AN EXPERIMENTAL COCKPIT DISPLAY FOR TDWR WIND SHEAR ALERTS*

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1. INTRODUCTION

This paper describes an experimental system for cockpit display of Terminal Doppler Weather Radar (TDWR) wind shear warnings. The TDWR is a ground-based system for detecting wind shear hazards that pose a threat to aviation. During the Summer of 1990, wind shear warnings generated by the Lincoln-operated TDWR testbed radar at Orlando, Florida were transmitted in real-time to a research aircraft performing microburst penetrations. This test marks a milestone as being the first time that TDWR wind shear warnings were successfully transmitted and displayed in an aircraft in real-time.

This effort was supported by NASA Langley Research Center as part of an program to investigate techniques for integrating airborne and ground-based wind shear information for cockpit display. The three main goals for 1990 were 1) to conduct microburst penetrations with an instrumented aircraft, 2) demonstrate real-time data link and cockpit display of TDWR warnings, and 3) to compare a hazard estimate called the F factor (Bowles, 1990) for airborne and TDWR data.

All three of these goals were successfully carried out. The research aircraft, a Cessna Citation II operated by the University of North Dakota (UND) Center for Aerospace Sciences conducted over 80 microburst penetrations in Orlando over a six week period with TDWR testbed radar surveillance. The cockpit display system was operated during the latter part of the flight test period, and proved useful in aiding the Citation crew in locating microburst and gust front events. Initial postprocessing analysis in comparing the aircraft and TDWR F factors has begun.

There were three main objectives in the development of the cockpit display system. First, the real-time display was intended to aid the Citation crew in locating microburst and gust front events. This capability was desired both to aid the crew in locating events to penetrate, and to improve safety by providing a better information about the location of the wind shear events.

A second objective was to demonstrate the feasibility of transmitting TDWR wind shear warnings to aircraft in real-time. This demonstration is an important element in the eventual development of an integrated cockpit display incorporating both airborne and ground-based wind shear information. This study marks the first successful demonstration of real-time transmission of TDWR wind shear warnings to an aircraft in flight.

A third objective was to demonstrate the desirability of transmitting TDWR wind shear warnings to aircraft in real-time. Currently, the TDWR provides these warnings to controllers as textual messages, which are then relayed to pilots via voice communications. The TDWR also includes graphical displays of wind shear and precipitation products, but these are only provided currently to the Tower and TRACON supervisors.

A potential use of Mode S Data Link is to provide TDWR wind shear warnings directly to pilots. Automatic delivery of TDWR wind shear warnings potentially result in decreased controller workload and improved pilot information. Mode S Data Link is currently planned to provide textual wind shear warnings only. However, studies by Wanke and Hansman (1990) show that pilots substantially prefer graphical presentation of wind shear warnings over textual presentation.

The paper will first describe the organization of the system, including the process of generating the display messages in the TDWR testbed and data linking them to the aircraft. Second, the display format and operation of the cockpit display will be described. Next, an example of the operational use of the cockpit display will be presented, along with initial F factor results. Finally, the paper will conclude with a summary and plans for future work.

2. SYSTEM ORGANIZATION

The organization of the display system is shown in Figure 1. Radar data are obtained by the Lincoln-operated TDWR testbed radar and processed by prototype TDWR wind shear algorithms (Merritt et al, 1989). These algorithms recognize microbursts and gust fronts, and generate runway warnings. The testbed radar also intercepts beacon transponder data from the local ASR-9 radar to generate own aircraft position.

These data are sent to the Cockpit Display Server for processing for transmission to the cockpit display. The server software was implemented by one of the authors (DeMillo) in C on a Sun 3 workstation. The server converts

*The work described here was performed under Air Force Contract No. F19628-90-C-0002 and was sponsored by the National Aeronautics and Space Administration. The United States Government assumes no liability for its content or use thereof.

