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The Orlando TDWR Testbed and Airborne Wind Shear Data Comparison Results

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ORLANDO TDWR TESTBED AND AIRBORNE WIND SHEAR DATA COMPARISON RESULTS

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"Orlando TDWR Testbed and Airborne Wind Shear Data Comparison Results"

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The focus of this talk is on comparing Terminal Doppler Weather Radar (TDWR) and airborne wind shear data in computing a microburst hazard index called the F factor. The TDWR is a ground-based system for detecting wind shear hazards to aviation in the terminal area. The Federal Aviation Administration will begin deploying TDWR units near 45 airports in late 1992. As part of this development effort, M.I.T. Lincoln Laboratory operates under F.A.A. support a TDWR testbed radar in Orlando, FL.

During the past two years, a series of flight tests has been conducted with instrumented aircraft penetrating microburst events while under testbed radar surveillance. These tests were carried out with a Cessna Citation II aircraft operated by the University of North Dakota (UND) Center for Aerospace Sciences in 1990, and a Boeing 737 operated by NASA Langley Research Center in 1991. A large data base of approximately 60 instrumented microburst penetrations has been obtained from these flights.

The test flights in 1990 included the first-ever demonstration of real-time transmission of TDWR microburst graphical warnings to an aircraft for cockpit display. A similar demonstration was carried out in 1991, with the TDWR microburst alerts being used to direct the NASA aircraft in making microburst penetrations.

Post-flight analysis was performed under NASA funding to compare the F factor (Bowles & Targ, 1988) as measured by aircraft *in situ* sensors and estimated from TDWR microburst alarms. It was found that improvements are needed in the

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TDWR microburst alarm generation process to allow the aircraft F factor to be estimated accurately. These improvements include: shear-based outflow detection, physical model-based alarm representation, and compensation for the dependence of outflow intensity on altitude. The rationale for these improvements will now be discussed.

The aircraft F factor can be estimated from TDWR microburst alarms using a formula proposed by Bowles (1988):

$$F_{TDWR} = K' (\Delta V/\Delta R) \; [\, GS/g + 2h/TAS \,] = F_x + F_z \qquad (1)$$

where $\Delta V/\Delta R$ is the TDWR-measured shear, GS is the aircraft ground speed, g is gravitational acceleration, h is the radar beam height and TAS is the aircraft true airspeed. K' is a factor which attempts to relate the average shear in the microburst, $\Delta V/\Delta R$, to the peak shear in the microburst over a 1 km distance. The GS/g term corresponds to the horizontal component of F (F_x) and the 2h/TAS term is an estimate of the vertical (downdraft) component of F (F_z). It should be noted that the equation assumes that the aircraft penetrates through the center of the microburst.

It was found that applying Equation 1 to current TDWR microburst alarms often overestimates the aircraft F factor. Examination of TDWR radar data shows that strong microbursts often contain small regions of intense shear inside a larger region of less intense shear. These intense shear regions are not identified by the current microburst detection algorithm, which attempts to identify the peak-to-peak velocity loss, rather than shear. Because of this, the shear associated with a microburst alarm is underestimated for strong microbursts. Applying the K' factor to this underestimated shear leads to the correct F factor estimate for strong microbursts, but overestimates the F factor for weak microbursts.

In order to better quantify the shear for use in Equation 1, a least-squares shear estimator was developed. The base polar radar data was first smoothed using a 0.5 km x 0.5 km median filter. The least-squares estimator was then applied over a seven-gate window of TDWR velocity data for an effective distance of 0.9 km (i.e., 6 gates center-to-center x 150 m per gate). The corresponding shear values were then applied to the following equation:

$$F_{SHEAR} = (dV/dR)|_h \; [\, GS/g + 2h/TAS \,] \qquad (2)$$

where $(dV/dR)|_h$ is the least-squares shear at the radar beam height.

It was found that Equation 2 was an improvement but still often overestimated the aircraft F factor. Further examination of the radar data showed that there was a strong dependence of the outflow strength on altitude. Work by Mark Isaminger and Paul Biron of Lincoln showed that the outflow strength decreases linearly with height above the surface. This result was consistent with an analytical model of microburst outflows developed by Vicroy of NASA Langley (1991); this model is a modification of an earlier model developed by Oseguera and Bowles (1988). In the Vicroy and Oseguera & Bowles models, the horizontal shear is described by a shaping function, p(z), which is zero at the surface, reaches a peak at height h_m and then drops off with increasing altitude.

Using the altitude shaping function, p(z), the horizontal shear at the aircraft altitude, a, can be estimated:

$$(dV/dR)|_a = (dV/dR)|_h \mid p(a)/p(h) \mid \quad (3)$$

and the revised F factor estimate can be written as:

$$F_{ALT.CORR.} = (dV/dR)|_a \mid GS/g + 2a/TAS \mid \quad (4)$$

where we now use the aircraft altitude, a, in the downdraft estimation term, 2a/TAS. This formula reflects the concept that as the aircraft altitude increases, the horizontal shear will decrease but the downdraft component will increase.

Equation 4 was found to estimate the F_x component quite accurately, but still tends to overestimate the F_z component. Further reflection shows that the 2a/TAS term leads to an overestimate of the vertical component, since it is assumed that the aircraft flies directly through the center of the microburst. In fact, many of the penetrations were made at the edge of the outflow where the Vicroy model predicts an updraft, rather than a downdraft.

Accordingly, a final modification was tested which divided the aircraft data into center and edge penetrations. For center penetrations, the unmodified Equation 4 was used; for edge penetrations, the vertical component estimator was changed to -a/TAS (i.e., an updraft at the edge equal to half the center downdraft):

$$F_{HOR.CORR.} = (dV/dR)|_a \mid GS/g + 2a/TAS \mid, \text{ center} \quad (5a)$$
$$= (dV/dR)|_a \mid GS/g - a/TAS \mid, \text{ edge} \quad (5b)$$

Applying Equation 5 yielded an improvement in the mean F_z component, however, the data points were clustered as either too high or too low. A further refinement would be to scale the vertical compensation according to distance from the outflow center.

These results lead to the notion that several improvements could be made to the existing TDWR microburst recognition algorithm to allow accurate F factor estimation. First, shear-based outflow detection at multiple thresholds would allow regions of intense shear to be identified inside of larger outflow regions. Second, these shear regions could be used to create a microburst representation based on a physical model consisting of an outflow center and an outflow edge. Third, an analytic microburst model or other technique could be used to compensate for the dependence of outflow intensity on altitude. Fourth, the improved microburst representation could be used to estimate the vertical component of the microburst based on distance from the outflow center.

A key goal for operations during the summer of 1992 will be to more accurately characterize the altitude dependence of microburst outflows. It is planned to accomplish this goal by carrying out rapid, low-altitude scans of microburst outflows by three radars during aircraft penetrations. The three radars will be the TDWR testbed plus two C-band radars operated under F.A.A. funding by the University of North Dakota and Massachusetts Institute of Technology. These radars are situated in such a fashion to allow triple-Doppler reconstruction of the three-dimensional wind fields at the Orlando airport. These triple-Doppler wind field reconstructions will allow both the horizontal and vertical components measured by airborne and ground-based sensors to be compared.

In summary, a large data base of instrumented microburst penetrations while under TDWR testbed radar surveillance has been obtained over the past two years at Orlando. These tests also marked the first-ever demonstration of real-time data link transmission of TDWR microburst alerts to aircraft for graphical display in the cockpit. Additional flight tests will be performed in 1992, including penetrations with rapid update, low-altitude triple-Doppler radar scans.

Sixty microburst penetrations have been examined to determine how well the aircraft F factor can be estimated from TDWR data. Analysis of the data shows that several improvements to the current microburst recognition algorithm would be needed to allow the aircraft F factor to be accurately estimated. These improvements would improve the quality of the microburst alerts currently supplied to ATC personnel and, in the future, supplied to pilots directly via Mode S Data Link.

References:

1. Bowles, R.L. and R. Targ: Wind Shear Detection and Avoidance: Airborne Systems Perspective, International Congress of Aeronautical Sciences, Jerusalem, Israel, August-September, 1988.

2. Vicroy, D.D.: A Simple, Analytical, Axisymmetric Microburst Model for Downdraft Estimation, NASA Technical Memorandum 104053, NASA Langley Research Center, Hampton, VA, February, 1991.

3. Oseguera, R.M., and R.L. Bowles: A Simple, Analytic 3-Dimensional Downburst Model Based on Boundary Layer Stagnation Flow, NASA Technical Memorandum 100632, NASA Langley Research Center, July, 1988.

OUTLINE

- TERMINAL DOPPLER WEATHER RADAR (TDWR) PROGRAM
- ORLANDO FLIGHT TEST & DATA LINK ACTIVITIES
- TDWR F FACTOR ESTIMATION ISSUES:
  - HORIZONTAL SHEAR COMPUTATION
  - MICROBURST ALARM REPRESENTATION
  - ALTITUDE DEPENDENCE
  - DOWNDRAFT ESTIMATION
- SUMMARY

