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Computer-Automated Opponent for Manned Air-to-Air Combat Simulations

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SUMMARY

Two versions of a real-time digital-computer program that operates a fighter airplane interactively against a human pilot in simulated air combat have been evaluated. They function by replacing one of two pilots in the Langley differential maneuvering simulator. Both versions make maneuvering decisions from identical information and logic; they differ essentially in the aerodynamic models that they control. One is very complete, but the other is much simpler, characterizing primarily the airplane's performance (lift, drag, and thrust). Both models competed extremely well against highly trained U.S. fighter pilots. Although data from the evaluation indicate that the more complete model outperformed the pilots to a greater degree than did the simpler one, evidence is not sufficient to conclude that the complete model is inherently superior.

INTRODUCTION

In support of the studies in advanced aircraft maneuvering concepts being conducted in the Langley differential maneuvering simulator (DMS), Langley Research Center has pursued the development of a logic to effectively maneuver an airplane in simulated air combat against a human pilot. This effort has resulted in a real-time digital-computer program known as the adaptive maneuvering logic (AML) program. The AML can be used to replace one of the DMS pilots and to provide the remaining pilot with a tough, competitive, realistic adversary. The AML is completely deterministic, yet because its maneuvering is a complex interaction between its own present state and that of its opponent's immediate past, it minimizes, if not completely eliminates, any appearance of predictability. In fact, the likelihood of any two AML runs against a human pilot being identical is no greater than that of the human pilot identically repeating a sequence of maneuvers.

George H. Burgin of Decision Science, Inc., under contract to Langley, first formulated the most basic concepts of the AML and demonstrated their functioning in a batch-processing digital-computer program. It was originally intended that those batch programs be used to provide preliminary indications of the results of studies to be conducted with human subjects in the DMS. However, as the AML development progressed, it became increasingly evident that it could be adapted for real-time operation against human pilots. The airplane models originally driven by the AML primarily characterized airplane performance (lift, drag, and thrust), with minimal modeling of the airplane's rotational characteristics. These simplified airplane models were generally considered to be acceptable, particularly in light of the more important need at that time to enhance the maneuver logic and achieve real-time operation. When real-time operation was ultimately achieved, the AML was enthusiastically accepted by the fighter pilots who flew against it. However, because the airplane model controlled by the pilots was different from that controlled by the AML, a question persisted as to whether the AML could perform maneuvers that the pilots

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could not. Thus, a new effort was begun to develop a control system which would allow the AML to control the same airplane model controlled by the human pilots in the DMS. The magnitude of this new program would have far exceeded the capacity of the already overburdened Control Data series 6600 computer which was operating the combined AML-DMS program. Fortunately, the more powerful Control Data CYBER series 175 computer became available at about the same time the new program was ready and was able to easily handle it.

With the new "control model" available, it was desirable to compare it with the older "performance model" since a favorable comparison would increase confidence in the validity of results obtained in previous studies which had used the performance model. It would also help justify the continued use of performance models for most applications. Their continued use is desirable because they are much simpler and more readily programmed for additional airplanes. Presently, only the F-4 airplane has been fully modeled with a control system for operation with the AML.

During late January 1978, four current U.S. Air Force and U.S. Navy fighter pilots flew against an improved maneuver logic that controlled both a performance model F-4 and a control model F-4. It is the primary purpose of this paper to report the results of that study. The data analysis will attempt to assess the maneuvering effectiveness of both the AML models relative to current U.S. military fighter pilots and indirectly to each other.

Detailed descriptions of the AML and associated airplane models may be found in references 1, 2, 3, and 4. This paper will not attempt to repeat the information contained in these publications, but will merely summarize in the body of the paper some of the more basic concepts. It will use two appendixes to provide more in-depth explanations of previously unpublished modifications and improvements made to the AML. Appendix A, entitled "Performance-Model Modifications," was authored by Bobby J. Glover of Kentron International, Inc., whose efforts have constituted an invaluable input to Langley's AML development work. Appendix B describes real-time implementation and refinement of the AML control model.

SYMBOLS

$a_{n,c}$ commanded normal acceleration, g units (1 g = 9.8 m/sec^2)

b wing span, m

C_D drag coefficient

C_L lift coefficient

C_{L_α} $= \frac{\partial C_L}{\partial \alpha}$, per degree

C_l rolling-moment coefficient

C_{l_β} $= \frac{\partial C_l}{\partial \beta}$, per degree

$C_{l_{\delta_a}}$ rolling moment due to aileron deflection

$C_{l_{\delta_{sp}}}$ rolling moment due to spoiler deflection

C_m pitching-moment coefficient

C_{m_q} $= \frac{\partial C_m}{\partial q}$, per degree

F_c thrust command, N

g acceleration due to gravity, m/sec^2

h altitude, m

I_{XX} moment of inertia about X body axis, $kg\text{-}m^2$

M Mach number

p,q,r roll, pitch, and yaw angular velocities, respectively, rad/sec

$\bar{q}$ dynamic pressure, N/m^2

S wing area, m^2

t time, sec

u,v,w components of velocity along X, Y, and Z body axes, respectively, m/sec

W weight

x_i,y_i,z_i coordinates of inertial axis system

X,Y,Z body axes

α angle of attack, deg

β angle of sideslip, deg

$\delta_a,\delta_e,\delta_r$ aileron, elevator, and rudder deflections, respectively, deg

δ_{sp} spoiler deflection, deg

λ off-boresight angle, deg

ϕ bank angle, deg

ϕ_c bank-angle command, deg

ψ,θ,ϕ Euler yaw, pitch, and roll angles, respectively, of body axis system referenced to inertial axis system

$\bar{\psi},\bar{\theta},\bar{\phi}$ Euler yaw, pitch, and roll angles, respectively, of maneuver plane axis system referenced to inertial axis system

Abbreviations:

ACM air-combat maneuvering

AML adaptive maneuvering logic

AMLS adaptive-maneuvering-logic score

DMS Langley differential maneuvering simulator

MMP moving-maneuver-plane axis system

TOA time on offense with advantage

A dot over a symbol indicates derivative with respect to time.

LANGLEY DIFFERENTIAL MANEUVERING SIMULATOR

The AML program operates in real time on the DMS which has been in operation for about 8 years. It permits two pilots to maneuver their simulated airplanes interactively and has been used extensively in performance evaluations of fighter-type airplanes in a one-on-one environment.

Figure 1 is a diagram of the DMS. It consists of two 40-foot-diameter projection spheres, with cockpits located in such a way as to position the pilot's eye at the center of the sphere. The projection equipment, which is located above the rear of the cockpits, projects images of the sky, Earth, horizon, and opposing aircraft onto the spheres. The resulting projected images move in proper perspective for each of the two pilots. The state of the pilot's aircraft is revealed through cockpit instrumentation, visual displays, and secondary cues such as g-suit, blackout, altitude warning, buffet, and thrust noise.

Figure 2 is a block diagram illustrating the operation of the DMS with two pilots. The human pilot reacts to information displayed in his sphere and outputs stick, rudder-pedal, and throttle commands. These are transmitted to the equations of motion which compute the state of the aircraft corresponding to them. The equations of motion consist of both force and moment equations that use tabulated aerodynamic derivatives which define the aircraft being flown. The two aircraft may be the same or dissimilar. The relative states of the aircraft are computed, and that information is used to drive the display systems in the spheres. Additional information may be obtained from reference 5.

AML PROGRAMS

The AML programs are digital-computer programs which interface a guidance law for interactive air-combat maneuvering with computer models of fighter airplanes. These programs may act as real-time opponents for human pilots in the DMS or they may control two math-modeled airplanes against each other in an off-line batch-processing mode. The programs are deterministic, giving their users ready access to the causes of all actions taken by the AML.

The logic for selecting maneuvers is common to all the AML programs. However, two different types of airplane math models are used with this logic. They are called the performance model and the control model. The differences between these two forms of the AML program will be illustrated by comparing and contrasting how each of them operates when used in conjunction with the DMS.

Figure 3 illustrates how the DMS works when a pilot flies against the AML performance model. The human-pilot loop is exactly as it was in figure 2. The block labeled air-combat maneuvering (ACM) logic is the heart of the AML program. This logic will be described later. Note that two basic simplifications have been made with respect to the human-pilot loop. First, the ACM logic outputs bank-angle and load-factor commands directly to the equations of motion rather than stick and rudder-pedal displacements. Second, rather than using moment equations, the computer-controlled airplane is driven directly in attitude through its body rates. Filters and rate limits are used to insure smooth transitions. Because the airplane is modeled primarily through its performance characteristics (lift, drag, and thrust), this form of the AML program is called the performance model.

A second form of the AML program, called the control model, contains a more comprehensive airplane model (fig. 4). Note now that the equations of motion in the AML loop are identical to those in the human-pilot loop. What is different is the addition of a control system to convert the AML bank-angle and load-factor commands to control surface commands. Because of the time required and the difficulty of designing this control system, the control-model form of the AML has to date been assembled only for the F-4 airplane. This model enjoys the advantage of greater user confidence in the realism and accuracy of the simulation. It also, in contrast to the performance model, eliminates the question of whether the computer-controlled airplane can perform maneuvers that the pilot, at least in theory, cannot perform.

Rather than use classical maneuvers such as a high-speed yo-yo, the AML uses simpler, more elemental maneuvers. These elemental maneuvers consist of segments of circular flight paths lying in planes. The plane curve is specified by the throttle setting and the percentage of available load factor. The bank angle is chosen such that the curved path remains in the desired plane. The airplane continues to fly in the specified plane until a new maneuver is chosen. When this occurs, the airplane transitions to a new plane of flight by rolling until its wings are properly alined to cause all net forces to lie in the new plane. The flight then continues. Figure 5 illustrates how several elemental segments may combine to form a three-dimensional space curve.

To maintain flexibility in reevaluating the tactical situation for possible maneuver changes, the time interval between maneuver decisions must be short. The AML uses 1-sec intervals. When the elemental maneuvers are put together, they quite often resemble classical maneuvers.

Maneuver Selection Logic

Figure 6 is a simplified flow chart of the AML program. The maneuver-selection logic is the section of the chart contained between the dashed lines.

The program uses a fixed logic to decide which maneuver to make next. The concept is very simple. The program predicts the future state of its opponent over a short time interval. It then computes what its state would be if it performed each of several optional maneuvers over the same time period. The computed state of each trial maneuver is compared with the predicted state of the opponent, and the most promising trial maneuver is chosen as the next to be performed.

When the program makes maneuvering decisions, it evaluates several standard maneuvers, depending upon its assessment of its current tactical situation. The maneuvers being discussed here are those considered applicable to a "normal situation." The methods employed to handle special problems such as ground avoidance and energy management will be discussed later. Under normal circumstances the program evaluates some or all of the following maneuvers: (1) continuing the maneuver currently being performed, (2) a maximum load-factor turn in the current plane, (3) maximum load-factor turns in planes banked 10° to either side of the current plane of flight, (4) flying straight, (5) maximum load-factor turns in the "intercept maneuver plane" (the intercept maneuver plane is defined as the plane which contains the current velocity vector of the computer-controlled airplane and the predicted position of the opposing airplane), (6) maximum load-factor turns in planes banked 10° to either side of the intercept maneuver plane, (7) maximum load-factor turns in planes banked 90°, 180°, and 270° from the intercept maneuver plane, and (8) a turn with a load factor computed to yield a circular flight path in the intercept maneuver plane which will exactly intercept the opponent at his predicted position. The AML extrapolates the opponent's position (and other state variables) at the end of a preselected time interval, nominally 2 sec, from the current time using a second-order curve containing the opponent's present and two previous positions.

For each trial maneuver, the program computes what the state of the airplane under its control would be at the end of 2 sec. The computed state variables resulting from each trial maneuver are then compared with the predicted state variables of the opponent by means of a set of questions which results in a numerical score, and the maneuver with the highest score is chosen as the next to be performed.

Scoring Trial Maneuvers

The following 14 questions are those used to obtain the numerical score for each trial maneuver. The questions are worded in such a way that they can be answered either "yes" or "no." A yes answer is considered good and is assigned a value of 1. A no answer is assigned a value of 0.

	Answers	
	Yes	No
1. Is opponent ahead of attacker?	1	0
2. Is attacker behind opponent?	1	0
3. Can attacker see opponent?	1	0
4. Is opponent uable to see attacker?	1	0
5. Is attacker in certain cone behind opponent?	1	0
6. Is opponent not within certain cone behind attacker?	1	0
7. Can attacker fire at opponent?	1	0
8. Can opponent not fire at attacker?	1	0
9. Are both answers to questions 1 and 2 yes?	1	0
10. Is attacker closing on opponent?	1	0
11. Is attacker's predicted altitude greater than 91.44 m?	[a]0	[a]–13
12. Are both the answers to questions 3 and 4 yes?	1	0
13. Is attacker's line of sight less than 60°?	1	0
14. Is attacker's line of sight zero or decreasing?	1	0
SCORE	13	–13

[a]A "yes" receives a zero; a "no" receives –13.

Although stated here in words, the questions actually evaluate specific relative-state characteristics. That is, the questions involve such quantities as positions, angles, velocities, and distances. The reader should note in studying these questions that the airplane controlled by the computer model is referred to as the attacker. A detailed explanation of each question will not be given here. Two questions will be discussed, however, as typical of the information being evaluated. Question 1 asks whether the opponent is in front of the attacker. Stated in geometric terms, the question asks whether the angle between the attacker's X body axis and the line of sight to the opponent's center of gravity is less than 90°. A slightly more complex example is question 5, which asks whether the attacker is within a certain cone behind the opponent. Specifically, the program determines whether the attacker is in a 60° cone behind the opponent at a range of less than 914.4 m. All 14 questions are evaluated for each trial maneuver to obtain the numerical score.

The idea of flying in maneuver planes is more a goal with the AML than it is a fact. It provides an especially good mechanism through which to set up trial maneuvers and to evaluate them. Because of the mathematical scheme used to simulate airplane motion in the performance model, the performance model probably comes closer to achieving piecewise planar flight than does the control model. The transitioning between maneuver planes may require a large part of the time between decisions. During this time, the airplane's flight path is obviously not planar. In addition, it is often not possible to maintain planar flight once it has begun. The control model uses the maneuver-plane concept only at maneuver-decision intervals, and then only to specify a bank angle and a percentage of available load factor to use until the decision time occurs again.

