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**Role of FAA/NWS Terminal Weather Sensors and Terminal Air Traffic
Automation in Providing a Vortex Advisory Service***

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1. INTRODUCTION

Existing and planned FAA/NWS terminal weather sensors and weather information systems are expected to provide an adequate sensory basis for a useful wake vortex advisory service (WVAS). These meteorological sensors, which provide broad terminal area coverage, should make it possible to reliably estimate and forecast when wake vortex advection characteristics make it possible to reduce the spacings between aircraft on final approach.

Effective operational use of such a weather adaptive WVAS would be very difficult without computerized scheduling and spacing aids for terminal air traffic controllers. The developmental Terminal Air Traffic Control Automation (TATCA) program will provide precisely the planning and spacing tools necessary to help controllers take advantage of wake vortex (WV) advisories and forecasts to improve terminal throughput and efficiency.

Wake Vortex Separation Standards

Current separation standards are larger than the required runway occupancy time for runways dedicated to landings. Depending on the weight class of the leading and trailing aircraft (AC), separation standards call for 3-, 4-, 5-, or 6-nm spacings. If there were no concern for the effects of wake vortices, spacings of less than 2.5 nm could be used safely at many airports under normal runway surface conditions.

Currently, there are three main reasons for conservative safety margins on separation:

- Uncertainty in predicting WV strength, movement, and decay rate – (meteorological uncertainty),

* This work was sponsored by the Federal Aviation Administration. The views expressed are those of the authors and do not reflect the official policy or position of the U.S. Government.

- Inherent imprecision in spacing aircraft on final approach, and
- A need for operational simplicity which argues against the use of complex or variable separation rules (operational difficulties).

The Benefits of Reduced Wake Vortex Separations

Credeur [1] has analyzed the capacity improvement that could be achieved by means of a WVAS for a single runway in Instrument Flight Rules (IFR) with 20% heavy aircraft and 80% large aircraft landing in order. If all the aircraft are landed with 10-s standard deviation in inter-arrival spacing, the maximum theoretical landing rate (i.e., the capacity) with current separation standards is about

$$C = 32 \text{ AC/hr}$$

The most immediate and realizable goal of a wake vortex advisory system is to identify conditions when it is safe to reduce all inter-arrival spacings to 3 nmi. Eliminating all spacings greater than 3 nm would increase the capacity to about

$$C_3 = 35 \text{ AC/hr}$$

This 10% increase seems modest, but a 10% increase in capacity can significantly reduce average delay when the system is operating near its capacity limit. A more ambitious reduction in spacing to 2.5 nm between all aircraft would give an approximate capacity of

$$C_{2.5} = 42 \text{ AC/hr}$$

This is a 31% increase in capacity. Although the feasibility of using a wake vortex advisory system to permit 2.5 nm separations between all aircraft types has not been established, it is a worthy goal. A capacity gain of this magnitude would result in a significant reduction in delay during busy periods.

A WVAS has another significant potential benefit in that it would tend to improve airport acceptance rates by a larger factor in IFR than in Visual Flight Rules (VFR). At many airports a WVAS could thereby reduce the severity of the capacity reduction that currently disrupts activity when visibility changes result in IFR conditions.

2. THE USE OF EXISTING AND PLANNED FAA/NWS TERMINAL WEATHER SENSORS AND WEATHER INFORMATION SYSTEMS IN PROVIDING A WAKE VORTEX ADVISORY AND PREDICTION SERVICE

Basic Approach

Past research [2] has shown that the wake vortex separation can be safely reduced when the vortices are being advected out of the arrival path of following aircraft or if atmospheric conditions are causing the vortices to dissipate prior to encounter. Wind advection can be easily analyzed to first order and has been shown experimentally to be capable of indicating when conditions are safe for reduced spacing. [3] By contrast, the research on the relationship of vortex breakup to atmospheric stability and to readily measured atmospheric parameters in a much less conclusive stage. Hence, we recommend focussing on advection as the principal mechanism for an initial WVAS.

Additionally, we recommend focusing on WVAS service under IFR conditions. IFR conditions are a principal cause of delays at major airports (see Table 1) and the scheduled capacity of the airport in many cases is strongly weighted in the direction of the IFR capacity. During VFR conditions, many airports have excess capacity, and the aircraft may be able to fly profiles that reduce the impact of the wake vortex separations on capacity of individual runways.

Table 1.
Weather Causes of Serious Delays at Major US Airports*

AIRPORT	DAILY OPS.	CLIMATOLOGY (Days per Year)			DELAYS > 5 MIN.			
		T-Storm	Hvy Fog	Lo Vis.	Annual Delay Min X 1000			
					Th	Hvy Fog	Lo Vis.	Wx
Chicago	2175	38	16	109	412	94	185	87%
Atlanta	2156	50	30	136	538	174	229	90%
Los Angeles	1589	3	44	121	24	188	150	83%
Dallas	1578	45	11	86	354	47	106	87%
Denver	1438	41	10	57	294	39	64	85%
San Fran.	1255	2	17	101	13	57	99	74%
St. Louis	1178	45	11	156	265	35	143	89%
Boston	1162	19	23	125	110	72	113	84%
Phoenix	1142	23	2	5	131	6	4	72%
Detroit	1137	33	22	121	187	67	107	87%

* The delay estimates are based on climatology of the various airports and the results of detailed studies of delay at O'Hare airport. [14] This study suggests that at these airports, adverse weather accounts for 90 % of the serious delays (i.e., delays > 15 min.).

