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FLIGHT SIMULATIONS ON MLS-GUIDED INTERCEPTION PROCEDURES AND CURVED APPROACH PATH PARAMETERS

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Abstract

The paper presents a survey of two separate investigations carried out on the NLR flight simulator, using a Boeing 747 simulation model. The purpose of these investigations was to study the greater operational potential of the new approach and landing system MLS.

In the first investigation the feasibility of four MLS guided interception procedures was evaluated, thereby considering the appropriate turn techniques and required avionics equipment.

In a second flight simulator program an evaluation was carried out of the approach path parameters for curved paths. Seven oblique approach paths were investigated, varying in both straight final length and oblique angle. The investigation was carried out for various operating minima, while also the effects of wind, turbulence and cloud base had been considered. Results of the tests consisted of subjective data (effort ratings, questionnaire responses and pilot comments) and objective data (tracking performance, control activity, etc.).

1. Introduction

The present ILS (Instrument Landing System) has been the standard approach and landing aid in civil aviation for more than 40 years. It will be replaced in the period from now up to 1998 by the new approach and landing system MLS (Microwave Landing System).

From figure 1 it becomes clear that MLS offers a greater operational potential than ILS. Apart from the improved signal accuracy MLS allows, due to its wide coverage, the introduction of new approach and terminal area (TMA) procedures. In the last 15 years, at various institutions attention was paid to the feasibility of curved or segmented approaches using MLS as a means for guidance (1)-(7).

At the NLR, firstly some preliminary flight simulation investigations were carried out on the feasibility of laterally segmented or curved approach paths (4).

After that a simulation study was conducted on the use of MLS guidance during interception of these approach paths (8), (9). Four proposed concepts of MLS interception procedures, resulting from this study, were adopted by ICAO and RTCA (10) as possible interception procedures for future MLS use.

A subsequent flight simulation investigation was addressed to the evaluation of the typical parameters for curved approach paths (11), i.e. length of the straight final segment and magnitude of the turn angle, in dependence of wind, turbulence and the operating minima (decision height, visibility and runway visual range).

The last two flight simulation investigations, which are subject of the present paper, were carried out under contract with the Netherlands Department of Civil Aviation (RLD) and have been intended to serve as a Netherlands' contribution to the work done by the relevant ICAO panels.

2. Simulation facility and mathematical models

Flight simulator equipment

The flight simulation programs were carried out on the research flight simulator of the NLR. The simulator equipment consists of several modules:

- a multi-processor computer system,
- a TV-modelboard visual system,
- a four degrees of freedom motion system,
- a transport type aircraft cockpit, serving a 2-man crew with the possibility of an additional observer seat,
- a control desk,
- recording equipment.

Sophisticated systems and components have been used to achieve a realistic simulation in all considered aspects. Visibility effects such as flying in clouds, haze and fog were introduced by electronically altering the terrain image.

A picture of the cockpit interior showing the instrument panels and controls has been presented in figure 2. Both left and right panels include an ADI and HSI. An experimental navigation display was installed in the centre instrument panel.

Aircraft simulation model

A simulation model of the Boeing 747 aircraft was used to represent an aircraft type having the dynamic characteristics of a heavy weight type of aircraft. It is expected that this type of aircraft will be critical with respect to flying curved flight paths, due to its large mass and inertia and the higher approach speeds.

For maintaining a desired airspeed the pilots could make use of the available autothrottle system.

MLS guidance model

The position of the aircraft with respect to a curved path was computed by the MLS guidance model using the simulated azimuth, elevation and DME signals.

In order to improve the realism of the simulation, noise was added to the simulated azimuth and elevation signals. The corresponding

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noise levels had been based primarily on the ICAO SARP's specification for Annex 10.

Figure 3 illustrates the situation for an aircraft proceeding along a curved approach path. A curved approach path is defined by a combination of connected straight line and circular arc segments.

The variables used to express the relative aircraft position are:

- along track distance (ATD)
- cross track deviation (CTD)
- vertical track deviation (VTD)

With the use of the ATD, the linear track deviations CTD and VTD are reduced to the usual angular deviations.

3. Flight simulation study on MLS interception procedures

3.1 Description of interception procedures

As a result of extensive theoretical studies and a computer simulation investigation (8), a series of 4 MLS interception procedures was defined, which appeared promising for use in an MLS environment. The principles of the four proposed interception procedures, of which each is considered to serve an essential operational objective, are graphically represented in figure 4. These procedures have been designed for use in an MLS environment and are universally applicable to all laterally segmented and curved approach path types.

The algorithms for the interception procedures provide trajectories composed of straight and circular segments that smoothly connect the actual aircraft position, at the moment of intercept initiation, with the approach path. Originating from the condition that within the allowable speed range and for rather extreme wind vectors the required bank angle should remain within acceptable limits, a radius of 2 NM seemed to be an appropriate value for the circular segments.

The four interception procedures have been based on the following descriptions:

a. Procedural Interception

The procedural interception is carried out by flying to an imaginary "locator" defined on the MLS approach path some 8 NM before touchdown. This interception is intended to be used in case of a radar or radio failure or non-availability of this equipment. It has to be considered as the MLS alternative for the present-day ILS interception via a suitably located fix.

b. Minimum Fuel and Time Interception

The minimum fuel and time interception is similar to the procedural interception, except that for this procedure the approach intercept point is defined approximately 3 NM from touchdown on the final segment. This interception yields the shortest flown distance to the runway for normal operations.

c. Present Track Interception

The present track interception is carried out after end of vectoring by maintaining the present track until the final approach path is captured. This interception can be used in heavy traffic situations and is comparable to present-day radar vectors by ATC.

d. Fixed Angle Interception

The fixed angle interception is carried out by turning after vectoring to a 90 degree angle with respect to the runway centerline. This procedure will be applicable mostly in the case of downwind type approaches.

The procedures a and b have to be considered as "own navigation concepts", while c and d are intended to assist the air traffic controller in his radar vectoring task. A particular interception track is defined by means of transition point data. At the moment of interception initiation, these data are merged into the transition point data of the approach path, to obtain a uniform set of data that yield the basis for the guidance signal computations. In this way a constant glide slope (e.g. 3 degrees) can be maintained even in the interception phase of the approach.

The examples shown in figure 4 concerned normal interceptions, which means that the trajectories included always one straight segment. In figure 5 situations are outlined, in which the aircraft is so close to the approach path, that a normal interception is impossible. For these occasions solutions have been included in terms of S-type and overshoot interceptions.