Ground Avoidance and Energy Management

In addition to the basic concepts and guidance principles already discussed, there are two other major problems that the maneuvering logic must solve. One of these, as previously mentioned, is ground avoidance. The program continuously compares the flight-path angle of the computer-controlled airplane with tabulated values of the maximum dive angles from which the airplane can recover without crashing. As the flight-path angle approaches an unrecoverable value, the trial maneuvers that are permitted become more and more limited until only a maximum load-factor pull-up in the vertical plane remains. Considerable care must be taken in structuring the logic to prevent crashes because ground-avoidance maneuvers generally are not the most effective to use against the opposing airplane.

Energy management is a second area of concern. The particular reference here is not to optimizing energy management but, more specifically, to preventing an airplane from flying so slowly that it can no longer maneuver effectively. The program continuously monitors the load factor available to the computer-controlled airplane. When it diminishes to certain predetermined levels, the normal trial maneuvers are modified or different ones are brought into consideration. At some levels of available load factor, the airplane is restricted to maneuvers which do not exceed certain percentages of the airplane sustained load-factor capability. Under the worst of circumstances, the airplane may be required to relax load factor entirely. As with the ground-avoidance maneuvers, considerable care must be taken in devising the criteria for the use of energy-management maneuvers. Indiscriminate use of either type of these special maneuvers could seriously reduce interaction with the opponent. The logic gives priority to ground avoidance, energy management, and normal maneuvers, in that order. When special maneuvers are used, generally more than one is evaluated by using the same selection process as is used with the normal maneuvers. Thus, the program at least tends to choose maneuvers which keep the airplane turning in the direction of the opponent.

Although the program specifies a throttle setting to be used for each trial maneuver, whether it be standard, ground avoidance, or energy management, situations occur during the execution of maneuvers in which the throttle setting should be changed. Three basic situations are covered. First, a reduction in throttle setting may be required to prevent the computer-controlled airplane from overshooting its opponent. Speed brakes may also be employed under these circumstances. Second, a similar throttle change may be used to induce an overshoot by the opponent. Finally, the throttle is manipulated to cause the airplane to fly at or near its corner velocity (velocity at which the maximum lift capability of an airplane equals its structural load limit).

Lag and Lead

To simplify the earlier explanation of the AML evaluation of the predicted, relative future states of its own airplane and that of its opponent, a nominal value of 2 sec was specified for the prediction and extrapolation intervals. These values are seldom actually used, however. An important part of ACM strategy involves the employment of lags and leads. If the future state of the opponent is predicted over the same time interval that the future state of the AML-controlled airplane is extrapolated, the situation is near pure pursuit. Actually, it is a slight lead since collision-course trajectories are being compared.

If the AML extrapolates its airplane state over a longer time interval than it predicts its opponent airplane state, effectively it evaluates lag. Conversely, if the relative lengths of these time intervals are reversed, lead maneuvers are evaluated.

For most situations, the AML uses lag rather than higher risk lead maneuvering. Unless irrevocably committed to a given maneuver, an opponent who recognizes that his adversary is using lead pursuit may be able to readily alter his trajectory to put the adversary in a disasterous situation. Only in the case of equal (2-sec) extrapolation and prediction intervals does the AML even approach the application of lead. The degree of lag used varies with the degree of positional advantage enjoyed by the AML and the range between the airplanes. Large lags, for instance, are employed at very close ranges to prevent overshoots.

Finally, the AML uses long-range as well as short-range prediction and extrapolation. The longer the time interval over which the opponent's state is predicted, the less accurate it is likely to be because the opponent has more time to alter his trajectory. However, at long ranges where errors are less critical and softer maneuvering is more likely, longer prediction intervals may be safely used to devise longer term, less energy consumptive maneuvers. Even with the longer time-interval predictions, the AML still uses lag-type maneuvers. Long-term prediction (6 sec) is always used for ranges greater than 1524 m and is also used for ranges greater than 762 m if the AML has already acquired a large angular advantage.

Operational Modes

Two basic operational modes of the AML program exist, the off-line or batch-processing mode and the real-time simulation mode. The batch-processing mode controls two airplanes and supplies maneuvering logic, relative geometry computations, equations of motion, and aerodynamic characteristics of the two airplanes. Since the same maneuvering logic is used for both airplanes, measures of the relative maneuvering capability of two dissimilar airplanes can be obtained. The program can also be used to obtain preliminary indications of the outcome of pilot-versus-pilot studies.

The real-time simulation mode utilizes the DMS to allow the computer-controlled airplane to fly interactively one-on-one air-combat engagements against human pilots. Since the program is deterministic, it can act as an invariant or standard opponent whose logic and maneuvering performance can be kept constant from one simulator run to another, thus allowing variations in human-pilot performance to be measured with respect to it. The AML, in conjunction with a manned simulator, can offer significant potential in pilot training and proficiency maintenance.

A more comprehensive explanation of the AML program, including some detailed explanations of specific subroutines of the computer program, can be found in references 1 and 2.

DESCRIPTION OF TESTS

Objectives

A general procedure was developed to acquire data for evaluation of the two AML models. Three basic sets of data would be taken. The first set would be recorded from runs in which pilots flew only against other pilots in the DMS, and would provide a baseline with which to compare the remaining data. The other two data sets would consist of runs in which the same pilots flew against each of the two AML models. From analyses and evaluation of these data, an assessment would be made of the skill and effectiveness of the AML models relative to those fighter pilots. In addition, the maneuvering effectiveness of the two models relative to each other would be evaluated.

Procedure

A simulated F-4 was flown by both the pilots and the AML. The F-4 was chosen because it had been used as the baseline airplane throughout most of the development work on the AML and hence was the one most effectively driven by the AML. Also, it was the only airplane for which a control system had been designed to permit control through its full equations of motion. Furthermore, to eliminate the characteristics of the airplane itself as a variable in data comparisons, it was necessary to make all runs with the same airplane.

All runs were made in the DMS. Twelve sessions (1 session per day) of 3 hr each were conducted over a period of slightly more than 2 weeks. Pilot-versus-pilot runs utilized both DMS spheres while pilot-versus-AML runs utilized only one. Each data set consisted of 24 runs.

Run schedules were structured to minimize the effects of extraneous variables such as the order in which a given pilot made his runs. Each pilot flew four runs against every other pilot during the pilot-versus-pilot data set. These runs were ordered such that each pilot flew an equal number of runs in each of the two DMS spheres. In each of the AML-versus-pilot data sets, each pilot flew against the AML six times. Once a data set began, a log was maintained to show the length of each run, the identification of the pilots, the cause of run termination, and other such pertinent information.

From previous experience with the DMS, it was expected that after about three practice sessions, the pilots would be comfortable in the simulator, and learning processes with respect to it would have reached a plateau. This was expected to be especially true by the time data sets against the AML were begun. Thus, no practice runs against the AML were scheduled, and data runs were begun immediately upon introducing pilots to the AML models.

The same initial conditions were used for all runs. The airplanes were started head-on from a range of 3.6565 km. The initial altitude of both was 4.572 km and both had initial speeds of $M = 0.9$. Each data run was scheduled to last 3 min.

Sixty-eight variables were recorded every 0.5 sec during data runs. These included state variables of both airplanes (i.e., α, β, u, v, w, etc.), as well as relative geometric relationships between them.

The first 2-1/2 days of the experiment were used for familiarizing the pilots with the simulator. The schedule during this period was not rigid, but an attempt was made to approximately equalize the simulator time for each pilot. On the third day, pilot-versus-pilot data runs were begun. Departures and crashes were a problem from the beginning.

The extreme competitiveness of fighter pilots and the lack of life-threatening consequences in the simulator caused a large number of runs to terminate before 3 min had elapsed. About 4-1/2 days were required to complete this data set. In fact, in order to complete the experiment within the constraints of alloted simulator time and available pilot time, 9 runs with durations of less than 3 min but more than 2 min were accepted as data runs.

About 3 days were spent attempting to acquire the 6, 3-min runs for each pilot flying against the AML control system. Again, time constraints forced the acceptance of several runs of less than 3 min.

The AML performance model was the last in the series to be run. Only about 2 days were required to complete this set. Thus enough time was left to fill out the control-model data set with 3-min runs. Only the pilot-versus-pilot runs were left compromised by an incomplete set of 3-min runs. Upon completion of all runs, pilots were debriefed and their comments taped.

PILOTS

Pilot background was important because the AML maneuvering-performance results were to be compared with those of typical U.S. military fighter pilots. The background and experience level of the pilots covered a broad range. All four were currently flying F-4's, which was a requisite of the experiment. Two were U.S. Air Force pilots. The other two were U.S. Navy pilots. Two were instructor pilots. Flight experience varied from about 4000 hr in many types of aircraft, including helicopters, to only about 300 hr primarily in the F-4. The maximum F-4 experience was about 1800 hr.

Pilots were given a fairly comprehensive briefing, including the operation of the DMS and AML, the purpose of the study, methods of data analysis, and general procedures to be followed throughout the experiment. For instance, they were told to request rest periods as needed regardless of the run schedule. There were asked to make at least one nondata run each time upon entering the simulator to allow their eyes to accommodate to the simulator lighting. They were also instructed to tell the computer operator when they were ready to begin data runs.

No particular maneuvers were specified for the pilots to use. They were left entirely to their own resources to devise and use the most effective maneuvers. However, they were told that no simulated weapons would be fired and that runs would not be terminated when a pilot acquired the necessary conditions to fire a particular weapon at the other. Rather, their objective was to acquire and retain the best possible positional advantage relative to their opponent. Within this context, then, certain entries into weapon zones might be examined; however, these would function only to give a measure of the degree of positional advantage.

RESULTS AND DISCUSSION

Several methods of analysis and evaluation were applied to the data. Generally, these were comparisons of computed parameters which quantify various types and degrees of positional advantage attained by the pilots or the AML-controlled airplane during a run. Some statistical tests on these parameters were also made but were of very limited scope and depth. It is important that the reader not attach undue significance to these statistical tests, however. No absolute performance indexes have been found which measure the outcome of one-on-one simulated ACM. The parameters used in this paper should be considered merely as indicators of relative performance. Maneuvering in air combat is too complex and includes too many variables to be measured well by a single index. Thus, a comprehensive statistical analysis of a particular indicator could possibly produce erroneous results. However, it is believed that by considering all of the analyses which will be presented here, a valid assessment of the results can be obtained.

To permit direct comparisons with other data runs, some data were adjusted from the nine pilot-versus-pilot runs that lasted less than 3 min. The adjusted parameters are simply the accumulated times during a run that the pilot was able to remain within certain geometric zones defined by relative headings, range, and the like. They were adjusted by multiplying the observed parameters by the inverse of the actual run length to 180 sec. For example, assume that a run lasts 120 sec and that pilot X accumulates 30 sec of parameters Y. For comparison purposes, the effective accumulated seconds of parameter Y is

$$\frac{180}{120} \times 30 = 45 \text{ sec}$$

Before discussing individual performance indexes, time histories of basic run data will be presented.

Time Histories

From data recorded on magnetic tape, time histories of several airplane state variables, as well as computed geometric relationships between the airplanes, were plotted. Four of these variables that were found to be most descriptive of the ACM engagements are shown plotted for each run in figures 7 to 78. Off-boresight angle λ is the angle between the X body axis of a combatant's airplane and the line of sight to his opponent. If this angle is zero, the combatant is pointing the nose of his airplane directly at the center of gravity of his opponent's airplane. As λ increases, the combatant points farther and farther away from his opponent. The ideal situation for a given pilot, for example, is to have his $\lambda = 0^{\circ}$ while that of his opponent is 180°. The other three variables plotted are Mach number, altitude, and range. Figures 7 to 30 are pilot-versus-pilot runs. Figures 31 to 54 are pilot-versus-AML-control-model runs; and figures 55 to 78 are pilot-versus-AML-performance-model runs. These figures provide a broader perspective of the engagements than do certain signal-variable scoring criteria to be discussed later. They allow the viewer to follow each engagement from beginning to end. He can determine when each combatant had an angular advantage as well as other concurrent aspects of the fight which can influence the meaningfulness of the advantage. Also, certain tactical maneuvers may be observed. For instance, attempts by one pilot to "scrape" the other off by diving toward the ground may be detected in the altitude plots. Likewise, overshoot situations may be detected by observing the Mach plots in conjunction with the range plots.

Several general observations may be made by comparing the data in the various groups (pilot-versus-pilot, pilot-versus-AML-control-model, pilot-versus-AML-performance-model). Pilots appear to sustain higher altitudes and speeds against other pilots than they do against the AML models. The lower altitudes observed in the pilot-versus-AML runs were often critical for maneuvering. That is, many otherwise optional maneuvers were no longer available because of the low altitude. The longest endured critically low altitudes are more noticeable in the pilot-versus-AML-performance-model group.

Comparisons of the λ plots of the two AML models indicate that the control model was generally able to achieve a more desirable angular relationship against the human pilots. There are also indications that the control model has superior low-altitude maneuvering capability. These data have been presented at this point in the discussion of results to provide the raw results upon which many of the analyses to follow are derived.

Time on Offense With Advantage

The most often used parameter to evaluate the results of engagements in the DMS is time on offense with advantage (TOA). It is simply the accumulated time that one airplane is able to keep its opponent in front of its wing line and simultaneously to remain behind the opponent's wing line. Although this parameter covers a wide range of conditions from close tracking to near parallel flight at all ranges, it still seems to be a very good indicator of relative maneuvering performance. Many DMS studies attest to this fact.

Figure 79 is a bar chart showing the average TOA acquired by each pilot when flying against the other three pilots. The individual-run data are presented in table I.

Figure 80 is a bar chart comparing the individual TOA scores of each pilot with those of the performance model against him. The mean TOA of all pilots is also shown for comparison with the mean TOA of AML. Figure 81 presents the same information for the AML control model.

Kolmogorov-Smirnov tests for normality were applied to the data of figures 80 and 81. From these, it was concluded that the data could be assumed normal, permitting the use of t-tests to determine whether there are significant differences between the means of certain data groups. Overall pilot scores as well as those of individual pilots were compared with corresponding scores of the AML models. The results of these comparisons, including the individual TOA scores from which they were derived, are summarized in table II.

The following observations are noted:

1. For pilot-versus-AML-performance-model runs -

   The mean pilot TOA is significantly less than the mean TOA of the AML (dotted lines of fig. 80).