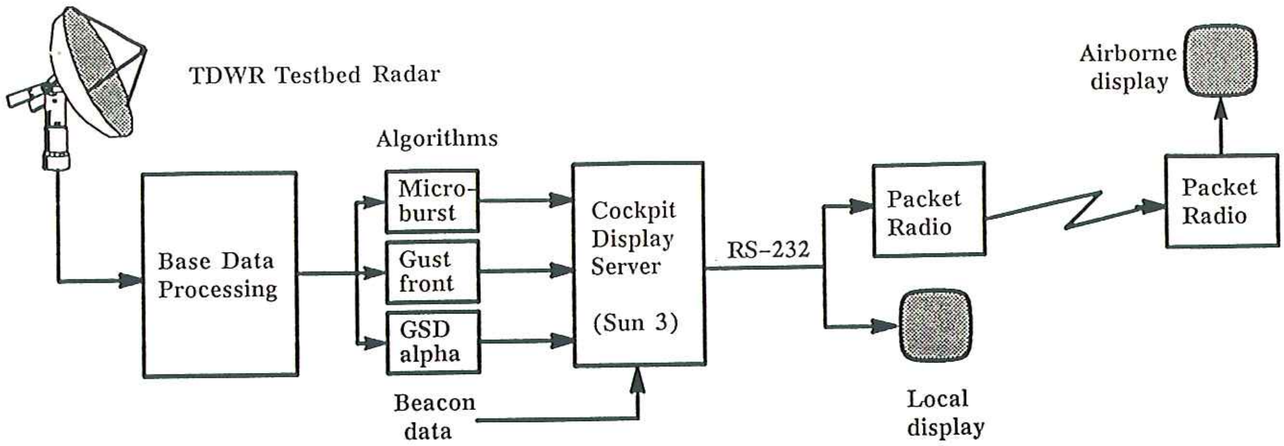

Figure 1. Cockpit display system organization.

the incoming data into airport-centered coordinates and performs other needed computations.

The output of the server is an RS-232 serial data stream, which is transmitted to the test aircraft via a packet radio system. The packet radio system consists of two Dataradio modems, which accept RS-232 information and transmit packetized data at a 4800 Baud rate.

The cockpit display was implemented using an Electronic Airborne Multipurpose Electronic Display (EAMED) from Eventide Avionics. This unit (shown in Figure 2) is a modified version of the Argus 5000 Moving Map Display. The EAMED unit contains a monochrome CRT with an active area of 1.7"W x 2.3" H and a resolution of 256 x 512 pixels. The unit includes a 68000 processor, two RS-232 serial ports and four front panel buttons. The unit

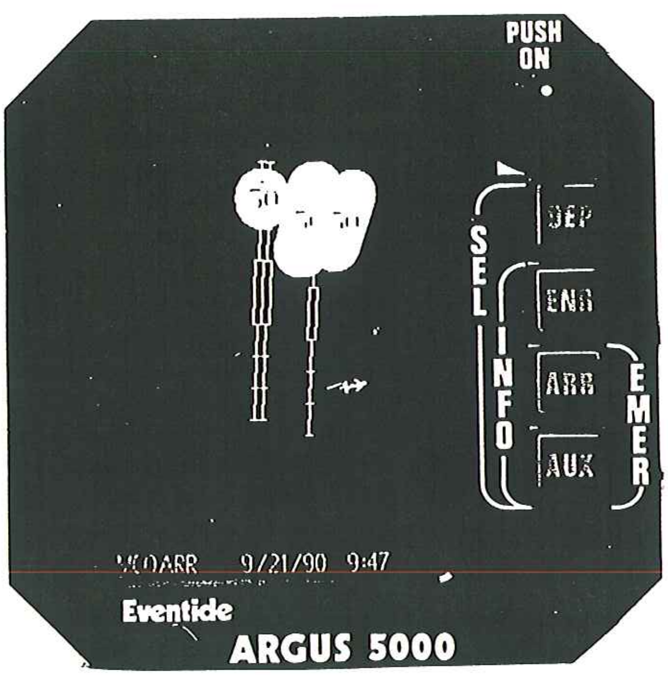

Figure 2. Experimental TDWR Cockpit Display.

is 10 inches long and fits in a standard 3" instrument panel space.

