PREDICTIONS OF COCKPIT SIMULATOR EXPERIMENTAL OUTCOME USING SYSTEM MODELS*

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ABSTRACT

This study involved predicting the outcome of a cockpit simulator experiment where pilots used cockpit displays of traffic information (CDTI) to establish and maintain in-trail spacing behind a lead aircraft during approach. The experiments were run on the NASA Ames Research Center multi-cab cockpit simulator facility. Prior to the experiments, a mathematical model of the pilot/aircraft/CDTI flight system was developed which included relative in-trail and vertical dynamics between aircraft in the approach string. This model was used to construct a digital simulation of the string dynamics including response to initial position errors. The model was then used to predict the outcome of the in-trail following cockpit simulator experiments. Outcome included pilot performance and sensitivity to different separation criteria. The experimental results were then used to evaluate the model and its prediction accuracy. Lessons learned in this modeling and prediction study are noted.

INTRODUCTION

This study was concerned with pilot manual control in a multiple cockpit simulator experiment at NASA Ames Research Center. Each pilot used a device called the Cockpit Display of Traffic Information (CDTI) to follow some assigned lead aircraft on approach to landing. In this way, several successive pilots formed a string of decelerating aircraft in the terminal area using some preassigned separation criterion. The CDTI application has three potential benefits - (1) reduced controller workload, (2) increased terminal airspace efficiency, and (3) increased flight safety.

To begin to answer many questions regarding the pilot interface and equipment requirements for the CDTI application, many previous cockpit simulator experiments had been run [1-3]. These experiments simulated the pilot following one or more lead aircraft while on approach to landing. One set of shakedown tests to evaluate in-trail following using the CDTI was made in April 1982 on the multi-cab simulator. Much was learned from these tests, and based on this information, the experimental scenario and simulator equipment were revised. With these modifications, a new in-trail following experiment using the multi-cab facility was run in February-March 1983.

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Previous to and during the simulator experiment, this study was organized into the following three phases:

1. Before the experiment was conducted, data and models from previous experiments and tests were combined to formulate a new flight system model. This model represented (a) the relative in-trail dynamics of the CDTI-equipped (Own) aircraft as it achieves and maintains designated in-trail spacing, and (b) the vertical aircraft dynamics, as the pilot attempts to remain on the glideslope. This model was used to predict the outcome of the simulator experiment.

2. The experiment was conducted, and data were collected and processed. The performance results were then plotted and compared to that predicted before the experiment.

3. Because differences existed between the predicted experimental outcome and the actual results, these differences were analyzed in terms of modeling error. The model was tuned to match the experimental results on a statistical basis. This required revision of the model structure as well as tuning of model parameters.

In going through this three-phase process to predict and analyze the outcome of the CDTI-based in-trail following experiment, we learned something. The following sections outline the results of the above three phases of study and the lessons that we learned.

FLIGHT SYSTEM MODEL

In the previous study [4], a mathematical model of the pilot/aircraft/CDTI flight system was developed to match the one-dimensional in-trail dynamics of "daisy chain" experiments conducted at NASA Langley Research Center (LaRC) [2]. A first-level block diagram of this heuristic model is divided into three subsystems - aircraft, cockpit displays, and pilot. The model is driven by the recorded groundspeed V_T of the lead aircraft. The model state variables are initialized to values recorded in the experimental runs; thereafter, the model runs itself. Model parameters are chosen for each run so that the root-mean-square differences between the model groundspeed V_M and actual simulator groundspeed are minimized. This previous model was used as a starting point to postulate an upgraded model to predict the outcome of the in-trail following experiments from the NASA Ames Research Center (ARC) multi-cab simulator facility.

The upgraded model was expanded to include vertical dynamics, as each pilot had the additional manual control task of keeping the aircraft on the 3° glideslope after capture. Previous to capture, the aircraft were to pass through two altitude windows at 12000 ft and 8800 ft when waypoints of 36 and 26 nmi-to-touchdown were passed on approach to San Jose airport. The new model was divided into the three subsystems as before - aircraft, display, and pilot; each is now discussed.

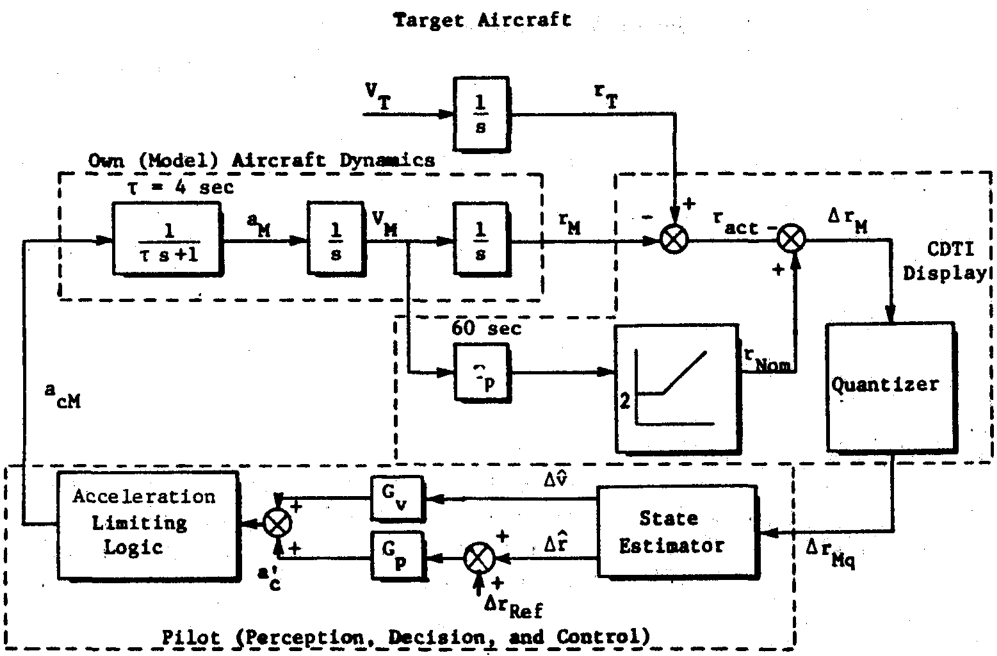

Fig. 1. First Level Block Diagram of In-Trail Following Flight System Model with CTP Criterion

Aircraft Dynamics

To simplify the aircraft longitudinal dynamics over a sample period of 4 sec, it was assumed that the short period motion of the aircraft dampens out from sample-to-sample. This implied that the pitch acceleration, pitch rate, and vertical acceleration terms could be set to zero. The control inputs were considered to be flight path angle γ, throttle setting δ_T, spoiler setting δ_S, flap setting δ_F, and gear position δ_G. Flaps and gear were set on an open-loop basis, dependent upon approach speed and altitude. The resulting equation governing angle-of-attack was

$$-3060\delta_F - 3040\delta_S - (9400 + 47\delta_S)\alpha + (160 - 1950\delta_F)\alpha^2 + \frac{2\,W}{\rho\,V_M^2} = 0\ , \quad (1)$$

where the numerical terms are generic for a B-727 [5]. Equation (1) is solved for each pass through the integration cycle to get the nominal angle-of-attack α.

