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LLWAS II AND LLWAS III PERFORMANCE EVALUATION

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1. INTRODUCTION

Low level wind shear has been identified as a cause or contributing factor in a significant number of aviation accidents. Research has shown that the most dangerous type of wind shear is the microburst (Fujita, et al, 1977 and 1979). Briefly, a microburst is an intense local downdraft that results in a strong divergent outflow near the surface. The diameter of the outflow region may vary from 3 to 10 Km. Although many of these accidents were nonfatal, six of them resulted in a total of 550 lives lost. During the past 17 years, the mainstay of the effort by the Federal Aviation Administration (FAA) to provide wind shear warnings to pilots has been the Low Level Wind Shear Alert System (LLWAS). The system has been redesigned, based on extensive operational experience and new knowledge about the nature of the aviation wind shear hazard (Goff and Gramzow, 1989). In a parallel development, the Terminal Doppler Weather Radar (TDWR) has provided a capable alternative for ground-based microburst detection (Turnbull, et al, 1989). Recent studies on the integration of LLWAS with TDWR have established the value of a combined TDWR/LLWAS wind shear detection system (Cole and Todd, 1993).

The LLWAS system is being developed in four phases, I, II, III, and IV, which reflect the chronology of operational deployments. The original LLWAS, now called LLWAS I, was designed for the detection of frontal shears under the assumption that hazardous wind shear is associated with large–scale meteorological features (Goff and Gramzow, 1989). This system was deployed at 110 airports between 1977 and 1987. LLWAS I had no microburst detection capability and had excessive false alerts.

LLWAS II was developed to reduce the false alert rate of LLWAS I and to provide a modest microburst detection capability. It is a direct response to recommendations by the National Research Council (NRS–NAS, 1983), following the 1982 microburst crash in New Orleans. This upgrade, deployed by modifying the software in LLWAS I, provided an improvement that would not suffer the delays and the costs of the major construction that is required for off–airport LLWAS III sensors. These upgrades to LLWAS I were installed between 1988 and 1991. LLWAS II will be the operational wind shear detection system at many airports until the late '90s.

LLWAS III was developed in response to the requirement that LLWAS have a microburst detection capability (NRS–NAS, 1983). This system was designed by a combination of computer simulation studies (Wilson and Flueck, 1986) and a successful field test of a prototype at Stapleton International Airport, Denver in August 1987 (Smythe, et al, 1989, and Wilson, et al, 1991). LLWAS III combines a dense sensor network and a sophisticated Wind Shear/Microburst (WSMB) detection algorithm to provide a substantial microburst detection capability. The prototype LLWAS III has continued to operate at Stapleton International Airport, Denver since 1987 and has been credited with the 'save' of a commercial airliner on July 8, 1989. Nine LLWAS III's are being installed this year.

LLWAS IV will be deployed at 83 airports in the late '90s. The LLWAS IV wind shear and microburst detection algorithms will be identical to LLWAS III. This system features a full hardware upgrade. Major improvements include an ice–free sensor and hardware that is more reliable and maintainable.

This report provides an evaluation of the effectiveness of LLWAS II and LLWAS III. The TDWR operational test bed at Orlando International Airport, Orlando (MCO) provides a unique data set for this evaluation. This test–bed features data from a 14–sensor LLWAS, the prototype TDWR, FL–2C, operated by MIT/LL, and the University of North Dakota meteorological radar (UND). Data from this test bed in the summers of 1991 and 1992 are used to provide an evaluation of LLWAS II and LLWAS III. Since LLWAS IV uses the same wind shear detection algorithm, it is expected that LLWAS III and LLWAS IV will have comparable wind shear detection capabilities.