Prediction Concept

The concept we recommend for an initial wind prediction product uses time-series analysis of the enhanced Low Level Wind Shear Alert System (LLWAS)¹ anemometers located near the approach zone in connection with areal estimates of the winds and overall environment using a volume scanning pencil-beam pulse Doppler radar such as the Terminal Doppler Weather Radar (TDWR).² [5] These sensors are used to predict when the winds will be outside a "safety ellipse" for wake vortex advection, such as was identified in the 1970's.³ Additional verification of the wind conditions in the approach zone would be obtained using *in situ* measurements of the winds by aircraft on approach using the Aircraft Communications Addressing and Reporting System (ACARS) [15] to

¹ The enhanced LLWAS differs from the previous LLWAS by providing a much greater density of anemometers in the final three miles of the approach, sensor siting to reduce sheltering, and improved data processing algorithms. [13]

² If, a scanning Doppler laser is also available (e.g., as a part of the overall wake vortex advisory and monitoring system, data from it would be used as well in the same manner as the data from the TDWR.

³ The "safety ellipse," defined in [6], had a cross-runway semi-minor axis of 6 knots and an along-runway semi-major axis corresponding to 12 knots of headwind.

downlink data to the ground. The combining of information from these various sensors will be accomplished by the Integrated Terminal Weather System (ITWS). [8] In this section, we discuss the considerations leading to the above recommendation and present some very preliminary experimental results using the TDWR and LLWAS anemometers.

Previous efforts at wind prediction in the wake vortex context used the short-term (e.g., eight minutes) past history of the wind at an anemometer near the approach zone to predict that the winds would continue to advect the wake vortices away from following aircraft in the near future.⁴ Although this approach could be reasonably successful in a highly stationary weather situation, it will not be satisfactory in convective weather and certain low-visibility weather situations where strong wind changes can occur fairly rapidly without warning.

One example of this type of rapid change is shown in figure 1 which shows the time trace of an Low Level Wind Shear System (LLWAS) anemometer at the Orlando International Airport on a day when delays were occurring due to thunderstorms in the terminal area. The wind was approximately 8 kts from the south for nearly an hour before suddenly changing to strong westerly flow at 1900 GMT. The likelihood of this sudden change that occurs at approximately 19:00 GMT could not be anticipated from the anemometer data alone up to 18:55.

From the TDWR testbed radar data obtained at the same time, the wind stationarity is apparent, as is the cause of a sharp change in the wind at 19:00. First, however, it is appropriate to make a few remarks about the application of Doppler weather radar to characterizing the wake vortex advection environment. Numerous scientific and operationally oriented experiments over the past 30 years have shown that winds near the surface can be measured with sensitive narrow-beamwidth pencil-beam Doppler radars out to a range of 40-50 km under the weather conditions identified in table 1, which also correspond to conditions of serious delays. It is important to note, however, that this wind measurement capability generally can be achieved in clear air conditions⁵ associated with adverse weather as well as in conditions where there is precipitation. Furthermore, even though the high-quality measurements needed for automatic data processing must often be accomplished in the presence of strong ground clutter, this clutter challenge has been largely surmounted in the case of the TDWR by the use of narrow beams (0.5 deg) and a variety of other clutter-suppression techniques. [5]

Figure 2 shows the TDWR radar reflectivity and radial velocity fields during the period of the time in which the anemometer winds were fairly stationary. The reflectivity values associated with the region near the anemometer are typical of those associated with clear air return in summer in central Florida, and the radial velocity field is largely homogeneous at about 8 kts within a radius of several miles about the anemometer. Under such homogeneous areal wind environment conditions, one expects that the anemometer winds will remain stationary for some minutes.

Figure 3 shows the reflectivity and radial velocity fields some 15 minutes before the sharp wind change occurs at the anemometer. It is shown that a region of heavy rain is approaching the anemometer from the west. A sharp radial wind change is associated with the leading edge of the storm outflow (i.e. gust front). Under such conditions, a sharp change in the anemometer wind is expected in the next few minutes.

⁴ Specifically, if the vector wind had been outside the "safety ellipse" for the previous eight minutes, it was considered safe to operate at a reduced wake vortex spacing for aircraft commencing final approach. [2]

⁵ Due to scattering from refractive index inhomogeneities, insects, and/or particles blown by the wind. [7]

Abrupt changes in the winds at a given location can arise from a variety of causes. Table 2 summarizes some principal causes of wind changes and the weather system observables which can be used to detect these changes. A few comments are in order regarding each of the phenomena:

Microburst Outflows

Microburst outflows can be very common in areas with substantial convective activity. For example, recent studies have concluded that near an airport, one can expect two to eight microbursts (and approximately two gust fronts) each day with thunderstorms. Microbursts are detected automatically by the TDWR and enhanced LLWAS, and it is expected that the detection probability of microbursts will be near unity for the airports where the warnings from these two systems are integrated.

The expected presence of a convective cell above a runway in the immediate future can be readily anticipated from the TDWR storm track algorithm applied to data from either the TDWR or the ASR-9 weather channel. The TDWR can determine, to some degree, when a microburst is imminent by noting the descent of reflectivity and the presence of velocity features aloft. However, the warning time is typically about five minutes, whereas at least 10-minutes warning is desirable for the WVAS. Thus, if the atmospheric conditions are such that microbursts may occur, the prudent course of action would be to suspend any reduced wake vortex separation operations until the cells were no longer at a location where a downdraft would occur in the area of concern.

Gust Fronts

2. The TDWR seeks to detect gust fronts at least 20 minutes prior to their arrival at the airport. Tracking algorithms operating on the gust front detections permit the prediction of the time of arrival of a gust front at an airport location to an accuracy of typically several minutes.[5] The winds behind the gust front are estimated by a least squares fit of an uniform wind field to the observed radial velocity field behind the gust front. Typical accuracies using Doppler radar data alone are currently 6 kts and 30 deg in angle behind a gust front.⁶ Table 3 summarizes the detection performance of the initial TDWR gust front/wind shift estimation algorithms (an improved algorithm is under development which should provide improved accuracy).

⁶ We recommend using anemometer data to improve on the accuracy of estimation for winds behind a gust front and to account for surface friction effects.