The relationship for pitch angle is

$$\Theta = \gamma + \alpha\ . \quad (2)$$

The in-trail acceleration equation was

$$\dot{V}_M = -g\Theta + \frac{g\rho}{2W} V_M^2 [-47\delta_S - 700\delta_F^2 - 28 - 20\delta_G$$

$$+ (110\delta_F - 304\delta_S)\alpha + 6400\alpha^2] + \frac{g\rho}{2W} \frac{T_{max}}{\rho_o} (1 - 0.72\, U/U_o)\delta_T \ . \quad (3)$$

In Eq. (3), the throttle input δ_T is at idle when the spoiler δ_S is on, and vice versa. Details of this dynamic model can be found in Ref. 6. The other equations governing the aircraft model are for altitude h_M and in-trail distance r_M, or

$$\dot{h}_M = V_M \gamma \ , \quad (4)$$

$$\dot{r}_M = V_M \ . \quad (5)$$

Equations (3)-(5) are integrated to derive the aircraft motion each sample time. The cross-coupling between the longitudinal and vertical axes is from the $- g\Theta$ term in Eq. (3). Thus, the pilot can control longitudinal acceleration by using the throttle/spoiler combination (δ_T/δ_S) or by changing his pitch attitude Θ.

Displays

The model of the glideslope indicator is shown in Fig. 2, where r_{TD} is the initial range to touchdown. The modeled glideslope deviation measurements $\Delta\lambda_M$ seen on the cockpit displays are the actual deviation plus a noise contribution η_λ.

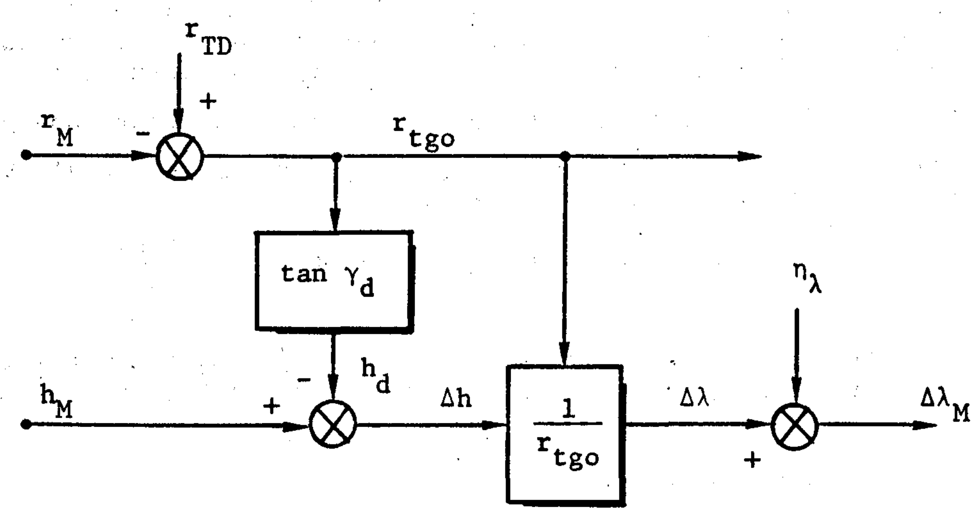

Fig. 2. Glideslope Indicator Model

For the experiments, the standard approaches began outside of localizer/glideslope coverage. Here, the pilots were assumed to maintain the 3 nmi-range-to-1000 ft-altitude sink rate (3-to-1 rule), based on displayed DME distance to runway. They also controlled altitude to pass through the two altitude windows mentioned earlier.

The primary quantities obtained from the CDTI display are the relative in-trail position r_{act} of own aircraft with respect to the immediate lead, the nominal separation r_{Nom}, and the separation error Δr_M. The nominal separation is dependent upon the separation criterion. For the Constant Time Predictor (CTP) criterion, this is a time constant T_p multiplied by own aircraft's groundspeed V_M. This is usually indicated by a vector protruing from own aircraft's symbol such as seen in the sketch in Fig. 3. For the actual separation to equal the nominal value, the tip of the follower's predictor vector should coincide with the lead aircraft (or target) position. Figure 1 contains the model of the CDTI display with CTP separation error Δr_M and its computation.

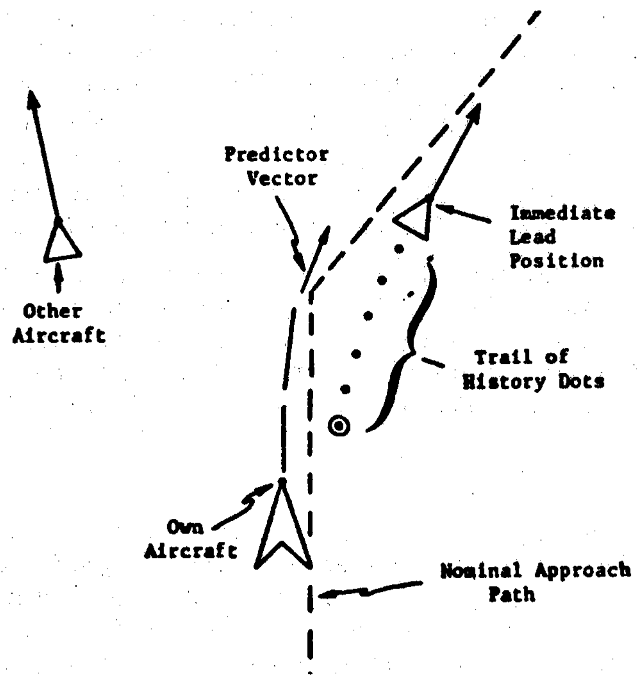

Fig. 3. Simplified Sketch of CDTI Display

For the Constant Time Delay (CTD) criterion, own aircraft is to be where the lead aircraft was a time constant T_D sec earlier. This is indicated by a trail of history dots dropped by the lead aircraft. For the actual separation to equal the nominal value, own aircraft's symbol should coincide with the history dot dropped T_D sec earlier. Figure 4 depicts the model of the CDTI display with CTD separation error and its computation.

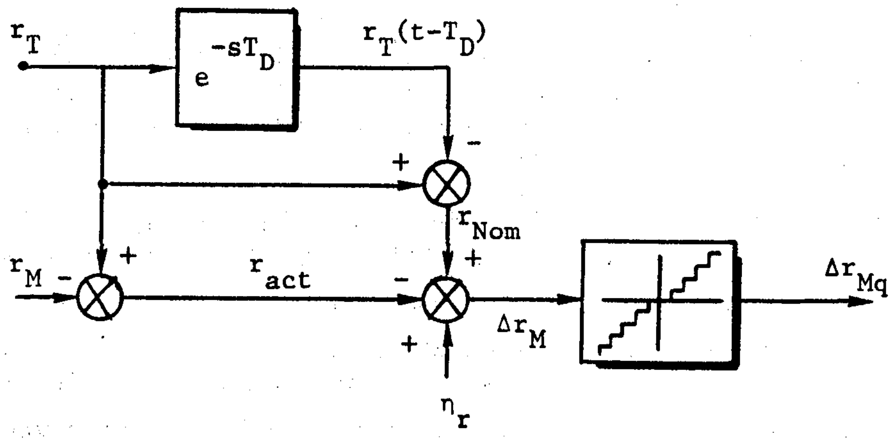

Fig. 4. Model of CDTI Display of Separation Error with CTD Criterion

For the third criterion of the experiment, the CDTI display was modified to indicate the effect of current acceleration on future longitudinal position. This was referred to as the acceleration cue (AC) criterion. Its display was a variation of both the CTD and CTP criteria. For the AC display, history dots are dropped at T_D, $T_D - \tau_d$, $T_D - 2\tau_d$, and $T_D - 3\tau_d$ sec earlier. These were 90, 70, 50, and 30 sec, respectively, in the experiment. The time predictor is modified to include the effect of currently measured acceleration a_M. The displayed predictor vector is cut into segments and used to predict where the own aircraft will be τ, 2τ and 3τ sec into the future. In the experiment, τ was 20 sec. For perfect separation, speed, and acceleration, the predictor vector segment tips will line up with the history dots. When there is separation error, the pilot can use the AC display to determine if current acceleration will yield the desired future position.