   The individual mean TOA of pilots C and E are significantly less than the corresponding ones of the AML.

2. For pilot-versus-AML-control-model runs -

   The mean pilot TOA is significantly less than the mean TOA of the AML (dotted lines of fig. 81).

   The individual mean TOA of all pilots except pilot E are significantly less than the corresponding ones for the AML.

3. The mean TOA of the pilots is approximately the same against both AML models. The mean TOA of the control model is much greater than that of the

performance model and differs significantly from it (student's t) at the 95-percent confidence level.

4. In only one comparison did a pilot TOA exceed that of the AML against him. Pilot D was able to accomplish this against the performance model, but the confidence level of the significance of the score difference is only 60 percent.

As previously stated, clear-cut win-loss criteria for simulated ACM engagements simply do not exist. Even so, it was decided that some such evaluation on a run-by-run basis might provide an enlightening alternative view of the data. Thus, a set of criteria believed reasonable, although arbitrary, was defined in terms of TOA scores to permit this evaluation. To win a run, a combatant had to have acquired at least 20 sec of TOA and at least twice as much TOA as his opponent. All other runs were considered draws. Using these criteria, it was determined that the control model won 17 runs, tied 5 and lost 2; and the performance model won 12 runs, tied 8, and lost 4.

AML SCORE

Another parameter often used to analyze DMS results is called adaptive-maneuvering-logic score (AMLS). The AMLS is computed simply by answering the following questions just as the AML does to make maneuvering decisions. The

	Answers	
	Yes	No
1. Is opponent in front of attacker?	1	0
2. Is attacker behind opponent?	1	0
3. Can attacker see opponent?	1	0
4. Is opponent unable to see attacker?	1	0
5. Is attacker in certain cone behind opponent?	1	0
6. Is opponent not within certain cone behind attacker?	1	0
7. Can attacker fire at opponent?	1	0
8. Can opponent not fire at attacker?	1	0
9. Is attacker closing on opponent?	1	0
10. Is attacker's line-of-sight angle less than 60°?	1	0
11. Is attacker's line-of-sight angle decreasing?	1	0
MAXIMUM AND MINIMUM SCORES	11	0

questions are evaluated every 0.5 sec of each run and averaged for each adversary. The value of the AMLS parameter then ranges from 0 to 11. Note that this set of questions is smaller than the set on page 7 because it represents an earlier version of the AML maneuver-selection criteria that was current at the time the DMS postanalysis programs were written. The parameter generally varies through a much narrower range than its possible extremes. Typically, its values are in the range of 4 to 6. Thus, very small changes can result from very large changes in maneuvering performance. An important advantage that the AMLS enjoys over TOA is that it accounts for many more aspects of the maneuver process than does TOA. On the other hand, the user has greater difficulty visualizing what is being measured as well as deciding what level of incremental change in the index is significant. Experience has shown that differences of 0.5 or greater generally occur in runs having large performance differences between opponents.

Figure 82 presents results for pilots flying against each other. It corresponds to the TOA data of figure 79. Data for individual runs are presented in table I.

Figures 83 and 84 are bar charts presenting individual comparisons of pilot AMLS values with those of the performance model and control model, respectively. These correspond to figures 80 and 81, respectively, which show TOA scores.

As with the TOA data, the AMLS data were tested using Kolmogorov-Smirnov tests. The student's t was used to test both overall and individual pilot differences between pilot-AMLS means and those of the AML. Table III contains these results.

The following observations are cited:

1. Both AML models achieved significantly greater overall mean AML scores than did the pilots against them.

2. The mean differences between the AML scores of the pilots and those of the opposing AML model were computed for the data of figures 83 and 84. The mean difference for the control-model data was found to be greater than that for the performance-model data, the difference being significant at the 85-percent confidence level using the t-test.

3. Only pilot E achieved a higher score than AML against him in the control-model runs. This difference was found to be significant at only a 55-percent confidence level, however.

4. Only pilot D achieved a higher score than the AML against him for the performance-model runs. Likewise, this difference was significant only at a 60-percent confidence level.

Missile and Gun Zones

In order to obtain additional insight into the degree of relative maneuvering advantage achieved by one DMS opponent over another, simulator runs are often analyzed to determine the time a pilot entered a defined weapon zone and how long he remained there. The zones used seldom bear more than a token relationship to any existing weapon, as is the case for all zone analysis performed in this paper. For this study, three zones were examined. A pilot was considered to have satisfied the parameters for entry into missile A zone if he reduced his off-boresight angle to less than 40° and maintained his range between 0.2096 km and 5.4864 km. Likewise, he entered missile B zone when his off-boresight angle was less than 20° and the range was between 0.609612 km and 3.6576 km. To enter the gun zone, a pilot's off-boresight angle had to be less than 10° while that of his opponent was greater than 120° and the range less than 0.91218 km. As can be seen, the difficulty of achieving these zones increases greatly from A to B to the gun zone.

Table IV contains the time of first entry and the duration of retention of each of these zones for each data run, as well as averages of these times. Figures 85 to 96 present most of the data of table IV in bar-graph form. In figures 85 to 88, the common opponent referred to is a control group consisting of the four human pilots. The control group was reduced to three pilots to obtain data for an individual human pilot since he obviously did not fly against himself. Thus, the common opponent for AML was four pilots. The common opponent for each pilot was the three other pilots. The reader is cautioned, in examining this analysis, that acquiring any of these zones may not necessarily have been the pilot's objective. Pilots were not instructed to seek these zones nor are the AML goals tailored specifically toward them. In fact, maneuvering to acquire the zones in the short term may be counterproductive to attaining a more secure long-term advantage. It is believed, in general, however, that rapid acquisition of these zones is consistent with getting and keeping the greatest positional advantage for the most time.

Some general characteristics and trends may be observed in the zone data of table IV. Generalizations will be grouped to assess: (1) how well pilots did against each other and against the AML models, (2) how well the AML models did against the pilots, and (3) how well the AML models did relative to one another.

Pilots:

1. Pilots were able to first enter missile A zone against each other and against the control model in about the same amount of time.

2. Pilots were able to acquire missile B zone against both AML models much sooner than they were against each other.

3. Pilots were able to remain in missile A zone against both of the AML models for approximately the same amount of time. Likewise, they were able to remain in missile B zone against both models for another duration of time approximately equal for both models. But they were able to remain in these same zones somewhat longer against other pilots.

4. Pilots were able to enter the gun zone against each other in 58.33 percent of the runs. They made entries against the control model in only 12.5 per-

cent of the runs and against the performance model in only 4.2 percent of the runs.

AML models:

1. Both AML models were able to acquire both missile zones much sooner than pilots were able to acquire these same zones against each other or against either AML model.

2. Both AML models were able to remain in both missile zones much longer than pilots were able to remain in these same zones against each other or against either AML model.

3. The control model made entries into the gun zone in 12.5 percent of the runs.

4. The performance model made gun-zone entries in 8.34 percent of the runs.

AML models relative to one another:

1. The control model enters missile A zone slightly sooner against pilots than the performance model does and remains in both missile zones longer.

2. The performance model enters missile B zone against pilots much sooner than the control model does.

3. Pilots enter both missile zones much sooner against the control model than they do against the performance model.

4. Pilots remain in both missile zones somewhat longer against the performance model than against the control model.

5. Bearing in mind that there were very few gun-zone entries by either pilots or AML against each other, out of the number of runs made, pilots made three times more entries against the control model than they made against the performance model, and the control model made three to two more entries against pilots than the performance model did.

Assessment of Results

This study has addressed two primary questions:

1. How well does the AML perform against current U.S. fighter pilots?

2. How do the two types of AML models compare with one another?

The performance of the AML models against human pilots was impressive, indeed. This was especially true of the control model. The same methods generally used to analyze the results of DMS studies were applied to the data from this study. In each analysis, the result was the same. The AML models clearly exhibited superior maneuvering. Even before detailed analyses of the data began, the result was obvious from observations of the runs as they took place.

The only real difficulty in addressing the question of how well the AML models did against the pilots was determining the amount by which the AML models won. The usual methods of analyzing DMS data are generally considered more applicable to determining trends in results than to determining the absolute magnitudes of relative performance. Thus, this report simply concludes that the performance of the AML models was far superior to that of the pilots.

In all fairness to these pilots, however, the AML did not win all of the runs. Furthermore, there was a great deal of variation in pilot performance. Not only were some individual runs won by pilots, but there were even cases in which an individual pilot either on the average won his runs against a given AML model or came very close. For instance, figures 80 and 83 show that pilot D defeated the performance model both on the basis of TOA and AMLS. However, figures 81 and 84 show that pilot D did very poorly against the control model with the same measures. Likewise, pilot E was only slightly inferior to the control model on the basis of TOA and was superior on the basis of AMLS. Conversely, he was substantially inferior to the performance model on both bases. Zone data (table IV) show similar trends for both these cases.

Before discussing the relative performances of the two AML models, perhaps a better understanding of the data analysis in general can be achieved by considering the apparent fact that the character of engagements between human pilots and AML models is different from that between human pilots only. Against the AML models, pilots produced measures of performance that were less variable than those they produced against each other. They much less frequently gained positions of extreme advantage against the AML models than they did against each other. But it is also true that the AML models seldom achieved the most desirable positions of relative advantage against the pilots. (See gun-zone data.) Looking at the question matrix on page 7, it can be seen that the AML gives about equal weight to defense and offense. Note that for most questions relating to an offensive advantage, there is a corresponding question relating to whether the opponent will gain that same offensive advantage. The structure of this question matrix, then, causes the AML to tend to choose maneuvers that are conservative. It will risk giving up one aspect of positional advantage only with the reasonable assurance of gaining at least as much offsetting advantage. Within the spectrum of maneuvers available to the AML, the option to run away does not exist. This is an aggressive constraint. Except for this constraint, then, the AML behavior seems to have defensive leanings.

The human pilot is much less constrained. He can do long-range, as well as short-range, planning. He can remember weaknesses of various opponents and structure tactics from the very beginning of a fight to capitalize upon them. He can also use such tactics as hit and run. On the other hand, pilots are sometimes at a disadvantage because of an element of inflexibility that results from rigid tactical philosophies. The possible disadvantages of a particular tactical philosophy may not readily show up as long as both opponents employ it and thereby neutralize the effects of its weaknesses. Along with the pilot's larger array of optional maneuvers go more ways to make disastrous mistakes and to capitalize on those of others. Thus, often pilots maneuver to the most extreme positions of relative advantage against each other. On the other hand, against the AML, the human pilot's maneuver choices become more limited because of the necessity to counter the AML narrower range of maneuvers. Being a deterministic tactical philosophy, the AML makes no mistakes although the maneuver it chooses may not necessarily be effective. The point is the AML is consistent, does not give up, continuously implements sound ground-avoidance and anti-departure measures, and uses reasonably good one-on-one air-combat maneuvers. An opponent possessing those characteristics has a tremendous psychological advantage in that it does not afford the opposing pilot many mistakes.

Even when a pilot is able to achieve a fairly good positional advantage over the AML, it is difficult for him to carry through to a good tracking solution because the AML models are extremely difficult to track and easy to overshoot. Likewise, perhaps because of their conservative maneuvering, the AML models also seem to have difficulty maintaining extremes of positional advantage against pilots.

Formulating a fair assessment of the relative maneuvering effectiveness of the two AML models against human pilots is difficult. Part of the assessment can, of course, be done in a straightforward manner since both models were operated against human pilots as a common opponent. Examinations of figures 79 to 96 and the question set on page 15 reveal that, in an overall sense, all three primary measures of performance (TOA, AMLS, and zone analyses) indicate that the control model outmaneuvered the pilots by a much greater difference than the performance model did. What is not known is how much of this result was produced by the order in which these models were flown against the pilots. However, the fact that the control model was presented to the pilots first and also defeated them by a much greater margin has positive implications. Even if the learning effects were large, the relative performance adjusted for learning effects would still probably show the control model to be at least as good as the performance model. As long as the control model performs at least as well as the performance model, it seems reasonable to assume that the performance model has not been "cheating." Any maneuvers that the performance model may have used against pilots which the pilots could not also use would not have made the performance model win by any greater amount than the "uncheating" control model would have won by anyway.

Some evidence exists that pilot learning contributed to the performance difference between the two models. Since both AML models are driven by identical maneuver logic, their performance against the same opponent should differ only to the extent that the ability of the two models to implement control commands differs. It seems reasonable to expect the performance model to execute control commands faster and more precisely, especially under low-speed conditions, because its attitude-control authority is constant. Its modeling scheme does not account for the influence of dynamic pressure on control authority. Only at high speeds should the control model have superior attitude control. Of course, one would expect this to produce a result opposite from that obtained.

The fact that the mean pilot TOA was about the same for both models but that the mean AML TOA was much lower for the performance model than for the control model suggests that the pilot's defensive tactics improved by the time the performance-model runs were made.

A comparison of AMLS parameters shows that the pilots' mean score improved from the control-model runs to the performance-model runs while the mean score of the AML models worsened. That both scores changed is to be expected and is consistent with TOA results since AMLS parameters are composite measures of both offense and defense. Although the AMLS parameters indicate that the performance difference between the models is large, it yields little, if any, information about the contribution of learning effects to the difference.

In an attempt to gain further insight into what caused the AML scores to change as they did, the AMLS parameter was slightly modified and recomputed. The objective was to divide the total score into offensive and defensive components to see how the constituents changed. To do this, question 9 of the question set on page 15 was omitted because it did not seem to reasonably fit into either an offensive or defensive classification. The remaining 10 questions were divided into 5 defensive and 5 offensive ones. Offensive and defensive AML scores were computed and tabulated (table V), along with a recomputed AMLS based on the 10 questions.

Offensive:

1. Can attacker fire at opponent?

2. Is opponent in front of attacker?

3. Is attacker behind opponent?

4. Is attacker in certain cone behind opponent?

5. Is attacker's line-of-sight angle less than 60°?

Defensive:

1. Can opponent not fire at attacker?

2. Can attacker see opponent?

3. Is opponent unable to see attacker?

4. Is attacker's line-of-sight angle zero or decreasing?

5. Is opponent not within certain cone behind attacker?

It appears that the defensive AMLS generally varies about some nominal value by only small increments although these variations may be meaningful. The offensive AMLS, on the other hand, undergoes much larger variations.

