Monitoring Information and Failure Warning to the Flight Crew during Autopilot Operation

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SUMMARY

The provision of monitoring information and failure warnings to the flight crew during autopilot operation is discussed, special emphasis being given to the approach and landing in conditions of very low visibility.

Following a brief outline description of the monitoring techniques and equipment for cruise and conventional coupled approach monitoring, the pilot monitoring of low-approach systems and automatic landing systems is reviewed in more detail and some of the special equipment required is described.

Reference is made to the experience currently being obtained from the Trident automatic landing programme which is aimed at obtaining clearance by 1968 for airline automatic landings in conditions of low visibility.

1. Introduction

The automatic control of aircraft with human pilot monitoring has long since become an accepted practice in airline operations. In his monitoring role the pilot checks the functioning of the control equipment and intervenes in the event of incorrect system behaviour. For this he requires information about what is happening, what should be happening and what action he should take in the event of faulty system functioning. All this may be generally included under the heading of monitoring information, the actual sources of which may be quite numerous and varied.

Incorrect system functioning might be detectable from outside visual references, motion sensation, normal flight instruments, special monitoring instruments and failure warning signals, whereas the action required may be obtained from a display, remembered from training or just simply instinctive.

For this reason, when considering the application of an automatic flight control system to a particular type of operation there is a need also to consider carefully the pilot's monitoring function and to determine whether special monitoring equipment and certain types of failure warning will be needed to supplement information available from other sources.

In this paper some of the problems associated with this aspect of flight control system design are discussed and some of the monitoring facilities that are incorporated with the systems produced by our Company are described.

Particular emphasis is given to those systems designed for use during the approach and landing in conditions of very low visibility. Under these conditions, the autopilot and the flight crew together perform a task which neither can attempt safely or economically without some assistance from the other. In this type of operation, the provision of adequate monitoring information and failure warning to the flight crew is of prime importance.

A broad outline of the background from which this type of operation has been evolved is first briefly described.

2. Outline of Background

In its initial application to the control of aircraft the automatic pilot served to relieve the human pilot of tedious and fatiguing control functions, such as the control of height and heading during a prolonged cruise.

In this mode of operation virtually all the monitoring information required can be obtained from basic flight instruments and motion sensation. Slow runaways can be detected from displayed attitude information, the airspeed indicator, or existing facilities such as the Mach warning horn. Motion sensation can be relied upon to alert the pilot in the event of a fast control runaway.

The pilot is expected to be strapped in his seat and it is assumed for certification purposes that he will take corrective action within five seconds of detecting a fault during cruise. The corrective action itself is usually instinctive.

More recently, the autopilot has demonstrated its ability to perform certain tracking tasks more accurately than the human pilot and advantage has been taken of this in its frequent application to the tracking of a radio beam during the descent through cloud down to a height of about 200 feet above the runway surface.

In this mode of operation the pilot requires to know whether the automatic system is tracking the glide slope and localiser centreline with sufficient accuracy and whether the equipment which is transmitting and receiving the radio guidance information is itself functioning correctly.

Signals representing unsatisfied manoeuvre demands are displayed on the flight director and the deviation signals from the radio receiver output (so-called raw information) are displayed on an I.L.S. cross-pointer meter which often forms parts of the flight compass instrument.

Using information displayed in this form, together with information displayed on other basic instruments, trained pilots can detect single failures in a control system which comprises only a single channel (simplex) autopilot operating from a single source of radio guidance information.

If the automatic control follows a slow drift in output from the demand computing, the flight director information may remain nulled, but the aircraft deviates from the radio beam and this is indicated by a slow divergence of the raw radio error signal from its null position.

If the automatic control functions incorrectly in the presence of correct demand computing and correct radio guidance information, errors are displayed on both the flight director and on the I.L.S. cross-pointer meter. These indications are sufficient to alert the pilot in the event of slow deviations and motion sensation alerts him to fast control runaways.

Radio guidance runaways, at a rate faster than the automatic control can follow, will appear as deviations on both the flight director and the cross-pointer meter, but slow radio guidance runaways will be followed by the automatic control and will not show up as errors on the monitoring displays. This type of fault can be detected from other basic flight instruments. Also, a considerable number of possible radio faults are covered by integrity monitoring within the radio equipment, and radio failure warning flags are used to indicate the presence of such faults to the pilot. For instance, the I.L.S. localiser transmitter may be switched off if its centreline monitor detects a deviation of more than a twentieth of the course sector width and this occurrence is indicated on the BEAM radio warning flag.

The safety of this type of operation is predicted on the assumptions that the pilot can adequately monitor for single faults using the type of information described above and that during the approach he will react within two seconds of detecting a fault. With a single channel autopilot and simplex radio guidance the safe operational limit is normally about 200 feet above the runway surface. Runaways which occur just before this point and slowdrifts which occur farther up the approach path can be detected and corrected so that a safe clearance above the ground is maintained.

Currently, automatic pilots which can safely control the approach to lower heights and some which can perform the landing manoeuvre itself are available and much effort is being applied to the proving of these systems for use by the airlines in conditions of very low visibility. The low approach systems will be limited in application down to a height of about 100 feet above the runway surface, but the automatic landing systems can, and ultimately will, be developed to the stage where landings in increasingly poor visibility can be made safely in civil airline operations.

To this end, certain milestones were agreed at the IATA 15th Technical Conference during 1963, and operational limits were categorised as shown in Fig. 1.