Pilot Modeling

In these experiments, the displayed quantities had low noise levels, so estimation inaccuracy was not considered to be a significant source of piloting error. The quantized signals taken from the CDTI display models were used to drive an estimation model which was assumed to be an α-β filter. The same estimation process was assumed to obtain vertical glideslope error and its rate.

There are four stages of decision making that a pilot goes through during an in-trail following task with the CDTI. These are (a) his choice of role to be in (controller, monitor, or inattention), (b) which displays to observe, (c) whether to be an active controller or to continue to monitor, and (d) which active control mode to use. The relevance of each stage is dependent upon the decision made in the previous stage.

The inattention choice was modeled to be of cyclic periods, initially of longer duration, but as the aircraft approached landing, the cycles became shorter but occurred more frequently. This model is based on the fact that as landing approaches, the pilot focuses more often on steering, his control tolerances tighten, and he changes roles more rapidly. The cyclic pattern of the attention/inattention decision and the corresponding model discrete D_1 are depicted in Fig. 5.

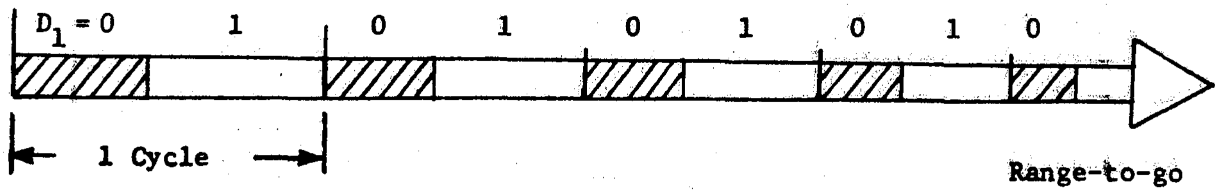

Fig. 5. Cyclic Pattern of Decision to Monitor/Control Aircraft (D_1 = 1) or Other Activity (D_1 = 0)

It was assumed prior to the experiments that the pilots would use their flight path angle control only to regulate vertical position and null out glideslope errors. It was also assumed that they would use throttle and spoiler control primarily to regulate in-trail spacing. Inherent in these assumptions is that vertical and in-trail control are independent.

The pilot model used the discrete D_2 to represent the in-trail control decision and D_3 to represent the vertical control decision. These discretes could be enabled or changed when the monitor/control discrete of Fig. 5 was set to 1. They remained fixed at their set positions until the state variable being controlled crossed a threshold indicating that a new control strategy was needed.

In the experiments, the initial separations between consecutive aircraft were set so that the followers were either too close (positive Δr_M), too far back (negative error), or within some acceptable threshold. Thus, it was assumed that the in-trail control would consist of initial capture followed by regulator control. The in-trail error term $\hat{r}_{fac}$ was defined as

$$\hat{r}_{fac} = C_1 \Delta\hat{r} + C_2 \Delta\hat{v} \; ; \qquad (6)$$

this is a combination of estimated separation error $\Delta\hat{r}$ and its rate $\Delta\hat{v}$. This term was used to govern which in-trail control was appropriate.

The model discrete logic governing the in-trail control decisions is shown in Fig. 6. For being initially too far back ($\hat{r}_{fac} < \varepsilon_1$), the decision/control logic of the following pilot model is

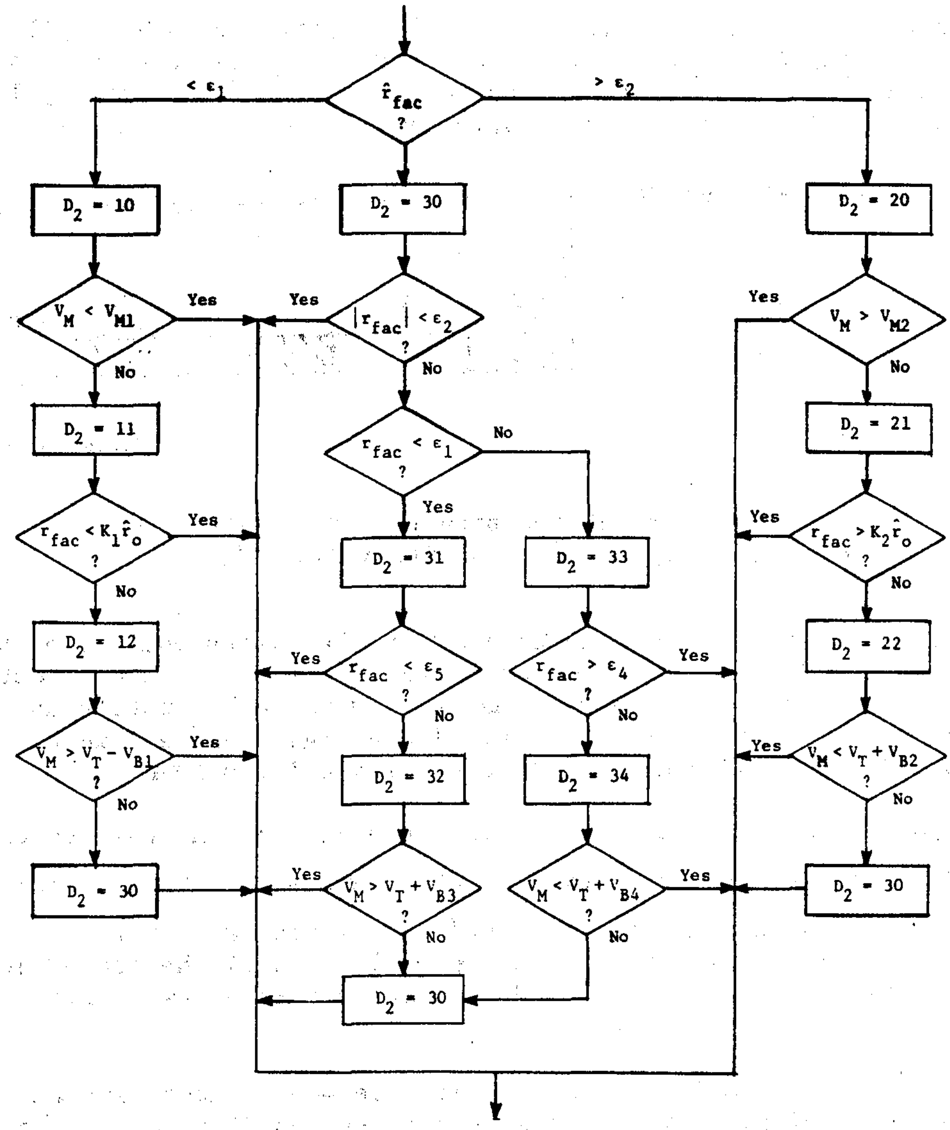

Fig. 6. Decision Logic to Predict Experimental Outcome

D_2 = 10 : Accelerate with throttle until $V_M \geq V_{M1}$;

= 11 : Hold speed constant until $\hat{r}_{fac} \geq K_1 \hat{r}_0$;
($\hat{r}_0 = \hat{r}_{fac}(t=0)$)

= 12 : Decelerate with spoilers until speed V_M is within V_{B1} of target.

