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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 began to deploy two new wind shear detection systems, the Terminal Doppler Weather Radar (TDWR) (Merritt *et al.*, 1989) and the anemometer network based third generation Low Level Windshear Alert System (LLWAS 3) (Wilson and Gramzow, 1991). Currently, nine of the largest US airports are planned to receive both a TDWR and LLWAS 3. Co–located systems will be integrated to provide a single consistent set of wind shear alerts, and to provide increased performance relative to each subsystem. LLWAS 3 provides better gust front detection and a faster update rate than TDWR, and is not hampered by dry conditions, while TDWR provides better detection of small microbursts than LLWAS 3 and has a larger region of coverage. Integration allows one system to cover for the other in the case of a missed alert, and when both systems detect the same event their estimates of the wind shear magnitude can be joined to give a more accurate estimate.

The effort to develop a TDWR/LLWAS 3 system started at the National Center for Atmospheric Research (NCAR) in 1988. A development effort at MIT Lincoln Laboratory began in 1990. These efforts led to three separate TDWR/LLWAS 3 integration algorithms. To meet TDWR production schedules, one of three integration algorithms had to be chosen for production by Fall 1991. To assess the relative performance of the three algorithms, Lincoln 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. The 1991 Lincoln study led to the FAA procurement of one of the Lincoln algorithms. This algorithm was tested operationally in 1992 by Lincoln at MCO and by NCAR in 1992 and 1993 at Denver.

The FAA has begun procurement of the initial Integrated Terminal Weather System (ITWS) scheduled for deployment at major US airports to provide improved weather information at TDWR airports. ITWS provides wind shear detections based on TDWR information. At airports with an ITWS and an LLWAS 3 system the wind shear warnings need to be integrated. The ITWS algorithm that detects wind shear with a loss of headwind provides a modest improvement over the TDWR system, but the ITWS algorithm that detects wind shear with a gain of headwind provides a significant improvement over the TDWR system. In addition to the upgrades in the detection of wind shear, ITWS also provides predictions of the most serious type of wind shear with a loss of headwind: microbursts. The production TDWR/LLWAS 3 integration algorithm was modified for use by ITWS to account for the increased capabilities of the ITWS wind shear warning algorithms.

This paper gives a brief overview of the history of the development of the TDWR/LLWAS 3 integration algorithms, a brief overview of the various algorithms, and a discussion of the comparative evaluation of the TDWR, LLWAS 3, and the three candidate TDWR/LLWAS 3 integration algorithms. This is followed by a more detailed description of the TDWR/LLWAS 3 integration algorithm chosen by the FAA for production, and a brief overview of the ITWS/LLWAS 3 integration algorithm.

The performance results presented for TDWR/LLWAS 3 integration 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 TDWR/LLWAS 3 integration algorithms do not vary significantly in this respect. The performance results are given in knots, not m/s, because these are the units used in the alert messages provided by the wind shear detection systems to air traffic controllers. For a quick conversion from knots to m/s, divide a value in knots by 2 (1.9438) to get an approximately equivalent value in m/s.

2. TDWR/LLWAS 3 INTEGRATION DEVELOPMENT HISTORY

The effort to integrate TDWR and LLWAS 3 started at NCAR (Cornman and Mahoney, 1991) in 1988. In 1988 both the TDWR and LLWAS 3 algorithm were in continuing development. The following considerations motivated the design of the NCAR algorithm:

1. There was a desire that the LLWAS wind shear with loss of headwind detections be displayed on the TDWR display just as the TDWR detections were displayed,
2. The prototype LLWAS 3 produced an abundance of false alerts on days with strong gusty winds,
3. The prototype TDWR was considered to produce sufficiently accurate wind shear with loss of headwind alerts, and
4. The LLWAS 3 gust front (wind shear with a gain in headwind) detection capability was far superior to the TDWR capability.

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In TDWR, the Doppler data are analyzed for regions of windshear with loss of head wind, and these regions are then modeled as microburst shapes. A microburst shape, sometimes referred to as a band–aid, is a rectangle with semicircles at either end and has an associated loss value. When one or more shapes intersect a given runway corridor an alert is produced for that runway corridor. The alerts are displayed as text on a special controller display, and the shapes are displayed on a Graphical Situation Display for use by supervisors. With a TDWR/LLWAS 3 integration without LLWAS shapes it would be possible to produce wind shear with loss of headwind alerts in regions where there were no regions of wind shear displayed graphically. The first consideration led to an NCAR algorithm that went to great lengths to produce microburst shapes from the LLWAS data. This gives a consistency between the integrated alerts and the display, but leads, at times, to an inconsistency between alerts generated by LLWAS as an independent system and alerts generated by the integration system from LLWAS data.