3.2 Turn techniques

For tracking of the straight segments use can be made of conventional autopilot and flight director control laws. For the turns, however, some new techniques have been developed. In earlier studies several turn concepts were studied. From these studies two concepts were proposed for further evaluation, namely:

- a closed loop and
- an open loop turn concept.

In the closed loop concept, turns are flown using the deviations from the circular ground track as feedback signals for guidance. In order to compensate for the circular flight path, a ground speed V_G dependent bank angle signal (ϕ) is added, according to:

$$\phi = \tan^{-1} \frac{V_G^2}{gR}$$

R = turn radius

g = acceleration due to gravity.

Turns will therefore be flown with a varying bank angle.

Essential for the open loop concepts is that no use is made of feedback signals from the circular reference track. In the open loop case turns are carried out applying a constant bank angle command. Several different open loop methods were studied, for further details of the open loop methods reference is made to (8).

3.3 Objectives

The main objectives for this flight simulator investigation were:
Firstly, to investigate the feasibility of the four proposed interception procedures and secondly, to evaluate the closed loop and the most promising open loop turn concept. Therefore two different flight director algorithms were developed and included in the simulation software.

Moreover an additional objective was to check if special avionics are required for the execution of these procedures. For that purpose an experimental navigation display was used. Figure 6 shows the lay-out of the display format. It shows a situation during an MLS interception of a curved approach path. The aircraft symbol is in the lower margin of the screen. The approach plate is continuously aligned with the actual aircraft track.

3.4 Simulation program

In behalf of this simulation program 7 worst case intercept types were selected, of which each was defined by a combination of: approach path, interception procedure and intercept initiation point. An example of one of the 7 types is presented in figure 7. It shows an S-type interception on an ILS type approach path. Glide path interception occurs in between the 2 turns.

Seven airline pilots and moreover 3 air traffic controllers participated in the simulation program, during which more than 300 MLS interceptions were made. Each intercept case was flown four times by one pilot during his program.

3.5 Summary of test results

A complete survey of the test results has been presented in the final report (9), only a few of these results will be discussed in this paper.

Figure 8 presents an example of the objective test results for the S-type interception case, showing the lateral trajectories for the closed loop and open loop flight director system respectively, as flown by one pilot.

It is obvious that the tracking accuracy of the closed loop system is much better than that of the open loop system.

An example of statistical objective test results is presented in figure 9. The diagrams show the relation between the roll control activity and the path tracking accuracy for the two flight director concepts. The data are related to two different intercept scenario's and were obtained from test runs of three pilots.

As a measure for the roll control activity the standard deviation of the control wheel deflection (σ_{CWD}) has been chosen. The path tracking accuracy has been expressed by the standard deviation of the cross track deviation (σ_{CTD}).

Most salient are the differences in path tracking accuracy between both flight director concepts. In general the closed loop data yields σ_{CTD} values of less than 0.5 dot, whereas in the open loop case all data points have been located right from the 0.5 dot line up to 2.5 dots.

When comparing the roll control activity (σ_{CWD}) required for either of these flight director systems, it appears that no significant difference exists. Apparently, there is not an increase of pilot control activity required to obtain the better path tracking accuracy provided by the closed loop flight director concept. The governing factor for the level of control activity appears to be the type of interception.

As an example of the subjective results, figure 10 shows the pilot opinion about these two systems. This result has been derived from the pilot questionnaire. The diagram shows a quantification of the preference of the pilots concerning either FD system. The closed loop system was qualified in about 90 % of the cases as satisfactory, whereas for the open loop system the score was less than 60 %.

From the effort ratings given by the pilots for the total approach execution it appeared that these ratings were strongly correlated with the length of the straight final segment. These lengths varied for the different simulation runs between 3 and 8 NM. As shown in figure 11 the pilot effort ratings were all in between the qualification "largely undemanding" and "mildly demanding". The rating scale, used to determine the pilot effort, was derived from (12).

3.6 Conclusions of interception procedures investigation

Based on the results as presented in (9), concerning the different flight director concepts, the following was concluded:

- The closed loop flight director provides very accurate tracking performance under all conditions; the path deviations for the open loop system can be substantial.
- Closed loop flight director requires constant pilot attention. With the open loop system more time is left for the monitoring task.
- For autopilot design: the closed loop principle is definitely preferred, because of the high tracking accuracy.

Concerning the interception procedures the following conclusions were made:

The MLS procedural interception appears to be very useful to replace the existing (procedural) ILS interception.

The minimum fuel and time interception is considered to be very attractive and logical, with respect to time and fuel saving aspects.

The present track interception yields a logical continuation of the present radar vectoring process. This interception is favoured by both air traffic controllers and pilots, due to its potential of providing for easy and accurate separation of air traffic.

The fixed angle interception was considered less useful, since the resulting tracks are less predictable and generally a lot of manoeuvring is required. This procedure was therefore only considered useful for downwind-type approaches.

4. Flight simulation evaluation of the MLS curved approach path parameters

4.1 Objective

The objective of this simulation program was to investigate the minimum straight final length (ℓ_F) and the turn angle (ω) in dependence of the operating minima such as decision height (DH) runway visual range (RVR), visibility and moreover of the wind conditions. Both pilot acceptance and tracking performance were investigated hereby.

4.2 Approach paths

Seven curved approach path geometries of the 2-segment type were considered of which the lay-out is graphically represented in figure 3, whereas the individual path parameters have been presented in table 1. As appears from the data in this table these parameters have been varied systematically. The final intercept altitude (h_F) varied from 200 ft to 800 ft, whereas turn angles (ω) between 20 degrees and 90 degrees were considered. Based on results of previous curved approach investigations a turn radius of 1.5 NM was selected for all approach paths. A fixed glide slope of 3 degrees was applied.

4.3 Test conditions

A selection of the test conditions had to be made concerning:

- visibility conditions
- decision height and cloud base
- wind profiles
- avionics equipment

In figure 12 the four selected decision heights (DH) and related cloud bases (cb) have been graphically represented. For the Cat. I and II conditions the aircraft is always on the runway centreline when visual contact has to be established, so the pilot knows where to look for the approach lights. In that case the cloud base was chosen only 50 ft above the DH. For the DH during the turn and oblique segment, the cloud base was chosen 200 ft above DH, in order to enable the pilot to obtain a sufficient impression of the runway-environment before making the decision of either to complete the landing or to go-around.

The visibility conditions were adapted to the cloud base values and reduced to corresponding slant range values.

