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LOW-LEVEL WIND VARIATIONS IN RELATION TO AIRCRAFT OPERATIONS

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Summary

This paper describes some aspects of the Windshear hazard to aircraft on the approach and climb-out phases, and the related topic of the representativeness of surface wind reports supplied to pilots shortly before touch-down or take-off. Ideas on the introduction of routine operational forecasts (or warnings) of Windshear at major airfields in the UK are discussed, and a review of progress in the development of remote-sensing wind measurement systems and their potential as all-weather operational tools is included.

1. Introduction

The operational problems experienced by modern large transport turbo jet aircraft (particularly in the civil sector) in the approach phase due to low-level wind variations fall into two main categories: the surface wind representativeness problem and the so-called 'Windshear' problem.

1.1 Surface-wind representativeness problem

This is concerned with the representativeness of the wind vector given by air traffic control to the pilot about to land or take-off. This problem has been present in some form since the beginning of aviation but has assumed increasing importance with increasing size of aircraft and number of passengers carried.

1.2 The Windshear problem

Windshear is now widely regarded as the most serious operational problem affecting modern aircraft but has only been recognised in the past decade as the cause of several landing and take-off accidents previously attributed to pilot error. It has to do with the handling problems of large aircraft created by large and sudden changes in airspeed encountered mainly within the height band 30-300 m when the aircraft is close to stalling speed.

The term 'Windshear' is a now generally accepted colloquial title of the problem which is only loosely related to the physical causes of sudden headwind changes.

The surface wind representativity problem is discussed in Section 2, and the Windshear problem in Section 3. Both problems overlap to some extent and the Meteorological Office contributions are described in Sections 2 and 4.1. Most of this work has been initiated at the request of, and in collaboration with, British Airways and the Civil Aviation Authority, but links on technical matters are maintained with the Royal Aircraft Establishment, Bedford.

Developments in instrumentation for remote sensing of wind fields, including acoustic and microwave radar, and airborne monitoring of wind variations are also described in Section 4.

2. Representativeness of surface wind reports to pilots

On the approach to landing or shortly before take-off, pilots require a statement of the wind which they are likely to experience at the touch-down or take-off point. CAA Airworthiness Division are of the opinion that a pilot can tolerate "100 per cent error in light winds, 50 per cent error in winds of 10-15 kt and 25 per cent error in winds of 15-25 kt". This is not inconsistent with another view that "random errors of the order of 5 kt in slight turbulence and about 10 kt in gusty conditions can be acceptable but systematic errors in the mean wind should be less than 2 kt". The touch-down/take-off wind is required by the pilot about one minute before touch-down/take-off; later information about the wind is of little help except in cases when an overshoot might be advisable. It is generally recognised that for a wind disturbance or gust to significantly affect the flight-path of modern civil transport aircraft, near touch-down/take-off, its characteristic dimension should be at least 200 m or so; shorter gusts cause bumpiness but no significant deviations from the intended flight-path. (On landing/take-off an aircraft would traverse a horizontal distance of 200 m in about 2-3 seconds.)

There are two main sources of error in the wind passed by ATC.

(i) If the airfield has a single anemometer, this may be some considerable distance away from the intended touch-down/take-off point, and spatial variability of surface wind is one obvious source of error. In this context ICAO[1] recommended that "for reports for take-off, the surface wind observations should be representative of the average lift-off area, and for reports for landing the observations should be representative of the touch-down zone" and that "representative wind observations should be obtained by using one or more sensors appropriately placed according to local conditions; for example separate sensors may be needed to obtain measurements representative of the lift-off and touch-down areas."

(ii) As mentioned above, the pilot requires the wind about a minute before touch-down/take-off, so that even if the anemometer is sited directly at the point of interest, the temporal variability of wind over the one-minute period at that point will introduce error. For a given time lag between the passing of the wind report to the pilot near touch-down/take-off, the errors due to temporal variability can be increased by the use of a wind-averaging period which is too short for the purpose. If, for instance, the anemometer is 2-3 km away from the point of interest and the wind is supplied to the pilot 1 minute before touch-down/take-off, the use of a 10-15 second average would be unjustified; the variability, both in time and space, of such a short period wind is such that, as a forecast of the wind affecting the aircraft near touch-down/take-off a short time later, it would always be more likely to contain a larger error than a wind averaged over a longer time interval. So there are two main areas, not unrelated, within the general field of surface wind representativeness, one to do with the averaging time of wind reports to pilots, and the other concerned with the requirement for multiple anemometer installations.

2.1 Optimum averaging period for wind reports to pilots

Given a continuous series of short period wind averages (eg 30 second winds) recorded at a single anemometer, it is possible to evaluate a frequency distribution of vector differences between (i) the wind averaged over time τ_1 (the ATC wind report) and (ii) the wind averaged over time τ_2 some time (Δt) later (the wind the aircraft experiences at touch-down/take-off). A series of near-continuous 30 second surface (10 m) winds exists for Heathrow (south-west site anemometer), recorded by a Meteorological Office Mark 5 wind system[2] with a DALE (Digital Anemograph Logging Equipment) unit attached[3] operating from January to December 1974. A total of 7298 hours are available for analysis. In the analysis performed on this data τ_1 and Δt were varied from 30 seconds to 10 minutes, and τ_2 was fixed at 30 seconds; distributions of the magnitude of vector error between the two winds were computed for each combination of τ_1 and Δt. Some of the results of this analysis are presented in Figure 1 which shows the frequency of differences or errors in excess of 10 kt, as a function of wind averaging period (τ_1) and lag (Δt). For operationally realistic lag times of about a minute the figure shows that an averaging period in the range 1 to 4 minutes minimises the frequency of occurrence of errors in excess of 10 kt. These results confirm the earlier findings of others[4,5] and lend support to the ICAO-recommended[1] 2 minute averaging period of ATC winds. Table 1 lists percentage frequencies of errors exceeding 6, 10 and 14 kt for a 1 minute lag and a 2 minute wind-averaging period, as a function of 2 minute wind speed. The figures in this table can be considered typical of a site similar to that of Heathrow's south-west anemometer (with generally similar synoptic experience) and since the assumption is implicit in the analysis that the anemometer is always directly at the point of interest, they probably represent error statistics that are slightly beyond (ie on the optimistic side of) the best operationally achievable.

Although the use of an optimum averaging period is important, Figure 1 shows that the frequency of large errors is generally more sensitive to variations in the lag (Δt) than to variations in the averaging period. So it is obviously important to ensure that this time lag is kept to a practical minimum.

2.2 Multiple anemometer installations

The number of long runways (3000 to 4500 m) has increased during the past 15 years by 30 to 40%, and the overall size of some airfields with multiple runways has, in some cases, tripled. In addition the number and size of buildings on airfields have increased. The results of an ICAO analysis of 35 airports in Europe and Asia revealed that the average distance of the anemometer from the runway centre line is about 300 m while the average distance from the runway threshold is about 1000 m. The average lift-off position for long-range jet transports was found to be about 1500 m from the nearest anemometer.

A recent study[6] undertaken for the CAA, based on the analysis of surface wind records from one anemometer (Heathrow 1974 - 30 second winds) has suggested that if about half of all touch-downs/take-offs take place near an anemometer (within about 300 m), the probability of large ATC wind errors could be reduced by a factor of 2 or 3 by upgrading to full anemometer coverage (anemometers near all touch-down/take-off points). The method of analysis was based on the assumption that the statistics of differences between winds at two points separated by horizontal distance d can be regarded as similar to the statistics of differences between winds at one point separated by a time interval $t \approx d/\bar{u}$, where $\bar{u}$ is the mean wind speed. Such a method implicitly assumes identical exposure of the two (real and hypothetical) sites. At Heathrow the surface wind near the threshold of runway 28R (in the north-east corner of the Airport) is thought to be influenced by nearby buildings and an additional anemometer was installed in this area during 1977; Heathrow's other anemometer is over 3 km away near the well exposed threshold of runway 10R in the south-west corner. As a logical follow-up to Dutton's[6] work giving estimates of the frequency distribution of two-point differences over a 2 to 3 km base-line, based on the records of a single anemometer, the Meteorological Office recommended to the CAA that the statistics of actual wind differences between the two Heathrow anemometer sites be investigated systematically by attaching a DALE unit to each anemometer to record 30 second wind averages continuously for a period of a year. This recommendation has been accepted by the CAA who believe that the results of such a study will help to shed light on the question of whether the different exposures of the two sites produce significantly different wind characteristics (eg are the mean winds and turbulence intensities significantly different as appears to be the case in certain situations? Can these situations be identified? Are the differences dependent on wind direction as might be expected?) In addition the data gathered may help to quantify the frequency of occurrence of very large systematic wind differences (horizontal wind shear) across the Airport due to passage of meso-scale disturbances such as thunderstorms or their gust fronts, or synoptic scale features such as active cold fronts with large wind-shifts; such information would also be useful in the Windshear studies.

A Working Group, formed in 1977 at the request of CAA, to assess the operational requirement for multiple anemometers at airfields, recommended that "the need should be considered for multiple anemometers at aerodromes where touch-down points have significantly different exposure from that of the standard airfield anemometer". The CAA[7] stated that "it does not appear that there is a general requirement for more than one anemometer at airfields in the UK, except to cater for special cases where there is disturbance due to local topography and buildings". The north-east site at Heathrow was just such a special case in the opinion of pilots using runway 28R.

ICAO are currently seeking opinions from Member States on the necessity for, and the feasibility of, quantitative guidance criteria to help determine whether the wind observations at a particular point on an airfield can be considered to be "representative" of the touch-down or lift-off areas; preferably these criteria should indicate how often differences of a certain magnitude or greater could be tolerated from an operational point of view, between the representative wind and that actually experienced by the aircraft at touch-down/take-off. The onus must be on the airlines, pilots and aviation authorities to decide on such quantitative criteria. However, in defining what the tolerances are for the wind reports that are required, it is important for the customer to bear in mind that:

(i) some degree of error in the ATC wind is inevitable, even if the anemometers are positioned close to all touch-down/take-off points; the best operationally achievable error statistics, those appropriate to full anemometer coverage and the minimum practical time lag (about one minute) between the passing of the wind report and touch-down/take-off have already been alluded to (Table 1). The table shows that over the year as a whole at least 0.76 per cent of ATC (2 minute mean) winds will be in error by 6 kt or more while at least 0.028 per cent will be in error by 10 kt or more.

(ii) estimates by Dutton[6] indicate that, on an airfield where exposure is good at all touch-down/take-off points, if about half of all touch-downs/take-offs are in areas 2 to 3 km distant from the nearest anemometer, the frequency of errors of 10 kt or more is increased by a factor of 2 or 3 more than the best achievable figures appropriate to full anemometer coverage.

In the event that wind information from more than one anemometer is available at an airfield, a suggested routine procedure for passing of wind reports to pilots would be as follows: ATC should pass a 2 minute average of wind (together with, if necessary, gust/lull information relevant to the previous 10 minutes) to the pilot shortly before take-off or touch-down; the final wind should be passed to the pilot not more than two minutes before take-off or touch-down. This information should be taken from the anemometer giving winds most representative of the planned take-off or touch-down position (not necessarily the nearest anemometer). Suitable displays (analogue or digital) of wind information, including 2 minute averages of wind and gust/lull values for the previous 10 minutes should be available to ATC. To avoid confusion however it is suggested that no more than two sets of winds are displayed to any one Air Traffic Controller at any one time; these would be the winds at (i) the standard airfield (well exposed) anemometer, and (ii) (if different) the anemometer giving winds most representative of the take-off or touch-down position of the next aircraft due for take-off or landing.

All other airfield winds such as those included in the half-hourly ATIS (Air Traffic Information Service) broadcast should be taken from the best exposed anemometer, and should be averaged over 10 minutes. In addition, decisions as to which runway to use should be based on the winds given by the best exposed anemometer. On this last-mentioned subject of runway selection, it is also suggested that in light surface wind conditions, when the choice of runway may be dictated by noise abatement rules alone, due account be taken of the upper winds (as estimated for example from the surface pressure gradient), especially when they are in excess of 30 kt or so. In such situations an appreciable vertical shear of wind is implied and the selection of a runway direction which will minimise the potential hazard posed by the shear may be important.

3. Windshear on the approach and climb-out

3.1 Definition of 'Windshear'

The rather indiscriminate use of the term 'Windshear' in aviation circles has lead to some confusion between cause and effect.

As we see it, 'Windshear' is the name given by the aviation world to a fairly specific effect of wind variations in producing large and sudden changes in air speed experienced by aircraft at low levels. In practice, 'Windshear' is sometimes taken to be the actual change in airspeed (very nearly equal to the headwind change) with no reference to an associated gradient distance (or equivalent time), but is more usually expressed as "x knots over t seconds" or as "y knots per second persisting for t seconds". (Where y = x/t). (see figure 2)

To the meteorologist, wind shear is the wind gradient normal to the mean horizontal wind (vertical or horizontal shear) - a gust being an along-wind change. Thus the wind structures responsible for causing a 'Windshear' incident may or may not include meteorological wind shear as a principal component.

In this paper a distinction is made between the two uses of wind shear by writing the aviation use as one word 'Windshear' and the meteorological use as two separate words 'wind shear'.

3.2 Effects of Windshear on aircraft

The effects of wind variations on aircraft landing or take-off are complex; they depend on the nature of the wind changes, on the aircraft's characteristics, its size and on the handling of the aircraft by the pilot.

Figure 3 illustrates typical values of descent rate, ground speed and the relationship between thrust (or power) settings required to maintain an approach along a 3^{o} glide-slope at constant airspeed ($75\ m\ s^{-1}$) in constant headwind conditions with (a) $10\ m\ s^{-1}$ headwind, (b) calm, and (c) $10\ m\ s^{-1}$ tailwind. It is necessary to bear in mind the relationships between these simple parameters in the different wind conditions before going on to look at the effect of an idealized instantaneous headwind change at some point on the glide-slope.