To accommodate the second and third considerations, the NCAR algorithm uses TDWR and LLWAS detections of hazardous weather to verify suspect LLWAS loss detections: LLWAS detections of weak wind shear with loss of headwind not in the vicinity of detections of possible hazardous weather are discarded. No such test of TDWR detections is used due to consideration 3.

Finally, due to consideration 4, in the NCAR algorithm all TDWR wind shear with gain in headwind (gust front) detections are discarded inside the coverage of the LLWAS anemometer network, so that only LLWAS gain in headwind alerts are generated for runway regions inside LLWAS coverage.

In 1990, MIT Lincoln Laboratory was funded to develop a TDWR/LLWAS 3 integration algorithm. Additionally, Lincoln was tasked with testing each integration algorithm as well as the TDWR and LLWAS 3 algorithms on a common data set from the TDWR testbed operated by Lincoln in Orlando, FL. The Lincoln algorithm development was motivated by the following considerations:

1. The LLWAS 3 production algorithm does not issue many false alerts on gusty days, as did the prototype LLWAS 3,
2. Over–warning in wind shear with a loss of headwind situations was common in the prototype TDWR algorithm in Orlando type environments, but this problem had been largely solved in later versions of TDWR, and issuing wind shear with loss of headwind alerts with a loss value of 30 knots or greater when the true loss is much less is especially problematic, since these alerts effectively shut down the effected runway.
3. Given the continuing TDWR and LLWAS 3 development, the TDWR/LLWAS 3 integration algorithm should take advantage of the recent upgrades in both systems, and should be designed to take advantage of as many known and unknown future algorithm upgrades as possible,
4. Integration should use the available information to reduce the remaining false alerts, over–warning, and nuisance alerts from both TDWR and LLWAS 3,
5. The TDWR gust front detection capability still significantly lagged the capability of the LLWAS 3 system, but development continued towards improving the TDWR gust front detection capability, and
6. The algorithm should be as simple and inexpensive for the TDWR contractor to implement as possible.

The Lincoln team decided to develop two new integration algorithms, one similar in some regards to the NCAR algorithm and the other an extremely simple algorithm based only on the wind shear alerts. Due to considerations 1–3, it was decided that integration alerts generated from TDWR data should agree with the alerts that TDWR would issue from the same data, and similarly, integration alerts generated from LLWAS 3 data should agree with the alerts that LLWAS 3 would issue from the same data. This should not be true only when consideration 4 comes into play. When both TDWR and LLWAS 3 detect an event, the two detections are considered jointly by the integration algorithm to produce a more accurate alert than the individual alerts. Both Lincoln algorithms produce microburst shapes from LLWAS 3 information. These microburst shapes are not visually as clean as the shapes produced by the NCAR integration algorithm, but they agree with the alerts generated by LLWAS 3 as a stand–alone system.

Due to considerations 3 and 5, it was decided that LLWAS 3 would provide the gust front detections inside the LLWAS coverage region, as did the NCAR integration algorithm, but that this would be controlled by site adaptation parameters so later if the TDWR gust front detection capability improved, the gust front detection could be jointly used as are the microburst detections. This is accomplished by setting thresholds so that TDWR gust fronts inside of LLWAS coverage are deemed to be false.

While generally accurate, both LLWAS 3 and TDWR occasionally issue incorrect alerts. For both systems, false alerts are usually weak. Other incorrect alerts occur when a wind shear is present, but the strength estimate is too high or too low. In both Lincoln algorithms, LLWAS 3 detections are used to confirm weak TDWR detections of wind shear with loss of headwind and TDWR information is used to confirm weak LLWAS 3 detections of wind shear with loss of headwind. Very weak wind shear alerts that are not confirmed are dropped and weak microburst level wind shear with loss of headwind that are not confirmed are reduced to a lesser category of wind shear. The more sophisticated of the two algorithms uses TDWR reflectivity products as well as TDWR Doppler velocity products to confirm suspect LLWAS 3 detections, where as the simpler algorithm only uses TDWR runway alerts for this purpose. When both subsystems detect a wind shear event, the simpler algorithm uses an averaging technique to increase the accuracy of the strength estimate.