2. THE LLWAS III DESIGN

LLWAS III is designed with attention to specific requirements by Air Traffic Control and pilot groups for capabilities of an improved LLWAS. These requirements are:

1. The system shall detect and identify microburst wind shear in corridors extending 3 miles beyond the ends of the runways.
2. The system shall issue a microburst alert (MBA) whenever it detects a microburst that impacts this runway corridor, and it should issue a wind shear alert (WSA) whenever it detects a non–microburst wind shear that creates a headwind loss or gain in excess of 15 knots along this corridor.
3. Alerts shall be runway–specific and contain the following information:
   - i. the type of shear: MBA or WSA,
   - ii. the location of the shear: integer nautical miles from the end of the runway,
   - iii. the intensity of the shear: magnitude of headwind loss or gain to the nearest 5 knots.
4. The system shall have few false alerts (not quantified).

The primary quantitative measures of the performance of LLWAS are the probability of detection (POD) and the probability of false alert (PFA). The probability of detection is the

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probability that the system will issue a wind shear or a microburst alert whenever a microburst occurs within the hazard region, the runway corridors extending to 3 miles beyond the ends of the runways. The probability of false alert is the probability that an issued alert is false, there is no evidence of wind shear. The NAS requirements are that POD shall be greater than .90 and PFA shall be less than .10.

The LLWAS III WSMB algorithm is designed to satisfy all of these requirements. The output is an alert message for Air Traffic Control of the form:

RUNWAY	ALERT	LOSS/GAIN	LOCATION
17D	MBA	–40k	1MD

where: "17D" indicates the runway affected, in this case departure runway 17, "MBA" indicates that a shear of microburst strength was detected, "–40k" indicates that a headwind loss of 40 knots will be encountered, and "1MD" indicates that an aircraft departing on runway 17 may encounter wind shear within 1 mile of the departure–end of the runway. The other alert possibility is WSA for wind shear alert. An MBA is issued if the estimated headwind loss exceeds 30 knots and a WSA is issued for a headwind loss between 15 and 25 knots or for a headwind gain.

In the WSMB algorithm, all wind shear and microburst alerts are based on the detection of a significant convergence or divergence of the horizontal wind field. The algorithm measures the divergence of the wind field on edges and triangles formed by pairs and triples of sensors. Edges must have lengths between 1 km and 5 km. Triangles must have sides that are acceptable edges and must have no angle of less than 25 degrees. It is permissible for the triangles to overlap one another. This redundant coverage provides better detection than would be afforded by a strict triangulation. Since the size of these divergence–detecting elements is limited, the detection analysis is unaffected by the size of the sensor network.

The WSMB algorithm issues a wind shear alert only if divergent or convergent shear is detected. Very strong divergent shear is the basis for an MBA. Weaker divergent shear, accompanied by a directly measured headwind loss, is the basis for a WSA–with–loss on a runway. Convergent shear, accompanied by a directly measured headwind gain, is the basis for a WSA–with–gain on a runway. If there are multiple shears on a runway, an alert arbitration process determines the most hazardous situation and an alert is issued only for that case. The affected runways are those which are near the edges and triangles that are detecting the divergence or convergence.

A significant part of the technical sophistication that makes LLWAS III so effective lies in implementation issues that go beyond the algorithm design. There are two classes of issues:

1. Network design and the siting of the sensors,
2. The Airport Configuration File (ACF), a file of site–adaptable parameters that interprets the specific network and runway geometry for each airport.

The network design, including issues of sensor height, are described in FAA Order 6560.21, dated 19 February 1988. In cases where geographic or economic considerations force a deviation from these guidelines, the performance of the system may be significantly impaired. For example, if it is not feasible to install sensors to give coverage to at least 2.5 miles beyond the ends of the runways, then protection for that runway will be compromised. The ACF is constructed to obtain the best–possible performance for any network design. The issue here is that to achieve real–time data processing efficiency, critical ACF parameters are calculated during preprocessing. Examples are tables that describe the proximity of runways to the edges and triangles for runway alert generation, the divergence detection thresholds, and the effective lengths, which are used to estimate accurately microburst head wind loss values. The scientific basis for these computations will be presented elsewhere.