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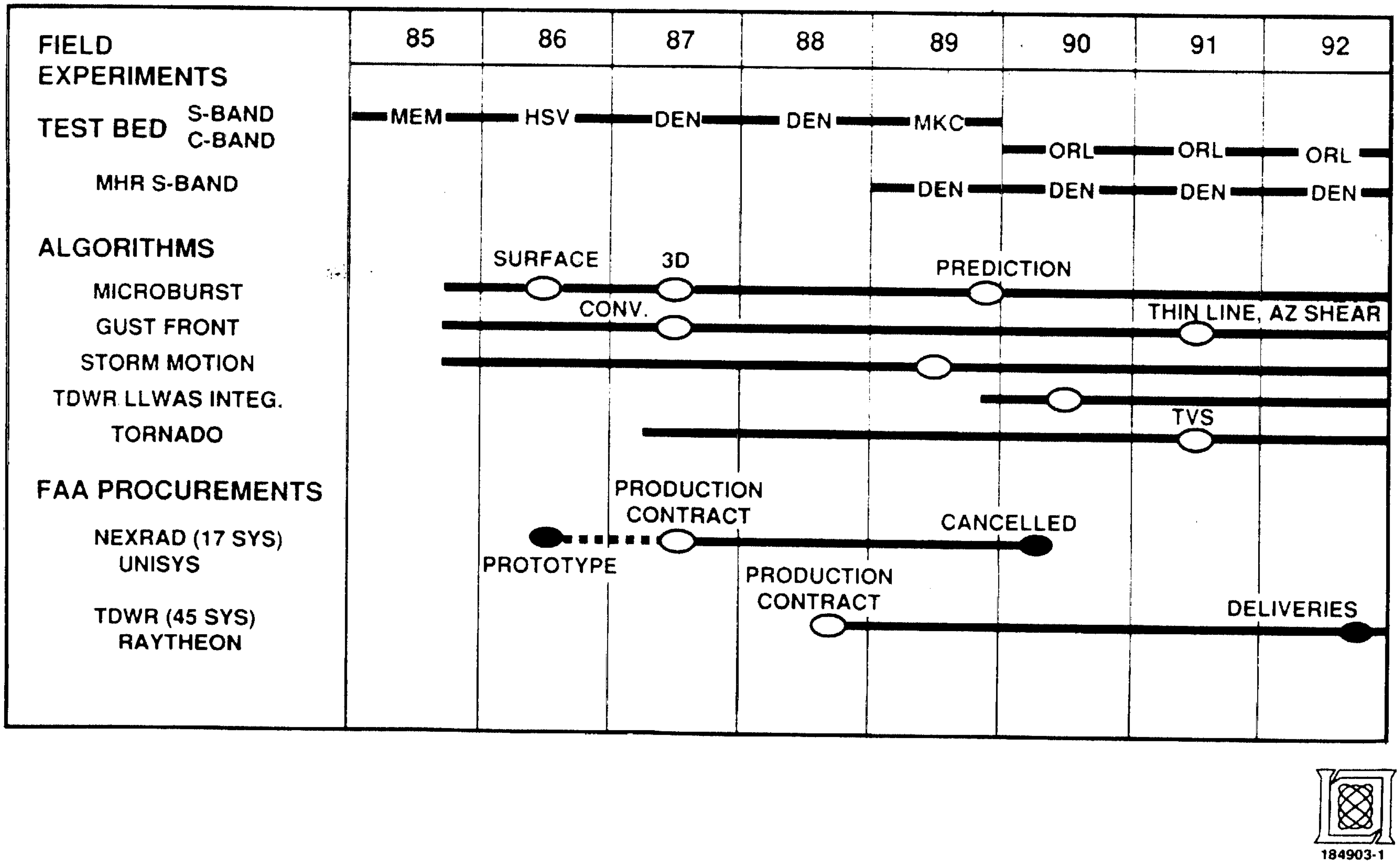
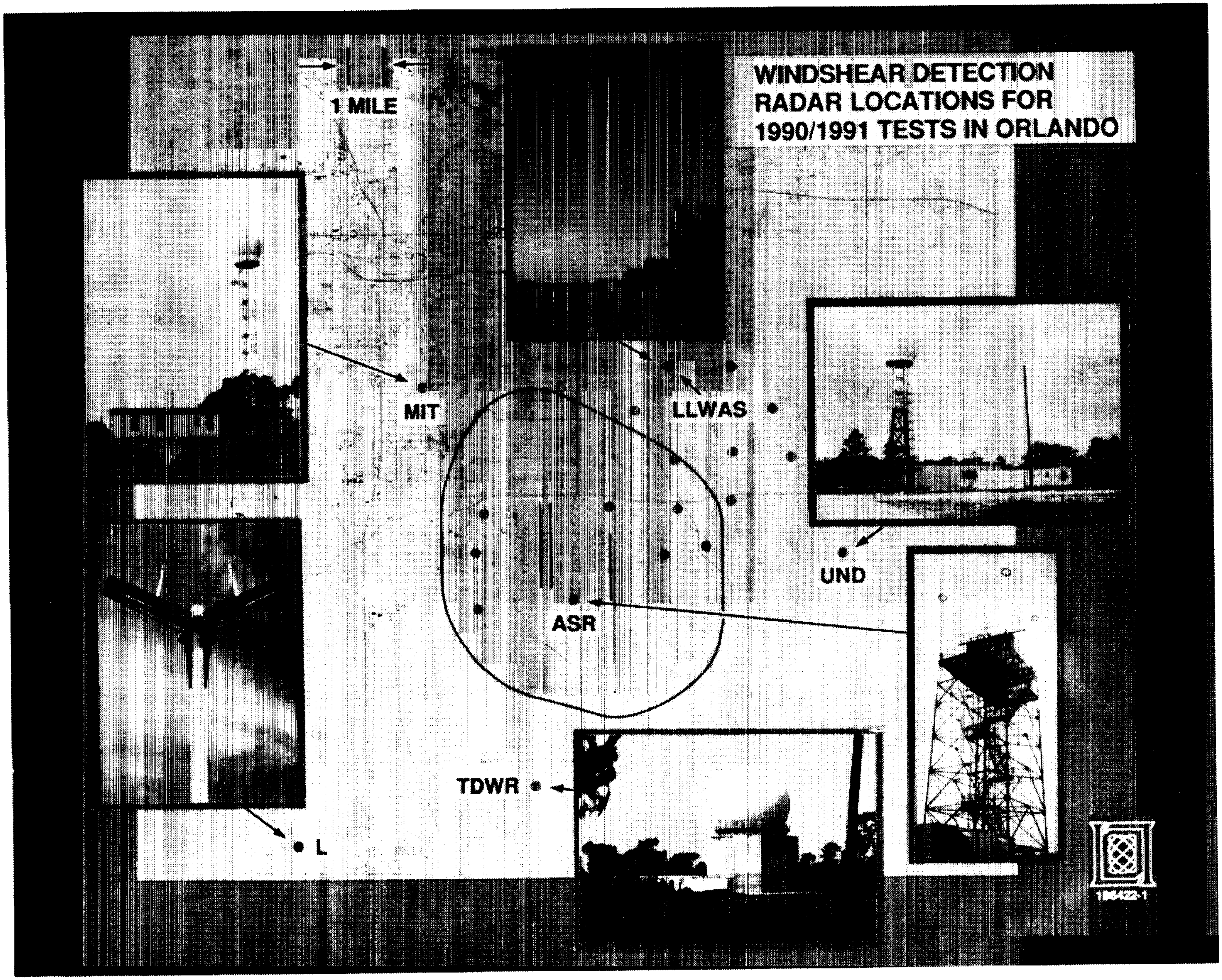
TERMINAL DOPPLER WEATHER RADAR PROGRAM




WINDSHEAR DETECTION
RADAR LOCATIONS FOR
1990/1991 TESTS IN ORLANDO
1 MILE
MIT
LLWAS
UND
ASR
TDWR
L

TDWR MICROBURST DETECTION PERFORMANCE

	Probability of Detection		Probability of False Alarm
HUNTSVILLE '86	$\Delta V > 30$ kt	1.0	.05
	$\Delta V > 20$ kt	.89	
DENVER '87 – '88	$\Delta V > 30$ kt	.98	.04
	$\Delta V > 20$ kt	.86	
KANSAS CITY '89	$\Delta V > 30$ kt	.97	.09
	$\Delta V > 20$ kt	.94	
ORLANDO '90	$\Delta V > 30$ kt	1.0	.02
	$\Delta V > 20$ kt	.93	

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ORLANDO '91 TDWR TESTBED ACTIVITIES

- FLIGHT PATH SHEAR INTEGRATION
  - SIGNIFICANTLY REDUCED OVERWARNING PROBLEMS NOTED IN PRIOR YEAR DEMONSTRATIONS
- TDWR/ELLWAS INTEGRATION
  - PERFORMS MESSAGE LEVEL INTEGRATION OF TDWR AND ENHANCED LLWAS WIND SHEAR WARNINGS
- OPERATIONAL DEMONSTRATION
  - TESTBED RADAR IS FUNCTIONALLY IDENTICAL TO TDWR SYSTEMS TO BE DEPLOYED BY F.A.A.
  - WIND SHEAR WARNING PROVIDED OPERATIONALLY TO ORLANDO ATC DURING 6 WEEK PERIOD

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FLIGHT TEST ACTIVITY AT ORLANDO

- SUMMER '90:
  - UNIVERSITY OF NORTH DAKOTA (UND) CESSNA CITATION II RESEARCH AIRCRAFT
  - FIRST DEMONSTRATION OF DATA LINKING TDWR MICROBURST ALERTS TO AIRCRAFT IN REAL–TIME
  - 40 MICROBURST PENETRATIONS WITH TDWR SURVEILLANCE
- SUMMER '91:
  - NASA LANGLEY RESEARCH CENTER B737 AIRCRAFT
  - DATA LINKED TDWR MB ALERTS USED TO GUIDE MICROBURST PENETRATIONS
  - 20 MICROBURST PENETRATIONS WITH TDWR SURV.