Lincoln, in 1991, put together a large network of carefully sited anemometers in conjunction with the LLWAS anemometer network in place a the Orlando International Airport (MCO) to gather the anemometer data for the comparison study. The Lincoln TDWR testbed radar (FL–2C) provided the TDWR base data. In addition to the prototype TDWR at MCO, Lincoln also gathered data from the University of North Dakota (UND) Doppler weather radar. The TDWR and UND radars were used together to build a data set of wind shear cases against which the algorithms were evaluated.

Lincoln, in conjunction with NCAR, developed a scoring methodology to be used in assessing the performance of each algorithm. The performance evaluation was performed in early Fall of 1991 followed by an in depth review of the results at NCAR. The results showed similar detection performance and somewhat less similar false alert performance for the various algorithms. The outcome of the review was a joint Lincoln/NCAR recommendation that the FAA procure the simplest of the Lincoln algorithms. This decision was based on the similar detection capabilities of the candidate integration algorithms, the reduced false alerts and over–warnings produced by the Lincoln algorithm, and it's greatly reduced procurement cost relative to the other algorithms.

3. TDWR, LLWAS 3, AND INTEGRATION ALGORITHM OVERVIEW DESCRIPTIONS

The 1991 study analyzes the performance of 6 algorithms, the three candidate TDWR/LLWAS 3 integration algorithms, the TDWR and LLWAS 3 algorithms, and a very simple integration algorithm used as a baseline against which to judge the benefits of the three candidate integration algorithms. 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 operational runway is issued a separate alert. Each alert contains 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

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 TDWR/LLWAS 3 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 TDWR/LLWAS 3 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 four TDWR/LLWAS 3 integration algorithms used in the 1991 study are:

- Prototype Product Level (PL–A)
- Product Level (PL–B)
- Message Level (ML)
- Union (UN)

3.1 TDWR

TDWR detects wind shear with a loss of headwind by analyzing Doppler radar returns from an area covering the airport. Each radial of Doppler values is searched for runs of values indicating decreasing headwind, called loss segments, and the loss segments are grouped together. Each group of loss segments is modeled as a microburst shape and the microburst shapes are then intersected with runway corridors to determine if an alert is issued. 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, and was developed to reduce the problem of over–warning. 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 does not utilize flight–path shear integration. Because the TDWR wind shear with a loss of headwind capability is far superior to its capability to detect wind shear with a gain of headwind, when TDWR detects both conditions on a runway, a wind shear with a loss of headwind alert is issued.

3.2 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 anemometers are used to estimate divergences and convergences in the surface wind field. If LLWAS determines from these divergence and convergence estimates that a hazardous wind shear condition exists, the divergence and convergence detections are used to generate the alpha–numeric runway alerts. The LLWAS 3 algorithm contains arbitration logic for use when both wind shears with a loss of headwind and a gain in headwind are detected for a single runway. This logic determines which condition is the greater hazard and issues the corresponding alert.

3.3 Product Level–A

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

The PL–A algorithm does not utilize flight–path shear integration to reduce TDWR over–warning or the LLWAS data filtering developed to reduce LLWAS false alerts in gusty wind conditions. The PL–A algorithm also does not contain loss vs. gain alert arbitration logic. When both wind shear with a loss of headwind and wind shear with a gain in headwind are detected, the loss alert is always issued.

3.4 Product Level–B

The PL–B algorithm is a product level integration 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.

The reduction in false alerts is accomplished by requiring weak alerts to be near additional indications of hazardous weather. If weak alerts 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. This alert reduction process is only carried out for alerts generated inside of the LLWAS coverage region. The thresholds that control how aggressively the false alert reduction logic is applied are set separately for each operational runway. Alerts for runways with good sensor geometry require less verification than alerts for runways with poor sensor geometry.

After possibly dropping or reducing some alerts the algorithm issues the strongest loss alert generated from either LLWAS or TDWR for each operational runway if both TDWR and LLWAS 3 are issuing loss alerts, the LLWAS gain alert if both are issuing a gain alert, and uses the LLWAS 3 alert arbitration logic if there is both a loss and a gain alert. The PL–B algorithm utilizes flight–path shear integration to reduce TDWR over–warning and the LLWAS data filtering developed to reduce LLWAS false alerts in gusty wind conditions. The microburst shapes generated from LLWAS generated divergence values produce alerts that agree with the LLWAS 3 stand–alone system.

