Airborne Infrared Low-Altitude Wind Shear Detection Test

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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, 2.87×10^6 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, %
$\phi(\nu)$	= 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 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

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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

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

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

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

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.

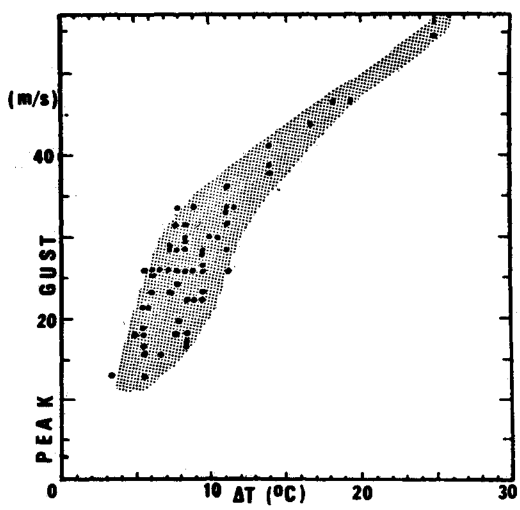

Fig. 1 Outflow peak gust vs temperature drop in thunderstorm.

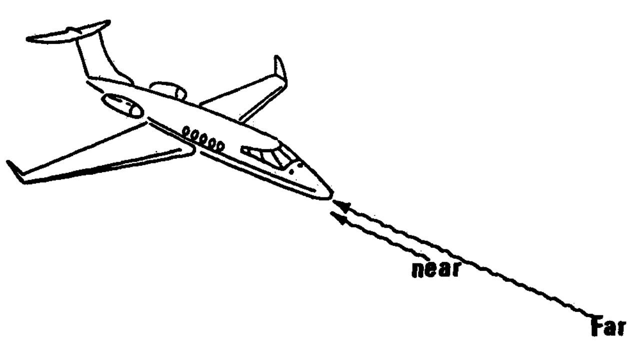

Fig. 2 Airborne infrared low-altitude wind shear detection system.

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.

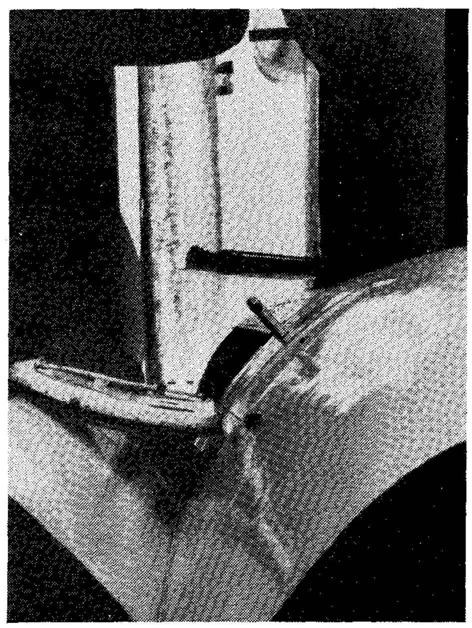

Fig. 3 Installation of infrared low-altitude wind shear probe on NASA B57B.

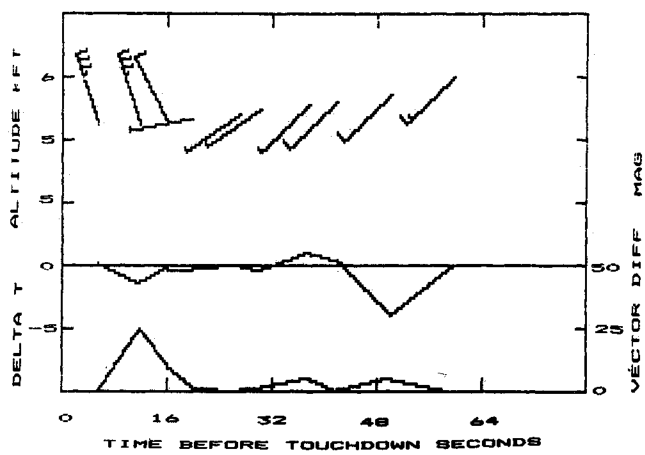

Fig. 4 Computer reproduction of B57B approach on track angle 271 deg. Right ordinate is wind vector difference magnitude in knots; abscissa in seconds before touchdown; left lower ordinate is T(°C); left upper ordinate is altitude in kilofeet. See text for explanation of curves. Flight 7/15/82-17.

