N82 34041

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THE EFFECT OF VISUAL INFORMATION ON THE MANUAL APPROACH AND LANDING

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ABSTRACT

The visual scene is an important source of information for the manual approach and landing task. This paper deals with the effect of this information in combination with basic display information on the approach performance. In this context, a pre-experimental model analysis has been performed in terms of the optimal control model.
The resulting aircraft approach performance predictions were compared with the results of a moving base simulator program.

The results illustrate that the model provides a meaningful description of the visual (scene) perception process involved in the complex (multi-variable, time varying) manual approach task with a useful predictive capability. The theoretical framework has been shown to allow a straightforward investigation of the complex interaction of a variety of task variables.

INTRODUCTION

The manual approach and landing is a complex manual control task. The process is time (range) varying and involves multivariable task objectives, visual scene and display information and a complex pilot's control strategy. Although many studies have dealt with a variety of aspects of this approach and landing task, accident statistics indicate that there are still important unanswered questions.

This paper summarizes the results of a theoretical and experimental program addressing the effect of visual information on the manual approach and landing. Specifically, this concerned visual scene information which was the subject of a previous study (Refs. 1 and 2) and basic (head-up) display information. From that study it could be concluded that the visual scene perception process can be modelled (described) on the basis of linear perspective geometry and relative motion cues.

In the present study the effect of visual scene information was investigated by considering three (good, poor and night) visibility conditions. These three conditions were combined with three basic head-up display (HUD) configurations representing a variety of visual cues. This is discussed in the following.

A pre-experimental model analysis has been performed resulting in a variety of aircraft approach performance predictions. These predictions will be compared with the results of an experimental program on a moving base simulator in order to investigate the predictive capability of the model.

VISUAL INFORMATION IN THE MANUAL APPROACH

Visual approach scene

The visual scene provides a variety of perspective geometrical and relative motion cues. A previous study (Ref. 2) has demontrated that these characteristics can be considered as separate cues among which the human operator must divide his attention. A schematic version of the visual approach scene is shown in figure 1. The cues which are assumed to be derived from this scene are indicated.

The most important cue for lateral guidance is derived from the inclination of the runway sides and/or the runway centerline. The lateral deviation is zero if the inclination of both runway sides is the same ($\omega_r = \omega_\ell$) and the inclination of the centerline is zero ($\omega_c = 0$).

Vertical guidance must be based on the (average) inclination of the runway sides when no runway end and no horizon is visible. In that case, the observer must know the nominal inclination (which is range varying). However, a better indication of the vertical position can be obtained when the depression of the runway threshold with respect to the horizon is visible. Also in that case, the observer must know the nominal depression angle, which is, however, constant during a standard approach (i.e. 3 deg). The final approach and landing requires also the estimation of the distance to touchdown. This can be based on the apparent size of ground objects, the most important one probably being the runway width.

Aircraft attitude providing "inner loop" information for aircraft control can be derived from the relative position and inclination of (e.g.) the horizon and any aircraft reference. In the figure the three attitude angles are indicated.

In this paper the effect of two visual scene conditions is considered: a good visibility condition (GV) implying that the complete visual scene including the horizon is visible and a poor visibility condition (PV) such that no runway end and no horizon can be discerned. These visual scene conditions were combined with three display configurations resulting in six task configurations considered in the following theoretical and experimental analysis.

Display information

In a visual approach the pilot is provided with not only the visual scene but also display information. Typical aircraft variables of interest are the rate of descent, airspeed, or groundspeed, aircraft position, etc.. In the study described in this paper three display configurations were involved so as to investigate the effect of various aircraft variables on the manual approach performance and their interaction with the visual scene information.

