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Airborne Detection of Low-Level Wind Shear

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Recent studies of accidents/incidents attributed to wind shears encountered during takeoff or landing approach have indicated the necessity of quantifying the combined effect of downdraft and horizontal shear. This paper discusses the development of a system to compute and display to the flight crew this loss of performance capability. Preliminary results from simulation, flight test, and in-service evaluation are discussed in terms of performance margins and implications for pilot technique in the recovery from a severe wind shear encounter.

Nomenclature

D = drag, lb
DDA = downdraft drift angle, rads
EPR = engine pressure ratio
g = acceleration due to gravity, 19.04 knots/s
GS = groundspeed, knots
h = altitude, ft
IAS = indicated airspeed, knots
T = thrust weight, lb
T_{req} = thrust acceleration required, knots/s
V = airspeed, knots
$\dot{V}$ = rate of change of airspeed, knots/s
V_{AP} = approach speed, knots
V_c = rate of climb, ft/s
V_{ref} = reference speed-1.3 V_{SO}, knots
V_{SO} = power off stall speed in the landing configuration, knots
W = weight, lb
WS_X = horizontal wind shear factor, knots/s
ΣWS = total wind shear, g
WV_Z = vertical wind velocity, knots
$\dot{X}$ = groundspeed, knots
$\ddot{X}$ = horizontal acceleration (inertial), g
$\ddot{Z}$ = normal (vertical) acceleration (inertial), g
α = angle of attack, deg
γ = flight path angle, deg
θ = pitch attitude, deg
k = $(1/19.04 \cdot \pi/180)$

Introduction

THE meteorological sources of low-level wind shear have been identified in the literature. Those sources which are of potential concern to air carrier operations in the terminal area are low-level jet streams, weather fronts, and thunderstorms.[1-4] Accidents/incidents, since the one in New York in 1975, have been investigated with an increased awareness of the potential presence of vertical winds (herein termed downdraft).

Aircraft performance in wind shear has been addressed by airframe manufacturers, operators, and regulatory agencies in an attempt both to assess reserve margins and to propose flight crew techniques for handling wind shear penetration or, in severe instances, recovery. Common to each approach is the concern that a control law be established that will optimize the flight path terrain clearance profile through the correct management of potential and kinetic energy.[5-10]

A National Transportation Safety Board (NTSB) accident data file search was conducted by the Federal Aviation Administration (FAA) in an attempt to identify wind shear/downdraft as a contributing factor to accidents during the period 1960 through 1976. The review of these data is important to the development of an understanding of the vertical component, both in terms of the magnitude and, when compared with the horizontal vector, relative lack of awareness gained through traditional cockpit instrumentation.

To date, the systems proposed for the display of wind shear guidance for the flight crew vary widely in design concept. With the exception of the system described in this paper, none of the proposed methods considers the downdraft other than as a second-order effect; that is, a deviation in flight path will result in a subsequent deviation in the speed/lift/thrust condition.[11-13]

Landing Approach

The ability of an airplane to maintain its landing approach profile during a wind shear encounter is limited by the availability of excess thrust. The availability of excess thrust to correct for both glide path maneuvering and deviations due to wind assumes increasing importance, as below a minimum safe height the pilot does not have the option of trading altitude for airspeed. At this point, the options for the pilot lie in the speed/performance margin at the onset of the shear, and the extent to which thrust is available to be added to the system's energy.

With both flight path and speed constrained, as in the case of a stabilized (unaccelerated) approach, the ability to maintain speed and profile under shear conditions may be expressed by:

$$\dot{V} = g(T\text{-}D)/W - g\sin\gamma \tag{1}$$

The reserve or go-around capability of a typical 3-engine transport at maximum landing weight is:

$$\dot{V} = \frac{19.04(50{,}000\text{-}32{,}500)}{150{,}000} - (19.04\sin -3\ \text{deg})$$

$$= 3.2\ \text{knots/s}$$

Table 1 shows a listing of the approximate acceleration capability of representative transport types in the landing configuration (at maximum landing weight) on a 3-deg glide slope.

