways, designated 17L and 17R. The alphanumeric data on the right side of the screen indicates a wind shear alert in the approach corridor, with the gust front shown on the geographic display within the three mile final corridor and the prediction line indicating the arrival of the gust front at the runways in approximately 10 minutes. Figure 5 shows the actual situation approximately 12 minutes later. In this figure, the controllers have reconfigured the airport so the runways are now 35L and 35R, the gust front has now arrived on the airport, and a wind shear alert is now being given for both approaches and departures.



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CONFIG  SOUTH
TIME  07/08/1999-21:50:10
GF     140 11

•17LA WSA 20K+ 3MF 140 06
•17LD 120 08
•17RA WSA 20K+ 3MF 150 05
•17RD 130 11
 35LA 130 11
 35LD 150 05
 35RA 120 08
 35RD 140 06

• = ACTIVE RUNWAY
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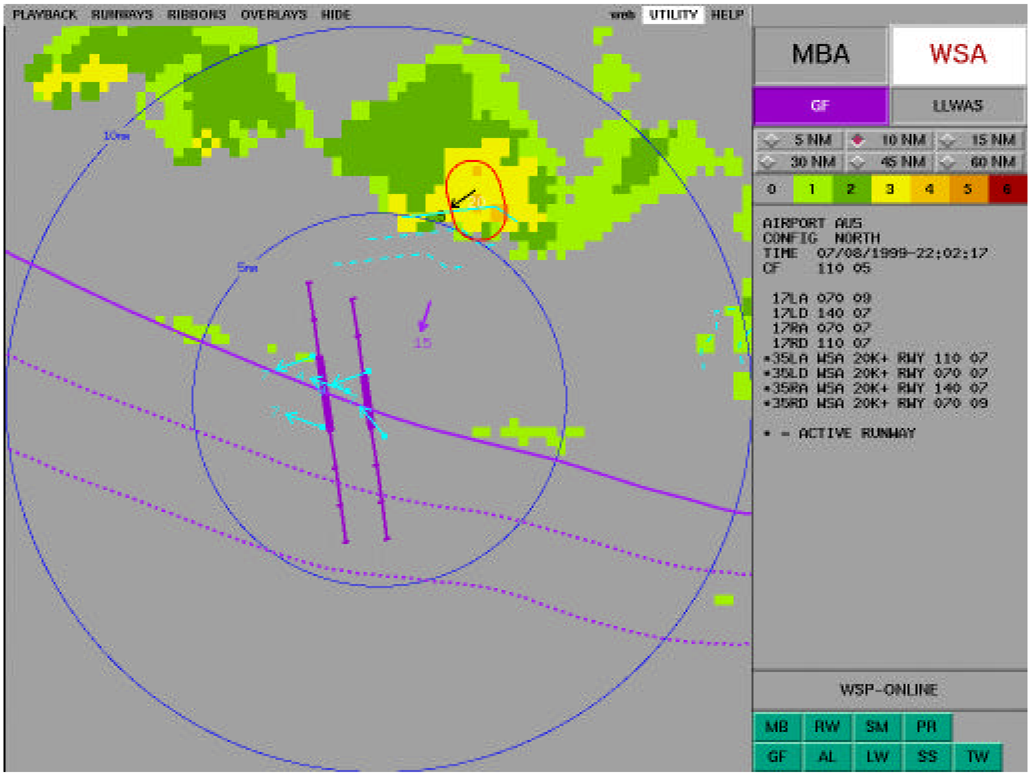
Figure 4. Situation Display depiction of a gust front impact at Austin International Airport.



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 17LD 140 07
 17RA 070 07
 17RD 110 07
•35LA WSA 20K+ RWY 110 07
•35LD WSA 20K+ RWY 070 07
•35RA WSA 20K+ RWY 140 07
•35RD WSA 20K+ RWY 070 09

• - ACTIVE RUNWAY
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Figure 5. Situation Display depiction gust front and microburst activity at Austin International Airport.