3.5 Message Level

The ML algorithm is a message level algorithm developed at MIT Lincoln Laboratory (Cole, 1992, Cole and Todd, 1993). 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. As with PL–B, the thresholds that control how aggressively the false alert reduction logic is applied are set separately for each operational runway. Alerts for runways with good sensor geometry require less verification than alerts for runways with poor sensor geometry.

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. Similar averaging logic is used when both systems are issuing gain alerts, but until the TDWR gust front detection capability is improved, parameters are set so that the LLWAS gain alert is issued. Finally, in the case of competing alert types, the ML algorithm uses the LLWAS 3 alert arbitration logic.

Since the inputs to the ML algorithm are the subsystem alerts, flight–path shear integration and the latest LLWAS filtering are automatically used as are any future TDWR and LLWAS algorithm upgrades. Microburst shapes can be provided for LLWAS microburst detections, but the FAA decided that they were not needed.

3.6 Union

The Union algorithm is a very simple message level algorithm that issues the strongest alert from either system for each operational runway. Any loss alert overrides any gain alert, and no attempt is made to reduce false alerts or to adjust the loss or gain strength estimates. This simple algorithm is used as a baseline for measuring the benefits of the other integration algorithms as they increase in complexity and cost from ML to PL–B to PL–A.

4. DATA COLLECTION

The data for the 1991 study were collected at the Lincoln Laboratory test bed at the Orlando International Airport (MCO). The test bed layout is shown in Figure 1.

4.1 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 synchronous data records with a 10 second update rate 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.

4.2 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.

4.3 Dual Doppler Data

Each system's performance was evaluated by comparing its alerts to alerts generated from dual Doppler wind fields. The radar data used to generate the dual Doppler wind fields 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 anemometer network. Both the TDWR and UND radars were calibrated daily to ensure good data quality.

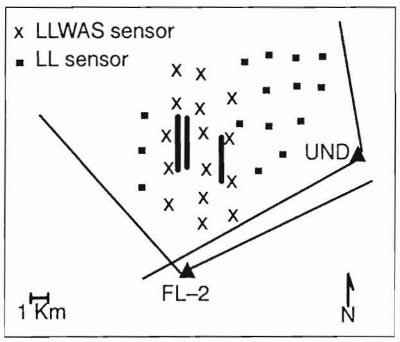

Figure 1. Orlando 1991 Test Bed

4.4 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.

5. EVALUATION METHODOLOGY

A dual Doppler based wind shear detection algorithm was built, and its alerts 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.

5.1 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.

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.

The rationale taken in this study is that a system should be penalized for issuing a clearly false alert or clearly false non–alert, but a system should not be penalized for issuing an alert or non–alert that is questionable, but perhaps correct. This rationale is implemented by requiring 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.

5.2 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

5.2.1 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.

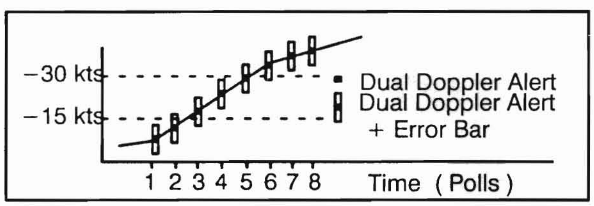

Figure 2. Effect of the 5 knot uncertainty in dual Doppler alerts

5.2.2 Computing Detection Statistics

Three principal measures of detection were used to evaluate each algorithm: the probability of a loss given a microburst–POD(L|MB), the probability of a loss given a microburst or a wind shear with loss–POD(L|L), and the probability of a microburst given a microburst–POD(MB|MB). 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(L|MB) is the probability that either a WSL or an MBA was issued when the dual Doppler alert indicates an MBA.

The POD(L|L) 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(MB|MB), is the probability that an MBA was issued when the dual Doppler alert indicated an MBA.

5.2.3 Computing False Alert Statistics

Four principal false alert statistics were used to evaluate each algorithm: the probability of false microburst alert, PFA(MB); the probability of false wind shear alert, PFA(WSL); the probability of false loss alert, 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.