The two main types of Windshear are:

(i) Instantaneous tailwind increase (Figure 4a)

Assuming that the aircraft is initially stabilised on the approach, when the tailwind increase is encountered the loss of lift and the natural tendency for the aircraft to pitch nose down cause it to accelerate downwards away from the 3^{o} glide-slope. When the pilot becomes aware of the deviation his usual reaction is to increase power to regain the desired airspeed. If the Windshear is encountered close to the ground the aircraft response may be too long and a short hard landing may result. If however the Windshear is encountered at a high enough altitude to allow time for the aircraft to regain the glide-slope, assuming no further wind changes take place the aircraft will continue rising above the glide-slope unless the pilot reduces engine power; the headwind is now below its original value (it may have changed to a tailwind) and the power necessary to maintain the 3^{o} glide-slope is less than was required to maintain the glide-slope before the Windshear. So, unless the pilot makes the necessary reduction in power shortly before regaining the glide-slope, there is a danger of overshoot or, at least, a 'long' landing.

(ii) Instantaneous headwind increase (Figure 4b)

With again the assumption that the aircraft is initially stablized on the approach a headwind increase will induce an increase in lift and the natural tendency for the aircraft to pitch the nose up will cause it to accelerate upwards away from the intended glide-slope. In response the pilot tends to reduce power to regain the desired airspeed. If the Windshear is encountered close to the ground a 'long' landing may result but if it is encountered at a higher altitude, assuming no further wind changes take place and the pilot fails to increase power fairly promptly as the glide-slope is regained, the aircraft will develop a high rate of descent, and a hard landing may result; as the headwind is now above its original value the power necessary to maintain the 3° glide-slope is greater than was required to maintain it before the Windshear.

The two cases described above involve changes in headwind within much shorter periods than the aircraft response time to wind variations. In most real situations the nature of the wind variations will be complex, often involving large changes of wind on time scales which are comparable with or larger than the aircraft response time. In particular the effect of headwind changes are accentuated if they are consecutive and of opposite sign, ie a headwind increase followed by a headwind decrease (or vice versa) in a time comparable to the aircraft response time. Thus aerodynamicists now consider that the magnitude of certain second differential (or curvature) properties of headwind variation may be of greater operational significance than the first differential (gust or shear) properties. For typical modern civil transport aircraft, the implication is that turbulent eddies of characteristic dimensions 0.5-1 km will be closely tuned to aircraft responce. This also happens to be the range of scales in which a substantial part of boundary layer turbulence resides.

The aircraft handling problems created by these types of wind variation are more severe for modern turbo-jet aircraft than for their piston-engined predecessors for two main reasons:

(i) The aircraft response time referred to above is an overall factor comprised of pilot reaction time plus engine response time in response to a change in power setting plus aircraft inertial response to the resultant change in thrust. The considerable increase in the latter two factors due to larger engines, the transition to jet mode, and the much increased momentum, greater weight and higher approach speeds of jets, have contributed to the problem. In addition the extra lift generated by a propeller slipstream is absent on jet aircraft.

Using typical figures for aircraft weight, drag, thrust and target threshold airspeed, it is possible to obtain a measure of the potential acceleration for level flight (in units of gravity) or the climb gradient achievable in unaccelerated flight, from the ratio of maximum thrust minus drag (available excess thrust) to weight. This potential acceleration or climb gradient can be expressed in respectively knots per second and feet per second (aviation units) and it is then a short step to Figure 7, taken from Hopkins[9], which attempts to illustrate for different types of jet aircraft on approach at maximum landing weight and at ISA + 10°C, the aircraft's capacity, using the energy stored as excess available thrust, to counteract a steady downdraught and/or rate of change of headwind. For a given aircraft type the area above the line represents combinations of downdraught and rate of change of headwind that the aircraft, given the stated conditions, would be unable to counteract even at maximum thrust; note however that this inability to maintain the desired airspeed and/or glide-slope persists only as long as the particular combination of downdraught/headwind change rate persists.

(ii) The relationship between the approach airspeed and the 'minimum drag speed' (V_{MD} the airspeed at which total aircraft drag is a minimum) for modern jets renders them more susceptible than piston-engined and early jet aircraft to changes in headwind on the approach and climb-out[8]. The 'target threshold speed' (V_{AT} - intended airspeed over the runway threshold) of an aircraft is based on its stalling speed (V_s), which is itself a function (Figure 5) of aircraft weight (W) ($V_s \propto W^{\frac{1}{2}}$ approximately) and configuration (eg 'full flap' V_s is substantially less than 'clean' V_s). The nominal V_{AT} is typically about 1.3 V_s for both piston-engined and jet aircraft, but it is normal for pilots to add to this some proportion, usually half, of the reported surface headwind. The 'speed stability' of the aircraft at a given airspeed is determined by the slope of the 'total drag curve'. Figure 6 shows schematically a typical drag curve; the speed stability over the airspeed range of the curve where its slope is positive is termed 'stable', since a decrease (increase) in airspeed due to headwind changes results in decreased (increased) drag leading to some recovery (loss) of airspeed, assuming no thrust changes. The speed stability over the range where the slope of the curve is negative, below the minimum drag speed, is termed 'unstable', since a decrease (increase) in airspeed here results in increased (decreased) drag leading to further loss (increase) of airspeed. Over the range of airspeed near V_{MD} the speed stability is 'neutral'.

The approach speed stability state of most modern jet aircraft in the full-flap configuration is, at best, neutral, with the majority being definitely unstable; typically $V_{MD} \approx 1.4\ V_s$. (The phrase "on the back of the drag curve" refers to aircraft operating on the unstable part of the drag curve.)

For piston-engined aircraft $V_{MD} \approx 1.2\ V_s$ ('full-flap'), typically. It is not therefore difficult to understand why modern jets tend to be more susceptible to wind variations than their earlier propeller-driven counterparts.

For a good account of the effects of Windshear on aircraft see Luers and Reeves[10].

3.3 Sources of Windshear incidents

3.3.1 Vertical shear of the mean horizontal wind

This type of wind shear involving a variation in the mean horizontal wind speed and/or direction (averaged over periods greater than 10 minutes or so) is always present to some extent in the atmospheric boundary layer, usually in the form of an increase of mean wind speed and veering (in the Northern Hemisphere) of wind direction with increasing height, due to the interaction of pressure and Coriolis force with the frictional retardation exerted by the earth's surface. The size of the vertical wind shear that can be supported across a layer of atmosphere is related to the thermal stability within the layer; the more stable the layer the greater the magnitude of vertical wind shear that can be supported without breakdown of the airflow into turbulence. In consequence abnormally large vertical wind shears tend to be associated with stable layers. The most commonly observed significant wind shears of this type, within the lowest 1 km or so, are associated with the formation at night of ground-based inversions due to rapid radiational cooling of the surface after sunset under conditions of clear skies and relatively light winds. In some instances the reduction of wind to near-calm at the surface may be accompanied by an (inertial) acceleration of the airflow near the top of the ground-based inversion, due to frictional de-coupling of the upper flow from the surface leading to an inertial oscillation (period of about 16 hours at 50°N) of the ageostrophic component of the wind. A maximum wind speed (from the direction of the geostrophic wind) near the top of the inversion is generally achieved 4 to 8 hours after sunset. This phenomenon has become known as a nocturnal low-level jet[11,12]. An analysis of ten years of captive balloon ascents from Cardington has shown that it can be observed, usually in a weak form, on about one night in five. Figure 8 shows an example of such a low-level jet observed at Cardington, Bedfordshire; low-level jets of this magnitude were observed on about one night in fifty within the (biased) Cardington data set. Figure 9 shows seasonal mean wind speed profiles, derived from the same data set, for Spring.

Wind shears of the order of 0.05-0.1 s^{-1} over the lowest 200-300 m associated with ground-based inversions (with or without the low-level jet feature) have been known to create problems for aircraft on approach or climb-out; the problems experienced may not be entirely due to headwind variations - the associated, often appreciable, temperature/density variations produce variations in lift and engine performance. In addition the change in wind is usually fairly gradual over a relatively deep layer, and the often smooth turbulence-free flying conditions give no indication of any problem unless instrument readings are carefully monitored.

Elevated inversions or stable layers also frequently support substantial vertical wind shears and these may be, most commonly, synoptic-scale anticyclonic subsidence inversions, usually found above about 300 m, or synoptic-scale frontal zones which extend down to the surface. The presence on the glide-slope of a frontal zone and associated wind shear was, according to the National Transportation Safety Board (NTSB) of the USA, a contributory factor in an accident to a DC-10 at Logan International Airport on 17 December 1973[13]. The aircraft was making an ILS (Instrument Landing System) approach to runway 33L (orientated 322° true) and encountered the vertical wind profile shown in Table 2.

A slow-moving cold front had passed through Logan and surface winds were northwesterly while the winds above the frontal zone were generally southerly. The approach through the cold frontal zone to runway 33L was handled by the autopilot down to 200 ft where the pilot had to take over control because the ILS glide-slope was unusable below this level; down to 200 ft the autopilot had made gradual power and pitch attitude reductions but the effects of the wind shear were most pronounced at a time when the captain had to take over, and because of his preoccupation with trying to obtain visual cues in poor visibility he failed to react quickly enough as the aircraft developed a high rate of descent after passing through the wind shear layer and into an airflow with roughly constant headwind component. The autopilot had been gradually reducing power and pitching the nose down so that the aircraft was decelerating gradually; when the wind shear effectively ceased at about 200 ft rapid increases in power and pitch attitude were necessary to halt the inertial deceleration, which, in the then roughly constant headwind, was producing an equivalent airspeed decrease and hence loss of lift. The pilot failed to make the necessary thrust and pitch attitude changes sufficiently quickly and the aircraft crashed short of the runway threshold. Flight simulator tests showed that, under the existing flight conditions, a significant pitch attitude increase and thrust additions were required within 6 seconds (the pilot took 9 seconds) after the autopilot was disengaged, to arrest the high rate of descent.

The NTSB concluded that the probable cause of this accident was that "the captain did not recognise, and may have been unable to recognise, an increased rate of descent in time to arrest it before the aircraft struck the approach light piers. The increased rate of descent was induced by an encounter with low altitude wind shear at a critical point in the landing approach where he was transitioning from automatic flight condition to manual flight control ...."

The types of wind shear so far described within this section do not generally involve significant mean vertical velocities and the levels of turbulence are normally low in the case of wind shear associated with ground-based inversions and low-level jets, but may be appreciable in the region of active frontal zones.

In this sub-section dealing with vertical shear of the mean horizontal wind, other relevant sources of abnormal shears include sea- or lake-breezes, (and their nocturnal counterparts) sometimes a source of minor difficulty at some airfields near coasts or large bodies of water, orographic effects (including flow separation, and other lee effects in mountain-wave conditions) which can concentrate the free-flow vertical wind shear[14,15], and the effects of man-made obstructions and buildings[16]. All of these last mentioned phenomena can and often do involve non-negligible mean vertical velocities and levels of turbulence. Where they occur, their effects may persist for times of the order of several minutes to several hours.

Estimates of the overall frequency of vertical wind shear for a conglomerate of worldwide airfields for which such data existed, were presented at the 8th Air Navigation Conference of ICAO[1]. These estimates related only to the 10-40 m layer and to two-minute averages of vector and shear magnitudes, and were as follows:

Vertical Wind Shear	Percentage of Time Exceeded
3 kt per 30 m	50
5 kt per 30 m	17
8 kt per 30 m	2
10 kt per 30 m	0.4

For the types of wind shear that have been described in this sub-section, those involving vertical shear of the mean horizontal wind and usually persisting for times of the order of an hour up to several hours, the aircraft's low angles of descent ($\sim 3^{\circ}$) or ascent ($\sim 15^{\circ}$) on approach or climb-out often preclude large rapid variations of wind along the flight path. The variations are normally gradual across layers perhaps 100-300 m deep, representing 30-100 s of aircraft time on descent and 5-15 s on ascent.

3.3.2 Wind variations over relatively short time or distance

a. Thunderstorms

Mesoscale wind variations associated with deep convection have long been known to be hazardous to aircraft. The most extreme of such variations near the surface are associated with mature thunderstorms, in particular with the downdraught region and the gust front which is produced as the downdraught diverges at the surface, manifesting itself as a sudden surge of wind speed at the discontinuity between the cold dense air and the less dense air being displaced. Typically the outflow air is about 1 km in depth and its movement over the surface is difficult to predict, being influenced by topography, low-level atmospheric stability and the free-flow wind direction[17] outside the storm.

Evidence exists of instability and lobing structure within gust-fronts and they have been known to advance at speeds of 10-20 $m\,s^{-1}$ for distances of up to 30 km, persisting for as long as one hour after their formation[18]. In addition strong vertical wind shear and turbulence are often present near the top of the out-flowing cold air.

The downdraught region and the gust-front can involve very large and rapid wind variations for aircraft traversing them and are probably the most hazardous of all sources of Windshear.

Descriptions of two accidents caused by the airflow near thunderstorms will serve to illustrate this.

Accident at John F Kennedy (JFK) Airport, 24 June 1975[19,20]

Surface temperatures in New Jersey, away from the coast, had reached 32-34°C during the afternoon of 24 June 1975 and by 1900 GMT (3.00 pm local time) several weak thunderstorms had developed over northern New Jersey and were heading towards JFK Airport, where the surface temperature was 25°C under the influence of a sea breeze. By 1945 GMT the radar echoes, one of which had developed into what is termed a "spearhead" echo 8 km wide and 32 km long had advanced to affect the approach to runway 22L at JFK.

During a 25 minute period, 1945-2010 GMT, 14 aircraft landed or attempted to land on that runway. Each of the 14 aircraft flew through a portion of the 'spearhead' echo, experiencing situations ranging from no problems to serious difficulties (3 aircraft), including the accident which occurred involving a B-727 aircraft. On the approach shortly before 2005 it encountered heavy rain at 150 m (altitude). The approach lights became visible at 120 m whereupon the airspeed dropped from 71 to 63 ms^{-1} within 7 seconds. The aircraft sank in a 6.7 ms^{-1} downburst at 60 m and hit the approach lights at 2005 GMT about 730 m short of the runway. The variation of vector wind along the glide-slope was determined to be the cause. Figure 10, reconstructed from various sources of data, attempts to illustrate the sequence of winds and the resultant flight path experienced by the aircraft during the final stages of descent through a downburst cell. The term downburst has been coined by Fujita and Byers[21] as referring to a particularly intense downdraught; they proposed the use of this term when the downdraught speed becomes comparable to or greater than the approximate rate of descent or climb of a jet aircraft on the final approach or take-off at 90 m above the surface. The horizontal dimensions of the downdraught are also involved in the full definition of a downburst which is a localised, intense downdraught with vertical currents exceeding a downward speed of 3.6 ms^{-1} at 90 m above the surface. The areal extent of a downburst is 800 m or larger in diameter, characterized by a 0.04 s^{-1} or larger divergence.