The EAMED unit can be programmed by the user for new applications, while taking advantage of a library of user-callable graphics and utility functions supplied by Eventide. The unit is programmed in C language and the code stored in EPROMs. Because of a previous development at Lincoln for the TCAS collision avoidance system by one of the authors (Daly), an experienced programmer and a software development system were available to support this effort.

3. COCKPIT DISPLAY

Figure 3 shows the layout of the cockpit display for various mode selections. The display is centered on the airport and is oriented to Magnetic North. Microbursts and gust fronts are depicted graphically, plus own aircraft position and airport runway locations. At the bottom of the display are included the textual warnings for approach and departure.

There are four buttons which control the operation of the display, as illustrated in Figure 3. When "DEP" (departure) or "ARR" (arrival) are pressed, the display has a maximum range of 5 nm, with up to four lines of alphanumeric alerts at the bottom. When the Departure mode is selected, the departure alphanumeric alerts are displayed (likewise for Arrival mode). When the "ENR" (enroute) button is pressed, the maximum range is 15 nm North–South and 12 nm East-West. Alphanumeric messages are not displayed in this mode. When the "AUX" (auxiliary) button is pressed, the storm cell information is displayed until the next screen update (nominally 15 seconds); the AUX button can be used in conjunction with any of the other modes.

The symbology for representing microbursts and gust fronts follows that used in the TDWR Geographic Situation Display (GSD) or tower supervisor's display. Microbursts are represented as either circles or boxes with rounded ends; these microburst shapes are open if the microburst loss is less than 30 kts and and filled if the loss