5.2.4 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.

6. RESULTS AND DISCUSSION

6.1 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 results for this case are shown in tables 1 and 2. The POD statistics without flight path shear integration show that each algorithm has a high level of skill in detecting microbursts. However, TDWR without flight path shear integration issues a large number of false alerts and microburst over–warnings, 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.

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

	TDWR	LLWAS	UN	PL–A	PL–B	ML
POD(L|MB)	99	97	99	98	100	99
POD(L|L)	92	76	93	93	94	93
POD(MB|MB)	97	90	98	97	99	97
PFA(MB)	4	3	5	6	4	2
PFA(WS)	22	2	22	23	22	19
PFA(L)	15	2	15	14	15	13
OW(MB)	31	25	33	37	31	27

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

	TDWR	LLWAS	UN	PL–A	PL–B	ML
% ± 2.5 knots	8	16	8	8	8	17
% ± 7.5 knots	28	50	28	31	28	43
% ± 12.5 kts	53	74	54	59	54	63
% ± 17.5 kts	70	88	71	76	71	78
median error (kts)	11.7	3.5	11.6	10.7	11.6	8.6

6.2 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 3 contains the probability 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 least microburst over–warnings of the integration algorithms.

Algorithm accuracy statistics are provided in table 4 and figures 3–6. Table 4 shows that the candidate integration algorithms are more accurate that the UN algorithm, with the ML algorithm being significantly more accurate than the other two integration algorithms. A comparison of tables 1 and 3 and a comparison of tables 2 and 4 shows that the addition of flight–path shear integration to TDWR has greatly reduced the false alerts and increased the accuracy of the TDWR alerts with very little loss in detection capability.

From the loss accuracy histograms, figures 3 – 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 3. Probability Statistics: W/Flight Path Shear Integration

	TDWR	LLWAS	UN	PL–B	ML
POD(L|MB)	98	97	99	100	98
POD(L|L)	89	76	91	92	90
POD(MB|MB)	96	90	97	98	96
PFA(MB)	1	3	3	2	1
PFA(WS)	10	2	11	10	9
PFA(L)	7	2	8	7	7
OW(MB)	8	25	23	17	14

Table 4. Accuracy Statistics: W/Flight Path Shear Integration

	TDWR	LLWAS	UN	PL–B	ML
% ± 2.5 knots	19	16	15	16	23
% ± 7.5 knots	57	50	47	49	60
% ± 12.5 knots	83	74	75	76	81
% ± 17.5 knots	93	88	89	90	93
median error (kts)	5.6	3.5	7.5	7.1	4.6