The B-727 aircraft lost airspeed suddenly at 91 m when a 8 ms^{-1} headwind changed into a 6.4 ms^{-1} downburst. It apparently flew straight into the downburst centre. The sudden loss of airspeed and the intensity of the downburst were so severe that the pilot could apparently do little to avoid the crash.

Accident at Stapleton Airport, Denver, 7 August 1975[19,22]

With surface temperatures above 30°C, thunderstorms affected Stapleton Airport, Denver from about 1430 local time (MDT) onwards on 7 August 1975. A B-727 aircraft took off on runway 35L at 1610 MDT using maximum take-off thrust. Indicated airspeed was 40 ms^{-1} (80 kt) as it entered rain shortly before lift-off. Following a normal lift-off, and climbing at an angle of 14°, the airspeed decreased from 81 to 60 ms^{-1} in about 5 seconds at about 30 m above ground (ie rate of loss of airspeed was about 4 ms^{-2}). As the aircraft started to descend the captain lowered the nose to about a 10° pitch but the aircraft continued descending and just before it struck the ground, the stall warning system was activated.

Following careful examination of weather radar information Fujita and Caracena[19] concluded that a spearhead echo existed over Stapleton runway 35L at the time of the accident at 1611 MDT, and that the aircraft flew through what was undoubtedly a strong downburst. The spearhead echo over Stapleton was about half the size of that associated with the JFK storm.

A further accident apparently involving a downburst occurred to an aircraft on approach to Philadelphia International Airport on 23 June 1976; it apparently flew through the centre of a downburst cell with an intense core of heavy rain, and an eyewitness saw the aircraft crash on the runway "after emerging out of a wall of water[19]". Again, a large spearhead echo near the site of the crash was identified on weather-radar pictures.

The Fujita-Byers model of a spearhead echo is summarised briefly in Figure 11.

The accidents described above all apparently involved penetration of the horizontally divergent windfields beneath intense downdraughts, or so-called downbursts, created within so-called spearhead echo thunderstorms. Fujita and Caracena[19] point out that most USA National Weather Service (NWS) radar sites are remote from the airports they serve and that, from these sites the storm echoes which contain the hazardous downbursts do not appear particularly impressive, and spearhead echoes are not easily identified as such. They suggest that some form of computer-enhanced images of the radar echoes over airport area space be made available to ATC; identification of the most hazardous storms may then be facilitated.

Although the UK does not experience intense thunderstorm activity with the frequency that many parts of the USA do, it is certainly no stranger to severe thunderstorms[23,24] and their associated downdraughts or gust fronts. Figure 12 shows an example of the passage of a gust-front at Heathrow on 20 October 1974; the figure shows the time variation of 30 second averages of surface (10 m) wind speed and direction as recorded at the south-west site anemometer. In this instance a burst of heavy rain associated with a thunderstorm followed, about 3-4 minutes after the initial wind-speed surge. Figure 13 shows a series of gust front or squall-type events which occurred at Heathrow on 9 April 1977; convective activity was pronounced, several showers being reported (although none was heavy) during the course of the day. Surface wind events of this type at Heathrow are the subject of a current investigation within Met O 9; they may represent the most hazardous source of Windshear for aircraft operating into and out of Heathrow.

b. Fronts

Figure 14 is a good illustration of the fact that wind variations of this type need not necessarily be associated with severe convective phenomena. It shows the passage of a cold front through Heathrow (south-west site anemometer) at 1310 GMT on 22 February 1974; the cold front was not particularly active, producing only light rain at most but, as can be seen, the associated wind direction shift was large, accompanied by a sudden increase in wind speed which subsided gradually over the subsequent 15-20 minutes. This feature is known to have caused a hard landing to an aircraft landing at Heathrow on runway 28R (oriented about 270 degrees true). Synoptic scale cold fronts do, however, frequently contain marked convective activity, including thunderstorms, and active cold fronts producing thunderstorms are therefore a potential source of the large rapid wind variations generally associated with individual thunderstorms. The same is true of so-called line-squalls.

c. Strong Winds

Turbulence in strong winds near the surface, even in steady state conditions when the long period mean wind is approximately constant, has long been recognized as a source of potentially hazardous wind variations for aircraft on approach and climb-out. The scales of wind variations involved often cause handling difficulties for large jet aircraft, particularly those operating on the approach and flare stages. In the neutral atmospheric stability conditions that are usually associated with strong surface winds, the spectrum of horizontal wind variance in the lowest 100 m peaks at a wavelength of about 300-600 m (Figure 5). (The scale length, λ_m, of the turbulence process is defined[25] as the wavelength corresponding to the peak of the quantity $\lambda S(\lambda)$ v. $\ln\lambda$ where $S(\lambda)$ is the spectral density or variance per unit wavelength interval. λ_m increases slowly with height from about 300 m at 10 m height to about 600 m at 100 m height.) A substantial part of the variance of horizontal wind therefore resides in wavelengths which are sufficiently long to have a significant effect on the flightpath and/or attitude of an aircraft; typically, a jet aircraft on approach would traverse a 600 m wavelength disturbance in about 8 seconds.

It is when flying in these conditions that the second derivative of wind with respect to time (see Section 3.2) is significant. The combination of a large positive gust persisting for several seconds followed by a large negative gust of similar period, could be particularly hazardous for jet aircraft within the lowest 100 m on the approach. This effect is also called 'rate of shear change'.

When the mean surface wind is strong, the vertical shear of the mean horizontal wind will usually also be appreciable within the lowest 100 m or so, and although the 'noise' of the turbulent fluctuations of wind along the flight path may tend to drown the 'signal' of the mean vertical wind shear (see Figure 16) the latter must undoubtedly constitute an added complication in what may already be a difficult situation on approach or climb-out. (For a roughness length of about 0.1 m, there is a 50% increase in mean wind speed from 10 m to 100 m above ground). In addition, handling difficulties in strong winds during the final approach and flare stages may be aggravated by wake turbulence from airfield buildings[16], particularly in cross-winds.

Incident at Heathrow, 11 January 1978

On 11 January 1978 an aircraft taking off from runway 10R (oriented 090° true) at Heathrow, with mean surface winds of 360/31 kt (gusts to 54 kt), encountered at lift-off what may have been a wake vortex shed from the central Airport complex (to the north of the runway). The aircraft lost 32 kt of airspeed in about 1 second, and fortunately regained it almost immediately. The presence of a strong cross-wind aggravated the aircraft's problems and a violent rolling motion dipped one wing within 0.2 m (computed from flight record) of the ground before the pilot was able to regain sufficient control. This 'event' is currently being investigated by the CAADRP (Civil Aviation Authority Data Recording Programme) Panel, a group of experts who regularly monitor and examine such 'events' which are the output of a computer-programmed sifting process of aircraft flight-record data. The programme searches through the flight records highlighting the 'events' where aircraft recorded variables fall outside prescribed limits.

4. Operational Aspects of Windshear

4.1 Operational Forecasting

At the eighth Air Navigation Conference of ICAO[1] the Commission on Aeronautical Meteorology (CAeM) recommended that there be an operational requirement for low-level wind shear and turbulence information to be provided to aircraft at the beginning of the final approach and immediately prior to take-off.

Currently, sources of airfield low-level wind information available on a routine operational basis are sparse, and often originate from instrumented towers not more than 100 m high and which are necessarily sited some distance from the region of interest. Radar wind data from nearby routine radiosonde stations generally contain little useful wind information below 500 m or so and are subject to the limitations of representativeness normally associated with balloon-tracking methods of wind measurement. Measurement of wind profiles using captive balloons (supporting the necessary sensors) is limited by strong winds and the risk of lightning.

Some success has been achieved in identifying meteorological conditions in which there exists a significantly higher probability than average that aircraft will experience difficulties due to Windshear. These conditions, discussed in some detail above, are:

(i) The presence of active fronts or other major discontinuities, such as squall-line or sea-breeze fronts, near the airfield.

(ii) The presence of strong convective activity, particularly large cumulonimbus or thunderstorms, near the airfield.

(iii) The existence of a large vector difference between the mean surface wind and the gradient wind estimated from the surface pressure field (supported by radar-wind information where possible).

(iv) The existence of strong surface winds.

(v) The existence of a significant nocturnal low-level jet.

In addition most investigators have found that the best indicators or predictors (for periods up to an hour ahead) of Windshear and turbulence are pilots' reports themselves, passed back to ATC by pilots on the approach and climb-out. It should be stressed that in any operational warning system of the type envisaged here, it is essential that such reports assume the greatest importance, and should be passed on to pilots of following aircraft whenever possible.

4.1.1 British Airways/Meteorological Office Windshear Forecasting Trials

In 1976 British Airways, spurred by efforts in the operational forecasting of Windshear at some airfields abroad (mainly in USA), asked the Meteorological Office if they could provide some form of forecast or warning to aircraft of Windshear on the approach or climb-out, the accent being on the lowest 600 m above ground. Accordingly the Office operated two Windshear Warning Trials, one covering January/February/March 1977 (Winter Trial) and the other covering July/August/September 1977 (Summer Trial) at London (Heathrow), Glasgow (Abbottsinch) and Birmingham (Elmdon) Airports, and at six Royal Air Force airfields. A set of meteorological criteria, based on those listed above, were defined in an attempt to distinguish periods when difficulties due to Windshear were significantly more probable than average. Every hour throughout the trials, Meteorological Office staff assessed the existing meteorological conditions and incoming pilots' reports of shear, and if any of the criteria were satisfied, or if a pilot's report of Windshear was received during the previous hour, a Windshear warning was passed to pilots via the half-hourly ATIS (Air Traffic Information Service) broadcast.

Pilots (of British Airways only at civil airfields) operating into and out of the airfield during periods when a warning was in force were asked to complete a standard reporting form (Figure 17 shows the form used at civil airfields; a similar one was used at RAF airfields) whether or not they experienced Windshear, or what they suspected was Windshear, on the approach or climb-out. Pilots were also asked to complete this form whenever they experienced Windshear during periods when no warning was in force.

Results from the Heathrow Winter Trial, considering only hourly periods for which at least ten BA aircraft took-off or landed, showed that:

(i) during periods when no warning was in force (about 92% of all hourly periods) pilots reported Windshear (slight, moderate or severe) on 0.39 per cent of take-offs/landings (71 out of 18298).

(ii) during periods when a warning was in force (about 8 percent of the time) pilots reported Windshear on 3.89 per cent of take-offs/landings (84 out of 2162).

The overall background frequency of reports of slight, moderate or severe Windshear was 0.76 per cent. So, expressed as a proportion of the background or average frequency, the above figures of 0.39 and 3.89 per cent become 0.51 and 5.1; that is, the frequency of encounter with Windshear when a warning has been issued appears to be about five times the background frequency indicating some degree of predictive skill.

However, the results of the Trials are not conclusive and must be treated with caution. It is suspected that this factor of five may be unrealistically high due to a significant but unquantifiable psychological factor, in that the issue of a warning would have served as a reminder to the pilot of the necessity to submit a report form; if a pilot experienced Windshear when no warning was in force, this reminder was absent and he may have been less likely to submit the necessary report.

During the Trials, in addition to pilots' reports, a representative selection of digitized flight records for BA aircraft taking-off and landing on days when warnings were issued, were supplied by British Airways, the intention being to extract computed variations of headwind along the flight-path for each of the flights. It is expected that reliable information on headwind variations will be derivable for about half of the 1000 or so flight records supplied. This objective source of data should help to distinguish situations in which aircraft actually experience significant Windshear. It may also be possible, from this information, to determine the strength of the relationship between pilots' reports of Windshear and the aircrafts' actual experiences.

Thus the conclusions arising out of the analysis of pilots' reports from the Winter and Summer 1977 Trials are tentative and it is proposed that a further Windshear trial involving pilots' reports take place during the coming winter at one or two UK airfields, London (Heathrow) and, possibly, Glasgow (Abbottsinch). More satisfactory data than that gathered during the 1977 Trials would result if it could be arranged for pilots to submit a return, including nil reports, for every take-off and landing at the selected airfields, without the 'benefit' of a warning system. To ensure and maintain a reasonable response from pilots during such a Windshear survey, it would probably be necessary to operate it in relatively short periods (one week on, one week off, for example) over a total period of about 3 months. In this way the unquantifiable bias associated with the pilots' reports from the 1977 Trials would be eliminated, and the pilots' reports gathered during such a survey would be correlated,on an hourly basis, with a number of different meteorological indicators/predictors, and with other pilots' reports received during the previous hour.

The analysis of results from these proposed trials and from the flight records obtained in the 1977 Trials will form a basis on which to recommend the initiation of routine operational Windshear forecasts at major airports.

4.1.2 Overseas Trials

In late 1976 the US National Weather Service began a six-month trial of low-level Windshear forecasting at Newark, Le Guardia, JFK, Philadelphia International, Atlantic City, Washington National and Washington Dulles Airports. The National Weather Service attempted to forecast three hours in advance the wind shear associated with frontal conditions below 2000 feet. The forecasts were included in terminal weather broadcasts and made available continuously during the alert period. The information supplied to pilots included the type of shear, duration, wind (direction and speed) above and below the frontal surface, and the severity of any associated turbulence. The accuracy of the forecasts was to be assessed from pilots' reports and from measurements made by instrumented FAA (Federal Avaiation Agency) aircraft flown through the forecast Windshear zones. As yet, to the author's knowledge, no report of this trial has been forthcoming.

Within the USA some of the airline companies have organised their own operational Windshear warning schemes[26] based mainly on pilots' reports of Windshear with some meteorological input.