Aircraft performance loss due to vertical air motion has been recognized as a contributing factor in recent accidents at

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Table 1 Flight path acceleration on a 3-deg glide slope

Aircraft	Thrust × 10^3, lb	Weight × 10^3, lb	Inertial acceleration, knots/s
B747-200B	204	564	3.6
B737-200	31	105	2.9
B727-200	46.5	154.5	3.0
B707-320C	76	247	3.0
DC-10-10	123	403	3.0
DC-9-30	31	110	2.8
DC-8-61	72	240	3.0
L1011-1	126	358	3.5
A300B4	106	293.2	3.6

New York, Denver, Philadelphia, and in an incident at Tucson. Due, in part, to an increased understanding of the downburst/downdraft factor, prior accidents have been reviewed to re-examine the meteorological and/or flight path data to see if the presence of a vertical wind would better explain the profile. As a result of this approach, the 1974 Pago Pago landing accident was redetermined by NTSB to have been a wind shear encounter. Figure 1 shows the meteorological conditions at the time of the 1975 John F. Kennedy Airport, New York landing accident as developed by T. T. Fujita.[4] The significance of the verticals may be seen when one notes that the downdraft velocity exceeds 10% of the forward speed of the airplane.

As the flight crew endeavors to maintain a speed/glide path profile in an encounter, the loss of energy may not become apparent until the limit of thrust is approached. While airline flight departments have stressed the importance of a stabilized approach as a means of providing advance shear indication, post-accident analysis, as well as training simulator studies, have shown this to be of limited value under the distracting conditions of an encounter. There are several reasons for this, some of which are suggested for consideration here. During an approach where wind shear has been reported or is suspected, flight crews often select target approach speeds at, or in excess of, manufacturer and/or company guidelines. (A guideline used in many training departments is $V_{AP} = V_{\text{ref}} + \frac{1}{2}$ the reported surface wind plus all of the reported gusts, with the total addition to V_{ref} not to exceed 20 knots. However, it should be noted that in the Philadelphia accident, the approach speed flown was V_{ref} + 40 knots. This is not considered by many line pilots to be extraordinary.) In addition to the still-air problems of decreased reaction time associated with the higher approach speed (increased rate of descent, more critical flare maneuver, unstabilized final segment, increased control response, longer ground roll requirement, increased susceptibility to hydroplaning, etc.), the nominal values of attitude, airspeed, vertical speed, and thrust are not those of a nonwind shear approach. Thus, variations due to the shear itself tend to be masked.

A second consideration lies in the related area of pilot instrument scan during the transition to the visual portion of an instrument approach and the contribution of additional flight crew member callouts to the pilot. It has been demonstrated in simulation that the addition of outside references in the approach and threshold visual environment reduces the pilot's instrument scan during the transition.

In an informal study conducted by the author to test for flight crew attention to thrust control, it was concluded that the awareness of applied thrust, either through engine instrumentation or, somewhat surprisingly, thrust lever position, is often unsatisfactory. The test was carried out in a DC-9-10 training simulator and introduced a tailwind shear which would require slightly in excess of go-around thrust to maintain the descent profile, concurrent with the introduction of the visual runway environment (at about 200 ft above the runway). After each approach (all landings were successfully accomplished), the pilots were asked what was the highest engine pressure ratio (EPR) indicated during the approach. In all cases, both pilots agreed that 1.4 EPR was the highest thrust observed. (This was approximately the value at the introduction of the tailwind shear and the transition to visual cues.) In all cases, the applied EPR exceeded 1.85.

