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

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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.

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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-

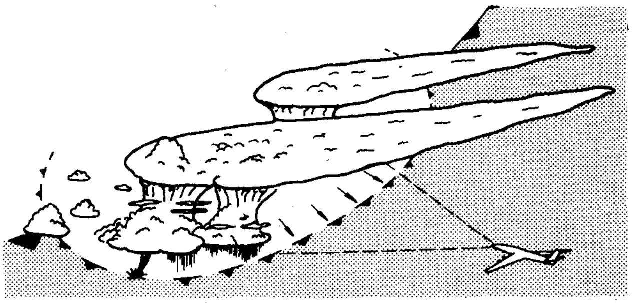

Fig. 1 Aircraft approach into gust front.

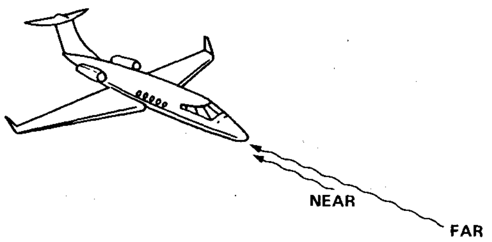

Fig. 2 Schematic depiction of the operation of a two-channel i.r.-LLWS radiometer system.

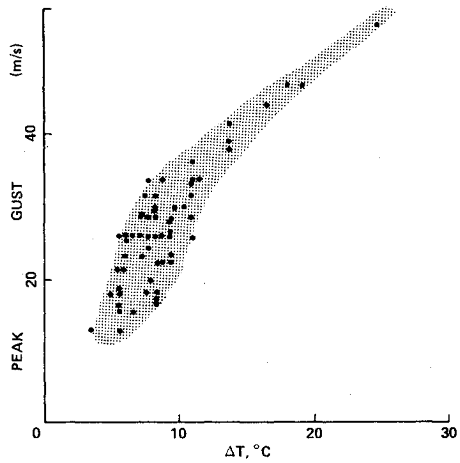

Fig. 3 Relation between peak gust in outflow vs the drop in temperature from the thunderstorm environment.[5]

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

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

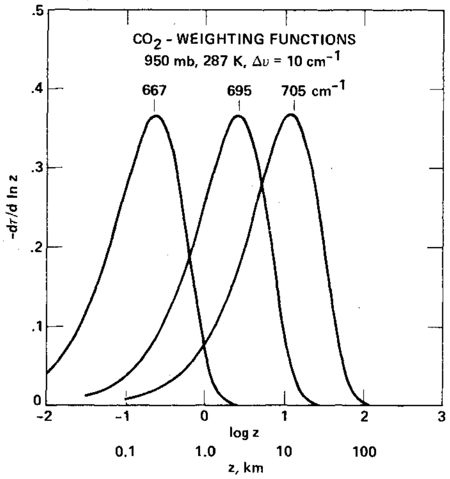

Fig. 4 CO_2 weighting function for 10-cm^{-1}-wide passbands.

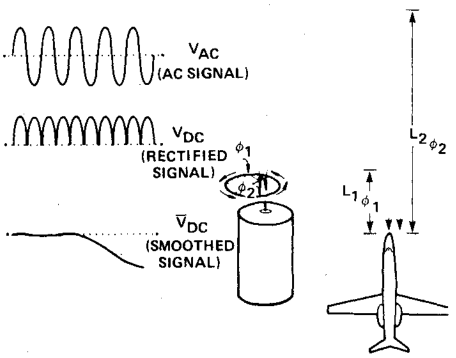

Fig. 5 Depiction of operation of the i.r.-LLWS detection system.