Besides cloud base, DH and visibility conditions also different wind profiles were defined. A series of 5 wind profiles was established, varying from light winds with moderate shears to stronger winds with severe shears.

A survey of the selected wind profiles is presented in figure 13. Both linear shears and vector shears have been considered hereby. Wind profile 3 contains two severe wind shears of 10 kts per 100 ft. An indication of the severity of this shear is provided by ICAO, which estimates that wind shears in excess of 10 kts per 100 ft may be expected on 4 per 1,000 approaches and take-offs.

The vector shear of wind profile 5 was determined in such a way that it was aggravating the effect of the turn in the approach path.

The finally selected set of conditions have been summarized in table 2. A distinction was made hereby between conditions to be considered for approach paths having moderate turn angles (up to 40 deg) and conditions for approach paths with large turn angles. Because of the limited azimuth angle of the visual system of the simulator, the conditions with DH on the oblique segment had to be deleted for the approach paths with large turn angles.

The Cat. II condition was always flown as an autopilot approach, whereas the other conditions were carried out as flight director approaches. Because of the required precision during the turns in the final approach, the closed loop flight director and autopilot system concept was applied in this program. In all conditions, except the last one, the pilot could make use of the available navigation display.

4.4 Simulation program

Each simulation session was carried out by a cockpit crew consisting of a pilot flying PF, being the subject pilot, and a pilot-not-flying (PNF). Seven pilots participated as subject pilots, of which 5 were airline captains on wide-body aircraft and 2 were first officers on Boeing 747 and 737 aircraft respectively. A number of 350 test runs were made. In order to accommodate to the curved approach character, special cockpit procedures were developed for the PF and the PNF. For statistical reasons a subject pilot flew a particular test case 4 times. These test runs were randomly distributed within a pilot's program. Each test case was flown by 3 different pilots.

4.5 Summary of test results

The test results of this investigation consisted of recorded objective data and subjective results derived from: effort ratings, responses to questionnaires and pilot comments. The complete test results are extensively discussed in (11). Some of these results will be presented hereafter.

A statistical result concerning the tracking accuracy is shown in fig. 14. The diagrams show histograms of cross track deviation (CTD) (fig. 14a) and vertical track deviation (VTD) (fig. 14b) at decision height. Each diagram presents separate histograms for autopilot and flight director approaches. It appears that the lateral tracking accuracy of the autopilot runs is obviously better than that of the flight director runs, although for both cases the results are highly satisfactory. On the contrary, the glide path deviation histogram indicates that the 1-dot deviation level was exceeded substantially in a large number of cases.

As appeared from a detailed investigation, this was mainly due to the inability of the autothrottle system to manage the strong wind shears of wind profile 3. As shown in table 3, these wind shears also caused the major number of missed approaches (10 out of a total number of 17 missed approaches).

A series of histograms has also been determined for the maximum bank angle appearing during the turn to final. According to the histograms in figure 15, the maximum bank angles during the autopilot runs were in between 11 and 17 degrees. In case of the flight director approaches the variation in maximum bank angle was considerably higher. As appears from the distribution, however, in less than 1 % of the cases the bank angle exceeded a value of 25 degrees.

The subjective data obtained from the pilot questionnaire have been considered also separately for autopilot and flight director. It appeared that the pilots could evaluate the various questions better for the flight director than for the autopilot runs. This may be attributed to the fact that pilots are thoroughly aware of what is going on when they fly in the flight director mode, while it is difficult for a pilot to qualify an automatically flown approach since in that case he has to draw his conclusions merely from monitoring based impressions.

By means of two questions, the pilots were asked to evaluate the stabilization altitude on final. In figure 16 the corresponding questionnaire results have been plotted versus the final segment altitude (h_F). The diagram shows that this altitude h_F could be as low as 400 ft as far as pilot opinion is concerned. An important result was obtained from the responses to the question concerning the acceptability of the approaches as future standard procedures. In this diagram the responses to this question are shown. An increasing trend in acceptability with increasing final intercept altitude is observed, which is indicated by a dashed line. Note also that even in case of approach paths with very low final segment altitude (h_F), the answer "acceptable" scored still 40 % to 65 %.

4.6 Conclusions of the curved approach path evaluation study

Based on the complete amount of experimental results, which have been described in (11), the following conclusions were made:

- The lateral tracking performance of the curved approach paths is very high, even in case of the flight director approaches.
- The vertical tracking performance is also satisfactory, provided that no strong wind shears are encountered.
- As far as the approach path acceptance by the pilots is concerned, it appeared that:
  - the minimum acceptable straight final segment length is approximately 1.25 NM which equals a final segment altitude of 400 ft.
  - the turn angle is restricted by MLS coverage limitations, not by pilot acceptance.
  - the selected turn radius of 1.5 NM kept the bank angle range during the turns within acceptable limits.
- The approaches are feasible under both Cat. I and II conditions. For Cat. II an adequate autopilot/autothrottle system is indispensable.
- The turns to final have to be flown closed loop.
- Wind shear is obviously the single most limiting factor regarding the feasibility of curved approaches.
- A map display format similar to the one simulated is highly appreciated and is preferred by far to the conventional HSI format, since it contributes to an improvement of the situational awareness.
- It was emphasized by all pilots that conventional autothrottle systems, which operate independently from autopilot and flight director, are less suitable for the execution of curved approaches. For these procedures, especially in those cases where the final segment is short and wind shear is encountered, an integrated "wind shear capable" autothrottle, autopilot and flight director system is recommended.

5. Recent study and future MLS activities

In a recent flight simulator investigation, the use of MLS for departure guidance was evaluated. Attention was paid hereby to two levels of RNAV capabilities, i.e. conventional navaids and advanced navaids respectively.

Preliminary results indicate that MLS can also contribute to improved tracking accuracy during the departure phase and that the use of MLS guidance for departure guidance is appreciated by the majority of the subject pilots.

As future areas of MLS research can be mentioned:

- definition of MLS missed approach procedures.
- development of obstacle clearance criteria for segmented and curved MLS paths.
- use of MLS for realization of 4-D nav.
- transition from en-route guidance to MLS guidance.
- further development of MLS display formats for use with MLS procedures.
- investigation of effect of failures on MLS procedures (e.g. engine failure during critical flight phases).