Table 2.
Principal Causes of Rapid Surface Wind Changes in the Approach Zone and Predictive Clues that Would be Utilized by an Integrated Terminal Weather System

Meteorological Phenomena	Frequency	Predictive Clues
Microburst Outflows	Common on thunderstorm days. Can occur in semi-arid environments (e.g., high plains east of Rocky Mts.) without thunder.	Convective cells developing and/or moving toward approach zone. Precursors aloft in storm. [5] Movement of a microburst outflow toward approach zone.
Gust fronts	Common on thunderstorm days.	Sharp propagating changes in Doppler velocity fields. Propagating lines of enhanced reflectivity.
Frontal bands	Common in snow storms and frontal rain storms.	Propagating surface radial velocity changes in bands. Propagating bands of precipitation.
Thermal instabilities	Common in summer.	Spatial variations in surface velocity field. Enhanced Doppler spectrum widths. Temperature lapse rate in lowest 1000 ft.

Table 3.
Baseline TDWR Gust Front/Wind Shift Planning Product Performance

	Ff	10 Min. Forecast		20 Min. Forecast		Wind Shift Estimate	
		Pcf	Pff	Pcf	Pff	Ve(M/s)	Ae(°)
Denver 1988	.45	.97	.11	.83	.18	3	30
Kansas City	.50	.97	.18	.94	.21	3	30
Orlando	.56	.95	.13	.75	.30	2	15

Ff: fraction forecasted; Pcf: probability of correct forecast ; Pff: probability of false forecast; Ve: mean absolute velocity error (m/s); Ae: mean absolute direction error (deg)

Frontal Bands

3. The wind shifts associated with frontal snow and rain bands in areas of widespread precipitation can be detected by techniques similar to those used for gust fronts.

Thermal Instabilities

4. Thermal instabilities can cause strong localized changes in surface winds on days with substantial solar heating of the ground. These instabilities are typically manifested by a high degree of variation in the surface radial velocity fields over small spatial scales (e.g., a square km) and an increased spectrum width.⁷ By contrast, laminar flow associated with relatively stable winds has a low spatial variation over areas of several square km and a low spectral width. The temperature lapse rate can be determined by the ITWS using ACARS derived temperature profiles together with surface temperatures from the Automated Surface Observing System (ASOS) and the Automatic Weather Observing System (AWOS).

In view of the importance of the TDWR gust front/wind shift detection algorithm to the predictive capability needed for a WVAS, a few remarks are in order on the algorithm status. Until recently, gust front detection and wind shift estimation had received much less emphasis in the TDWR program than microburst detection. However, recent TDWR operational tests at Denver, Kansas City, and Orlando have shown that the wind shift prediction functions are very enthusiastically received by air traffic control personnel as a planning aid for minimizing the delay associated with runway shifts. As a consequence, an aggressive program is underway to improve the performance of the algorithm.

It also should be noted that the current TDWR algorithm was designed to detect very sharp wind changes that could lead to hazardous shear for aircraft. Performance scoring has not, in general, considered all the wind shifts that might be of concern for a WVAS. Consequently, there needs to be some focussed research on developing and evaluating algorithms to explicitly accomplish the following:

1. Determine that the wind field is likely to be stationary over periods (e.g., >10-15 minutes) which are consistent with the operational considerations discussed below, and
2. Identify periods in which the wind field cannot be estimated reliably or may change adversely at least 10 minutes in advance.

The "fusion" of TDWR and anemometer data required to produce the desired wind field predictions would be accomplished by the ITWS. ITWS (see figure 4) has access to a variety of data from the FAA and NWS terminal sensors [8] as well as access to NWS high-resolution numerical weather prediction results. It is expected that the initial ITWS system will be deployed in 1996, with enhancements occurring through the year 2000.

⁷ The TDWR estimates both the mean radial velocity and the standard deviation of the radial velocity field in the radar resolution volume (typically about 120 m x 120 m x 120 m). Increased standard deviations (the "spectrum width") correspond to cases with a high degree of turbulence or velocity dispersion within the resolution volume. [7]

3. THE OPERATIONAL PROBLEM

Although the necessary sensors and weather information processing system are becoming available to support a WVAS, present-day terminal radar control equipment and procedures would limit the ability of controllers to use either static or dynamic information from such a WVAS effectively.

Operational Barriers to the Use of Variable Wake Vortex Separations

The resolution limitations of the current Automated Radar Terminal System (ARTS) displays, limited control precision in spacing aircraft on final, and the need to minimize controller workload have led to separation standards that place aircraft at easily remembered, easily visualized, and conservative integer-mile spacings based on a small number of weight classifications.

Control precision in spacing aircraft on final has been consistently shown to have a standard deviation of about 20 seconds from the desired inter-arrival spacing value. For jet aircraft, 20 seconds translates into about a one-mile standard deviation on minimum spacing. Thus, if a safe wake vortex separation is determined for a given condition, the controller must aim for at least one more mile of separation to avoid violating the desired spacing. Taken together, the effect of these constraints is that it would be very difficult for controllers to make use of tighter and more complex separation standards in today's manual control environment.

The Role of the TATCA Final Approach Spacing Tool

As separation standards are reduced, the safety margins associated with spacing imprecision (whether arising consciously or not) become increasingly significant limitations on throughput. Hence, increased spacing precision will be important in realizing the benefits of reduced wake vortex spacings. Computerized aides for final approach controllers, provided by the FAA's developmental Terminal Air Traffic Control Automation (TATCA) system will make it easier for controllers to achieve the precise separations suggested by wake vortex advisories. TATCA's Final Approach Spacing Tool (FAST) [9] is being designed to assist controllers in meeting any desired minimum separation standard with increased precision.

Studies [10, 11] have shown that final approach spacing aids can improve control precision by roughly a factor of two, to a standard deviation of 0.5 nm in minimum spacing between arrivals. If necessary, FAST could be extended to handle more numerous and complex WV aircraft categories. The exact recommended separation for each aircraft pair could be provided directly by giving the final vector controller easily visualized, time-based, turn-to-final advisories. Human memory and low-resolution radar images would no longer limit aircraft delivery precision.