Here,

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

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_l and θ_2 refer to near and far look-distance filters at the radiometer head and L_l 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

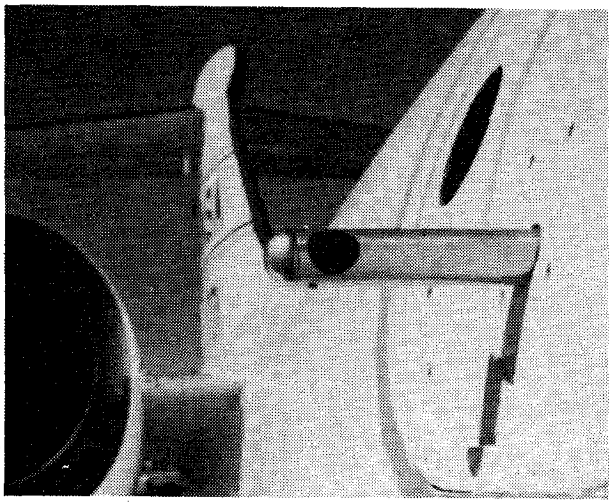

Fig. 6 Optical i.r. probe on starboard side of NASA Ames Learjet.

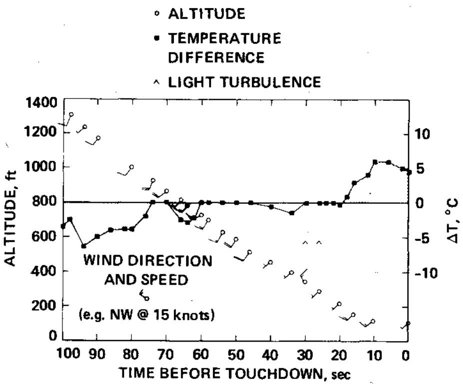

Fig. 7 Learjet data plots for approach to Travis Air Force Base, 1448 Pacific Daylight Time (PDT), Sept. 1, 1981.

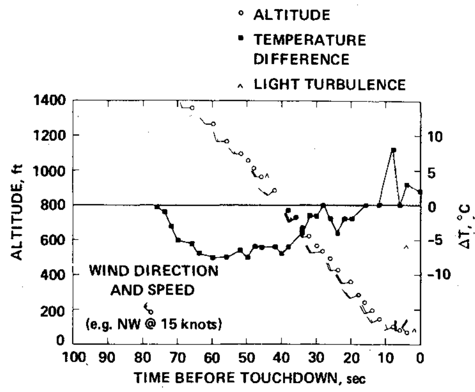

Fig. 8 Learjet data plots for approach to Travis Air Force Base, 1340 Pacific Daylight Time (PDT), Aug. 31, 1981.

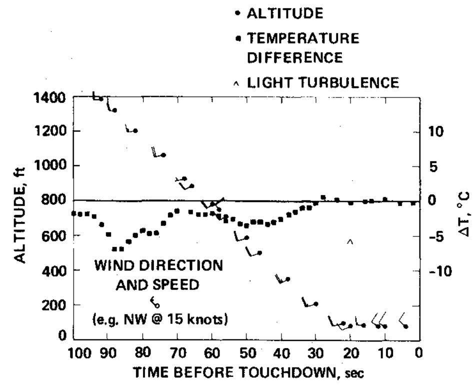

Fig. 9 Learjet data plots for approach to Suisun Bay, Calif., 1328 PDT, Aug. 31, 1981.

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

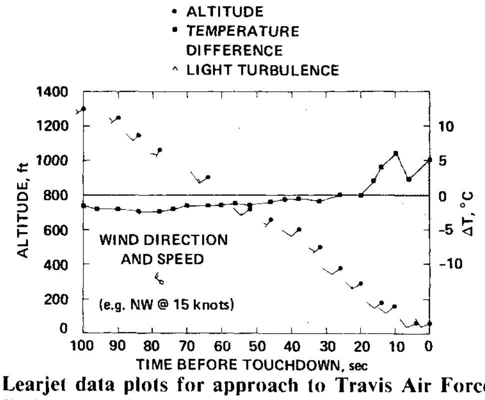

Fig. 10 Learjet data plots for approach to Travis Air Force Base, 1411 Pacific Daylight Time (PDT), Sept. 2, 1981.

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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