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 ab scissa

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 dif ference 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

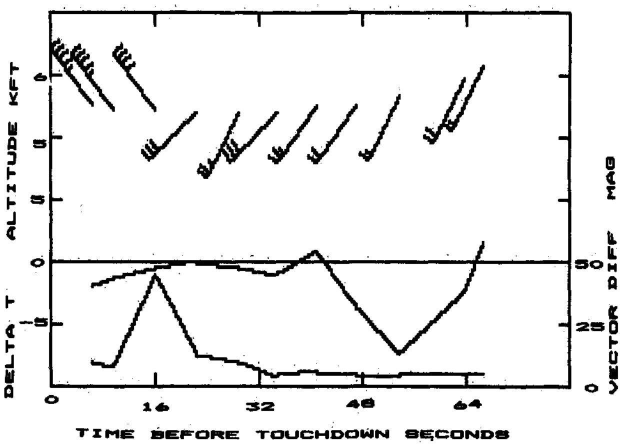

Fig 6 Computer reproduction of B57B approach on track angle 225 deg; all labels as in Fig 4; Flight 7/14/82 21

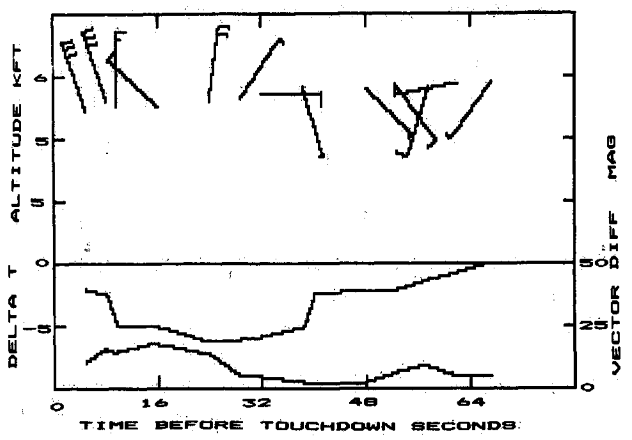

Fig 5 Computer reproduction of B57B approach on track angle 271 deg; all labels as in Fig 4; Flight 7/14/82 17

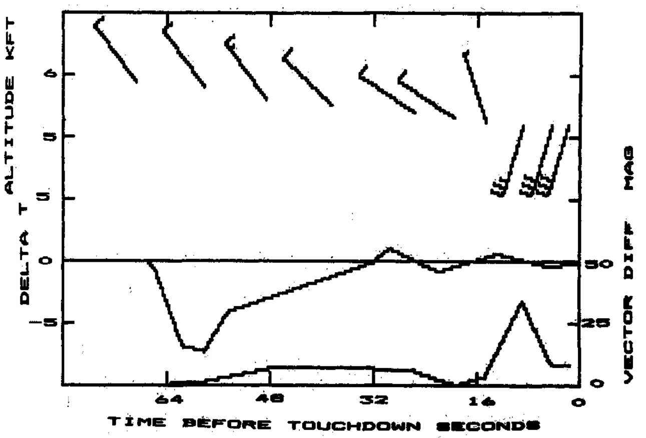

Fig. 7 Computer reproduction of B57B approach on track angle 45 deg; all labels as in Fig 4; Flight 7/15/82 10

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 differ ence 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 in strument 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 ex pressed in knots (n m /h) per ft or in inverse seconds (s^{-1}) This relation may be expressed as:

$$\frac{du}{dz}=\left(\frac{\text{knots}}{100\ \text{ft}}\right)=\frac{\text{n mi}}{3600\,\text{s}}\,\frac{6020\,\text{ft}}{\text{n mi}}\,\frac{1}{100\,\text{ft}}=\frac{0\ 01672}{\text{s}} \tag{4}$$