D. Cost Effectiveness of WSP

WSP is a relatively inexpensive solution when compared to the other existing ground-based wind shear detection systems. Another system offering similar hazardous weather detection capability is the Terminal Doppler Weather Radar (TDWR). The TDWR is a stand-alone system having its own radar transmitter and receiver, computer processing system, and display systems. The current estimated cost of a WSP site, including installation, is $800,000 US dollars. Compared to the TDWR, which is currently estimated at a per-site cost ranging from $8,600,000 to $9,400,000 US dollars, WSP can be obtained at a significantly lower cost.

The primary reason WSP is much less expensive is that the WSP solution is designed to work with the existing airport surveillance radar and as such does not include the additional cost of a radar transmitter and receiver. The WSP provides products similar in format and content to TDWR products at only slightly reduced performance levels.

Another aspect of cost effectiveness is the cost benefit analysis, which is a comparison of the system cost to the benefit (as expressed in monetary terms) that is realized. A cost benefit analysis of the WSP was documented in the “Investment Analysis Report (IAR) for Weather Systems Processor, October 15, 1996” [10]. The findings of this IAR concluded that WSP is cost beneficial for at least 34 US airports, where deployment of a TDWR at almost all of these would not be considered cost beneficial. These are generally medium-density (medium traffic) airports with significant exposure to thunderstorm activity.

Potential safety and delay benefits establish the pool of available benefits that may be provided by a wind shear detection system. The information provided by the WSP gust front, storm motion, and precipitation products is a significant aid in terminal air traffic management during adverse weather. The delay benefits calculated in the IAR were based on [11]. This analysis indicates that the delay benefits exceed, in equivalent dollar value, the safety benefits realized through the planned 34 WSP deployment by a factor of approximately five. The delay benefits are realized through the reduction of airline direct operation costs due to delayed flights and unnecessary diversions, passenger delay in arrival at their destination airports, and "downstream" delay costs accrued when delayed aircraft and/or flight-crews are unable to complete subsequent flight legs on schedule.

In summary, WSP capability can be provided at low cost on existing airport surveillance radars, namely ASR-9. ASR-9's are deployed at over 130 airports within the United States and internationally at the sites indicated in Table 1.

Table 1
ASR-9 International Sites

International Sites	
India, Trivandrum, Hyderabad Ahmedabad, Guwhatti	4 Systems
Taiwan, Taipei, Kaohsuing, Taichung	3 Systems
Tunisia, 1 System – Tunis	1 System
Philippines	1 System
Morocco, Casablanca	1 System
Belgium, Brussels	1 System
Aruba, Aruba	1 System
China, Long Dong Bow (Guiyang)	1 System
Panama, Panama City	1 System
Poland, Warsaw	1 System

III. WSP's "Intelligent" Data Processing Algorithms

The ASR-9 is not optimally designed from a weather surveillance perspective. Successful realization of the operational benefits described above has required utilization of a number of innovative data processing techniques to extract necessary information from the sometimes ambiguous signals returned by the atmosphere to the radar.

A. Digital Signal Processing

Radar returns are digitized by the WSP receiver and processed initially to reject interference (for example "ground clutter" caused by reflections from objects on the ground) and to develop images of atmospheric "reflectivity" and Doppler velocity. Reflectivity is a measure of the number density and size of atmospheric scatterers and can be related to the intensity of rainfall. Doppler velocity measures the component of wind along the radar line-of-sight.

To develop these images, the WSP must adapt to the ASR-9's parameters – for example, its antenna beam shape and pulse transmission sequence – and the local ground clutter environment. Innovative receiving hardware and signal processing algorithms allow the system to:

(i) process signals varying in input intensity over more than eight orders of magnitude. This very wide "dynamic range" allows WSP to detect both "dry" and "wet" wind shear signatures in the presence of very strong ground clutter returns;

(ii) reduce the intensity of ground clutter returns by up to six orders of magnitude using novel digital filters that optimally address the variable time intervals between the electromagnetic pulses transmitted by the ASR-9;

(iii) tailor the level of ground clutter suppression to the local environment using high resolution "clear day maps". Where ground clutter is intense relative to the return from co-located atmospheric targets, a high level of suppression is applied; when the converse situation applies, the amount of suppression is reduced. This adaptive approach minimizes distortion of the weather returns which could result as an unwanted by-product of the clutter suppression process;

(iv) focus the WSP meteorological detection algorithms on returns from low altitude where wind shear phenomena are manifest. This is accomplished by inter-comparing signals from the two broad elevation receiving beams of the ASR-9;

(v) recognize and censor false "weather" returns that result when ground targets are more strongly illuminated during ducting, or "anomalous propagation" conditions. This involves analysis of the received signal power spectrum (i.e. the distribution of power versus Doppler velocity).