6. References

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TABLE 1:
CONSIDERED PATH CONFIGURATIONS

PATH NR	ℓ_F	h_F	ω
	NM	ft	deg
01	0.63	200	20
02	0.94	300	20
03	1.26	400	30
04	1.26	400	40
05	1.5	480	60 *
08	2.0	640	90 *
09	2.5	800	90 *

approach altitude 2000′

approach altitude 1500′

GLIDE SLOPE: 3°
TURN RADIUS: 1.5 NM

*) extended azimuth coverage required (60°)

TABLE 2:
CONSIDERED CONDITIONS PER APPROACH PATH

$\omega \leqslant 40^\circ$

COND		DH	WIND PROFILE	AP/FD	NAV. DISPL.
①	CAT II	100	1	AP	+
②	CAT I	200	2	FD	+
③		DH_{TURN}	3	FD	+
④		DH_{OBL}	4	FD	+
⑤		DH_{OBL}	5	FD	–

$\omega > 40^\circ$

COND		DH	WIND PROFILE	AP/FD	NAV. DISPL.
①	CAT II	100	3	AP	+
②	CAT I	200	2	FD	+
③		DH_{TURN}	5	FD	–

TABLE 3: **GO-AROUNDS**

TOTAL nr. OF MLS APPROACHES : 320

OF WHICH 17 RESULTED IN A G.A. (5.3%)

ANALYSIS :