TATCA/FAST Implementation

The TATCA program is placing priority upon delivering an early developmental FAST capability to the field. Prototyping in developmental laboratories is currently refining the automation logic and its associated human-system interfaces. A field installation for developmental purposes is planned for the DFW Terminal Radar Approach Control (TRACON) Facility in FY 1993.

Commercially-available auxiliary workstations will be installed at DFW to perform the major software functions. A special hardware interface – the TATCA Interface Unit (or TIU) – will acquire data from existing communications and radar processors. At ARTS IIIA sites, the existing displays will be replaced with Full Digital ARTS Displays (FDADs). FAST advisories will be passed to the FDADs directly by the TIU. A limited national deployment of FAST is planned to begin in FY 1996.

Operational Barriers to the Automatic Execution of Wake Vortex Advisories

There is, however, another operational consideration posed by the dynamics of air traffic management. An automatic WVAS coupled to terminal ATC automation tools could conceivably be designed to initiate, plan, coordinate, and execute significant capacity fluctuations in terminal airspace without requiring conscious intervention on the part of the controller team. In this sense, the capacity changes initiated by the automatic wake vortex advisor would be fundamentally different from capacity changes caused today by runway configuration changes, visibility changes, and even emergencies and other unpredictable events. Currently, no such change can be introduced without the active planning and volition of the controller team. Even though an urgent need for such a change in capacity can come without warning, the controller team can delay or prolong the change in order to assure safety and satisfy other constraints on the air traffic management process.

There are two approaches to this problem. One is to require controller intervention or approval before a change of any significant magnitude is allowed to be executed by the automatic system. The other approach is to force the wake vortex advisor to continually look ahead and provide the traffic management system with reliable forecasts of changes in wake vortex separations. Both approaches would allow the controllers time to evaluate the proposed change and intervene if the anticipated result were not to their liking. The latter approach would not only provide a foundation for an eventual full automation of the advisory system, but it would also satisfy other important operational requirements for efficient and safe air traffic management. Let us now examine these operational requirements.

Forecasting Reductions in Runway Capacity

As an aircraft approaches the final approach path, its controllability (the ability to delay or expedite it relative to its current planned arrival time) steadily decreases. It would be difficult for the final vector control position in the TRACON to react to a suddenly mandated increase in minimum separation once he has several aircraft established on final. If aircraft are landing at a rate approaching the theoretical capacity of the runway and if the TRACON and final approach path are fully loaded with aircraft, an abrupt and unforeseen reduction in separation standards could easily result in a string of missed approaches. Thus, it seems essential to have the ability to forecast significant reductions in runway capacity.

Forecasting Increases in Runway Capacity

Sudden increases in runway capacity are welcomed by controllers and do not on first inspection seem to pose operational problems. However, a reliable forecast of a future increase in runway capacity would allow the TRACON traffic manager, the en route metering system, and other upstream components of the air traffic management system a little more time to “fill the pipelines” with arrivals or departures. This would let controllers take greater advantage of the newly available airspace and concrete, thereby reducing congestion and delay.

Illustration of TRACON Controllability

Vandevenne, et al. [12] treat the available controllability for aircraft approaching the Boston, Denver, and Atlanta airports. For direct approaches to certain runways (like the Providence approach to runway 4 at Boston), the principal means for expediting an arrival is to delay the mandatory speed reductions to make them occur as late as possible. This provides only about one minute of speed-up capability. On the other hand, it is possible to delay arrivals to most runways by over six minutes with the use of path stretching vectors.

Warning Time Needed to Accommodate a Reduction in Capacity

Consider an example of a sudden capacity reduction. Assume the traffic pipeline in the TRACON is full and all aircraft are landing with 2.5 mile separations at 90% of capacity, or a rate of 38 AC/hr. If the standards were now to suddenly revert to 3-, 4-, 5-, and 6-nm separations, it would be difficult to accommodate the aircraft already inside the TRACON without at least one missed approach. If aircraft numbers two and three in the landing stream are both set up for 2.5-nm spacing, number two will have to go around. If the first plane in the landing stream is a "heavy," at least two following aircraft will have to go around.

The problem of a sudden capacity reduction is not as severe at the edge of the TRACON. If the flight length of a typical TRACON approach path is 60 miles and the average ground-speed on the paths in the TRACON is 180 kt, each aircraft will spend 20 minutes traversing the TRACON before landing, and there will be at least 12 aircraft airborne in the TRACON at any time. If the landing rate suddenly drops to 29 AC/hr (which is 90% of 32 AC/hr), the next aircraft to enter the TRACON will not be allowed to land for about 25 minutes. That extra five minutes could be absorbed in the TRACON by early speed reductions and path stretching. However, that five-minute delay might well be increased if one or more aircraft on final are required to execute missed approaches.

In order to avoid these difficulties, a certain minimum warning time for the increase in aircraft separation is essential. Fortunately, the required delay for each aircraft becomes smaller along with the decrease in the available controllability for that aircraft as it approaches the final approach zone. For the reduction in landing rate from 38 AC/hr to 29 AC/hr considered above, a calculation based on a simple but reasonable model of available delay in a typical TRACON airspace indicates that an advanced warning time of about 10 minutes for increased aircraft separation would permit the traffic to be smoothly rescheduled so that no aircraft pairs violate the new larger separations after those new separations go into effect. Although a more detailed analysis based on actual TRACON arrival paths should be performed to verify this result, the resulting warning time seems consistent with the predictive capabilities of the wake vortex advisory system proposed above.