Figure 2 contains the visual information involved in the three head-up display (HUD) configurations. The "no HUD" configuration (NH) involves only an aircraft reference allowing a rough estimation of the aircraft attitude. The "simple HUD" configuration (SH) is included to investigate the effect of accurate, aircraft attitude information. This configuration involves a fixed reference line which nominally coincides with the touchdown line. This reference provides primarily accurate aircraft attitude information and, to some extent, approach position information. The "advanced HUD" configuration (AH) contains, in addition, the aircraft velocity vector (earth-related), the runway contours including the centerline and touchdown line and the horizon line. This configuration was intended to investigate the effect of precise movement information and synthetic perspective runway information which was hypothesized to become useful in reduced visibility situations.

The six task configurations are summarized in table 1.

MODEL ANALYSIS

Once the visual scene characteristics are <u>linearly</u> related to the aircraft variables of interest (system states) the visual cues of both the visual scene and the HUD can be described in terms of the perception and information processing model (Refs. 1 and 2) which is part of the optimal control model (Ref. 3).

The approach task considered consisted of the control of a medium weight twin engine jet in the presence of moderate turbulence (details are given in reference 4). A steady-state model analysis was performed assuming that the aircraft was "frozen" at a fixed point of the approach path corresponding with a nominal altitude of 200 ft for a 3° approach. In addition, a time varying model analysis was performed accounting for the time varying turbulence characteristics during a descent and the time varying (range varying) visual cues.

Model parameters

Model parameters can be divided in parameters which are constant for all configurations and parameters which were considered as the remaining model variables.

It was assumed that the pilot adopts a control strategy that minimizes a performance index consisting of a weighted sum of mean-squared path, attitude and control variables. The weightings were selected by first determining maximum allowable values ("limits") of each variable and then setting the weighting equal to the square of the reciprocal of the corresponding limit. For details the reader is refered to reference 4.

The selection of the visual perception parameters is based on the results of previous studies (Ref. 2). The key model parameters are the perceptual thresholds summarized in table 2. Herein, ε is the approach angle (deviation), δ is the velocity vector deviation from the touchdown point; the subscript o means: with respect to touchdown and the subscripts g and ℓ refer to the vertical (glideslope) and lateral (localizer) direction, respectively. Only those variables are given among which the pilot divides his attention (optimally, i.e. minimizing the afore-mentioned performance index). An equal attention was assumed between the vertical and lateral task.

Typical values were used for the remaining model parameters which have been found to be relatively constant or insensitive (task independent): a perceptual time delay of 0.2 s, an overall level of attention of -18 dB and a motor noise ratio of -25 dB.

Steady-state model analysis

Based on the model assumptions and parameter values discussed before model predictions could be made for the six task configurations of table 1. The results consist of standard deviations of system variables (path errors d and y, forward velocity u, aircraft attitude angles θ, ϕ and ψ and control deflections δ_e and δ_a) and pilot workload. The latter can be predicted using the workload model discussed in reference 5.

System performance is summarized in table 3 for tasks C1 to C4. The model predicts that approach performance is clearly improved when the simple HUD is provided. A substantial improvement is obtained for the advanced HUD. This demonstrates clearly the favourable effect of HUD information on the manual approach performance, both vertically and laterally, especially in terms of path deviations.

The effect of visibility can be appreciated by comparing configuration C1 with C4. The model predicts that reduced visibility results in a minor performance deterioration laterally. The vertical performance remains the same. This somewhat surprisingly result is explained by the predicted pilot's shift in attention allocation among the visual cues (Ref. 4). For the simple and advanced HUD configurations the effect of visibility is negligible. Because of the favourable HUD information almost (in case of simple HUD) all (in case of the advanced HUD) attention is devoted to the HUD cues. Consequently, a reduction in visibility has no effect as long as the touchdown point is visible (or indicated).

Pilot workload predictions (W) are also given in table 3 containing also the overall performance index J. Workload is relatively constant for the four vertical control configurations. Significantly more effect is predicted for the lateral tasks. The workload results for the combined tasks indicate that pilot's workload is the same for the good and poor visibility condition. Furthermore, the effect of the simple HUD is favourable with respect to not only the approach performance but also the corresponding workload. The model predicts that the superior performance of the advanced HUD corresponds to a somewhat higher level of pilot workload than corresponding to the simple HUD configuration.