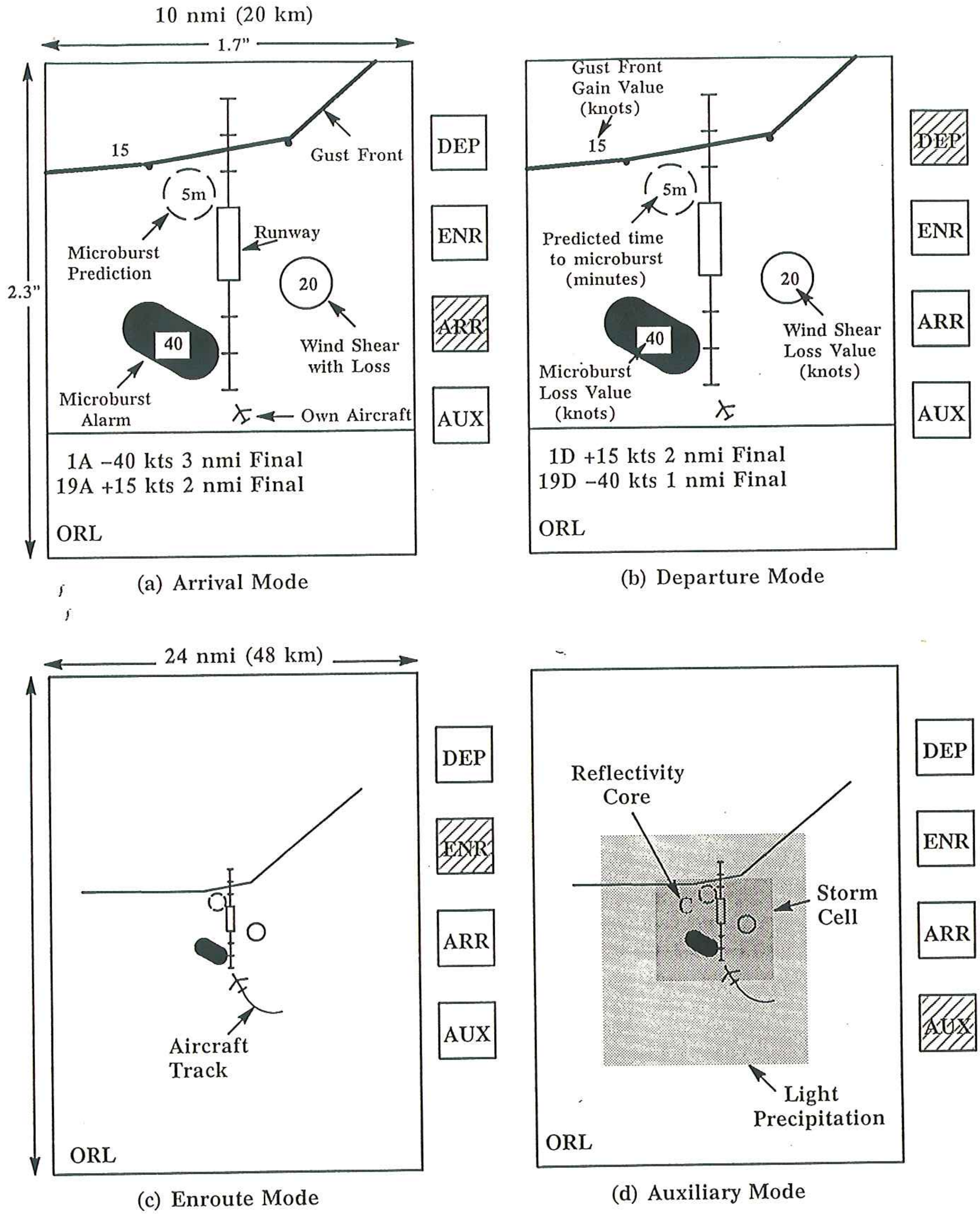

Figure 3. Cockpit wind shear display layout for selected modes (a) Arrival, (b) Departure, (c) Enroute and (d) Auxiliary.

is 30 kts or greater. The loss value is drawn inside the microburst shape. Gust fronts are represented as polylines and the gain value is drawn near the gust front. Alphanumeric alerts (similar to those presented on the Ribbon Display Terminal (RDT) or individual controller's display) are shown at the bottom of the display.

The display includes two additional items of information. An experimental microburst prediction product is displayed as a dashed circle with a time to expected microburst. Also included is a selectable capability for displaying approximate storm cell locations. There are three levels of storm cell reflectivity: low, moderate and high. The areas of low and moderate reflectivity are indicated by rectangular stipple patterns of different density. The high reflectivity areas are indicated by a "C", indicating the location of a reflectivity core.

It was originally intended to display the F factor (described in Section 5) for each of the microburst shapes, instead of the loss value. It was also planned to compute and display the aircraft F factor in real-time. The TDWR F factor was computed by the Cockpit Server and sent to the aircraft, but it was not possible to compute the aircraft F factor in real-time due to various hardware and software limitations. It was therefore decided to display the loss value for each shape, instead of the F factor.

Post-flight data processing capabilities have been developed at Lincoln which allow the TDWR and aircraft F factors to be compared. An example of this comparison will be discussed in Section 5. This post-flight data processing capability will allow extensive future evaluation of candidate crew warning procedures and cockpit display concepts.

4. FLIGHT OPERATIONS

Eight weeks of test flights were carried out at Orlando during two periods (6/16–7/25, 9/17–9/28) for a total of 35 flights (including 9 test flights for various purposes). At least 80 microburst penetrations were accomplished with TDWR testbed radar surveillance.

The test aircraft was a Cessna Citation II twinjet operated by the University of North Dakota (UND) Center for Aerospace Sciences. This aircraft is instrumented to record meteorological data (e.g., temperature, dew point, liquid water content, water particles, etc) and aircraft information (e.g., roll, pitch, altitude, position, true airspeed, etc). These data are recorded on a nine-track tape at a 24 Hz rate. A Turbulence Prediction Systems (TPS) Advance Warning Airborne System (AWAS) passive infrared spectrometer was also installed in the Citation aircraft.