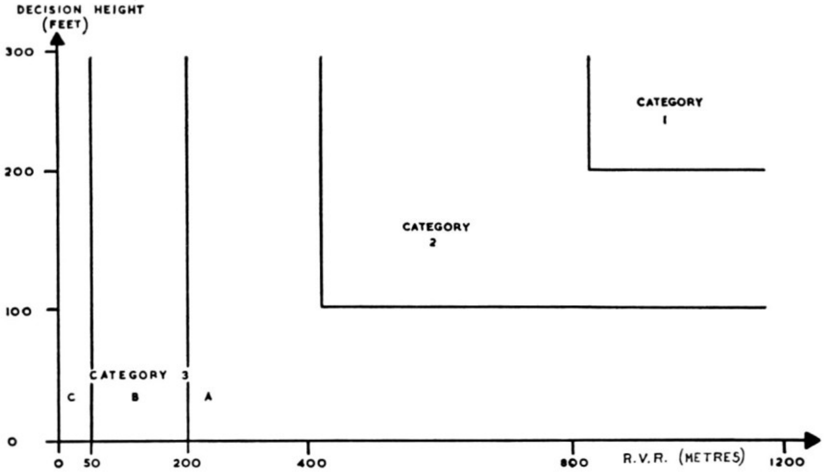


FIG. 1 — I.A.T.A. categories

This shows the limiting decision height and the limiting runway visual range, (R.V.R.) for each category.

At the decision height in Category 1 and Category 2 conditions the pilot must decide whether to continue with the landing or to abandon the attempt and overshoot. This decision depends to a large extent on whether he can see the runway sufficiently well to judge whether a manual landing can be attempted safely.

In Category 3 conditions the decision will be less dependent on information obtained from outside visual references, and more emphasis will be placed on monitoring information displayed within the cockpit.

The provision of monitoring information and failure warnings to the flight crew during autopilot operation in Category 2 and Category 3 conditions will now be discussed.

3. Pilot Monitoring of Category 2 Approaches

3.1. *General*

Category 2 operations are an extension of Category 1 operations to a lower decision height in which additional equipment is required to overcome the safety problems that have limited the Category 1 operation to 200 feet.

The problem of autopilot runaways at low height is overcome by the use of special automatic autopilot monitoring which will reduce the effects of control malfunction to a lower level than that achievable with a single channel, unmonitored autopilot.

This so-called fail-soft autopilot will operate on signals from an autopilot computer which takes its radio guidance information from one of two airborne receivers. Guidance information from the other receiver will feed into a separate flight director computer which operates the flight director display, and into the I.L.S. cross-pointer meter of the flight compass.

Using this arrangement it is expected that certain faults, such as radio guidance failures, will be more readily detected so that approaches to within 100 feet of the ground can be made with adequate safety.

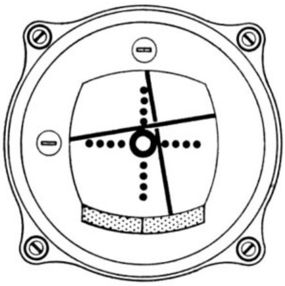
The ground transmitter will itself be automatically monitored to within close limits and either a self-monitored radio altimeter or two cross-monitored radio altimeters will be used to give a safe and precise indication of height during the latter stages of the approach.

Although the source of information is of higher integrity than that required for Category 1 operations, the appearance to the pilot can be virtually the same and one might be led to believe that the monitoring task itself would not require any further additional equipment or special features. In fact, information so far promulgated by the Certification Authorities for Category 2 operations does not specifically call for any more extensive airborne monitoring equipment.

However, although it is generally agreed that malfunctions can be detected and corrected in time, there are diverse opinions on whether information for monitoring the tracking performance is adequate and whether the pilot will require some instrumental assistance in judging the landing flare in conditions of poor visibility.

3.2. *Performance monitoring*

During the instrument approach to decision height in Category 1 operation, the pilot is accustomed to monitoring for faults and to assessing the tracking performance as indicated on the I.L.S. cross-pointer meter (Fig. 2). He is



	HEIGHT ON 3 DEGREE GLIDE SLOPE	
	100 FEET	200 FEET
VERTICAL DISPLACEMENT (GLIDE SLOPE) FULL SCALE	$\pm$17 FEET	$\pm$34 FEET
LATERAL DISPLACEMENT (LOCALISER) FULL SCALE	$\pm$380 FEET	$\pm$460 FEET

FIG. 2 — Standard I.L.S. cross-pointer meter

reasonably satisfied if the lateral radio errors are contained within $\pm 20\%$ deviation on the display (*see* Fig. 2) because, on becoming visual at 200 feet, he can easily correct a lateral displacement of this order and align the aircraft with the runway centre-line prior to flare. He has about fifteen seconds within which to make a decision and to execute the manoeuvre. From 100 feet, the time for decision and sidestep manoeuvre prior to flare is reduced to about five seconds and the lateral correction manoeuvre which can be made within this time is considerably reduced.

Figure 3 shows the magnitude of the sidestep manoeuvre which can be made before flare, plotted against height on a 3 degree glide slope. The

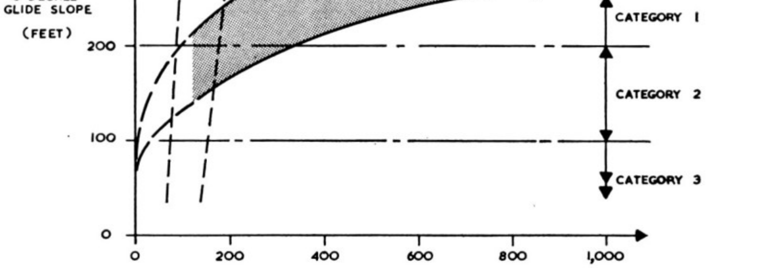


FIG. 3 — Sidestep manoeuvre limits

shaded region includes many measured test points for airline pilots flying a variety of aircraft types[1] and the boundaries are extrapolated down to 50 feet height on the basis of estimates for typical bank angles and roll rates likely to be used. Also shown are the equivalent deviations from the runway centre-line in terms of percentage localiser scale deflection.