This is using the throttle/spoiler to first accelerate, then coast, and then decelerate to null the error and return to an appropriate following speed.

The same model procedure was used in reverse to remove an initial "too close" error by using discrete D_2 set at 20, 21, and 22. Here, parameters, V_{M2}, K_2, and V_{B2} govern logic switching, as shown in Fig. 6.

After initial capture has taken place, the discrete D_2 is set to 30 to indicate $\hat{r}_{fac}$ is within ε_2 of null. D_2 is set to 31 and then 32 for catchup control if the follower falls behind ε_1 of the target. This indicates that throttle followed by spoiler control is required. If the follower becomes closer than ε_2, D_2 is set to 33 and then 34 to activate spoiler and then throttle control to cause the follower to drop back. The discrete D_2 was used subsequently to govern position of throttle δ_T and spoiler δ_S as inputs to the aircraft dynamic model (Eq. 3).

Each follower began at 15000 ft altitude, 340 kt speed, and 52-55 nmi from touchdown. The initial vertical objective was to pass through the two windows at 12000 ft and 8800 ft. The model governing vertical control was open loop in nature with the discrete D_3 set to five consecutive values:

D_3 = 0 : Descend at $\gamma_{CM} = G_{M1}$ until altitude h_{C1} (= 12000 ft);

= 1 : Hold $\gamma_{CM} = G_{M2}$ (~ 0) until range r_{t1} (= 36 nmi);

= 2 : Descend at $\gamma_{CM} = G_{M3}$ until h_{C2} (= 8800 ft);

= 3 : Hold $\delta_{CM} = G_{M4}$ (~ 0) until r_{t2} (= 26 nmi);

= 4 : Glideslope capture and hold.

PREDICTED EXPERIMENTAL OUTCOME

The flight system model just described was used to simulate strings of six following aircraft. The string model was driven by recorded lead profiles, where the data were taken from the cockpit simulator. These data represented the profile followed by the lead aircraft in the experiments. Each run of six followers represented a prediction of the performance of the in-trail following experiments. The parameters in the decision and control logic of the model were modified until "reasonable" performances were achieved in terms of string following dynamics.

Three cases (or strings) of six followers were run - one for each of the three separation criteria. For each case, the initial separation errors were set to alternate between being too close, too far back, and nominal.

An example of the predicted performance of a follower using the CTD criterion and being initially too far back is shown in Fig. 7. This compares own and lead groundspeed, separation error (where nominal is 90 sec), altitude, and throttle/spoiler inputs as functions of range-to-go. As seen, the initial separation error of 3 nmi is driven to less than 0.5 nmi by 30 nmi-to-go. In-trail control alternates between throttle and spoiler input.

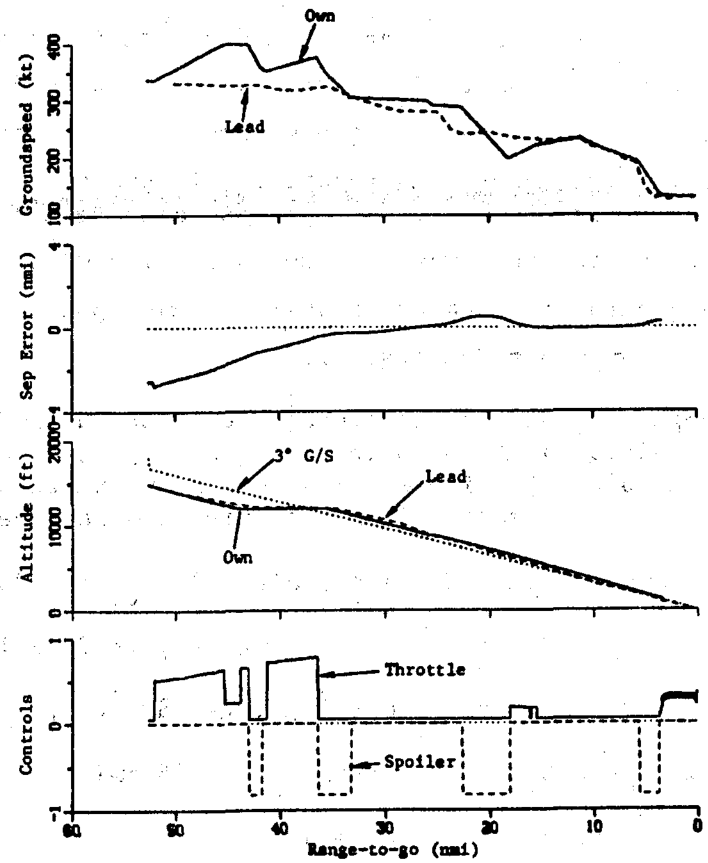

Fig. 7. Predicted Performance for the CTD Criterion. No. 1 Follower

The speed vs range-to-go prediction summary for every other follower using the CTD criterion is shown in Fig. 8. It is seen that there is about a 100 kt band of speeds about the lead profile after capture. This was consistent with previous shakedown results from the multi-cab simulator [3].

In terms of estimated performance, there are various statistical measure which could be used to categorize the overall following performance of the six aircraft. For the CTD criterion, these included, for six followers:

Own - Target Groundspeed	Mean:	0.2 kt;
	1σ :	33.2 kt;
Longitudinal Error	Mean:	-0.19 nmi;
	1σ :	0.37 nmi;
Average Throttle	0.16;	
Vertical Error	Mean:	0.32°;
	1 :	0.06°;
Time to Land Six Aircraft	4515 sec;	

where 1σ is the standard deviation. Vertical error is measured after glide-slope capture.

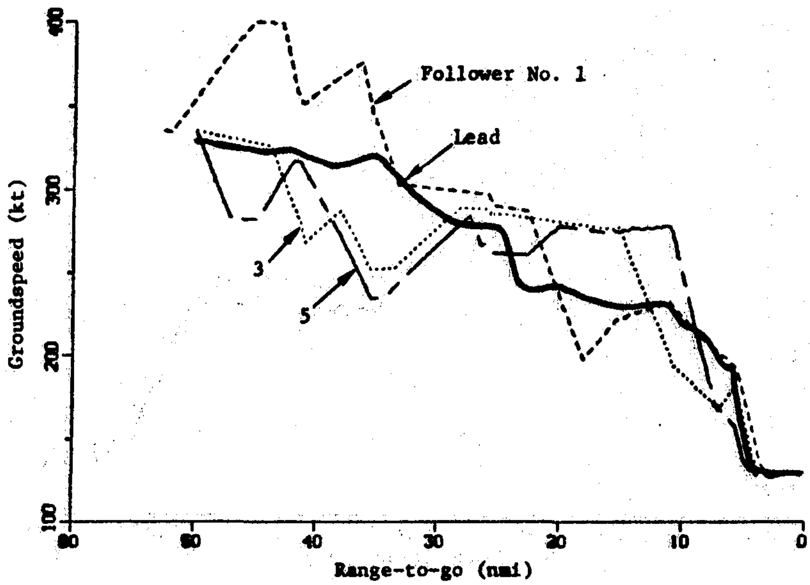

Fig. 8. Predicted Groundspeed vs Range-to-go in String with CTD Criterion

To design good performance into the model, the objectives would have been to keep the landing times for all six aircraft reasonably close, to use minimum throttle to remove the separation errors, and to minimize separation error after capture. In examining the data used to generate Figs. 7 and 8, it was seen that flight times (time to land) varied from 735 to 764 sec, or under 4% variation. The mean longitudinal error varied from +0.091 nmi to -0.454 nmi. These values depended upon whether the particular modeled follower was initially too close, too far back, or at a nominal separation.