During test flights, the UND aircraft was kept under surveillance by the TDWR testbed radar and voice communications were maintained. In the interests of safety, the microburst penetrations were flown at a high speed (160 kts) and in a clean configuration (gear and flaps up).

The cockpit display was installed in a spare DME slot on the copilot side of the instrument panel. Due to interface and data link problems, the cockpit display did not become operational until July 11th, so operational flight time was less planned. Operation time was also impaired because the TDWR testbed radar was out of commission for the latter part of July.

The cockpit display system was operated successfully for six days during which significant microburst activity occurred. The two pilots in command of these missions were interviewed to obtain their reactions to the information provided by the cockpit display (as opposed to the details of the display format). Their comments are summarized as follows.

The pilots indicated that the wind shear information provided by the cockpit display was highly desirable. It was noted that visual cues might be obscured due to clouds or haze, and that the hazard might be embedded in a larger region of impaired visibility. The graphical display allowed the hazard region to be better localized and confirmed against other data sources, such as visual cues and on-board radar.

The graphical display of microbursts and gust fronts allowed clearer visualization of the hazard situation than could be obtained from ATC wind shear warnings and pilot reports (PIREPS). In particular, the cockpit display showed the relationship of the wind shear hazards to the runway complex. This information was useful in two respects.

First, it allowed the pilot to make a better judgement about whether to continue the approach. For example, if the microburst hazard was just touching the far end of the runway, then the pilot might well elect to continue the approach since the aircraft would land well short of the microburst. Similarly, if the microburst was to the left or right of the approach path, then the pilot could reasonably expect to encounter a crosswind only on approach. On the other hand, if the microburst was directly on the approach path at the near end of the runway, then the pilot might well elect to abort the approach.

Note that the current TDWR verbal message issued by the controller would not allow the pilot to differentiate between these different situations. In each case, the ATC message might well be "Microburst alert, Runway 18 Left, 40 knot loss". PIREPS are also of limited value because they do not localize the hazard clearly and they provide information which tends to be several minutes old. The ATC verbal warning and PIREPS were only sufficient to provide a "heads up" concerning the potential threat, but did not provide all the information desired for planning the approach.

Second, the graphical display of wind shear hazards allows the pilot to better plan potential escape maneuvers in the event of a missed approach. It was noted that the high cockpit workload during approach makes it important to have this information readily available. In particular, it allowed the pilot to plan a heading for escape maneuvers.

Several other comments were noted. The display was sufficiently timely to locate microbursts in the approach pattern; when the microbursts occurred away from the airport, they had often dissipated by the time the aircraft reached them. The gust front display was useful in helping to anticipate where turbulence on approach would be encountered. There was limited opportunity to use the precipitation display mode, but it having this information available (at higher resolution) was viewed as desirable, especially since on-board radar tends to be placed in standby or checklist mode while in the terminal area. Finally, it was viewed as useful to have this information available to relay to passengers when delays on approach and departure were encountered.

5. F FACTOR COMPUTATION

The F factor is a microburst wind shear hazard index proposed by Roland Bowles of the NASA Langley Research Center (Bowles, 1990). The F factor is defined by :

$$F = \frac{\dot{w}_x}{g} - \frac{w_z}{TAS} = F_x + F_z \qquad (1)$$

where w_x and w_z represent the along track and vertical components of the wind field acting on the aircraft, g is the gravitational acceleration constant, TAS is the true airspeed, and F_x and F_z represent the horizontal and vertical components of F. The F_x is positive for a decreasing headwind (or increasing tailwind), and F_z is positive for a downdraft.

The F factor indicates the impact of a microburst wind shear on aircraft potential climb angle, α, defined by:

$$\alpha = \frac{\dot{z}}{TAS} = \frac{T - D}{W} - F \qquad (2)$$

where z is the altitude, T is the thrust, D is the drag and W is the weight of the aircraft.