NR. OF G.A. FOR WINDPROFILE 3 (SHEAR : 10 kt/100 ft) : 10 ×

- COMBINATION AP+WINDPROFILE 3 : 9 ×
- COMBINATION FD+WINDPROFILE 3 : 1 ×

WINDPROFILE	NUMBER OF G.A.
1	1
2	4
→ 3	10 ←
4	0
5	2

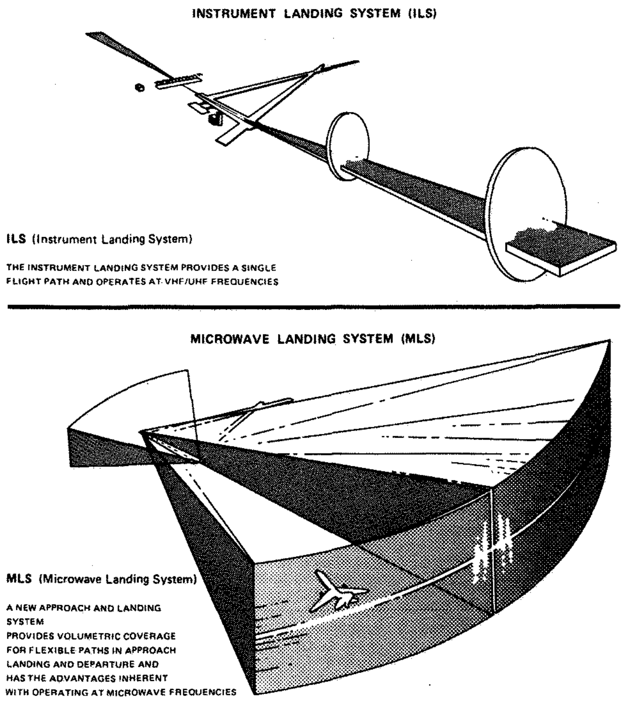


Fig. 1 Microwave versus Instrument Landing System signal coverage

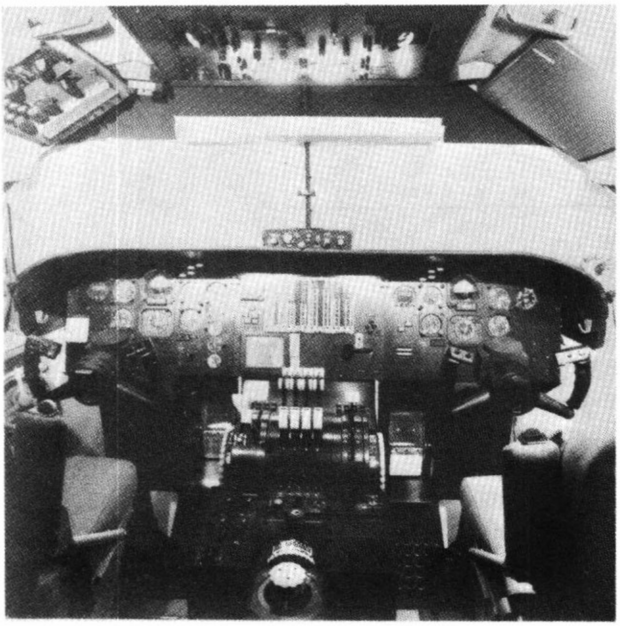


fig. 2 Picture of the simulator cockpit interior

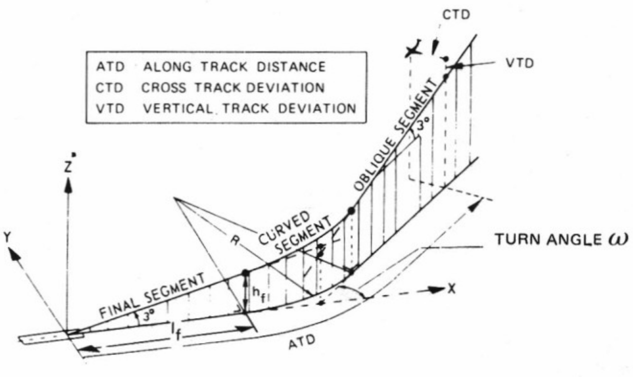
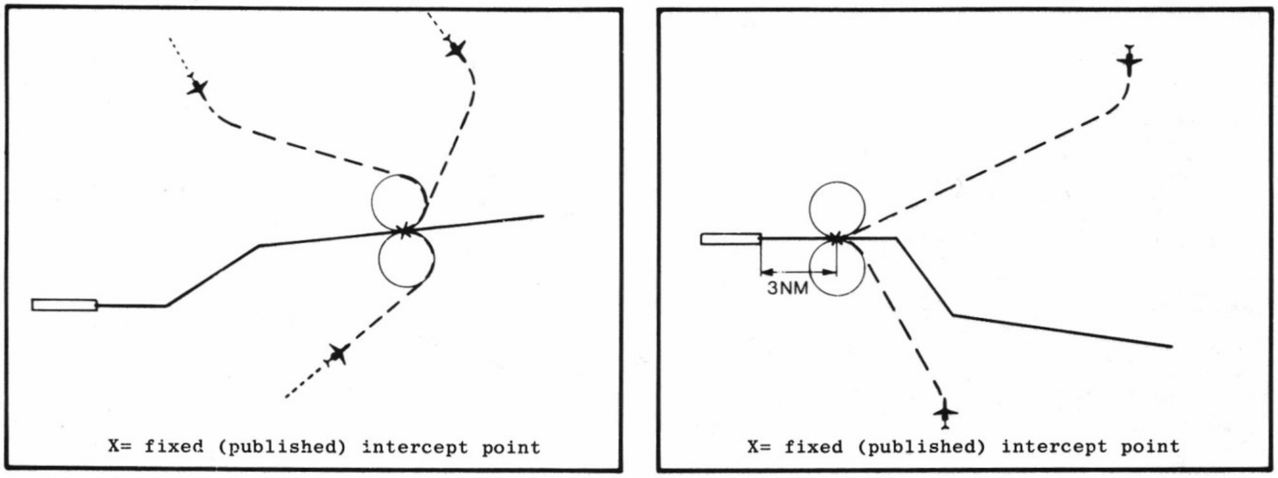
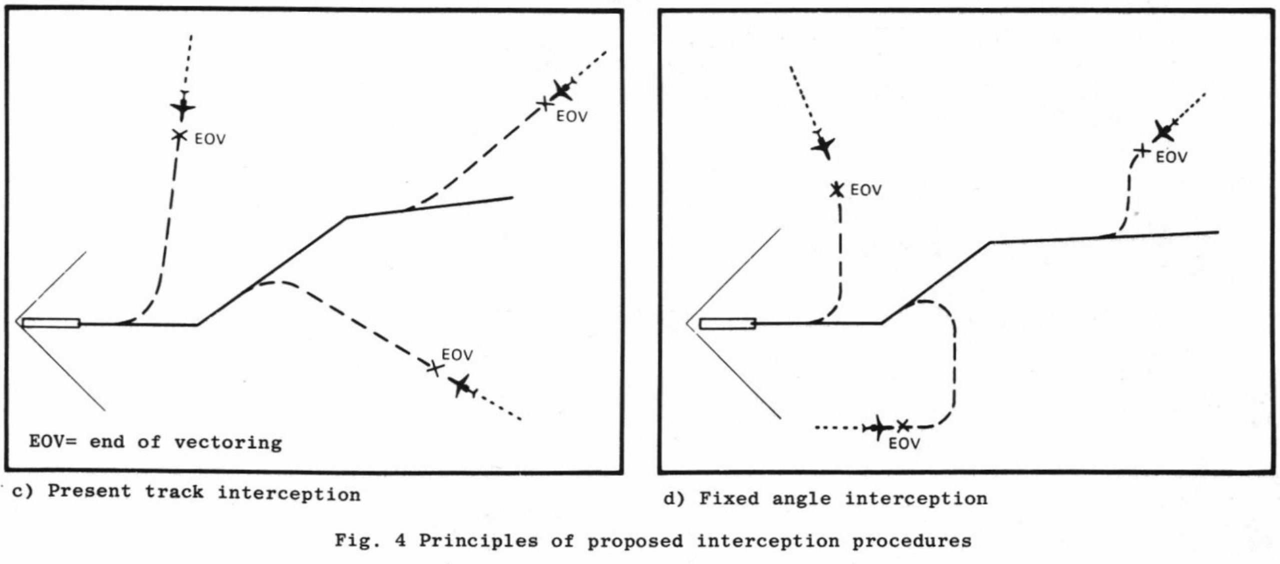