At Sydney Airport in Australia a Terminal Area Severe Turbulence (TAST) service is in operation; under this scheme forecasts are provided to ATC at ten-minute intervals of areas affected by severe turbulence/wind shear associated with thunderstorms within a radius of 60 nautical miles of the Airport[27]. During TAST operations the radar is normally maintained at 3° elevation except when echoes are within 20 nautical miles; an iso-echo contoured PPI display is used to track major echo features. Under this service extreme conditions associated with the storms occurring near Sydney Airport on 10 November 1976 forced its closure for an hour.

4.2 Remote Detection of Windshear along the Glide-slope

With the technological advance over the last decade or so in remote wind measurement systems employing the basic technique of emitting electromagnetic radiation or acoustic pulses and detecting/analysing the back-scattered return, attention has turned in recent years to the assessment of such devices as potential all-weather operational tools in the measurement of boundary layer wind fields over and around airfields.

A dual acoustic Doppler-microwave radar system was installed at Dulles International Airport near Washington, DC in late 1976 to monitor the vertical profile of wind from the surface to 500 m, in 30-m height increments. The acoustic system operated as far as was possible under clear-air conditions, the microwave radar taking over automatically when precipitation was present. An initial trial period of six months (up to February 1977) has been reported[28] in which two sources of independent wind measurements from balloon-borne anemometers and radiosondes were compared with the results given by the system. So far it seems that this particular system may be inadequate for reliable operational use, mainly due to problems of ambient acoustic noise. Noise from aircraft, birds and high surface winds tended to drown the scattered signal giving decreased reliability, although the use of a 6-minute averaging period for the winds partly helped to overcome the problem if the duration of noise was less than a minute or so. In addition the high cost of installation casts doubt on the potential as an operational tool of acoustic Doppler systems at airports. It was also recognised that its main area of use lay in detecting fairly persistent vertical wind shear, typically associated with frontal zones and inversions; the system is not designed to detect and give adequate warning of smaller scale transient wind variations such as thunderstorm gust-fronts (relatively common features of North American weather) or large gusts embedded in strong wind turbulence. For the purpose of attempting to track the progress into the airport area of hazardous gust-fronts, an array of 125 pressure jump sensors, spaced about 1 km apart and designed to respond only to relatively sudden pressure increases (about 0.5 mb in about 2 minutes), have been installed around Dulles Airport, all the data being passed via telephone lines to a central data processing unit. A network of ten anemometers recording on strip charts was also used[17]. The authors of the report on this system are of the opinion that, ultimately, the entire three-dimensional wind field (including gust-fronts) could be monitored by scanning radar and/or lidar systems but that, in the interim, a network of inexpensive pressure-jump sensors will give a timely indication of the progress of hazardous wind variations associated with gust-fronts. The system apparently showed good promise; with a fully operational array of sensors, necessarily covering a large area outside the airport boundaries, an estimated warning time of 7 minutes for a discontinuity travelling at 20 ms^{-1} has been quoted. This would be sufficient for ATC to hold all operations until the discontinuity had passed through the airport and its approaches.

In the UK it has been demonstrated[29] that a suitably modified microwave (pulsed) Doppler radar can detect wind gradients with good spatial resolution (about 30 m) using signals back-scattered from aerosols or refractive index inhomogeneities associated with humidity and/or temperature fluctuations which are detectable most of the time in the boundary layer, especially where there is strong shear and turbulence. One major advantage of such a radar system is that radiation of the wavelength used (10.7 cm) is hardly attenuated even by heavy rain whereas acoustic and laser sounders tend to become unusable in anything more than light precipitation. Current research (jointly between the Meteorological Office Radar Research Laboratory and the Royal Signals and Radar Establishment at Malvern) involves the specification of the required performance of a smaller lower cost unit (a 25 m diameter aerial is currently used), which could be installed on an airfield to give real-time displays of wind gradients along the glide-slope (take-off and landing).

Chadwick et al[30] similarly demonstrated the all-weather potential of a frequency-modulated continuous wave (FMCW) Doppler radar in the USA as a ground-based system for the remote detection of boundary layer winds via a scanning technique. In the USA investigations into the potential of a pulsed coherent lidar (CO_2) system which analyses the Doppler shifted radiation back-scattered from aerosols, are continuing. Preliminary calculations and limited tests have indicated that adequate boundary layer wind measurements with CO_2 lidars are certainly feasible[31], but a more complete assessment of such a system is awaited. As a system that can be used to scan a large volume over and around the airfield (in contrast to sensing a single fixed, relatively limited, volume as in the case of an acoustic system) the Doppler lidar is similar to the FMCW Doppler radar but at the moment it appears that the latter system has the edge as far as all-weather capability is concerned. Also in the field of laser detectors work is now in progress at the Stamford Research Institute, California, to compare laser radar results with in situ measurements of wind velocity components, temperature, humidity and pressure, and to develop numerical models of the boundary layer that are based on the use of laser radar data as input.

In the UK assessment of a ground-based laser (CO_2) anemometer is in progress at the Royal Aircraft Establishment (RAE), Bedford, as part of their studies into low-level wind characteristics, including the applicability of Taylor's Hypothesis (often used as a basis for transforming fixed point time series of wind data into an equivalent spatial wind field along the direction of the mean wind). This instrument has also been used to study the behaviour of building wakes and aircraft vortices. Their plans include the development ultimately of a compact airborne version of this equipment which will detect wind variations (component along laser beam only) along the projected flight path of the aircraft, about 1 km or so ahead of it, this information being passed directly to the aircraft's automatic guidance and control systems which would be programmed to apply the control inputs most likely to maintain a stabilised flight-path; the pilot would also be warned of any need for drastic action. However, this aspect of RAE's laser anemometer studies is still in its early stages, and such a system for routine airborne remote detection of wind variations on the projected flight-path is likely to be a few years away; an airborne laser anemometer is expected to be ready for in-flight trials (in a HS-125 aircraft) during 1979.

A steering Group on the acquisition and operational use of Boundary Layer Measurements has recently been set up within the Meteorological Office, its terms of reference being:

(i) To keep under review the requirements for observations in the boundary layer for operational purposes, as well as potential methods of satisfying such requirements.

(ii) To make recommendations concerning the conduct of trials to determine the feasibility of observational techniques and the utility of the observations so acquired.

(iii) To consider the results of any trials and to make proposals concerning the operational introduction of instruments and methods.

So far the Group has made no firm proposals concerning trials or operational introduction of remote sensing devices to monitor wind variations at airfields; developments in this field in the USA are to be kept under close review and action will be suggested in due course, dependent on the degree of operational reliability achieved with such devices in the American airfield trials, particularly at Dulles International and Chicago O'Hare Airports.

4.3 Aircraft Monitoring of INS-derived Winds

Aircraft fitted with INS (Inertial Navigation System) can continuously monitor the headwind component and its rate of change along the flight-path using the difference between the aircraft's inertial and airspeed accelerations. For an aircraft to regain the intended glide-slope and airspeed following an encounter with Windshear, a thrust change proportional to the vertical current and/or rate of change of headwind is necessary. Typical maximum values of downdraught/rate of change of headwind that different types of aircraft are able to counteract (under a stated set of conditions), by use of reserves of thrust, have already been indicated in Figure 5.

The reserve thrust available for recovery of airspeed and/or glide-slope for a jet transport aircraft on the approach, generally varies from about 0.15 to 0.25 of the aircraft weight; downdraughts (updraughts) and decreases (increases) in headwind component will reduce (increase) the excess thrust available. Greene[32] has described the development of an airborne device referred to as a "Windshear Warning Computer" which determines the change in excess thrust available when the aircraft is under the influence of Windshear; the system continuously monitors the level of available thrust computed from rate of change of headwind and downdraught drift-angle. The system could be programmed to alert the pilot if a substantial reduction in available thrust persisted for more than a few seconds. Greene suggests that in future pilots of aircraft fitted with such a system, or similar ones based on the same principle, could be instructed to abandon an approach if the rate of reduction of headwind and/or the presence of a downdraught were sufficient to prompt an alert from the device. But the main point about this system is that the pilot is made aware of the existence of vertical currents and headwind changes within a second or so of their occurrence, where previously he might only have become aware of the hazard several seconds after its onset, when the aircraft had responded significantly.

A similar system to the one described by Greene is described by Klass[33]. It should be stressed that such a system would not remotely sense the wind field ahead of the aircraft; it would simply monitor and make aware to the pilot with minimal lag, existing wind variations at the aircraft. Greene implies that if such a system, programmed to alert the pilot when the excess thrust was reduced by 75 per cent, had been in use on the aircraft involved in the JFK accident, the pilot would have been made aware of his predicament a few seconds earlier, and might have been able to take action to avert the accident.

4.4 Flight Simulator Studies of Windshear

Flight simulator studies of Windshear and the operating techniques necessary to counter its effects are in progress at BAe (Filton) and RAE (Bedford). These studies include examination of the requirement for new or additional instrumentation. A total of about 75 pilots from civil airlines, RAE and the CAA will be exposed to various Windshear conditions while flying approaches, both manual and auto-coupled, through varied visual sequences. The aircraft simulated are of the BAC 1-11/Trident type. The objective of these studies are as follows:

(i) To generate a realistic simulation of the wind structures typical of those found in the meteorological conditions (described in Section 3.3) likely to produce severe Windshear incidents.

(ii) To establish the validity and limitations of current handling techniques and procedures.

(iii) To indicate any need for additional or modified handling procedures or instrumentation to help counter the effects of Windshear.

(iv) To evaluate any procedures or instrumentation indicated by (iii).

(v) Ultimately, using the Filton simulator purely as a computer without pilot involvement, an attempt will be made to assess the capability to utilize advance information on the atmosphere, such as might be available from an airborne remote-sensing laser anemometer.

Items (ii) to (v) lie outside the province of the meteorologist, but he has an important role to play in (i) in providing a description of the atmosphere tailored to the particular needs of aircraft design or operation in which advice or information is being sought.

Statistical models of atmospheric turbulence which attempt to combine the quasi-continuous nature of atmospheric turbulence with the occurrence of occasional large discrete gusts have been developed over the past decade by aeronautical engineers, notably by Jones[34,35] in order to evaluate aircraft response mainly for design purposes, but also to generate synthetic turbulence histories for flight simulation[36]. This analysis identifies the gust patterns producing maximum response - the curvature effect described in Section 3.2 being the simplest version of such a pattern.

REFERENCES

1. ICAO 1974 Report of the Eighth Air Navigation Conference, Montreal DOC 9101, AN-CONF/8, Montreal.

2. Else C.V. 1974 The Meteorological Office Mk5 wind system. Met Mag Vol 103, pp 130-140.

3. Burtonshaw A.E. and Munro N 1977 The Meteorological Office Digital Anemograph Logging Equipment (DALE) Met Mag. Vol 106, pp 204-211.

4. Hardy R.N. 1974 A note on the optimum averaging time of wind reports for aviation. Met Mag. Vol 103, pp 99-105.

5. Dutton M.J.O 1975 Optimum averaging time of wind reports for aviation. Met Mag, Vol 104, pp 231-243.

6. Dutton M.J.O. 1978 Variability in space and time of the 30-sec average wind at the surface and its relevance to the siting of multiple anemometers at airfields. Met. Off. (Met O 9) IDTN No. 12 (unpublished note)

7. CAA 1978 Windshear Study Programme - progress report up to February 1978. (unpublished)

8. Davies D.P. 1973 Handling the big jets. London, CAA (reprinted 3rd edition)

9. Hopkins 1977 Windshear: only your very best is good enough Flight Int. 16 April 1977 pp 1030-1031

10. Luers J.K. and Reeves J.B. 1974 Effects of shear on aircraft landing NASA CR-2287

11. Blackadar A.K. 1957 Boundary layer wind maxima and their significance for the growth of nocturnal inversions Bull.Am.Met.Soc., Vol 38, pp 283-290

12. Thorpe, A.J. and Guymer, T.M. 1977 The nocturnal jet. Quart.J.R.Met.Soc., 103, pp 633-654.

13. Anon 1975 NTSB assays Iberia accident at Logan. Aviation Week & Space Tech., Apr 7 1975 pp 54-59. also: Wind factor studied in Iberia crash. Aviation Week & Space Tech. Apr 14 1975 pp 53-56

14. WMO 1960 The airflow over mountains. Geneva, WMO, Tech Note No.34.

15. WMO 1973 The airflow over mountains: research 1958-72 Geneva, WMO, Tech Note No. 127.

16. Fichtl G.H. Camp W. Frost W. 1977 Sources of low-level wind shear around airports. J.Aircraft, Vol 14, pp 5-14.

17. Bedard A.J. Hooke W.H. Beran D.W. 1977 The Dulles Airport pressure-jump detector array for gust-front detection. Bull.Am.Met.Soc. Vol 58, pp 920-926.

18. Bedard A.J. Beran D.W. 1977 Detection of gust-fronts using surface sensors. NOAA Tech Memo. ERL WPL-20 15pp

19. Fujita T.T. and Caracena F 1977 An analysis of three weather-related aircraft accidents. Bull.Am.Met.Soc., Vol 58, pp 1164-1181.

20. Fujita T.T. 1976 Spearhead echo and downburst near the approach end of a John F Kennedy Airport runway, New York City SMRP Res. paper 137, Univ of Chicago, 51pp.

21. Fujita T.T. and Byers H.R. 1977 Spearhead echo and downburst in the crash of an airliner Mon.Wea.Rev, Vol 105, pp 129-146.

22. NTSB 1976 Aircraft accident report. Continental Airlines Boeing 727-224, N88777, Stapleton Int Airport, Denver, Colorado, Aug 7 1975. US Govt Rep No. NTSB-AAR-76-14.

23. Browning K.A. and Ludlam F.H. 1962 Airflow in convective storms Q.J.R. Met. Soc. Vol 88, p. 117-135.

24. Ludlam F.H. 1963 Severe local storms: a review Am.Met.Soc.Met.Mon., Vol 5, p 1

25. Pasquill F 1974 Atmospheric Diffusion. 2nd Edition. Ellis Horwood Ltd, Chichester.

26. Sowa D.F. 1974 Low level wind shear ...... its effects on approach and climbout. DC Flight Approach (No. 20) June 1974.