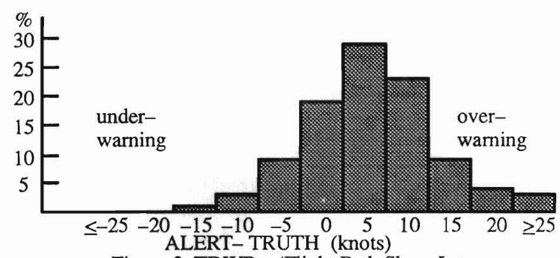

Figure 3. TDWR w/Flight Path Shear Int.
Loss Accuracy Histogram

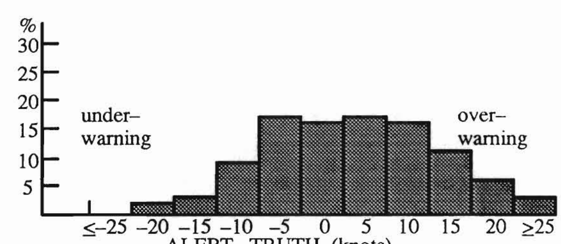

Figure 4. LLWAS Loss Accuracy Histogram

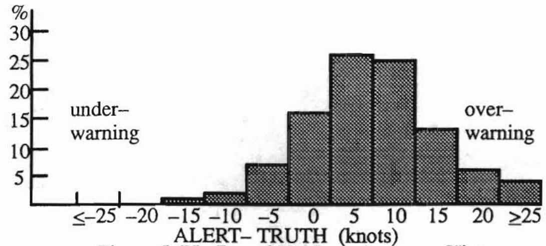

Figure 5. PL–B and UN Loss Accuracy Histogram

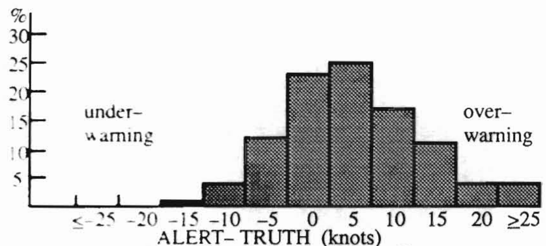

Figure 6. ML Loss Accuracy Histogram

7. DETAILED MESSAGE LEVEL ALGORITHM DESCRIPTION

This algorithm integrates the runway alerts generated by the TDWR system and LLWAS 3 to give a single runway alert for each operational runway.

7.1 Design Goals

1. The primary goal of integration is to issue all correct alerts from either subsystem. If only one of the systems detects an event, say TDWR misses a dry microburst, or LLWAS misses a very small microburst, the alert generated by integration should agree with the (stand alone) system making the detection. The only time this should not be true is when the integration algorithm decides that the alert should be altered in the interest of the second design goal.

2. Integration should use the available information to reduce false alerts, over–warning, and nuisance alerts. This is accomplished by dropping weak windshear alerts if there is no additional evidence that they are correct, reducing weak microbursts to wind shear alerts if there is no additional evidence that they are correct, and using both systems to determine the loss or gain value when both detect an event. Dropping weak microburst alerts without evidence of nearby hazardous weather provides a greater reduction in the false alert rate than reducing the severity of the alert to wind shear level, however this will on rare occasions cause no alert to be issued when in fact a real hazard exists. In the interest of safety, it was decided that if either system issues a microburst level alert that the integrated system should at least issue a wind shear level alert, even if the alert is likely to be false.

7.2 Inputs

1. LLWAS runway alerts for each operational runway (loss/gain value and location).
2. TDWR runway alerts for each operational runway (loss/gain value and location).
3. Various control parameters.

7.3 Outputs

1. Runway alerts for each operational runway (loss/gain value and location).

7.4 Algorithm Logic

The algorithm proceeds through the following tasks: alert screening to drop or reduce weak alerts issued by only one system, joining of alerts when both systems are issuing like alerts, and arbitration of alerts when one system is issuing a loss alert and the other is issuing a gain alert. The processing logic is described below and the determination of what category an alert falls into, for example weak or strong, is determined for a range of values controlled by input thresholds.

The thresholds are set separately for each system being screened and for each operational runway. This allows for setting the difficulty of the screening tests to depend on the subsystem performance for each operational runway. For example when TDWR has a favorable viewing angle for a runway the thresholds are set low so that all but the weakest alerts automatically pass the screening tests, but when TDWR does not have a good viewing angle the thresholds are raised so that fewer alerts automatically pass the screening tests. Nominal values for the thresholds are provided below, but these values will vary from runway to runway.

7.4.1 Alert screening

The subsystem alerts are first screened before being joined using the following logic:

1. Strong microburst alerts, nominally a loss of 35 kts or greater, pass forward.
2. Weak microburst level alerts, nominally 30–34 kt loss, are passed forward unchanged if there is a loss from the other system, otherwise the alert is reduced to the maximum allowed windshear with loss alert.
3. Strong windshear with loss alerts, nominally 20–29 kts, are passed forward.
4. Weak windshear with loss alerts, nominally less than 20 kts, are passed forward unchanged if there is a loss from the other system, otherwise the alert is dropped.
5. Weak windshear with gain alerts are passed forward unchanged if there is a gain from the other system, otherwise the alert is dropped.
6. Strong windshear with gain are passed forward.

In general there are 6 thresholds used to screen an alert:

1. Thresh1 defines weak WSA/gain: Any gain alert between 0 and Thresh1 requires confirmation from the other system.
2. Thresh2 is the threshold for confirmation of a weak gain. The weak gain from 1 is confirmed if the other system issues an alert above Thresh2.

3. Thresh3 defines weak WSA/loss: Any loss alert between 0 and Thresh3 requires confirmation from the other system.

4. Thresh4 is the threshold for confirmation of a weak loss. The weak loss from 3 is confirmed if the other system issues an alert below (i.e. stronger loss than) Thresh4.

5. Thresh5 define weak MBA: Any loss alert between the minimum MBA and Thresh5 requires confirmation from the other system.