Time varying analysis

A time varying analysis was performed to account for possibly range dependent effects of the approach task involved in the simulation program. Apart from the height dependent turbulence (only a varying turbulence bandwidth was considered) the range varying viewing characteristics were included in the analysis. The latter implied range varying visual cues and pilot's control strategy. For further details the reader is referred to reference 4.

It was assumed that the pilot's allocation of attention among the visual cues was constant during the approach. This "average" allocation of attention was identical to the optimal allocation of attention (yielding the best approach performance) computed in the steady-state model analysis. Also the same (equal) division of attention between the vertical and lateral task was assumed.

The experimental approach task which will be discussed in the next chapter began at a range of 5813 m from the touchdown point (corresponding with a nominal altitude of 1000 ft) with zero intial deviations. The same initial condition was adopted in the following model analysis.

The model results of configuration C1 are given in terms of the standard deviation of the path errors (in figure 3a) and of the aircraft attitude angles and control deflections (in figure 3b) as function of the range. It will be clear from the figure that (linear) path deviations (d and y) are strongly range dependent.

Pitch attitude and elevator activity increase during the approach. This result orginates partly from the model assumption that the pilot's control strategy is determined by the angular glidepath deviation. This implies that during the approach relatively more weight is placed upon (linear) glidepath error than upon pitch attitude and elevator deflection.

The roll angle and aileron activity increase somewhat during the approach. Heading is slightly decreasing. Analogous to the vertical task this results from the range varying control strategy.

It is interesting to compare the results of the time varying analysis with the steady-state results. Therefore, steady-state results are indicated in figure 3 corresponding with a nominal altitude of 200 ft and a nominal altitude of 600 ft. Both the path errors and the attitude and control scores closely agree for the steady-state analysis and the time varying analysis (with the exception of the low range height error and pitch attitude angle). Thus , range varying effects can be investigated by a steady-state model analysis at different approach positions. Tedious time varying analysis is necessary, however, when dealing with deterministic processes such as windshears (Ref. 6).

EXPERIMENTAL PROGRAM

The objective of the experimental program was to test the foregoing model results. In addition, the experimental results might allow model refinements thereby extending the predictive capability of the pilot-aircraft model.

Description of the experiment

The experiment was conducted on the NLR moving base simulator. Details about the apparatus, experimental and data analysis procedures are given in reference 4. The flight simulator was configured to represent the linear equations of motion of a medium weight twin engine jet transport having a weight of 29,000 kgf.

The task was to track a 3° flight path to touchdown under VFR conditions beginning at a range of 5813 m from the touchdown point. Each run lasted approximately 90 s. The subjects were instructed to conceive the task as a realistic approach task (given the simplified circumstances) using exclusively the outside world information. Apart from the aforementioned good and poor visibility conditions also a night condition was included. These visual scene conditions were combined with the aforementioned three HUD configurations yielding 9 experimental conditions.

Three experienced pilots participated in the experiment. In each session the 9 configurations were presented to the pilots in a random order. On the first two days and at the beginning of the third day each pilot was trained such that a relatively stable performance level was reached for each condition. All together, 225 training trials were performed. On the third and fourth day the subjects "flew" 6 formal sessions containing the 9 configurations in a random order for data collection. Thus, 6 replications per experimental condition per pilot were obtained. No performance was fed back during the formal sessions. Data were collected in terms of a variety of system variables and subjective ratings concerning pilot workload and visual informational aspects.

Comparison of model and experimental results

For an extensive presentation of all experimental results the reader is referred to reference 4. In this paper, only the principal experimental results of the same configurations as involved in the model analysis will be considered.

The model performance predictions reflect the stochastic nature of the approach task. The statistical measures are given in terms of standard deviations of path errors and aircraft attitude and control angles. These random deviations result from the system disturbances (turbulence) and pilot's randomness in perceiving and processing information and executing control deflections. The corresponding experimental measures for the vertical approach task are the standard deviations of the ensemble (six replications times three subjects). The ensemble means of some configurations clearly reflect specific control strategy. This is discussed in reference 4. For the lateral approach task no systematic ensemble mean has been found. So for this task the best overall experimental measure of random pilot control behavior is the root-mean-squared value (RMS).