A typical value for (T–D)/W for aircraft in landing configuration is 0.1 to 0.15 (Bowles, 1990). Airborne reactive (accelerometer-based) wind shear detection systems are required to produce an executive alert when a wind shear of 0.105 or greater is detected. Thus, an F factor of 0.1 can be viewed as a substantial threat to aircraft, especially on approach where thrust is low and drag is high.

The aircraft F factor can be computed directly from the measured winds acting on the test aircraft. The TDWR F factor can be estimated from a formula developed by Bowles (1990). A simplified version of the formula is presented below:

$$F_T = K \frac{\Delta V}{\Delta R} \left(\frac{TAS}{g} + \frac{2h}{TAS} \right) \qquad (3)$$

where K is a constant, ΔV is the velocity difference measured by the TDWR across the microburst outflow, ΔR is the distance over which the velocity difference occurred, and h is the altitude of the radar beam at the microburst outflow. The constant K relates the observed TDWR shear ($\Delta V/\Delta R$) to the estimated F factor over a scale length, D, which is nominally 1 km. The value of K depends on ΔR and D, but is on the order of $\pi/2$. The term in parentheses is typically on the order of 10 sec. Therefore, an F factor of 0.1 might typically correspond to a TDWR-observed shear of 6.7 m/s/km.

The TDWR F factor, F_T, was computed (in real-time and in post-processing) by applying the Bowles formula (Equation 3) to the microburst shapes produced by the testbed radar. The aircraft F factor, F_C, was computed in post-processing using the defining equation for F factor (Equation 1). The peak aircraft and TDWR F factors are then determined for a given microburst penetration.

The peak aircraft F factor is determined for the interval over which the aircraft was in stabilized flight (aircraft turning and banking disrupts the F factor calculation). The peak TDWR F factor is determined by computing when the Citation aircraft was inside a microburst shape or shapes, and taking the largest F factor value. The peak TDWR F factor for the penetration is then obtained.

Figure 4 shows an example of the aircraft and TDWR F factor comparison for a microburst penetration which occurred on July 7, 1990 at Orlando. This microburst event began on 1850Z and intensified to 50 knots by 1855Z when the Citation penetration occurred. The figure shows the aircraft and TDWR F factors in the upper right hand graph. The lower right hand graphs show aircraft bank angle and altitude. The upper left hand graph shows the TDWR microburst alert and the path of the Citation aircraft.

As seen in Figure 4, there was a reasonable correspondence between the aircraft and TDWR F factors for this case. An initial evaluation of 50 microburst penetrations resulted in mean values of 0.069 for the peak aircraft F and 0.081 for the peak TDWR F. In general, one would expect the peak TDWR F to be larger than the peak aircraft F, since the aircraft may not penetrate the region of greatest shear within the microburst shape. Work is currently in progress to refine the TDWR F factor estimate.

6. SUMMARY

This paper has reported the first successful ground-to-air data link and cockpit display of TDWR wind shear warnings in real-time. Pilot responses indicate that the information provided by the cockpit display was useful in visualizing the location of wind shear hazards. The