These results show that the pilots were able to improve their offensive AMLS against the performance model relative to the control model by about 8.4 percent while causing the AML offensive score to decrease by 10.7 percent. The increase in pilot offensive score along with the decrease in the AML offensive score from the control-model runs to the performance-model runs reinforces the idea that the primary difference between outcomes of the runs against the two models was caused by the pilots' learning how to neutralize some of the AML offense. The increase in the pilot's offensive score may be accounted for by the fact that, in some runs, the pilots were able to defend themselves well enough to allow implementation of some successful offensive maneuvering.

Although every way that the data have been analyzed shows the control model to have done at least somewhat better than the performance model, it is felt that the data available from this study are insufficient to conclude that either model possesses inherently superior maneuvering performance with respect to the other.

If, in fact, neither model has any real maneuvering advantage over the other, a very good situation exists. Much simpler airplane models requiring only performance data may be quickly assembled for use in air-combat simulation studies or pilot training. Control models will, however, continue to benefit from enhanced pilot confidence and a sense of fair treatment. Care should be exercised in assuming that the results of this study apply to any other simulated airplanes. The relative maneuvering performance of the two different models may be very different for airplanes other than the F-4.

PILOT COMMENTS

During the course of this study and immediately following its completion, several comments were extracted from discussions in which the pilots gave their opinions of the AML programs. The pilots' opinions were directed toward the overall operation of the real-time programs, the individual characteristics of each program, and how the programs compare with each other.

The pilots were in mutual agreement in their opinions on the overall operation of the AML programs. They felt that the AML had tremendous potential as a training aide. They felt it could increase the proficiency of the pilots since it was always aggressive and appeared to do the right things. However, the pilots were of the opinion that the AML did not always utilize the full capability of the controlled airplane at low altitude. In addition, they all believed that the AML did not adequately take advantage of opportunities to improve its angular advantage in many situations. It is believed these weaknesses can be improved with refined low-altitude tactics and with more accurate predictions of the relative state between the controlled airplane and its opponent.

In discussing the individual characteristics of each program, the pilots noted that the control-model program was more likely to work the vertical whereas the performance-model program stayed low and tended to minimize its vertical maneuvering. They felt that the control-model program performed more rolling-type maneuvers than the performance model. One pilot thought that the performance model was unable to perform many of its selected roll maneuvers because of its low altitude. A complaint was registered against the performance-model program. Two of the pilots felt that the performance model occasionally made unrealistic changes in attitude. This could possibly be caused by the incomplete modeling of the airplane's body rates. The other two pilots did not express their opinions on this subject; however, all the pilots agreed that the control model was smoother than the performance model in attitude changes.

The pilots had varying opinions as to which of the two models was the better opponent. One pilot said it was difficult for him to say. Two of the pilots, however, made more definite statements on the subject. One said that the performance model was better because it was harder to predict and appeared to have better control of the fight. The other pilot felt that the control model was easier to predict and would, therefore, allow him to enjoy more success in combating it. According to the opinion of this last pilot, one could deduce that the overall performances of the two models were about equal. He stated that the control model was more difficult to stay behind than the performance model; however, it was more difficult to get behind the performance model.

FUTURE APPLICATIONS

It is recommended that several areas of research be pursued with the AML. In order to continue to improve the tactical logic, the capability of riding in the AML-controlled airplane needs to be implemented. All that is required is to drive the display systems in the second DMS sphere. This simple task would permit fighter pilots to observe the functioning of the AML from two points of view, thus supplying them with a much broader insight into the strengths and weaknesses of the logic. This information could be supplied to engineers who would use it to improve the AML.

Through advanced displays, the AML could provide suggested maneuvers to fighter pilots. The AML could even assume control of a fighter airplane in emergencies such as complete loss of pilot consciousness during sustained high g maneuvering.

The AML might be used to guide remotely piloted vehicles that act as wingmen for fighter airplanes. Studies need to be done to assess the most effective ways of employing vehicles of this type and to determine how the human pilot would coordinate and communicate with such partners.

The principles of the AML need to be extended to the multiaircraft environment. Here one might envision a two-tier logical process. Rather than evaluate maneuvers against only one airplane, it would evaluate a set of maneuvers for each of n hostile airplanes, choosing the most effective to be used against each. These n chosen maneuvers would then be reevaluated on an overall level, selecting the one which exposes the AML airplane to the least threat from n hostile airplanes and which, in addition, provides the greatest opportunity for aggressive activity. Furthermore, if more than one AML partner is present, the maneuvers could be assessed on an even higher (third) level, allowing one AML-controlled airplane to come to the aid of another.

CONCLUDING REMARKS

A digital-computer program known as adaptive maneuvering logic (AML) has evolved from a batch-processing program driving greatly simplified airplane math models in interactive air-combat maneuvers against each other to a highly refined real-time program driving a complex math-modeled F-4 airplane in successful, interactive, simulated air-combat maneuvers against skilled human pilots. If the pilots in this study had encountered, for the first time, real-world hostile airplanes controlled by a logic that performs even close to as well as the AML, they would have suffered near total defeat. Of course, many problems would have to be solved to implement the AML in real-world airplanes. However, the technology to solve these problems will soon be available if it is not already. Three primary technical problems must be overcome. First, sensors must be developed that are capable of determining with spherical coverage the relative position of the opponent in space. Although the present AML programs use perfect sensor information, they probably can perform well with much less accurate information. Studies need to be made to assess this requirement. Second, the airplane would need computers with sufficient capacity to perform the AML functions. Again, the magnitude of this requirement has not been determined. The requirements would be not nearly so great, however, as those presently to drive the DMS-AML program, which must carry out many more functions than just AML computations. Third, the AML now controls its airplane in an idealized aerodynamic environment. There are no winds, no gusts, and the like, and the airplane model obeys exact equations of motion. The control system would have to be reconfigured to function in a real-world environment.

Although not proven by this study, the results indicate that performance models which are much more readily programmed and which require fewer computations than control models may be sufficient for many applications of the AML. This study has also greatly enhanced confidence in the results obtained from earlier studies that used performance models.

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APPENDIX A

PERFORMANCE-MODEL MODIFICATIONS

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Appendix A covers modifications made to the real-time and batch AML performance-model programs. It should be noted that this appendix does not cover all the changes made to the original version of the AML. Instead, it primarily covers the major changes that were made after the contractor reports of references 1 and 2. Many other changes such as plotting capabilities, printout, minor logical manipulations, and program sequencing are not discussed.

The modifications are discussed alphabetically with respect to the subroutine that contains them even though some are not directly applicable to the basic function of the subroutine. The discussions may appear brief since no attempt was made to cover previously published material. Therefore, it is necessary for the reader to have a good understanding of references 1 and 2 before he can fully comprehend the meaning and impact of some of the changes. A current program listing would also be a valuable tool when reviewing the changes. The AML computer programs LAR-12301 and LAR-12553 are available from COSMIC, 112 Barrow Hall, University of Georgia, Athens, GA 30602.

Each individual change made to the AML programs was verified in either the real-time or batch mode, and generally was verified by both. Evaluation of the results revealed that most changes improved the AML capability.

Subroutine AERF4

Although subroutine AERF4 retains the same name used in previous versions of the AML programs, the interpolation intervals and variable output have been reconstructed. The subroutine now performs a linear interpolation and outputs the variables given in the table on the following page.

With the exception of the thrust variables, the variables listed are either new or their data arrays have been expanded or modified to allow program consistency with airplane simulation programs on the Langley differential maneuvering simulator (DMS). The new variables are maximum and sustained lift coefficients, corner velocity, and angle of attack. The corner velocity is the Mach number at which the controlled airplane can achieve its highest turn rate.

The tables of maximum and sustained lift coefficient were installed in AERF4 to replace the tables of maximum and sustained load factor. The storage interval, along with the linear interpolation, had caused excessive drag, especially in the Mach regime between 0. and 0.5. In this regime, load-factor data were stored at Mach numbers of 0.2 and 0.5. Load factor was held constant below $M = 0.2$ and computed by linear interpolation between Mach numbers of 0.2 and 0.5. It was discovered that by holding the load factor constant at

Variable	FORTRAN name	Function of -
Military thrust	TMILX	h, M
Afterburner thrust	TABX	h, M
Idle thrust	TIDLEX	h, M
Speed-brake drag	CDSBX	M
Corner velocity	CORVX	h
Dive recovery angle	RECANX	h, M
Maximum lift coefficient	TCLMX	h, M
Sustained lift coefficient	TCLSX	h, M
Coefficient of drag	CDX	C_L, M
Angle of attack	ALFATX	C_L, M

M = 0.2, incorrect lift coefficients C_L were computed and used in the table lookup for drag. The C_L used in the table lookup was computed by the following equation:

$$C_L = \frac{(W)(\text{Load factor})}{\bar{q}S}$$

Since $\bar{q}$ decreased with decreasing Mach number while load factor, W, and S remained constant below M = 0.2, C_L increased, which caused drag to increase (C_D increases with C_L). An atttempt was made to correct this problem by computing load factors between M = 0. and M = 0.2 with the same linear interpolation scheme that is used to compute load factors between M = 0.2 and M = 0.5. However, this linear interpolation still did not provide the required accuracy. Ultimately, the load-factor tables were replaced with tables of lift coefficients. The value of C_L was assumed to remain constant below M = 0.2. This change has proven quite satisfactory.

The corner velocity, which was incorporated into this subroutine, is tabulated as a function of altitude and is used by the throttle-control subroutine in determining the throttle setting during normal maneuvering conditions. The throttle logic sets the throttle position to idle, military, or afterburner thrust in order to maintain the designated corner velocity. Consequently, the airplane's speed control is aimed at a level near that at which it can achieve its highest turn rate.

The table lookup for α as a function of C_L and M replaced the α computation, which was based on a linear relationship between C_L and α by

$$\alpha = \frac{C_L}{C_{L_\alpha}}$$

with C_{L_α} being a function of Mach and altitude. This computation, due to the linear assumption, caused incorrect values for α at high C_L and consequently created a misalinement problem in the body axes of the controlled airplane. The tabulated values of α as a function of C_L and M not only eliminate the linear assumptions but also provide a better definition of α over a broader regime.

Subroutine EQMOTT

EQMOTT is one of the more important subroutines contained in the performance versions of the AML programs. It has the responsibility of executing the selected maneuvers. Force and attitude equations are driven by its controlled bank, load factor, and thrust designations until the desired situation is achieved. Digital filtering is provided each cycle for the rotational rates of the controlled airplane's body axes. This smooths the attitude transition of the controlled airplane when it is commanded to change its maneuver plane.

Several modifications were made to this subroutine to enhance the simulated flight characteristics of the controlled airplane. The subroutine is now more effective in executing the selected maneuvers, which increases the overall performance of the maneuver logic. Because of the length of the modifications and the involvement of the logic, only the basic concepts of the changes and their contributions to the performance or realism will be discussed.

Computations of aerodynamic quantities and roll angle.- These computations pertain primarily to the transition mode in which the controlled airplane rolls from one maneuver plane to a new commanded plane. Prior to modification, the magnitude of lift, angle of attack, drag, and thrust was held constant during transitions between maneuver planes. This reduced the validity of the model and created unnecessary discrepancies between the Euler angles of the maneuver plane and the Euler angles of the controlled airplane body axes. These discrepancies prevented the maneuver logic from selecting the best maneuver for the airplane. In order to correct this problem, the flow of the subroutine was rearranged. The computations of the previously mentioned quantities are currently performed during every iteration.

The bank-angle computation, which is also performed during the transition mode, currently updates the basic roll-angle command by the amount that the controlled airplane rolled during the previous program iteration. Previously, maneuver-plane transitions were performed by driving the attitude equations with a constant roll rate for a computed number of program iterations. The number of program iterations required for a particular transition was dependent on the magnitude of the desired roll-angle change and on the maximum roll rate of the controlled airplane. This technique created maneuver-plane errors when the airplane was unable to achieve the commanded roll angle. The present roll transition process drives the attitude equations to null the error between the commanded roll angle and the airplane's current roll angle.

C_L filter.- Jerky and erratic motions had been noticeable in the real-time flight trajectories of the controlled airplane when it was required to perform a maneuver with a much higher or much lower C_L than the previous one. It was determined that maneuvers of this nature caused large instantaneous changes in the controlled airplane's loading, thus changing its state in an unrealistic manner. To correct this problem, logic for filtering the lift coefficient was developed and installed in EQMOTT.

The basic concept of the filter is to increase or decrease the C_L of the previous maneuver by small constant increments until the required C_L is reached. This smooths the flight trajectory by eliminating the instantaneous load changes.

Situation energy management.- The energy-management function slightly digresses from the basic function of EQMOTT. It is part of the tactics logic; however, due to the accessability of the required variables, the logic was installed in EQMOTT.

The energy-management logic reduces the magnitude of a commanded load factor for certain situations that occur after a near head-on pass. The magnitude of the load-factor reduction is dependent on the type of airplane that is modeled. However, in most cases, the level will be between what the airplane can sustain and its maximum capability for a given condition. This allows the airplane better management of its energy and at the same time provides a positional situation which is as good as the situation achieved when the airplane utilized its full load-factor capability.

After a near head-on pass, the commanded load factor is reduced (1) when the two airplanes have moderately large separations without the opposing airplane having a small λ and (2) when the airplanes' separation is not large, but they have large separation rates and large values of λ.

"Over-the-top" problem.- For some time, it was observed that the AML performance model occasionally had difficulty completing vertical loops. It would appear to lose interaction with the opponent and roll in a confused, unordered fashion, often resulting in a hammerhead stall. The airplane just could not get "over the top." If the plane of the loop was inclined slightly from the vertical, however, the problem was not apparent.

The mechanics of the over-the-top problem are involved and difficult to discuss with reasonable brevity. Especially with the performance model, considerable background familiarity with the way in which the equations of motion are modeled is required to fully understand the problem and its solution. For more complete information, the reader is referred to pages 19 through 26 of reference 2, as well as to an actual current FORTRAN listing of subroutine EQMOTT.

A very brief background will be presented here, but it is considered minimal, at best. Recall that the performance model utilizes a number of approximations to characterize its equations of motion. It must do this because it has no means of implementing commands from the logic by deflecting control surfaces. It simply assumes that the commanded bank angle and load factor can be achieved and essentially places the airplane in the commanded attitude. To maintain a degree of reality and continuity in the attitude motion, rotations about the body axes are driven by commanded body rates that are filtered and limited. As has already been discussed, the angle-of-attack change is smoothed indirectly by filtering changes in lift coefficient. In all computations that are made to drive the airplane's attitude, the angle of sideslip is considered zero. This does not mean that it actually is zero, only that it is not accounted for in determining attitude driving rates.