Similar results to those shown in Figs. 7 and 8 were generated for strings of six followers using both the CTP and AC criteria. The estimated speed vs range-to-go summarizes for the AC criterion is shown in Fig. 9.

ACTUAL EXPERIMENTAL OUTCOME

The NASA Ames Research Center multi-cab simulator facility was used to conduct the CDTI in-trail following studies in February-March 1983. Six weeks of experiment were conducted, where six different sets of three airline pilots were used as test subjects each week. The first two weeks were devoted to using the CTD criterion; the CTP criterion was used the second two weeks. Eight sets of nine-aircraft strings were generated for each criterion. Thus, a total of twenty-four sets of nine-aircraft strings (192 followers in all) were generated.

The approach paths used for the experiments are shown in Fig. 10. Both the Shark and Big Sur paths were used which caused dog-leg lateral maneuvers to be required for the approach. The pilots were instructed to cross the first waypoints at 12000 ft (down from 15000 ft.) and the second waypoints at 8800 ft. The indicated airspeed was to be kept below 250 kt when flying below 10000 ft.

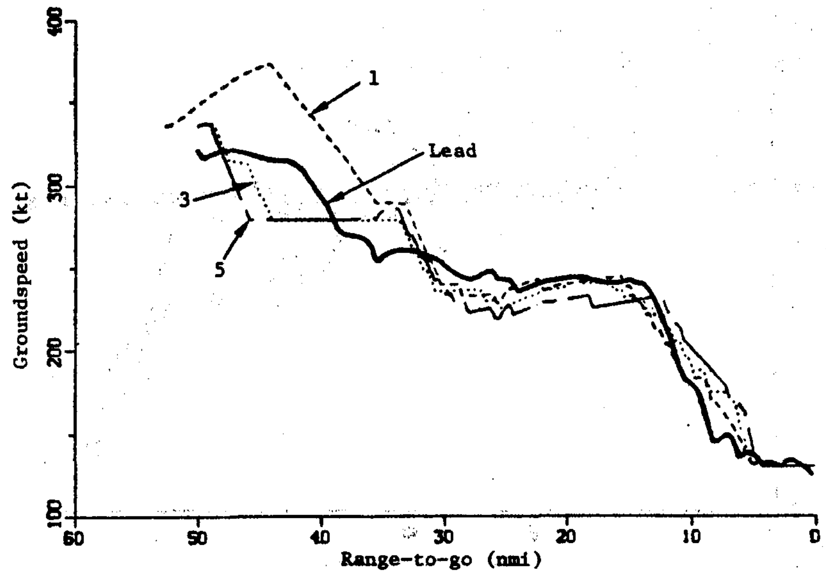

Fig. 9. Predicted Groundspeed vs Range-to-go in String with AC Criterion

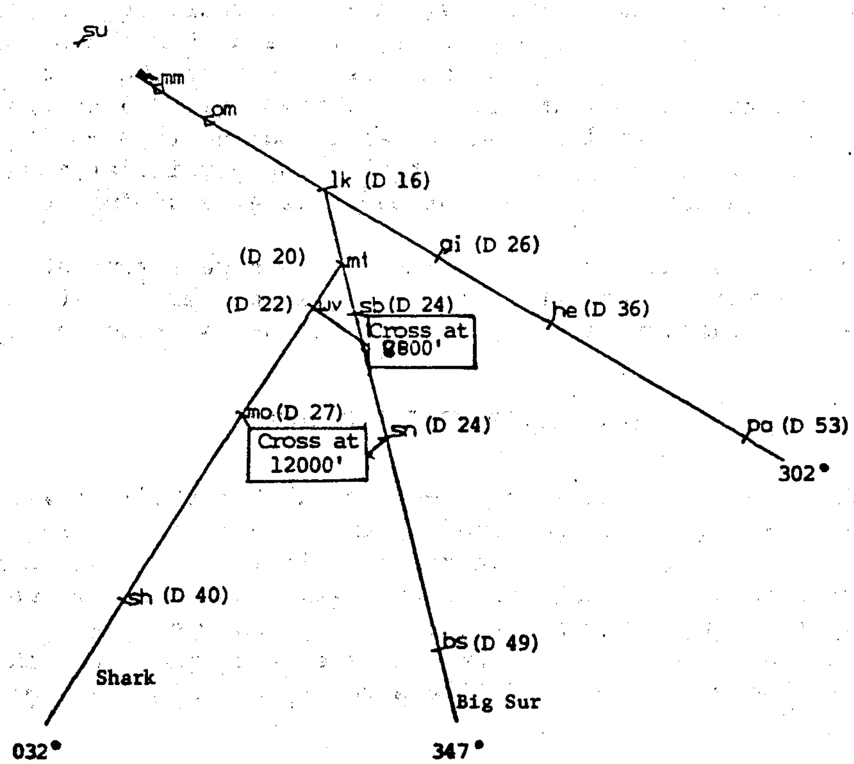

Fig. 10. Shark and Big Sur Approach Paths to San Jose Airport

The display for the Acceleration Cue criterion is shown in Fig. 11. Note that the predictor vector has three 20-sec segments, and three history dots are shown at 30, 50, and 70 sec behind the lead's location. In addition, the 90-sec history dot is replaced by a "box" consisting of two parallel lines at ± 15 sec about the 90-sec point. The predictor vector length is adjusted to account for own aircraft's measured longitudinal acceleration.

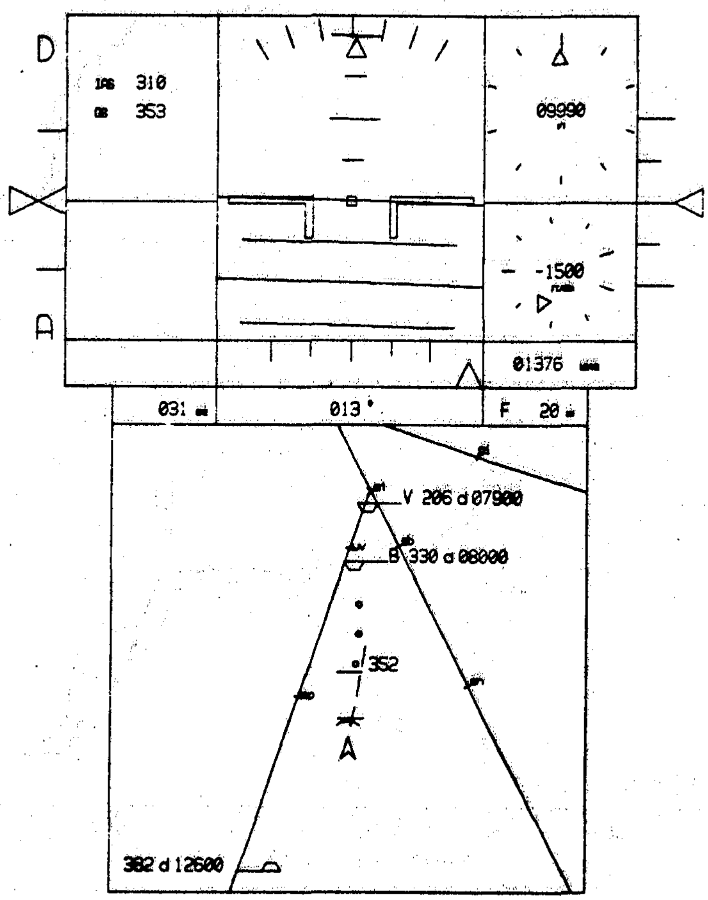

Fig. 11. Multi-cab Display for Acceleration Cue Logic

Three strings, each using a different separation criterion, were chosen to evaluate our specific prediction results in terms of the qualitative dynamic characteristics of the string. The CTD and AC strings chosen can be qualitatively summarized by the groundspeed vs range profiles as shown in Figs. 12a-b. These should be compared to the predicted results of Figs. 8 and 9, for a quick assessment.