Warning Time Needed to Accommodate an Increase in Capacity

Let us now address the question of how far in advance the advisory system should forecast an increase in capacity. Consider a case in which the initial landing rate is 29 AC/hr and the wake vortex monitor (without advanced warning) indicates that the landing rate can immediately increase to 38 AC/hr. At the time of the landing rate change, there are 10 aircraft in the TRACON. Rather than landing in 20 minutes as originally scheduled, the 10th aircraft would now have to land in 16 minutes to keep up

with the new, increased landing rate. However, since it is impossible to expedite an aircraft by more than about one minute in the TRACON, pockets of excess spacing will appear in the landing sequence.

The discrepancy between adding delay versus increasing throughput is also large in en route airspace. When the terminal capacity increases, aircraft farther upstream need to catch up by more than those downstream in order to keep the pipeline full. If it is desired to take full advantage of the increased capacity when wake vortex separation reductions are anticipated, the forecast should be made as early as possible. Unless there is considerable excess traffic in the pipeline, at some point far upstream of the terminal, gaps are unavoidable. Gaps in the stream waste runway capacity. But, unlike the case of a capacity reduction, advanced warning is never essential to maintain safe separation when a capacity increase is anticipated.

In the special case in which there are holding stacks in en route airspace available to respond to the excess capacity in the TRACON, then it is possible to calculate exactly how much warning is needed to maintain an uninterrupted, efficient flow. The limiting case is easily understood. If the forecast is made a full 20 minutes in advance of the actual capacity increase, all of the planes currently in the TRACON can land at the old rate, and the next one to enter can be brought out of a holding stack just in time to smoothly transition to the new landing rate. If the TRACON is then continuously fed at the new rate, there will be no need for any expediting action inside the TRACON. Thus, the minimum forecast time that will maintain gap-free flow is clearly always less than the TRACON transit time when a supply of aircraft is available outside the TRACON. The actual minimum forecast time that achieves uninterrupted flow can be calculated by using the following reasoning.

Gaps can be avoided in the TRACON arrival stream if the forecast time is chosen far enough in advance so that after the forecast is delivered, the first aircraft to enter the TRACON – if fully expedited – is just able to catch up with the preceding aircraft and land with the new reduced separation. For the example in which the capacity jumps from 29 to 38 AC/hr and there is one minute of expediting available in the TRACON, the minimum forecast time that achieves uninterrupted flow is calculated to be about 14 minutes. This warning time is also consistent with the capabilities of the proposed wake vortex advisory system.

The Role of the TATCA Traffic Management Advisor

It is unlikely that introducing a look-ahead capability into today's manual terminal air traffic management system would have immediate benefits because of the difficulty of assimilating such information into a manual planning operation. Fortunately, another TATCA automation tool is being developed specifically to address and mitigate the problem of planning in the terminal environment. It is the Traffic Management Advisor (TMA).

The TMA is the scheduling and planning component of the TATCA system. The TMA will use aircraft performance characteristics along with current flight plan data, surveillance data, wind information, runway configuration information, and airport acceptance rate goals to begin preliminary planning for arrivals before the top-of-descent point in en route airspace, typically 150 nm (roughly 30 minutes) from the airport.

The TRACON component of the TMA will re-plan the arrivals within the TRACON and will allow arrival schedules to be adjusted dynamically as late as five minutes before landing. The resulting range of TMA planning times is expected to allow

runways to be reassigned, aircraft to be re-sequenced, and traffic to be delayed or expedited in a more coordinated and efficient manner than is possible today.

Another function that the TMA can easily perform is to make its own estimate of the current and near-future landing rate based on its current arrival schedule and the degree of conformance of the current arrivals with that schedule. It can continually and automatically pass that information upstream to the en route metering system to assist in providing a well-matched and steady flow of traffic into the terminal.

Thus, the TMA has all of the capabilities necessary to handle complex replanning and scheduling actions and to disseminate dynamically generated plans to the controller team. These are precisely the operational capabilities that are essential if the terminal air traffic control system is to smoothly and efficiently react to the forecasts that will flow from a well designed wake vortex advisory system.

SUMMARY AND RECOMMENDATION

The combination of improved weather sensing and automation and planning assistance would enable the ATC system to achieve more organized and efficient runway utilization in two ways. Peak runway throughput could be increased by improved knowledge of current wake vortex behavior. Congestion, disorder, and delay could be reduced by an improved ability to predict and utilize variable wake vortex separations.

Safe and effective operational use of an automatic wake vortex advisory system relies on an ability to forecast short-term (10- to 15-minute) changes in wake vortex advection characteristics. A wide area wind field assessment using Doppler radar together with the dense anemometer arrays of the enhanced LLWAS system can likely provide the necessary predictions of changes in wake vortex advection characteristics with forecast times that are reasonably well matched to the traffic management needs of terminal radar control. Continuous analysis of forecast accuracy will allow a quantitative confidence level to be associated with each value of forecast time. If the current conditions only instill high confidence that detrimental wind shifts will not occur within less than, say 10 minutes, the advisory system can be designed to recommend current wake vortex spacings that assure the ability to gracefully recover in the future to safer spacings in less than 10 minutes.

Operational difficulties as well as meteorological uncertainties must be addressed to achieve significant increases in landing capacity. Without computer aides for controllers, the need for simple, invariant, and conservative rules for controllers to use in spacing aircraft on final could limit the benefits of wake vortex monitoring and prediction technology.

As separation standards are reduced, the safety margins associated with spacing imprecision become relatively more significant limitations on throughput. Hence, increased spacing precision will be important in realizing the benefits of reduced wake vortex spacings.

The key elements of the necessary controller assistance system are now being developed as part of the Traffic Management Advisor and Final Approach Spacing Tool of the TATCA program. These aides will make it possible to integrate the information derived from a wake vortex monitor directly into the final approach spacing information presented to controllers on current and planned displays.

Figure 5 summarizes the overall system recommended for increasing runway capacity in the absence of a collateral safety monitor. If a safety monitor such as suggested in [4] were to be implemented, the information it obtained on wake vortex transport would be provided to the WVAS to produce improved estimates of the expected vortex behavior.