The resulting approach performance of configuration 1 (good visibility, no HUD) is shown in figure 4 as a function of the range The agreement between the model predictions and experimental height errors is excellent. The lateral deviations do not match as well. The model predicts somewhat larger errors than the experimental scores. A close match, however, can easily be obtained when assuming that somewhat more attention is devoted to the lateral task (corresponding with a reduced observation noise ratio of 2 dB). This is indicated in the figure by the dashed line.

The aircraft attitude and control scores are summarized in table 4 as averages over four range intervals. The agreement for the pitch attitude and elevator deflection is quite good. The model predicts an increase in pitch angle with decreasing range. This effect is only partly reflected by the experimental pitch angles for this configuration 1. However, the experimental pitch attitude results of almost all other configurations did confirm this model prediction (Ref. 5).

The roll angle scores agree closely. Both the model and experimental results exhibit an increase in roll angle with decreasing range. The model predicts a heading angle and aileron activity which are clearly larger than the corresponding experimental scores. This could be the result of a somewhat different pilot's control strategy.

The effect of visual scene information can be appreciated by comparing configuration 1 and 4. The model predicts that reduced visibility does not result in a deterioration of the vertical approach performance. This is confirmed by the experimental results showing no significant difference between both configurations. Laterally, however, the model predicts that reduced visibility results in a (15 %) larger lateral deviation. This trend is in accordance with the experimental results: the lateral deviation of configuration 4 is, on the average (30 %) larger than the one of configuration 1.

As predicted by the model no significant effect of visual scene information was found experimentally for the simple and advanced HUD configurations.

The effect of HUD information is illustrated in figure 5 for the good visibility condition. The model predicts that the simple HUD yields an improvement in vertical approach performance. The experimental results show the same (statistically significant) trend although the effect is larger than predicted. The model predicts a substantial improvement in vertical performance when the advanced HUD is provided. This corresponds rather well with the experimental results showing approximately the same fractional (statistically significant) improvement.

Laterally, the model predicts that the simple HUD, providing the pilot with more accurate attitude information, results in reduced lateral deviations. This result is not obtained experimentally. Figure 5 shows that the simple HUD results in substantial larger lateral deviations.

One explanation might be that the pilot spent, during the first part of the approach, less attention to the lateral task than assumed in the model analysis. This is illustrated in figure 6 showing the lateral model results of the simple HUD configuration for both the orginally assumed level of attention and for half of this level. During the first part of the approach the data closely match the model results assuming half of the original level of attention. In the course of the approach (below a range of 3 km) the level of attention is increased resulting in lateral approach performance as approximately predicted by the model.

Pilot workload results in terms of normalized subjective ratings and the model predictions (larger values signify higher pilot workload) are summarized in table 5. The experimental differences are not statistically significant (at the 0.05 level) partly because of the subject variability. Nevertheless, the model prediction that the simple HUD (C2) corresponds with a lower workload level than the no HUD configuration (C1) seems to be supported experimentally. Furthermore, the model prediction that the advanced display (C3) corresponds to a lower workload level than the no HUD configuration is not supported experimentally. The model predicts that visibility has hardly any effect on pilot workload (c.f. C1 and C4). On the average, this seems to be supported by the subjective ratings.

CONCLUDING REMARKS

A detailed comparison of model predictions and experimental results of the "good visibility, no HUD" condition has demonstrated that the predictive capability of the pilot-aircraft model describing the complex, time-varying approach task is substantial.

The model predicts that reduced visibility has no effect on the vertical approach performance and some negative effect on the lateral approach performance. This is supported by the experimental results. Furthermore, as predicted by the model, no significant effect of visual scene information was found experimentally for the simple and advanced HUD configuration.

