APPLICATION OF INFRARED RADIOMETERS FOR AIRBORNE DETECTION OF CLEAR AIR TURBULENCE AND LOW LEVEL WIND SHEAR

FINAL REPORT

31 DECEMBER 1982 - 31 MARCH 1985

AIRBORNE INFRARED LOW LEVEL WIND SHEAR DETECTION TEST

NASA ARC CONTRACT (NAS2-10592)

31 MARCH 1985

P. M. KUHN

NORTHROP SERVICES, INC.

CONTENTS

1.0 INTRODUCTION: BACKGROUND, OBJECTIVES

a. Aircraft Instrumentation

From the commencement of this research in April 1982 the objective of the effort is to investigate the feasibility of infrared optical techniques for the advance detection and avoidance of low level wind shear (LLWS) or low altitude wind shear hazardous to aircraft operations. A primary feasibility research effort was conducted with infrared detectors and instrumentation aboard the NASA Ames Research Center Learjet (Figure 1). The infrared window of the original sensor system is evident above the nose of the aircraft. Details of the basic instrumentation system are presented by Kuhn, Kurkowski and Caracena[1] (1983). The main field effort was flown on the NASA-Ames Dryden B57B aircraft (Figure 2). The Learjet data analysis has been published and the data returned to NASA Ames.

The evolution of mounting techniques for the infrared probe is evident in Figures 1 and 3. The original approach visualized a forward-looking, infrared transmitting (KRS-5) window through which signals would reach the detector. The present concept of a one inch diameter light pipe with a 45° angled mirror enables a much simpler installation virtually anywhere on the aircraft coupled with the possibility of horizontal scanning via rotation of the forward directed mirror.

The scanning and ranging concept for approach (or departure) is illustrated in Figure 4. Present infrared detectors and filters would certainly permit ranging and horizontal scanning in a variety of methods. CRT display technology could provide a contoured picture with possible shear intensity levels from the infrared detection system on the weather radar or a small adjunct display. This procedure should be further developed and pilot evaluated in a light aircraft such as a Cessna 207 or equivalent.

Figure   1

Figure   3

Figure   2
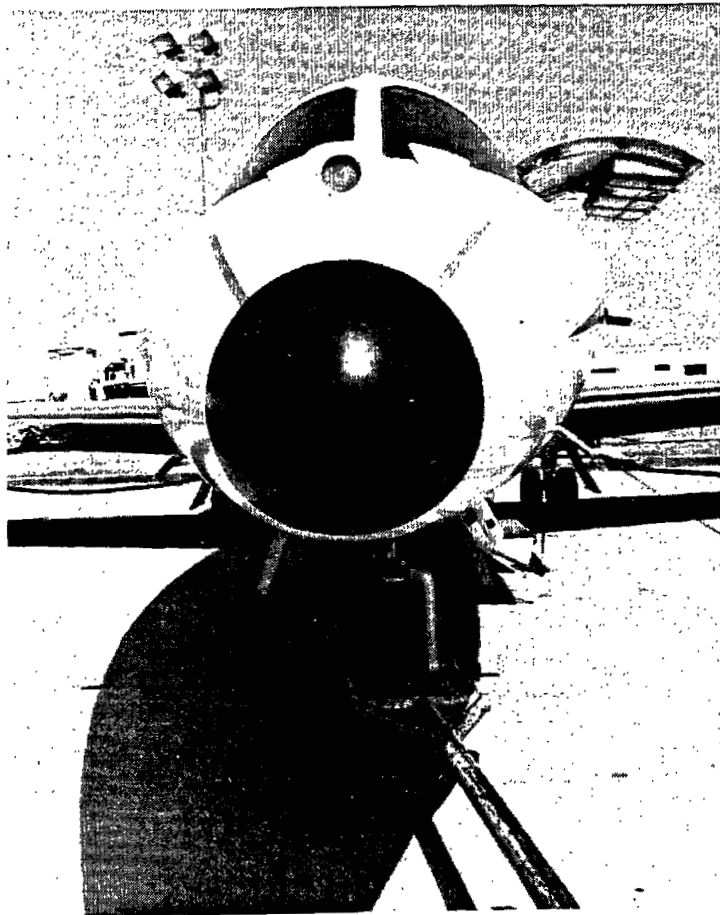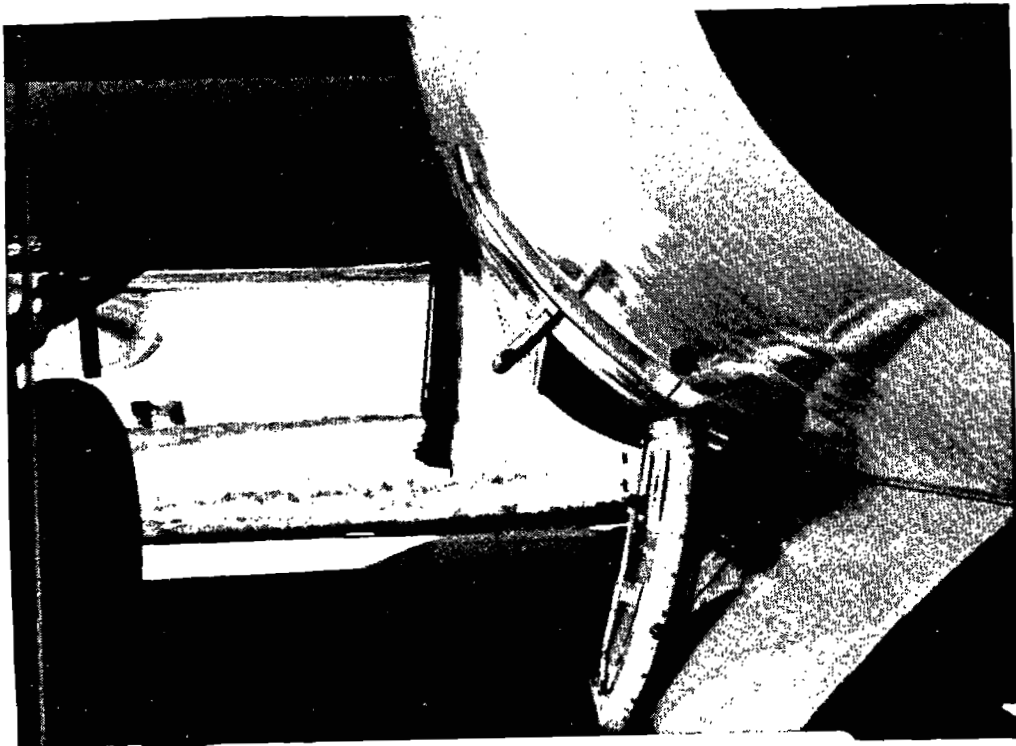
IR SHEAR SCANNER
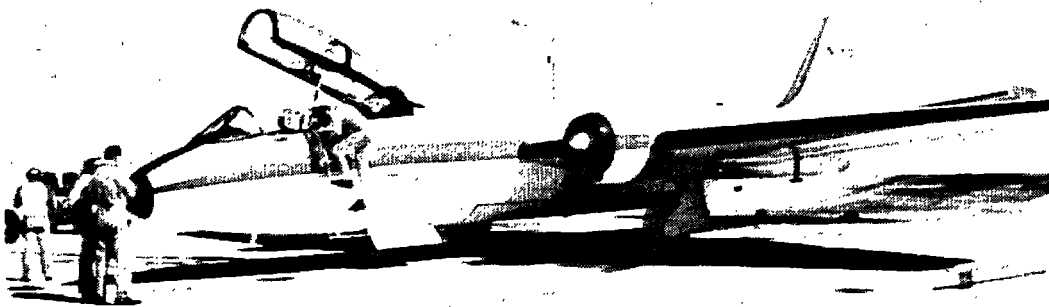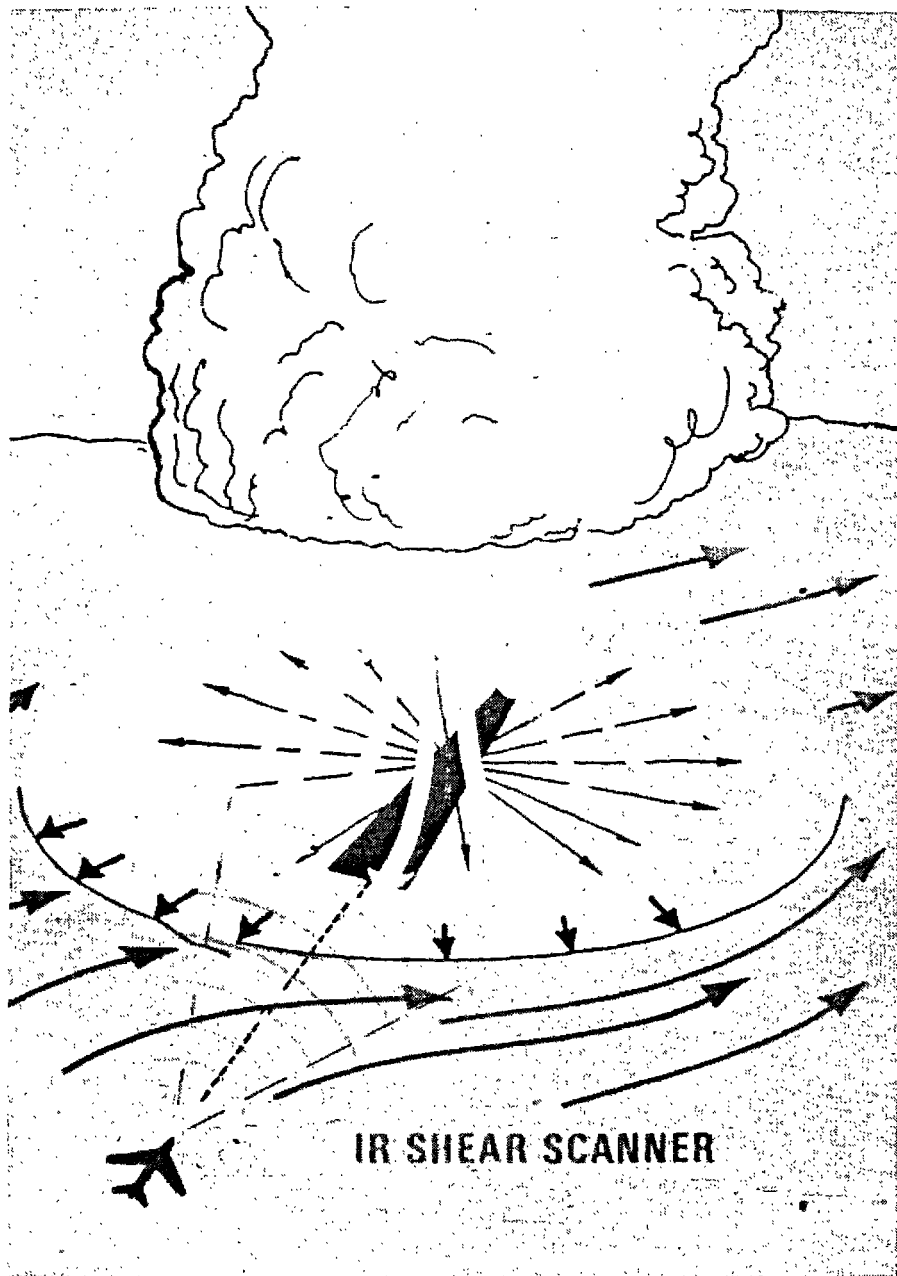
Figure 4

Two data sets were to be furnished the Principal Investigator (Kuhn), one of B57B data collected during The Joint Airport Weather Studies (JAWS) research of summer 1982 and a second set collected aboard the NASA B57B during the Norman-Oklahoma City, Oklahoma summer severe storms flight research in 1983. The first set of data was forwarded to the Principal Investigator by NASA officials and is reported herein as final. The second set of data, due to computer priorities, has not been delivered.

b. Gust Fronts and Aircraft Operation

Connective generated wind shears resulting in abrupt changes in wind direction and spped over very limited vertical distances can exceed the performance capability of any aircraft, light or heavy. Unusually severe downdrafts or microbursts are an occasional occurrence of thunderstorm density currents that produce the much more widespread and frequent gust fronts. This study is directed toward the hazards associated with the much more frequent and area extensive thunderstorm generated gust fronts.

These strong wind shears at low altitudes present severe hazards to aircraft during landing approach and takeoff. With aircraft operating near stall speed, a significant change in the wind speed and/or direction can result in a rapid loss or gain in altitude. Our objective is to describe the test of a prototype system for airborne, advance detection of such wind shear by means of infrared remote sensing. The test was conducted during the Denver Joint Airport Weather Studies (JAWS) project in the summer of 1982 aboard the NASA Ames B57B jet aircraft during several landing approaches and departures.

As stated the intent is to present analyses of the major results of this test and suggest its application to the passive, airborne detection of hazardous low level wind shear (LLWS) before an aircraft encounter. This is critical for aircraft operating in and out of airfields without LLWS ground

warning systems. The airborne wind shear detection and avoidance system described is intended to augment the advanced, ground-based microwave, lidar and low altitude wind shear alert equipment as a secondary, airborne system. Even at distances as great as 20 km (12.5 miles) from thunderstorms, the wind shear in storm density currents can pose a real hazard to approaching and departing aircraft. It is concluded that the prototype airborne radiometer, sensing in the 13 to 16 micrometer portion of the atmospheric molecular spectrum of CO_2, can sense the cold current outflow or gust front directly associated with low level wind shear (LLWS) in the vicinity of thunderstorms at ranges up to four miles.