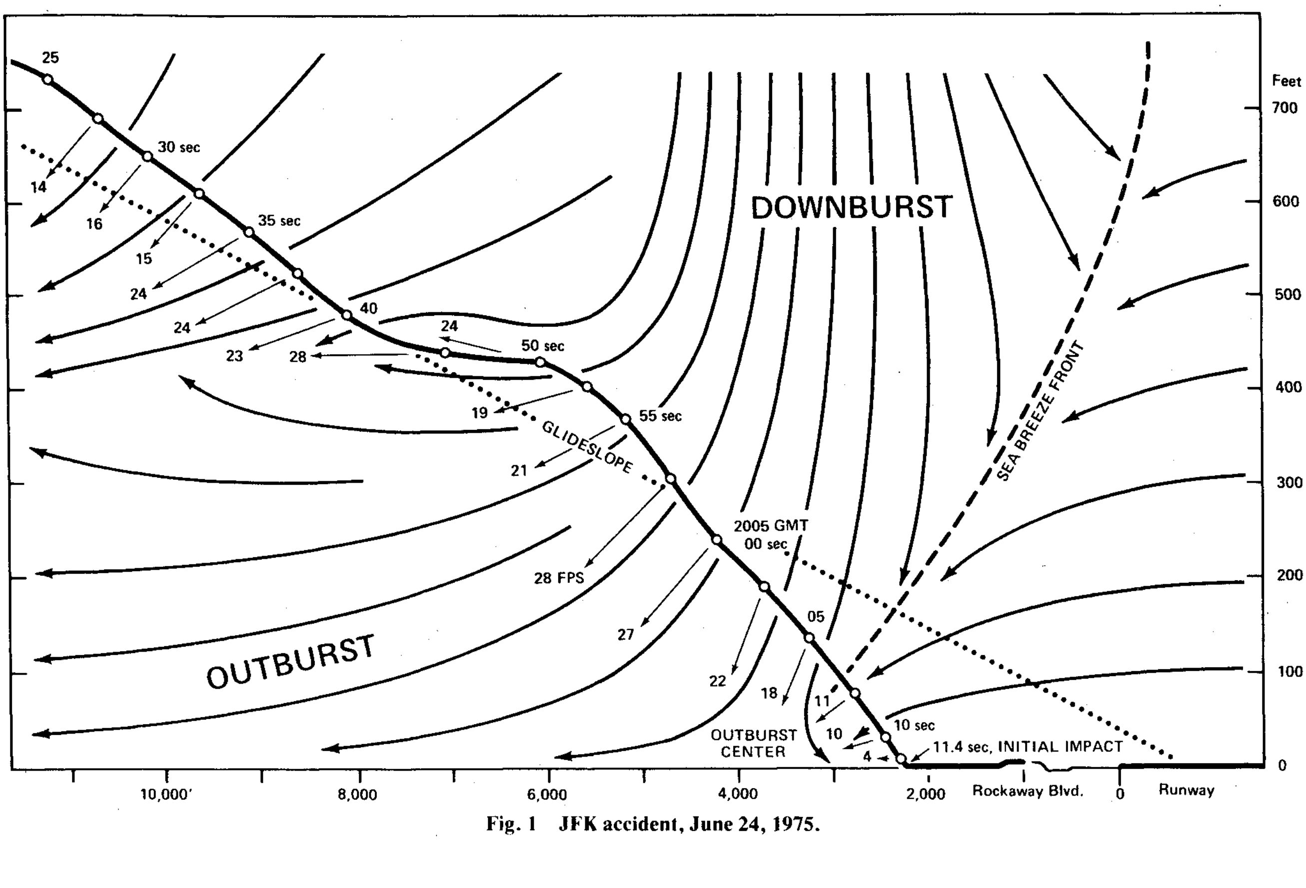

Fig. 1 JFK accident, June 24, 1975.

The Hazard Defined

Government- and industry-sponsored investigations into possible airborne solutions to the wind shear hazard have been primarily concerned with groundspeed control. These investigations have emphasized the importance of maintaining an airspeed consistent with a minimum acceptable groundspeed in anticipating a tailwind shear. Thus, these programs have led to hardware suggestions which incorporate groundspeed displays intended to aid the pilot in a wind shear encounter. Overlooking for the moment the issue of the vertical, the present airspeed/groundspeed proposals raise some conceptual questions.