These WSP digital signal processing algorithms are described in detail in [12].

A. Microburst Detection

Reflectivity and Doppler velocity images are processed by meteorological algorithms to provide the products described previously. The WSP microburst detection algorithm [13] is a two-stage process. A "front-end" identifies candidate Doppler velocity signatures using a pattern search for the increasing (with range) run of velocity measurements that is characteristic of surface outflows. These candidate detections are then passed on to a "verification" process that ensures that they are physically plausible. The verification involves image processing and expert system components to determine whether the spatial structure of the storms within which the outflow signatures are detected is consistent with scientific knowledge of microburst generation processes. Features such as the area extent, absolute reflectivity, reflectivity spatial gradients and characteristics of the Doppler velocity structure are assessed in making a decision as to whether a microburst alert should be output to the user displays.

B. Gust Front Detection

The WSP Machine Intelligent Gust Front Detection algorithm (MIGFA) [14] employs multiple, independent "functional template correlators" that search the WSP's reflectivity and Doppler velocity imagery for features that are indicative of gust fronts. These include:

(i) "thin line echoes" – the arc of slightly enhanced radar reflectivity that occurs along the leading edge of a gust front owing to concentrations of insects and other scatterers in the converging winds at that boundary;
(ii) convergent Doppler wind patterns associated with the wind shear region at the leading edge of the front;
(iii) movement of the above features through a background of stationary ground clutter residue and slower moving storm cells.

Each such feature detector encapsulates detailed human knowledge on the size, aspect ratio, range of probable reflectivity/velocity values, and movement speeds associated with the gust front signature for which it is searching. Dynamic processing recognizes and excludes from consideration regions where the feature being sought will be masked. For example, the interior of storms will be masked to the thin-line detector since thin lines will be obscured by moderate or strong precipitation.

The output of the feature detectors are expressed as "interest" images, whose values (0 to 1) specify the degree of evidence that a gust front is present. The multiple interest images are fused to form an overall map of evidence for the locations of possible fronts. From this interest image, fronts are extracted as chains of points ("events") and correlated with prior events by establishing point to point correspondence. This history of scan-to-scan event correspondences is used to make predictions of where points along the front will be a future times. This prediction serves both as an operational product for planning of gust front arrivals at an airport, and as an in input to an "ANTICIPATION" interest image that serves to heighten MIGFA's sensitivity where fronts are expected to be.

C. Storm Motion

The storm motion algorithm uses scan-to-scan correlation of the WSP's reflectivity images to estimate the speed and direction of storm advection. These images are partitioned into "correlation boxes", typically 10 km on a side. For each box, a scan-to-scan displacement vector is computed by finding the displacement that maximizes the cross correlation between image N and N-1. The uniform grid of displacement vectors so derived is smoothed spatially and temporally. The final stage of processing is an analysis of the original reflectivity image to identify local reflectivity maxima corresponding to distinct storm cells. The closest gridded displacement vector is used to estimate the speed and direction of storm motion for each storm cell.

IV. Pre-Planned Improvements

Ongoing field evaluation of WSP prototypes has indicated areas where the wind shear detection algorithms could be enhanced by incorporating meteorological context information and data from other sensors. These insights have spurred effort to program the system's algorithms to more closely mimic the observations and reasoning applied by humans in analyzing the data available to WSP.

A. Dynamic Algorithm Adaptation

Much of the WSP development and testing has been concentrated in meteorological environments characterized as "barotropic". This environment, typical of the southern U.S. during summer months is characterized by light, weakly-sheared environmental winds and an absence of large scale dynamic forcing. Thunderstorms forming in a baratropic atmosphere are of the "air mass" variety. In many parts of the U.S., particularly during the cool and transitional seasons, convection is organized by large-scale forcing (e.g. warm/cold fronts). This "baroclinic" situation is characterized by much stronger environmental winds with significant variation in both the horizontal and vertical dimensions.