2. NOMENCLATURE: SYMBOL TABLE

cm	wavelength
Cp	specific heat at constant pressure, $m^2 s^{-2} K^{-1}$
du/dz	vertical shear, s^{-1} or knots/100 ft.
g	gravitational acceleration, ms^{-2}
N,B	radiance, $w\ cm^{-2}\ sr^{-1}$
K	temperature °K
k	CO_2 absorption coefficient, $cm^2 g^{-1}$
P	pressure, $g\ cm^{-1} s^{-2}$
q	mass mising ration of CO_2, $g\ g^{-1}$
R	gas constant, $2.87 \times 10^6\ cm^2\ s^{-2} K^{-1}$
T	temperature °C
u	optical thickness of CO_2 gas ($g\ cm^{-2}$), $q \dfrac{P}{RT} x$
x	horizontal distance, cm
z	vertical distance, m
$\Delta T/\Delta t$	forward looking IR air temperature minus static air temperature at aircraft, $°C\ s^{-1}$
$\Delta \nu$	optical filter band widt, cm^{-1}
θ	potential temperature (°K), $T + gz/CP$
ν	wave number, cm^{-1}
τ	CO_2 transmission, %
ρ	air density, $g\ cm^{-3}$, P/RT
$\phi(\nu)$	radiometer filter transmission, %

3. ATMOSPHERIC PHYSICS OF GUST FRONT DETECTION

The physical basis for the IR temperature sensing wind shear predictor system is the demonstrated relationship between the temperature gradient from undisturbed air across a shear-producing gust-front or downburst outflow and the wind speed and direction of the gust front outflow wind (Fig. 5). The higher temperature gradients produce higher wind shear or peak gusts. Fawbush and Miller[2] provided a physical basis for predicting peak gusts caused by thunderstorm density currents. Temperature drops of 5C may readily produce peak gusts of 35 miles per hour while those of 15C produce peak gusts of 80 miles per hour (Fig. 5). The IR radiometer senses the cold outflow of the gust front downdraft well before the aircraft encounters the region. The precision of the IR radiometer is ± 0.5C, allowing for consecutive observations sampled at a 0.5 Hz rate to vary by only ± 0.5C. Signal integration will, of course, provide a standard error as low as ± 0.1C. Shear alerts occur when a defined temperature difference between this "forward" IR air temperature and the ambient air temperature at the aircraft, defined as a threshold criterion of -0.5C/sec, is reached or exceeded. Alternatively the "forward" air temperature may be converted to potential temperature, θ, which is essentially constant during landing and takeoff in a neutrally stratified atmospheric layer. If negative anomalies exist in the profile of θ which exceed a defined value, these can also be the basis of LAWS alerts aboard the aircraft. The "forward" air temperature minus the "near" air temperature at the aircraft provides a temperature difference change per second $\Delta T/\Delta t$. This change is then compared with the shear test criterion to initiate a shear warning if warranted . The criterion to warn of potential shear is a negative 0.5C/sec. or greater temperature change. As the temperature difference per second increases, the algorithm applied to the radiometer output
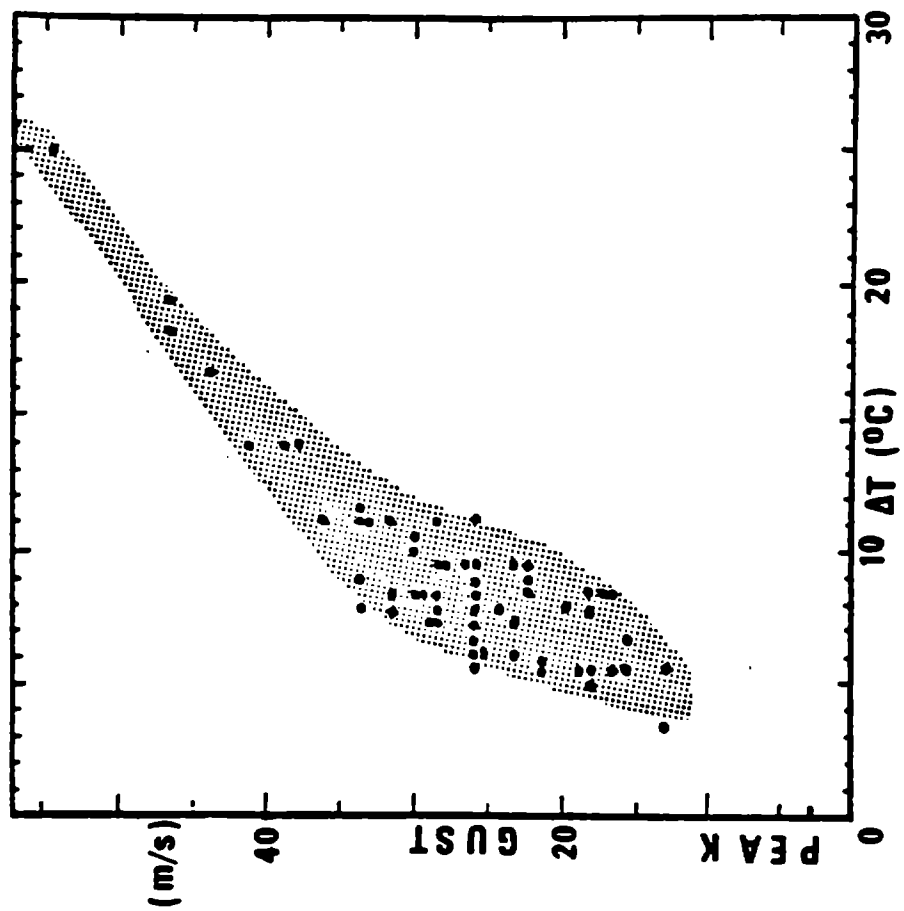
Figure 5

predicts gust front shear to also increase. The technical operation of the IR airborne system has been described by Kuhn, Kurkowski, and Caracena[1] (1983).

In a horizontally uniform temperature field both the near filter channel of the radiometer or the static air temperature measured at the aircraft and the forward, long range sensing filter channel of the radiometer sense the same temperature. As a cool outflow gust-front is approached, the long range channel begins to sense a cooler temperature well before the aircraft reaches the gust front, and the near channel senses the warmer static temperature at the aircraft until the cool downdraft or gust front is penetrated. At this point both radiometers sense the same temperature for a period of time. No alert for LLWS is produced until the temperature difference between the forward sensed temperature and the aircraft temperature reaches the pre-determined negative threshold. Alert conditions are, of course, continuously upgraded. The precision of the forward sensing radiometer filter combination is approximately 0.5C, as previously noted.

4. INFRARED RADIATION AND THE DETECTOR SYSTEM

The width of the IR radiometer filter pass band, $\delta\nu$, is an important consideration in designing the optics of the IR LLWS radiometer (Caracena, et al.).[3] Theoretical considerations show that narrow pass bands give the best spatial discrimination of thermal perturbations, while broad pass bands produce the strongest corresponding perturbation signal in the radiometer output.

Radiation in the atmospheric molecular spectrum of carbon dioxide reaching the radiometer optics may be expressed as

$$\overleftarrow{N} = -\int_\nu\int_x B(\nu,T)\phi(\nu) \; \left(\frac{\partial\tau(u[CO_2])}{\partial x}\right) dxd\nu \tag{1}$$

In Eq. (1) the horizontal transmission may be expressed as

$$\tau_{\Delta\nu} = \exp(-k_{\Delta\nu}q\rho x) \tag{2}$$

where the product, $q\rho$, is the density of carbon dioxide gas. The horizontal "look-distance" or weighting function distance in Eq. (1) is given by $\delta\tau/\delta\ell nx$ as a function of the horizaontal path distance, x. Eq. (2) may be differentiated with respect to distance, x, to give,

$$\frac{\delta\tau}{\delta\ell nx} = -k_{\Delta\nu}q\rho\tau x \tag{3}$$

An evaluation of Eq. (3) as a function of various horizontal distances, x, and altitudes (33 to 490 m) over various pass bands at 10 cm^{-1} intervals in the 600 to 710 cm^{-1} portion of the CO_2 spectrum resulted in the best weighting function or look-distance centered at 695 cm^{-1} providing a horizontal look-distance of 5 km (2.9 miles). This would give approximately 70 seconds warning time to shear encounter.

5. DATA ACQUISITION AND PROCESSING

The NASA Dryden B57B aircraft was the landing-approach platform for the IR LAWS sensor system during JAWS.[4] This fully instrumented gust gradient aircraft, carrying an elaborate data acquisition system and the IR sensor, among many other instruments, provided time, latitude, longitude, track angle, heading, altitude, static air temperature, E-W wind speed, N-S wind speed and airspeed for the airborne IR study. The IR LAWS optics installation aboard the B57B appears in figure 3 as the probe just off of an instrument access hatch on the starboard side, forward of the wing root section. Adjustable optics allow for horizontal leveling of the "look" angle.

Data tapes were processed via a Cyber 150-700 and Apple II Plus to obtain the final computer generated plots that appear in figures 6 through 12. These six figures are typical examples out of a total of forty-two processed flight approaches into potential shear conditions. Algorithms to compute all the approach data for the wind speed and direction arrows, altitude, vector difference magnitude, ΔT threshold, cross wind to aircraft track component, vertical shear, and aircraft horizontal and vertical position enabled the figures to be directly computer-generated via appropriate algorithms from original NASA tapes.

Each flight track figure displays the following:

The date and run number are shown.

The time before touchdown is given in seconds as abscissa.

The lower left ordinate is ΔT in °C (Shear alert threshold)

The upper left ordinate is altitude in kilo-feet.

The right ordinate is the vector difference magnitude in knots.

The lowest computer-plotted curve is the vector difference magnitude.

The middle computer plotted curve is $\Delta T(°C)$ (Shear threshold) tracing about zero. Negative ΔT defines a colder forward temperature.

The top side of the figure is north with the other directions as on any map. Thus a landing approach at 270° would be depicted from right (east) to left (west).

The top computer plotted curve is flight approach track with wind arrow flying into the curve. For example, a north wind comes from the top of figure onto curve. Wind speeds and direction are standard meteorological station plots.

Each full feather or barb denotes a speed of 10 knots. A half barb denotes a speed of 5 knots and an open triangular feather, 50 knots.

Recall that ΔT is defined as the forward air temperature minus the aircraft ambient temperature. From the $\Delta T/\Delta t$ (°C/sec) is readily determined and compared with the shear-alert threshold of negative 0.5C/second. Post-flight analyses as in this test will be replaced by microprocessor-driven, alerting displays.

6. DISCUSSION: SHEAR DETECTION MEASUREMENTS

As a prologue to the discussion of the remote measurements during the Joint Airport Weather Study (JAWS) Project[4] and their meaning, three observed phenomena resulting from wind shear, all or any of which can impair aircraft operations, are considered in each flight sequence. They are vertical shear, vector-difference magnitude and aircraft cross-wind component. This summary considers these meteorological phenomena that can be hazardous to aircraft operations. The low-altitude wind shear detection test offers advance determination of dangerous atmospheric conditions into which an aircraft may proceed.

Figures 6 through 12 graphically illustrate six examples from the group of forty-two B57B approaches into shear conditions at Stapleton International Airport and vicinity and the JAWS network in July of 1982[7] (Kuhn and Kurkowski, 1984). Table 1, providing the results of all forty-two approaches, summarizes the analyses of each run. A reference to the preceding section, "Data acquisition and processing," is suggested for the figure explanation.

In column 4 of Table 1 the radiometric advance alert during approach along the glid path is given as "t" minus a number of seconds. This is time in seconds before touchdown or simulated touchdown. Vertical shear, du/dz, columns seven and eight of the table, appear in units of sec^{-1} and knots per 100 meters. "-AS" indicates a loss of airspeed exceeding 30 knots. The figures are presented with standard aeronautical and meteorological symbols and nomenclature.

Two of the flight approach examples, runs 17 of the 14th and 15th of July (Figures 6 and 7) illustrate encounters with strong vertical shear, du/dz, in the lower 100 m (503 feet) and the operation of the airborne IR LLWS instrument system preceding the encounter. Hall et al.[5] have provided experi-