27. Morgan P.A. 1978 The Sydney thunderstorms of 10 November 1976. Royal Met Soc, Weather, Vol 33 (in press)

28. Hardesty R.M., Mandics P.A., Beran D.W., Strauch R.G. 1977 The Dulles Airport acoustic-microwave radar wind and wind shear measuring system. Bull.Am.Met. Soc., Vol 58, pp 910-918

29. Browning K.A., James P.K., Parkes D.M., Rowley C, Whyman A.J. 1978 Observations of strong wind shear using pulse compression radar. Nature, Vol 271, pp 529-531.

30. Chadwick R.B., Morgan K.P., Strauch R.G., Morrison G.E., Campbell W.C. 1976 A new radar for measuring winds Bull.Am.Met.Soc., Vol 57, pp 1120-1125

31. Huffaker R.M., Beran D.W., Little C.G. 1976 Pulsed coherent lidar systems for airborne and satellite-based wind field measurement. Boston, Am. Met.Soc, 7th Conf. on Aerospace and Aeronautical Met. and Symposium on Remote sensing from satellites (Melbourne, Fla) pp 318-324.

32. Greene R.A. 1977 A wind detection system for airline aircraft. London, Shell-Mex & B.P. Ltd, Shell Aviation News, No. 445, pp 8-11.

33. Klass P.J. 1976 Airborne wind shear sensor developed. Aviation Week & Space Tech., March 22 1976, pp 42-43.

34. Jones, J.G. 1976 Modelling of gusts and wind shear for aircraft assessment and certificates. Aeronautical Research Council, ARC 37668

35. Jones J.G. 1977 Aircraft longitudinal ride-bumpiness: an application of statistical discrete gust shears. Royal Aircraft Establishment. TN.77020

36. Tomlinson, B.N. 1975 Developments in the simulation of atmospheric turbulence. AGARD Flight Mechanics/Guidance and Control Panels Joint Symposium in Simulations. The Hague, Netherlands, Oct 1975.

TABLE 1. Percentage frequencies of ATC wind errors exceeding 6, 10 and 14 kt. as a function of 2-min mean wind speed, for a 2-min averaging period (ATC wind report) and a 1-min lag (between the passing of the wind report and aircraft touchdown/take-off). The 'error' is the magnitude of the vector difference between the ATC wind and the wind experienced by the aircraft at touchdown/take-off.

(data source: 30-sec winds, Heathrow, Jan-Dec 1974. 7298 hours, sampled once every 2-min)

mean wind speed(kt)	percentage frequency of errors ≥ 6 kt	10 kt	14 kt	rms error	sample size
0 - 5	0.09 (45)	0.002 (1)	0.0 (-)	0.92	50667
5 - 10	0.23 (214)	0.010 (9)	0.002 (2)	1.60	92412
10 - 15	0.92 (458)	0.016 (8)	0.004 (2)	2.34	49638
15 - 20	2.97 (489)	0.091 (15)	0.006 (1)	3.02	16488
20 - 25	8.76 (266)	0.593 (18)	0.033 (1)	3.88	3036
≥ 25	20.30 (150)	1.083 (8)	0.271 (2)	4.72	739
ALL	0.76 (1622)	0.028 (59)	0.004 (8)	1.89	212980

(figures in parentheses are actual numbers of events)

Table 2. Profile of mean horizontal wind at Logan International Airport at the time of the accident (1543 EST) on 17 August 1973. (derived from aircraft-recorded variables)

ALTITUDE (feet)	WIND DIRECTION (deg)	WIND SPEED (kt)	TAILWIND (kt)	CROSSWIND (kt)
1000	191	35	23	26*
900	192	34	22	26
800	191	34	22	25
700	191	33	22	25
600	192	32	21	24
500	194	29	18	23
400	199	21	12	17
300	211	14	5	13
200	278	5	-4	3
100	310	6	-6	2
surface	308	5	-5	2

* all crosswinds were from the left

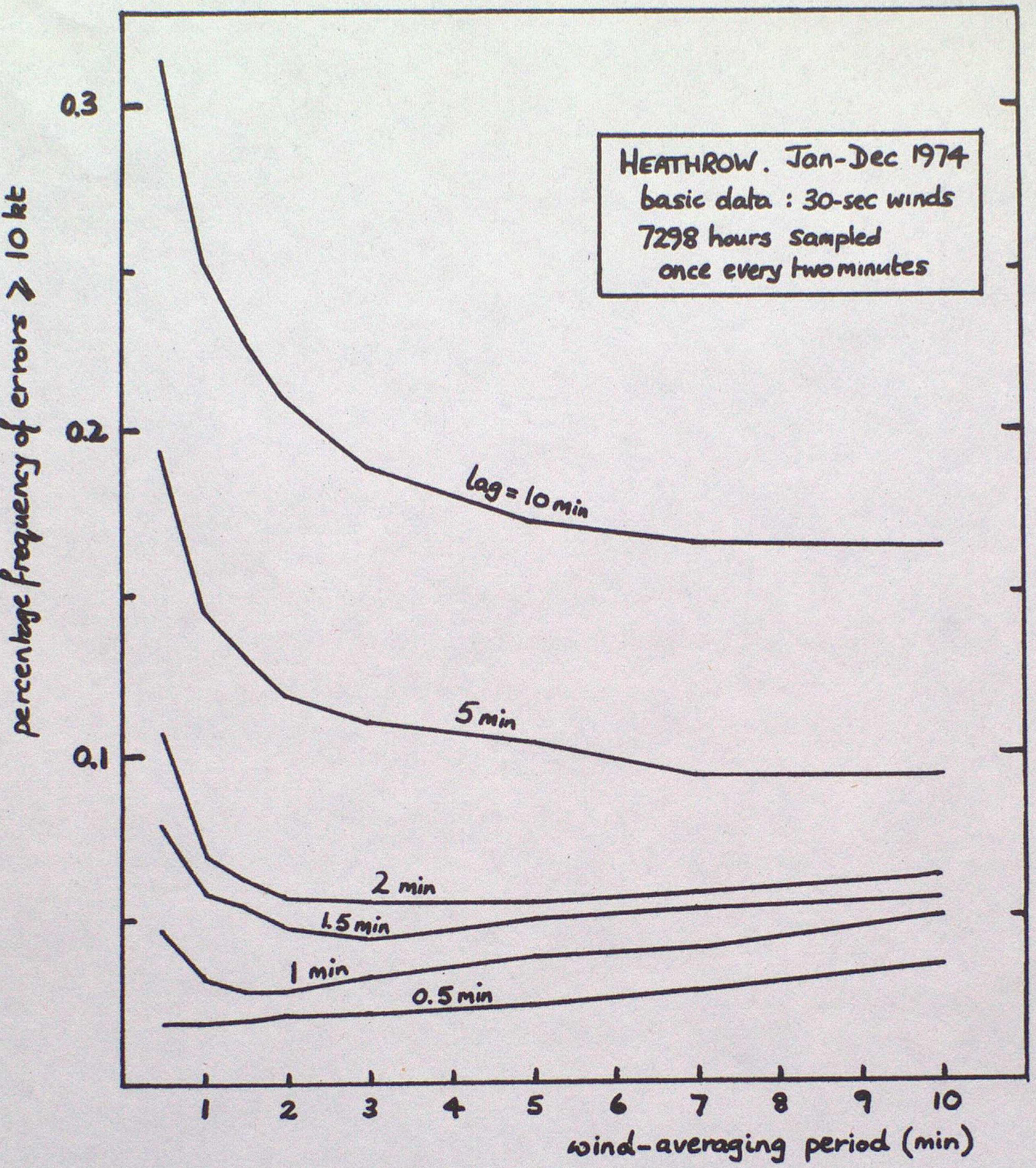
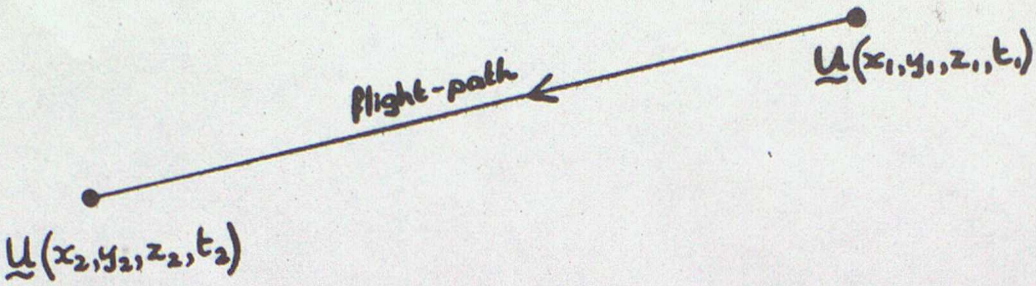


Figure 1 . Variation in the frequency of differences (errors)≥10 kt between ATC wind report and the wind the aircraft actually experiences at touchdown/take-off, as a function of the averaging period of the wind report and the time lag between the passing of the report to the pilot and touchdown/take-off.



$\underset{\sim}{U}(x, y, z, t)$ – vector horizontal wind

$$\text{Wind shear} = \frac{\underset{\sim}{U}(x_2, y_2, z_2, t_2) - \underset{\sim}{U}(x_1, y_1, z_1, t_1)}{(t_2 - t_1)}$$

(rate of change of vector horizontal wind along the flight-path)

Figure 2. Wind shear in the aviation context

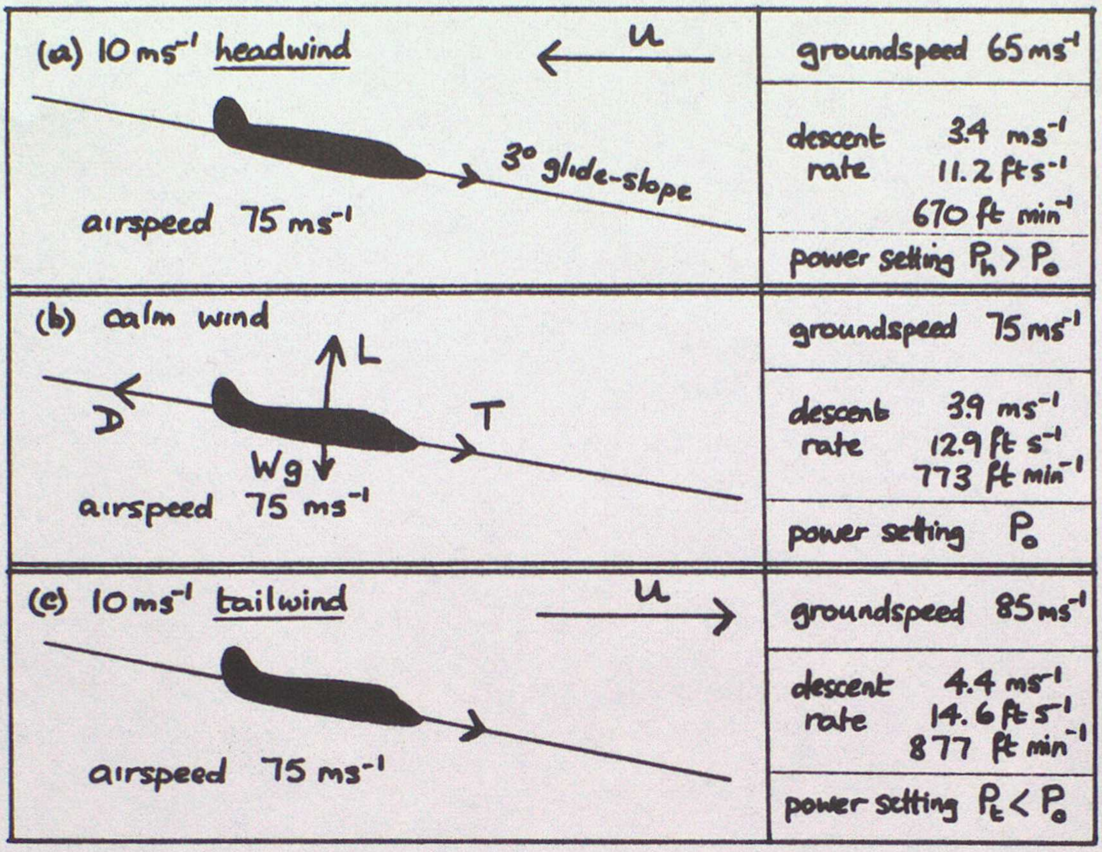


Figure 3. Descent rates and relative power settings necessary to maintain a 3° glide-slope at a constant airspeed ($75\ ms^{-1}$) in steady wind conditions.

descent rate = groundspeed $\times$ $\tan(3^{\circ})$

$\tan(3^{\circ}) \approx 0.05$

W - total aircraft weight
D - total drag
T - thrust
L - lift
g - acceleration due to gravity

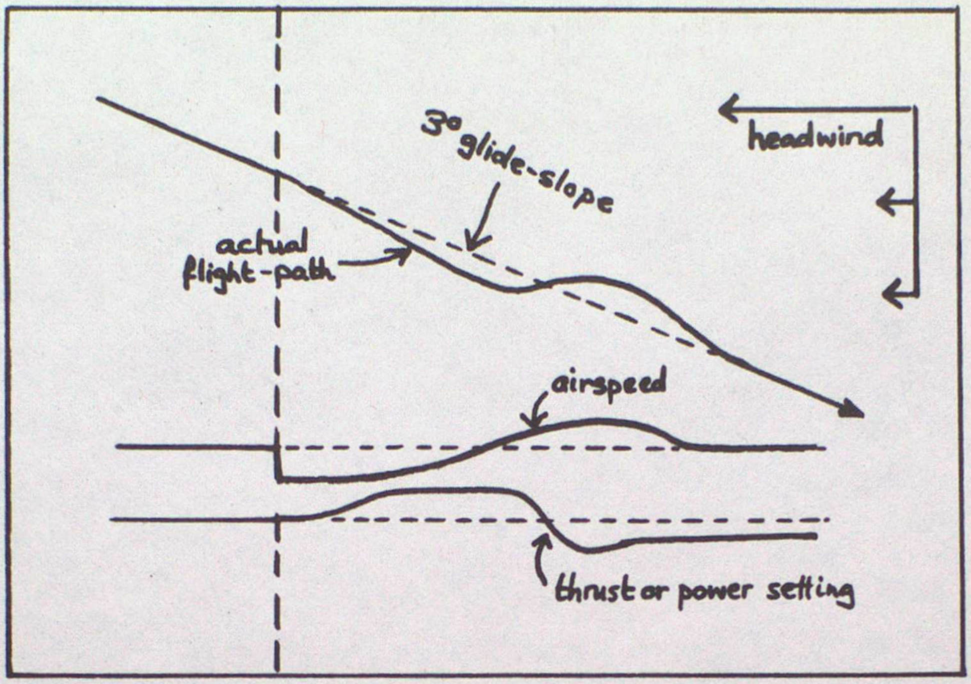


Figure 4a. Effect of a decrease of headwind (or increase of tailwind) on approach.