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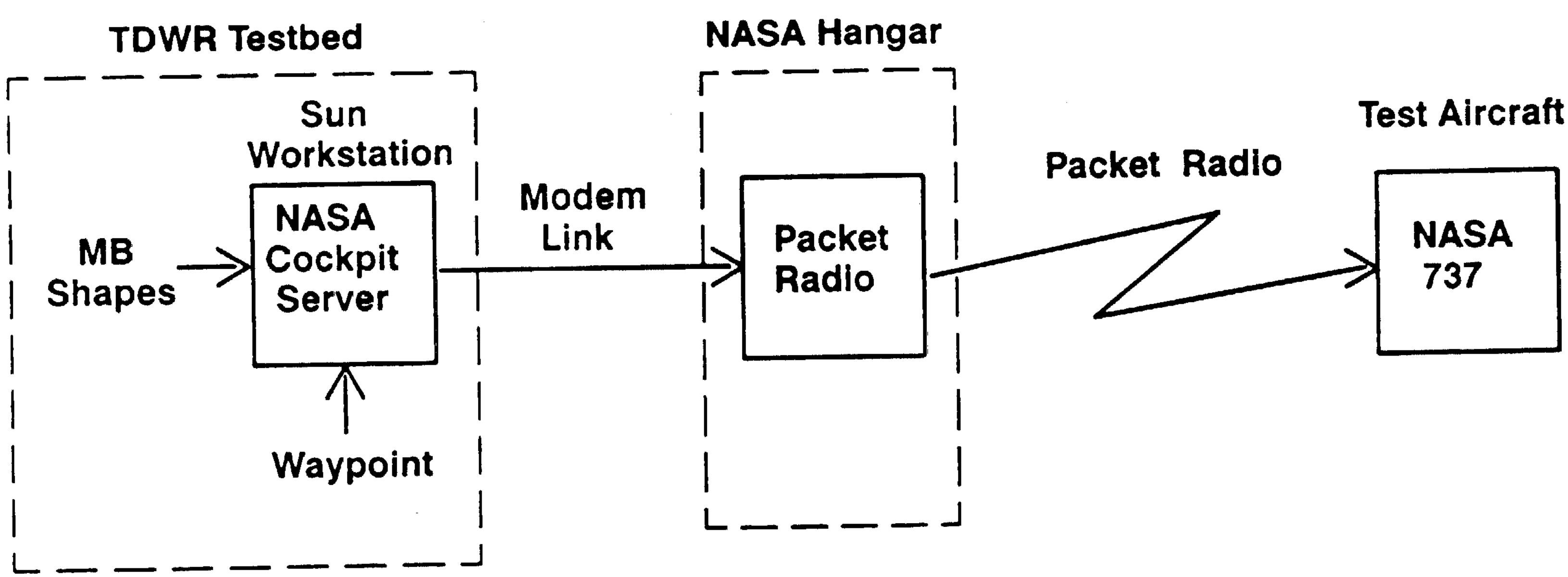
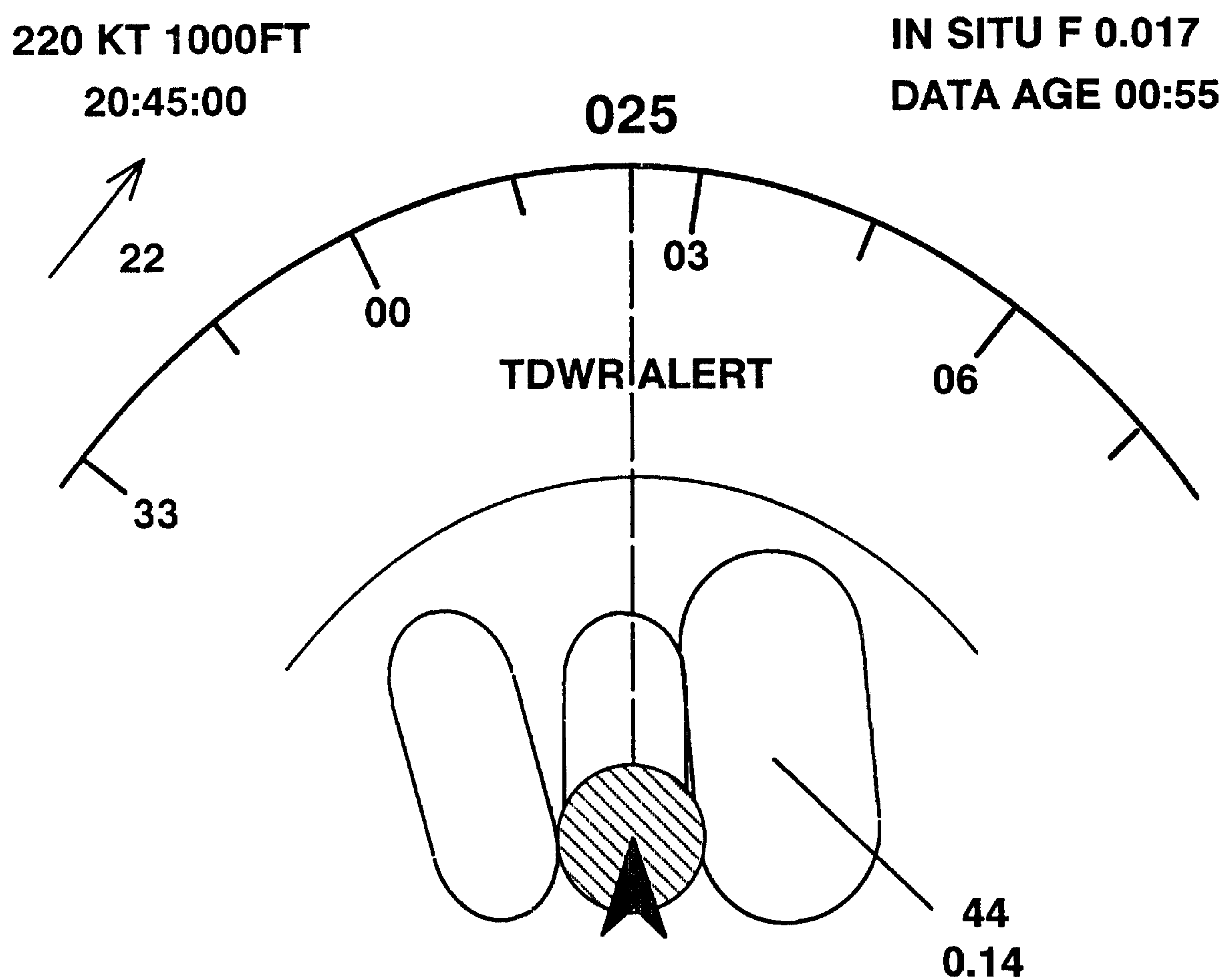
DATA LINK TO NASA B737



NASA COCKPIT DISPLAY



TDWR F FACTOR ESTIMATE

$$F = \frac{\dot{W}_x}{g} - \frac{W_z}{TAS} = F_x + F_z$$

ASSUME:

$$\dot{W}_x = \frac{\Delta V}{\Delta R} GS$$

$$W_z = -2h \frac{\Delta V}{\Delta R}$$

$$\hat{F}_{TDWR} = K' \frac{\Delta V}{\Delta R} \left(\frac{GS}{g} + \frac{2h}{TAS} \right)$$

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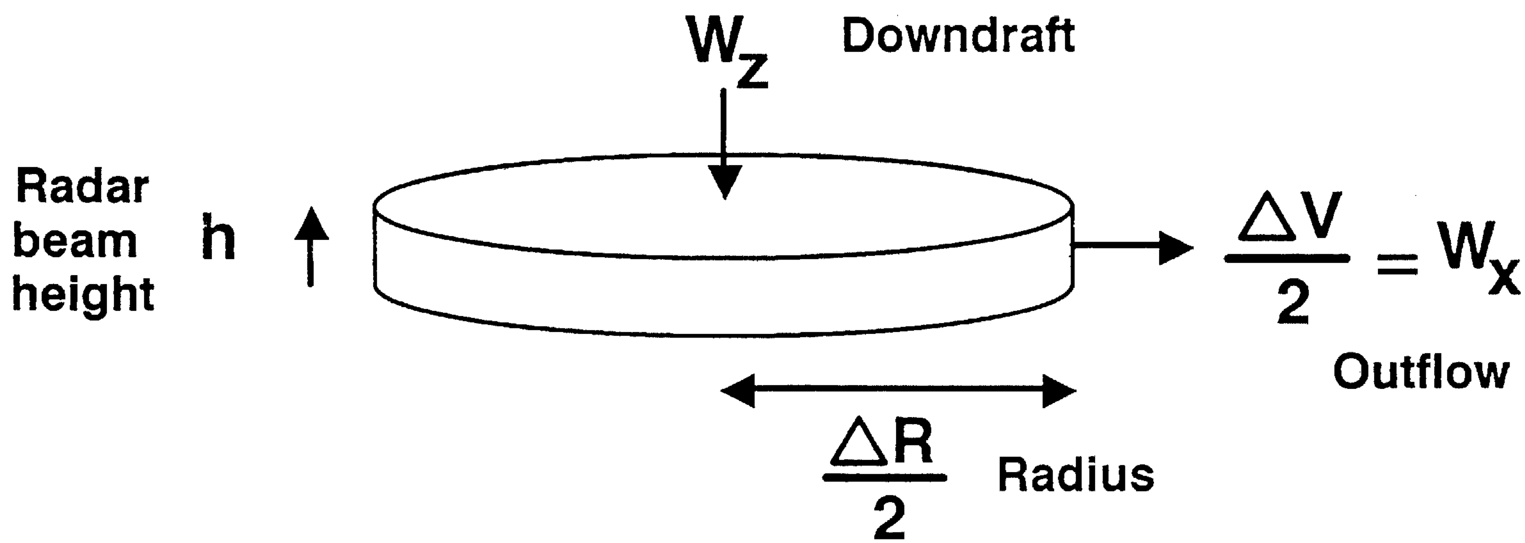
CONTINUITY



$$W_z \pi \left(\frac{\Delta R}{2}\right)^2 = \frac{\Delta V}{2} \, 2\pi \, \frac{\Delta R}{2} \, h$$