3. THE LLWAS II DESIGN

The LLWAS II algorithm uses those concepts from the LLWAS III algorithm that are appropriate for the data and display limitations of the LLWAS I anemometer spacing and displays. The most significant limitations are the sparse sensor spacing and the failure to cover the full hazard region. With typical distances of 3–5 Km between sensors, it is not feasible to design an algorithm that depends solely on the estimation of wind field divergence for the detection of wind shear. The sensors are also too widely separated to provide a reliable divergence estimate for smaller microburst features or to estimate headwind loss or gain along the runways. Finally, the LLWAS I displays are not able to provide runway–specific messages. The combination of data and display limitations led to the design of a system that issues sector alerts (regions of the airport, e.g. Center, Northeast, Northwest, Southeast, Southwest) instead of runway alerts, and that makes no attempt to distinguish between microbursts and other wind shears or to estimate headwind loss or gain. The output of this algorithm is a wind shear alert message of the form:

SECTOR NAME   WSA   SECTOR WINDS

The LLWAS II algorithm first looks for indications of wind field divergence and convergence, based on estimates from the few edges and triangles that can be formed by the six sensor positions. A shear event must be within the coverage perimeter and of sufficient geographic extent to be detected. Since such detections are rarely made, the mainstay of this algorithm is the detection of anomalous sensor winds, similar to the LLWAS I algorithm. LLWAS II compares each sensor wind with the mean network wind. A Chi–squared test is used instead of the 15 knot threshold that is used in LLWAS I. This test provides alerts only for statistically significant and hazardous wind shear, a design feature that is intended to reduce false alerts. Any persistent shear, indicated either by divergence/convergence or by anomalous winds at a sensor, causes a wind shear alert to be issued. The alerted sector is selected based on the location of the detecting sensor, edge, or triangle. There is no mechanism for estimating headwind loss or gain or for using a loss/gain test in this algorithm. This is an important design difference between LLWAS II and LLWAS III. LLWAS II is designed to issue wind shear alerts based on shear in any direction and LLWAS III is designed to issue wind shear alerts only for shear with a significant velocity component parallel to a runway.

4. COVERAGE AREA

There are two measures of performance: (1) the skill for detecting wind shear within the coverage area, and (2) the skill for detecting wind shear in the airport hazard region. The latter is the driving operational issue and the former is what is easily measured. The LLWAS II network contains only six anemometers, and this network provides less coverage than the LLWAS III network. Specifically, LLWAS III provides coverage out to approximately 2.5 nautical miles from the runway ends, most of the hazard region. LLWAS II usually provides coverage to less than 1 nautical mile, approximately 60% of the hazard region. Six sensors provide even less coverage at larger airports. In addition, LLWAS II detects wind shear with less skill within its coverage area. The sensor positions and the coverage areas for MCO are indicated in Figure 1.

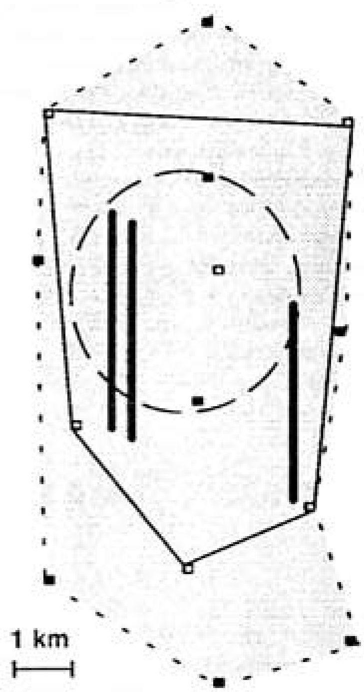

Figure 1. The LLWAS sensors in the Orlando test bed. A 4 Km microburst outflow region is superimposed on the network coverage regions of the LLWAS II (sensors indicated by white boxes) and LLWAS III (sensors indicated by black and white boxes).

5. LLWAS III PERFORMANCE EVALUATION

The basis for the performance evaluation of LLWAS III is the comparison of runway alerts generated from dual Doppler radar observations to the LLWAS III runway alerts. The results of this comparison are used to generate performance statistics, the POD and the PFA. This methodology is described in the evaluation of several wind shear detection algorithms, including LLWAS III, which is presented in Cole and Todd, 1993.