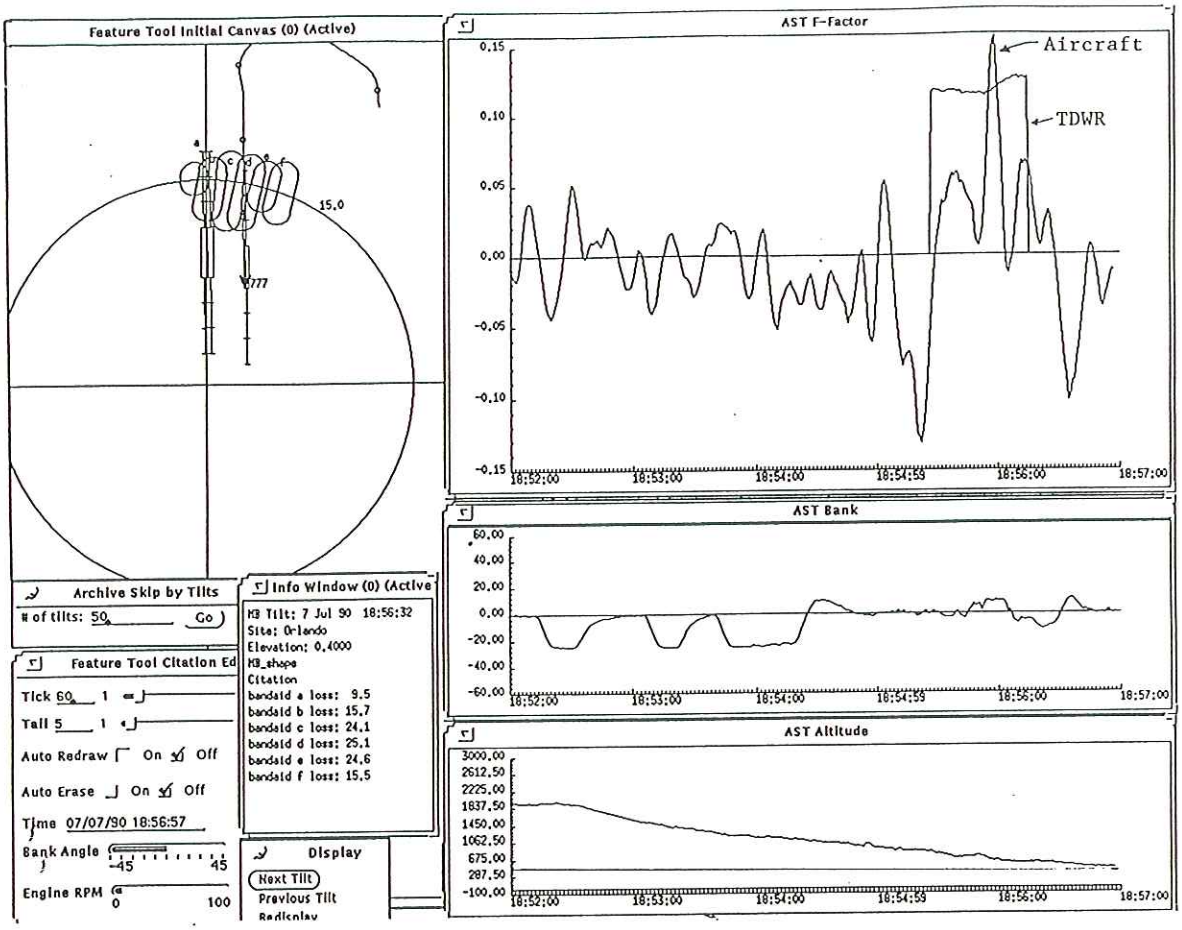

Figure 4. Comparison of aircraft and TDWR F factors for July 7, 1990 microburst penetration at Orlando, FL.

graphical display of microburst hazards provided better information than that currently provided by ATC verbal messages and PIREPS. This information was useful in assessing the microburst hazard, deciding whether to continue the approach and planning escape maneuvers.

Although not practicable in the real–time tests, post–flight comparison of the aircraft and TDWR F factors has begun. Processing of over 80 microburst penetrations from last summer's operations is in progress, and additional flights are planned for next summer in Orlando and Denver using an instrumented NASA B737 aircraft.

7. ACKNOWLEDGEMENTS

The authors wish to thank UND pilots Kent Streibel and Roger Tilbury for their comments on the cockpit display, and Fred Remer of UND for his efforts in generating flight notes and Citation aircraft data. We also wish to acknowledge the contribution of Anthony J. Berke of Lincoln for his work on the post–flight data reduction and display software. Finally we wish to thank Roland Bowles and David Hinton of NASA Langley Research Center for their support of this work.

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