From this it can be seen that although a pilot might find it reasonably easy to land on the centre-line after a 20% deviation at 200 feet, the same cannot be said if the same deviation exists at 100 feet. In fact, he might just be able to manoeuvre to within about 50 feet of the runway centre-line before the start of the flare manoeuvre.

We can perhaps get a better impression of the changed situation if we view it from the pilot's seat and the next two figures are an attempt to indicate the pilot's view at decision height in Category 1 and Category 2 operations respectively, the downward viewing angle being cut off at about 12 degrees.

Figure 4 shows the view at a height of 200 feet on a 3 deg glide slope with a runway visual range of about 800 metres. The lateral displacement is equivalent to a 20% localiser scale deflection and from this point the pilot could land on the runway centre-line.

Figure 5 shows the view at a height of 100 feet on a 3 deg glide slope with a runway visual range of about 400 metres. The lateral displacement in this case is also equivalent to a 20% localiser scale deflection and from this point

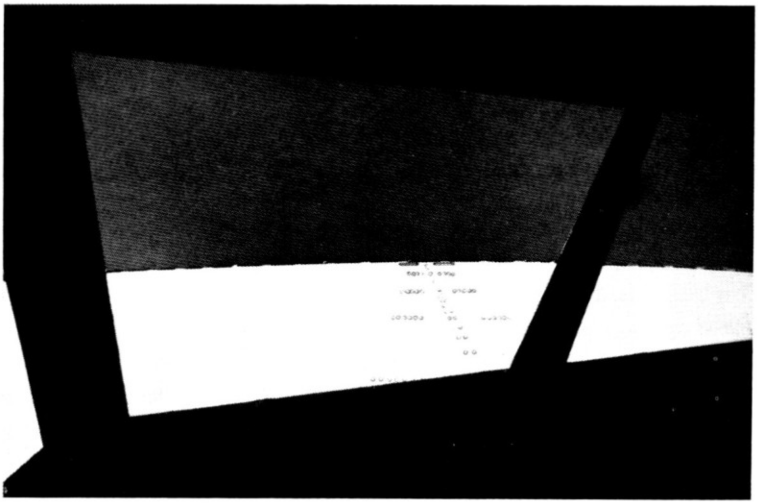


FIG. 4 — Pilot's view in Category 1 weather limits
Wheel height = 200 ft
3 degree glide slope
20% localiser scale deflection
Localiser beam offset = 15 ft at runway threshold

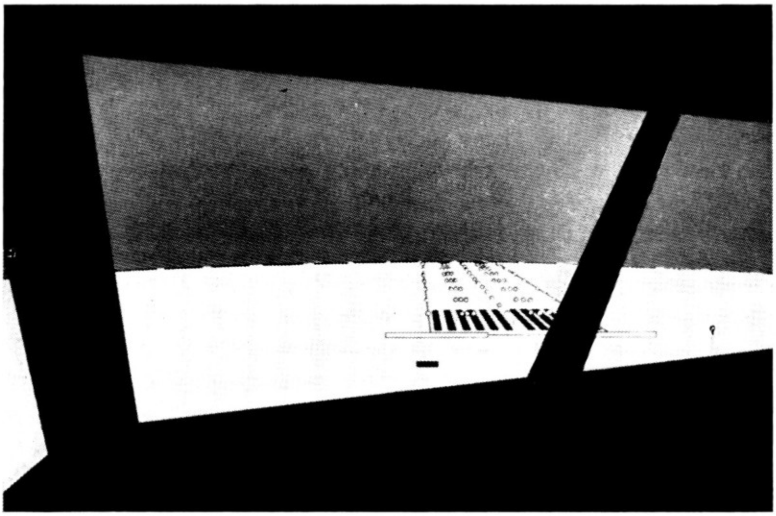


FIG. 5 — Pilot's view in Category 2 weather limits

Wheel height = 100 ft
3 degree glide slope set to 60 ft over threshold (maximum glide slope tolerance)
20% localiser scale deflection
Localiser beam offset = 15 ft at runway threshold

it is unlikely that the pilot could land the aircraft on the runway centre-line, although he might get within 50 feet of it. It is a situation from which the pilot would probably initiate overshoot action.

Because of this difference between Category 1 and Category 2, it has been suggested that the pilot should monitor the tracking performance during a Category 2 approach to within about 10% scale deflection instead of within 20% as in Category 1 approaches and, that to do this with sufficient accuracy, he will require the localiser deviation information on an expanded scale. As an alternative to this it is suggested that the radio deviation signal could be made to illuminate a warning light at about the 10% deviation level, thus indicating that overshoot action should be initiated before the decision height is reached.

Other suggestions are that the pilot should be provided with both an expanded deviation scale and an excess deviation warning light.

These suggestions require careful consideration for two reasons. The first is that although the occurrence of a lateral deviation equivalent to 20% deflection at heights below, say, 200 feet might be reasonable grounds for suspecting that the attempt to land will be unsuccessful, it is quite probable that a satisfactory landing after 10% deflection at 100 feet could be made.

As shown in Fig. 6, the landing after a 20% scale deflection at 100 feet would be dangerously close to the edge of a 150 feet wide runway, even if it occurred on the more advantageous side of an offset localiser beam. The beam centre-line offset shown in Fig. 6 and the localiser sensitivity tolerance bands correspond to Category 2 localiser standards.

