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A COMPARATIVE PERFORMANCE STUDY OF TDWR/LLWAS 3 INTEGRATION ALGORITHMS FOR WIND SHEAR DETECTION

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1. INTRODUCTION

In 1993 the FAA will begin to deploy two new wind shear detection systems, the Terminal Doppler Weather Radar (TDWR) (Merritt *et al.*, 1989) and the third generation Low Level Windshear Alert System (LLWAS 3) (Wilson and Gramzow, 1991). Eventually, up to 45 airports may receive both a TDWR and an LLWAS 3. Co-located systems will be integrated to provide a single set of wind shear alerts, and to provide increased performance relative to each subsystem.

To meet TDWR production schedules one of three integration algorithms had to be chosen for specification by Fall 1991. To assess the relative performance of the three algorithms we performed a comparative study of the integration algorithms, and the TDWR and LLWAS 3 algorithms at Orlando International Airport (MCO) in the Summer of 1991.

This paper gives an overview of this study. The algorithms are described briefly, followed by a section on data collection at the Orlando test bed. Next, a methodology for estimating various algorithm performance statistics based on a comparison with a dual Doppler algorithm is detailed. Lastly, some results of applying this methodology to the various algorithms are presented and discussed.

The results presented pertain to the detection of wind shear with a loss of head wind, considered the primary aviation wind shear hazard. While important, the ability to detect wind shear with a gain of head wind was not a determining factor in the comparison since the integration algorithms do not vary significantly in this respect.

2. ALGORITHM DESCRIPTIONS

This study analyzes the performance of 5 algorithms, the three candidate integration algorithms, TDWR, and LLWAS 3. Each algorithm produces a set of runway alerts. Each runway is associated with four operational runways, two for arrivals and two for departures, and each is issued a separate alert. The alerts contain an alert type, and an intensity estimate. The alert types are:

- MBA, a wind shear with a loss of head wind of 30 knots or greater
- WSA, a wind shear with a loss of head wind of at least 15 knots and less than 30 knots, or a gain of head wind of 15 knots or greater

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*The work described here was sponsored by the Federal Aviation Administration. The United States Government assumes no liability for its content or use thereof.

The intensity is the loss or gain in head wind that an aircraft flying along the flight path will experience (rounded to the nearest 5 knots).

The three candidate integration algorithms are of two types, message level, and product level. Message level algorithms integrate the alpha-numeric runway alert messages. Product level algorithms integrate intermediate algorithm products such as TDWR microburst shapes, TDWR features aloft (Campbell and Isaminger, 1989), and LLWAS divergence values. The integrated products are used to generate the alpha-numeric alerts.

All of the integration algorithms issue wind shear alerts with a gain of head wind using the same basic logic. LLWAS provides the wind shear with gain alerts inside its coverage region and TDWR provides them outside of this region.

The three integration algorithms are:

- Prototype Product Level (PL-A)
- Product Level (PL-B)
- Message Level (ML)

2.1. TDWR

TDWR detects wind shear by analyzing Doppler radar returns from an area covering the airport. Two versions of the TDWR microburst algorithm were used to generate alerts for this study. The first is the algorithm used in the initial deployment, and the second is an upgrade to the first deployment. The difference is *flight-path shear integration* which sharpens the accuracy of the intensity estimates. The TDWR deployed with LLWAS 3 systems will use flight-path shear integration. The non-shear integration method is included in this study because the PL-A algorithm software did not utilize flight-path shear integration.

2.2. LLWAS 3

The LLWAS 3 algorithm detects wind shear by analyzing wind data gathered from a network of anemometers surrounding the airport runways. Triples and pairs of these anemometers are used to estimate divergences and convergences in the surface wind field. If LLWAS determines from these divergences and convergences that a hazardous wind shear condition exists they are used to generate alpha-numeric runway alerts.

2.3. Product Level-A

The PL-A algorithm is the prototype product level integration algorithm developed at the National Center for Atmospheric Research (NCAR) (Cornman and Mahoney, 1991). This algorithm attempts to reduce the number of false wind shear level loss alerts generated from LLWAS data by dropping weak wind shear level LLWAS detections that are not near additional indications of hazardous weather – strong TDWR or LLWAS detections, or TDWR features aloft . After possibly dropping weak wind shear level LLWAS detections, the algorithm issues the strongest alert generated from either LLWAS or TDWR for each operational runway. A prototype of this algorithm was installed and operated at Stapleton International Airport in Denver from 1988 to 1991.