The model predicts that the simple HUD yields an improvement in vertical approach performance. The experimental results show the same trend although the effect is larger than predicted. The model predicts a substantial improvement in vertical performance when the advanced HUD is provided. This agrees well with the experimental results. Laterally, the model predicts that the simple HUD results in a better approach performance. The experimental results, however, show larger lateral deviations. This can be closely matched by the model when assuming that for this configuration less attention is dedicated to the lateral task during the first part of the approach. The same applies to the advanced HUD.

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CONF.	DISPLAY	VISIBILITY
C 1	NO HUD	GOOD
C 2	SIMPLE HUD	
C 3	ADVANCED HUD	
C 4	NO HUD	POOR
C 5	SIMPLE HUD	
C 6	ADVANCED HUD	

Table 1 Task configurations

PARAMETER	DISPLAY		
	NH	SH	AH
ρ_o	1	0.1	0.1
$\dot{\theta}_o$	1	0.2	0.2
ϕ	1 (2)	0.2	0.2
ψ	1 (2)	-	-
ψ_o	1	0.1	0.1
ε_g	0.5 (2)	0.5 (2)	0.2 (2)
ω_c	2	2	2
δ_g	-	-	0.1
δ_ℓ	-	-	0.1

(·): poor visibility condition; all variables in units of degrees visual arc

Table 2 Visual thresholds used for the model analysis

TASK	PARAMETER	CONFIGURATION			
		C1	C2	C3	C4
VERTICAL	σ_d (m)	7.1	5.8	4.1	7.2
	σ_θ (deg)	1.5	1.3	1.1	1.5
	σ_u (m/s)	1.4	1.2	1.3	1.3
	σ_{δ_e} (deg)	1.1	1.0	1.1	1.1
	J (-)	0.14	0.09	0.06	0.14
	W (dB)	10.1	9.7	10.4	9.0
LATERAL	σ_y (m)	9.4	7.1	6.0	10.6
	σ_ϕ (deg)	3.6	[illegible]0	3.1	4.1
	σ_ψ (deg)	3.5	3.4	3.4	3.6
	σ_{δ_a} (deg)	2.6	2.4	2.7	2.8
	J (-)	0.48	0.35	0.35	0.54
	W (dB)	14.0	13.0	13.4	13.8
total	J_t (-)	0.62	0.44	0.41	0.69
	W_t (dB)	16.4	15.5	15.8	16.2

Table 3 System performance and workload predictions

PAR.	RANGE INTERVAL	R1	R2	R3	R4
θ	measured	1.1	1.1	1.5	1.2
	model	0.9	1.0	1.4	2.0
δ_e	measured	0.52	0.72	0.77	1.1
	model	0.43	0.51	0.74	1.2
ϕ	measured	3.3	2.9	2.9	4.4
	model	3.1	3.4	3.5	3.8
ψ	measured	2.1	2.3	2.1	2.3
	model	3.8	3.9	3.8	3.6
δ_a	measured	1.6	1.5	2.3	1.7
	model	2.5	2.6	2.6	2.7

Table 4 A comparison of model and experimental attitude and control scores - Configuration 1

Workload measure	CONFIGURATION			
	C1	C2	C3	C4
model prediction	16.4	15.5	15.8	16.2
demand rating	-.17	-.58	-.25	.03
effort rating	-.16	-.39	-.07	-.24