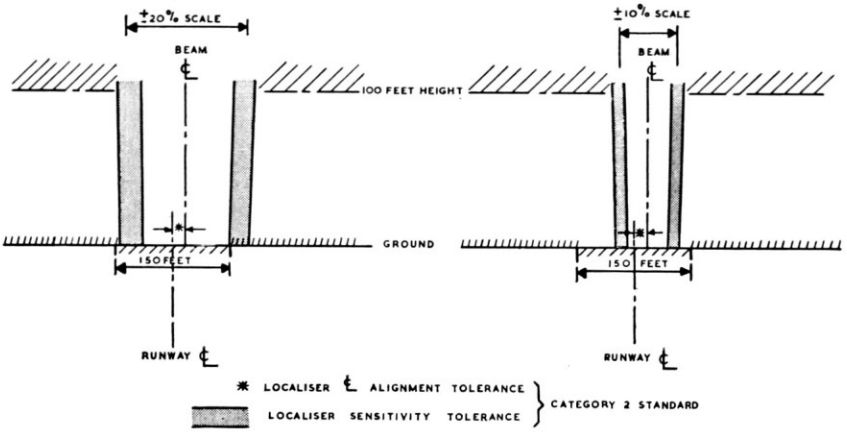


FIG. 6 — 10% and 20% radio deviations relative to runway edge

The right-hand figure shows that a landing from a 10% deviation at 100 feet could well be satisfactorily completed on to a runway of only 150 feet in width, and it would appear that a lateral deviation of this magnitude is not really a very sound basis for abandoning the approach above decision height.

The second consideration is that a warning light operated by a deviation signal equivalent to a 10% scale deflection could well be unsatisfactory, unless some automatic discriminating features are provided in the warning system to prevent its functioning during the early part of the approach, when a warning at such a small deviation would be unnecessary and perhaps distracting.

Operation of the warning during the beam capture phase would provide a means of checking before the approach that it will function, but there is perhaps a need to consider whether, once the beam has been captured, the warning should be inhibited until some lower height.

To avoid complexity of this sort, some arrangements, based simply on the magnitude of the deviation signal, require the pilot himself to adhere to a fairly complicated formula such as to ignore the signal completely above a certain height and to ignore it within a lower height band if the warning duration is less than a certain time. For longer warning durations within this height band, or for any warnings at all below the height band, the pilot is to initiate overshoot action.

Clearly, this procedure imposes an additional work load on the pilot. Also, a practice which requires a warning to be ignored on some occasions is not a particularly good one and, as has already been indicated, the 10% triggering level may not be grounds for overshooting before the 100 feet decision height.

It would appear from the points mentioned above that one consequence of very close pilot monitoring of the tracking performance during Category 2 approaches will be an increase in the number of overshoots.

The total overshoot rate must be acceptable to the Air Traffic Control system and it has been suggested[2] that this should not exceed a rate of one in twenty. Three main causes of overshoot action are envisaged, namely:

(*i*) Lack of visual guidance at decision height.
(*ii*) Faults arising in the control equipment and in other aircraft systems.
(*iii*) Unsatisfactory approach system performance.

Allowing each to have an equal share of the total rate and sharing the cause due to unsatisfactory approach system performance equally between pitch and lateral, gives an acceptable rate for excess lateral deviations of one in a hundred and twenty and to achieve this, 2·7 standard deviations of lateral tracking performance error should not be greater than the maximum lateral deviation from which a safe landing can be made.

Assuming that, at the lowest decision height of 100 feet, no significant lateral corrections can be made manually before flare, the half width of the 'visual acceptance' window is probably about 50 feet. A typical design aim for the lateral approach coupler performance is then a standard deviation of lateral error at 100 feet of just over 18 feet. But the instrument window for a $\pm 10\%$ scale deflection is only about 38 feet in half width so that, using an approach coupler with a performance standard suitable for visual acceptance at 100 feet, the attempt would be rejected before decision height on an instrument indication equivalent to about two standard deviations of control tracking performance. This would lead to an overshoot rate due to this cause alone of about one in twenty, which is the maximum allowable rate for all causes.

Another point to be considered when deciding the indicated tracking deviation at which the attempt to land should be abandoned before decision height, is that it should not be inconsistent with the deviation at which overshoot action would be initiated by a pilot who can see the runway.

This is an important consideration in a Category 2 operation being conducted by a two-man crew, where it will be necessary to ensure that the instrumental reject level for the head-down pilot is correctly related to the visual acceptance level for the head-up pilot.

The latter will be somewhat variable, of course, but the two criteria should be related so that the head-down pilot does not too frequently reject approaches which would have led to a successful landing and so that the head-up pilot on becoming visual is not too frequently presented with a situation from which a landing cannot be made.

The approximate order of the instrumental reject level is indicated by the information presented on Fig. 7. This shows the magnitude of sidestep

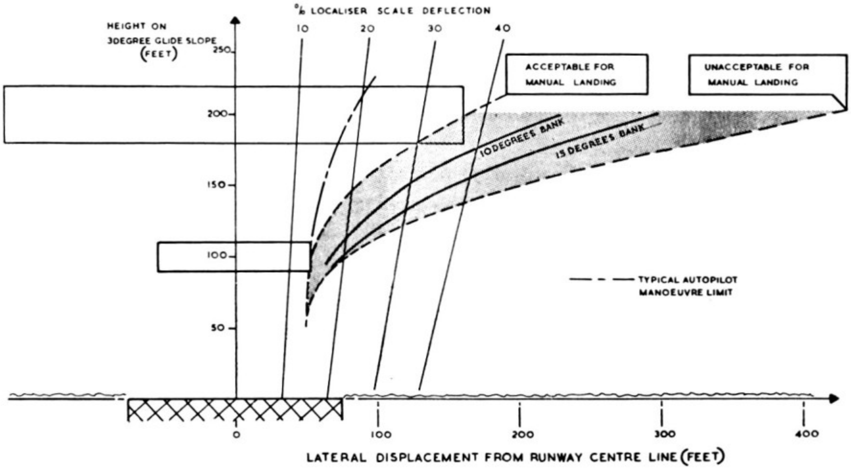


FIG. 7 — Visual acceptance windows

manoeuvre for manual control (taken from Fig. 3), offset from the centre-line of the runway by 50 feet. These occupy the shaded area of the slide. Also shown are typical acceptance windows at 200 feet and 100 feet, each having a width no greater than the minimum sidestep manoeuvre limit.