2.4. Product Level–B

The PL–B algorithm is a product level algorithm developed at MIT Lincoln Laboratory. This algorithm is similar to PL–A, but uses streamlined processing, and attempts to reduce false wind shear level alerts from both TDWR and LLWAS 3, and false microburst level alerts from both TDWR and LLWAS 3 by requiring weak alerts to be near additional indications of hazardous weather. If they are not near additional indications of hazardous weather, weak wind shear level alerts are dropped, and weak microburst level alerts are reduced to wind shear level alerts. After possibly dropping or reducing some alerts the algorithm issues the strongest alert generated from either LLWAS or TDWR for each operational runway.

2.5. Message Level

The ML algorithm is a message level algorithm developed at MIT Lincoln Laboratory (Cole, 1992). This algorithm attempts to reduce false wind shear level alerts from both TDWR and LLWAS 3, and false microburst level alerts from both TDWR and LLWAS 3 in much the same way that PL–B does. Since this is a message level algorithm the only indications of hazardous weather are the alerts themselves. Weak wind shear level alerts given by only one system are dropped, and weak microburst alerts given by only one system are reduced to wind shear level. Unlike the product level algorithms, when both systems are issuing a loss alert the integrated loss estimate is based on an averaging technique to sharpen the estimated loss.

3. DATA COLLECTION

The data for this study were collected at the Lincoln Laboratory test bed at the Orlando International Airport (MCO). The test bed layout is shown in Figure 1.

3.1. LLWAS Data

The LLWAS data were collected from three anemometer networks: six–sensor LLWAS, nine–sensor LLWAS, and 15–sensor LL mesonet. The six–sensor LLWAS network is the Phase II LLWAS used by the FAA to provide wind shear detection coverage for MCO. The six commissioned sensors were moved to sites chosen for the LLWAS 3 and located on LLWAS 3 poles. The nine–sensor anemometer network is a non–commissioned Phase II LLWAS that has been modified to poll nine sensors. It consists of nine sensors that are to be added to the original six sensors to complete the LLWAS 3 for MCO. A 15–sensor anemometer network on 100–ft. poles was installed by MIT Lincoln Laboratory to enlarge the coverage region.

The asynchronous data from the three networks were merged into ten–second synchronous archive records by resampling, with each record containing the sensor winds at all 30 sensors for a 10–second time period. The resulting data records are similar to the data records in the LORAL Data Systems LLWAS III. Each record contains the most recent data from each sensor during the previous ten seconds. Missing and/or corrupted data were flagged in the archive.

3.2. TDWR Data

The Lincoln Laboratory TDWR testbed radar (FL–2C) provided the TDWR base data. The TDWR products needed for the product level integration algorithms were collected during normal FL–2C operations. TDWR alerts were generated using the TDWR runway alert algorithm both with and without flight–path shear integration.

The TDWR microburst shapes and alert values needed by PL–A were generated by software provided by NCAR.

3.3. Dual Doppler Data

The radar data used to generate the dual Doppler wind field were collected from FL–2C and the University of North Dakota Doppler radar (UND). The FL–2C radar scanned the standard TDWR coverage region mandated for MCO. The UND scan sector was chosen to completely cover all of the LLWAS network. Both the TDWR and UND radars were calibrated daily to ensure good data quality.

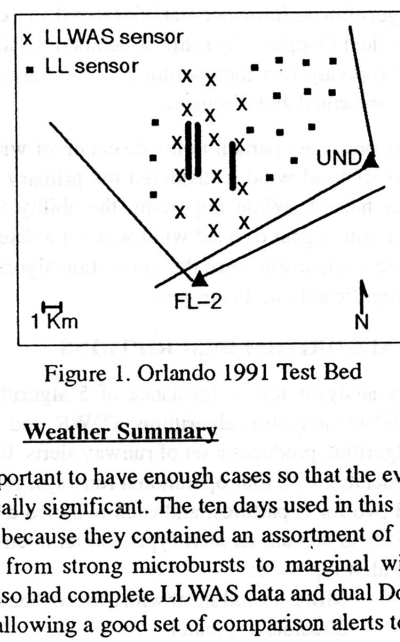

Figure 1. Orlando 1991 Test Bed

3.4. Weather Summary

It is important to have enough cases so that the evaluation is statistically significant. The ten days used in this study were chosen because they contained an assortment of wind shear events, from strong microbursts to marginal wind shears. They also had complete LLWAS data and dual Doppler coverage, allowing a good set of comparison alerts to be generated.