Since the velocity vector is very accessible, it provides a good reference on which to base many computations. Thus, an axis system called the moving-maneuver-plane (MMP) axis system is defined with the velocity vector serving as its X-axis. Rotations made about the velocity vector by using the "right-hand rule" define maneuver planes in which the airplane is controlled to fly. During transitions from one commanded bank angle to another, the airplane is assumed to fly in intervening "instantaneous maneuver planes," with its wings perpendicular to them. The transition continues until the maneuver plane corresponding to the new commanded bank is reached. Both the X-axis and the Z-axis of the MMP system lie in the maneuver plane. In general, the axis system of airplane body relates to the maneuver plane in exactly the same way. That is, its X- and Z-axes are also contained by the maneuver plane. Since the sideslip is assumed to be zero, the velocity vector and the X body axis are always separated by α. Lift and drag forces are set up directly in the MMP with thrust forces transformed to it by α. The direction cosines of the MMP axis system are used to transform the forces to the inertial axis system.

Concentrating on the rolling process, now follow through a cycle to see how the driving body rates are determined. To effect the roll maneuver, the airplane is assumed to roll at some fixed rate. From this, a fixed number of degrees of roll per iteration are computed. This incremental change in bank angle then becomes the goal or desired change during the current program iteration. Since the incremental bank of the airplane will be the same as that of the instantaneous maneuver plane, a unit vector along the X body axis may readily be transformed to the MMP system. It will project along the X and Z MMP axes by the $\cos\alpha$ and $\sin\alpha$, respectively. The value of α is determined from a table for the current conditions of Mach number and lift coefficient. The direction cosines of the MMP system are used to ultimately determine the inertial components of the unit vector. These are then used to compute the Euler angles (ψ and θ) of the attitude to which it is desired to drive the body during the current program iteration. From these desired Euler angles, the known present ones, and the iteration rate, the required Euler rates ($\dot{\psi}$, $\dot{\theta}$, and $\dot{\phi}$) are computed. They are transformed to body rates (p, q, and r), filtered, and limited. Finally, the body rates are used to update body quaternions which yield the airplane's new actual attitude at the end of the current iteration.

The scheme functions well as long as the Euler roll angles of the MMP and the body are approximately the same. It should be noted, however, that although an incremental roll about the X-axis of the MMP is exactly the same as that required about the X body axis of the airplane in order to maintain its wings perpendicular to the maneuver plane, the corresponding Euler roll angles of the MMP and the airplane body are not equal in the general case. They may both legitimately be zero, or they may both legitimately be $\pm 180^\circ$. Otherwise, they are equal only if the angle of attack is zero. The performance model, however, makes the assumption that they are always equal. The assumption is a good approximation throughout most of the flight regime. Although the accuracy of the approximation decreases as α increases, α never exceeds 30°. Thus, by itself, it creates no great problems. The accuracy of the approximation also decreases as the magnitude of the pitch angle of the velocity vector increases. Severe breakdowns of the approximation take place if both the velocity vector and the X body axis are contained by a vertical or near vertical plane (perpendicular to the X-Y inertial plane) and the pitch angle of the velocity vector summed with the angle of attack exceeds 90°. A similar situation occurs in the vicinity of -90°. Consider, for example, a vertical-plane situation in which both the velocity vector and the X body axis have positive pitch angles, with the pitch angle of the X body axis being the greater. The Euler roll angles of both the MMP and the body axis system must be zero. If the airplane continues to pitch upward, it will pass through a pitch angle of $+90^{\circ}$. When it does, its body-axis roll angle should change from 0° to 180° instantaneously, but the roll angle of the MMP obviously should remain zero until the velocity vector transitions through 90°. Clearly, this is the worst possible conflict between what should happen and the approximation of equal Euler roll angles.

As previously mentioned in the discussion of this subroutine, two different control modes operate within the routine. In the maneuver mode, the objective is to sustain planar flight once the commanded maneuver plane has been reached. The desired roll angle of the body axis is determined from the bank of the MMP, which is the reference to be maintained. If the geometric conditions are such that the approximation of equal Euler angles breaks down, the body-axis roll is driven in a meaningless way. If the same conditions exist in the transition mode which drives the body from one commanded maneuver plane to another, an incorrect approximation is made to determine the MMP Euler roll. Thus, in one case, the bank of the MMP is correct, but the corresponding bank of the airplane is not, and vice versa. Both cases result in unrealistic dynamic behavior. The forces acting on the airplane are improperly oriented and/or the attitude of the airplane is driven in an improper manner.

The vertical-plane example cited is a maneuver-mode case. When the body axis passes through $+90^{\circ}$, the quaternions recognize this and correctly switch the body roll to $\pm 180^{\circ}$. The approximation of equal Euler angles, however, requires that body roll be equal to the MMP roll which is still zero. Thus, large body rates are imposed upon the quaternions to accomplish this.

In an effort to reduce the problem, a "fix" was devised for the most severe cases. Specifically, the vertical-plane case was attacked. Two conditions identify the vertical-plane problem. The plane is determined to be vertical if a unit vector along the cross product of the X body axis and the velocity vector does not project onto the inertial Z-axis. Secondly, for the equal Euler angle approximation to break down, the body axis and the MMP axis must be on opposite sides of the 90° pitch-angle point. This condition exists if their respective Euler yaw angles differ by 180°. Inexact conditions are applied to the identification of the vertical-plane situation to cause planes inclined slightly to either side of the vertical to be identified and treated in the same manner as the vertical planes are treated.

If these vertical-plane conditions are present, the Euler roll angles are recognized to be different and are assigned corrected values. In addition, no changes in bank-angle commands are permitted until the airplane has maneuvered out of the abnormal condition.

Although this fix has not completely eliminated the problem, it has greatly improved maneuvering effectiveness of the performance model.

The previous over-the-top problem is no longer a noticeable deficiency in the model's dynamic behavior. On the contrary, it is very competitive with smooth, realistic attitude motion. Yet it is believed that further improvement can and should be made by those who use the program in the future.

It should be possible to drop the equal Euler angle approximation entirely and replace it with expressions which give the second required Euler angle in terms of the known one. The attitude of the MMP axis system may be expressed in terms of three Euler rotations $(\bar{\psi},\bar{\theta},\bar{\phi})$ from the inertial axis system. From the MMP system, the body-axis system may be expressed as a fourth rotation α about the MMP Y-axis. Multiplying the four matrices associated with each rotation (beginning with inertial axes), a three-by-three direction cosine matrix locating the airplane's body axes in terms of the inertial axes may be obtained. Individual terms in this matrix may be equated to corresponding terms in the standard three-by-three direction cosine matrix which relates one axis system to another in terms of three standard Euler rotations. Designating the three rotations as simply ψ, θ, and ϕ and considering them to be Euler rotations from the inertial axes to the body axes, the rotation ϕ may be obtained by dividing the second element of the third column by the third element of the same column. The expression obtained is

$$\phi = \tan^{-1}\left[\frac{\cos\bar{\theta}\sin\bar{\phi}}{(-\sin\bar{\theta})\sin\alpha + \cos\bar{\theta}\cos\bar{\phi}\cos\alpha}\right]$$

Manipulating this expression yields the corresponding expression for the Euler bank of the MMP in terms of the Euler bank of the body.

$$\bar{\phi} = \cos^{-1}\left[\frac{-\tan\bar{\theta}\sin\alpha\tan^2\phi\cos\alpha \pm \sqrt{-\tan\phi\tan^2\bar{\theta}\sin^2\alpha + \tan^2\phi\cos\alpha + 1}}{\tan^2\phi\cos^2\alpha + 1}\right]$$

In the maneuver mode, the expression for ϕ should be used. Likewise, in the transition mode, the expression for $\bar{\phi}$ should be used. Some difficulties may be encountered with the sign of the radical in the expression for $\bar{\phi}$ and will require additional logic. However, since it is known that for angles of attack equal to zero, $\bar{\phi}$ must equal ϕ, it can be shown that the positive radical will satisfy this condition for positive values of $\phi \leqq 90^\circ$. For $180^\circ \geqq \phi > 90^\circ$, the negative radical should be used. If ϕ is negative, $\bar{\phi}$ will also be negative. Thus, ϕ should be limited such that $180^\circ \geqq \phi > -180^\circ$. The $|\phi|$ should be substituted into the expression for $\bar{\phi}$. Finally, the computed $\bar{\phi}$ should be given the same sign as ϕ. Similar reasoning may be used to resolve difficulties encountered in computing ϕ from $\bar{\phi}$. Some problems may also still occur with the Euler angles at pitch angles of $\pm 90^{\circ}$, but a fix similar to that in the present program should be able to handle it.

Subroutine EXTRT

Subroutine EXTRT predicts the opponent's position, velocity, and attitude at the end of a preselected time in the future. The technique involves making a polynomial curve fit through the present and two past points along the opponent's flight path. These points are 1 sec apart and represent the opponent's position in three dimensions. Once the polynomials are obtained, the opponent's state variables are extrapolated to a designated time.

It was determined by evaluating real-time and batch-processing data that maneuvering of the AML-controlled airplane is enhanced by making both the opponent's extrapolation time and the controlled airplane's prediction-time variables which are dependent on the relative states of the airplanes. In effect, depending on the values of the times, it can be assumed that this technique can be used to make the controlled airplane either lead, lag, or purely pursue the opponent. Since the lead, lag, and pure-pursuit situations have previously been discussed in the body of this report, they will not be discussed as such here. Instead, the conditions are discussed for changing the extrapolation time and the values obtained. It must be remembered that the controlled airplane's prediction time is varied in conjunction with some of the opponent's extrapolation times. The discussion of the variable prediction-time logic for the controlled airplane is contained in subroutine REACTT.

The values of the opponent's extrapolation time were chosen by evaluating the performance of the AML while varying the extrapolation time in conjunction with various range and relative deviation-angle conditions. A situational type logic controls the various values that can be assigned to the time. The logic keys on range and the deviation angles of the opposing airplane in determining if the extrapolation time is to be changed from its nominal setting. Deviation angle is defined as the angle between the line of sight and the velocity vector of the airplane. Depending on the value of the previous variables, the extrapolation time is allowed to vary between a minimum of 1 sec and a maximum of 4 sec. The 4-sec extrapolation is used for ranges greater than 1524 m and for situations in which the AML has achieved a fairly good tracking solution. The minimum value of 1 sec is selected when the range is below 304.8 m and the opponent has an angular advantage. Once the range increases and the opponent's angular advantage decreases, the extrapolation time is increased to 2 sec. In case none of these situations exist, the extrapolation time retains its nominal setting (1.5 sec).

Subroutine GETRXN

GETRXN uses discrete maneuver-plane rotation increments (ROTNCT) to assign trial maneuver planes for the controlled airplane. ROTNCT is commonly referred to as the angle between maneuver planes. The value of ROTNCT depends on the number of optional maneuver planes (NTILTT) per quadrant. Since the maneuver-plane designations start at zero, the angle between planes is computed as

$$\text{ROTNCT} = \left(\frac{\pi}{2}\right)\Big/(\text{NTILTT} + 1)$$

During evaluations of the real-time control- and performance-model programs, NTILTT was varied in an effort to assess its effect on the maneuvering of the controlled airplane. The nominal value of NTILTT had always been 8, which established 10° between maneuver planes. Performance evaluation showed that the maneuvering capabilities of the controlled airplane were degraded when the angle between maneuver planes was decreased below the nominal value (NTILTT was increased). As the angle was decreased, the trial maneuvers became more clustered about the maneuver currently being performed and about the plane nearest the opponent. Since this situation was undesirable, the angle between maneuver planes was increased in several small increments beyond the nominal setting until a more satisfactory value was determined. This occurred when the angle between maneuver planes was 12.86° (NTILTT = 6). Angles greater than this limited the airplane's capabilities by reducing the number of optional maneuver planes. Smaller angles caused too much clustering.

Subroutine REACTT

REACTT is executed at each decision interval (nominally 1 sec) to determine the most promising maneuver for the controlled airplane and to define the variables required by subroutine EQMOTT for execution of the selected maneuver. It utilizes the output of several other subroutines in accomplishing its purpose. At each decision interval, the opponent's flight path and attitude are extrapolated to a specified time in the future. Next, the controlled airplane's flight path and attitude are predicted for each of the trial maneuvers. The relative geometry between the extrapolated state of the opponent and the computed future state of the controlled airplane is then evaluated. Each maneuver is assigned a value resulting from the evaluation. The maneuver with the highest value is the one selected to be performed next.

The changes made to REACTT range from minor logic manipulations to more complex logical evaluations and computations. For example, the segmentation in the subroutine has been completely eliminated. That is, it no longer requires four iterations of the program for completing the computations in the subroutine. The subroutine is now always completed in one iteration. The incorporation of the AML program on a faster computer made this possible and thus eliminated the delay in command to the controlled airplane.

Currently, the decision interval is not constant. The time between decisions can now be greater than or less than 1 sec, depending on the situation. Dive recovery is one situation which affects it. REACTT contains similar dive-recovery logic to subroutine TRYNXT. Once the altitude of the controlled airplane is below 1066.8 m and its flight-path angle is greater than the recovery angle, a dive-recovery maneuver is selected and the time counter for the standard decision interval is reset. The prevention of crashes between decision intervals is assisted by this logic.

The decision interval time is also affected by the airplane's attitude. As previously discussed in subroutine EQMOTT, there is an over-the-top problem. The airplane retains the previous commanded maneuver as long as this situation exists. This scheme prevents the selection of an improper maneuver and has proven to be very effective in handling the situation.

Several other modifications were incorporated into this subroutine. These modifications are not only more complex than the ones previously discussed, but they are also more pertinent to specific areas of the maneuver selection process. Consequently, they have been categorized and are discussed in the following sections.

Initial maneuver selection.- REACTT saves the opponent's two previous positions for use in the future extrapolation of his position, velocity, and attitude. This presents somewhat of a problem at the beginning of the engagement since the two positions do not exist. Previous versions of the AML programs dealt with this problem by preventing the AML-controlled airplane from selecting a new maneuver for the first 3 sec of the engagement. During this period of time, the opponent's positions were stored and the controlled airplane continued its initial input maneuver, which was generally straight flight. The technique sufficed for head-on initial conditions but was extremely unfavorable for the controlled airplane in some other initial conditions.