Table 1. SUMMARY ANALYSES OF AIRBORNE RADIOMETRIC SHEAR ALERT EPISODES WITH SUBSEQUENT APPROACH CONDITIONS ENCOUNTERED

| Date Run No.	Track Angle	Weather	Threshold (-sec)	Wind Cross Component (knots)	Vector Difference (knots)	Vector Shear (knots/ 100 ft)	Air Speed Loss
7/14/82-1	280		53	S7-P8	34	7	
7/14/82-2	210		50	S4-S22	47	4	
7/14/82-3	210		35	S6-S29	32	8	
7/14/82-4	030	Lt. Rain	42	0-P26	39	12	
7/14/82-5	172	Radial Dust	52	S5-S27	38	10	-AS
7/14/82-6	175		50	S3-S10	34	6	
7/14/82-7	355		44	P7-P22	48	22	-AS
7/14/82-8	178		64	0-S15	30	5	
7/14/82-9	168	Radial Dust	49	S5-S18	38	10	
7/14/82-10	354	Radial Dust	39	P10-0	41	8	-AS
7/14/82-11	174	Radial Dust	65	S15-2	42	15	-AS
7/14/82-12	360	Lt. Rain	68	S10-S18	38	9	
7/14/82-13	325		42	S16-S27	35	10	
7/14/82-14	145		51	S6-S22	42	20	
7/14/82-15	160		40	S8-S18	37	14	
7/14/82-16	271		29	P8-P29	18	15	
7/14/82-19	054		42	0-S22	43	20	
7/14/82-20	235		51	P3-P28	53	7	
7/14/82-21	225	Virga	50	0-S40	47	10	-AS
7/14/82-22	270	Lt. Rain	42	P5-S20	56	12	-AS
7/14/82-23	120	Lt. Rain	45	P15-0	33	8	
7/14/82-25	300		61	P6-P27	46	15	-AS
7/14/82-26	271		47	P5-P10	39	10	
7/14/82-27	180		38	0-S22	35	9	
7/14/82-28	85		50	S5-S23	57	11	-AS
7/14/82-29	271		46	P23-P6	42	20	
7/14/82-30	181		42	S7-S29	43	22	
7/14/82-31	270		51	P20-P4	38	14	
7/14/82-32	85	Lt. Rain	53	P6-P27	51	13	
7/14/82-33	271		64	P22-P5	41	5	
7/14/82-34	90		45	S6-P21	45	7	
7/14/82-37	184		15	S6-S15	42	20	-AS
7/14/82-41	270		35	0-S28	46	21	-AS
7/15/82-10	45		64	0-S11	34	12	-AS
7/15/82-11	226		14	P6-P15	22	4	
7/15/82-12	45		20	P24-P3	47	10	-AS
7/15/82-13	225		40	S36-S25	36	5	
7/15/82-14	45		48	S8-0	59	18	
7/15/82-15	272		44	P5-P31	34	10	
7/15/82-16	89		31	P22-P4	29	15	
7/15/82-17	271	Lt. Rain	58	0-S33	26	20	-AS
7/14/82-17	271	Virga	43	S5-S28	20	10	
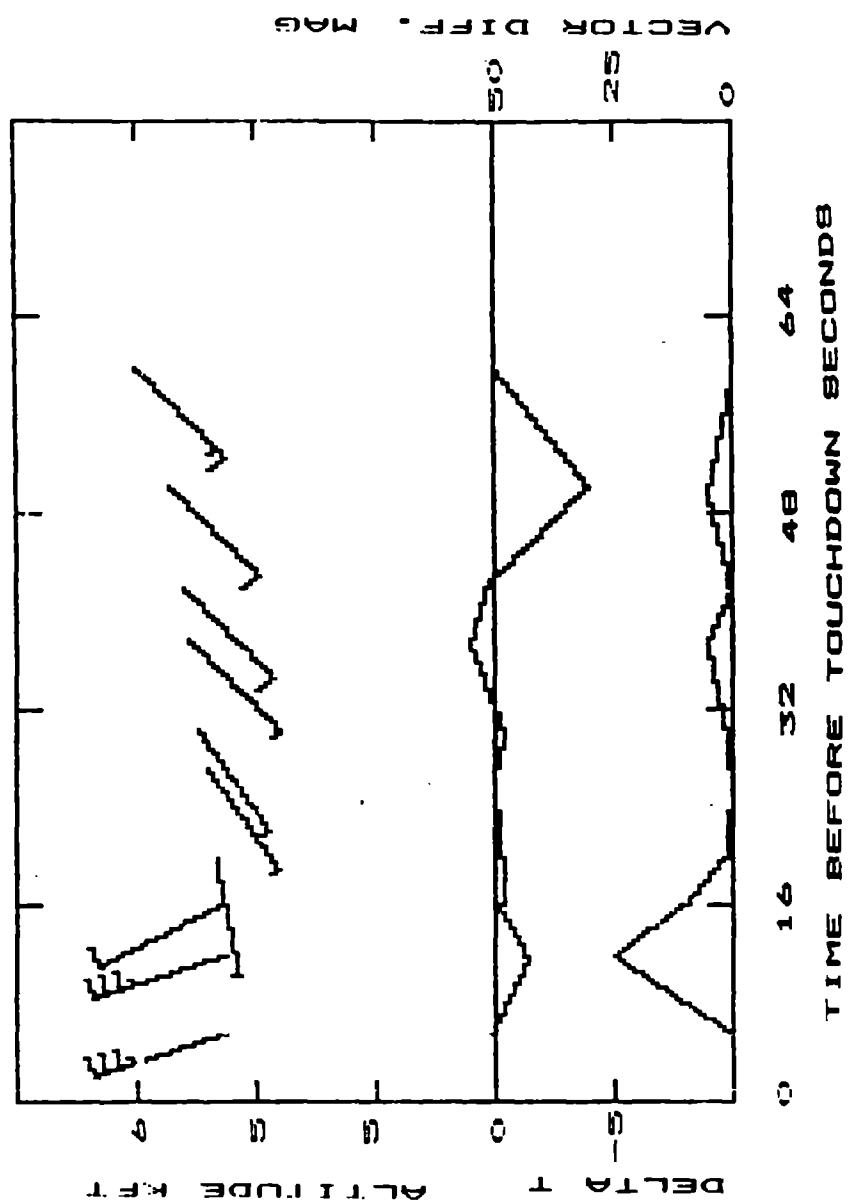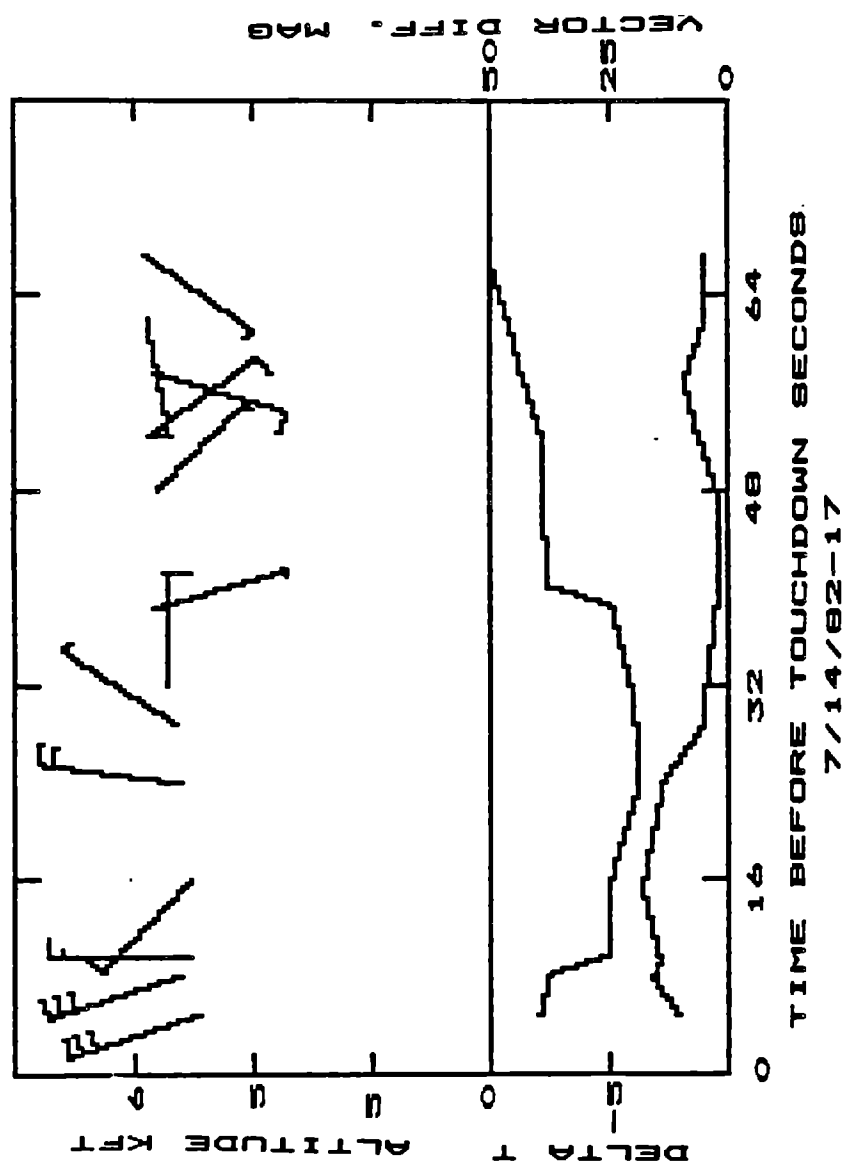
Figure 6

Figure 7

mental evidence of the relation between vertical wind shear du/dz and the temperature drop across a gust front or thunderstorm density current outflow. Figure 8 illustrates this relatinship. The vertical shear may be expressed in knots (nautical miles per hour) per 100 feet or in inverse seconds (s^{-1}). This relation may be expressed as:

$$\frac{du}{dz} \quad \frac{knots}{100\ ft} = \frac{nautical\ mi}{3600\ seconds} \times \frac{6020\ feet}{nautical\ mi} \times \frac{1}{100\ ft} = \frac{.01672}{second} \tag{4}$$

NASA JAWS Run 17 (Figure 6) is an example of an approach in light rain on track angle 271° with winds varying from 225° to 230° at 5 to 10 knots through 24 seconds prior to touchdown to 330° at 35 to 40 knots at 14 seconds before touchdown (BT). At 58 seconds before touchdown (BT) the IR radiometer sensed the threshold of 0.5C/second indicating strong cool air outflow ahead. Light rain and virga does not appear to extinguish the signal from the cool outflow ahead. The vertical shear between 18 seconds and 13 seconds BT (as the aircraft descended 100 feet) was .15 sec^{-1} or 9 knots per 100 feet. Snyder[6] has shown that vertical shears greater than 0.1 sec^{-1} are hazardous to large, swept-wing, jet aircraft. The plotted run of figure 7 exhibits similar features with a 43 second alert.

Abrupt changing cross winds nrmal to the flight approach track present problems in the flight approach runs plotted in figures 6, 9 and 11. The approaches plotted in figures 6 and 9 illustrate a shear threshold at 58 and 50 seconds before touchdown, some two to two and one-half miles at altitudes of six to seven hundred feet. The onboard radiometer system did not provide sufficient advance alert to the cross wind shear in approach 12 plotted in figure 11.

Vector difference magnitudes occurring within a 10 second interval appeared potentially hazardous in the approaches computer plotted from the
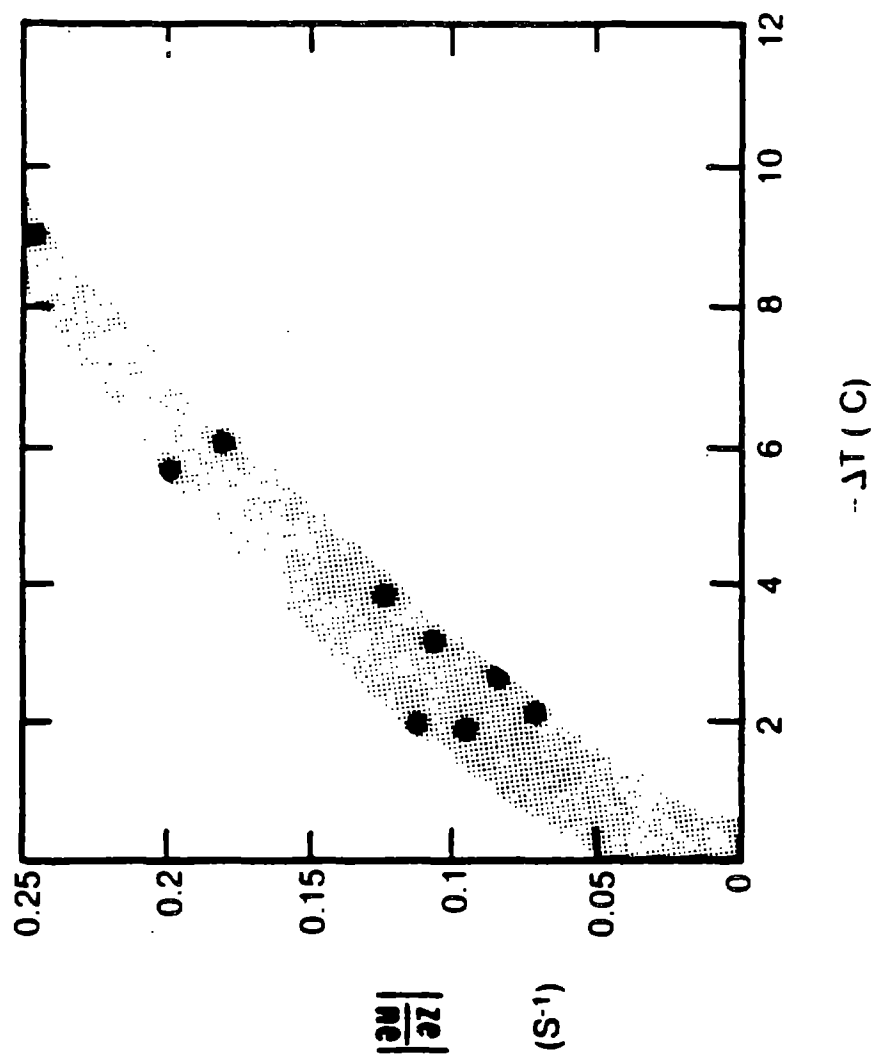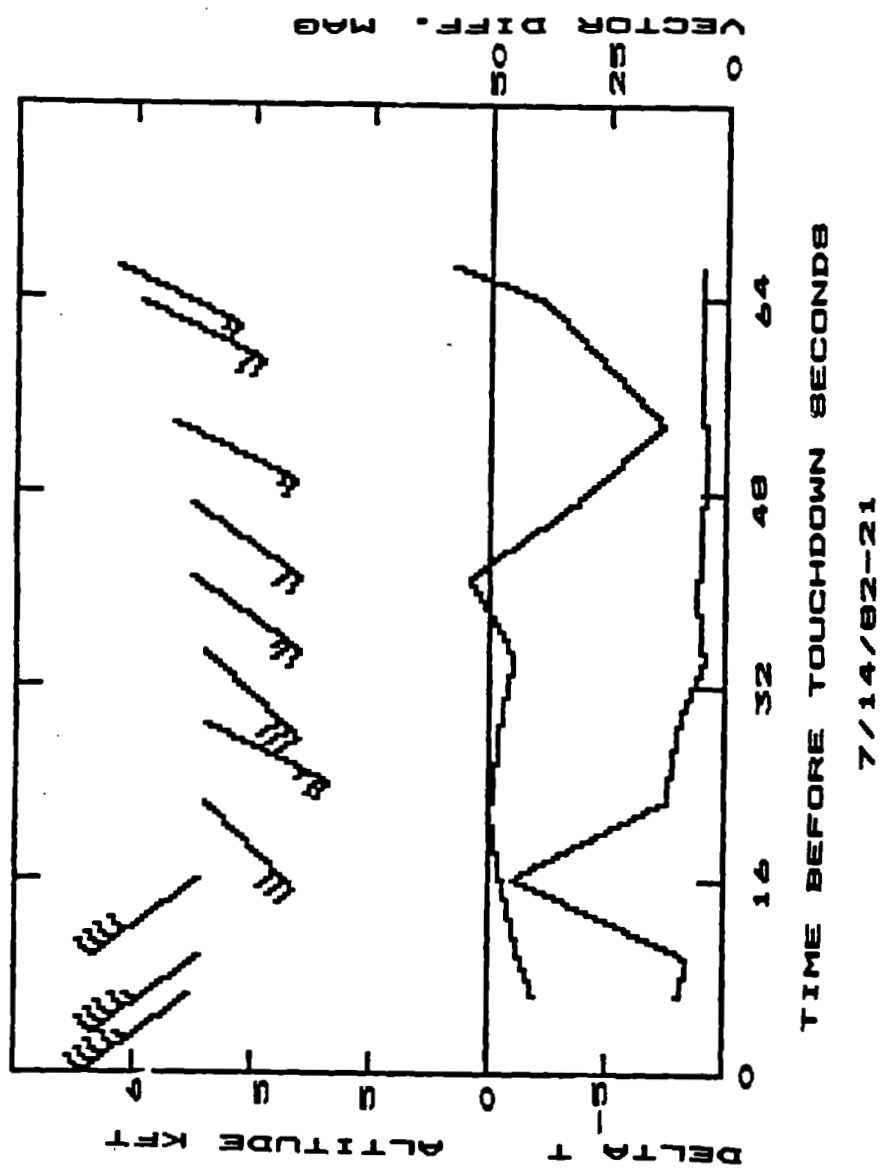
Figure 8

Figure 9

data of runs 10, 12 of 15 July 82 and 21 of 14 July 82 (Figs. 10, 11 and 9).

The vector difference magnitudes of 34 to 47 knots seemed large enough to

suggest problems. For run 12 of 15 July 1982 (Fig. 11') the radiometer system

failed to provide sufficient advance warning of the ensuing shear encounter.

A warning of 35 seconds or less was arbitrarily considered a failed alert.

However, of the six illustrated approaches into potential thunderstorm shear

conditions, the system operated successfully five times with an average

advance alert to following shear of 51 seconds before encounter. Kuhn and

Kurkowski (1984)[7] have summarized but six of 42 approaches or departures into

potential shear conditions, with five detected successfully an average of 51

seconds before encounter. In one case (Fig. 11) advance detection was not

successful. The success rate of 83% for the six events reviewed corresponds

to a success rate of 35 advance detections out of the total 42 encounters

summarized in table 1. Figure 16 summarizes the results of the 42 encounters

in a frequency histogram. Figures 13 and 14 illustrate computer generated

winds at an interval on track of 7 seconds for each of the six examples cited.

During the infrared, airborne wind shear prediction test forty-two wind

shear encounters were identified as such from the B57B aircraft data tapes and

pilot response. In all of these encounters the infrared airborne detection

system was operational. These shear encounter episodes and the frequency of

their pre-encounter detection in ten-second interval cells (detection time

before encounter) appear in Figure 15. Each histogram cell is ten seconds

wide, centered on even 10, 20, 30, 40, 50, 60 and 70 second advance detection

time. Just above the frequency graph of pre-encounter detection time is a

mean wind vector difference magnitude (in knots) plot. The right hand tick

mark on the vector difference bars is the standard deviation for the means.