4. EVALUATION METHODOLOGY

A dual Doppler based wind shear detection algorithm was built, and its alerts were compared with the alerts generated by the different wind shear detection algorithms. The results of this comparison were used to generate performance measures such as probability of detection, probability of false alert, and overall system accuracy.

The dual Doppler runway alerts were generated from 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. A dual Doppler algorithm will contain its own defects, but provides a good estimate of the actual wind shear conditions.

The three real runways at MCO cover only a small region limiting the number of microburst impacts. Furthermore, TDWR is is sited to look directly down the real runways, which is an especially advantageous situation for the TDWR algorithm. Fourteen imaginary runways were laid out in the region covered by the anemometer network to capture additional microburst impacts and to give an assortment of runways at different angles to the TDWR line of sight.

4.1. Dual Doppler Algorithm

The dual Doppler alerts are constructed in three steps. First, a two–dimensional wind field is computed using standard dual Doppler analysis (Ray *et al.*, 1980). Next runway alerts are computed for each dual Doppler wind field, and lastly these alerts are interpolated in time to produce dual Doppler alerts at the time of the algorithm alerts.

Once the two–dimensional wind field has been computed loss alerts and gain alerts are computed for each operational runway flight path. This is done by computing the runway oriented components of each wind vector near a flight path and using these components to find the maximum sustained loss and the maximum sustained gain above a specified shear threshold along the flight path.

Two sets of dual Doppler alerts are computed. One set is computed using dual Doppler data points within a narrow (300 meter wide) corridor centered on each runway, extending out from the runway 3 nm for arrival runways and 2 nm for departure runways, with a loss shear threshold of 2.5 m/s/km and a gain shear threshold of 1.9 m/s/km. These shear thresholds correspond to a loss of 20 knots over a distance of 4 km, and a gain of 15 knots over 4 km. The other alert set uses dual Doppler data points within a wide (1800 meter wide) corridor centered on each runway, and a loss shear threshold of 2 m/s/km and a gain shear threshold of 1 m/s/km.

The viewpoint of the study is that a dual Doppler alert in the narrow corridor must be matched by an algorithm alert and that an algorithm alert is not considered false if it is matched by a dual Doppler alert in the wide corridor. That is, an unmatched dual Doppler alert in the narrow corridor is counted as a missed alert, and an algorithm alert that is unmatched by a dual Doppler alert in the wide corridor is considered a false alert.

Since a dual Doppler analysis is available approximately every 60 seconds and algorithm alerts are issued every 10 seconds, linear interpolation between dual Doppler values is used to find the dual Doppler alert value at the time of the algorithm alert. We require that the time difference between the dual Doppler analyses just before and after the algorithm alert time be less than 90 seconds.

4.2. Performance Statistics

Performance statistics such as probability of detection (POD) and probability that an issued alert is false (PFA) are computed by comparing algorithm alerts to dual Doppler alerts. Each operational runway is in one of four alert states, microburst (MBA), wind shear with loss (WSL), wind shear with gain (WSG), and no alert (Null). The performance statistics assess the ability of an algorithm to place a runway in the alert state determined by the dual Doppler algorithm.

Computing performance statistics for each algorithm consists of four steps:

- Building contingency tables
- Computing detection statistics from contingency tables
- Computing false alert statistics from contingency tables
- Building loss accuracy histograms

4.2. 1 Building Contingency Tables

Each row of a contingency table represents a different alert state as determined by the algorithm: MBA, WSL, WSG, or Null. The columns represent the same alert states for the dual Doppler algorithm. The table entries are filled by matching each algorithm alert and its associated dual Doppler alert and incrementing the appropriate entry. The entries are then used to compute the various system performance probabilities.

During dual Doppler processing the data are smoothed and interpolated to the grid points of interest. This causes errors in the resulting dual Doppler wind field. Additional errors in the dual Doppler alerts are introduced by the temporal interpolation. A margin of error of ± 5 knots was used in building the contingency table to account for these inaccuracies.

Figure 2. illustrates the effects of this margin of error. For poll 1 only a Null alert is considered correct. For polls 2 and 3 only a Null alert or a WSL alert is considered correct. For poll 4 only a WSL alert is considered correct. For polls 5 and 6 only a WSL alert or an MBA alert is considered correct. And for polls 7 and 8 only an MBA alert is considered correct. So, for example, given a 30 knot algorithm alert and a 27 knot dual Doppler alert, both dual Doppler and the algorithm are tallied as issuing microburst alerts. Thus the counter corresponding to the first row and first column of the contingency table would be incremented by one.