Recent experience with the WSP prototype at Austin, TX has provided significant new insights on algorithm performance in the baroclinic environment characteristic of that site during the winter and spring. Data collected during the large-scale frontal passages that produce Austin's convective weather during those seasons indicate that the WSP's performance will improve if it dynamically adapts to the meteorological scenario in which it operates. The processing range for the wind shear detection algorithms is being expanded beyond the near-airport region (0 to 15 nmi from the radar) where wind shear is of most operational concern to landing or departing aircraft. Increasing the field-of-view permits these algorithms to better assess the type of rain system (e.g. stratiform, air-mass convection, line-storm) affecting the airport and to adapt parameters accordingly. Detectors are being implemented that will recognize strong, large-scale wind conditions that may induce false wind shear detections (e.g. "cloud streets" blowing with the prevailing wind in a manner that mimics gust front thin lines). Algorithm sensitivity in such scenarios will be decreased as appropriate.

The presence of tilted thunderstorms caused by vertical shear in the environmental winds may be inferred through comparison of reflectivity in the ASR-9's high and low elevation receive beams. "Overhang" regions where the high-beam echoes are more intense than low beam echoes have been shown to be potentially associated with false alarms. In addition, surface wind measurements available to the WSP from the airport centerfield wind sensor may be compared to winds aloft as deduced from the system's storm tracking function. (Storms are advected by winds prevailing at the height at which the precipitation is generated – 1 to 5 km above the surface.) When vertical shear is detected through either of these two mechanisms, the WSP's parameters may again be dynamically adjusted to account for this situation.

Finally, seasonal and site specific parameter adaptations are being programmed into the algorithms. As mentioned, baroclinic systems are most prevalent in fall, winter and spring and at more northern sites. Thresholds for microburst and gust front detection must be adjusted for arid environments where both clear-air and storm reflectivities are generally lower than at most U.S. airports. Careful monitoring of data from WSP systems that will be deployed nationally over the next years, as well as ongoing studies using weather radars already deployed in the U.S. will aid in this process of site/season algorithm adaptation.

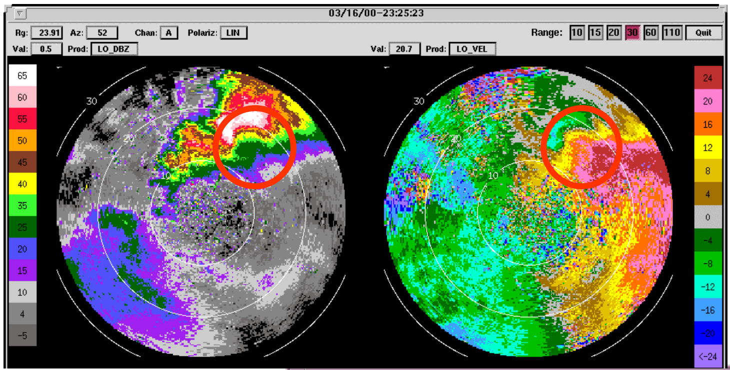
B. Integration with External Systems

Intelligent integration of data from airport wind sensors may improve WSP algorithm performance. All sites will accept data from a centerfield wind sensor. At some airports, one or more additional boundary sensors may also be available. Although these do not provide a capability for stand-alone wind shear detection, their data may be compared to that from the ASR-9 to confirm or disconfirm wind estimates provided by the radar. For example, the "interest" associated with a marginal gust front signature in the radar data might be below the threshold for generating an alert. However, if the indicated wind shift was observed at an airport wind sensor as the radar signature passed over, this additional evidence can be used by the WSP to boost interest sufficiently to generate the alert. A number of analogous applications of airport wind sensor data are under investigation.

Real-time temperature, dew-point and cloud-cover information available from the Automated Surface Observing Stations (ASOS) to which WSP will interface could cue the meteorological algorithms to the likelihood and expected characteristics of convective weather.

Data available from national-scale lightning detection networks provide an independent detector of thunderstorm activity. Since lightning rate is closely coupled to the updraft strength and vertical extent of a storm, these data complement the inherently two-dimensional ASR-9 measurements in delineating the intensity of a thunderstorm.