For example there occurred fifteen pre-encounter detection "alerts" thirty-
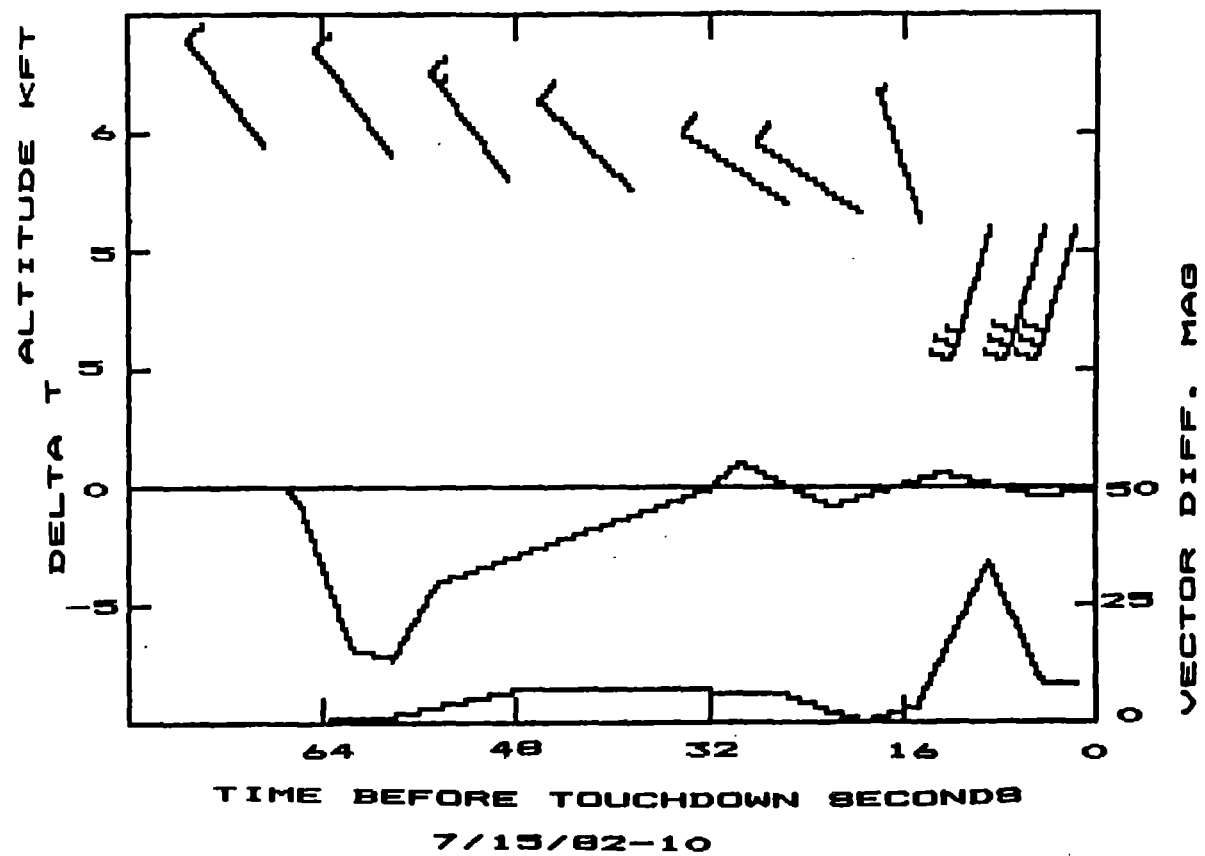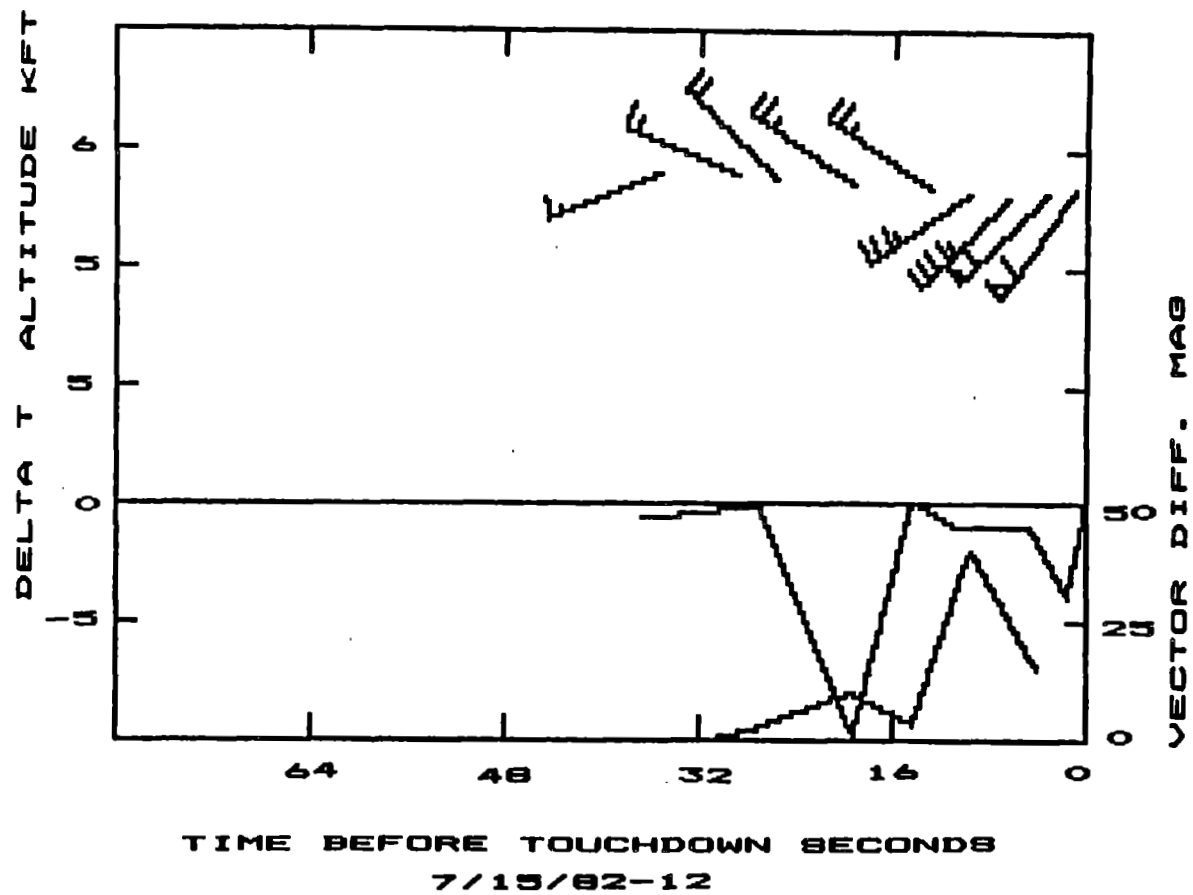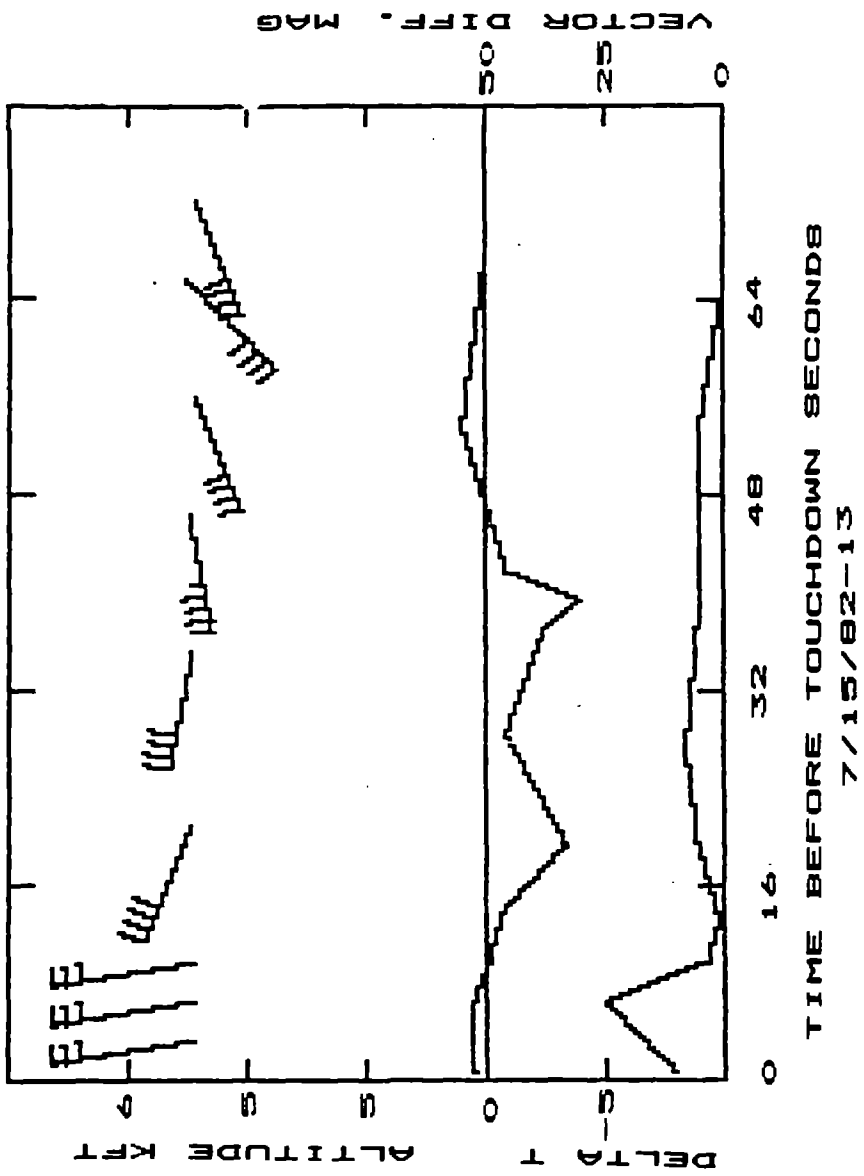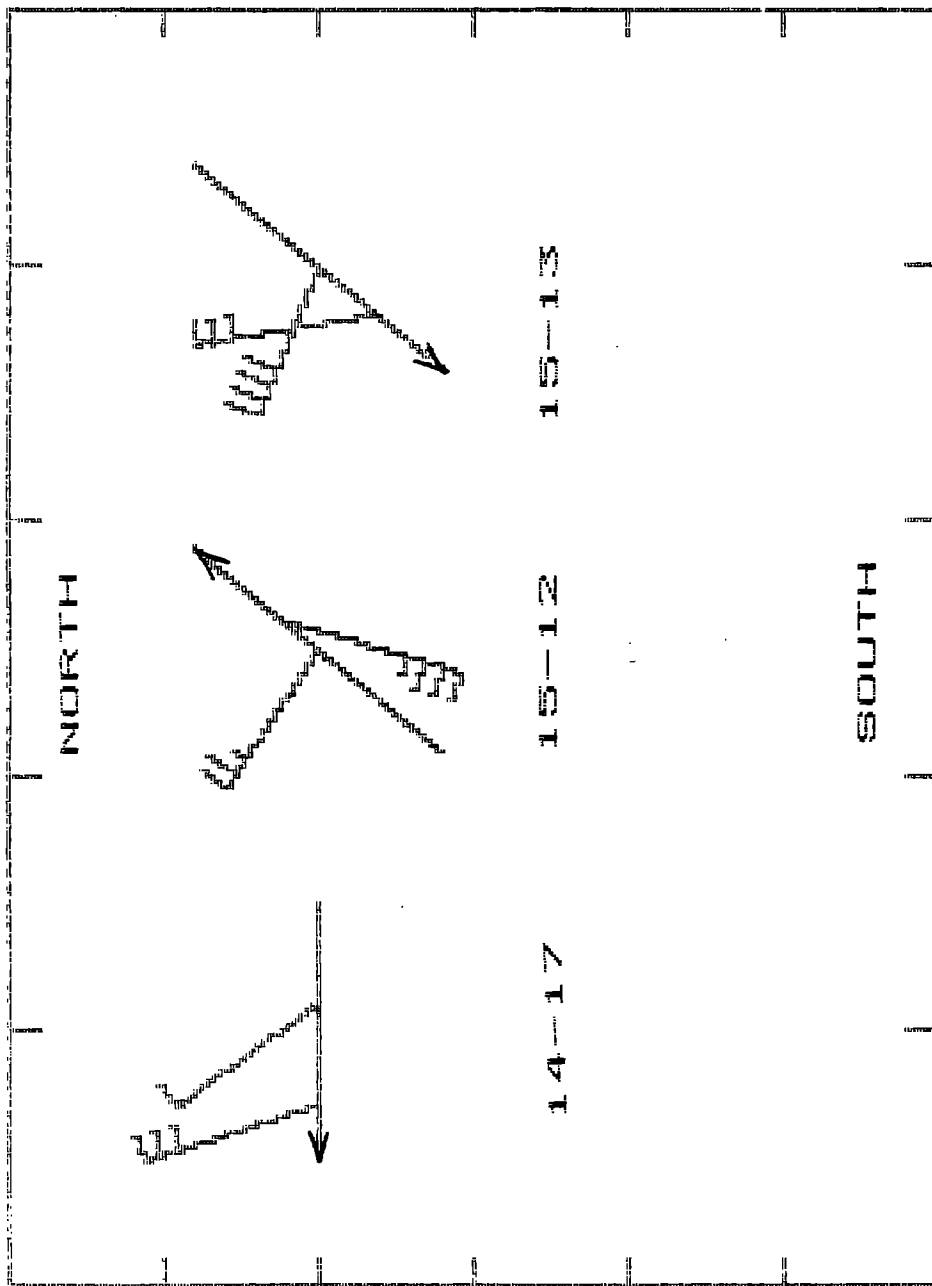
Figure 10

Figure 11

Figure 12

NORTH   SOUTH

14-17   15-12   15-13

Figure   13

Figure 14

WIND VECTOR DIFFERENCE

(KNOTS)