Figure 12a is compared to the CTD predicted profiles of Fig. 8. As can be seen, the actual speed profiles lie in a close band after 30 nmi-to-go. Followers 1 and 5 have 40 kt changes between 20 and 10 nmi, but this is closer than predicted in Fig. 8. Also, there is less variation in speed than is shown in the prediction plot after the first maneuver to capture.

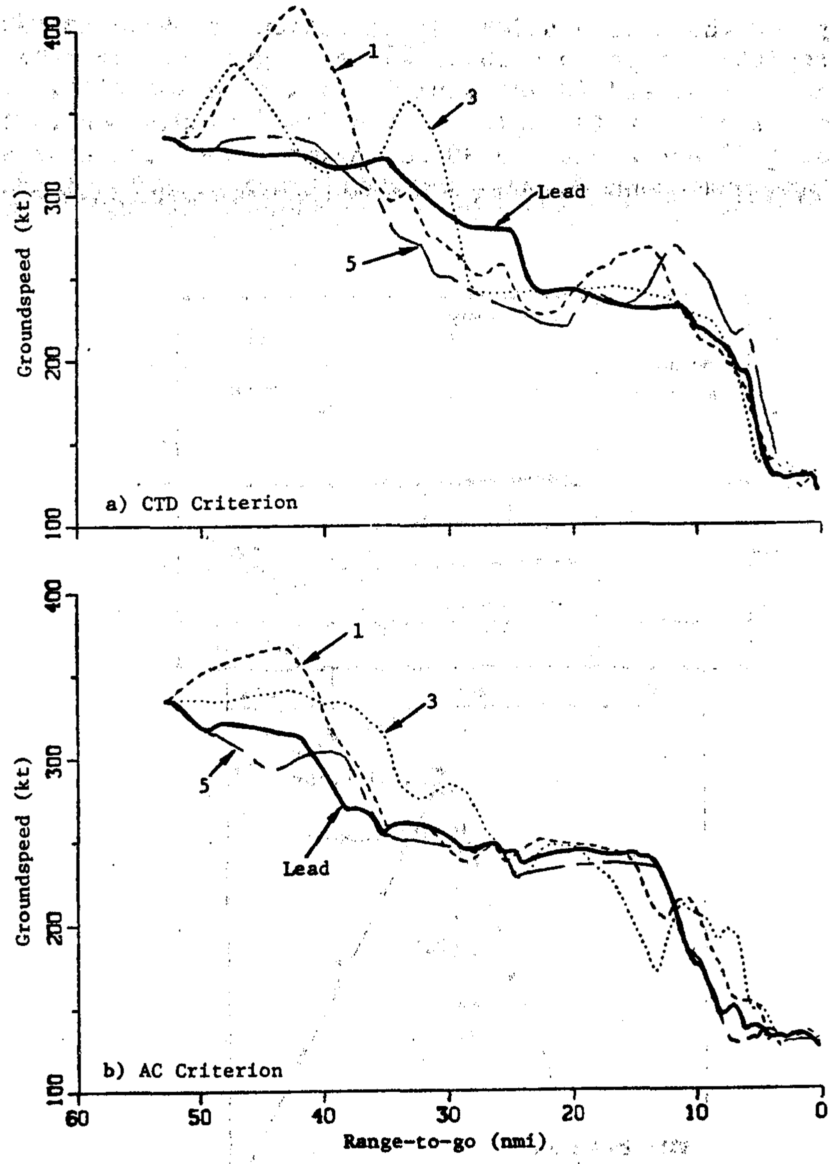

Fig. 12. Groundspeed vs Range-to-go for Every Other Aircraft

For the CTD criterion, the performance statistics for eight followers of the chosen string were:

Own - Target Groundspeed	Mean: -1.2 kt;
	1σ : 24.9 kt;
Longitudinal Error	Mean: -0.12 nmi;
	1σ : -.37 nmi;
Average Throttle	0.17
Vertical Error	Mean: 0.05°;
	1σ : 0.35°;

Time to land varied between 745 and 807 sec which is a ± 4.2% variation. In comparing these values with our predictions, we see actual own - target speed difference deviation was 8 kt less; longitudinal error was very close; and actual average throttle was 6% higher. Actual glideslope error was considerably more than we modeled (0.35° vs 0.06°), indicating that either the pilots continued to use glideslope for partial control or just did not control this dimension as accurately as we had supposed.

Figure 12b is compared to the AC predicted profiles of Fig. 9. Here, our predicted profiles look good. The actual speed profiles have some uneven variations (No. 3 has a 40 kt variation at 15 nmi). The other differences seem to be due to the order of initial separation errors modeled.

In our predicted results, there was a great deal of on-off spoiler control activity. For the actual performances, the spoilers were used only sparingly. The throttle was used mostly for catchup speed control before 40 nmi. Thereafter, it was mostly set at idle. Thus, the chief control from about 35 nmi-to-go to 15 nmi was flight path angle. This was contrary to our assumption that the vertical control was independent. During this period, the speed was held close to 250 kt. Gear and flaps were used for the final deceleration.

Another observation was that aircraft initially too close (No. 2 and No. 4 in the AC string) did not decrease speed rapidly to reduce this error. Rather, they let the aircraft that were initially too far back (No. 1 and No. 3 in the AC string) first accelerate to remove their separation errors; this also took care of the "too close" problem. This indicated that the pilots look ahead to assess what their immediate leads' strategy will probably be. This feature was not included in our predictive model.

It was seen, for all three separation criteria, that there frequently was large (more than 15 sec) separation errors that built up after 10 nmi-to-go was passed. This is illustrated in Fig. 13 for Follower Nos. 2-4 from the AC criterion string. Apparently after 10 nmi, the pilots tend to neglect separation error and concentrate on landing. Thus, our prediction of tight separation control at the end was not correct.

Finally, it is useful to compare the statistics of the errors in the displayed longitudinal separations and glideslope deviations of all the experimental runs to those predicted by our models. In this way, we get an overall average of experimental performance that takes into account differences in pilots, pilot order of flight, and approach paths. These comparisons are made in Table 1 for the three separation criteria.