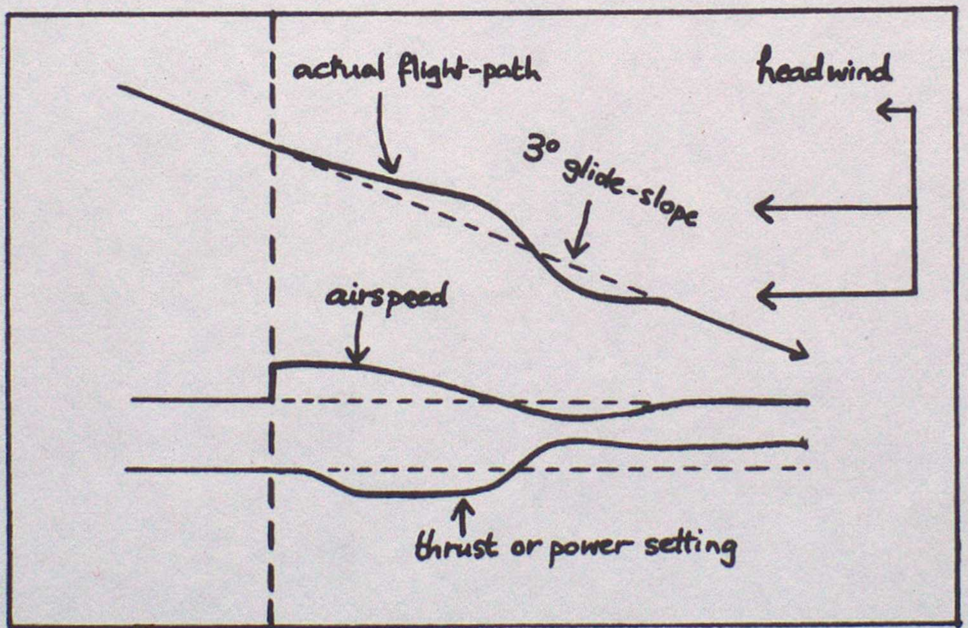


Figure 4b. Effect of an increase of headwind (or decrease of tailwind) on approach.

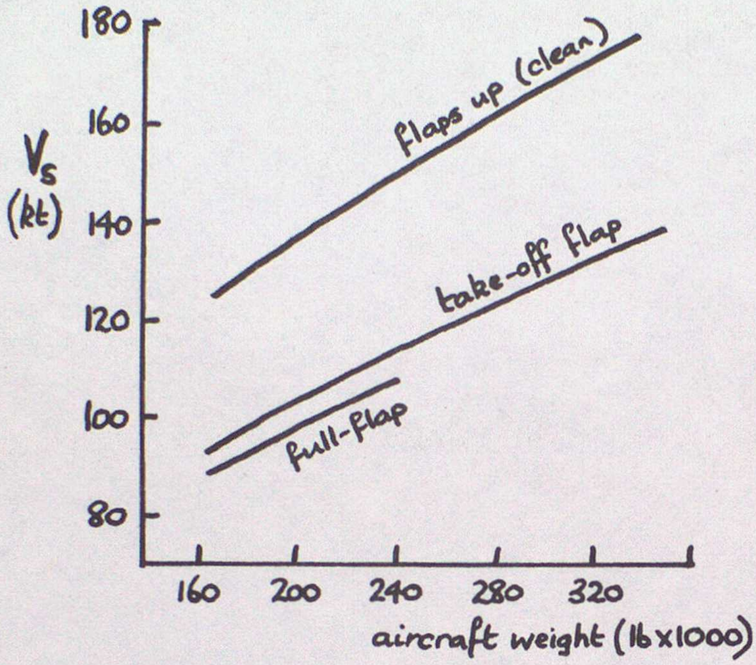


Figure 5. Typical variation of stall speed (V_s) with aircraft weight and flap configuration, for modern civil transport jet aircraft. (after Davies (1973))

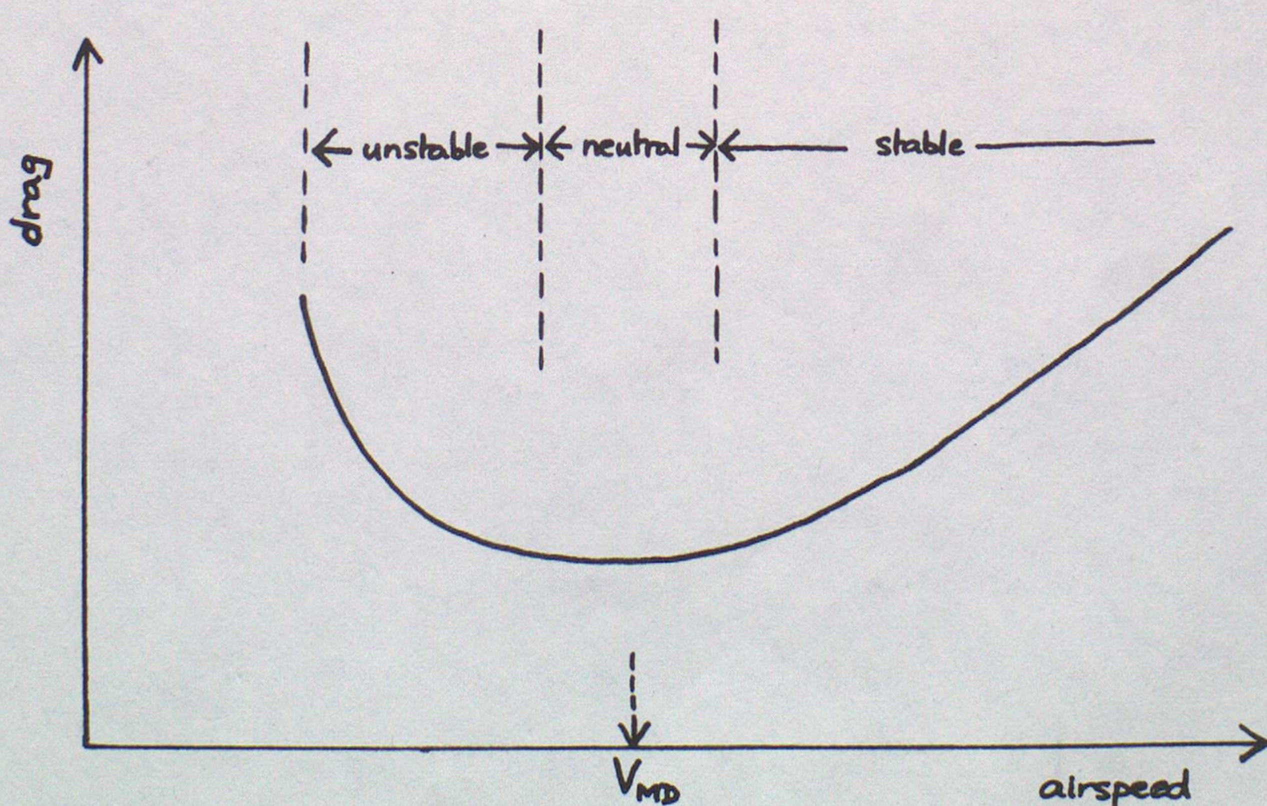


Figure 6. Typical variation with airspeed of total drag.

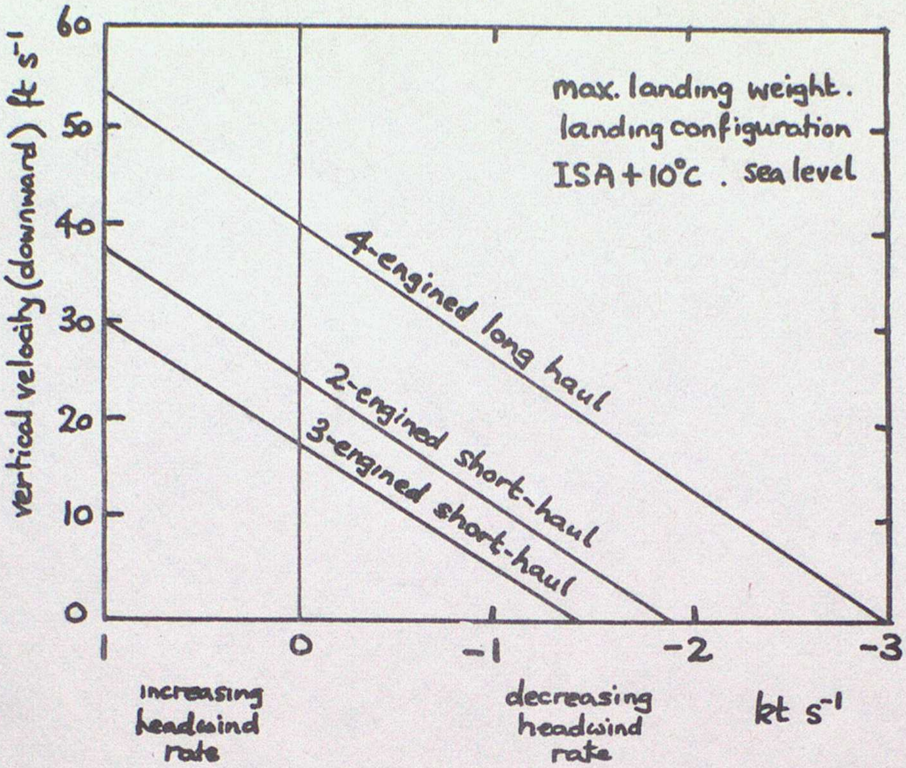


Figure 7. Aircraft capacity to counteract sustained shear and/or downdraught under the stated conditions. (after Hopkins(1977))

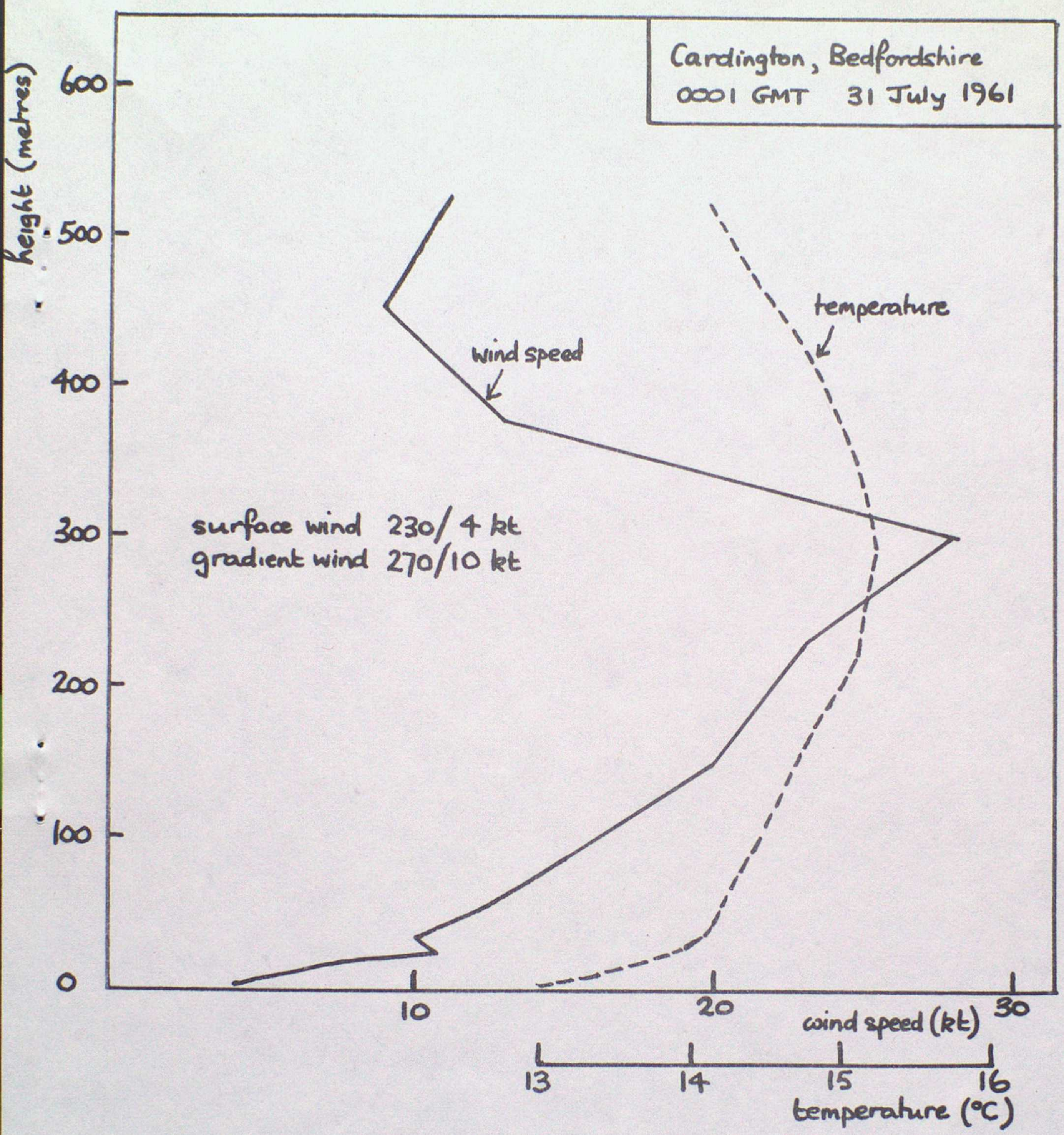


Figure 8. Low level jet at Cardington (Bedfordshire), 0001 GMT 31 July 1961.