Airplane response to wind shear may be viewed in terms of glide path/airspeed performance and stability and control. The performance problem is essentially defined by the airplane's ability to accelerate inertially (in a tailwind shear/downdraft) in order to be able to maintain the desired airspeed and profile. This ability is limited by the reserve of thrust in excess of that required to maintain unaccelerated flight. The stability and control problems are areas not to be excessively covered here, yet one example will serve to outline the case—a 20-knot airspeed loss on landing approach is a hazard to the flight as a function of the rate at which it occurs. This is countered by the airspeed acceleration capability ($\Delta T/W$) and the longitudinal trim response rate.

The matter is further complicated by the time available from the end of the encounter to the commencement of the threshold deceleration and flare maneuver. Thus, if a 20-knot linear shear is experienced at 200 ft above ground level for 40 s, the loss of headwind component will go all but unnoticed and poses little difficulty to the crew. The incremental thrust application for a 0.5 knot/s shear is hardly discernible in the noise of glide slope bracketing and atmospheric turbulence. Yet a step 20 knot loss inside the Middle Marker, even when the loss was anticipated and compensatory speed held over V_{ref}, will require a large thrust adjustment and/or large trim change. Thus, for both control and performance, the determination of hazardous levels of wind shear/downdraft has to be evaluated primarily in terms of rate of change of the component/vector and not, as presently viewed, in terms of airspeed/groundspeed delta or knots per hundred feet of altitude. While it is acknowledged that there is value to the flight crew in advance warning of a significant airspeed/groundspeed differential, it is suggested that the application of that information becomes useful only when used in the form of the horizontal wind shear factor WS_X.

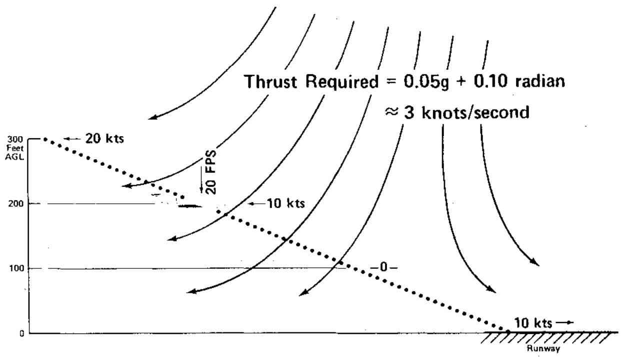

Fig. 2 Horizontal wind shear plus downdraft drift angle.

$$WS_X = V - \dot{X}/h/V_c \tag{2}$$

In the example above the shear of 20 knots between 400 ft and the surface results in a shear representing 1/6th of the typical transport recovery capability.

$$WS_X = \frac{140\text{-}120}{400/-10} = -0.5 \text{ knots/s}$$

However, the same IAS-GS difference appearing at an altitude of 100 ft has a rather different significance in terms of airplane control. A compensation through increased airspeed may satisfy the required lift margins, but the rapid destabilization of the final approach and flare may pose a more significant hazard. For example, consider a -2 knots/s shear superimposed on an airplane that is typically decelerating at -2 knots/s in the flare and trimmed for 140 KIAS. The net -4 knots/s deceleration may result in a control problem, a short landing, or both.