Finally, opportunities exist to integrate rapid-update measurements of storm intensity and Doppler velocity from the ASR-9 WSP with more slowly scanning, three-dimensional Doppler weather radars such as TDWR and NEXRAD. Where coverages overlap, the WSP data can be used to dynamically adapt the pencil beam scanning patterns so as to concentrate on the storms of most operational concern. Observations of severe storm systems passing the WSP prototype site in Austin, TX have indicated a robust capability for detecting the Doppler and reflectivity signatures associated with hail, damaging straight line winds and tornadoes [Figure 6]. Optimal use of all available weather surveillance assets will enhance the capability to generate timely and accurate severe weather warnings for both aviation and the general public.



03/16/00–23:25:23

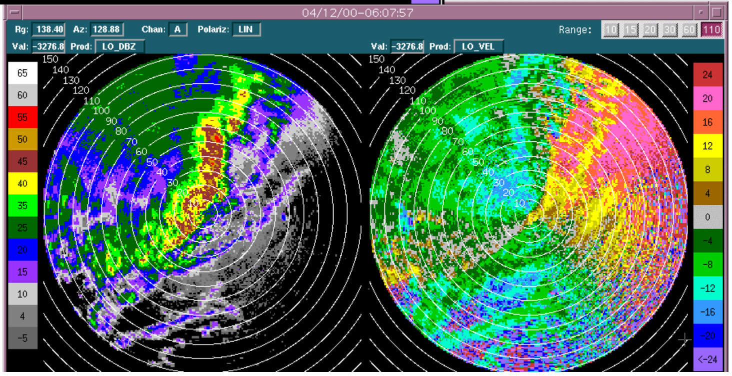
Rg: 23.91 Az: 52 Chan: A Polariz: LIN

Val: 0.5 Prod: LO_DBZ

Val: 20.7 Prod: LO_VEL

Mesocyclone (Tornado Precursor) Austin, 16 March 2000

Line Echo Wave Pattern (Severe Straight Line Winds) Austin, 12 April 2000



04/12/00–06:07:57

Rg: 138.40 Az: 128.88 Chan: A Polariz: LIN

Val: -3276.8 Prod: LO_DBZ

Val: -3276.8 Prod: LO_VEL

Figure 6. Examples illustrations ASR-9 WSP capability to detect severe weather.

V. Utility of WSP in Accident Investigations

The WSP can provide aircraft accident investigators several useful analytical tools. Among these are reconstruction of the detected meteorological data pre- and post-impact, analysis of the weather products derived by WSP, and reconstruction of the displayed information pre and post impact. (See reference [15] for a detailed information on archiving capability.)

The reconstruction data is based on the fact that the WSP automatically and continually records and stores two types of data – base data and product data. The WSP processes the ASR-9 (radar return) data, to produce images of weather reflectivity and Doppler velocity -- base data. Product data is generated by the WSP meteorological processing algorithms, using base data as input. It is this product data that forms the basis for the user display systems. By having the base and product data archived, the controller displays can be recreated. All archived data is time stamped.

Prompt post-accident requests for permanent archiving is essential since routine base data is only stored for twenty (20) hours under normal conditions. The product data is archived normally and retained for fifteen (15) days.

In the United States, the FAA will generally immediately initiate a permanent archive of ASR-9 data for an accident-affected airport. The WSP base data and product data will be transferred to tape for long term or permanent retention. The archived data on the WSP tapes can subsequently be displayed for and evaluated by parties to the investigation at the WSP support (non-operational) systems and on a schedule that is mutually suitable to the parties. Participation by appropriately credentialed meteorologists is recommended to ensure that both the base data and the product data are correctly interpreted.

While these capabilities and tools describe those presently in place in the United States, they would potentially be available for those nations interested in deploying similar systems. For U.S. led investigations, parties may request WSP and other meteorological reconstruction through the meteorology group, if one is formed. Otherwise, requests should be directed through the designated investigator in charge. The FAA will provide appropriate support staff to read out the archived data on a non-operational system, and will provide technical details on the performance characteristics of the WSP and ASR-9 systems at the accident site, including maintenance and performance histories.