We note two points from this table. First of all, there was little difference in the overall experimental results between the three criteria. Separation error was about -0.1 ±0.6 nmi, and glideslope error was about ±0.5°, for the three criteria. The second point is that our model predictions are consistently optimistic for both the vertical and in-trail standard deviations. The model predicts a mean of about 0.25° with small variation (±.06°) for the vertical. This indicates that more randomness is required in the model's pilot behavior to get the same in-trail and vertical

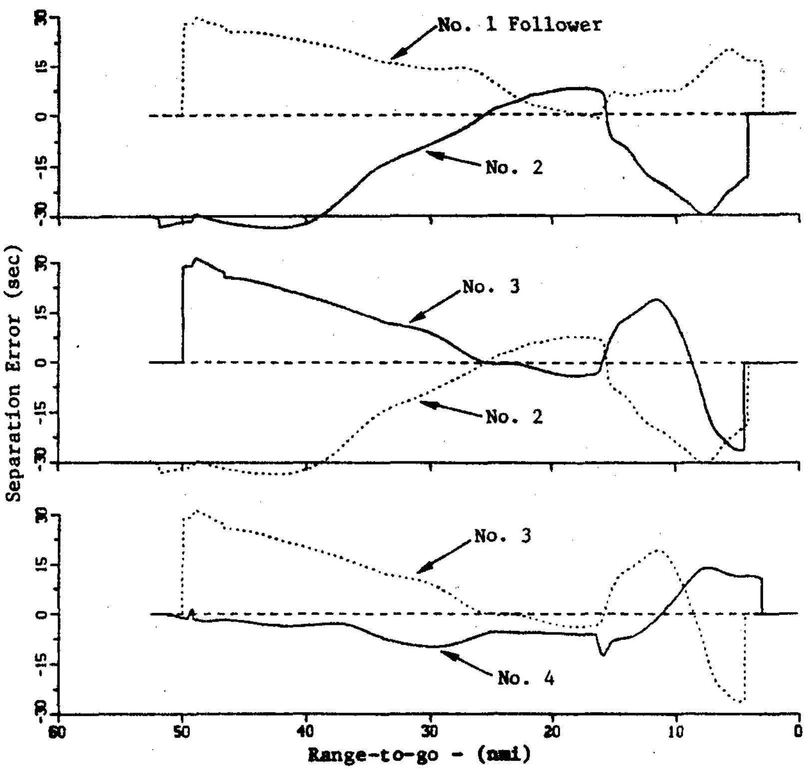

Fig. 13. Separation Errors in Time for Actual AC Data

Table 1. Comparison of Predicted and Actual Separation and Glideslope Tracking Performance After Capture Using All Experimental Data

Criterian	Longitudinal Error (nmi)				Vertical Error (deg)			
	Actual		Predicted		Actual		Predicted	
	m	σ	m	σ	m	σ	m	σ
Constant Time Delay	-.134	.606	-.190	.370	.08	.52	.32	.06
Constant Time Predictor	-.131	.586	-.048	.261	-.01	.48	.22	.05
Acceleration Cue	-.069	.585	-.077	.154	.03	.52	.22	.06

variations. This means that we have to increase drag in the model so that the average glideslope error can be lowered 0.25°

MODEL ADJUSTMENTS TO MATCH EXPERIMENTAL RESULTS

To match experimental results, we began by adjusting the model which uses the CTD criterion. Model parameters and structure were changed to achieve a closer match in the groundspeed vs range-to-go record and the in-trail statistical measures.

First, the sequence of initial separation errors of the model was changed to be the same as that of the chosen CTD experimental string. The second change was to put minimum and maximum speed limits into effect below 10000 ft (after nominal in-trail capture) for each follower. These limits represent the fact that each pilot has a nominal approach speed profile that he tends to follow. He deviates from this profile to null separation error but only up to some acceptable amount that is consistent with his training. The speed limits and point of gear deployment were then tuned to adjust model profiles.

The result of this CTD model adjustment of speed vs range is shown in Fig. 14; a qualitative agreement exists with the experimental results shown in Fig. 12a. The revised statistical parameters of the modified CTD model are presented in Table 2, along with the experimental results. Good agreement exists in all but the glideslope error statistics. By using the model sensitivity results, it is possible to tune the model to get as close as we wish for in-trail statistics comparison. Thus, the tuned mathematical model is a good representation of the piloted multi-cab simulator using the CDTI for in-trail spacing. However, we next had to address the descrepancies in the control and glideslope error time histories.

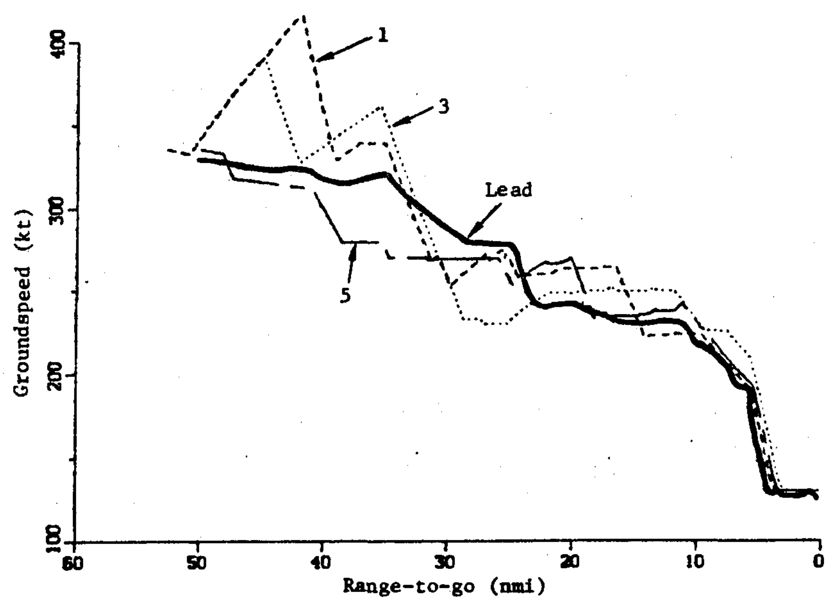

Fig. 14. Modified CTD Model Results

Table 2. Statistical Comparison of Revised CTD Model and Experimental Results

Quantity	Model	Actual
Longitudinal Separation Error (nmi) (After Capture)	-0.11 ±0.34	-0.12 ±0.37
Vertical (Glideslope) Error (deg) (After Capture of Localizer)	0.22 ±0.06	-0.05 ±0.35
Ground Speed Difference (kt)	1.8 ±27.6	-1.2 ±24.9
Average Throttle	0.172	0.170

Figure 15 is a comparison of the vertical profile (altitude vs range) and control sequence used by the first follower in the Experimental and modeled AC criterion string. Note that the actual flight path angle has considerable more fluctuation than does the model. The model has more throttle/spoiler activity than the experiment. This same results was true for the other followers. This indicates that the pilots tend to use flight path angle to a greater extent for in-trail control than we assumed in the model. (i.e., the pilots use flight path angle for both in-trail and vertical control.)

To show that flight path angle could be used for both in-trail and vertical control by the model, the acceleration cue (AC) based model was modified to use primarily γ control by inhibiting the use of spoilers. The resulting model was tuned so the resulting speed vs range curves approximated those results shown in Fig. 12b. The match of separation error for the No. 1 follower in the model and the experiment is shown in Fig. 16. Similar results for all followers proved that the aircraft is fully controllable with flight path angle and throttle variations.

The statistical results before and after the AC model was modified based on the actual experimental outcome are shown in Table 3. We see that using γ for primary control shifts the mean separation error forward 0.15 nmi, increases both the mean and standard deviation of vertical error, and decreases the average throttle position. If throttle activity was increased to 0.17, as in the experiment, it would be required to have an even larger mean flight path angle error.

Changing the model did succeed in raising the glideslope error standard deviation from 0.06 to 0.19. Larger variations in this control are possible with an accompaning increase in standard deviation in separation error.