$$WS_X = \frac{140\text{-}120}{100/-10} = -2 \text{ knots/s}$$

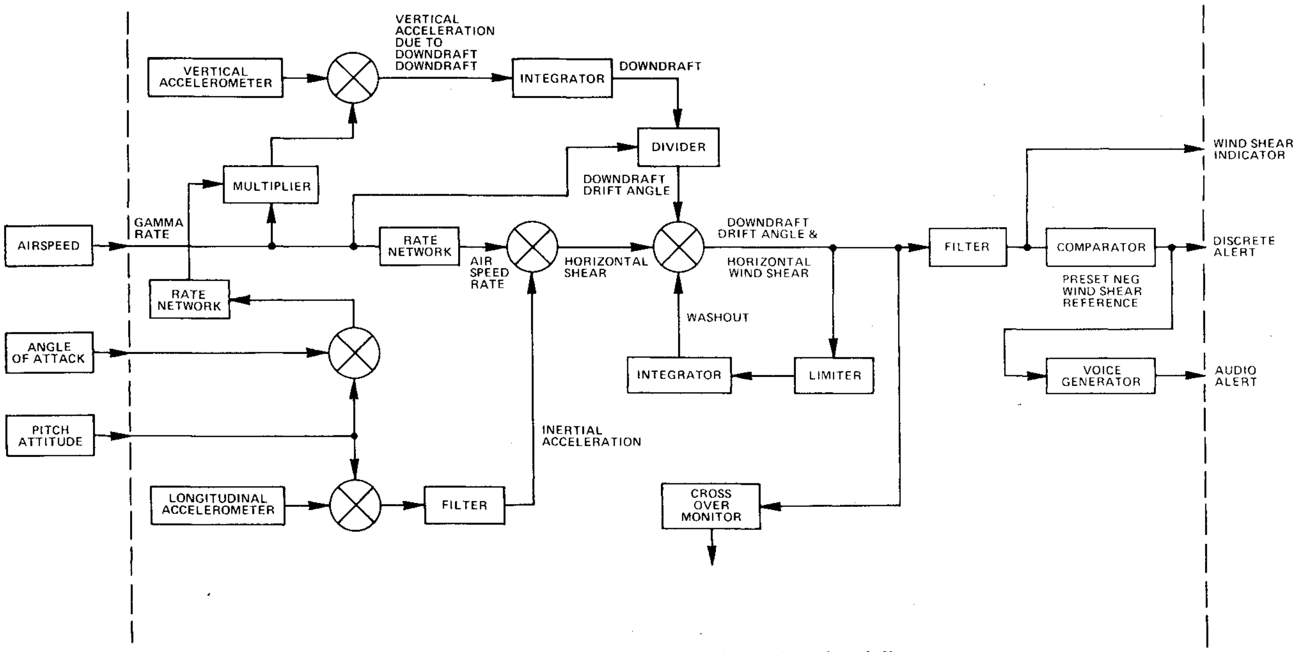

Fig. 3 Wind Shear Monitor system block functional diagram.

Before the contribution of the verticals is discussed, one further question must be addressed regarding the significance of a groundspeed display. In current proposals, the surface wind value below the aircraft is assumed to be identical to that on the runway surface. Assuming the disturbance is on a track opposite the approach path at 20 knots and the airplane is at an airspeed of 140 knots, the groundspeed will be 120 knots. In this example (Fig. 2), however, the outflow beyond the downdraft has a 10-knot component in the direction of the approach course which will not be reflected by groundspeed until that airmass has been penetrated. (In the JFK accident, the reported surface wind was a 6-7 knot headwind, while the threshold wind component calculated by Dr. Fujita was on the order of a 10-15 knot tailwind.) It should be noted that where tower-located anemometers only are available, the reported wind may be considerably at variance with the threshold environment.

Wind Shear Monitor System

As it is the rate of change of headwind/tailwind component along the flight path that is of concern to the pilot, the Wind Shear Monitor compares inertial rate, derived from an accelerometer which has been pitch-compensated, to an airspeed-rate signal. The output of this circuit is the measure of the acceleration required to maintain the target speed.

$$WS_X = dV/dt - \ddot{X} \tag{3}$$

Downdraft Drift Angle

The ratio of the velocity of the downdraft to the forward speed of the airplane is the measure of the angular displacement of the airplane from its previous flight path. We term this displacement the downdraft drift angle (DDA).

$$DDA = WV_Z / V \tag{4}$$

When the DDA is expressed in radians, the thrust required to overcome a given displacement is equivalent to that required to overcome a similar value of horizontal wind shear, when that shear is expressed in units of acceleration. Thus, a glide path displacement of 0.05 rad requires the same thrust to maintain the intended flight path angle and airspeed as a horizontal wind shear of 0.05 g (1 knot/s). The summation of horizontal shear (in g's) and downdraft drift angle (in radians) is a measure of the total performance loss due to the two orthogonal components of a wind shear encounter. Primarily, it was this relationship that led to Safe Flight's development of the Wind Shear Monitor.