Fig. 3 Lay-out of the curved approach path geometry



a) Procedural interception

b) Minimium fuel and time interception



c) Present track interception

d) Fixed angle interception

Fig. 4 Principles of proposed interception procedures

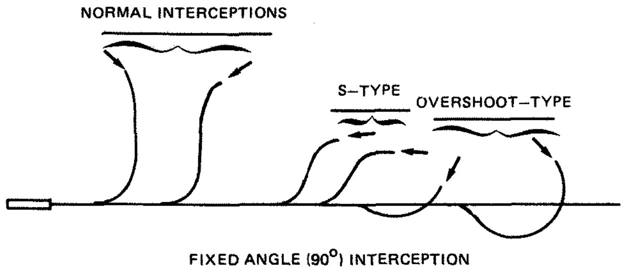


Fig. 5 Examples of S-type and overshoot-type interceptions

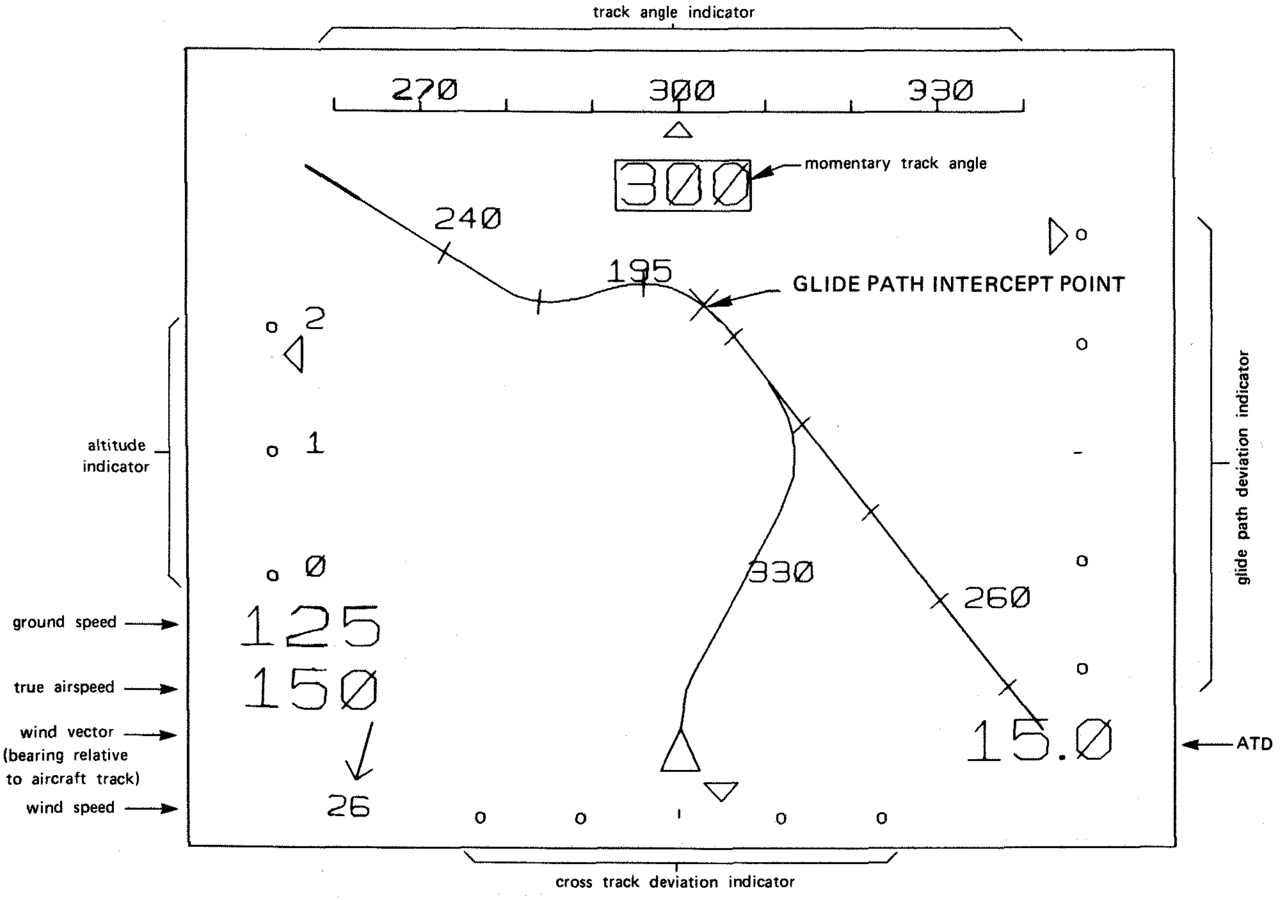


Fig. 6 Lay-out of the experimental navigation display

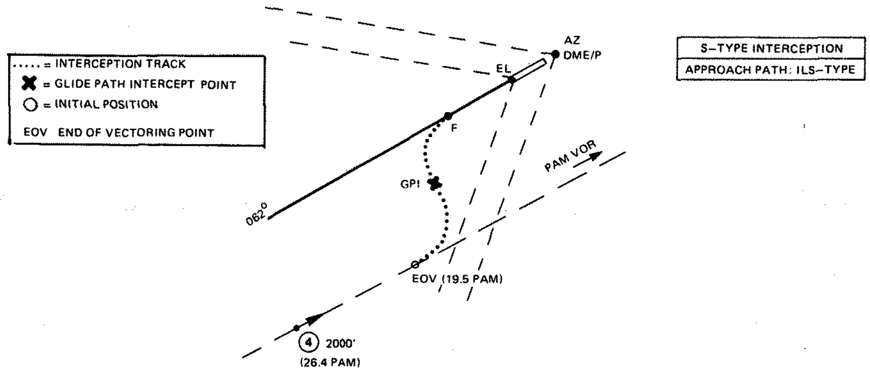


Fig. 7 Example of a simulated interception scenario

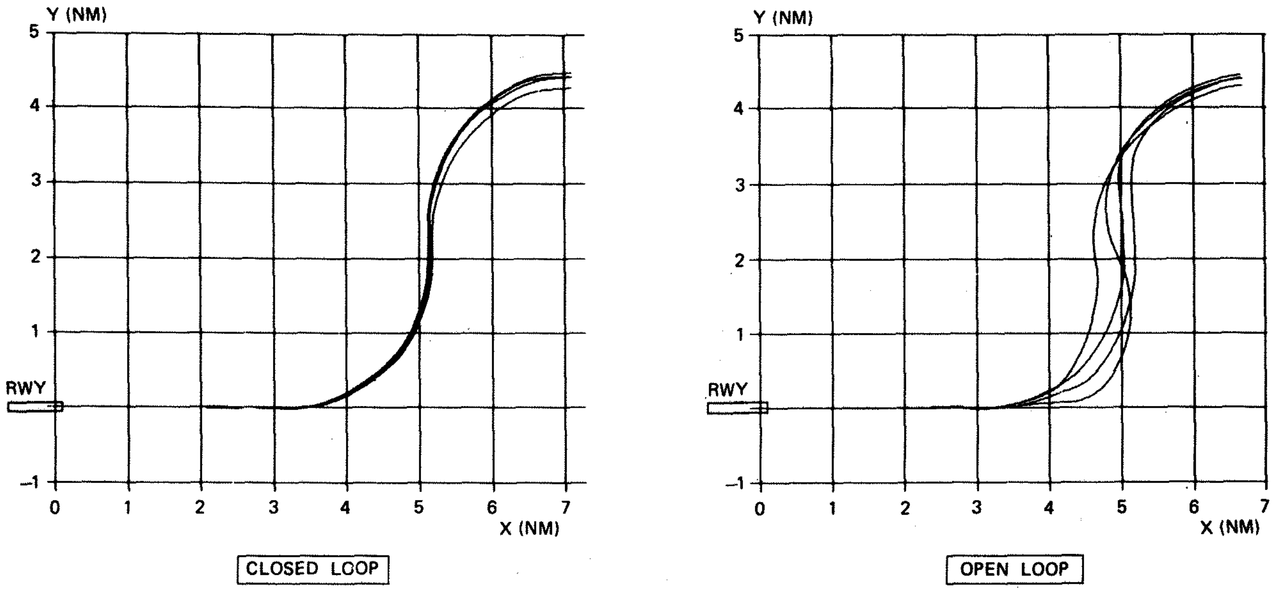


Fig. 8 Comparison of trajectories for the S-type interception

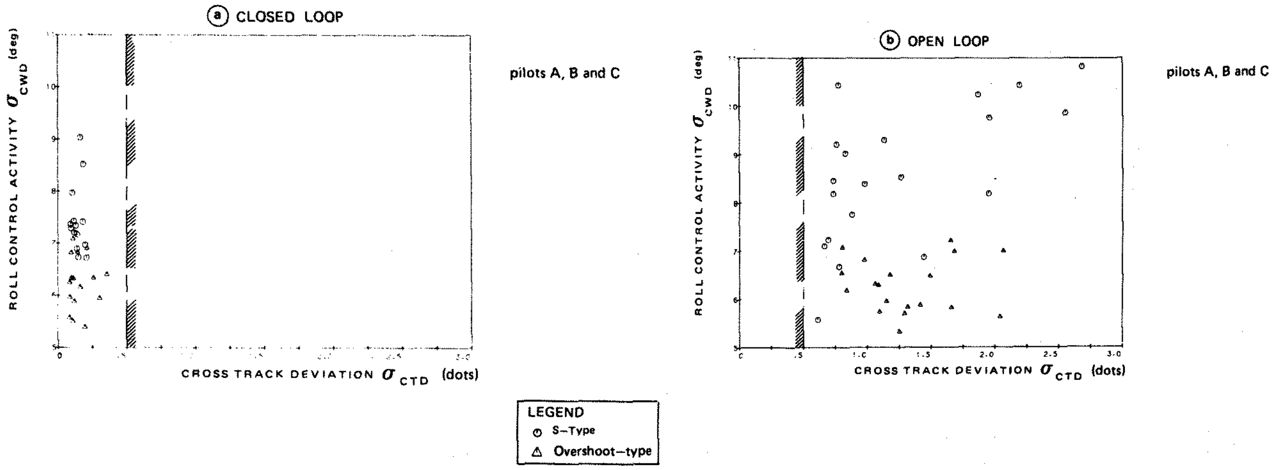


Fig. 9 Roll control activity (σ_{CWD}) as a function of cross track deviation (σ_{CTD})