Dual Doppler runway alerts are generated using a dual Doppler wind field. When good radar data are available, the meteorological community generally believes that dual Doppler radar analysis is the best way to obtain a measured wind field. This measured wind field is independent of LLWAS measurements. The methodology of this study is to build the dual Doppler wind field, to compute the shear and the headwind loss or gain along each runway corridor, and to compare these values with the LLWAS alerts. LLWAS is expected to issue a wind shear alert whenever the Dual Doppler analysis indicates a headwind loss or gain in excess of 20 knots and a microburst alert whenever the Dual Doppler analysis indicates a headwind loss in excess of 30 knots. An LLWAS alert is false if the Dual Doppler analysis does not indicate a loss or gain of at least 10 knots over the 3 mile runway corridor. The details of this analysis are described in Cole and Todd, 1993.

The comparison of the LLWAS III alerts with the Dual Doppler alerts is the basis for the LLWAS III performance statistics at MCO . POD(WS) is the probability that a WSA is issued when wind shear is on the runway. POD(MB) is the probability that a MBA or WSA (with loss) will be issued for a runway when a microburst is on the runway, and P:MB is the probability that a MBA will be issued when a microburst is present. PFA(RWY) is the probability that an issued MBA or WSA is false, not substantiated by a dual Doppler indication of wind shear along the runway.

The performance statistics are obtained by analyzing the data from the full afternoons (8 hours each day) of 18 days in 1991 and 1992 when there was some microburst activity and all data collection systems were operating at full capacity. This test set includes 51,840 data polling cycles. LLWAS III issued 2090 departure runway alerts during this period, of which 776 were microburst alerts. LLWAS II issued 1043 sector alerts during this test period.

6. LLWAS II PERFORMANCE EVALUATION

It is difficult to compare LLWAS II alerts with the runway shears from the Dual Doppler analysis since LLWAS II issues sector alerts, based on shear from any direction, rather than runway directed alerts. In its normal application, LLWAS III also issues runway-oriented alerts. However, by adjusting a parameter, we can have it issue alerts for all wind shear. For this reason, we decided to evaluate how well LLWAS II alerts compare with LLWAS III alerts, with the appropriate adjustments. The basis for our comparison is the geographic proximity of LLWAS III runway alert locations and LLWAS II alert sectors.

To make the alert comparison, we need to estimate the extent of the wind shear event. The LLWAS III shear region along a runway is bounded by the departure alert location and the arrival alert location. The basic approach that we have taken is that a departure alert on the runway corresponds to an LLWAS II alert in the center sector, a departure alert at one mile corresponds to an LLWAS II alert in a boundary sector, and departure alerts at two miles do not require alerts by LLWAS II. The LLWAS II sectors do not correspond exactly with the LLWAS III runway locations, as is illustrated in Figure 2. There are cases where the LLWAS III alert is close but not exactly on the sector.

We have dealt with these problems by developing three gradations for the LLWAS III evidence that a sector should have a wind shear alert:

YES	There is LLWAS III evidence that there is wind shear in this sector,
MAYBE	There is LLWAS III evidence of wind shear near this sector (within one mile),
NO	There is no LLWAS III evidence of wind shear in or near this sector.

This mapping of runway alerts to sector alerts permits the scoring of LLWAS II alerts according to LLWAS III alerts.

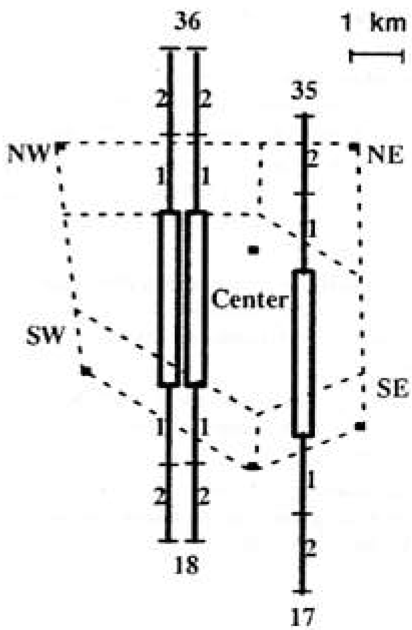

Figure 2. MCO LLWAS II sectors superimposed on LLWAS III runway location boxes

Table 1 shows the mapping of observed LLWAS II sector alerts into these LLWAS III alert categories. The possibilities are labelled as follows:

CA	Correct Alert	AA	Allowable Alert
MA	Missed Alert	AM	Allowable Miss
FA	False Alert	CN	Correct Null Alert

	LLWAS III Indication		
LLWAS II Alert Status	YES	MAYBE	NO
Alert	CA	AA	FA
No Alert	MA	AM	CN

Table 1. Mapping of LLWAS II sector alerts into LLWAS III alert categories.

Comparing the LLWAS II alerts with the LLWAS III alerts for the same time, we obtain counts of the number of occurrences of each type. POD and PFA are computed by the following formulas:

$$POD(WS) = \frac{\# CA}{\# CA + \# MA}$$

$$PFA = \frac{\# FA}{\# CA + \# AA + \# FA}$$

POD(WS) is the probability that LLWAS II will issue a sector alert when there is a clear indication by LLWAS III that an alert is required. POD(MB) is the probability of an LLWAS II alert when LLWAS III detects a microburst, the analogue of the LLWAS III POD(MB). PFA(RWY) is the probability that an LLWAS II alert will be issued without any LLWAS III evidence for that alert.

We have described the discrepancy between the ways that LLWAS II and LLWAS III deal with cross-runway wind shear. If we were to compare these systems by simply matching alerts in the same geographic locations, then we would score some alerts from LLWAS II which are the result of cross-runway wind shear as false alerts since there would be no matching LLWAS III alert. In one sense, this is a correct deduction, since the user community has required alerts only for situations where the shear is directed along the runway. On the other hand, LLWAS II is designed to issue these alerts. It is desirable to know how many of the false LLWAS II alerts are issued during the occurrence of cross-runway wind shear and how many are issued at times when there is no wind shear at all.

We can gain insight into the cross-wind shear issue by a creative use of the WSMB algorithm. The WSMB algorithm first checks for shear and then cancels the alert for each runway for which there is no associated 15 knot headwind gain or loss. By reducing this test to check for a 0 knot gain or loss, we allow all detected wind shears to create runway alerts. In particular, the cross wind shears will issue alerts. Any LLWAS II alerts issued when there is no evidence of these LLWAS III alerts are pure false alerts. We shall denote the probability of these false alerts as PFA(ALL).

7. RESULTS

The prototype LLWAS III system at Denver has performed very well, and the prolonged operation has provided an opportunity to fine-tune the system before procurement. With the operational tests of the TDWR and the ongoing LLWAS research at Denver and Orlando, the performance of this system has been watched very closely (1987 to 1992) and it is not known to have ever missed the detection of a microburst event on the runways. The final form of the WSMB algorithm has benefited from lessons learned from the analysis of the technical and operational effectiveness of this prototype system.

A preliminary performance evaluation was conducted, based on human analysis of Denver radar and LLWAS data for 15 microburst days in 1988 and 1989, Wilson, et al, 1991. These results are presented in the last column of Table 2. There was no estimate of POD(WS) in the study. In the same study, LLWAS I alerts are compared to LLWAS III alerts by a method similar to the approach that is used in this report. This informal study indicated that LLWAS I has a POD(MB) of .33 in the coverage region and a PFA(ALL) of .60, confirming the suspicions of the aviation community that LLWAS I has excessive false alerts.

The evaluation results, based on dual Doppler analysis for full days when microbursts occurred at Orlando, are provided in column 3 of Table 2. LLWAS III alerts are compared with the results of the dual Doppler analysis. The system has nearly full coverage. The Denver results reflect performance in the coverage region. LLWAS II alerts are compared with the LLWAS III alerts at MCO. LLWAS II results are provided for the LLWAS II coverage area (COV – column 1), and for the hazard region of the airport (HAZ – column 2). The LLWAS II detection probabilities are low, even for the coverage area. However, issued alerts are credible since PFA(ALL) is acceptably small.