Table 5 Model and experimental workload measures

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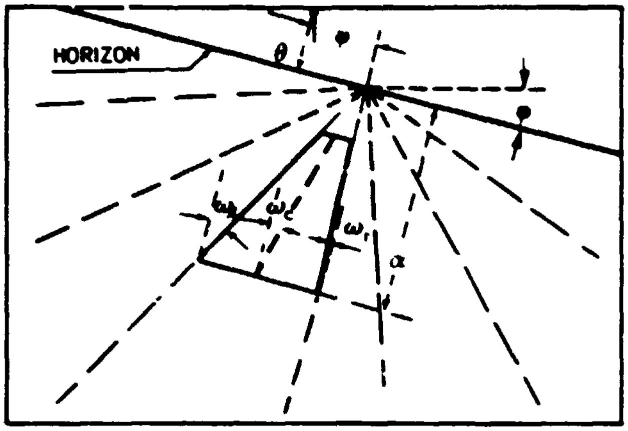
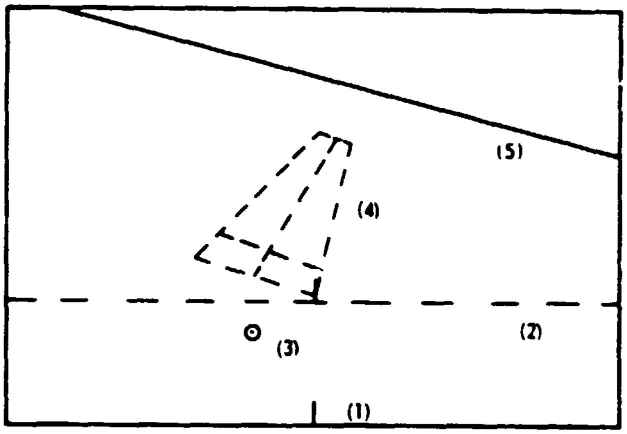


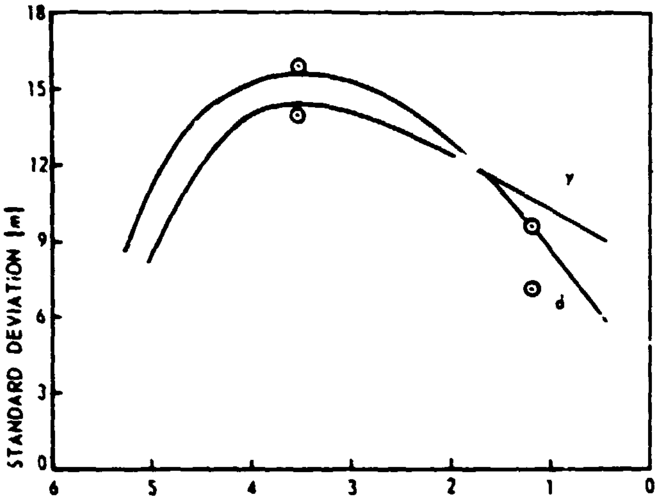
Fig. 1 Cues derived from the visual approach scene



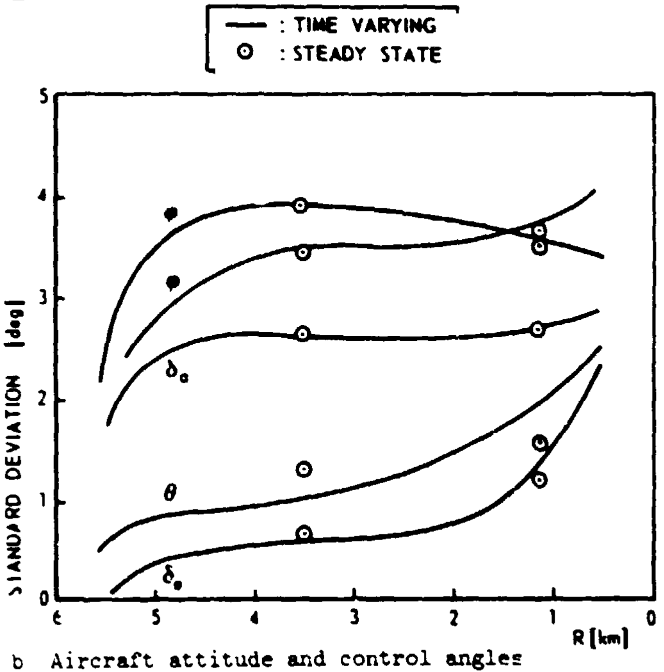
CONF.	CUES
NO HUD, NH	(1)
SIMPLE H., SH	(2)
ADVANCED H., AH	(2),(3),(4),(5)