EVENT FREQUENCY
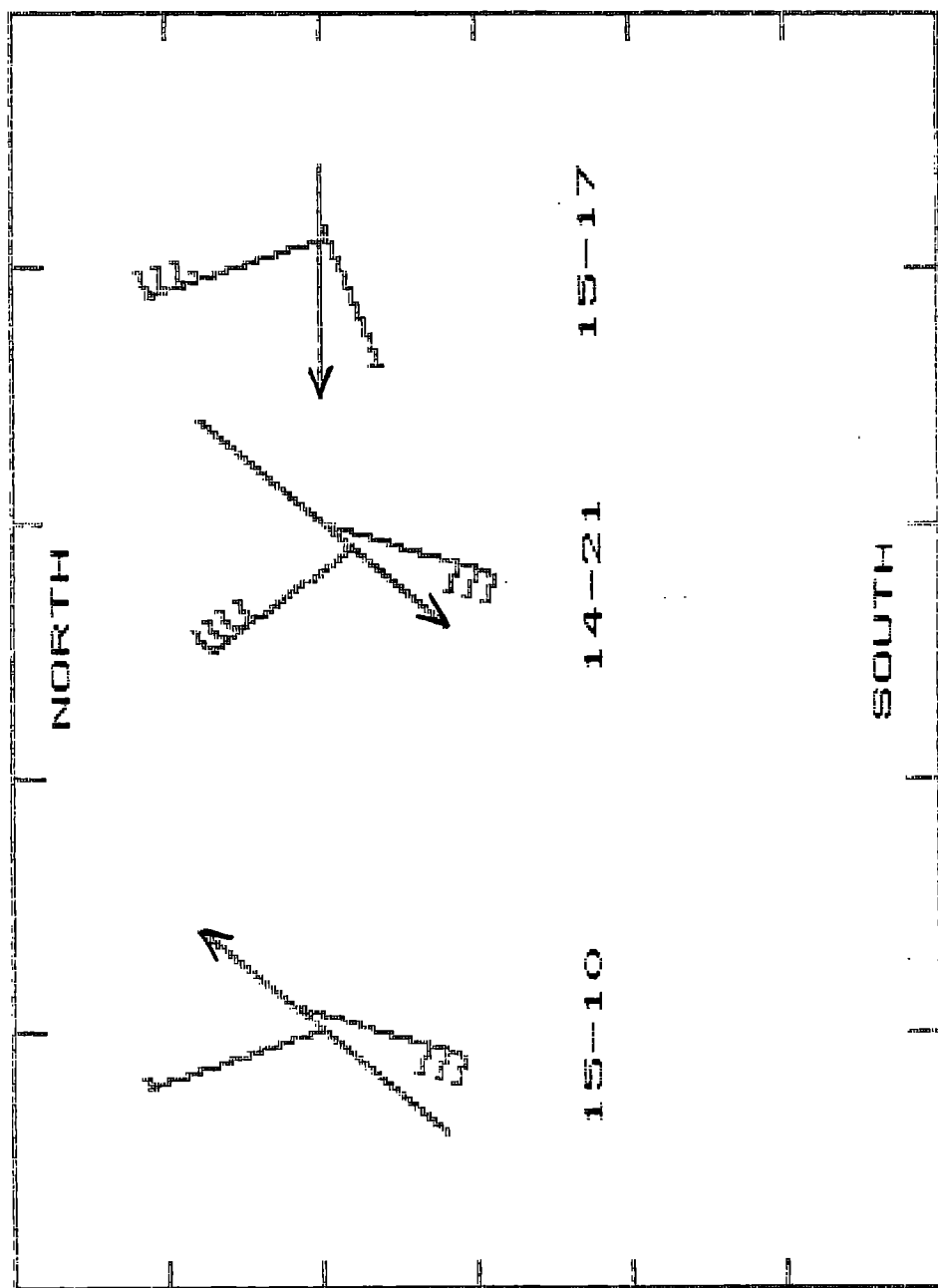
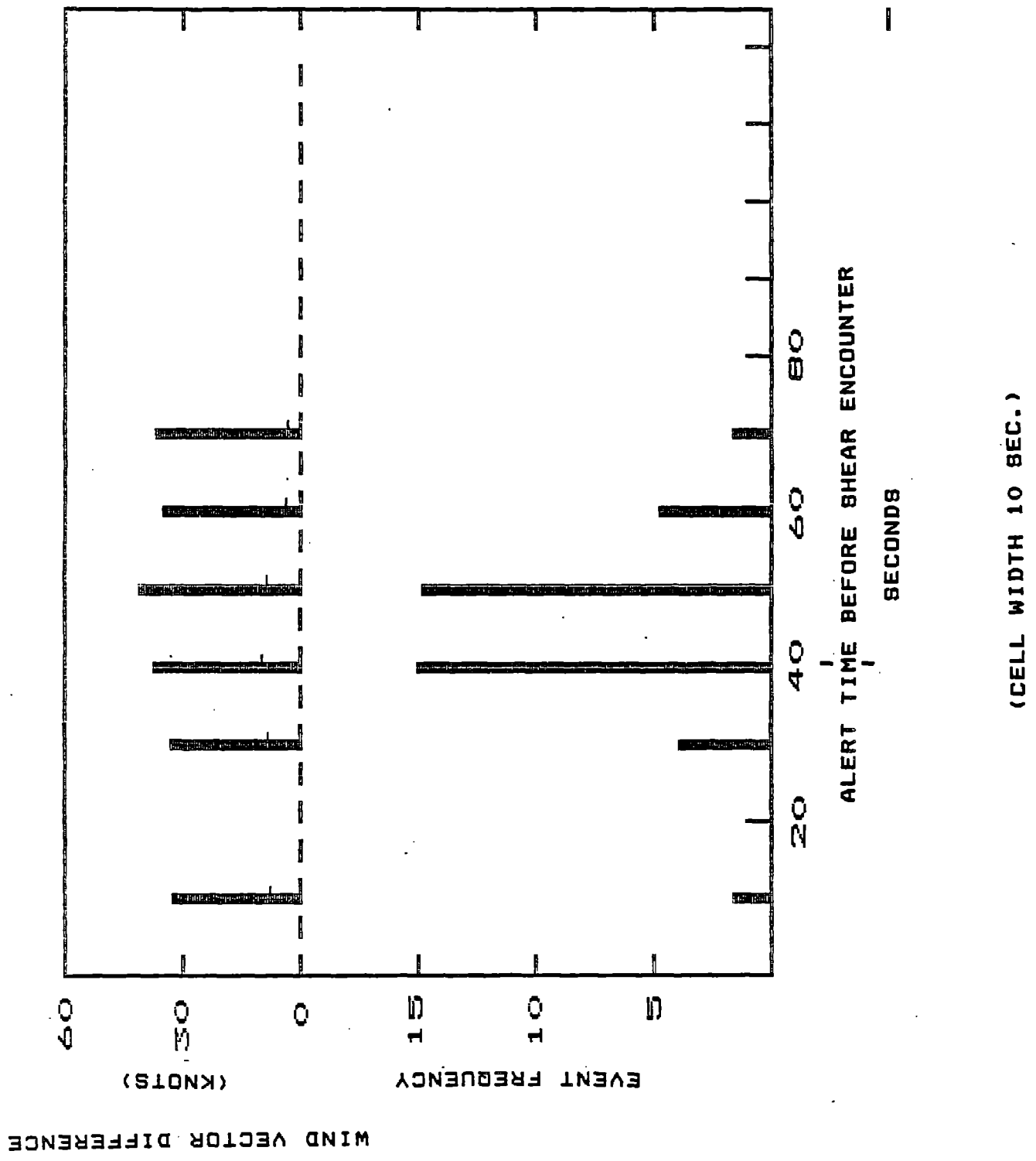ALERT TIME BEFORE SHEAR ENCOUNTER

SECONDS

(CELL WIDTH 10 SEC.)

Figure 15

five to forty-five seconds before these encounters. Of these fifteen "alerts" the subsequent shear encounters involved wind vector difference magnitudes averaging thirty-eight knots, large enough to be potentially hazardous to approach or departure operations. Reference this figure, the seven 10 and 30 second pre-encounter detections were considered failures.

7. CONCLUSIONS

The results of this airborne infrared low-level wind shear predictor system test provide an initial indication of the potential feasibility (83% success) of passive IR remote sensing of horizontal temperature gradients associated with shear producing gust fronts or thunderstorm density currents. During approach to touchdown alert times averaging 51 seconds correspond to approximately two miles out from touchdown and should thus provide sufficient time for a "go around" decision. The shear index $(\Delta T/\Delta t)$, determined with a limited amount of sample data, is evidently related to the vertical shear, du/dz, the vector different magnitude and cross wind shear. The effects of "looking" through light rain or virga do not appear to pose a problem and are being studied further. Weighting function changes via different IR filters, ranging and azimuthal scanning can add to the potential usefulness of this passive IR airborne shear predictor system by providing increased range and avoidance possibilities.

When considering this infrared, airborne shear detection system one should note that it was only the second airborne test of the concept, the first of which aboard the NASA Ames Lear 25 operated on the cool sea breeze in the Bay Area to simulate gust fronts. The second test with the NASA B57B during JAWS at Denver in 1982 was carried out on a modest budget with refurbished (15 year old) radiometers and but one available infrared filter limiting the forward shear alert time to a maximum of 50 to 60 seconds or approximately 2.0 to 2.5 miles out. This would correspond roughly to an approach altitude at alert of 600 to 700 feet during a 12 foot per second descent rate.

These comments are not meant to denigrate in any way the NASA support received as this was an initial test. It is, however, strongly believed by

the writer and several others, in particular Dr. Fernando Caracena, a theoretician of the NOAA Boulder Laboratories experienced in the analysis and physical interpretation of wind shear, that further experimentation and testing could produce dramatic results employing this concept. Twelve months of research with current radiometric equipment and a selection of three or four infrared optical filters could determine, finally, the systems value in the airborne detection before encounter, ranging and scan avoidance of hazardous gust front wind shear and even imbeded "downbursts." The employment of a cost effective, meteorologically instrumented, available light aircraft would greatly reduce the cost of a final test flight series.

8. ACKNOWLEDGEMENTS

The successful conduct of this research effort required the efforts of many individuals from both NASA Ames Research Center, Dryden Flight Research Facility and the George C. Marshall Space Flight Center. We are indebted to L. J. Ehrenberger, lead meteorologist for the research and W. D. Painter, mission manager. NASA Dryden test pilots F. L. Fulton and D. L. Mallick assisted by NASA pilots V. W. Horton and R. Young provided totally successful flight operations for the experiment. M. R. Bohn-Meyer capably engineered the infrared instrumentation aircraft installation and J. A. Duffield provided the needed electronic support for the system. R. L. White and E. J. Nice kept the NASA B57B flying for the entire experiment. Sincerest thanks are extended to all these excellent researchers.

9. COMPUTER ALGORITHMS

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]LIST

10  REM   ROUTINE TO PLOT WIND      VECTORS                  NOTE: NO ER
    ROR CHECKING IS PRESENT
15  REM   THIS PROGRAM MUST BE RUN IN 40 COLUMN MODE, ONLY!!!!
16  REM   THIS VERSION IS THAT OF 29 SEPTEMBER 1983
17  REM   THIS VERSION INCLUDES A TECHNIQUE TO ELIMINATE VECTORS TOO NEAR
18  REM   THE TOP OF GRAPH CAUSING ILLEGAL QUANTITY IN 180 OR USING ONERR
19  REM   THIS IS DONE BY COMPUTING A Y ORDINATE & RELATING TO GRAPH TOP
20  REM
INITIALIZATION


21  REM   NOTE WHICH PLTFRM IS STORED
30  ONERR  GOTO 50
40  HGR : HCOLOR= 3
41  HOME
45  PRINT  CHR$ (4)"BLOAD PLTFRM I"
49  VTAB 22
50  INPUT DE,I,J,VE
55  IF DE < 270. AND DE > 0. GOTO 63
57  ALPHA = DE - 270.
58  ANS = 30. *  SIN (ALPHA * .0174533):ANSS = J - ANS
59  IF ANSS <  = 0. GOTO 50
61  GOTO 80
63  IF DE > 90. AND DE < 270. GOTO 80
65  ALPHA = 90. - DE
67  ANSI = 30. *  SIN (ALPHA * .0174533):ANSSI = J - ANSI
68  IF ANSSI <  = 0. GOTO 50
80  GOSUB 100: CLEAR : GOTO 50
100 PI = 3.13149:F = 1:R = 30:N = 36
110 INC = (2 * PI) / N
111  REM   F= FUDGE FACTOR FOR CORRECTING TENDENCY OF CIRCLE TO BE OVAL SHA
    PED
112  REM   R= RADIUS OF CIRCLE WHICH IS LENGTH OF WIND VECTOR
113  REM   N=NUMBER OF SIDES OF POLYGON WHICH ARE PLOTTED AND CORRESPONDS T
    O NUMBER OF DEGREES BETWEEN ARROWS (360/36= 10 DEGREE INCREMENTS)
120 DE = DE / 5:DE =  INT ((DE + .5) / 1) * 1:DE = DE / 2: IF DE * 5 <  >
     INT (DE * 5) THEN DE = DE + .5
130  FOR T = 0 TO 2 * PI + .01 STEP INC
140  IF FLAG THEN L = R *  SIN (T):M = R *  COS (T) / F:FLAG = 0: GOTO 130

150 KK = KK + 1: IF KK <  > DE + 1 THEN  NEXT T
160 X = R *  SIN (T):Y = R *  COS (T) / F
170 FLAG = 1: NEXT T
180  HPLOT I,J TO I + X,J - Y
190 L1 = X - L:M1 = Y - M
200 T = T - INC
210 VE = VE / 5:VE =  INT ((VE + .5) / 1) * 1:VE = VE / 2
220  IF VE * 5 <  >  INT (VE * 5) THEN NF = 1
230 ST = 30
240  IF VE < 1 THEN NU = 30:NF = 1: GOTO 380
250  IF VE >  = 5 THEN TF = TF + 1:VE = VE - 5: GOTO 250
260  IF  NOT TF THEN 340
270 R = 33
280  FOR RE = 1 TO TF
```

```
290 R = R - 3:X = R * SIN (T):Y = R * COS (T) / F: HPLOT I + X,J - Y TO
    I + X - L1,J - (Y - M1):X2 = X:Y2 = Y
300 R = R - 3:X = R * SIN (T):Y = R * COS (T) / F: HPLOT I + X,J - Y TO
    I + X2 - L1,J - (Y2 - M1)
310  NEXT RE
320 ST = R - 3:NU = ST
330  IF VE < 1 THEN 380
340  FOR NU = ST TO (ST + 3) - (VE * 3) STEP  - 3
350 R = NU
360 X = R * SIN (T):Y = R * COS (T) / F: HPLOT I + X,J - Y TO I + X - L1
    ,J - (Y - M1)
370  NEXT NU
380  IF NF THEN R = NU:X = R * SIN (T):Y = R * COS (T) / F: HPLOT I + X,
    J - Y TO I + X - (L1 / 2),J - (Y - (M1 / 2))
390  RETURN
500  GOTO 50
```

```
]LIST

4  REM  ROUTINE5
5  REM  THIS PROGRAM IS SIMILAR TO ROUTINE4 EXCEPT THAT THE Y, DELTA T DAT
      A IS CALCULATED SO THAT NEGATIVE DELTA T APPEARSBELOW THE LINE INDICA
      TING A COLDER TEMPERATURE.
6  REM  PLOTTER
10  INPUT X1,Y1
11 X1 = X1 * 3.125
20 Y1 = 100 + (5 * Y1)
21  INPUT X2,Y2
22 Y2 = 100 + (5 * Y2)
23 X2 = X2 * 3.125
45  HPLOT X1,Y1 TO X2,Y2
47 X1 = X2
49 Y1 = Y2
51  GOTO 21
```

```
]