$$W_z = -2h \frac{\Delta V}{\Delta R}$$

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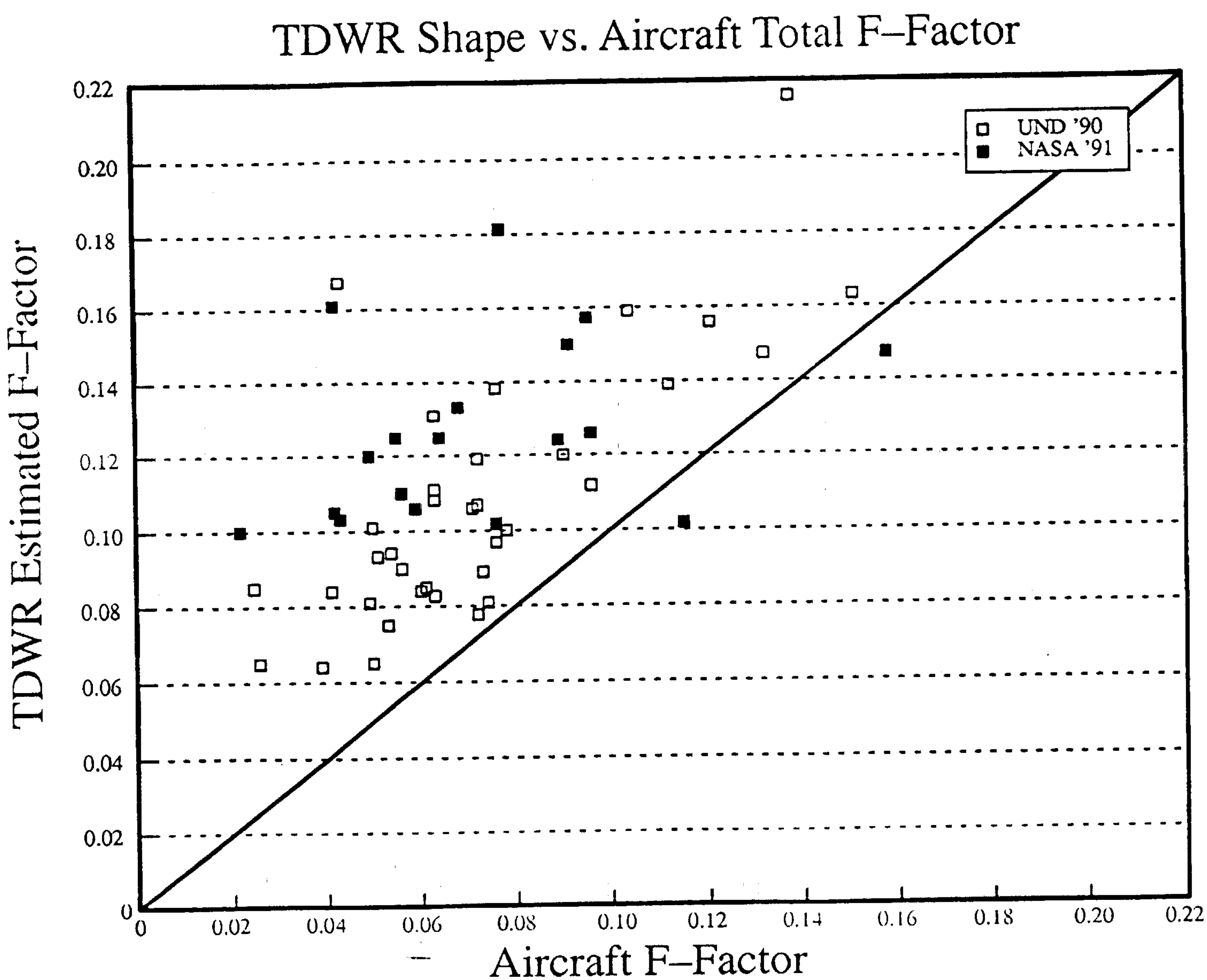
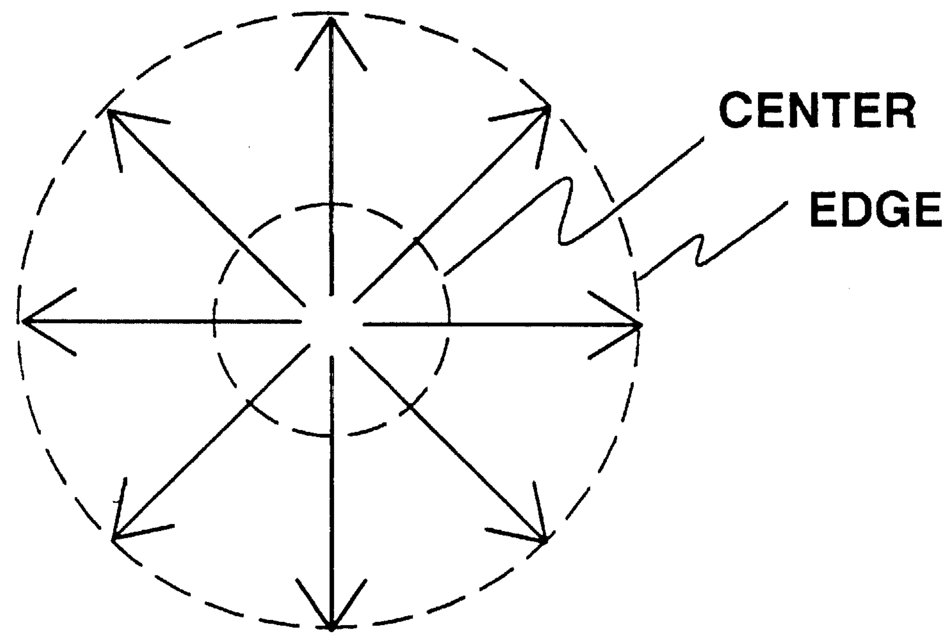

TDWR Shape vs. Aircraft Total F–Factor
UND '90
NASA '91
TDWR Estimated F–Factor
Aircraft F–Factor
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22

MICROBURST REPRESENTATION



PHYSICAL MODEL:

- STRONG SHEAR & DOWNDRAFT AT CENTER
- WEAKER SHEAR & UPDRAFT AT EDGE
- ALTITUDE DEPENDENT

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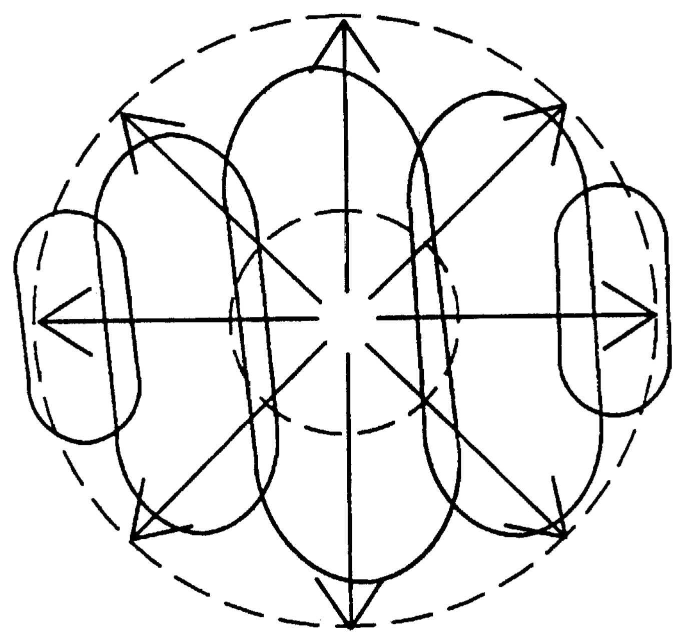
MICROBURST REPRESENTATION



CURRENT MICROBURST SHAPES:

- CENTER NOT WELL LOCALIZED
- EDGE EXTENT UNDERESTIMATED
- NO ALTITUDE DEPENDENCE

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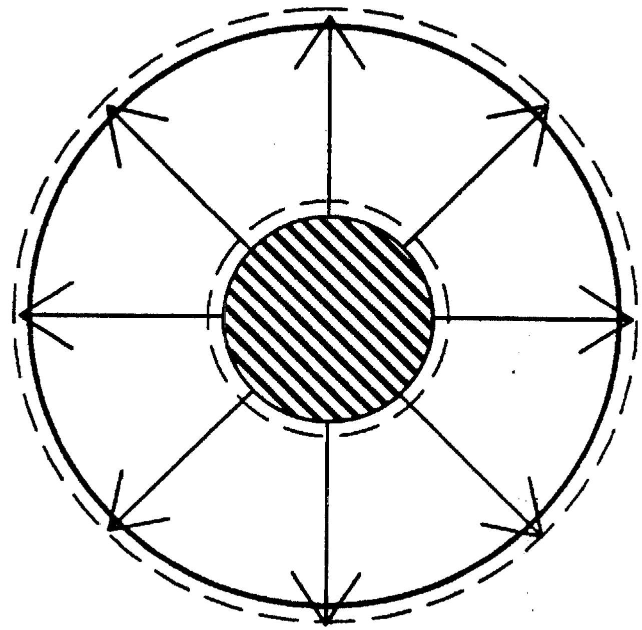
MICROBURST REPRESENTATION



PROPOSED SHAPE IMPROVEMENTS:

- SHEAR–BASED OUTFLOW DETECTION
- LOCALIZE CENTER AND EDGE
- ALTITUDE COMPENSATION

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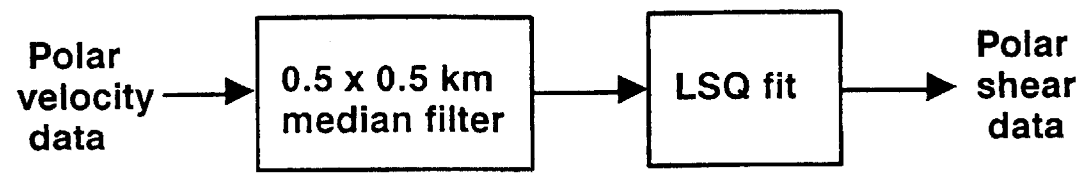
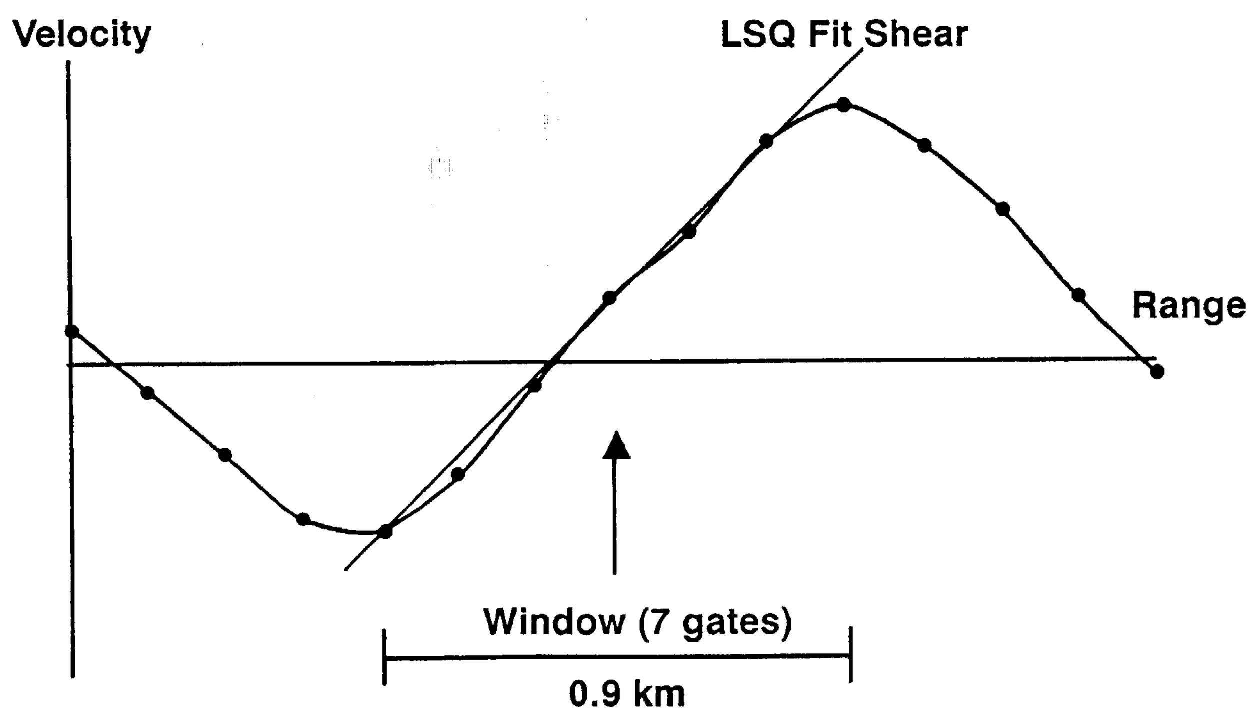
SHEAR COMPUTATION





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SUBSTITUTE LSQ SHEAR

$$\hat{F}_{SHEAR} = \left(\frac{dV}{dR}\right)_{h_r} \left(\frac{GS}{g} + \frac{2\,h_r}{TAS}\right)$$

WHERE:

h_r = RADAR BEAM HEIGHT

$\left(\frac{dV}{dR}\right)_{h_r}$ = COMPUTED LSQ SHEAR

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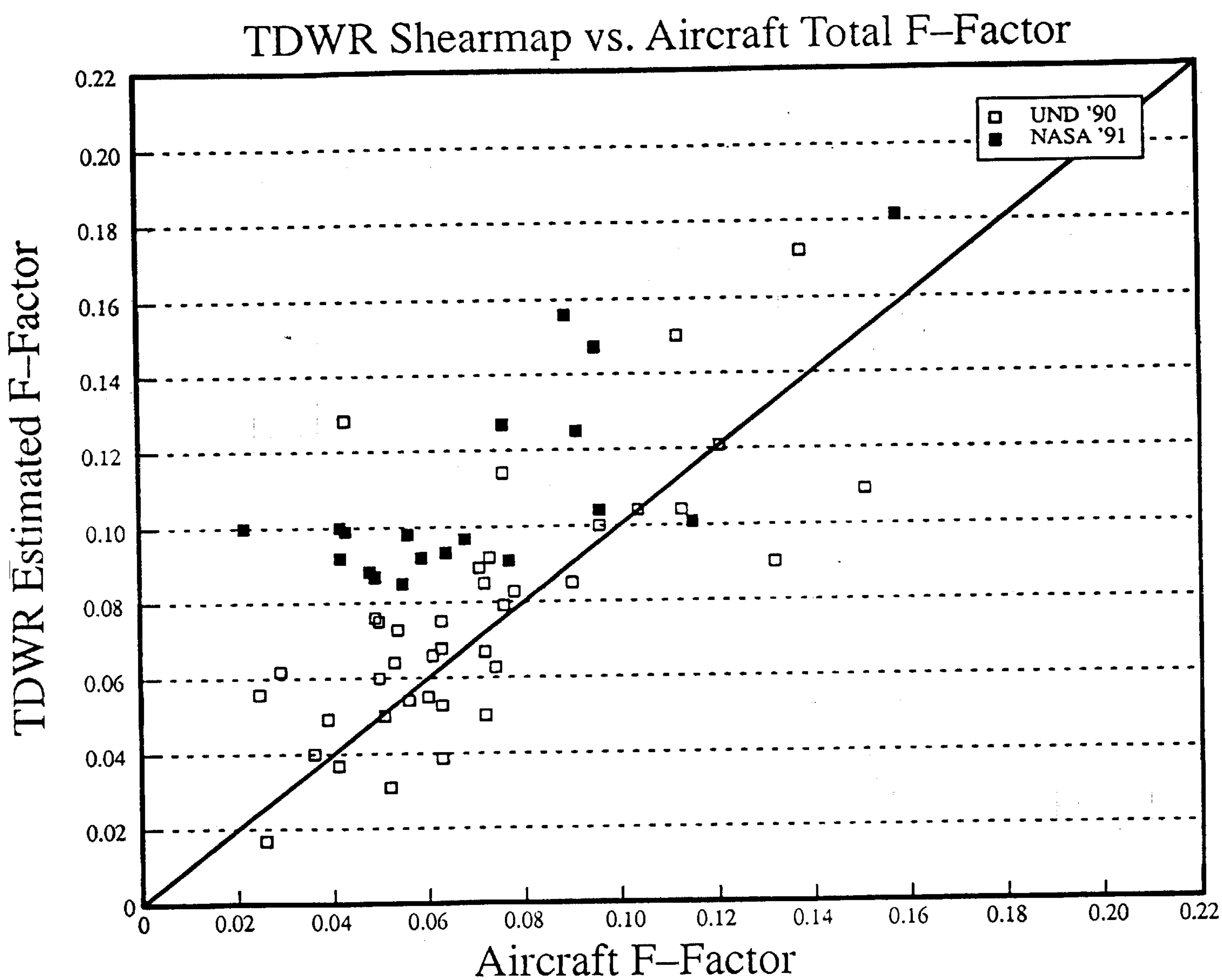
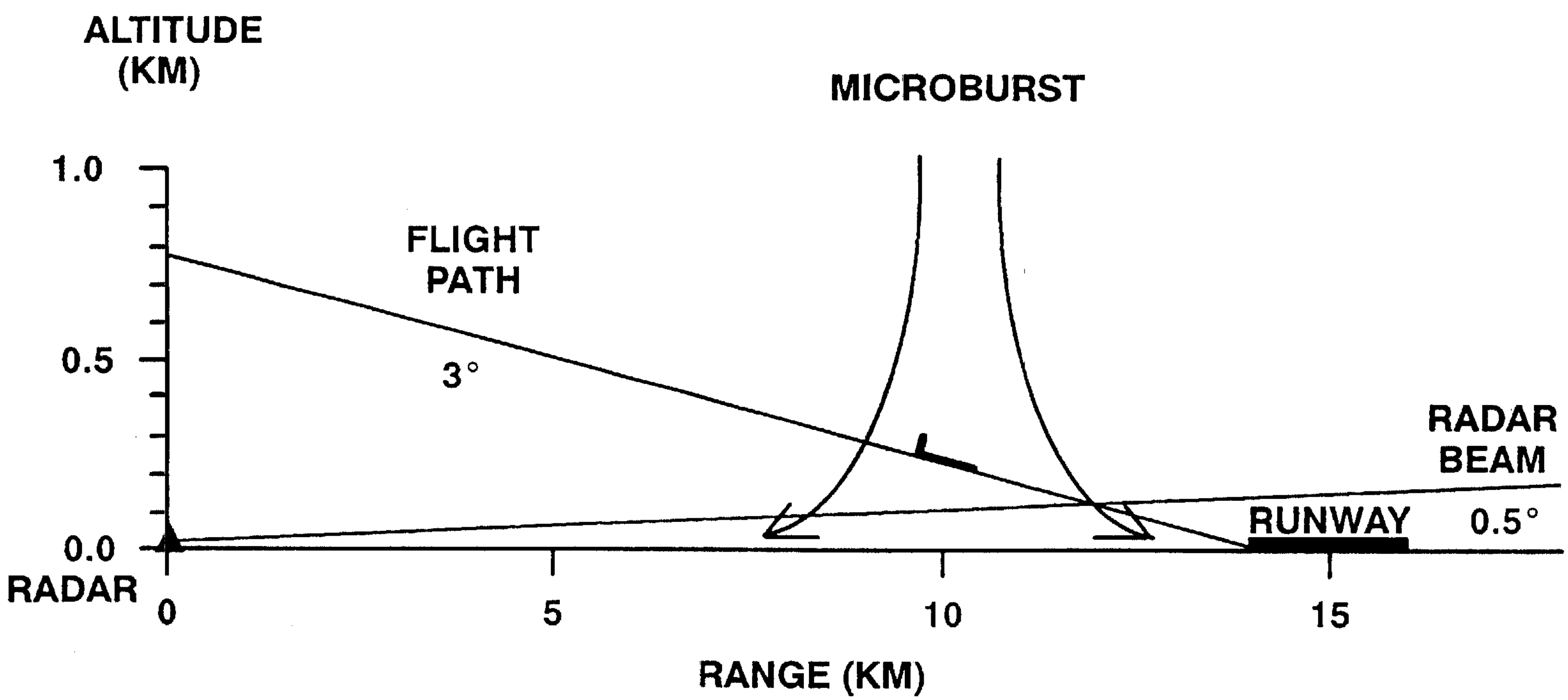


TDWR Shearmap vs. Aircraft Total F–Factor
UND '90
NASA '91
TDWR Estimated F–Factor
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
Aircraft F–Factor