This indicates that most pilots would probably decide to continue with the landing after a deviation of about 15% scale deflection at 100 feet.

Figure 7 also shows that to reject the approach at the 10% deviation level would be unnecessary and that to continue the approach below 150 feet down to 100 feet with a 20% scale deflection could cause the head-up pilot, who might become visual within this height band, to attempt the landing from a difficult position or to become anxious before the initiation of overshoot by the head-down pilot at 100 feet.

It would seem reasonable to suggest therefore, that in Category 2 operations the head-down monitoring pilot should reject the approach on the grounds of unsatisfactory lateral tracking performance at about the 15% deviation level below 150 feet and that if excess deviation warning lights are being used, they should be set to operate at about the 15% deviation level.

3.3. *Flare guidance*

Another aspect of Category 2 operations which requires some consideration is that concerning the provision of director guidance during the manual flare manoeuvre.

In conditions of very low visibility, it has been shown that, although visual cues may be satisfactory for the manual judgment of lateral control, there is a distinct tendency for the pilot to believe that he is high on the approach. This is probably because the visibility limit has the appearance of the horizon being situated rather low in his field of vision. This causes the pilot to try to duck under what is, in fact, the correct path.

Also, it is possible that a sudden deterioration of visibility could occur after the decision to land has been taken, leaving the pilot with inadequate visual cues from which to judge the landing flare manoeuvre.

It would appear that some form of head-up director guidance will be essential to ensure a safe completion of the landing under these conditions and in the low approach systems we have produced this is provided on the P.V.D. facility, shown in Fig. 8.

A deviation from the correct flare path is detected by a flare computer causing the helically striped poles in the display units to rotate in a direction which indicates the control action required.

When the displays are mounted as shown in Fig. 8, their movement can be seen by a pilot who is looking through the windscreen, and the information

FIG. 8 — P.V.D. installation in the Dove

obtained from them can give valuable head-up guidance for landing in conditions of low visibility.

Currently, much work is being done on the use of collimated displays for providing head-up director guidance and it is likely that these also will fulfil a useful purpose in low visibility landings.

3.4. *Mode annunciators*

The full integrity of a Category 2 system will not be achieved unless all the correct selections have been made on the equipment to be used. These can be quite numerous and it is considered that a Mode Selection Annunciator will be required to assist the pilot in confirming that the necessary actions have been taken.

A typical list of the necessary cockpit checks is as follows:

(*i*) Radio selector switch in APPROACH.
(*ii*) Autothrottle ENGAGED.
(*iii*) Radio Altimeter ON.
(*iv*) P.V.D. Power ON.
(*v*) Beam PRIMED.
(*vi*) Glide PRIMED.
(*vii*) Beam CAPTURED.
(*viii*) Glide CAPTURED.

All these conditions can be checked automatically by 'OR' and 'AND'

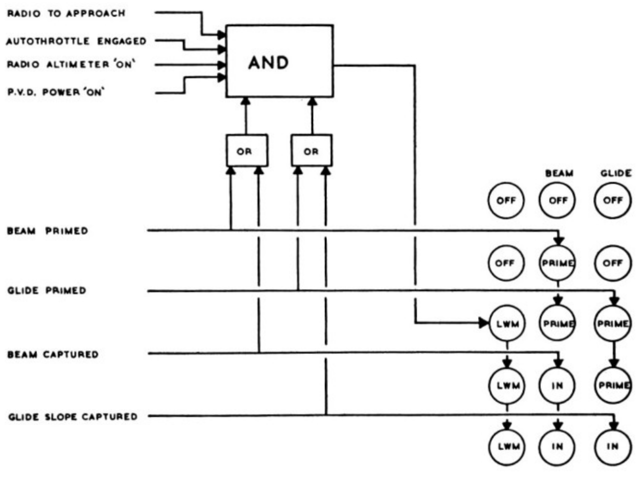


FIG. 9 — Mode annunciator for Category 2 operations

logic circuits and the necessary information can be shown on a magnetic indicator, as shown in Fig. 9. This shows a typical list of cockpit selections, typical logic circuits and the sequence of indications on three 3-way magnetic indicators.

Two of these indicators simply show the state of the glide and beam coupling equipment, either OFF, PRIMED or captured (IN). The other indicates OFF until all the necessary selections for a (L)ow (W)eather (M)inima approach.

4. Pilot Monitoring of Category 3 Operations

4.1. *General*

Because of the reduced amount of information that can be obtained from outside visual references, Category 3 operations will be more dependent on the use of automatics for the safe completion of the landing manoeuvre.

As the aircraft approaches the height below which a safe overshoot cannot be made, the pilot will be assessing the risk of allowing the automatics to complete a landing in which he himself may not be able to assist significantly should adverse circumstances be encountered below the safe overshoot height.

For a safe overshoot the risks of hitting the ground, of stalling and of striking an obstacle, must not be greater than certain specified levels and for a safe continued landing the risks of landing off the runway, of landing with an excessive rate of descent and of landing in an exaggerated attitude must also not be above acceptable levels.