Currently, the opponent's previous two positions are computed with the initial velocity components. Naturally, these computations assume that the opponent has been flying along a straight line with constant velocity. However, they permit a maneuver to be selected during the first iteration of the program, thereby enhancing the maneuver logic for all initial conditions.

Undesirable extrapolation detection.- The extrapolation-detection logic identifies relative situations that cause the extrapolation subroutine (EXTRT) to yield undesirable extrapolated variables for the opponent. The problem occurs when the opponent is in the rear hemisphere of the controlled airplane and the controlled airplane in the front hemisphere of the opponent. In this relative situation, it is possible for the AML to extrapolate the opponent's position to a point in front of the AML-controlled airplane. When this occurs, it is not very difficult for the opponent to stay behind since the trial-maneuver selection assumes the opponent is in front. The extrapolation is not in error. The relative velocity is such that the extrapolated range is greater than the range between the two airplanes.

To correct this problem, the actual range between the airplanes is compared with an extrapolated range. If the extrapolated range is greater than the actual range, the opponent's position, velocity, and attitude are not extrapolated. The trial maneuvers are evaluated with respect to the present position, velocity, and attitude of the opponent.

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Variable prediction.- In conjunction with varying the opponent's extrapolation time as discussed in subroutine EXTRT, the capability of varying the prediction time for the controlled airplane was installed in REACTT. Two situations exist for changing the prediction time from its nominal value of 2 sec. The time is changed to 6 sec when the range between the airplanes is greater than 1524 m and an undesirable extrapolation has not been detected. It is also changed to 6 sec for ranges down to a minimum of 304.8 m if the controlled airplane's deviation angle is less than 30° and the opponent's deviation angle is greater than 135°. Increasing the prediction time serves a purpose similar to that of increasing the extrapolation time of the opponent.

Load-factor reducer.- With the exception of the soft-turn and low-energy recovery maneuvers, the AML trial maneuvers command the maximum load-factor capability of the controlled airplane. Consequently, for hard-turning fights, the controlled airplane will sometimes have to resort to low-energy recovery maneuvers, forcing it to relinquish any angular advantage it might have achieved. To help prevent this problem, the selected trial maneuver is now reevaluated to determine if the commanded load factor can be reduced without affecting the value of the maneuver.

The selected trial maneuver is reevaluated when the range between the two airplanes is greater than 1524 m, the controlled airplane is behind the opponent and the opponent is in front of it, straight flight has not been selected, and the controlled airplane is not in a dive recovery. When these conditions exist, two new trial maneuvers are set up, differing from the selected maneuver only in load-factor level. Their load-factor levels are 85 and 80 percent of the commanded load factor, respectively. The new maneuvers are then evaluated and scored by the same process used for all maneuvers. The two are compared with the selected maneuver, and the maneuver with the highest value is selected. If two maneuvers have equal value, the one requiring the lesser load factor is selected.

Subroutine STATET

Subroutine STATET evaluates the relative predicted and extrapolated state variables of the AML-controlled airplane and its opponent and assigns a numerical score for each trial maneuver. The score or value of a particular maneuver is obtained by answering a set of 14 questions covering specific areas and quantities of interest. These include angular relationships, distances, and velocities. The questions and a hypothetical score are shown in the question set on page 7, with the AML-controlled airplane referred to as the attacker. The questions are worded in such a way that they can be answered by either "yes" or "no." The yes answers are assigned a numerical value of 1 and the no answers are assigned 0. Once the evaluation is complete, the answers are summed for a numerical score. The score is returned to the calling subroutine and stored for comparison with the other trial maneuvers.

The question set on page 7 depicts the questions which are currently used by STATET. They differ from the original questions in that one question has been deleted and three questions have been added. The deleted question evaluated the specific energy rate of the controlled airplane. That is, once the controlled airplane's specific energy rate was less than -30.48 m/sec, a value of 0 was assigned to the question. This at times caused straight flight to be selected for the controlled airplane when other optional maneuvers were better for the current situation. The question was removed after real-time evaluation revealed that all the AML-controlled airplanes were able to perform as well and generally better without it.

Three evaluation-type questions were added to STATET in an effort to enhance the maneuver selection process. Two of the questions combine existing questions in the question array to form new questions. For example, looking at the question set on page 7, question 9 was worded so that it will be assigned a value of 1 when questions 1 and 2 are each assigned a value of 1. Likewise, question 12 will be assigned a value of 1 when questions 3 and 4 are each assigned a value of 1. This places more emphasis on situations in which the AML-controlled airplane has a decided advantage over its opponent. The new questions are effective when several of the maneuvers have near equal values, with one or more having values of 1 on questions 1 and 2 and/or 3 and 4. When this occurs, the new questions will insure that one of the maneuvers with values of 1 on questions 1 and 2 and/or 3 and 4 will be selected.

Question 11 was added to the question array to assist in preventing crashes. It keys on predicted altitude of the AML-controlled airplane. For maneuvers that have a predicted altitude of less than 91.44 m, a value of -13 is assigned to the question. Therefore, the highest value these maneuvers can have is 0. When this question is answered yes, a value of 0 is assigned to it so it will not affect the maneuver selection process.

Subroutine THROTLT

Subroutine THROTLT is called each iteration of the AML programs to determine the proper throttle setting for the AML-controlled airplane. The throttle setting is designated by the variable TPOST. TPOST is set equal to 0, 1, and 2 for idle, military, and afterburner thrusts, respectively. Although all the trial maneuvers designate afterburner thrust, this subroutine can change the throttle setting if the AML-controlled airplane's variables and other geometric conditions warrant it.

The logic which defines the situations for changing the throttle setting is completely different from previous versions of the AML programs. An important feature of the present version of the subroutine is that it now uses corner velocity for determining the throttle setting in some situations. The corner velocity, as previously defined in subroutine AERF4, is the Mach number at which the controlled airplane can achieve its maximum turn rate. It is compared with the airplane's Mach number to determine the throttle setting when the range is less than 1828.8 m and neither the AML-controlled airplane nor the opponent has achieved a good tracking solution. The logic is designed to set the throttle to idle, military, or afterburner, depending on the speed of the controlled airplane. If the airplane exceeds its corner velocity by 20 percent, the throttle is set to idle. Likewise, if the airplane is 10 percent below its corner velocity, the throttle is set to afterburner position. Military power is used when the airplane's speed is between the specified levels.

Another section of the throttle logic is designed to prevent the AML-controlled airplane from overshooting the opponent once it achieves a good angular relationship. In this section, a delta range is calculated by using the controlled airplane's total acceleration, range rate, and distance from the opponent. The delta range serves as a prediction of an overshoot situation. If the situation exists, the throttle is set to idle.

The last section of the throttle logic deals with the reverse of the previous situation. It was designed to cause the opponent to overshoot once he achieves a good angular relationship and is close behind the controlled airplane with a high closure rate. Once again, the idle setting is used when this condition exists.

Subroutine TRYNXT

Subroutine TRYNXT sets up trial maneuvers for evaluation at each decision interval in the AML programs. The number of maneuvers can vary between 1 and 10, depending on the state of the AML-controlled airplane and its relative situation with the opponent. The state of the controlled airplane determines the types of maneuvers to be set up. The maneuvers are divided into the categories of dive recovery, low-speed recovery or energy conservation, and normal conditions. Dive recovery and energy conservation have priority over the normal condition maneuvers. They set up trial maneuvers that are designed to either prevent the airplane from crashing or from losing so much energy that it can no longer maneuver effectively. If neither of these conditions exist, the situation is considered to be normal and trial maneuvers are set up based primarily on maneuver-plane rotations that are defined by the controlled airplane's velocity vector and the extrapolated opponent's position.

The current version of this subroutine contains several modifications. The order of priorities for the categories remains unchanged. However, each category contains either improved logical constraints or additional trial maneuvers. The dive-recovery section, first in priority, currently contains fewer maneuvering constraints for the prevention of crashes. The dive angle is not monitored until the controlled airplane flies below 1066.8 m. Below this level, the airplane is commanded to pull up in a vertical plane once its dive angle reaches the maximum angle for recovery. These tests are performed at each decision interval in the program. The same tests are performed in subroutine REACTT to detect crash situations between decision intervals. If one is detected, TRYNXT is called and a dive-recovery maneuver is set up.

The energy-conservation section is another area in which the logical constraints have been improved. The modifications may seem minor upon initial investigation; however, real-time performance evaluation of the controlled models revealed that they are very important to the overall operation of the maneuver logic.

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The energy-conservation section has the second highest priority to dive recovery. Its trial maneuvers are dependent on maximum available load factor and the pitch angle of the velocity vector, the load factor being the more important variable. Once the maximum available load factor, which is computed from the maximum C_L, decreases to specified levels, trial maneuvers are set up which are designed to assist the controlled airplane in regaining energy. The load-factor levels were initially assigned values of 1.5 and 1.0, respectively. Real-time evaluation revealed that these designated levels placed too much restriction on the maneuvering capabilities of the controlled airplane. Currently, the load-factor levels are assigned values of 0.5 and 0.25, respectively. These levels permit a greater degree of maneuvering freedom and at the same time allow the airplane to recover from stall situations.

The energy maneuvers controlled by the velocity-vector pitch angle were redefined in conjunction with the newly specified load-factor levels. Originally the controlled airplane was commanded to continue pulling maximum load in the maneuver plane nearest the opponent if its load factor had fallen below the specified level and the flight-path angle was greater than 80°. It was discovered that the airplane could not always successfully perform this maneuver. In many instances, its energy level became so critical that all positional advantages, if any, were relinquished. This logic has been eliminated.

The final category in which modifications were made to TRYNXT is the normal-condition section. Several trial maneuvers were added to the existing maneuvers in this section. These maneuvers not only increase the maneuvering freedom of the controlled airplane but also refine the maneuver selection process. An example of the refinement is depicted by the utilization of the soft-turn maneuver. This maneuver, as in previous versions of TRYNXT, is a trial maneuver which will approximately result in a trajectory intercepting the opponent at its extrapolated position. The soft-turn maneuver is currently the only maneuver set up for the controlled airplane when its deviation angle is less than 40° and the opponent's deviation angle is greater than 120°. This constraint forces the controlled airplane to perform what is considered the best of the trial maneuvers once it has achieved a fairly good tracking solution.

Four other trial maneuvers were added to TRYNXT for evaluation during normal conditions. Three of the trial maneuvers have their maneuver planes defined in 90° intervals with respect to each other, with the maneuver plane nearest the opponent being the plane of reference. That is, their respective maneuver plane rotations are 90°, 180°, and 270° away from the plane nearest the opponent. These maneuvers prove beneficial once the tactical position of the AML-controlled airplane deteriorates to a level at which all the trial maneuvers have a low value assigned to them. The controlled airplane is often in this situation after a dive recovery or low-energy recovery. Its state variables are such that it cannot achieve much success by performing the other trial maneuvers. These three maneuvers provide what could be considered alternatives in this situation.

The other trial maneuver added to the normal-condition section is a dive-recovery maneuver. This maneuver instructs the controlled airplane to pull up in a vertical plane with maximum load factor. The selection of the maneuver from this section could prevent a critical situation in which the airplane would need more time for recovery. It generally will not be selected from the normal-condition section; however, it is felt that the airplane should have the option of performing this maneuver since crashes have always been somewhat of a problem in the AML programs.

APPENDIX B

REAL-TIME IMPLEMENTATION AND REFINEMENT OF AML CONTROL MODEL

A control system which converts AML commands of bank angle and load factor to appropriate aileron, spoiler, stabilator, and rudder commands was developed for the F-4 airplane (as simulated on the Langley differential manuevering simulator (DMS)) by Decision Science, Inc. (DSI) under contract to Langley Research Center and was delivered in the form of a batch-processing computer program. A more detailed description of this program and its design philosophy may be found in reference 4.

At Langley, a number of program evaluations and refinements have been made. The system's ability to execute many types of very demanding command sequences was studied, along with conditions under which it might be unable to prevent the controlled airplane from departing. As expected, large changes in bank angle at high pitch angles were often either performed at very low roll rates or the airplane departed. To produce more desirable responses, it was decided to use a quasi-sequential scheme of roll and then pitch to effect these maneuvers. This problem and the procedures for handling it will be discusssed in more detail later.

When the Control Data CYBER series 175 computer became available for use with real-time simulations, the control model was interfaced with the basic DMS program. Prior to this time, computing capacity had been insufficient to do it.

The control model was designed to replace, in a modular form and, as nearly as possible, on a one-for-one basis, the performance model already operating in real time. This was done to have the program ready as soon as the new computer became available and to minimize real-time checkout. Because of this, however, the AML-DMS program is not as efficient as it could be. Much tabulated aerodynamic data, as well as routines for solving equations of motion, could be shared with the piloted airplane.

Concurrent with its implementation in real time, the maneuver logic and other AML functions independent of the control system itself were updated to the level of the latest performance-model program. Most of these have already been covered in appendix A and will not be discussed again.

In its first real-time flights, the control model did fly although it often crashed or departed and was of almost no competition to the human pilot. It was only through a long, drawn-out, mostly trial-and-error process in real time that the program was refined to be the super competitor that it is. Observing the real-time operation of the system was the only practical means to gain the needed insight to refine it. Otherwise, major deficiencies remained obscure and difficult to detect although they were often corrected by relatively simple modifications. In this perspective, then, the system designed by DSI was a good one which remains mostly intact. The company did not have access to facilities which could thoroughly exercise the program against a human pilot and in fact, at the time, neither did Langley Research Center.

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Some improvements which pertain strictly to the maneuver logic and not to the functioning of the control system itself were also devised during this time. These were also included in the performance model and are discussed in appendix A.

The same problem which had for so long plagued the performance-model program was present with the control model, though in a somewhat different form. The over-the-top problem was discussed in appendix A. With the control model, much of the problem was eliminated by simply referencing the maneuver-plane axis system to the X body axis of the airplane rather than to the velocity vector. Having a full complement of moment equations, the control model, unlike the performance model, does not depend on velocity-vector-based mathematical approximations to drive its attitude or to determine what its attitude is. Thus, it requires maneuver-plane concepts only to choose new maneuvers. A body-axis-based maneuver-plane system has worked well for this purpose. The primary program changes to make the maneuver-plane—axis-system conversion were made in subroutines REACTT and TRYNXT. In TRYNXT, the rotation about the maneuver plane X-axis to the plane containing the opponent (ROTT) is computed by using body angles rather than velocity-vector angles. Also, in the calls to NORPLN to get maneuver-plane normals, body Euler angles are now used. The subroutine NORPLN has been itself simplified to use these Euler angles directly to compute the direction cosines of the maneuver plane Y-axis. These are equivalent to the required inertial components of the maneuver-plane unit normal.