A major advantage of the recommended system is that most of the sensors and information processing systems required are in the process of development to meet other needs. Hence, a relatively modest investment to extend the planned capability to meet the needs for a wake vortex advisory service could provide the significant improvements in capacity that were discussed in Section 1. The specific areas requiring focussed R & D include the following:

1. Refinement of the operational interface and procedures between a WVAS, terminal automation, en route traffic management and centralized traffic planning,
2. Assessment of the cost/benefit at specific airports for a WVAS using only wind advection monitoring and prediction,
3. Quantification of wind prediction performance in the WVAS context using the extensive existing data sets obtained by the TDWR program, and
4. Assessment of the capability for wake vortex dissipation prediction using parameters other than the wind speed and direction.

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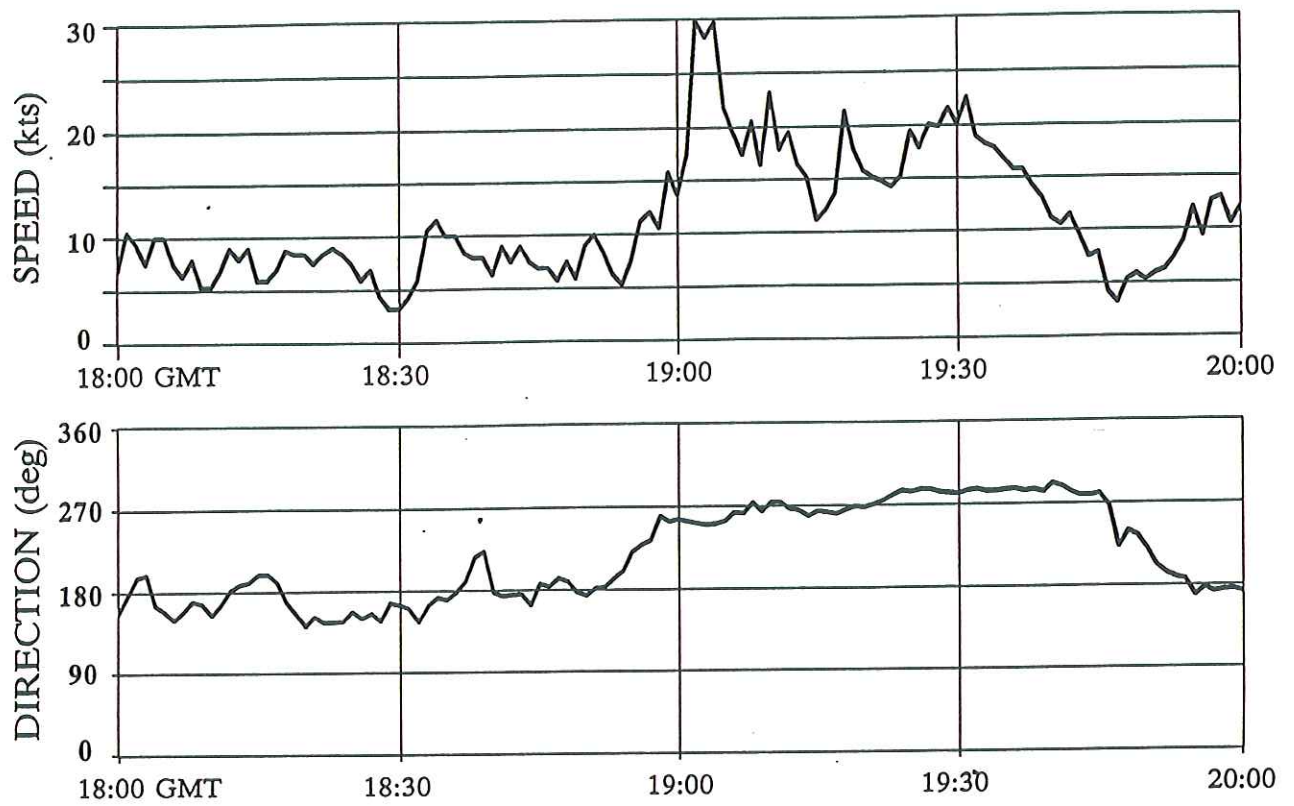


Fig. 1 LLWAS sensor winds observed on sensor 4 at Orlando International Airport on 13 July 1991.