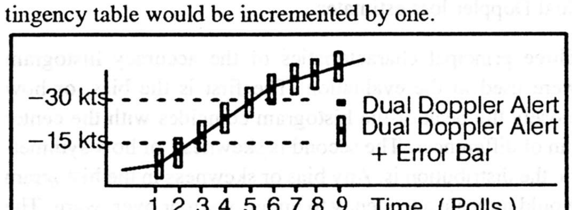

Figure 2. Effect of the 5 knot uncertainty in dual Doppler alerts

4.2. 2 Computing Detection Statistics

Three principal measures of detection were used to evaluate each algorithm: the probability of a loss given a microburst–POD(LIMB), the probability of a loss given a microburst or a wind shear with loss–POD(LIL), and the probability of a microburst given a microburst–POD(MBIMB). These are all computed from the contingency table built from the dual Doppler alerts from the narrow runway corridor and high shear thresholds.

The POD(LIMB) is the probability that either a WSL or an MBA was issued when the dual Doppler alert indicates an MBA.

The POD(LIL) is the probability that either a WSL or an MBA was issued when the dual Doppler alert indicated a WSL or an MBA.

The final detection statistic, POD(MBIMB), is the probability that an MBA was issued when the dual Doppler alert indicated an MBA.

4.2. 3 Computing False Alert Statistics

Four principal false alert statistics were used to evaluate each algorithm: the probability of false microburst–PFA(MB), the probability of false wind shear–PFA(WSL), the probability of false loss–PFA(L), and the probability of microburst over-warning–POW. These are all computed from the contingency table built from the dual Doppler alerts from the wide runway corridor and low shear thresholds.

The PFA(MB) is the probability that an MBA was issued when the dual Doppler alert indicates no loss.

The PFA(WSL) is the probability that a WSL alert was issued when the dual Doppler alert indicates no loss.

The PFA(L) is the probability that a WSL or an MBA alert was issued when the dual Doppler alert indicates no loss.

The final statistic, POW, is the probability that an MBA alert was issued when the dual Doppler alert indicates a WSL. That is the alert, while not false, is an incorrect use of MBA.

4.2. 4 Building Loss Accuracy Histograms

Another important aspect of system performance is the ability of an algorithm to correctly estimate the loss associated with a wind shear. This is evaluated by constructing a histogram of differences between algorithm loss estimates and dual Doppler loss estimates.

Three principal characteristics of the accuracy histogram were used in the evaluation. The first is the bias, or how closely the peak of the histogram coincides with the center bin of differences. The second is skewness, or how symmetric the distribution is. Any bias or skewness in the histogram would indicate a tendency to under-warn or over-warn. The third is variance, or how much the accuracy values are spread out among the bins. Ideally, the bin values should cluster strongly around the central bin.

5. RESULTS AND DISCUSSION

5.1. Without Shear Integration

The TDWR deployed with LLWAS 3 systems will use flight-path shear integration. The non-shear integration method is included in this study because the PL–A algorithm software did not utilize flight-path shear integration.

The POD statistics without flight path shear integration are slightly higher than those in Table 1., showing that all of the algorithms have a high level of skill in detecting wind shear with a loss of head wind. However, TDWR without flight path shear integration issues a large number of false alerts (PFA(WS)=.22), and microburst over-warnings (OW(MB)=.31), which in turn, tend to be issued by the integration algorithms.

TDWR without flight path shear integration tends to issue loss alert values that are stronger than the alert values determined from the dual Doppler algorithm. This causes the integration algorithms to over-warn.

The ML algorithm detects wind shear with a loss of head wind as well as the other integration algorithms, issues substantially fewer false alerts, and gives the most accurate loss estimates.

5.2. With Shear Integration

The performance numbers in this section more accurately reflect the performance of a fielded system since all TDWR co-located with LLWAS 3 will utilize flight path shear integration.

Table 1. contains the performance statistics for the algorithms utilizing flight path shear integration. All of the algorithms have a high level of skill in detecting wind shear with a loss of head wind. The false alert statistics show a large improvement for TDWR and the integration algorithms over the results obtained without flight path shear integration, with ML issuing the fewest false MBA of all algorithms and the fewest false WSA of the integration algorithms.

From the loss accuracy histograms, Figure 3.– Figure 6., we see that all of the algorithms show a tendency to issue stronger alert values than the dual Doppler algorithm, with ML showing the least such tendency.