Figure 2 depicts a model of the vertical and horizontal winds considered to be typically present in the downdraft and outflow of a thunderstorm cell. The effect upon the reserve performance capability of an airplane penetrating this shear at 120 KIAS on a 3-deg glide slope at a descent rate of 600 ft/min is as follows: The loss of headwind component of 30 knots in the 30 s required to descend the final 300 ft requires a 1 knot/s or 0.05 g acceleration. The peak downdraft of 20 ft/s would result in a 6-deg glide path displacement if uncorrected. To prevent this, an additional 1/10 g is required to maintain airspeed as the pitch attitude is increased. As the thrust required for level flight is equivalent to 1 knot/s, a typical transport would be unable to successfully perform a go-around in this shear.

$$\begin{aligned} T_{req} &= 0.05\ g\ (1\ \text{knot/s}\ WS_X) \\ &+ 0.10\ g\ (6\ \text{deg DDA}) \\ &+ 0.05\ g\ (-3\ \text{deg}) \\ &= 0.20\ g \text{ or } 4\ \text{knots/s} \end{aligned}$$

where thrust required is for level flight in the landing configuration.

In order to make a decision to abandon a landing approach due to wind shear/downdraft, the flight crew must be presented with the total performance loss due to the encounter. From a system design standpoint, this means that the thrust required must be determined and displayed independently of corrections made to counteract the shear condition. It is apparent that if the crew recognizes the glide path deviation due to a downdraft, they will correct for it. Yet it is important, particularly in a slowly developing shear/downdraft, that the correction (thrust addition/increase pitch attitude) be recognized in order to assess the impact on reserve performance. Figure 3 shows the system block diagram of the Wind Shear Monitor. It may be seen that if the pilot maintains a constant indicated airspeed in a tailwind shear, the output of the horizontal circuit will be the result of an inertial forward acceleration due to applied thrust. In the case where the airspeed loss is unobserved by the crew, the inertial rate will be near zero, while the negative airspeed rate will be sensed by the monitor as a tailwind shear. In either instance, the display is identical, showing the crew the effects on performance of the conditions experienced.

The vertical computation is similarly displayed. The flight path angle is computed by summing the angle of attack from the aircraft's stall warning system with a pitch attitude reference signal.

$$\gamma = \theta - \alpha \tag{5}$$

The gamma reference is differentiated and multiplied by the airspeed signal to produce a maneuvering load term. This value represents the calculated incremental normal acceleration due to flight path angle changes. After comparison to the output of the computer-contained normal accelerometer, any differences must be the result of vertical air motion. Thus, the net reduced normal acceleration experienced in a downdraft is detected. When integrated, this term represents the vertical wind.

$$WV_Z = \int_0^t \left[\ddot{Z} - \left(1 + V\frac{d\gamma}{dt}k\right)\right]dt \tag{6}$$

The vertical wind velocity divided by the airspeed determines the downdraft drift angle.

As in the horizontal case, a pitch correction made to overcome the downdraft does not mislead the system. An uncorrected vertical displacement will result in a near constant normal acceleration with a developing negative gamma rate; a nose-up correction to maintain glide path will develop less than the calculated increased normal acceleration, showing the performance loss due to the downdraft.