Although the maneuver-plane—axis-system change allowed the quaternions to do their job without problems of Euler angle incompatibility, a minor problem still remained. When the X body axis (now also the maneuver plane X-axis) transitioned through a pitch angle of 90°, the reference with respect to which the commanded bank was determined changed. The problem was solved simply by evaluating and choosing a new maneuver whenever this occurred. In subroutine GETCOM, the pitch-angle transition is detected by a change of 180° in body yaw between two consecutive program iterations, and a flag is set. This flag signals REACTT to initiate an immediate new maneuver selection by using the new reference.

As previously mentioned, under certain conditions the airplane had very poor roll response, as well as a tendency to depart. In general, these conditions were characterized by a low airplane energy state, high airplane pitch angle, high angle of attack, and a large commanded change in roll angle. The general approach to solving the problem was to trade normal acceleration for increased roll response by using a modified roll-then-pitch sequence to effect commands. Even in the absence of the previously mentioned problems, it may be reasonable to attempt to have roll changes lead (i.e., be completed slightly before) pitch changes. This is especially true where the desired change in roll angle is large and the desired change in pitch angle is positive. If it is assumed that there is only one direction, in terms of a rotation about the airplane's body axis, in which a lift vector of given magnitude should be directed to execute each elemental maneuver, then directing this vector fully along the interim path of bank is probably undesirable. Energy may be wasted and the airplane's path of flight temporarily curved in a direction other than that upon which the maneuver's choice was based. This is particularly true of the AML because of the way it evaluates and selects maneuvers. No consideration is given to transition banking. For evaluation purposes, it is assumed that the airplane's flight path will be planar over the duration of the evaluated maneuver, beginning at the specified bank angle. Thus, lift used before achieving the selected bank angle reduces the validity of the maneuver evaluation logic.

Primarily the modified process of carrying out AML commands was implemented in subroutines AUGCONT, GETCOM, and LOCNTR. Because AUGCONT is an entirely new subroutine, it is included in a more detailed separate section which follows the present one. In GETCOM, provisions were made to reduce the commanded angle of attack during large commanded roll changes without regard for the remaining airplane state variables. No action is taken if the commanded roll change is less than 30°. If it is greater, the angle of attack (consequently the load factor) is reduced in proportion to the amount that the commanded roll change exceeds 30°. The computations which reduced angle of attack for "violent roll maneuvers" in subroutine LOCNTR have been removed. The change in GETCOM is less restrictive but covers the problems previously handled by this logic.

Subroutine AUGCONT

Except for the subroutine AMLVS3 which interfaces the AML control-system model with the basic real-time DMS computer program, the subroutine AUGCONT is the only entirely new subroutine added to the control-system program. The purpose of the routine is to insure that the commanded bank changes will be performed at some minimum roll rate. For a given Mach and altitude condition, the effectiveness of the ailerons and spoilers can generally be increased by lowering the angle of attack. Under certain circumstances, the rudder may also be used to increase roll response. However, care must be taken in the use of the rudder to prevent departures.

Since both load factor and bank angle are essential to air-combat maneuvering, the wisdom of trading normal acceleration for improved roll response may be questioned by some. The philosophy on which this routine is based is that unless the load factor desired is oriented in the proper direction, or very nearly so, it accomplishes very little and may actually have a negative tactical effect.

The trade-off is not always made, but only in circumstances in which roll authority has decreased to a predetermined minimum.

If the desired change in roll is less than 5°, the routine does nothing.

If the desired change is greater than 5°, an estimate of the time t_e required to complete the change (assuming a minimum desired roll rate of 20°/sec) is calculated by

$$t_e = \frac{\phi_c - \phi_p}{20}$$

where ϕ_c is the commanded bank angle and ϕ_p is the present bank angle.

Then assuming the ailerons and spoilers to be deflected to their maximums in a direction to reduce the roll error, the maximum rolling acceleration that they can generate for the present Mach number, altitude, and angle of attack is computed from the following equation:

$$\ddot{\phi} = \frac{\bar{q}Sb}{I_{XX}}\left[\left(C_{l_{\delta_a}}\right)\left(\delta_a\right) + \left(C_{l_{\delta_{sp}}}\right)\left(\delta_{sp}\right)\right]$$

The estimated roll-angle change $\Delta\phi_E$ that would result from using this rolling acceleration over the time t_e is given by

$$\Delta\phi_E = \frac{\ddot{\phi}(t_e)^2}{2} + p(t_e)$$

The estimated roll change is compared with the actual desired roll change $(\phi_c - \phi_p)$. If $\Delta\phi_E$ is greater, no action is taken. Otherwise, the commanded angle of attack is reduced by 5° and $\Delta\phi_E$ is recomputed and again compared with the desired roll change. The process is continued until sufficient rolling acceleration is obtained to produce the desired roll change in time t_e or until the commanded angle of attack has been reduced to zero.

If reducing the angle of attack to zero still does not provide enough roll authority, consideration is given to using the rudder to effect the roll. If both the angle of attack and angle of sideslip are each below 15°, the rudder is deflected to its maximum in the direction to produce the desired roll. This is accomplished by setting a flag which signals the subroutine LACTNR to actually set the rudder deflection.

This routine is executed during every program iteration (1/32 sec). The original angle-of-attack command is restored before entering the routine on successive iterations. Thus, the amount, if any, of angle-of-attack reduction is continuously updated. Likewise, the use of rudder is reevaluated during each iteration.

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TABLE I.- TOA AND AMLS VALUES FOR PILOT-VERSUS-PILOT RUNS

Run	TOA and AMLS values for pilot-versus-pilot runs for -					
	Sphere A			Sphere B		
	Pilot	TOA, sec	AMLS	Pilot	TOA, sec	AMLS
1	C	9	4.2	D	84.	6.2
2	C	0.	3.1	D	146.5	7.6
3	C	38.	5.4	F	12.	4.8
4	C	41.5	5.3	F	19.5	4.8
[a]5	C	8.6	3.9	E	107.3	6.2
6	C	13.	5.	E	19.5	5.2
7	F	23.	4.4	C	94.5	6.0
[a]8	F	.6	3.4	D	118.	7.1
9	F	3.5	3.8	D	98.5	6.7
[a]10	E	43.3	5.8	D	2.1	4.5
11	E	108.5	6.6	C	0.	3.9
[a]12	E	93.	6.3	F	1.7	4.1
13	E	126.	6.8	F	12.5	3.6
14	D	81.5	6.	F	11.5	4.1
15	D	7.0	4.6	F	51.5	5.6
16	D	36.5	5.3	C	17.	5.
17	D	33.	5.4	C	9.5	4.8
[a]18	F	24.3	4.5	E	72.3	5.9
[a]19	D	.53	4.3	E	76.2	6.1
[a]20	D	3.6	4.4	E	65.5	5.9
21	F	104.5	6.5	C	0.	3.7
[a]22	E	101.	6.1	C	2.2	4.2
[a]23	E	106.	6.5	D	10.6	4.1
24	F	11.5	4.8	E	53.	5.4
Mean		42.4	5.1		45.23	5.23
Standard deviation . .		42.3	1.07		44.71	1.11

[a]Data extrapolated.

TABLE II.- TOA DATA AND STATISTICS

(a) Pilot-versus-control-model runs

Pilot	TOA each run, sec	Mean	Standard deviation	Pilot	TOA each run, sec	Mean	Standard deviation	Student's t	Degrees of freedom	Confidence level of mean difference, percent
C	0.			AML	47.					
	0.				68.					
	.5				77.5					
	0.				77.					
	3.5				44.					
	0.	0.67	1.4		82.5	66	16.58	9.62	5	99.5
D	4.0				27.					
	13.5				18.5					
	0.				68.					
	0.				131.5					
	35.5				18.					
	22.	12.5	14.18		39.5	50.42	43.87	2.01	6	95
E	5.5				82.5					
	2.0				32.5					
	3.0				91.5					
	0.				35.					
	112.5				9.5					
	104.5	37.92	54.76		2.5	42.25	37	.16	10	55
F	0.				54.5					
	5.0				95.					
	0.				90.					
	24.				56.5					
	46.5				64.5					
	41.0	19.42	20.89		45.0	67.58	68.58	1.645	6	90
All		17.63	31.32			56.56	31.37	4.3	48	99.5

TABLE II.- Concluded

(b) Pilot-versus-performance-model runs

Pilot	TOA each run, sec	Mean	Standard deviation	Pilot	TOA each run, sec	Mean	Standard deviation	Student's t	Degrees of freedom	Confidence level of mean difference, percent
C	0.			AML	91.					
	3.5				92					
	0.				91.5					
	0.				51.5					
	1.5				54.5					
	0.	0.83	1.44		86.	77.75	19.32	9.74	5	99.5
D	18.5				29.					
	11.				55.5					
	10.				10.5					
	0.				83.5					
	76.				3.5					
	121.5	39.5	48.46		0.	30.33	33.15	.38	10	60
E	10.				18.					
	16.				6.					
	1.				35.					
	24.				29.					
	0.				65.					
	24.5	12.58	10.8		45.5	33.08	20.76	2.15	8	95
F	5.				10.					
	0.				79.					
	2.5				26.5					
	48.5				8.0					
	29.5				15.5					
	33.0	19.75	20.01		5.5	24.08	27.92	.31	11	60
All		18.17	28.8			41.31	32.5	2.6	47	99.5

TABLE III.- AMLS DATA AND STATISTICS

(a) Pilot-versus-control-model runs

Pilot	AMLS each run	Mean	Standard deviation	Pilot	AMLS each run	Mean	Standard deviation	Student's t	Degrees of freedom	Confidence level of mean difference, percent
C	4.6			AML	5.8					
	4.4				5.7					
	4.2				6.					
	4.3				6.1					
	4.6				5.8					
	3.9	4.33	0.26		6.4	5.97	0.26	10.9	12	99.5
D	4.8				5.6					
	5.				5.3					
	4.3				6.					
	3.6				7.1					
	5.2				5.					
	4.9	4.63	.59		5.4	5.73	.75	2.82	11	99
E	4.4				5.7					
	4.8				5.3					
	4.1				6.					
	4.4				5.8					
	6.6				3.9					
	6.7	5.17	1.17		3.8	5.08	.98	.15	12	55
F	4.3				6.1					
	3.8				6.8					
	4.4				6.					
	4.7				5.8					
	4.8				5.5					
	5.2	4.53	.48		5.2	5.9	.55	4.57	12	99.5
All		4.67	.73			5.67	.73	4.76	48	99.5

TABLE III.- Concluded

(b) Pilot-versus-performance-model runs

Pilot	AMLS each run	Mean	Standard deviation	Pilot	AMLS each run	Mean	Standard deviation	Student's t	Degrees of freedom	Confidence level of mean difference, percent
C	4.3			AML	6.1					
	4.1				6.4					
	4.2				6.					
	4.5				5.9					
	4.5				5.8					
	4.1	4.28	0.18		6.3	6.08	0.23	15	11	99.5
D	5.				5.4					
	4.8				5.7					
	5.2				5.2					
	4.2				6.2					
	5.8				4.5					
	6.9	5.32	.93		3.9	5.15	.83	.33	12	60
E	4.9				5.3					
	5.3				5.1					
	4.7				5.6					
	4.8				5.					
	4.3				5.7					
	5.0	4.83	.33		5.4	5.35	.27	2.99	12	99
F	5.1				5.4					
	4.4				5.9					
	4.8				5.6					
	5.6				4.8					
	5.0				5.					
	5.4	5.05	.43		4.9	5.27	.44	.88	11	80
All		4.87	.64			5.46	.6	3.28	45	99.5

TABLE IV.- MISSILE AND GUN-ZONE ENTRIES

(a) Pilot versus pilot

Run	Sphere A							Sphere B						
	Pilot	Times of first entry			Average time in zone			Pilot	Times of first entry			Average time in zone		
		Zone A	Zone B	Guns	Zone A	Zone B	Guns		Zone A	Zone B	Guns	Zone A	Zone B	Guns
1	C	31.	180.	------	8.	5.	------	D	27.5	36.5	70.	56.5	30.	7.
2	C	------	------	------	0	0	------	D	19.	20.5	100.5	116.5	86.5	29.
3	C	16.	17.5	------	46.5	28.	------	F	17.	136.	------	14.	5.5	------
4	C	20.	113.	------	44.5	14.	------	F	20.	22.	------	28.	19.	------
5	C	12.5	------	------	2.86	0	------	E	26.5	29.5	120.	35.77	10.	.72
6	C	16.	17.5	------	39.	20.5	------	E	44.	46.5	------	33.5	23.	------
7	F	20.5	------	------	3.5	0	------	C	16.5	19.	75.	63.	26.	.5
8	F	19.	------	------	5.84	0	------	D	19.	21.	92.5	35.	20.1	17.5
9	F	18.	------	------	13.	0	------	D	25.	78.5	153.	33.5	12.	1.5
10	E	20.5	23.	------	47.6	26.99	------	D	26.	------	------	2.13	0	------
11	E	17.	18.5	171.	79.	34.5	6.	C	20.	22.	------	7.5	1.5	------
12	E	22.	24.	147.	78.95	63.16	12.4	F	29.	32.5	------	9.02	2.82	------
13	E	23.5	24.5	75.	56.5	48.5	26.5	F	13.	------	------	1.5	0	------
14	D	66.	66.	------	26.	9.	------	F	72.	------	------	3.	0	------
15	D	22.5	------	------	6.	0	------	F	25.	26.5	------	19.5	7.5	------
16	D	36.	------	------	12.	0	------	C	41.5	------	------	9.	0	------
17	D	48.	99.	------	41.5	9.5	------	C	51.	55.	------	16.	7.5	------
18	F	24.5	------	------	13.2	0	------	E	31.	32.5	91.	55.6	29.9	9.
19	D	33.	------	------	15.45	0	------	E	25.	27.	158.5	42.1	27.18	11.19
20	D	24.	44.5	------	18.2	3.	------	E	22.5	24.	135.	18.8	10.9	9.1
21	F	36.	36.	48.	81.	55.	.5	C	39.	------	------	7.5	0	------
22	E	32.	34.	------	37.18	13.87	------	C	16.5	------	------	2.77	0	------
23	E	39.	42.	92.5	69.85	42.4	3.74	D	18.	20.	------	6.86	1.25	------
24	F	18.5	21.	------	26.5	16.5	------	E	18.5	------	------	19.	0	------
Average . . .		33.15	99.19		32.17	16.25			27.6	79.54		26.5	13.36	
Average of both spheres . .		30.37	89.37		29.34	14.81								