MICROBURST OUTFLOW ALTITUDE DEPENDENCE



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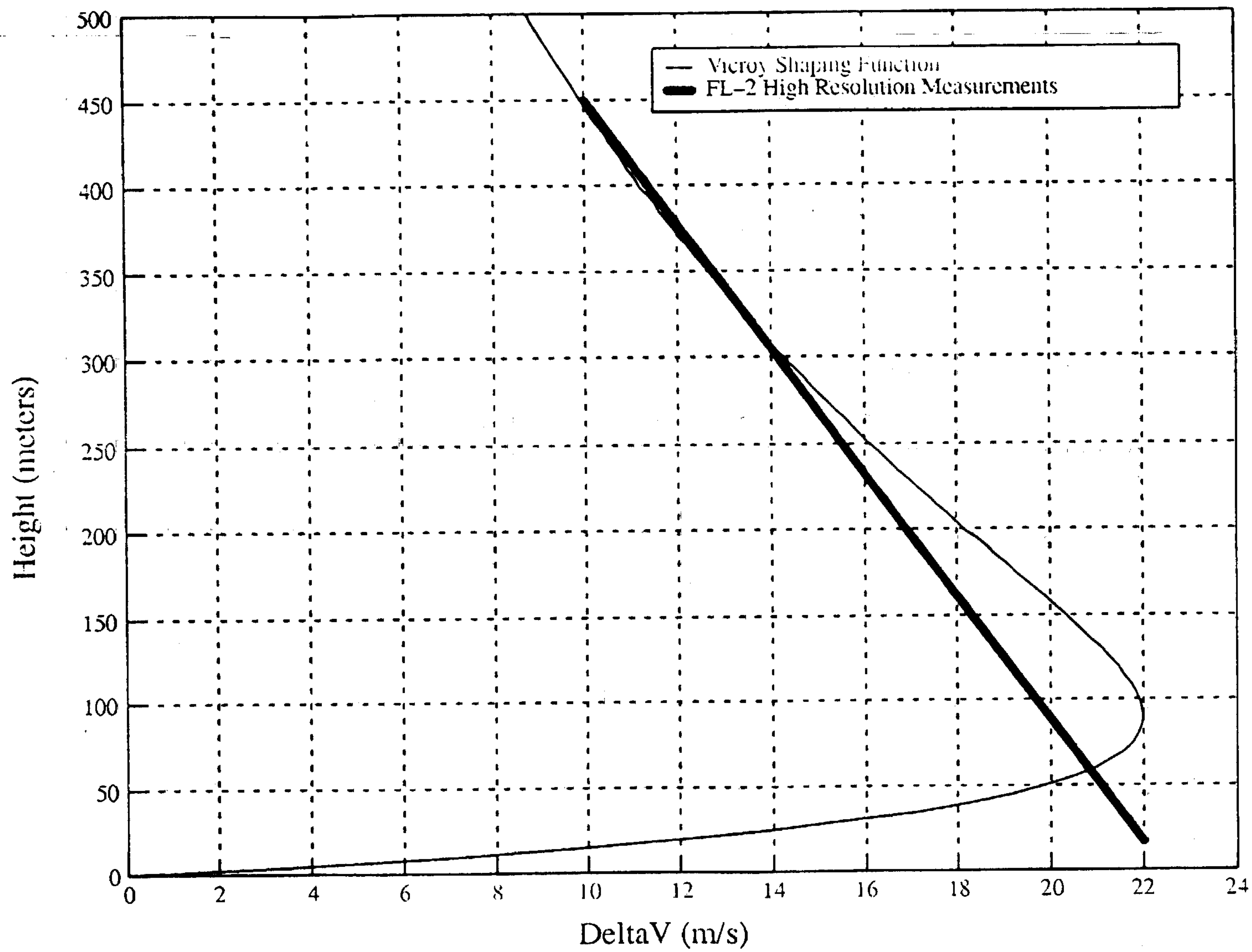
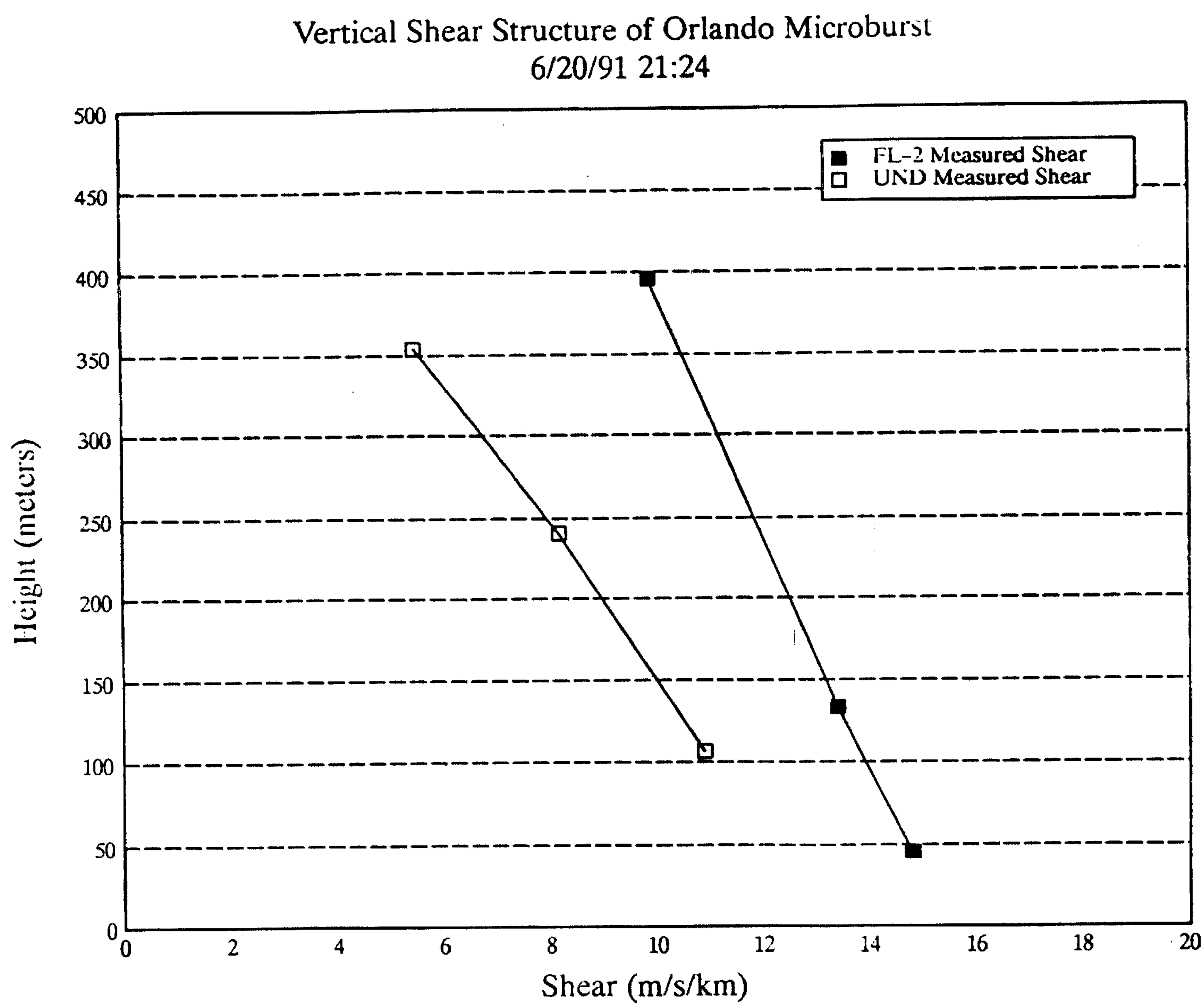
Mean Vertical Velocity Structure of Orlando Microburst
DeltaV Max = 22m/s




Vertical Shear Structure of Orlando Microburst
6/20/91 21:24
FL-2 Measured Shear
UND Measured Shear
500
450
400
350
300
250
200
150
100
50
0
Height (meters)
0
2
4
6
8
10
12
14
16
18
20
Shear (m/s/km)

CORRECT FOR ALTITUDE DEPENDENCE

$$\hat{F}_{\substack{\text{ALT.}\\ \text{CORR.}}} = \left(\frac{dV}{dR}\right)_{h_a} \left(\frac{GS}{g} + \frac{2\,\dot{h}_a}{TAS}\right)$$

WHERE:

$$\left(\frac{dV}{dR}\right)_{h_a} = \left(\frac{dV}{dR}\right)_{h_r} \left(\frac{p(h_a)}{p(h_r)}\right)$$

h_a = AIRCRAFT ALTITUDE

$p(z)$ = HORIZONTAL SHEAR VS. ALTITUDE (VICROY/O&B MODEL)