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

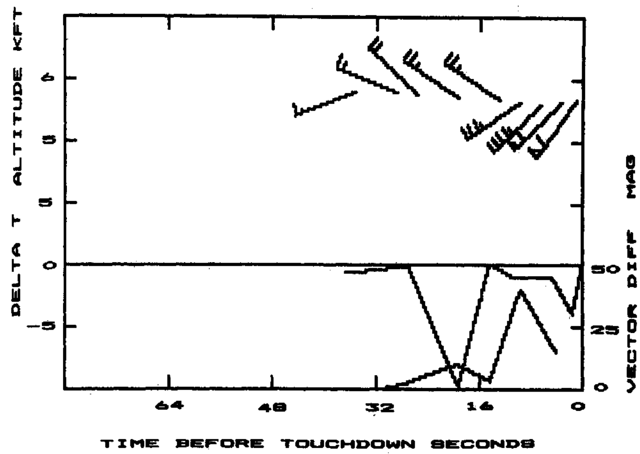

Fig 8 Computer reproduction of B57B approach on track angle 225 deg; all labels as in Fig 4; Flight 7/15/82 13

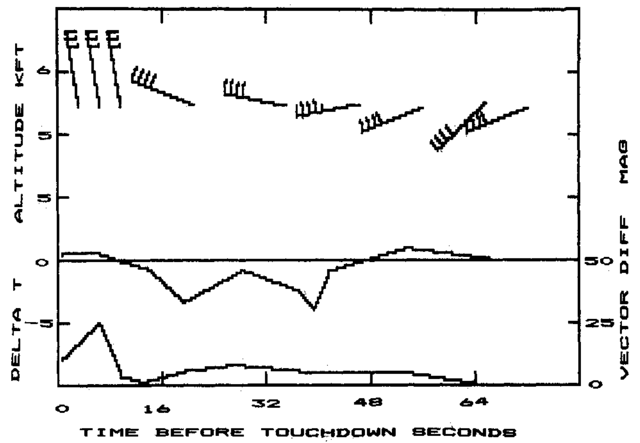

Fig 9 Computer reproduction of B57B approach on track angle 225 deg; all labels as in Fig 4; Flight 7/15/82 13

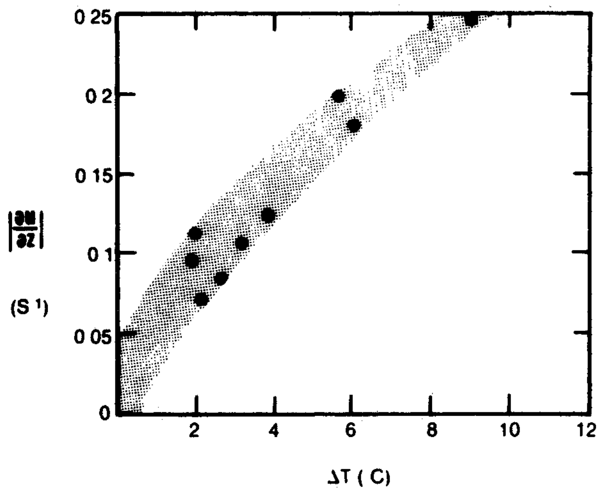

Fig 10 Thunderstorm vertical shear (s^{-1}) vs drop in temperature across gust front

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 in terval 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 con ditions, the system operated successfully five times with an average advance alert to following shear of 31 s before en counter

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 en counters

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

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References

[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

[2]Kuhn P M. Kurkowski R L , and Caracena, F Airborne Operation of an Infrared Low Level Wind Shear Prediction System *Journal of Aircraft* Vol 20, Feb 1983, pp 170 173

[3]Carcena F Kuhn, P M , and Kurkowski, R L Design and Preliminary Tests of an IR Airborne LLWS Remote Sensing System ' AIAA Paper 81 0239 Jan 1981

[4]The JAWS (Joint Airport Weather Studies) Project Operations Summary 1982, National Center for Atmospheric Research Boulder Colo and the University of Chicago Illinois Feb 1983

[5]Hall F F , Neff W D and Frazier T V ' Wind Shear Ob servations in Thunderstorm Density Currents " *Nature* Vol 264 Dec 1976, pp 408 411

[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