REFLECTIVITY

RADIAL VELOCITY

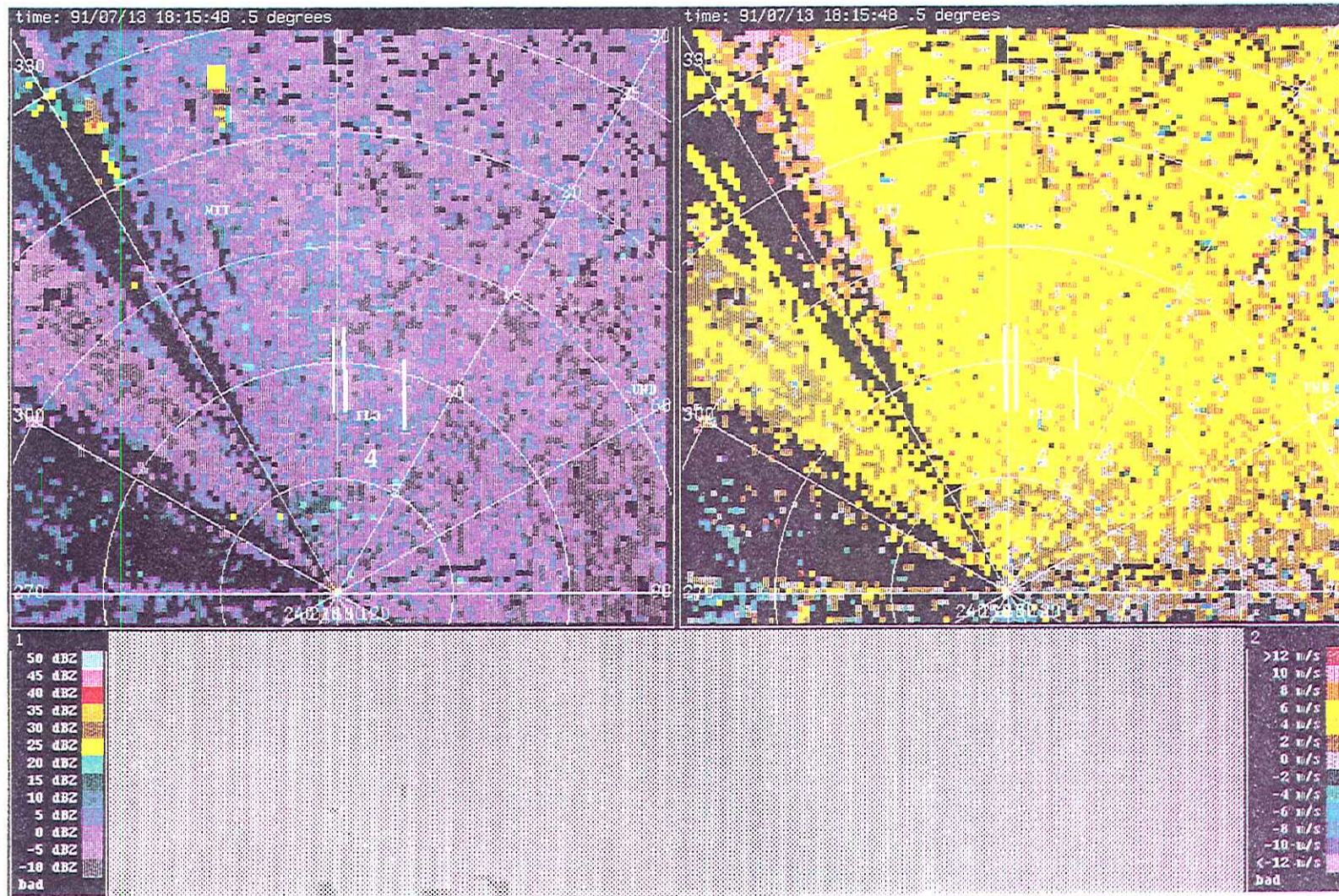


Fig. 2 TDWR prototype radar reflectivity and radial velocity fields near Orlando International Airport at 18:15 GMT on 13 July 1991. The range rings are in km. The airport runways are the three vertical lines approximately 10 km (5 nmi) north of the radar. The LLWAS anemometer indicated by the number 4 to to south of the runways. The radial winds indicate a constant wind from the south at approximately 8-12 knots with a patch of velocities closer to 4 knots to the south of the anemometer.