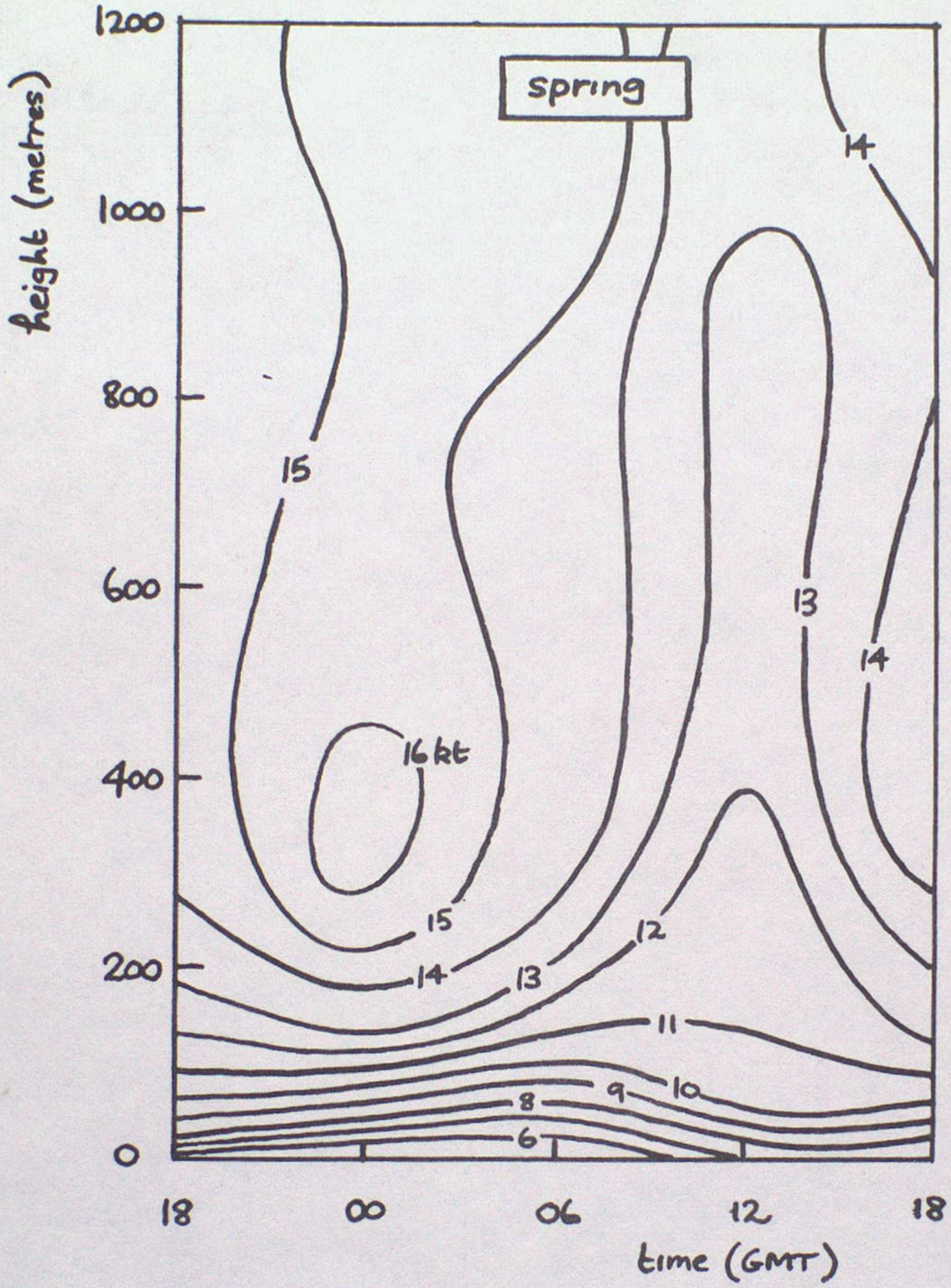


Figure 9 . Mean wind speed at Cardington (Bedfordshire), 1957-1966. Spring months (March/April/May)

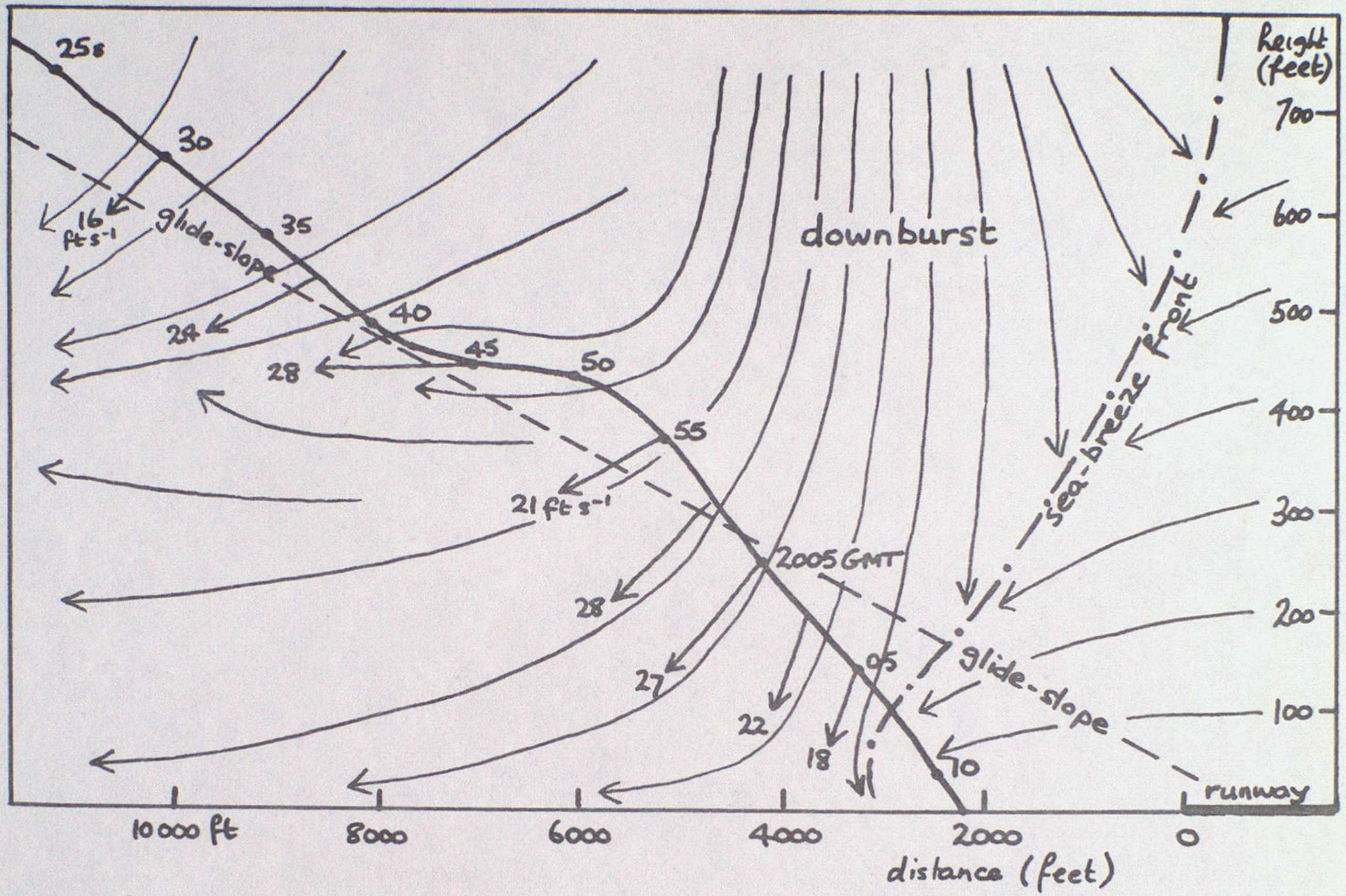


Figure 10. Wind field experienced by B727 which crashed at JFK on 24 June 1975 (after Fujita[20] (1976))

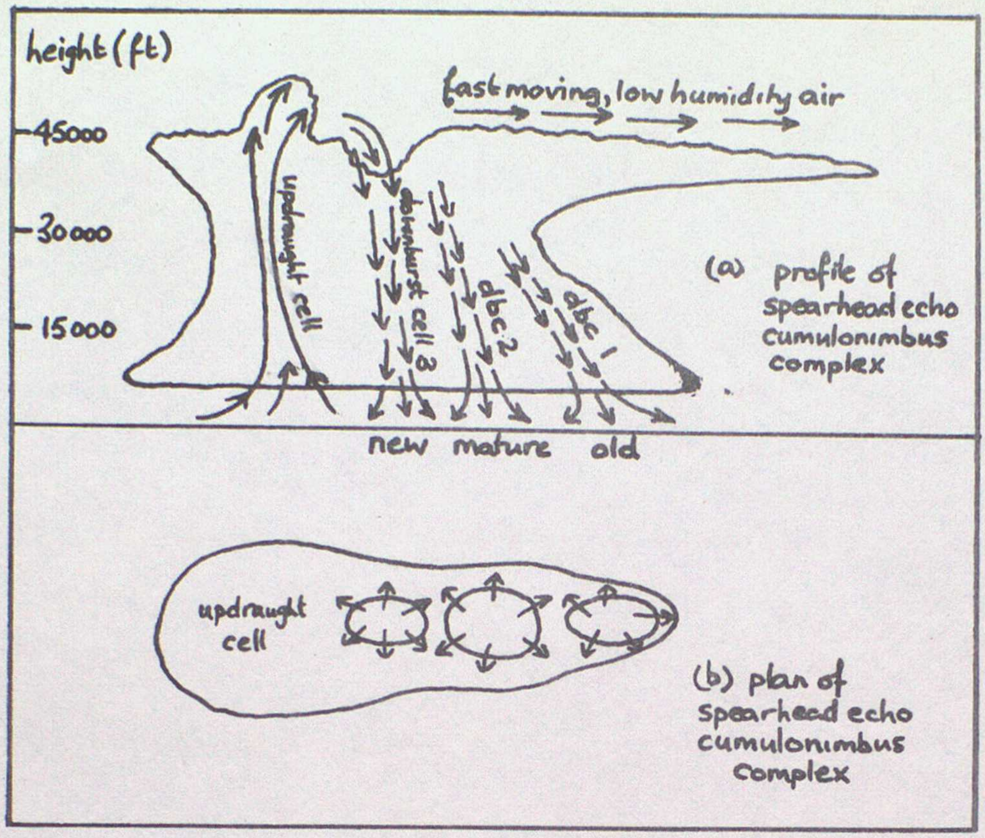


Figure 11. The Fujita-Byers model of a spearhead echo, so-called because of the shape of the radar echo (PPI). They assumed that fast-moving air is brought into the source region of the downburst when an overshooting top collapses into the anvil cloud. By virtue of the higher horizontal momentum drawn into a downburst cell, the cell advances more rapidly than other parts of the echo. In effect the downburst cells run away from the parent echo and weaken, resulting in a pointed shape of the forward end of the echo.

(taken from Fujita[20] (1976) and Fujita and Byers[21] (1977))

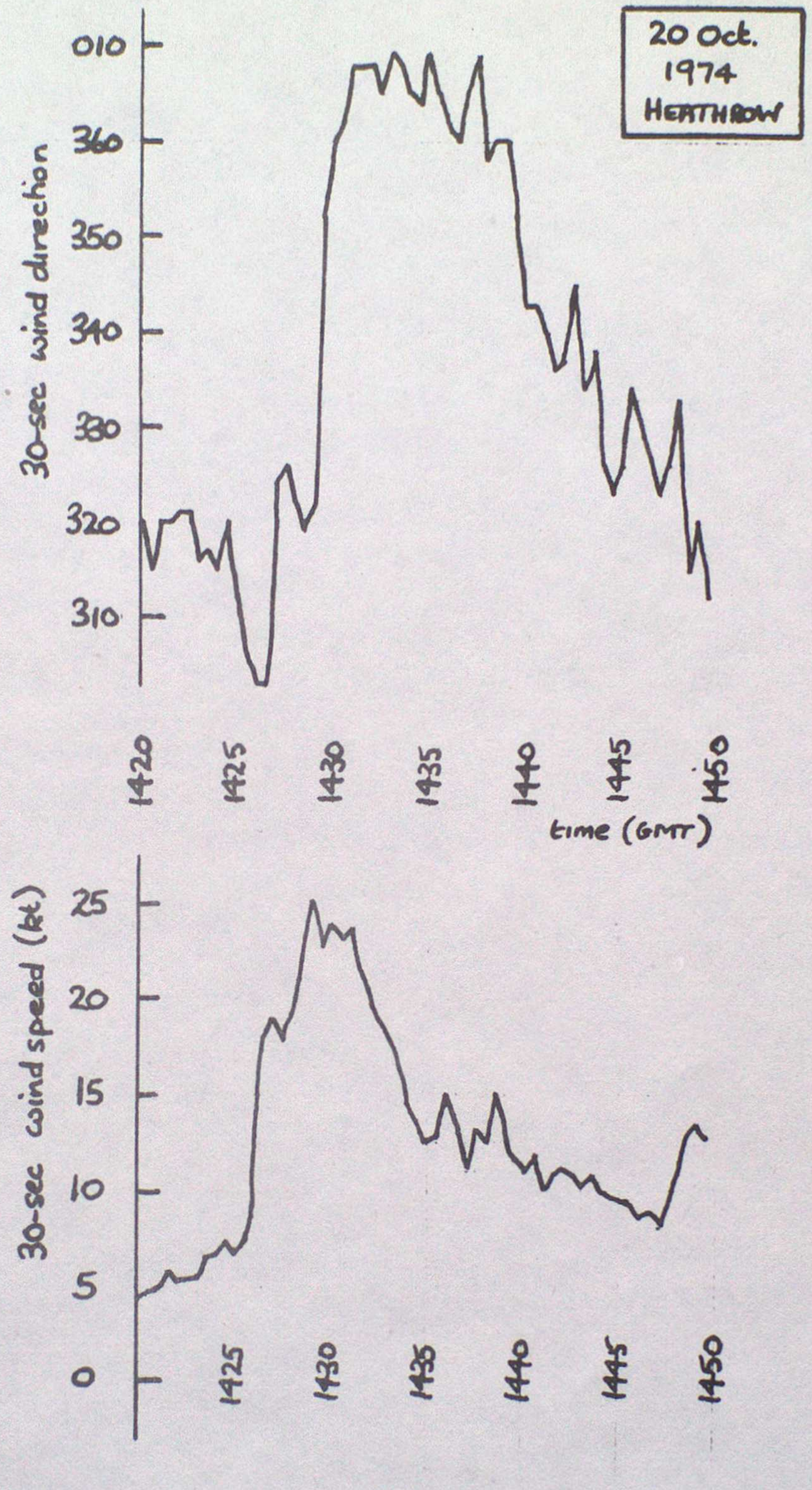


Figure 12. Passage of a gust-front at Heathrow, 1426GMT on 20 October 1974.
(30-sec winds at south-west site)