(1) AIRCRAFT REFERENCE
(2) REFERENCE TO TOUCHDOWN POINT
(3) VELOCITY VECTOR
(4) RUNWAY CONTOURS
(5) ARTIFICIAL HORIZON

Fig. 2 Head-up display information



a Approach performance



b Aircraft attitude and control angles

Fig. 3 Approach performance predictions as a function of range - Configuration C1

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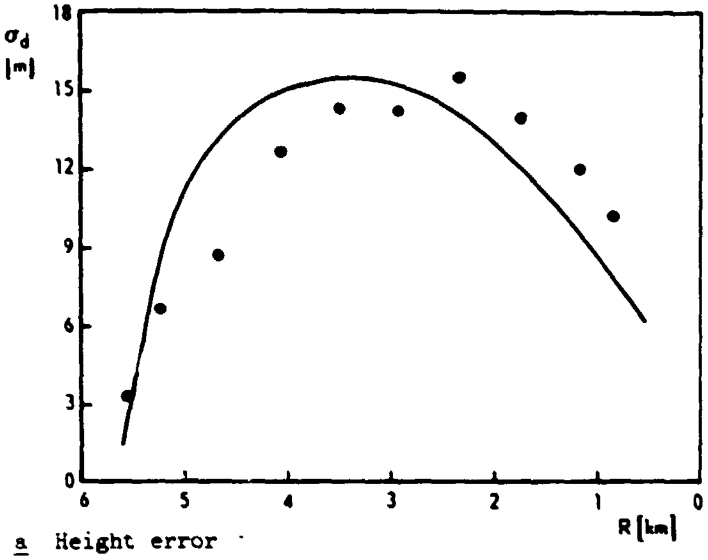
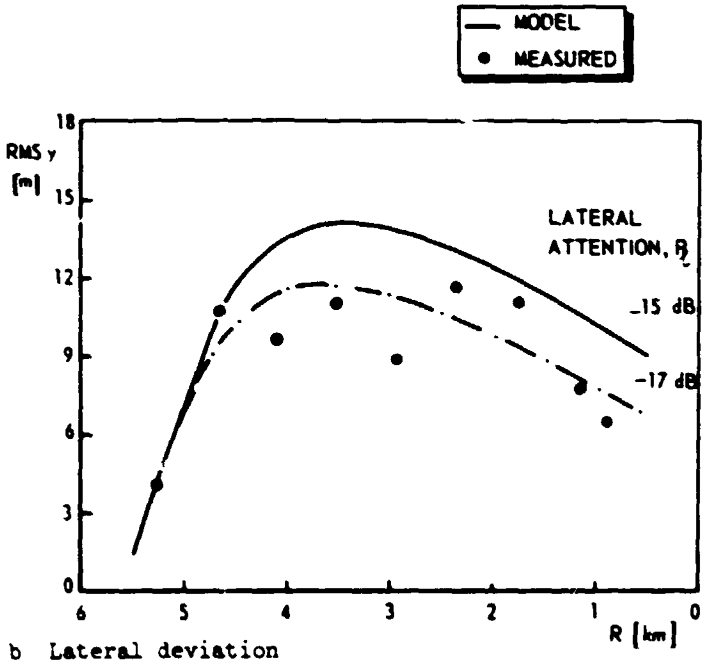
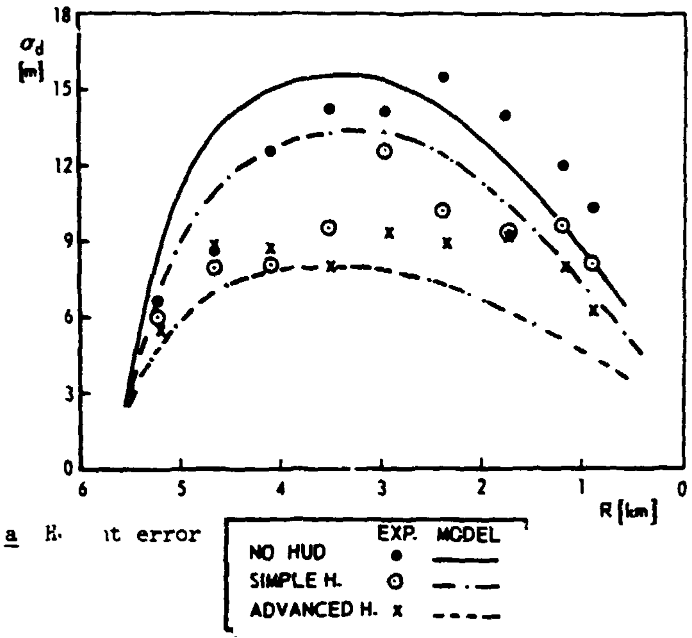