REFLECTIVITY

RADIAL VELOCITY

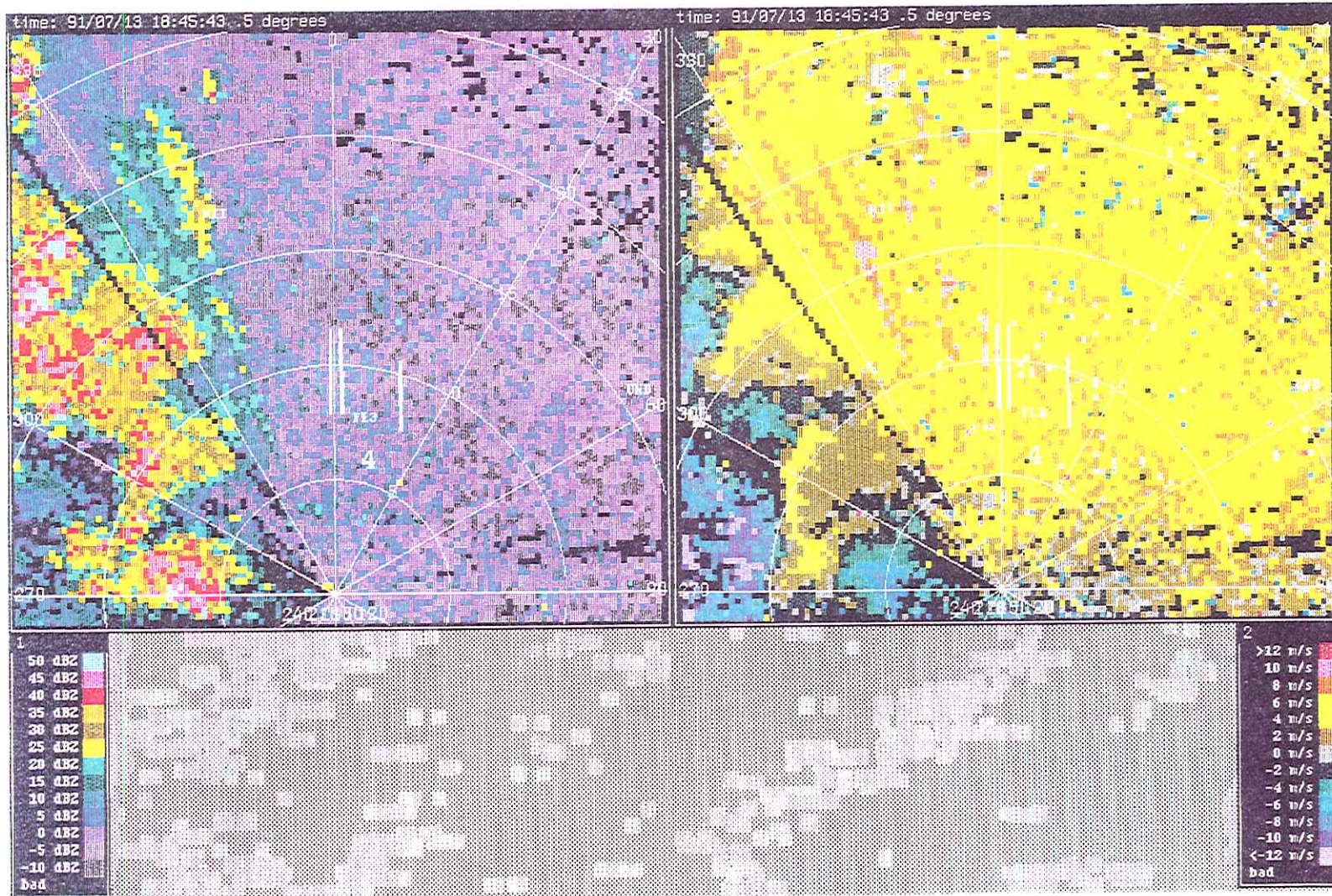


Fig. 3 TDWR prototype radar reflectivity and radial velocity fields near Orlando International Airport at 18:45 GMT on 13 July 1991. A line of thunderstorms is approximately 6 km (3 nmi) to the west of the anemometer with a microburst approximately 7 km directly west of the radar. A gust front generated by outflows from the thunderstorms is forming approximately 4 km to the west of the anemometer.

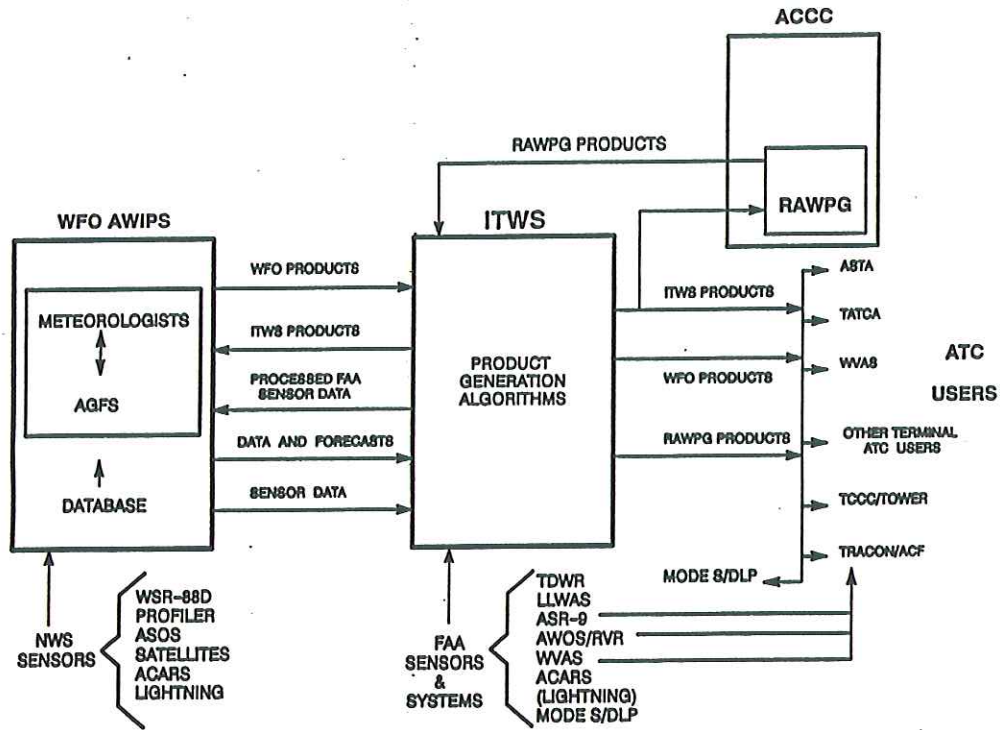


Fig. 4 Integrated Terminal Weather System (ITWS) information sources and recipients. There is a high degree of connectivity to the National Weather Service Weather Forecast Office (WFO) Aviation Gridded Forecast System (AGFS) and to the NWS sensors in the terminal weather. Additionally, aviation weather products generated by the meteorologists at the enroute Area Control Computer Complex (ACCC) are provided by the Regional Aviation Weather Products Generator (AWPG).

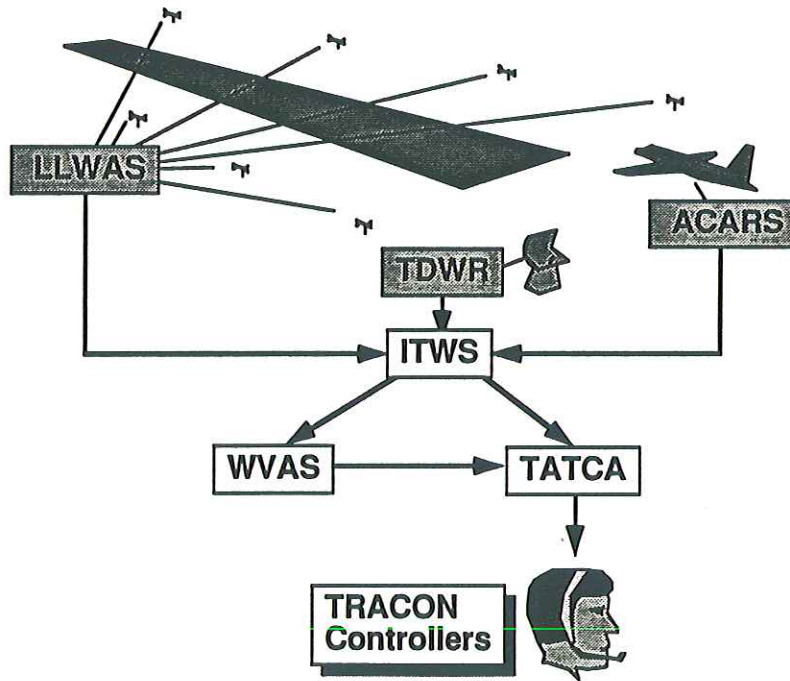


Fig. 5 Block diagram of major components of the recommended system for weather adaptive aircraft wake vortex spacings.