At the lowest limit of Category 2 operations all these factors are reasonably well covered by the 100 feet decision height and by the pilot's assessment of his own ability to land the aircraft, given outside visual references and sufficient time to anticipate the necessary control actions.

In Category 3 conditions they must be covered by the provision of monitoring information which can indicate to the pilot, before the minimum overshoot height, whether the automatics can be expected to complete the landing with the required level of safety.

The safety of the complete operation will then depend upon the pilot monitoring performance down to the minimum overshoot height and on the automatic control performance below this height.

The important link is the monitoring information itself, which must take into account all the relevant limitations of the automatic control system performance and be presented in a manner such that the required level of pilot monitoring performance will be achieved.

The ability of the automatic control system to complete the landing with the required level of safety will depend on a number of factors, such as:

(*a*) Wind speed and direction.

(*b*) The accuracy, reliability and noise levels of the radio guidance equipment.

(*c*) The system selections made by the pilot.

(*d*) The degree of system redundancy at the beginning of the landing.

(*e*) The displacement and rate of deviation of the aircraft's flight path relative to the correct path at the start of the manoeuvre.

(*f*) The control system performance variability through the landing manoeuvre.

The first two items, limiting wind conditions and the radio guidance standard, will be specified for the Category 3 operation but the other items have a direct bearing on the special monitoring equipment required.

The detailed design of the monitoring equipment will depend, of course, on the type of control system being used, but a description of the arrangement in the Trident will indicate the type of monitoring equipment required.

The flight control system currently undergoing flight evaluation includes triplex pitch and roll control channels and a duplex autothrottle system.

In the triplex arrangement three similar autopilot sub-channels apply control collectively. A faulty sub-channel is out-voted by the other two sub-channels and automatically disengaged. The active system is then duplex and the occurrence of a further significant disagreement causes both channels to disengage, leaving the aircraft's flight path undisturbed. This arrangement provides a failure survival capability to meet the autopilot safety standards specified for civil airline operations in Category 3 conditions.

4.2. *System selection monitoring*

Figure 9 shows an annunciator from which the pilot can readily check that all the correct selections have been made in preparation for an automatically controlled low approach.

The arrangement used in the Trident and known as the Flight Control System Indicator Unit is shown in Fig. 10. This is mounted on the flight panel near the primary flight instruments.

A selection made on the autopilot controller causes the appropriate window of the Indicator Unit to light up and the windows themselves are so arranged that the complete lower row should be illuminated during the approach.

This indicates that the auto-throttle is engaged, the lateral control is in a track mode, and that the localiser beam and the glide path have been captured.

4.3. *Control system redundancy monitoring*

During the early part of the approach, the degree of control system redundancy and other aspects of the system functioning can be checked on a

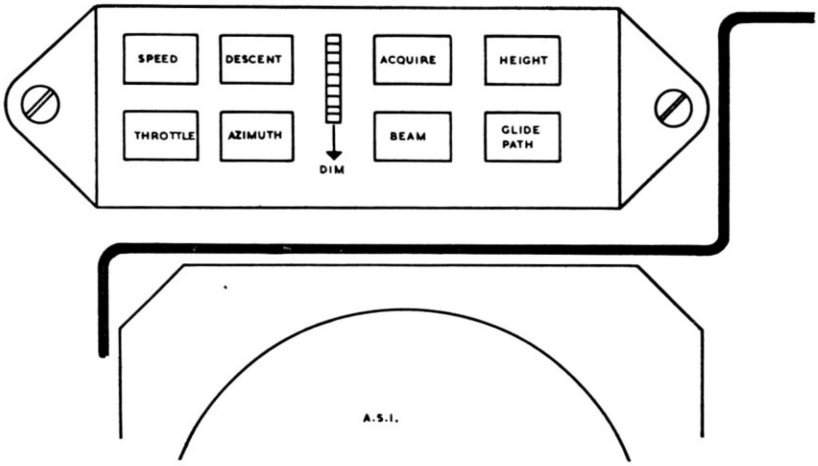


FIG. 10 — Trident F.C.S. indicator unit

Flight Systems Panel which is situated in the flight engineer's position.

The Flight Systems Panel for the Trident's triplex system is shown in Fig. 11 and from this the number of sub-channels engaged in both roll and pitch can be seen from the lower row of dolls-eye indicators.

The figure shows the panel indicating that one roll sub-channel and one pitch sub-channel are disengaged.

For redundancy monitoring during the later stages of the approach, the control system redundancy information is repeated on the flight panel by a single dolls-eye indicator which shows whether or not the control system is operating at the full triplex redundancy level.

This is shown on a diagram of the Trident flight panel layout in Fig. 12 (left-hand side) which shows also, the Flight Control System Indicator Unit (above the airspeed indicator).

4.4. *Performance monitoring*

The performance monitoring equipment for Category 3 operations should give an indication of whether the risk of an accident due to adverse system performance during a continued landing below the minimum overshoot height is greater, or less, than an acceptable level.

Considering, for instance, the lateral tracking performance, the risk of landing off the edge of the runway during a particular flight should be less than about one in a hundred thousand (1×10^{-5}), and the lateral performance monitoring should indicate when the risk on a particular flight is higher than this level.