]LIST

370  REM  "POLY PLOT" PROGRAM
380  TEXT
390  INPUT A0,A1,A2
420  HCOLOR= 3
430  HGR
500 XOLD = 6.
520 XMOVE = 2.
525  FOR I = 1 TO 100
530 XOLD = XOLD + XMOVE
540 YOLD = A0 + A1 * XOLD + A2 * XOLD ^ 2.
542 YOLD = YOLD * 3.
543 XOLD = XOLD * 2.3
545  IF YOLD < 0. GOTO 590
546  IF I = 1 THEN  HPLOT XOLD,YOLD
547  PRINT XOLD,YOLD
550  HPLOT  TO XOLD,YOLD
560 XOLD = XOLD / 2.3
580  NEXT I
590  STOP



]LIST

4  REM   ROUTINE 4
5  REM    THIS IS THE ROUTINE TO PLOT TIME VS GRAVITY UNITS
6  REM  PLOTTER
10  INPUT X1,Y1
11 X1 = X1 * 3.125
20 Y1 = 100 - (Y1 * 25)
21  INPUT X2,Y2
22 Y2 = 100 - (Y2 * 25)
23 X2 = X2 * 3.125
45  HPLOT X1,Y1 TO X2,Y2
47 X1 = X2
49 Y1 = Y2
51  GOTO 21
```

10. REFERENCES

[1]Kuhn, P. M., Kurkowski, R. L., and Caracena, F., "Airborne Operation of an Infrared Low-level Wind Shear Prediction System," _J. of Aircraft,_ Vol. 20, 1983, pp. 170-173.

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[6]Snyder, C. T., "Analogue Study of Longitudinal Response to Wind Shear and Sustained Gusts During Landing Approach," NASA TN D-4447, NASA Ames Research Center, Moffett Field, California 94035, 1968.

[7]Kuhn, P. M., and R. L. Kurkowski, "Airborne Infrared Low-Altitude Wind Shear Detection Test," _J. of Aircraft,_ Vol. 21, 1984, pp. 792-796.

11. FIGURE CAPTIONS

Fig. 1   NASA Ames Research Center Learjet with infrared low level wind shear system window about nose.

Fig. 2   NASA Ames Research Center - Dryden Flight Research Facility B57B airborne laboratory.

Fig. 3   NASA B57B low level wind shear detection system probe beneath wing on starboard side of hull.

Fig. 4   Airborne infrared scanning and ranging concept.

Fig. 5   Temperature change across gust front vs. peak gust of front.

Fig. 6   Computer reproduction of B57B approach on track angle 271°. Right ordinate is wind vector difference magnitude in knots; abscissa is seconds before touchdown; left lower ordinate is T(°C); left upper ordinate is altitude in kilofeet. See text for explanation of curves. Flight 7/15/82-17

Fig. 7   Computer reproduction of B57B approach on track angle 271°. All labels as in Fig. 6   Flight 7/14/82-17

Fig. 8 $\Delta u/\Delta z$ vs. temperature drop in thunderstorm.

Fig. 9   Computer reproduction of B57B approach on track angle 225°. All labels as in Fig. 6   Flight 7/14/82-21

Fig. 10   Computer reproduction of B57B approach on track angle 45°. All labels as in Fig. 6   Flight 7/15/82-10

Fig. 11   Computer reproduction of B57B approach on track angle 45°. All labels as in Fig. 6   Flight 7/15/82-12

Fig. 12   Computer reproduction of B57B approach on track angle 225°. All labels as in Fig. 6   Flight 7/15/82-12

Airborne Infrared Low-Altitude Wind Shear Detection Test

P.M. Kuhn and R.L. Kurkowski

Airborne Infrared Low-Altitude Wind Shear Detection Test

Peter M. Kuhn* and Richard L. Kurkowski†

NASA Ames Research Center, Moffett Field, California

Strong wind shears at low altitudes present severe hazards to aircraft during landing approach and takeoff. With aircraft operating near stall speed, a significant change in the wind speed and/or direction can result in a rapid loss or gain in altitude. Our objective is to describe the test of a prototype system for airborne, advance detection of such wind shear by means of infrared remote sensing. The test was conducted during the Denver Joint Airport Weather Studies (JAWS) project in the summer of 1982 aboard the NASA Ames B57B jet aircraft during several landing approaches and departures. The intent is to present analyses of the major results of this test and suggest its application to the passive, airborne detection of hazardous low-altitude wind shear (LAWS) before an aircraft encounter. This is critical for aircraft operating in an out of airfields without LAWS ground warning systems. This airborne wind shear detection and avoidance system is intended to augment the advanced, ground-based microwave, lidar, and low-altitude wind shear alert equipment as a secondary, airborne system. Even at distances as great as 12.5 miles (20 km) from thunderstorms, the wind shear in storm density currents can pose a real hazard to approaching and departing aircraft. It is concluded that the prototype airborne radiometer, observing in the 13 to 16 μm portion of the atmospheric molecular spectrum of CO_2, can sense the cold current outflow or gust front directly associated with low-altitude wind shear (LAWS) in the vicinity of thunderstorms at ranges up to 4 miles.

Nomenclature

cm	= wavelength
Cp	= specific heat at constant pressure, $m^2 s^{-2} K^{-1}$
du/dz	= vertical shear, s^{-1} or knots/100 ft
g	= gravitational acceleration, ms^{-2}
K	= temperature, K
k	= CO_2 absorption coefficient, $cm^2 g^{-1}$
N,B	= radiance, $w cm^{-2} sr^{-1}$
P	= pressure, $g cm^{-1} s^{-1}$
q	= mass mixing ratio of CO_2, $g g^{-1}$
R	= gas constant, $2.87 \times 10^6 cm^2 s^{-2} K^{-1}$
T	= temperature, °C
u	= optical thickness of CO_2 gas ($g cm^{-2}$), qP/RTx
x	= horizontal distance, cm
z	= vertical distance, m
$\Delta T/\Delta \tau$	= forward-looking infrared air temperature minus static air temperature at aircraft, °C s^{-1}
$\Delta \nu$	= optical filter bandwidth, cm^{-1}
θ	= potential temperature (K), $T + gz/Cp$
ν	= wave number, cm^{-1}
ρ	= air density, $g cm^{-3}$, P/RT
τ	= CO_2 transmission, %
$o(\nu)$	= radiometer filter transmission, %

Introduction

THE physical basis for the infrared (IR) temperature sensing wind shear predictor system is the demonstrated relationship between the temperature gradient from undisturbed air across a shear-producing gust front or downburst outflow and the wind speed and direction of the gust front outflow wind. The higher temperature gradients produce higher wind shear or peak gusts. Fawbush and Miller[1] provided a physical basis for predicting peak gusts caused by thunderstorm density currents. Temperature drops of 5°C may readily produce peak gusts of 35 mph while those

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*Senior Research Scientist, Northrop Services Inc. Member AIAA.
†Research Scientist. Member AIAA.

of 15°C produce peak gusts of 80 mph (Fig. 1). The IR radiometer senses the cold outflow of the gust front downdraft well before the aircraft encounters the region. The precision of the IR radiometer is ±0.5 C/s allowing for consecutive observations sampled at a 0.5 Hz rate to vary by only ±0.5°C. Signal integration will, of course, provide a standard error as low as ±0.1°C. Shear alerts occur when a defined temperature difference between this "forward" IR air temperature and the ambient air temperature at the aircraft, defined as a threshold criterion of −0.5 C/s is reached or exceeded. Alternatively the "forward" air temperature may be converted to potential temperature, θ, which is essentially constant during landing and takeoff in a neutrally stratified atmospheric layer. If negative anomalies exist in the profile of θ which exceed a defined value, these can also be the basis of LAWS alerts aboard the aircraft. The "forward" air temperature minus the "near" air temperature at the aircraft provides a temperature difference change per second $\Delta T/\Delta t$. This change is then compared with the shear test criterion to initiate a shear warning if warranted (Fig. 2). The criterion to warn of potential shear is a 0.5 C/s or greater temperature change. As the temperature difference per second increases, the algorithm applied to the radiometer output predicts gust front shear also to increase. The operation of a similar IR airborne system has been described by Kuhn et al.[2]

In a horizontally uniform temperature field both the near filter channel of the radiometer or the static air temperature measured at the aircraft and the forward, long-range sensing filter channel of the radiometer sense the same temperature. As a cool outflow gust front is approached, the long-range channel begins to sense a cooler temperature well before the aircraft reaches the gust front, and the near channel senses the warmer static temperature at the aircraft until the cool downdraft or gust front is penetrated. At this point, both radiometers sense the same temperature for a period of time. No alert for LAWS is produced until the temperature difference between the forward-sensed temperature and the aircraft temperature reaches the predetermined negative threshold.

Radiation Physics

The width of the IR radiometer filter pass band, $\delta \nu$, is an important consideration in designing the optics of the IR

LAWS radiometer.[3] Theoretical considerations show that narrow pass bands give the best spatial discrimination of thermal perturbations, while broad pass bands produce the strongest corresponding perturbation signal in the radiometer output.

Radiation in the atmospheric molecular spectrum of carbon dioxide reaching the radiometer optics may be expressed as

$$N = -\int_\nu \int_x B(\nu,T)\phi(\nu)\left(\frac{\partial\tau(u[CO_2])}{\partial x}\right)dx d\nu \qquad (1)$$

In Eq. (1) the horizontal transmission may be expressed as

$$\tau_{\Delta\nu} = \exp(-k_{\Delta\nu}q\rho x) \qquad (2)$$

where the product $q\rho$ is the density of carbon dioxide gas. The horizontal "look distance" or weighting function distance in Eq. (1) is given by $\partial\tau/\partial x$ as a function of the horizontal path distance x. Equation (2) may be differentiated with respect to distance x to give

$$\frac{d\tau_{\Delta\nu}}{d\ell nx} = -k_{\Delta\nu}q\rho\tau x \qquad (3)$$

An evaluation of Eq. (3) as a function of various horizontal distances x an altitudes (33-490 m) over various pass bands at 10-cm[-1] intervals in the 600 to 710 cm^{-1} portion of the CO_2 spectrum resulted in the best weighting function or look distance centered at 695 cm^{-1} providing a horizontal look distance of 2.9 miles (5 km). This would give approximately 70 s of warning time to shear encounter.
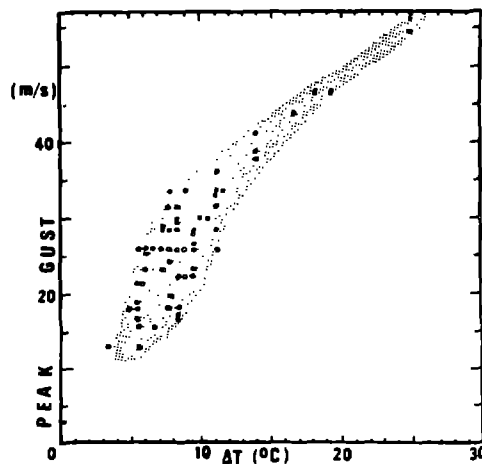
Data Acquisition and Processing

The NASA Dryden B57B aircraft was the landing approach platform for the IR LAWS sensor system during JAWS.[4] This fully instrumented gust gradient aircraft, carrying an elaborate data acquisition system and the IR sensor, among many other instruments, provided time, latitude, longitude, track angle, heading, altitude, static air temperature, E-W wind speed, N-S wind speed, and airspeed for the airborne IR study. The IR LAWS optics appears in Fig. 3 as the probe just off an instrument access hatch on the starboard side, forward of the wing root section. Adjustable optics allow for horizontal leveling of the "look" angle.

Data tapes were processed via a Cyber 150-700 and Apple II Plus to obtain the final high-resolution graphic plots that appear in Figs. 4-9. Algorithms to compute all the approach data for the wind speed and direction arrows, altitude, vector differences magnitude, ΔT threshold, cross wind to aircraft track component, vertical shear, and aircraft horizontal and vertical position enabled the figures to be computer-generated via appropriate algorithms directly from original NASA tapes.

Fig. 3 Installation of infrared low-altitude wind shear probe on NASA B57B.

Fig. 1 Outflow peak gust vs temperature drop in thunderstorm.

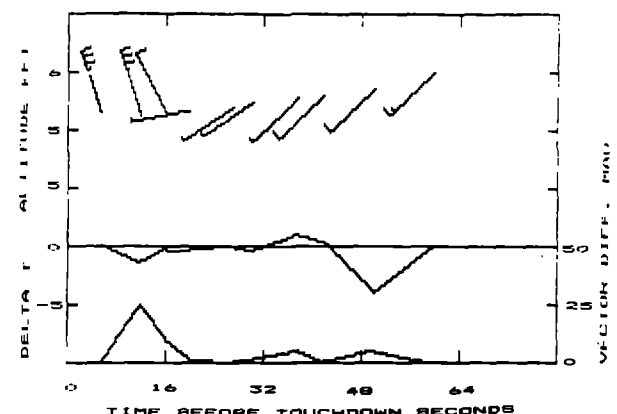Fig. 2 Airborne infrared low-altitude wind shear detection system.

Fig. 4 Computer reproduction of B57B approach on track angle 271 deg. Right ordinate is wind vector difference magnitude in knots; abscissa in seconds before touchdown; left lower ordinate is $T(°C)$; left upper ordinate is altitude in kilofeet. See text for explanation of curves. Flight 7/15/82-17.

Listed below is the information given by each flight track figure:

1) The date and run number are shown.

2) The time before touchdown is given in seconds as abscissa.

3) The lower left ordinate is ΔT in °C (shear alert threshold).

4) The upper left ordinate is altitude in kilofeet.