3) WHAT IS YOUR OVERALL OPINION ABOUT THIS TYPE OF FLIGHT DIRECTOR SYSTEM WITH A VIEW TO LATERAL PATH ACCURACY VERSUS ROLL BAR ACTIVITY?

☐ SATISFIED WITH THIS TYPE OF SYSTEM

☐ NOT SATISFIED, BECAUSE ....

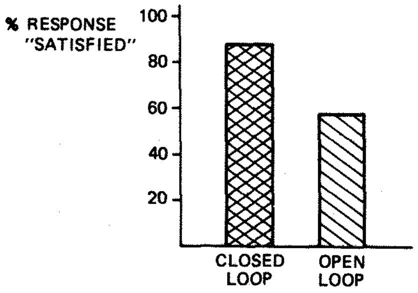


Fig. 10 Example of a questionnaire result

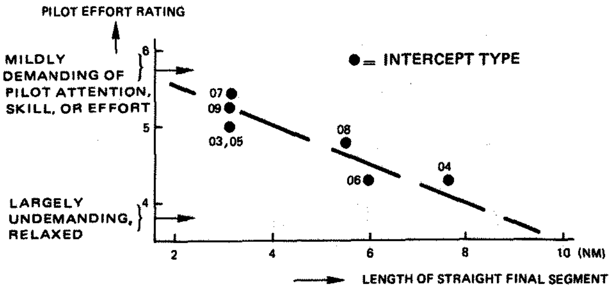


Fig. 11 Relation between final segment length and effort rating

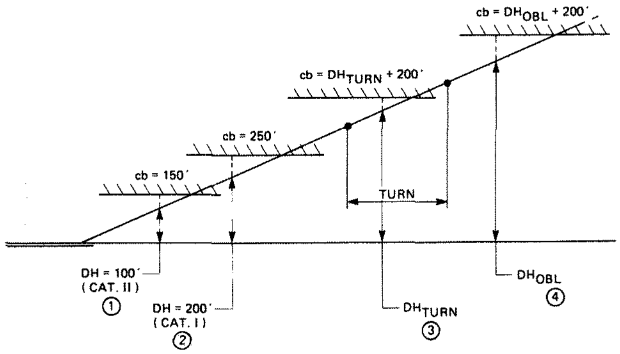


Fig. 12 Selected decision height (DH) and cloud base (cb) conditions

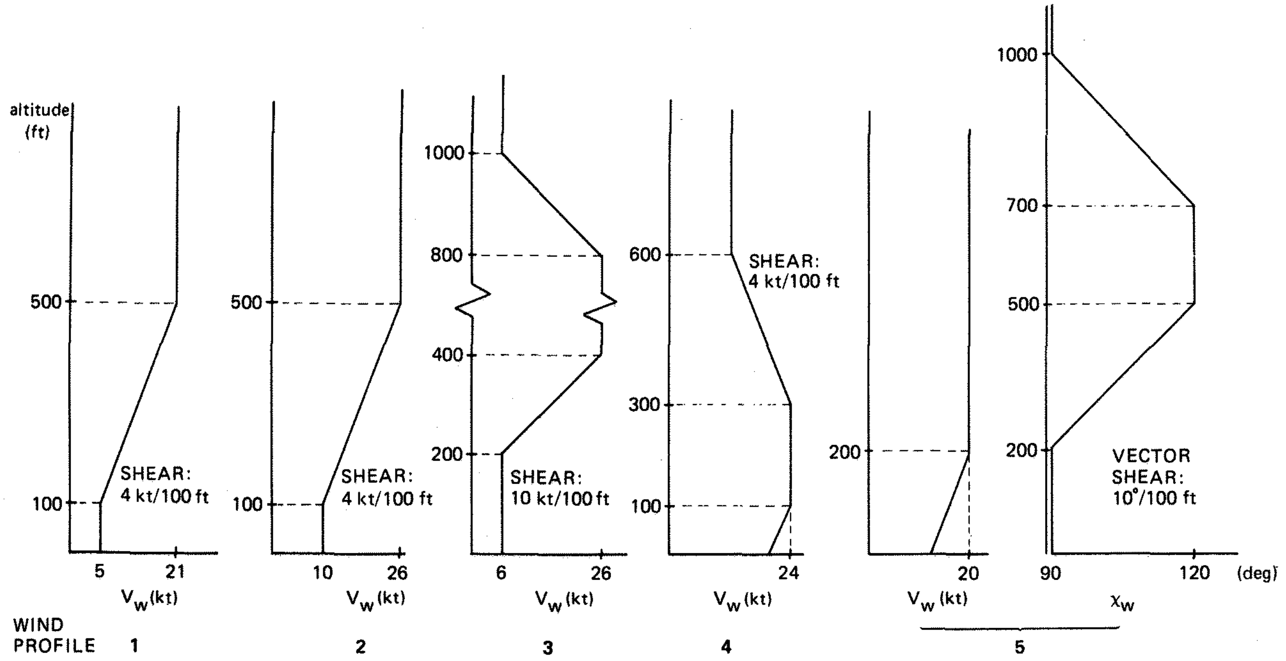


Fig. 13 Simulated wind profiles

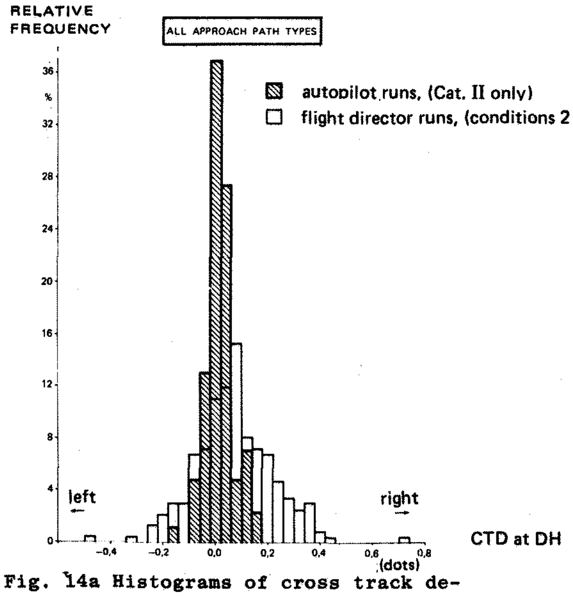


Fig. 14a Histograms of cross track deviation (CTD) at decision height (DH)