The difficulty of assessing this from the conventional deviation display can

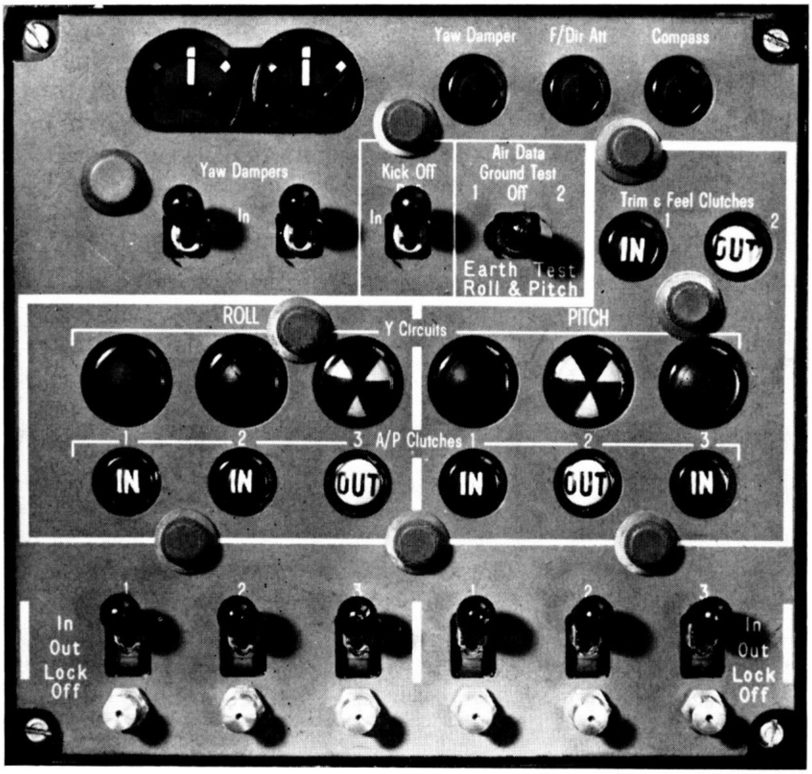


FIG. 11 — Flight systems panel

be demonstrated from an approximate analysis which indicates the probable order of magnitude of the width of the acceptance window for Category 3 operations.

Assuming that the landing is to be made on a runway which is 150 feet wide, the maximum allowable deviation of the aircraft from the runway centre-line at touch-down is about 60 feet. One main wheel will then be very close to the runway edge.

From just inside the acceptance window at the minimum overshoot height the probability of this occurrence must be not greater than about one in a hundred thousand (1×10^{-5}) which is equivalent to about 4·4 standard deviations of lateral tracking performance.

Also, the frequency of overshoots due to adverse lateral performance alone should not be greater than about 1 in 120, which is equivalent to about 2·7 standard deviations of lateral tracking performance.

To fulfil both objectives, namely a safe continued landing on automatics

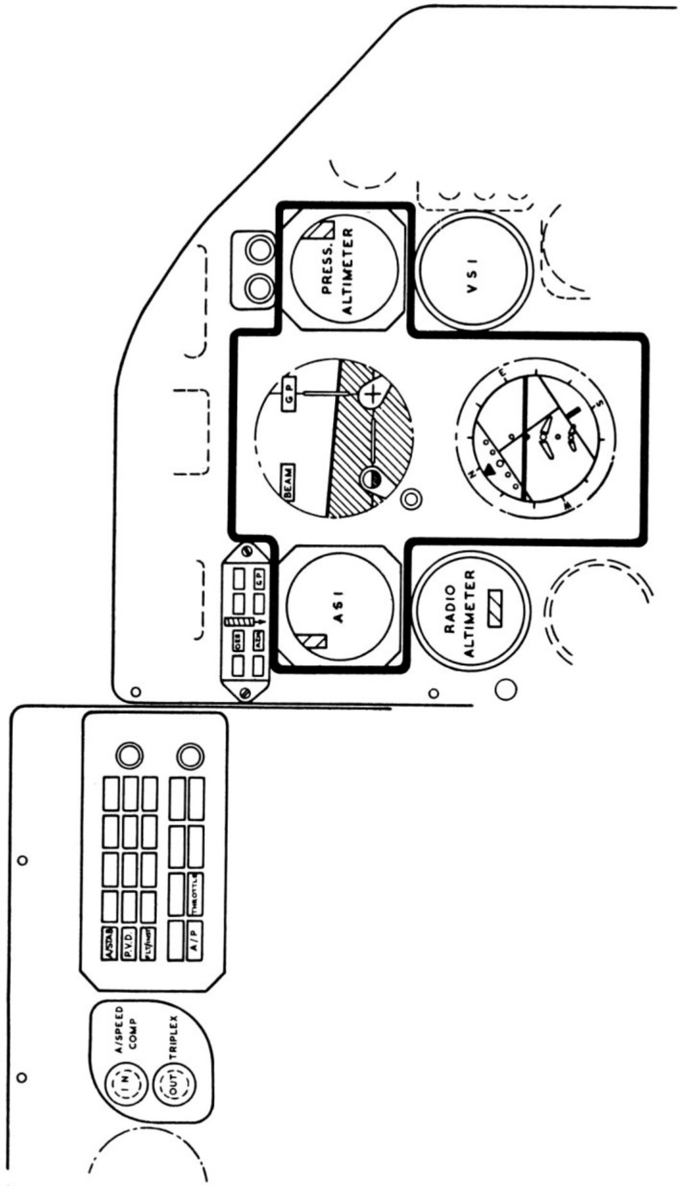


FIG. 12 — Trident flight panel

and a sufficiently low overshoot rate, the standard deviation of lateral tracking performance will need to be about 8½ feet and the half-width of the acceptance window would then be about 23 feet.

This is much less than 10% deviation on the conventional localiser deviation display and it is clear that an alternative means of providing performance monitoring information to the pilot for Category 3 operations will be required.

In the Trident's flight evaluations the two localiser signals will be measured and the AZIMUTH window of the Flight Control System Indicator Unit (*see* Fig. 12) will be made to flash when the sum exceeds a certain level.

A triggering level of 24 micro-amps total, which is equivalent to a displacement of about 28 feet, is being tried but the final setting will depend on the outcome of the flight trials.