5) The right ordinate is the vector difference magnitude in knots.

6) The lowest computer-plotted curve is the vector difference magnitude.

7) The middle computer plotted curve is ΔT(°C) (shear threshold) tracing about zero. Negative ΔT defines a colder forward temperature.

8) The top side of the figure is north with the other directions as on any map. Thus, a landing approach at 270 would be depicted from right (east) to left (west).

9) The top computer plotted curve is flight approach track with wind arrow flying into the curve. For example, a north wind comes from the top of the figure into curve while an east wind comes from the right margin into curve. Wind speeds and direction are standard meteorological station plots.

Each full feather or barb denotes a speed of 10 knots, a half barb denotes a speed of 5 knots, and an open triangular feather 50 knots.

Recall that ΔT is defined as the forward air temperature minus the aircraft ambient temperature. From this $\Delta T/\Delta t$ (C/s) is readily determined and compared with the shear-alert threshold of 0.5 C/s. Postflight analyses as in this test will be replaced by microprocessor-driven, alerting displays.

Shear Detection Measurements During JAWS

As a prologue to the discussion of the remote measurements and their meaning during the JAWS project,[4] it should be

mentioned that three observed phenomena resulting from wind shear (all or any of which can impair aircraft operations) that are considered in each flight sequence are 1) vertical shear, 2) vector-difference magnitude, and 3) aircraft cross-wind component. This summary considers these meteorological phenomena that can be hazardous to aircraft operations. This low-altitude wind shear detection test offers advance determination of dangerous atmospheric conditions into which an aircraft may proceed.

Figures 4-9 graphically illustrate six NASA B57B approaches into shear conditions at Stapelton International Airport and the JAWS network in and near Denver in July 1982. Table 1 and the figures (with standard aeronautical and meteorological symbols and nomenclature) summarize the
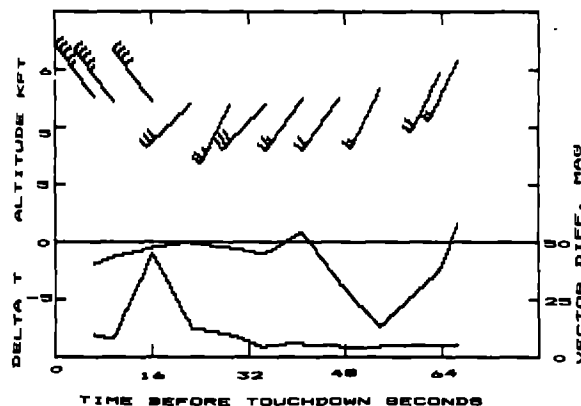

Fig. 6   Computer reproduction of B57B approach on track angle 225 deg; all labels as in Fig. 4; Flight 7/14/82-21.
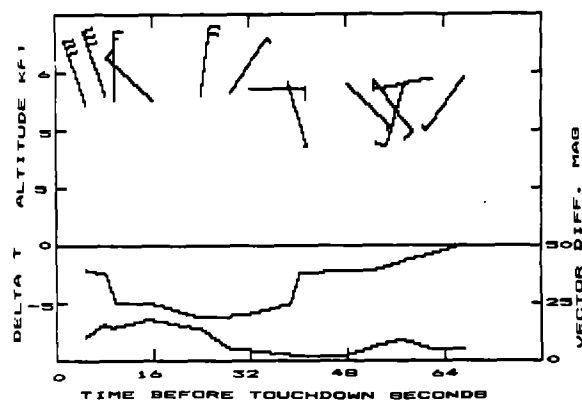

Fig. 5   Computer reproduction of B57B approach on track angle 271 deg; all labels as in Fig. 4; Flight 7/14/82-17.
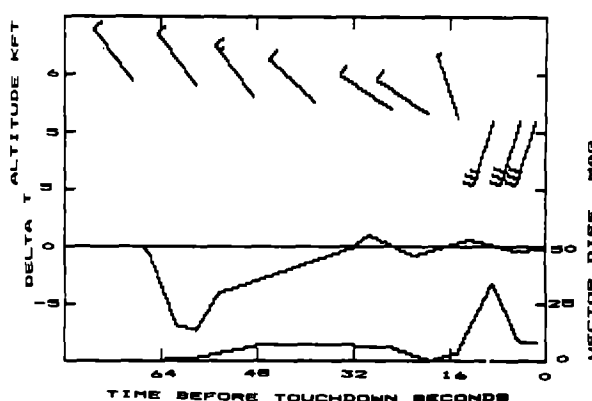

Fig. 7   Computer reproduction of B57B approach on track angle 45 deg; all labels as in Fig. 4; Flight 7/15/82-10.

Table 1   Summary analyses of airborne radiometric shear alert episodes with subsequent approach conditions encountered

Figure	Date/Run No.	Aircraft track angle, deg	Weather	Time that measured shear threshold occurs, s[a]	Crosswind component, knots[b]	Vector difference magnitude, knots[c]	Vertical shear du/dz, s[-1] & knots/100 ft
4	7/15/82-17	271	Light rain	t − 58	0-S33	26	0.33 20 − AS[d]
5	7/14/82-17	271	Virga[e]	t − 43	S15-S28	20	0.16 10
6	7/14/82-21	225	Virga	t − 50	0-S40	47	0.16 10 − AS
7	7/15/82-10	45	—	t − 64	0-S11	34	0.20 12 − AS
8	7/15/82-12	45	—	t − 20	P24-P3	47	0.16 10 − AS
9	7/15/82-13	225	—	t − 40	S36-S25	36	0.08 5

[a] t minus seconds refers to time before touchdown. [b] S or P designates a starboard or port component [c] Vector difference magnitude is computed over a 10-s interval. [d] − AS indicates airspeed loss of 30 or more knots. [e] Falling trails of precipitation.

analyses. A reference to the preceding section for the figure explanation is suggested.

In column 5 of Table 1, the radiometric advance alert during descent along the glide path is given as "*t*" minus some number of seconds. This is the time in seconds before touchdown, or simulated touchdown. Vertical shear, du/dz, columns eight and nine of the table, is given in units of sec^{-1} and knots per 100 meters. " – AS" indicates a loss of airspeed exceeding 30 knots.

Two of the flight approaches, runs 17 of the 14th and 15th of July 1982 (Figs. 4 and 5), for NASA B575B, on approach into Stapleton International during JAWS illustrate encounters with strong vertical shear, du/dz, in the lower 100 m (503 ft) and the operation of the airborne IR LAWS instrument system preceding the encounter. Hall et al[5] have provided experimental evidence of the relation between vertical wind shear du/dz and the temperature drop across a gust front or thunderstorm density current outflow. Figure 10 illustrates this relationship. The vertical shear may be expressed in knots (n. m./h) per ft or in inverse seconds (s^{-1}). This relation may be expressed as:

$$\frac{du}{dz} = \left(\frac{knots}{100\,ft}\right) = \frac{n.\,mi.}{3600\,s}\frac{6020\,ft}{n.\,mi.}\frac{1}{100\,ft} = \frac{0.01672}{s} \quad (4)$$

NASA JAWS Run 17 (Fig. 4) is an approach in light rain on track, angle 271 deg with winds varying from 225 to 230 deg at 5 to 10 knots through 24 s prior to touchdown to 330 deg at 35 to 40 knots at 14 s before touchdown (BT). From the figure
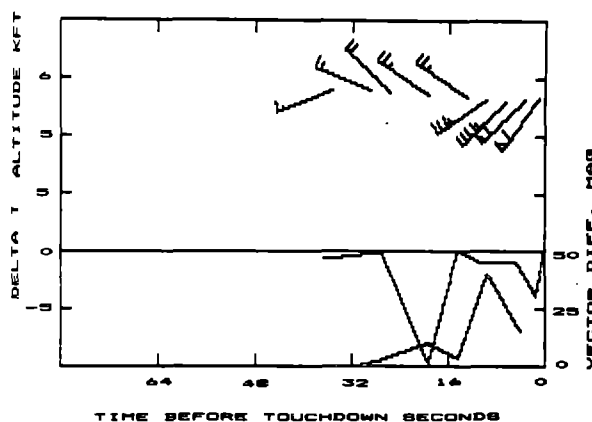

Fig. 8 Computer reproduction of B57B approach on track angle 225 deg; all labels as in Fig. 4; Flight 7/15/82-13.
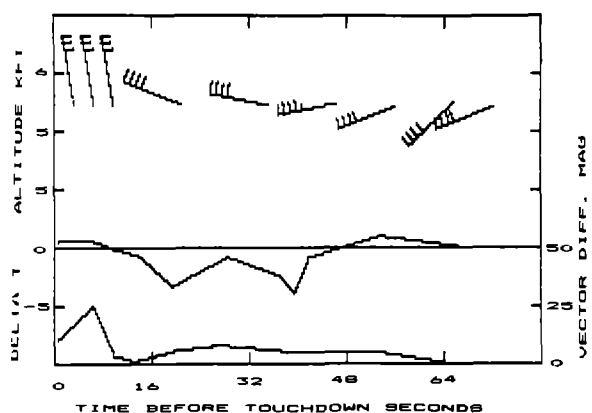

Fig. 9 Computer reproduction of B57B approach on track angle 225 deg; all labels as in Fig. 4; Flight 7/15/82-13.
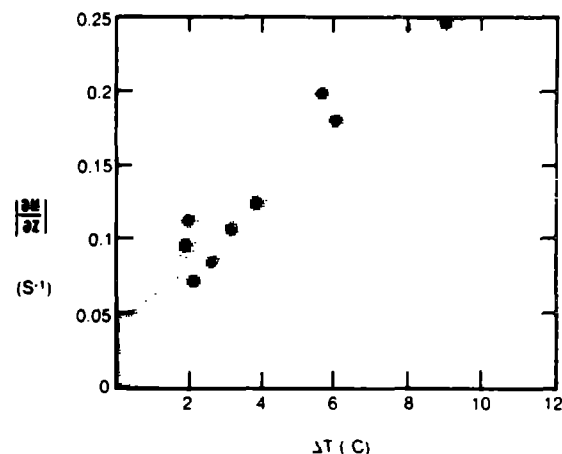

Fig. 10 Thunderstorm vertical shear (s^{-1}) vs drop in temperature across gust front.

it is clear that at 58 s before touchdown (BT) the IR radiometer sensed the threshold of 0.5 C/s, indicating strong cool air outflow ahead. Light rain and virga does not appear to extinguish the signal from the cool outflow ahead. The vertical shear between 18 and 13 s BT (as the aircraft descended 100 ft) was 0.15 s^{-1} or 9 knots/100 ft. Snyder[6] has shown that vertical shears greater than 0.1 s^{-1} are hazardous to large, swept-wing, jet aircraft. The plotted run of Fig. 5 exhibits similar features with a 43-s alert.

Abrupt changing crosswinds normal to the flight approach track appear to present problems in the flight approach runs plotted in Fig. 4, 6, and 8. The approaches from Figs. 4 and 6 evidenced a shear threshold at 58 and 50 s, some 2-2½ miles before touchdown at altitudes of 600-700 ft. The onboard radiometer system did not provide sufficient advance alert to the crosswind shear in approach 10 plotted in Fig. 7.

Vector difference magnitudes occurring within a 10-s interval appeared potentially hazardous in the computer-plotted approaches resulting from the data of runs 10, 12, and 21 (Figs. 6-8) of 15 July 1982. The vector difference magnitudes of 34-47 knots seemed large enough to suggest problems. There the radiometer system failed to provide sufficient advance warning of the ensuing shear encounter. However, of the six approaches into potential thunderstorm shear conditions, the system operated successfully five times with an average advance alert to following shear of 31 s before encounter.

We have summarized only six of 42 approaches or departures into potential shear conditions, with five detected successfully an average of 51 s before encounter. In one case (Fig. 8), advance detection was not successful. The success rate of 83% for the six events reviewed corresponds to a success rate of 35 advance detections out of the total 42 encounters.

Conclusions

The results of this airborne infrared low-level wind shear predictor system test provide an initial indication of the potential feasibility (83% success) of passive IR remote sensing of horizontal temperature gradients associated with shear-producing gust fronts or thunderstorm density currents. During approach to touchdown, alert times averaging 51 s correspond to approximately 2 miles out from touchdown and should thus provide sufficient time for a "go around" decision. The shear index ($\Delta T/\Delta t$), determined with a limited amount of sample data, is evidently related to the vertical shear, du/dz, the vector different magnitude, and cross wind shear. The effects of "looking" through light rain or virga do not appear to pose a problem and are being studied further.

Weighting function changes via different IR filters, ranging, and azimuthal scanning can add to the potential usefulness of this passive IR airborne shear predictor system by providing increased range and avoidance possibilities.

Acknowledgment

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[1] Fawbush, E. J., and Miller, R. C., "A Basis for Forecasting Peak Wind Gusts in Non-frontal Thunderstorms," *Bulletin of the American Meteorological Society*, Vol. 35, 1954, pp. 14-19.

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[6] Snyder, C. T., "Analog Study of Longitudinal Response to Wind Shear and Sustained Gusts During Landing Approach," NASA TN D-4447, NASA Ames Research Center, Moffett Field, Calif., 1968.

Airborne Operation of an Infrared Low-Level Wind Shear Prediction System

P. M. Kuhn, R. L. Kurkowski, F. Caracena

Airborne Operation of an Infrared Low-Level Wind Shear Prediction System

Peter M. Kuhn* and Richard L. Kurkowski†

NASA Ames Research Center, Moffett Field, California

and

Fernando Caracena‡

NOAA-ERL-OWRM, Boulder, Colorado

Airborne testing under simulated and actual low-level wind shear conditions is underway on a NASA Ames Learjet. An infrared CO_2 band radiometer with a forward "look-distance" of from 5 to 8 km measures the air temperature weighted to this range ahead of the approach configured aircraft. Shear alerts occur when the difference between the forward temperature and static air temperature at the aircraft exceed a set value or when a perturbation occurs in the normally constant potential temperature. Aircraft approaches into thunderstorm gust front phenomena were simulated by approaches into cool estuarine air adjacent to much warmer air over land and by actual light wind shear conditions at Travis Air Force Base. Conditions were verified by the radiometer system with extensive onboard data acquisition.

Nomenclature

B	= radiance, $W\,cm^{-2}\,sr^{-1}$
k	= absorption coefficient, $cm^2 g^{-1}$
N	= radiance, $W\,cm^{-2}\,sr^{-1}$
q	= mass mixing ratio of gas, gg^{-1}
T	= temperature, °C
t	= time, s
x	= horizontal distance, cm
z	= vertical distance, cm
θ	= potential temperature, K
ν	= wave number, cm^{-1}
ρ	= density, $g\,cm^{-3}$
τ	= gaseous transmission, %
ϕ	= radiometer filter transmission, %

Introduction

SEVERE wind shear at low level altitudes poses an extreme hazard to aircraft, especially large swept wing jet equipment during final approach and takeoff.[1] In these conditions, with the aircraft operation near stall speed, a significant change in wind velocity can easily result in a dangerous rate of descent. Research areas involving ground-based and airborne equipment to sense encountered shear are underway, with proponents of each citing their advantages and limitations.

The limitations of a ground-based system are obvious when one considers the magnitude and time-lag of such equipment to say nothing of its unavailability at many nonmajor commercial airports.

Most of the airborne equipment proposed and studied cannot sense the shear hazard before the aircraft encounter. Thus our caveat is to discuss results of tests of an airborne, infrared, remote-system that can sense the shear hazard before the aircraft encounters the hazard.

Low-level wind shear (LLWS) is defined as wind shear occurring between the surface and 490 m (1500 ft) above ground level. Wind shear is any change in wind speed and/or direction through a shallow layer of the atmosphere. The length and breadth range from 7 to 8 km to 25 to 30 km, while the vertical reach is in the hundreds of meters.