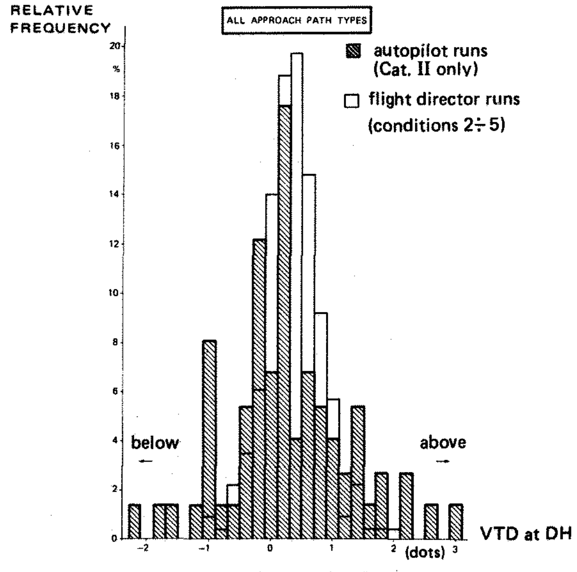


Fig. 14b Histograms of vertical track deviation (VTD) at decision height (DH)

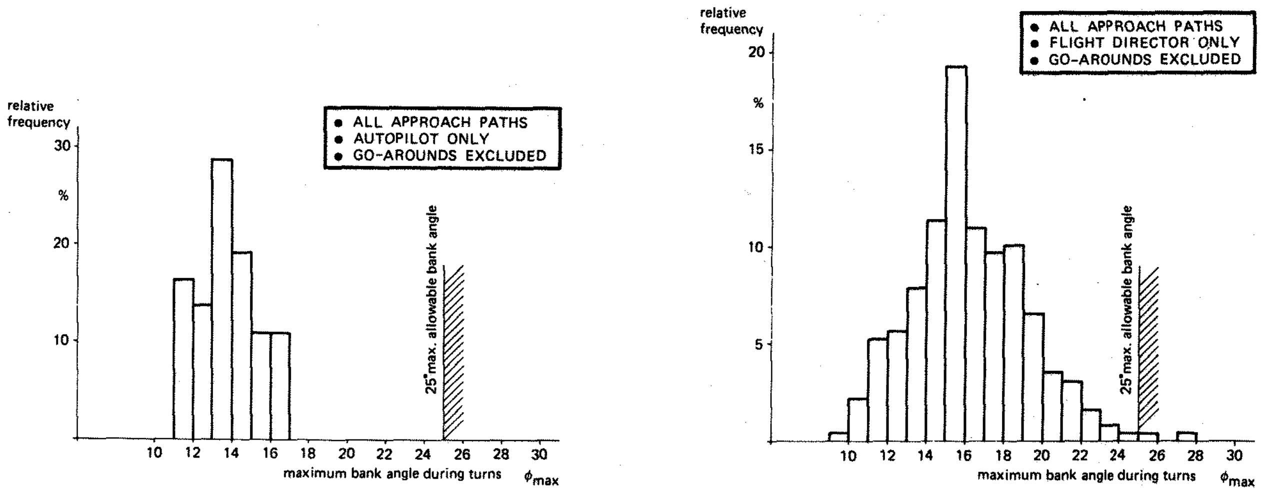


Fig. 15 Histograms of maximum bank angle during turns

⊡ What was the altitude at which the aircraft became completely stabilized on the extended runway centreline?

⊙ What would you consider the lowest altitude for manoeuvring prior to stabilization on the extended runway centreline?

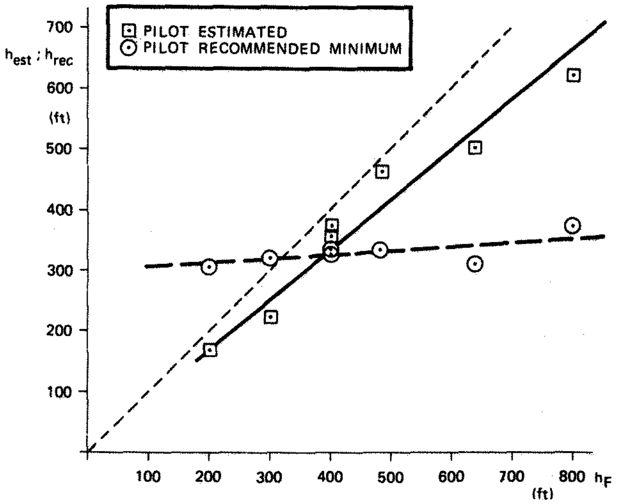


Fig. 16 Comparison of estimated stabilization altitude with recommended stabilization altitude

TOTAL APPROACH

Do you consider this approach, with corresponding operating minima, acceptable as a future MLS standard procedure?

░ yes

▩ marginal

■ no, because ....

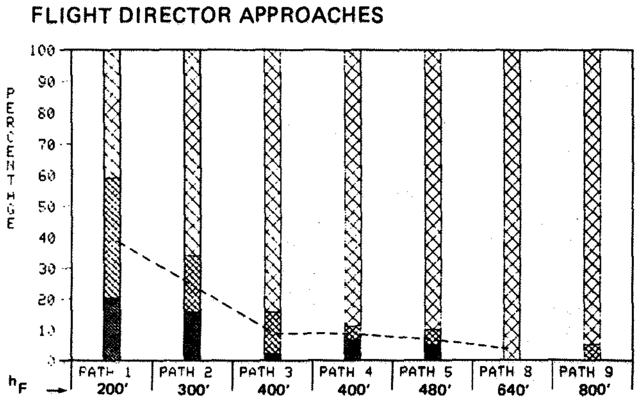


Fig. 17 Acceptability of the curved approach paths