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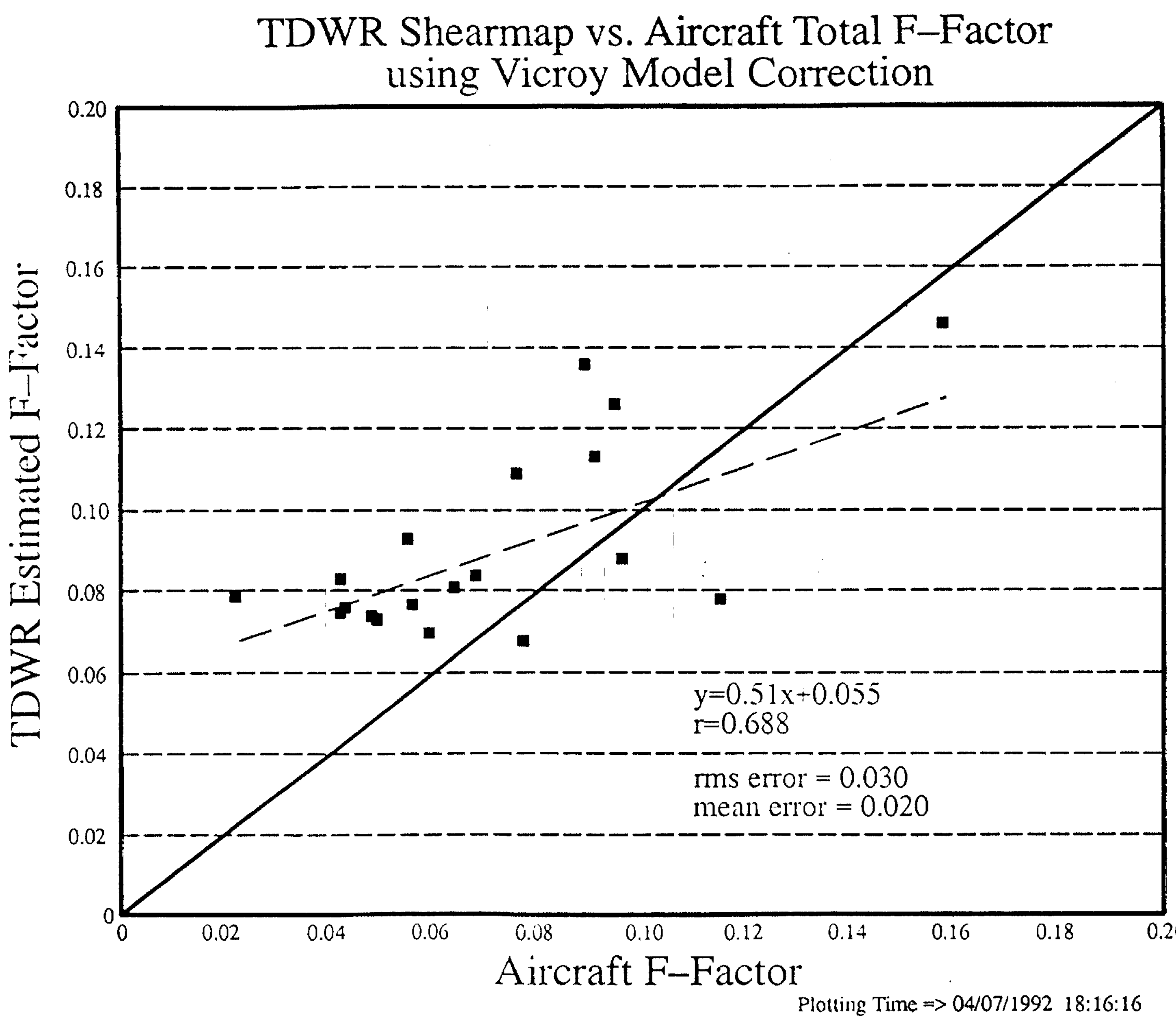
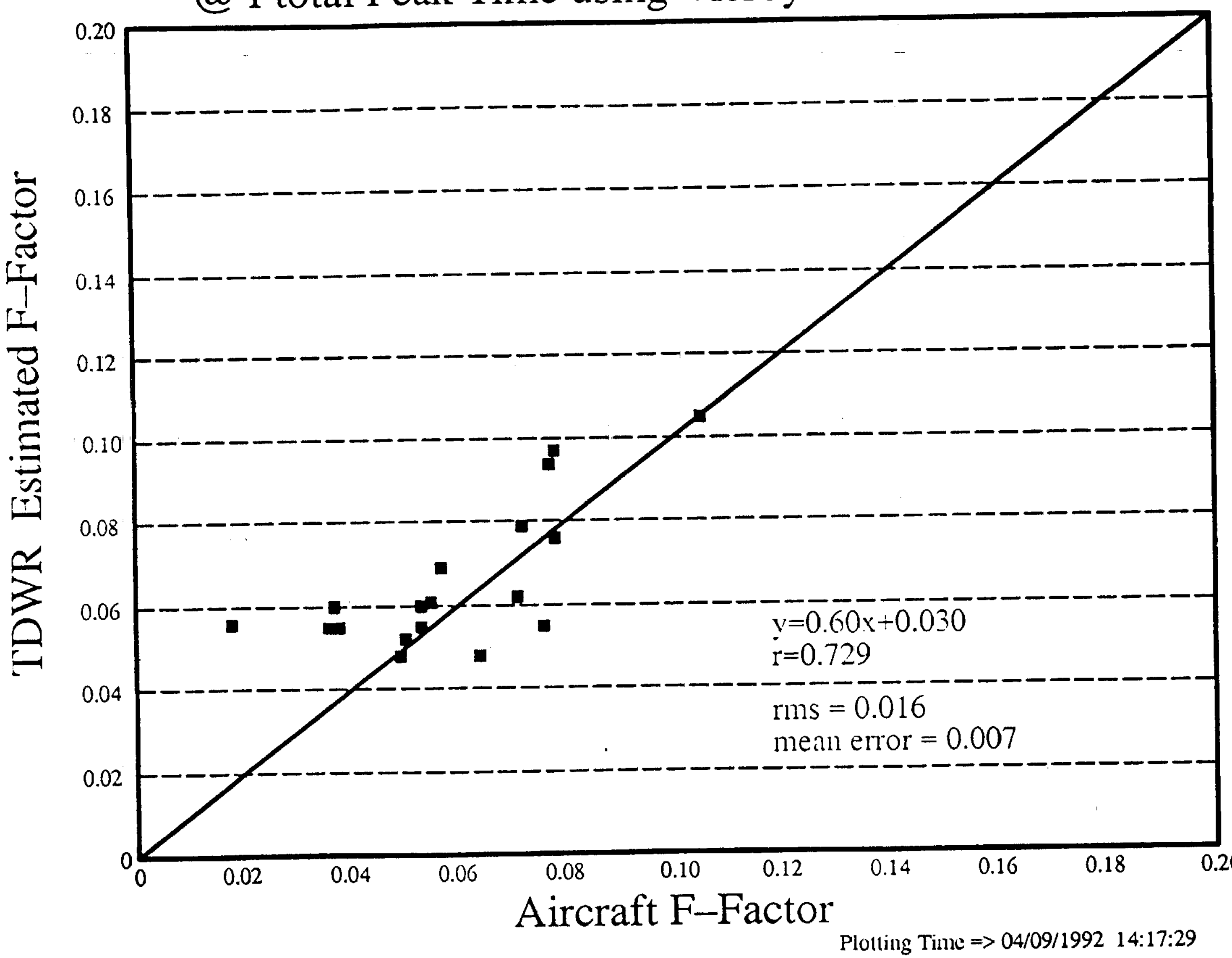
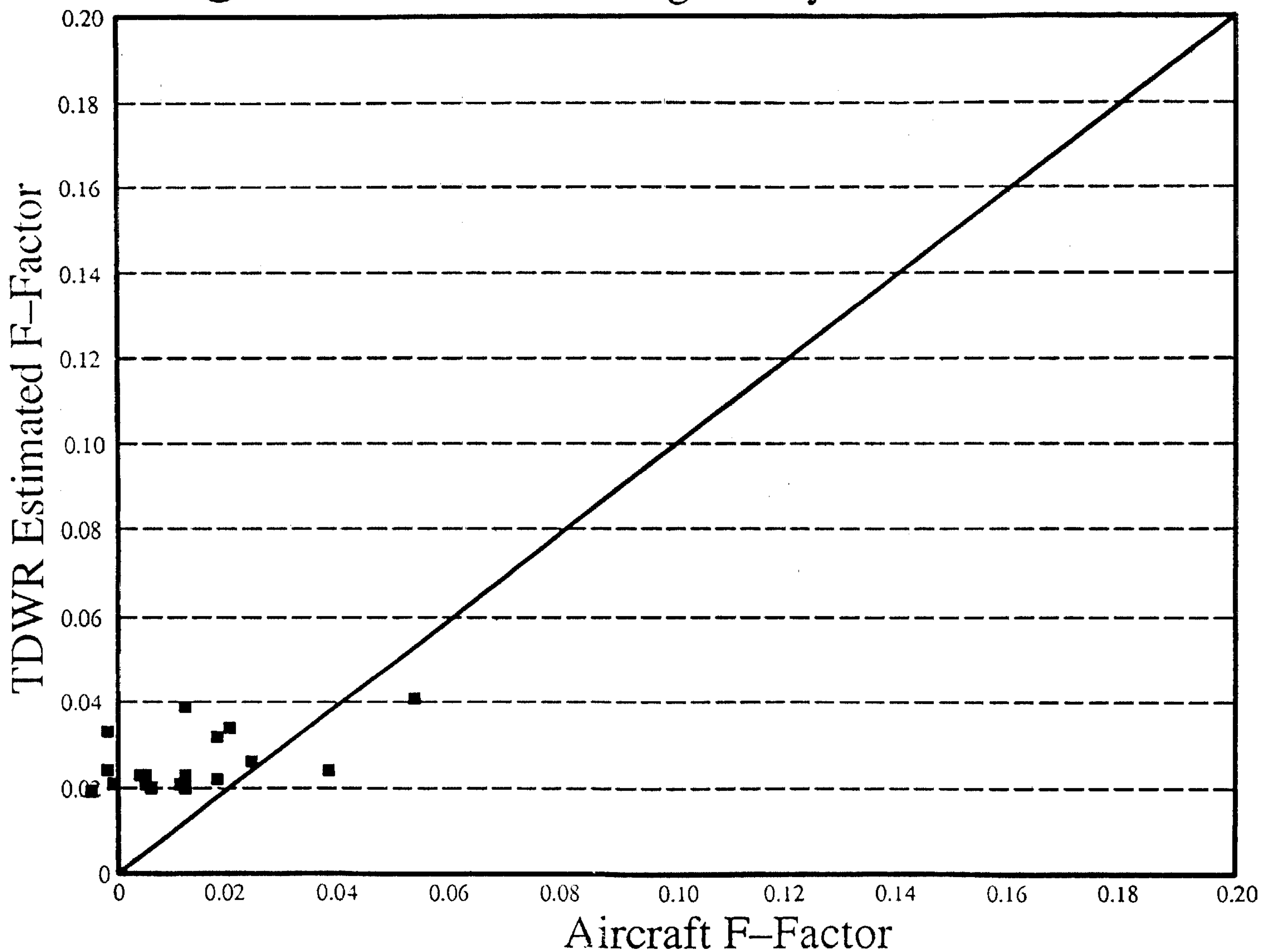