a Height error

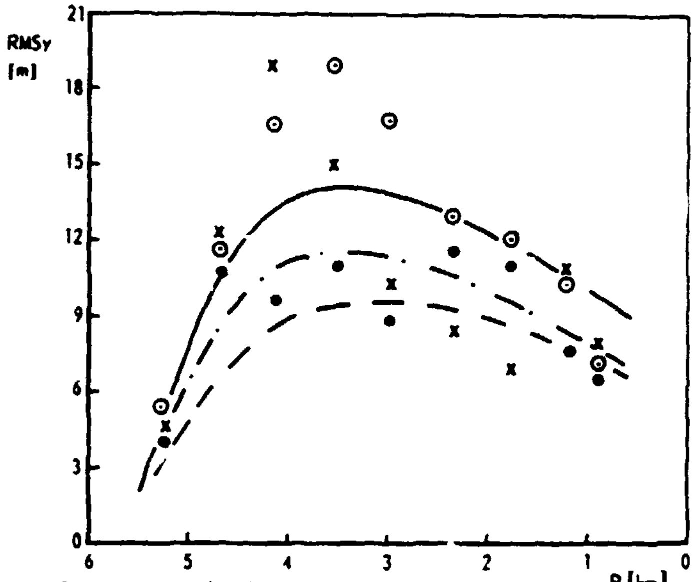


b Lateral deviation

Fig. 4 Comparison of model and experimental approach performance - Configuration C1



a Height error



b Lateral deviation

Fig. 5 Comparison of model and experimental approach performance–The effect of HUD information for the good visibility condition

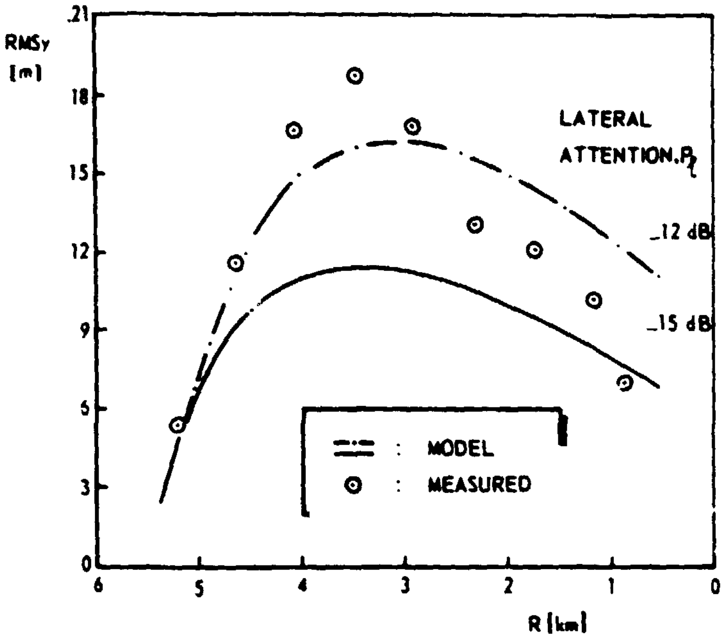


Fig. 6 Comparison of model and experimental lateral approach performance - Configuration C2