Table 1. Probability Statistics: W/Flight Path Shear Integration

	TDWR	LLWAS	PL–B	ML
POD(LIMB)	98	97	100	98
POD(LIL)	89	76	92	90
POD(MBIMB)	96	90	98	96
PFA(MB)	1	3	2	1
PFA(WS)	10	2	10	9
PFA(L)	7	2	7	7
OW(MB)	8	25	17	14

Table 2. Accuracy Statistics: W/Flight Path Shear Integration

	TDWR	LLWAS	PL-B	ML
% ± 2.5 knots	19	16	16	23
% ± 7.5 knots	57	50	49	60
% ± 12.5 knots	83	74	76	81
% ± 17.5 knots	93	88	90	93

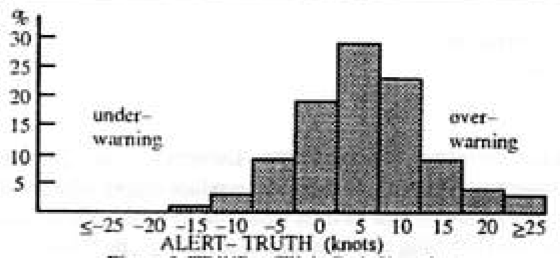

Figure 3. TDWR w/Flight Path Shear Int.
Loss Accuracy Histogram

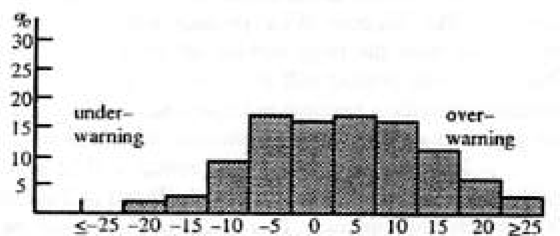

Figure 4. LLWAS Loss Accuracy Histogram

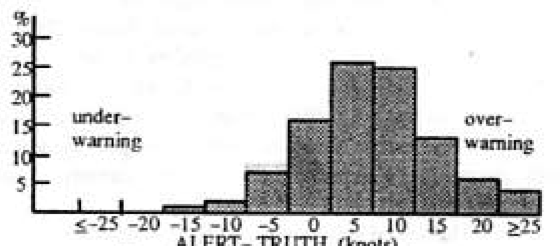

Figure 5. PL-B Loss Accuracy Histogram

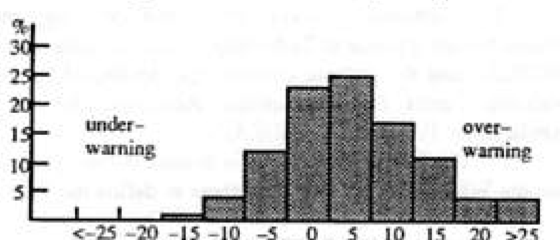

Figure 6. ML Loss Accuracy Histogram

6. CONCLUDING REMARKS

In part, the excellent performance of TDWR and LLWAS 3 is due to the test location. The Orlando environment is particularly favorable to wind shear detection algorithms. Microbursts there are usually large, symmetric, and have a high moisture content and so are easier for the integration subsystems to detect. It should also be noted that even in a benign environment, integration has an advantage over LLWAS 3 in detection of wind shear with a loss of head wind due to TDWR's greater coverage region, and spatial density of data. Integration also has an advantage over TDWR due to LLWAS 3's superior ability to detect wind shear with a gain of head wind, which was not considered in this study.

Based on an extensive review of the algorithms, evaluation methodology, and results, NCAR and Lincoln Laboratory issued a joint recommendation to the FAA that the Message Level algorithm be chosen as the production TDWR/LLWAS 3 integration algorithm. Raytheon is incorporating this algorithm into build 5 of the TDWR software.

In 1992, NCAR conducted an operational demonstration of the ML algorithm at Stapleton International Airport, and Lincoln Laboratory conducted an operational demonstration at Orlando International Airport. The NCAR results in Denver show that in that environment, the benefits of integrating TDWR and LLWAS 3 are much greater than in Orlando (NCAR/RAP, 1993).

7. ACKNOWLEDGMENTS

We would like to thank Larry Cornman, Dave Albo, and William Mahoney of NCAR/RAP for the use of the prototype integration software and for their help in installing this software in our system. We would like to thank Skip Copeland and all of the site personnel for their extremely hard work in finding sites for the mesonet, and installing and maintaining the mesonet stations. We would like to thank Ann Cope and Don McLaughlin for the very long hours required to put together the software for the Lincoln algorithms, and the numerous other software engineers that pitched in to help when time got short. Lastly, we would like to thank Wes Wilson for his support of this project.

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