Excess deviation from the glide path will be indicated also on the GLIDE window of the Flight Control System Indicator Unit. This will flash when the sum of two glide path signals exceeds a certain level. Also, because the three sub-channels of the triplex control system take their glide path signals from only one receiver, the GLIDE window will be made to flash when the difference between the two glide path signals exceeds a certain level.

The rate of descent just before decision height will need to be monitored closely and a scheme whereby the DESCENT window of the Flight Control System Indicator Unit is flashed for rates of descent greater than 1000 ft/min will be assessed during the flight trials.

Another aspect of the performance monitoring equipment in the Trident is the airspeed compensation IN/OUT dolls-eye indication shown in the top left hand of Fig. 12.

A term in the automatic flare computation which compensates for changes of airspeed due to wind shear and turbulence, has been found to reduce the variability of the longitudinal touch-down point and the variability of the touch-down descent velocity.

This compensation term is manufactured twice from two independent airspeed sources and one of the signals is fed into each of the three sub-channels of the triplex pitch control system. This is disconnected if a comparison of the two compensation terms indicates a significant difference and the Airspeed Compensation dolls-eye shows that the term is no longer present. In wind speeds greater than about 15 knots this indicates that the risk associated with adverse pitch performance is greater than an acceptable level.

During the flight trials of the Trident's automatic landing system, measurements of the variability of the touch-down performance and of conditions before decision height will be taken. The complete performance monitoring system will be assessed and the acceptance levels will be set to provide the pilot with indications when the risk of continuing the landing is above the acceptable level.

5. Failure Warnings

In addition to the autopilot monitoring information already described, flight control system warnings are required to indicate when equipment has ceased to function correctly.

In the past warning indications in general have been the subject of much heated controversy: warning lights, warning flags and audible warnings have all received some measure of criticism. Of course, lights, flags and noises each have certain special attributes which can assist best in some part of the process which takes place between the indication of a warning and the pilot's completion of the corrective action.

Flashing lights and noises can ensure a rapid reception of the warning, but may not always provide much assistance towards identification of the fault or information about the corrective action required. The reception stage might be slower with flag warnings, which can contain more information for assisting with identification of the fault.

In present-day aircraft the number of systems has increased and the need has arisen for an integration of failure warnings for the separate systems into a single warning facility, which has become known as the Central Warning System. This eases the pilot's task of monitoring for and identifying failures in aircraft equipment and in many ways it has eased the equipment manufacturers' task as well. The 'attention getting' features, the priority levels and identification assistance for many of the failures can be provided in the Central Warning system, which requires only the correct type of failure discriminant voltage to be supplied from the equipment itself.

The Trident's Central Warning System as it appears to the pilot is shown on Fig. 12.

Two lights, one red and one amber are situated on the flight panel in front of each pilot. System malfunctions which require immediate action cause the red ALERT light to flash. Other malfunctions or wrong pilot selections which require action on a more relaxed time-scale, cause the amber CAUTION light to flash. About twenty different warning circuits are connected to the red ALERT system and over forty circuits are connected to the amber CAUTION system.

Identification of the malfunction is assisted by the steady illumination of an appropriate window in the Central Warning System Display Panel which contains fifteen amber windows and eight red windows.

The flight instrument and automatic control system failure warnings occupy three of the amber windows and two of the red windows, as indicated in Fig. 12. The three amber windows indicate:

(*a*) Malfunction of the duplex yaw damper system.

(*b*) Incorrect selection of the Para Visual Director (P.V.D.) facility, and

(*c*) A fault in the flight instrument system, either in the flight director attitude display or in the compass display.

The two red windows indicate:

(*a*) A complete disconnect of either the roll or pitch control channels, and

(*b*) A disconnect of the duplex auto-throttle system.

In addition to the red ALERT warning, an audible warning is given for autopilot disconnects in all modes of flight.

The flashing light warnings can be cancelled by pressing the light itself, but the illuminated window remains displayed until the fault is cleared.

In addition to these central warning indications, flag warnings are provided on the individual flight instruments themselves, as shown on Fig. 12.

6. Conclusions

The provision of monitoring information and failure warnings to the flight crew during autopilot operation has been discussed and some of the current problems associated with Category 2 and Category 3 operations have been described.

For Category 2 operations it would appear that an expanded localiser scale or an excess deviation warning will be required for performance monitoring and that equipment from which the crew can readily check that all correct system selections have been made will be needed.

The coupling performance requirements for a low-approach control system will not be difficult to meet, given suitable radio guidance information, but it has yet to be established that in the minimum Category 2 weather limits the operation as a whole can be achieved with the required level of regularity and safety.

It is probable that some form of head-up flare guidance or perhaps an automatic flare control system will eventually be required as part of the Category 2 equipment.

For Category 3 operations, the monitoring information will be required to indicate whether the risk of committing the aircraft to an automatic landing is acceptable. This will involve a control system redundancy check and monitoring of the tracking performance to within closer limits than those applicable to Category 2 operations.

Some of the methods being tried in the flight development programme of the Trident's Category 3 system have been described and it is probable that more work will be required before a satisfactory arrangement of monitoring information is evolved.

This aspect is as important as the design of the control system itself and the achievement of airline landings in conditions of really low visibility will depend largely on the provision of suitable monitoring information and failure warnings to the flight crew.

References

(1) Perry, D. H., Port, W. C. A., Morrel, J. C., 'A Flight Study of the Sidestep Manoeuvre during Landing.' R.A.E. Report Aero. 2654 July 1961.
(2) 'Airworthiness Requirements for Landing in Restricted Visibility — Category 2 Operations,' A.R.B. Paper No. 423 Iss. 1, April 1965.