TDWR Shearmap vs. Aircraft Total F–Factor
using Vicroy Model Correction
TDWR Estimated F–Factor
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
Aircraft F–Factor
y=0.51x+0.055
r=0.688
rms error = 0.030
mean error = 0.020
Plotting Time => 04/07/1992 18:16:16

TDWR Shearmap vs. Aircraft Horizontal F–Factor
@ Ftotal Peak Time using Vicroy Model Correction



TDWR Shearmap vs. Aircraft Vertical F–Factor
@ Ftotal Peak Time using Vicroy Model Correction



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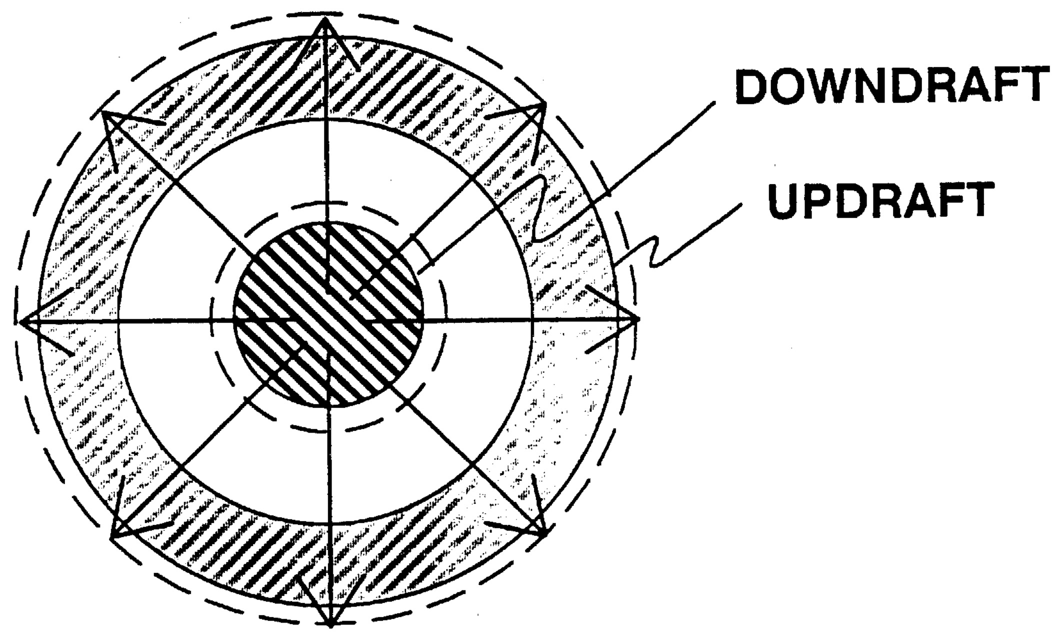
HORIZONTAL OFFSET COMPENSATION



VERTICAL COMPONENT:

- POSITIVE 2a/TAS FOR CENTER
- NEGATIVE a/TAS FOR EDGE
- NEED TO LOCALIZE OUTFLOW CENTER & EDGE

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CORRECT FOR HORIZONTAL OFFSET

$$\hat{F}_{\substack{\text{HORIZ.}\\ \text{CORR.}}} = \left(\frac{dV}{dR}\right)_{h_a} \left(\frac{GS}{g} + \frac{2\,h_a}{TAS}\right) \text{, CENTER PENETRATION (DOWNDRAFT)}$$

$$= \left(\frac{dV}{dR}\right)_{h_a} \left(\frac{GS}{g} - \frac{h_a}{TAS}\right) \text{, EDGE PENETRATION (UPDRAFT)}$$

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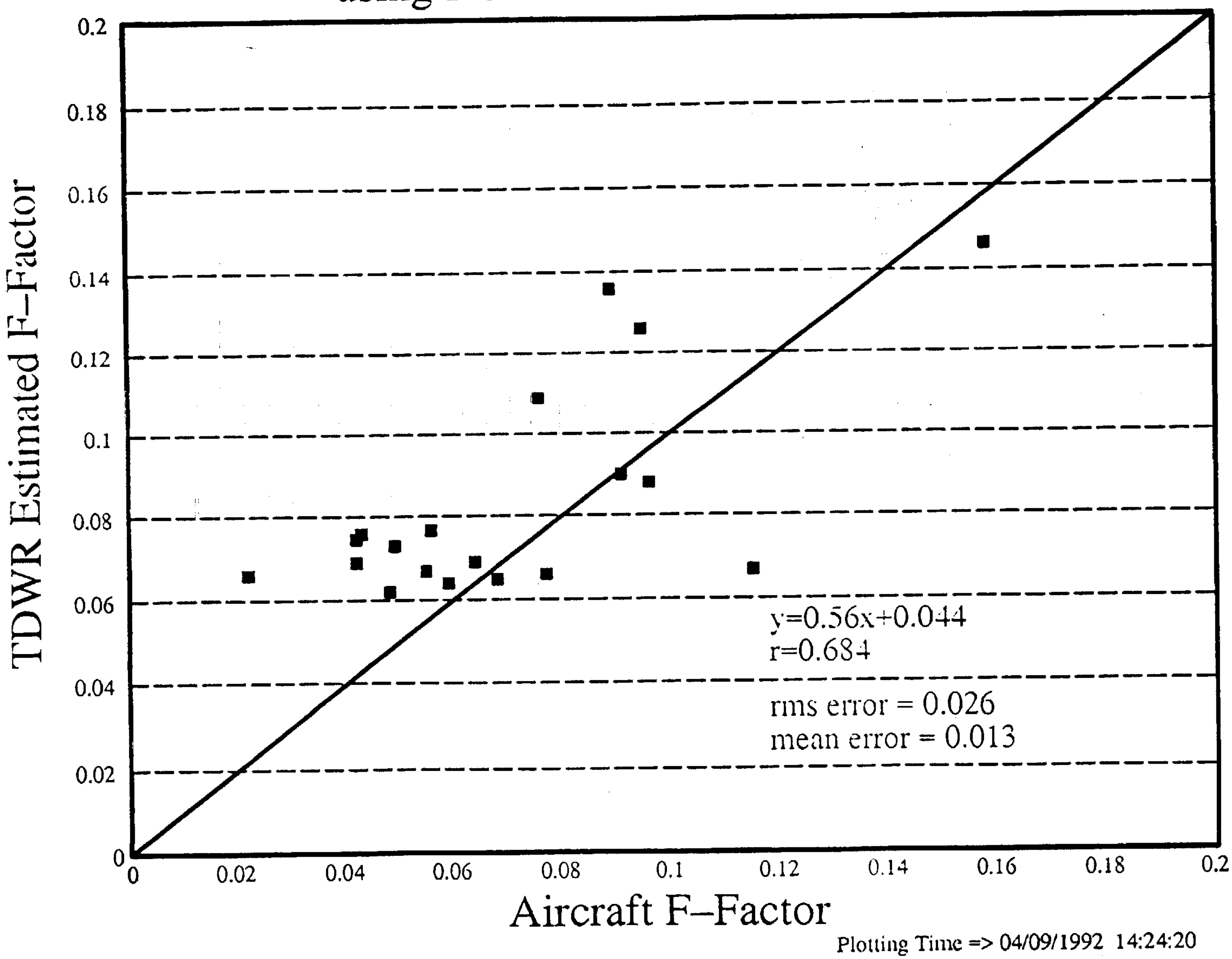
TDWR Shearmap vs. Aircraft Total F–Factor
using Horizontal Offset Correction



OPTIONS FOR MODIFYING TDWR SOFTWARE

- TERMINAL DOPPLER WEATHER RADAR PROGRAM:
  - TDWR CONTRACTOR (RAYTHEON)
    - CURRENTLY IN PROGRESS FOR FLIGHT PATH SHEAR INTEGRATION AND TDWR/ELLWAS INTEGRATION
  - PROGRAM SUPPORT FACILITY (F.A.A.)
    - CURRENTLY BEING ESTABLISHED AT OK CITY
- INTEGRATED TERMINAL WEATHER SYSTEM (ITWS):
  - WILL INVOLVE ADDITIONAL ALGORITHMS OPERATING ON TDWR REFLECTIVITY AND VELOCITY DATA
  - INTEGRATES DATA FROM GROUND-BASED AND AIRBORNE SENSORS (E.G., ACARS DATA)
  - OPERATIONAL TESTS IN 1993-1994, FOLLOWED BY INITIAL OPERATIONAL CAPABILITY (IOC) IN 1996

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SUMMARY

- FLIGHT TEST ACTIVITY AT ORLANDO TDWR TESTBED:
  - SIXTY INSTRUMENTED MB PENETRATIONS
  - DATA LINK DEMONSTRATIONS
- IMPROVING TDWR F FACTOR ESTIMATES:
  - SHEAR–BASED OUTFLOW DETECTION
  - PHYSICAL MODEL–BASED MICROBURST SHAPES
  - COMPENSATION FOR ALTITUDE DEPENDENCE
- FUTURE PLANS
  - NASA FLIGHTS IN '92 (PLUS OTHER AIRCRAFT)
  - RAPID TRIPLE–DOPPLER LOW–ALTITUDE SCANS

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The Orlando TDWR Testbed and Airborne Wind Shear Data Comparison Results

Questions and Answers

Q: Dan Vicroy (NASA Langley) - You pointed out some improvements or possible improvements to the TDWR algorithms. Can you comment on the implementation issues and what kind of time line you are looking at for implementing these improvements?

A: Steve Campbell (MIT Lincoln Lab.) - The TDWR was implemented as a very fast track program. We knew that there would be some refinements. When the TDWR was designed, the idea was that all you needed to do was detect the change in velocity. I think we now understand that it is not true. There are really two avenues through which we could make improvements. One is that the FAA expects to upgrade the TDWR algorithms over a period of time. The other is that there is another program which is starting up called the Integrated Terminal Weather System Program in which we will be incorporating data from a number of sources, TDWR, surface observations and aircraft data. That may also be an avenue for making these improvements. As far as how long that is going to take, well it is going to take some years. I think we are at least plugged into that process.