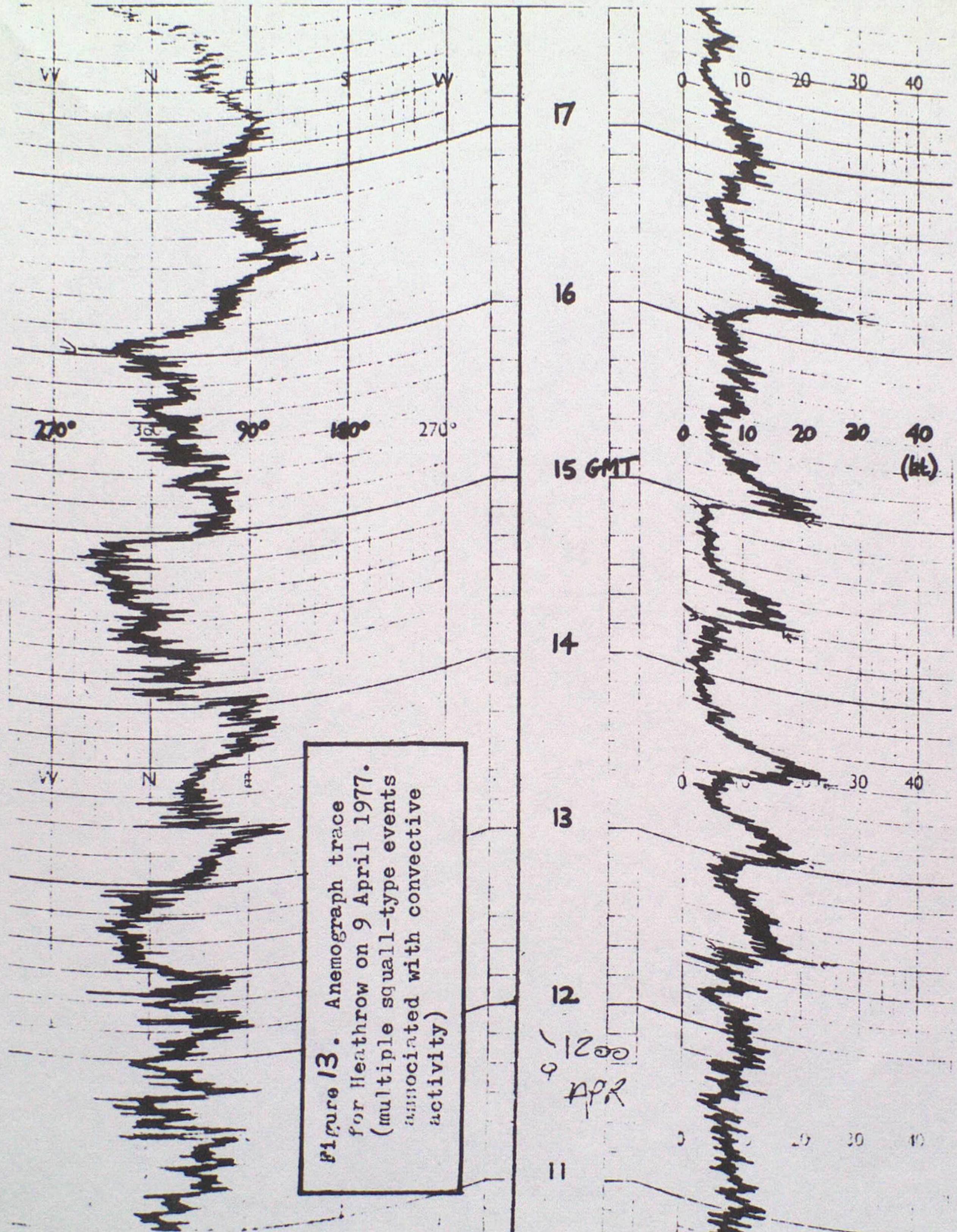


Figure 13. Anemograph trace for Heathrow on 9 April 1977. (multiple squall-type events associated with convective activity)

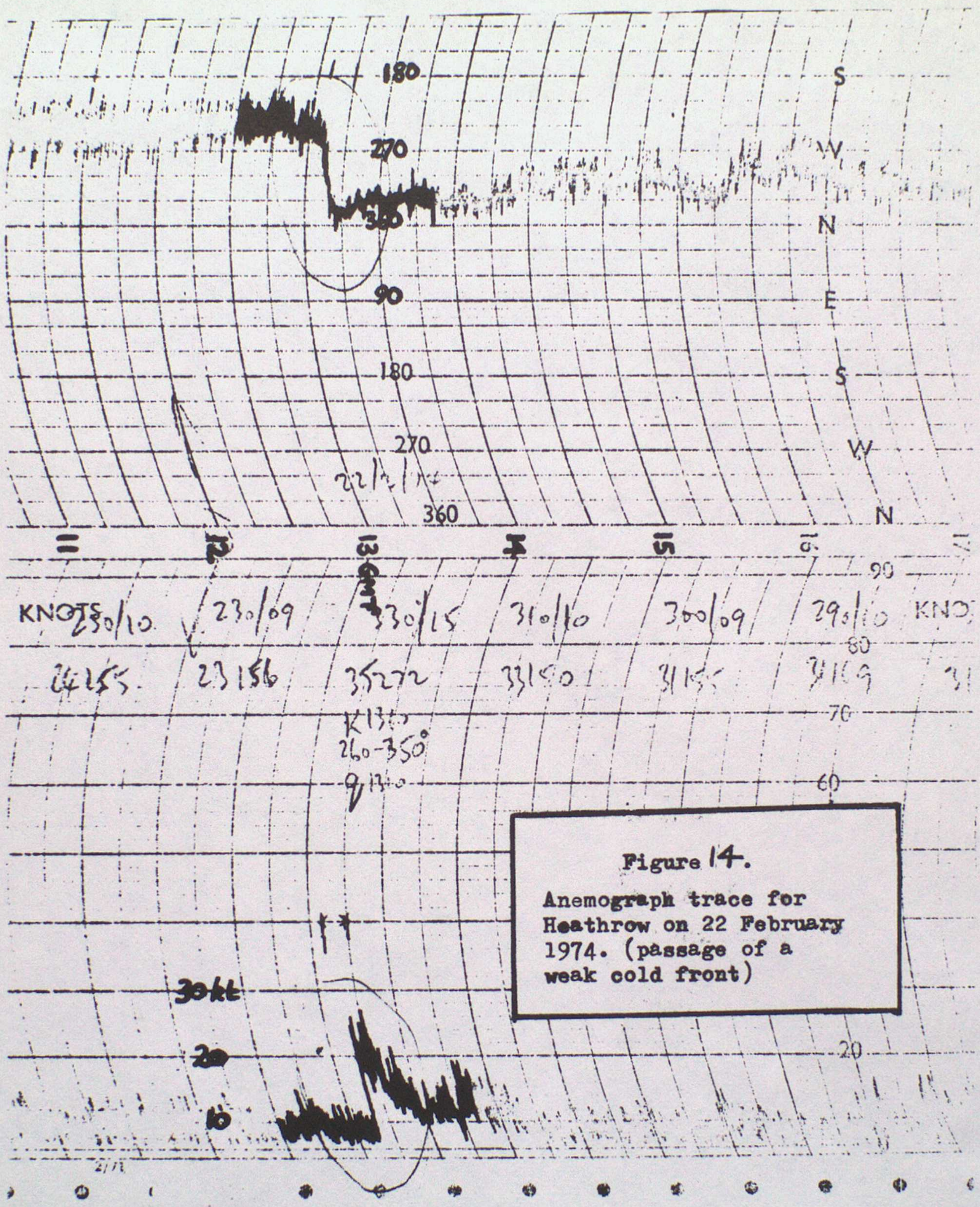


Figure 14.

Anemograph trace for Heathrow on 22 February 1974. (passage of a weak cold front)

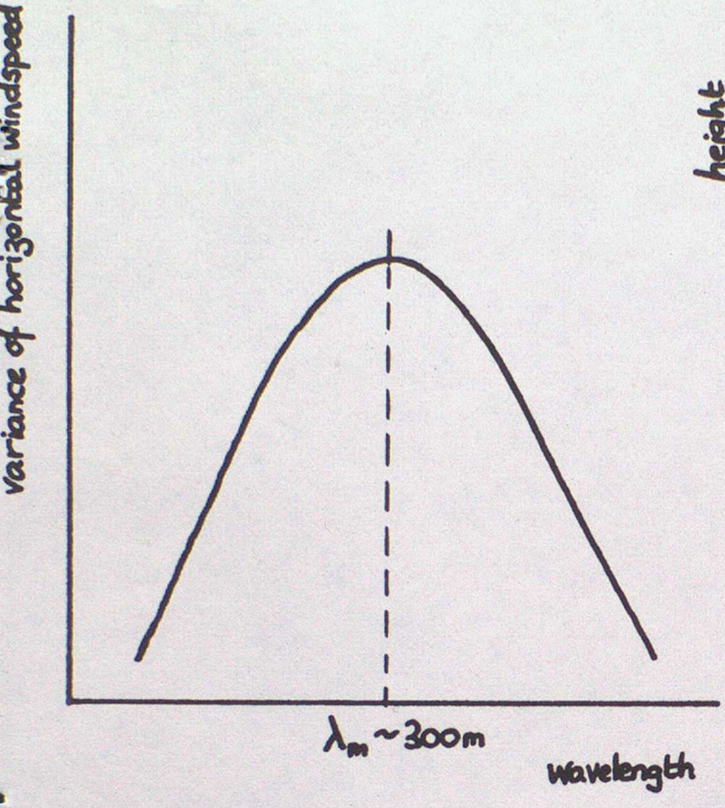


Figure 15. Schematic representation of the power spectrum of horizontal wind speed in steady state conditions with strong surface winds.

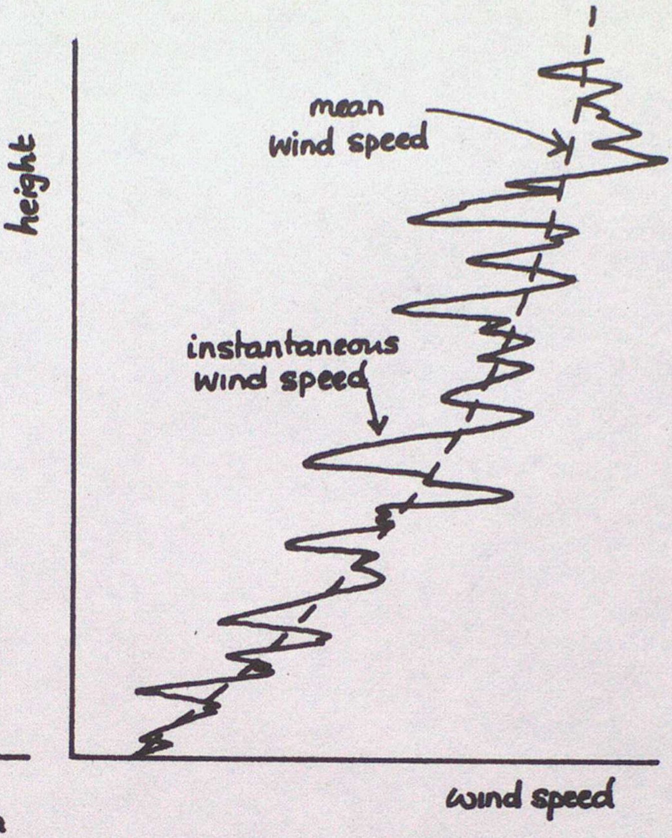


Figure 16. Typical variation with height of instantaneous wind speed in strong wind turbulence

Completed forms should be forwarded to:- **Superintendent Meteorological Services, Bealine House**

Low level wind shear investigation

When operating services into or out of London Heathrow, Glasgow or Birmingham, pilots are requested to co-operate with the procedure outlined below:-

Warning in force
On all occasions when a warning is in force, the standard reporting form should be completed. If no difficulty is encountered this should be stated. When difficulty is encountered please give as much detail as possible about the wind profile, nature and height of the difficulty experienced etc.

No warning in force
Pilots should complete a form only if difficulty is experienced in take-off or landing which might be attributed to wind shear. Give as much information on the difficulty encountered as possible.

Additional information

The UK Met Office in conjunction with British Airways are evaluating a wind shear forecasting technique at Heathrow, Glasgow and Birmingham.

The purpose of the trial is to assess the feasibility of providing a reliable wind shear forecasting service and to determine the value of such forecasts to pilots.

Report form

Flight and technical information

A/C type ________ Reg ________ Service Nr ________ Date ________

Captain ____________________ Base ________

	Delete as necessary
1 Aerodrome	Heathrow/Glasgow/Birmingham
2 Runway	________
3 Phase of flight	Taking off/landing
4 Time (GMT)	________
5 Wind shear forecast	Yes/No
6 Wind shear experienced	Yes/No
If answer to 6 is yes complete the following	
7 Was it	Slight/moderate/severe
8 At what height?	________ ft
9 How was wind shear recognised?	IAS increase/decrease ________ knots
	Height increase/decrease
	Other symptoms
10 Did you experience any handling difficulty?	Yes/No
11 Was Autopilot engaged?	Yes/No
12 Was Autothrottle engaged?	Yes/No
13 Did you disengage Autopilot?	Yes/No
14 Did you disengage Autothrottle?	Yes/No

15 Additional information (e.g. any wind measurements made, turbulance experienced etc.)

Figure 17. Low-level wind shear warning Trial. Pilot report form.

F430