The meteorological phenomena producing low-level wind shear are, primarily, thunderstorm gust fronts,[2] fast-moving frontal zones, and less frequently, low-level inversions. In most cases, by the time it is detected, it is usually after the fact. A typical aircraft approach into gust front conditions is depicted in Fig. 1.

The 13-16-μm portion of the molecular spectrum may be used to remotely sense LLWS in and around thunderstorm gust fronts.[3,4] It is not to be implied that this radiometric gust front detection system can remotely detect thunderstorm downburst conditions accompanied by heavy rain. Infrared (i.r.) signal attenuation precludes this capability. An infrared radiometer with an optically designed look-distance of 7-10 km senses an average air temperature ahead of the aircraft along the forward, horizontal path. Cockpit wind shear alerts are based on exceeding a defined difference between this "forward" air temperature and the air temperature at or near the aircraft. Alternatively, the "forward" air temperature is converted to potential temperature, θ, which is essentially constant during landing approach and takeoff departure. Negative anomalies in θ exceeding a defined magnitude are the basis for LLWS alerts aboard the aircraft. Figure 2 is a schematic depiction of the operation of the system.

Atmospheric Physics of Gust Fronts

The physical basis for wind shear alerts is the relation of Fawbush and Miller[5] which is presented in Fig. 3. This relation shows that a colder downdraft results in a higher outflow wind. Since the relation of the wind to the wind shear generated is geometrical, the scale of the wind shear (as measured by surface divergence outflow) also increases with the size of the negative perturbation of the gust front. See Ref. 6 for details.

An airborne infrared radiometer system sensing in one or more bands of a 13-16-μm portion of the carbon dioxide spectrum is being flight-tested. It is designed to provide in-
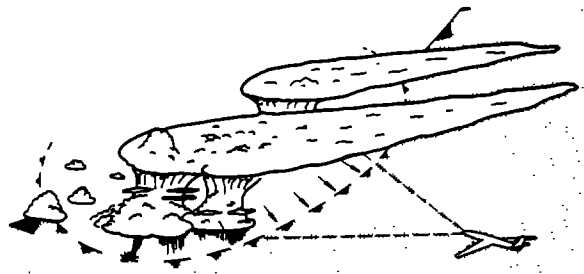
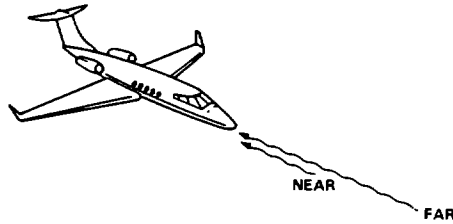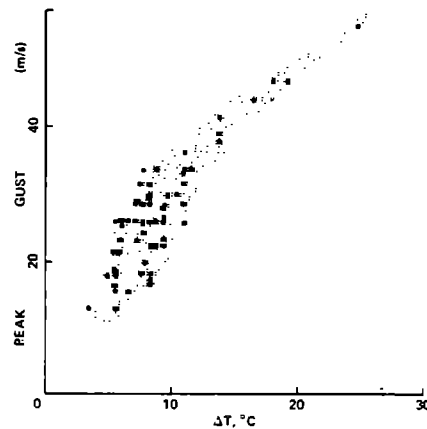Fig. 1 Aircraft approach into gust front.

Fig. 2 Schematic depiction of the operation of a two-channel i.r.-LLWS radiometer system.

Fig. 3 Relation between peak gust in outflow vs the drop in temperature from the thunderstorm environment.[5]

flight predictions or alerts based on remotely sensed horizontal temperature gradients resulting from thunderstorm gust fronts and fast-moving frontal zones.

When employed in a single-band mode with a forward weighting function defined as "look-distance," $\delta\tau(\nu,x)/\delta x$ (change in transmission with respect to horizontal path), peaking at 5.0 km, anomalies in the constancy with descent or ascent of the potential temperature, θ, provide the alerting criteria. In the two-band mode a second filter in the radiometer system, with a forward look-distance peaking at from 200 to 400 m, provides a reference ambient temperature. Differences between the sensed temperatures in the two bands, T, provide the alerting criteria. Pitch angle of the aircraft during approach is compensated for thus eliminating hard targets.

The design development of the infrared LLWS detection system is based on consideration of the radiative transfer equation (RTE) applied to atmospheric radiance received at a detector along a horizontal path. The RTE may be expressed as

$$N = \int_x \int_\nu B(\nu,T)\phi(\nu)\left(\frac{\delta\tau(\nu,x)}{\delta x}\right)dxd\nu \qquad (1)$$
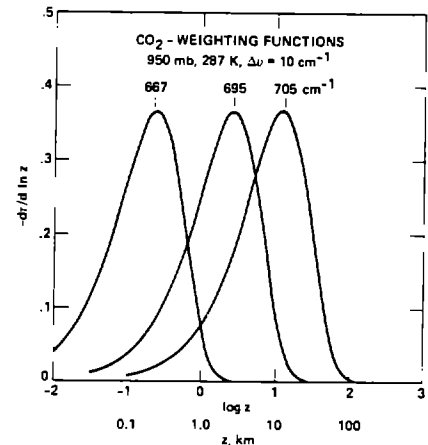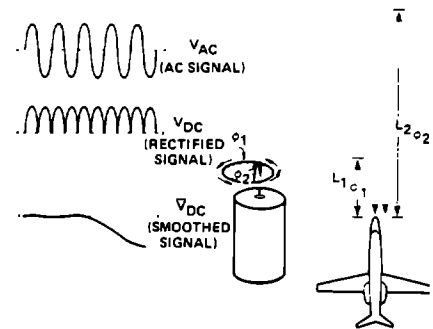

Fig. 4 CO_2 weighting function for 10-cm^{-1}-wide passbands.

Fig. 5 Depiction of operation of the i.r.-LLWS detection system.

Here,

$$\tau_{\Delta\nu} = \exp(-k_{\Delta\nu}q\rho dz) \qquad (2)$$

The look-distance or weighting function in Eq. (1) above may be expressed as $\delta\tau(\nu,x)/\delta x$ vs horizontal path, x.

Weighting functions at altitudes of 33 m (100 ft) through 491 m (1500 ft) were run in the 660-710-cm^{-1} passband at intervals of 10 cm^{-1}. The passband centered at 695 cm^{-1} provided the best look-distance or weighting function for the radiometer system (Fig. 4). The look-distance was approximately 5 km (2.9 miles), providing some 80 s of warning or alert time for a shear encounter.

Instrument System Operation

The operation of the i.r. gust front LLWS detection system is depicted schematically in Fig. 5. The i.r. radiometer, upon receiving a signal through its optical train, generates a smoothed dc signal from the ac signal produced by alternate CO_2 and reference sensing. Here θ_1 and θ_2 refer to near and far look-distance filters at the radiometer head and L_1 and L_2, near and far x distances. Figure 6 is the i.r. hull probe and right-angle, gold-coated mirror facilitating mounting in the aircraft in various locations. The probe for signal reception in the forward direction may be rotated to compensate for aircraft attitude during approach or departure. The operation of the radiometer has been described by Caracena et al.[3]

In a horizontally uniform temperature field both the near filter channel of the radiometer or the static air temperature at the aircraft and the forward far filter channel of the radiometer see the same temperature. As a cool outflow air mass is approached, the far channel will begin to sense a cooler temperature before the near channel responds and will
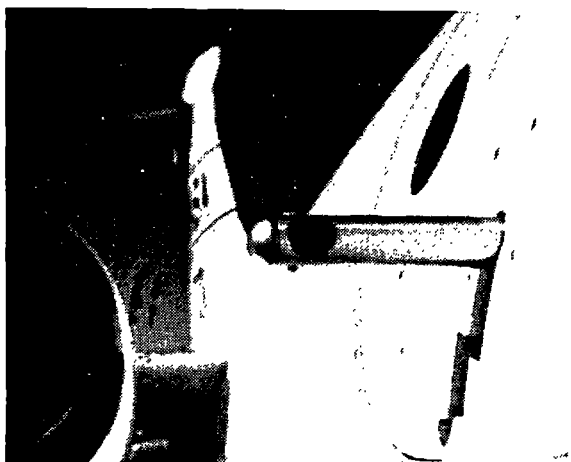
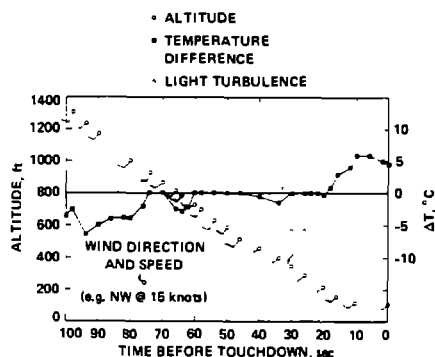Fig. 6   Optical i.r. probe on starboard side of NASA Ames Learjet.

Fig. 7   Learjet data plots for approach to Travis Air Force Base, 1448 Pacific Daylight Time (PDT), Sept. 1, 1981.
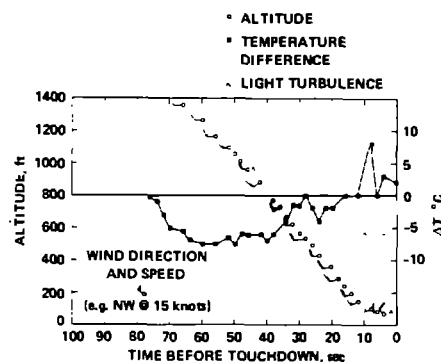

Fig. 8   Learjet data plots for approach to Travis Air Force Base, 1340 Pacific Daylight Time (PDT), Aug. 31, 1981.

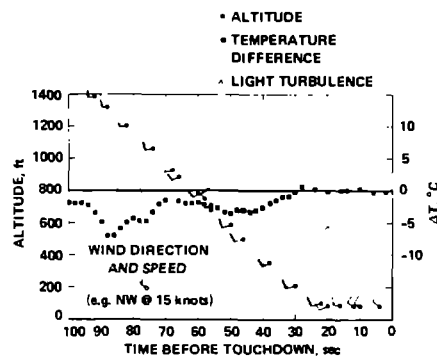Fig. 9   Learjet data plots for approach to Suisun Bay, Calif., 1328 PDT, Aug. 31, 1981.

continue to sense a cooler temperature until the cool air mass approaches the aircraft. Thereafter, for a period of time, the temperature sensed by both radiometers or by the forward looking radiometer and the static air temperature probe of the aircraft will approach one another until the far channel "looks" beyond the cool air mass. As stated, no alert for LLWS is produced until the temperature difference between the near and far sensors exceeds a predetermined threshold for wind shear. The alert is continuously upgraded. Of course, the far or forward "looking" channel senses only a fraction of the cool temperature perturbation at one look distance. It senses this fraction as a fluctuating radiometric temperature. This fraction is the required precision of the LLWS radiometer and is approximately $1°C$.

The width of the passband is important to consider in designing an i.r. LLWS radiometer. Theoretical considerations show that narrow passbands give the best spatial discrimination of thermal perturbations, while broad passbands produce the strongest corresponding perturbation in the radiometer output. Caracena et al.[3] discussed the feasibility of using specific passbands in the q branch of molecular CO_2 to best detect cold temperature anomalies associated with LLWS.

LLWS Radiometer Tests

Preliminary tests of the LLWS radiometer system have been conducted aboard the NASA Ames Research Center Learjet in the late summer of 1981 at Travis Air Force Base and Suisun Bay northeast of San Francisco. Data from these missions demonstrate the ability of the system to detect sea breeze effects on approach from altitudes of from 300 to 430

m (1000 to 1300 ft) at from 30 to 70 s prior to aircraft encounter with the cool air mass and, in one case, light wind shear.

Figure 7 presents the approach pattern and winds on Sept. 7, 1981 at Travis and the ΔT ($°C$) (forward i.r. radiometer air temperature minus the static air temperature at the aircraft) as a function of altitude and time before touchdown. The optics elevation angle with respect to the aircraft centerline is set at -4.0 deg. The nominal aircraft pitch angle for approach configuration is 3.0 deg with respect to the horizontal, and the radiometer elevation angle is then approximately -1.0 deg below the horizontal. At 68 s out, or $t-68$, the distance out at 140 knots is approximately 4.7 km (2.72 miles) and the minimum height of the cool air mass simulating a gust front would be 82 m (250 ft) for the radiometer to "see" it.

Based upon an examination of these early data, an indicator for predicting cool outflow ahead was arbitrarily chosen to be $\Delta T/\Delta t = 0.5°C/s$. The alert to this simulated cool gust front ahead could have occurred at approximately 100 s out but no later than 68 s before touchdown. In Fig. 7, at $t-20$, $\Delta T/\Delta t$ becomes positive as the radiometer begins to "see" warmer hill areas beyond Travis. The top of the cool air mass as the aircraft descended was observed at 95 m (290 ft) MSL. Light turbulence occurred at 105 m (320 ft).

A similar advance warning of a cool air mass, again simulating a gust front outflow, is depicted in Fig. 8. $\Delta T/\Delta t$ reached the 0.5°C/s threshold at $T-70$ s. Here, the approach on Aug. 31, 1981 to a simulated landing, is over Suisun Bay just south of Travis. Again at $t-12$, $\Delta T/\Delta t$ becomes positive but less pronounced than in the Travis approach (Fig. 7). The cooler oceanic inflow air is more extensive and the "look" angle of the radiometer is directed more to the larger bay and sea air. Light turbulence was encountered at an altitude of 49 m (150 ft) with a wind shift of from 250 deg at 15 knots to 310 deg at 20 knots. The height of the turbulence is directly related
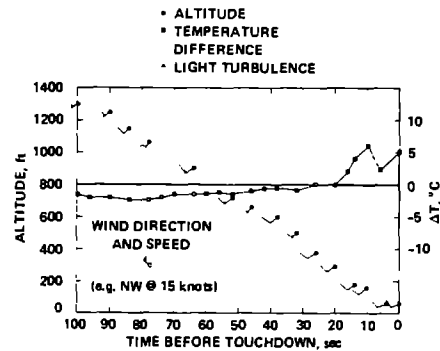
Fig. 10 Learjet data plots for approach to Travis Air Force Base. 1411 Pacific Daylight Time (PDT), Sept. 2, 1981.

to the shear zone in the vertical and horizontal but presumably can occur over considerable depth owing to mixing. In this approach, the top of the cool air was approximately 65 m (200 ft).

In Fig. 9, illustrating another approach to Suisun Bay on Aug. 31, 1981, $\Delta T/\Delta t$ exceeded the threshold indicating a cool, simulated gust front ahead at $t-90$ s. In both previous approaches, as in this and the succeeding approach, the patterns were flown between 1330 and 1500 Pacific Daylight Time (PDT). At $t-28$ s, the aircraft is obviously close to if not immersed in the cool air at an altitude of approximately 59 m (180 ft). As in the previous approach over Suisun Bay the background into which the radiometer looked was relatively cool for some distance out as evidenced by ΔT remaining essentially 0°C. Again, light turbulence occurred at 40 m (120 ft) MSL during a wind shift of from 250 deg at 20 knots to 300 deg at 10 knots. The turbulence does occur near the estimated top of the cool air mass.

On Sept. 2, 1981 (Fig. 10), during a midafternoon approach to Travis from $T-100$ to touchdown, $\Delta T/\Delta t$ did not reach 0.5°C/s. There was no following encounter with cooler than

ambient air and at $t-20$ the forward "looking" radiometer detected warmer air beyond the Travis runway area. No turbulence was encountered and no wind shift occurred during descent.

Conclusions

The preliminary results presented in this paper show that it is feasible to remotely sense horizontal temperature gradients associated with cool inflowing oceanic air masses ahead of an approaching aircraft with an onboard, i.r. radiometer system. Since gust fronts normally are associated with much stronger horizontal temperature gradients and often severe low-level wind shear, it appears logical to conclude such radiometer observation in the vicinity of gust fronts could readily detect these horizontal temperature gradients. It is believed that advance warnings are possible (with this system) up to 7 km (4.3 miles) in advance of wind shear encounters. This translates into a warning time of up to 102 s.

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