V. Summary

The ASR-9 WSP uses state-of-the-art processing technology to provide operationally beneficial wind shear and hazardous weather information from existing airport surveillance radars. This is achieved at moderate cost owing to elimination of requirements for new sensors and associated land and infrastructure acquisition. WSP deployment will substantially reduce the risk of wind shear related accidents at the airports it is deployed. Further, its comprehensive data archiving, playback and analysis capability will support detailed meteorological event reconstruction from all sites to which it is deployed. The extensive data monitoring and archiving capability that the WSP provides will support ongoing refinements to both the its meteorological processing algorithms, and the operational procedures that make use of the information it provides.

REFERENCES

1) Fujita, T.T., *The Downburst Microburst and Macroburst,* University of Chicago, Satellite and Mesometeorology Research Project (SMRP) Department of the Geophysical Sciences, Research Paper Number 210, 1985.

2) Fujita, T.T., *DFW Microburst on August 2, 1985,* University of Chicago, Satellite and Mesometeorology Research Project (SMRP) Department of the Geophysical Sciences, Research Paper Number 217, 1986.

3) Schlickenmaier, H.W., "Windshear Case Study: Denver, Colorado, July 11,1988," *Washington, DC. Federal Aviation Administration, DOT/FAA/DS-89/19*, November 1989.

4) Wilson, J.W., *et al. Microburst wind structure and evaluation of Doppler radar for wind shear detection.* J. Climate Appl. Meteor., 23, 898-915.

5) Wolfson, M.; Klingle-Wilson, D.; Donovan, M.; Cullen, J.; Neilley, D.; Liepins, M.; Hallowell, R.; DiStefano, J.; Clark, D.; Isaminger, M.; Biron, P., Forman, B., "Characteristcs of Thunderstorm-Generated Low Altitude wind Shear: A Survey Based on Nationwide Terminal Doppler Weather Radar Testbed Measurements," *Proceedings of the 29th IEEE Conference on Decision and Control* (Cat. No. 90CH2917-3) p.682-8 vol.2, 1990; 6 vol. 3671 pp.

6) Biter, C., "The Terminal Doppler Weather Radar / Low Level Wind Shear Alert Systems (TDWR/LLWSAS) User Working Group," Summary of the 15-17 February 1989 Meeting, *National Center for Atmospheric Research, Boulder, CO* (1989).

7) Vicroy, Dan D.; Bowles, Roland L.; Schlickenmaier, Herbert (Federal Aviation Administration, Washington, DC.), comps. "Airborne Wind Shear Detection and Warning Systems: Third Combined Manufacturers' and Technologists' Conference, part 1," *National Aeronautics and Space Administration. Langley Research Center*, NASA-CP-10060-PT-1; NAS 1.55:10060-PT-1; DOT/FAA/RD-9 1/2-PT-1, Jan. 1991.

8) Wilson, F.W. and Gramzow, R.H., "Fourth International Conference on the Aviation Weather Systems, Paris;" *The redesigned Low Level Wind Shear Alert System,* 1991.

9) Evans, J.E.; Turnbill, D., "Development of an Automated Windshear Detection System Using Doppler Weather Radar," *Proceedings of the IEEE* vol.77, no.11 p.1661-73, Nov.1989.

10) WSP Investment Anaylsis, *"Investment Analysis Report (IAR) for Weather Systems Processor, October 15, 1996."*

11) Rhoda, D.A.; Weber, M.E., "Assessment of the Delay Aversion Benefits of the Airport Surveillance Radar (ASR) Weather Systems Processor (WSP)," Lincoln Laboratory Project Report ATC-249, July 2, 1996.

12) Weber, M.E., *WSP Signal Processing Algorithms,* Lincoln Laboratory Project Report ATC-255 October 1, 1999

13) Cullen, J.; Pughe, W.; Troxel, S.; Newell, O., *ASR-9 Microburst Detection Algorithm (AMDA) for WSP*, Lincoln Laboratory Project Report ATC-273 October 15,1999.

14) Troxel, S., *Machine Intelligent Gust Front Algorithm for the WSP,* Lincoln Laboratory Project Report ATC-274 January 31, 2000.

15) Newell, O., *WSP Software Overview*, Lincoln Laboratory Project Report ATC-264 September 15, 1999.