6. Thresh6 is the threshold for confirmation of a weak MBA. The weak MBA from 5 is confirmed if the other system issues an alert below (i.e. stronger loss than) Thresh6.

7.4.2 Joining alerts

The screened runway alerts from the two subsystems are joined as follows:

1. If only one system is giving an alert it is used as the integration alert.

2. If both systems are giving a loss the location used is the first encounter from either system, and the loss value is the minimum of { the average of the two losses, αLLWAS loss, βTDWR loss } where α and β are between 0.0 and 1.0 (nominally 0.8).

3. If both systems are giving a gain the location used is the first encounter from either system, and the gain is the maximum of { the average of the two gains, γLLWAS gain, δTDWR gain } where γ and δ are between 0.0 and 1.0 (nominally 1.0).

4. If one system is giving a loss and the other is giving a gain, arbitrate using the LLWAS arbitration logic.

The loss given in 2 is just the average loss unless the average is much lower than the larger of the LLWAS loss and the TDWR loss. This allows for a more accurate loss estimate, and at the same time protects against dropping the loss estimate too far when one system is grossly underestimating the strength of the hazard. The gain estimate logic given in 3 is similar to the loss estimate logic.

The LLWAS arbitration logic selects the alert which posses the greatest aviation hazard. A microburst level wind shear alert is always considered to be a greater hazard than any gain alert. The more difficult decision comes when one system is issuing a wind shear with gain alert and the other is issuing a wind shear with loss alert. In this case, the loss alert is issued unless the gain is much stronger in magnitude. A secondary consideration is to keep the system from jumping between loss and gain alerts. This can occur for example when the turbulence behind a gust front crosses the LLWAS anemometer network. To reduce jumps from one alert type to another the definition of "much stronger" is adjusted to make it easier for current alerts to match the last alert issued. As above, the following values are controlled by input parameters, but typical definitions of "much stronger" are as follows:

1. If there was no previous alert, much stronger is 10 kts,

2. If the last alert was a gain, much stronger is 5 kts, and

3. If the last alert was a loss, much stronger is 15 kts.

So, if there were no previous alert, the gain alert is chosen over the loss alert only if the gain value is 10 kts or greater higher than the loss value. However, if the last alert were a gain, the gain alert will be chosen over the loss alert if the gain value is merely 5 kts or greater higher than the loss value. Similarly, if the previous alert were a loss it becomes harder for the gain alert to be chosen over the loss alert.

8. ITWS/LLWAS 3 INTEGRATION ALGORITHM OVERVIEW

The ITWS contains algorithms for issuing wind shear alerts based on TDWR data and will also receive LLWAS 3 wind shear alerts at some airports. The logic used to integrate these different alerts is based on the TDWR/LLWAS 3 integration algorithm. However, the wind shear warning capabilities of the ITWS wind shear detections based on TDWR data differ in two important respects for the capabilities in the TDWR system. The first is that ITWS provides predictions of microburst events. ITWS does this by looking at temporal changes in the reflectivity structure of storms and by looking at the thermodynamic structure of the atmosphere. When ITWS decides there will be a future microburst in a given location a microburst shape is produced for this location. This shape then triggers a microburst alert if it intersects a runway corridor. It is not possible to confirm or deny the validity of a prediction of future wind shear using current LLWAS information, so these alerts skip the alert filtering process. For similar reasons, the microburst prediction alert values are not averaged with the current LLWAS 3 alert values.

The second difference is that the performance of the ITWS gust front detection algorithm is much better than the performance of the TDWR gust front detection algorithm. This does not require a change to the TDWR/LLWAS 3 integration logic: the algorithm already uses TDWR gust front detections as long as their strength estimates are above a site specific threshold and they pass a confirmation test. In TDWR/LLWAS 3 integration the screening thresholds are set high enough that TDWR gust front detections are never used inside of the LLWAS network. In integrating ITWS and LLWAS 3 all that is needed is to use thresholds with a appropriate values: threshold values can be set so that LLWAS is used to confirm ITWS gust front detections and vice versa.

9. 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 the TDWR/LLWAS 3 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 incorporated this algorithm into build 5 of the TDWR software.

In 1992 and 1993, 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, NCAR/RAP 1994). The 1992 Lincoln results (Cole and Todd, 1994) in MCO show slightly reduced performance relative to the 1991 results.

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