Thus, the total performance loss in a wind shear encounter is computed by the Wind Shear Monitor as expressed by the algorithm:

$$\begin{aligned} \Sigma WS &= WS_X + DDA \\ &= \left(\frac{dV}{dt} - \ddot{X}\right) + \frac{\left(\int_0^t \left[\ddot{Z} - \left(1 + V\frac{d\gamma}{dt}k\right)\right]dt\right)}{V} \end{aligned} \tag{7}$$

Reliability

From one perspective, the benefit derived from a warning system is inversely proportional to the number of false alerts. In the case of systems where alert conditions are extremely rare (for example, fire detection), flight crew confidence falls rapidly with exposure to warning, the number of which might be tolerable in less flight-critical systems. Thus, of the several simulation and in-flight evaluation programs currently involving the Wind Shear Monitor, the recording program of over 400 flights on an in-service B727-200 airplane is most

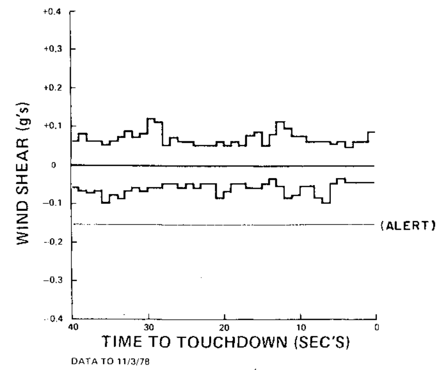

Fig. 4 Peak experienced wind shear UAL/B727-222, S/N 7623.

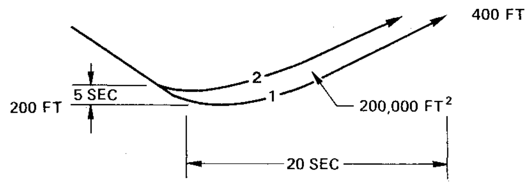

Fig. 5 Improved go-around performance.

significant. Figure 4 shows the peak levels of shear values recorded for each of the last 40 s of the landing approach. This time frame represents approximately the last 500 ft of descent during the landing. The margin between the data and the value nominally selected for a go-around provides confidence that a conservative alert point may be selected without false warnings. When the assumption is made that conditions indicating the advisability of a go-around may occur once every 2000-3000 landings, the computational reliability must be on the order of less than one false warning per 10,000 landings. This goal appears to be readily attainable by the Wind Shear Monitor as presently designed.

Wind Shear Recovery

It is unlikely that in the near future, advances in micrometeorology or airborne sensing will result in the availability to air carrier operators of a warning in advance of a wind shear encounter. It is also unlikely that the general weather conditions associated with severe shears and downdrafts will be sufficient cause for the precautionary closing of an airport. The widely varied experiences of each of the several aircraft preceding and following the one involved in the JFK accident indicates that landings can be made with safety in the climate of thunderstorm activity. One lesson the analysis of that accident demonstrates is the need for real-time performance information to be displayed to the flight crew.

The improvement in terrain clearance resulting from an early decision to make a go-around is dramatic. Figure 5 shows the higher flight profile obtained by a 5 s earlier go-around decision. It should be noted that the point at which the summed vertical and horizontal winds requiring the equivalent acceleration of 3 knots/s to maintain speed and glide slope in the JFK accident occurred 9 s prior to the go-around command recorded on the cockpit voice recorder (CVR). A decision to initiate the go-around 9 s earlier would have represented an improvement in profile of 360,000 ft^2.

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Announcement: 1979 Author and Subject Index

The indexes of the six AIAA achive journals (*AIAA Journal, Journal of Aircraft, Journal of Energy, Journal of Guidance and Control, Journal of Hydronautics, Journal of Spacecraft and Rockets*) will be combined and mailed separately early in 1980. In addition, papers appearing in volumes of the *Progress in Astronautics and Aeronautics* book series published in 1979 will be included. Librarians will receive one copy of the index for each subscription which they have. Any AIAA member who subscribes to one or more Journals will receive one index. Additional copies may be purchased by anyone, at $10 per copy, from AIAA EDP, Room 730, 1290 Avenue of the Americas, New York, New York 10019. **Remittance must accompany the order.**

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