SYSTEM:	II COV	II HAZ	III MCO	III DEN
POD(WS)	.39	.24	.76	—
POD(MB)	.62	.37	.98	.97
P:MB	NA	NA	.92	.92
PFA(RWY)	.18	.18	.03	.04
PFA(ALL)	.07	.07	NA	NA

Table 2. LLWAS performance statistics.

8. SUMMARY

We have described the evolution of LLWAS as an operational wind shear system and provided descriptions of the current systems. Performance evaluations of LLWAS II and LLWAS III are provided. It is important to note that this evaluation period did not include significant non–microburst weather such as the prolonged periods of strong, gusty winds, which occur in the Midwest, and which could cause increased false alerts.

LLWAS III has very strong microburst detection performance; POD(MB) = .98 and P:MB = .92. Very few of the issued alerts are unwarranted; PFA(RWY) = .03. At those airports where it is economically feasible to install sensors to give full coverage of the airport hazard region, LLWAS III is a fully capable microburst detection system. Since LLWAS IV will use the same WSMB algorithm and network geometry, its performance should be similar.

LLWAS II performance statistics indicate that this system is not able to provide full wind shear protection, and yet it has value. False alerts have been reduced substantially from LLWAS I; its alerts should be heeded. LLWAS II does only a moderate job of detecting microbursts in its coverage region and it fails to cover the full airport hazard region. The system cannot issue microburst alerts, even when a detection is made. There is a significantly reduced ability to detect weaker wind shear in all sectors. This is significant since early warnings of microburst wind shear by LLWAS III are often issued as wind shear alerts at a time when the event is still too weak to be rated as a microburst. Missing detections of weak wind shear by LLWAS II is an indication of a reduced ability to give early warnings for microbursts. The LLWAS II PFA(RWY) is high, but more than half of the false alerts are associated with cross–wind shear. The LLWAS II PFA(ALL) is acceptable.

REFERENCES

Cole, R.E. and R.F. Todd 1993. A Comparative Performance Study of TDWR/LLWAS 3 Integration Algorithms For Wind Shear Detection, these proceedings.

Fujita, T.T. and Caracena, F., 1977. An analysis of three weather–related aircraft accidents. Bull. Amer. Meteor. Soc., 58, 1164–1181.

Fujita, T.T., and Byers, H.R., 1979. Spearhead echo and downbursts in the crash of an airliner. Mon. Wea.rev., 105, 129–146.

Goff, R.C. and Gramzow, R.H., 1989. The Federal Aviation Administration's low–level wind shear alert system: a project management perspective. Preprints: Third International Conference on the Aviation weather System, Anaheim.

NRS–NAS 1983: Low altitude wind shear and its hazard to aviation. National Research Council of the National Academy of Sciences.

Smythe, G.R., Jaffe, K.D., and Page, R.D., 1989. Evaluation of the 12–station enhanced low level wind shear alert system (LLWAS) at Denver Stapleton International Airport, Preprints: Third International Conference on the Aviation Weather System, Anaheim.

Turnbull, D., Evans, J., McCarthy, J., Zirnic, D., 1989. The FAA Terminal Doppler Weather Radar (TDWR) program. Preprints: Third International Conference on the Aviation weather System, Anaheim.

Wilson, F.W., and Flueck, J.A., 1986. A study of the methodology of low–altitude wind shear detection with special emphasis on the low level wind shear alert system concept. FAA Report: DOT/FAA/PM–86/4.

Wilson, F.W., Goff, R.C., and Gramzow, R.H. 1990. The Phase III Low Level Wind Shear Alert System, Proceedings of the Air Traffic Control Association, Boston.

Wilson, F.W. and Gramzow, R.H., 1991. The redesigned Low Level Wind Shear Alert System, Preprints: Fourth International Conference on the Aviation Weather System, Paris.