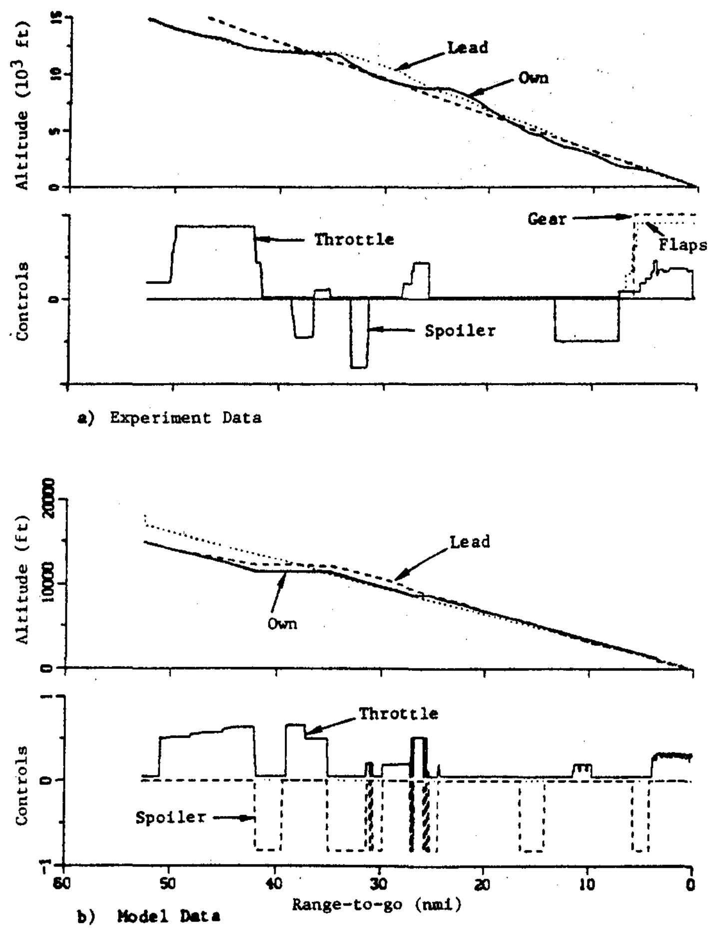

Fig. 15. Comparison of Flight Path Angle and Spoiler/Throttle Control for No. 1 Follower (AC)

That is, if the glideslope variation was tuned to increase from $\pm 0.19°$ to $\pm .35°$, the separation error deviation would move from ± 0.15 nmi closer to the ± 0.37 nmi of the actual results.

The vertical mean error of +0.38° indicates that the model has to have a mean positive (pitch up) error to slow the aircraft successfully for landing. This indicates that the actual similator dynamics has a drag (or decay) term affecting speed that is not in the model. The idle thrust level could be tuned in the model to improve the match between actual and modeled results.

CONCLUSIONS

This study demonstrated that a system model can be devised which duplicates the statistical performance, qualitative character, and control strategies of pilot and aircraft in a multi-cab experiment. This model can be used for future fast time simulation of in-trail following tasks. The process of

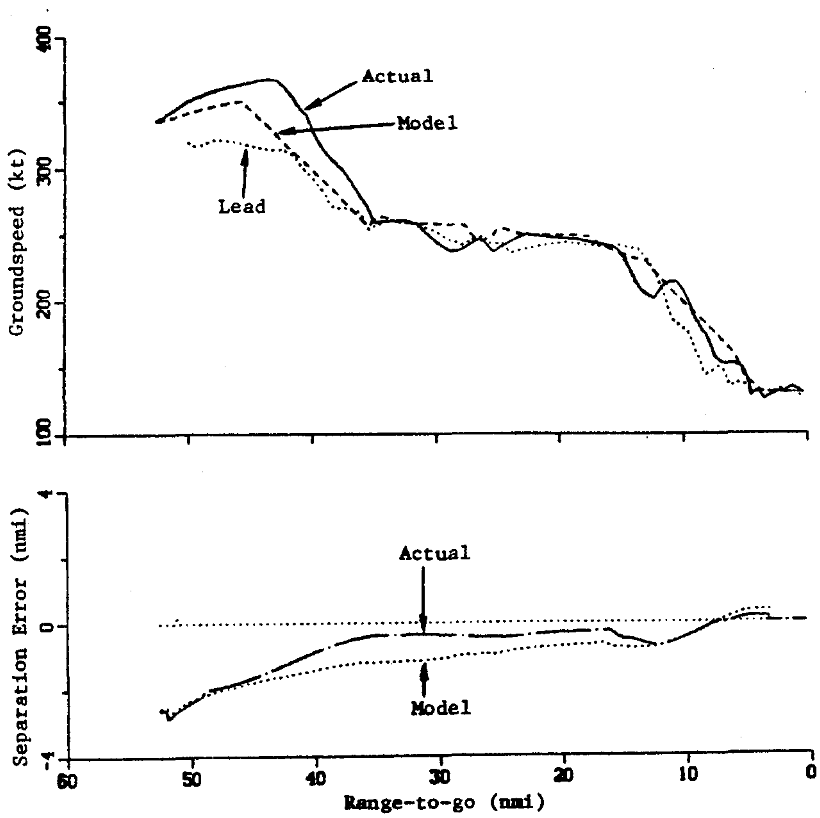

Fig. 16. Modified AC Model Match of No. 1 Follower Separation Error

Table 3. Statistical Comparison of AC Models and Experimental Results

Quantity	Original Model	Modified Model	Actual Experiment
Longitudinal Separation Error (nmi) (After Capture)	-0.08 ±0.15	0.07 ±0.15	0.02 ±0.37
Vertical (Glideslope) Error (deg) (After Localizer Capture)	0.22 ±0.06	0.38 ±0.19	-0.07 ±0.35
Groundspeed Difference (kt)	0.1 ±20.6	1.2 ±13.5	-0.2 ±17.8
Average Throttle	0.13	0.08	0.17

duplicating the actions of the pilot using the CDTI to regulate his aircraft position was facilitated by breaking those actions into estimation, decision, and control components.

The more significant lessons we learned were those resulting from our incorrect assumptions in predicting the outcome of the experiment. Some of the more important lessons were as follows:

1. In our design logic for decision and control to model the actual experiments, we assumed that because spoilers were present, the pilot would use primarily throttle and spoilers for in-trail spacing control. We assumed he would use flight path angle control strictly for meeting altitude windows and then later capturing and maintaining the glideslope. (i.e., we assumed that the two axes would be split by the control mechanisms used.) This was not the case. The pilots used the spoilers as little as possible. They used flight path angle for both speed control and vertical control, which is consistent with their training. The lesson: Build control logic based as closely as possible to the way pilots normally fly, even though a new requirement (regulating in-trail spacing) is added to their control requirements.

2. We assumed that the in-trail following task would be the primary objective that would govern the pilots' control of the speed of the aircraft during most of the approach. This was not true. After the initial capture phase where pilots would remove most of the initial separation error, they would stay close to a nominal approach speed as a function of range-to-go. Thus, this nominal speed had to be included in the longitudinal control laws and decision process of the model. The lesson: Again, the way the pilot flys a nominal approach must be factored into the model for prediction.

3. We assumed that tight in-trail spacing control would continue to the outer marker. The data incidated that the pilots would switch to a strategy of just concentrating on landing sooner than this, and the in-trail spacing errors would grow near the end. Again, this is inherent in the way they have been trained and what they have experienced over years of flying.

These lessons are all logical, and they would enable us to design a more accurate model and make better predictions of the experimental outcome sooner the next time.

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