TABLE IV.- Continued

(b) Pilot-versus-AML control model

Run	Sphere A							Sphere B						
	Pilot	Times of first entry			Average time in zone			Pilot	Times of first entry			Average time in zone		
		Zone A	Zone B	Guns	Zone A	Zone B	Guns		Zone A	Zone B	Guns	Zone A	Zone B	Guns
1	F	25.	28.	-----	7.5	1.5	----	AML	21.	28.5	-----	59.5	12.	---
2	F	18.5	21.	-----	23.	12.	----		19.	20.	171.	63.5	33.	2.5
3	D	28.5	31.	-----	33.5	19.	----		33.	36.5	-----	35.5	10.5	---
4	D	19.5	79.5	-----	38.5	14.5	----		18.	22.	-----	35.5	8.5	---
5	F	19.	21.5	-----	12.	1.5	----		18.	22.5	-----	48.5	22.5	---
6	F	16.5	18.	-----	8.5	1.5	----		17.5	18.	103.	71.	43.	3.
7	C	16.5	36.5	-----	26.5	9.5	----		15.5	16.	-----	51.	26.	---
8	C	32.	33.	-----	25.5	14.	----		26.5	63.	-----	42.	11.	---
9	D	41.	63.5	-----	16.	4.5	----		31.	42.5	-----	53.	13.	---
10	D	-----	-----	-----	-----	-----	----		26.5	28.5	-----	123.5	79.5	---
11	C	24.	25.5	-----	27.	14.	----		19.5	23.	-----	46.5	18.5	---
12	C	29.5	31.	-----	20.	10.	----		21.	25.	-----	67.5	25.	---
13	C	22.5	24.	-----	31.5	14.5	----		19.5	56.5	-----	43.5	13.5	---
14	C	23.5	26.5	-----	16.	7.	----		22.5	28.	165.5	74.5	39.5	2.5
15	E	63.	178.	-----	10.5	2.5	----		18.5	23.	-----	35.	18.5	---
16	E	52.5	-----	-----	9.5	0	----		29.	142.	-----	16.	2.5	---
17	D	19.5	21.5	-----	41.	17.5	----		18.	168.	-----	19.	4.5	---
18	F	20.5	60.5	97.5	29.	16.	0.5		19.	31.	-----	36.	19.5	---
19	E	18.5	21.5	-----	5.5	2.5	----		20.	23.5	-----	43.	15.5	---
20	E	15.	16.5	-----	14.5	2.5	----		16.	17.5	-----	41.	19.	---
21	D	31.	139.	-----	31.5	3.5	----		30.	33.	-----	21.5	2.	---
22	E	17.	18.5	72.5	38.5	21.	7.		19.	-----	-----	3.	0	---
23	E	16.	18.	105.	37.5	19.5	44.5		18.	36.5	-----	6.5	1.5	---
24	F	24.5	101.	-----	42.	28.5	----		21.5	25.5	-----	30.5	4.	---
Average . . .		32.23	57.23		22.71	9.88			21.56	46.25		44.44	18.44	

TABLE IV.- Concluded

(c) Pilot-versus-AML performance model

Run	Sphere A							Sphere B						
	Pilot	Times of first entry			Average time in zone			Pilot	Times of first entry			Average time in zone		
		Zone A	Zone B	Guns	Zone A	Zone B	Guns		Zone A	Zone B	Guns	Zone A	Zone B	Guns
1	D	54.5	58.	----	27.	8.5	---	AML	21.5	23.5	-----	41.	22.	--
2	D	20.	22.5	----	27.5	12.5	---		18.	22.5	-----	53.5	24.5	--
3	C	40.5	80.	----	11.	7.5	---		27.5	39.5	-----	65.5	24.5	--
4	C	30.5	32.5	----	20.5	13.	---		35.5	39.5	151.5	62.	36.	3.
5	C	30.5	0	----	5.	0	---		20.5	25.	-----	53.	17.5	--
6	C	27.	28.5	----	23.5	4.5	---		20.5	26.	-----	67.5	20.	--
7	C	28.	31.	----	32.5	21.	---		29.	31.5	-----	39.	16.5	--
8	E	16.	17.5	----	22.	10.	---		14.5	16.5	-----	33.	9.5	--
9	E	16.	32.5	----	41.5	18.5	---		15.	16.	-----	30.5	12.	--
10	D	28.	33.	----	36.	15.	---		32.	36.5	-----	25.5	8.5	--
11	D	51.	90.	----	13.	3.5	---		16.5	18.	-----	71.	33.5	--
12	F	16.5	18.	----	38.5	17.	---		16.	55.5	-----	38.5	19.	--
13	F	16.	18.	----	7.	1.5	---		15.	16.5	-----	58.5	15.5	--
14	F	17.5	40.5	----	51.5	30.	---		16.5	21.	-----	23.5	6.5	--
15	C	22.	24.5	----	7.	.5	---		19.	38.5	150.5	56.5	26.	1.
16	E	61.	177.5	----	17.	3.	---		17.5	19.	-----	38.5	15.5	--
17	D	26.5	29.	----	41.	15.5	---		30.5	0	-----	7.5	0	--
18	D	33.	69.	139.	59.	21.5	2.5		29.	36.5	-----	11.	1.	--
19	F	17.	19.	----	14.5	2.5	---		16.	19.	-----	32.5	13.5	--
20	E	-----	------	----	0	0	---		33.5	38.5	-----	15.	5.5	--
21	E	-----	------	----	0	0	---		40.5	47.	-----	35.	17.	--
22	E	30.5	33.	----	22.5	8.	---		32.5	35.	-----	35.5	12.5	--
23	F	25.5	28.	----	75.	48.5	---		30.5	33.5	-----	17.5	4.5	--
24	F	26.5	------	----	10.	0	---		26.5	29.5	-----	12.5	6.5	--
Average . . .		41.42	66.76		25.1	10.9			23.9	36.		38.5	15.32	

TABLE V.- OFFENSIVE AND DEFENSIVE AML SCORES

(a) Pilot versus pilot

Run	Sphere A				Sphere B			
	Pilot	Offensive AMLS	Defensive AMLS	AMLS	Pilot	Offensive AMLS	Defensive AMLS	AMLS
1	C	0.8	3.2	3.9	D	2.1	3.8	5.9
2	C	.2	2.5	2.8	D	3.4	3.8	7.2
3	C	1.6	3.6	5.2	F	1.1	3.6	4.7
4	C	1.5	3.7	5.2	F	1.2	3.5	4.6
5	C	.6	3.1	3.7	E	2.2	3.8	6.0
6	C	1.3	3.6	4.9	E	1.4	3.7	5.2
7	F	.7	3.3	4.1	C	2.0	3.6	5.6
8	F	.4	2.7	3.2	D	2.9	4.0	6.9
9	F	.6	3.0	3.6	D	2.4	4.0	6.4
10	E	1.8	3.8	5.6	D	.9	3.5	4.3
11	E	2.5	3.8	6.3	C	.5	3.2	3.7
12	E	2.3	3.8	6.1	F	.6	3.3	3.9
13	E	2.8	3.7	6.5	F	.5	3.2	3.7
14	D	1.9	4.0	5.9	F	.7	3.3	4.0
15	D	.9	3.5	4.3	F	1.6	3.8	5.4
16	D	1.5	3.7	5.2	C	1.1	3.7	4.8
17	D	1.6	3.7	5.3	C	1.1	3.6	4.7
18	F	1.0	3.3	4.3	E	2.1	3.6	5.7
19	D	.8	3.3	4.1	E	2.1	3.8	5.9
20	D	.9	3.3	4.2	E	2.0	3.8	5.8
21	F	2.5	3.9	6.4	C	.6	3.0	3.6
22	E	2.1	3.7	5.8	C	.5	3.3	3.9
23	E	2.6	3.6	6.2	D	.6	3.2	3.8
24	F	1.0	3.5	4.5	E	1.6	3.6	5.2
Average . .		1.41	3.47	4.89		1.47	3.55	5.02

TABLE V.- Concluded

(b) Pilot versus AML control model

Run	Sphere A				Sphere B			
	Pilot	Offensive AMLS	Defensive AMLS	AMLS	Pilot	Offensive AMLS	Defensive AMLS	AMLS
1	F	0.9	3.2	4.1	AML	2.1	3.9	5.9
2	F	.7	2.9	3.6		2.6	3.9	6.5
3	D	1.2	3.5	4.7		1.6	3.8	5.4
4	D	1.4	3.6	4.9		1.6	3.7	5.2
5	F	.6	3.5	4.1		2.1	3.7	5.7
6	F	1.2	3.3	4.4		1.9	3.7	5.6
7	C	1.0	3.4	4.4		1.8	3.8	5.6
8	C	.9	3.4	4.3		1.9	3.7	5.6
9	D	.9	3.4	4.3		2.0	3.9	6.0
10	D	.3	3.0	3.3		2.7	4.1	6.8
11	C	.9	3.3	4.2		2.0	4.0	5.9
12	C	.8	3.4	4.1		2.1	3.9	6.0
13	C	1.1	3.4	4.5		1.8	3.9	5.7
14	C	.7	3.1	3.8		2.3	3.9	6.3
15	E	.7	3.5	4.2		1.8	3.7	5.5
16	E	1.0	3.6	4.6		1.4	3.7	5.1
17	D	1.5	3.5	5.1		1.2	3.7	4.9
18	F	1.3	3.3	4.6		1.7	3.6	5.3
19	E	.6	3.3	3.9		2.2	3.7	5.9
20	E	1.1	3.3	4.3		1.9	3.8	5.7
21	D	1.2	3.5	4.7		1.4	3.7	5.1
22	E	2.6	3.7	6.3		.6	3.0	3.6
23	E	2.6	3.7	6.3		.5	2.9	3.5
24	F	1.4	3.5	5.0		1.5	3.5	4.9
Average . .		1.11	3.39	4.49		1.78	3.72	5.49

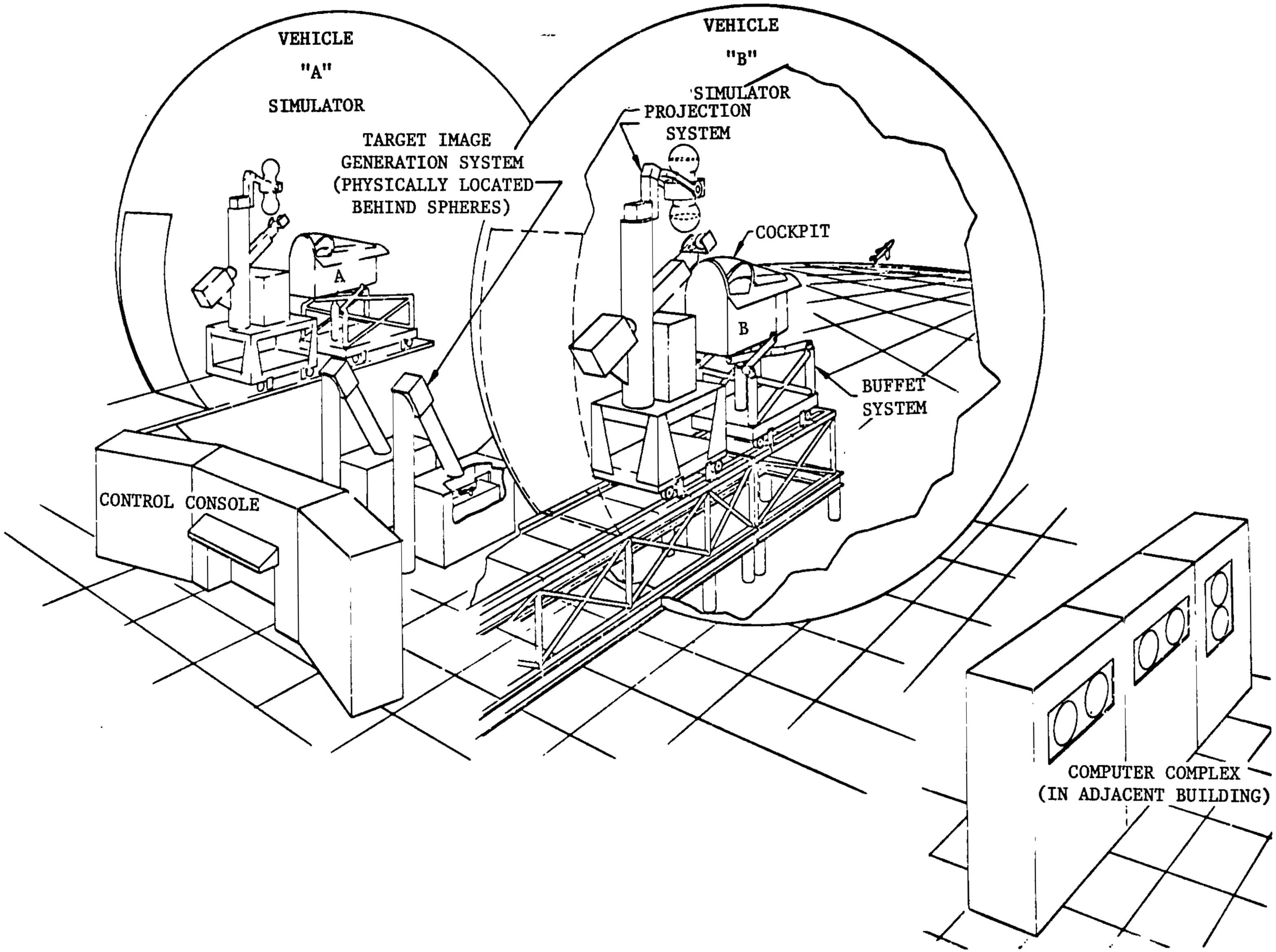


Figure 1.- Langley differential maneuvering simulator.

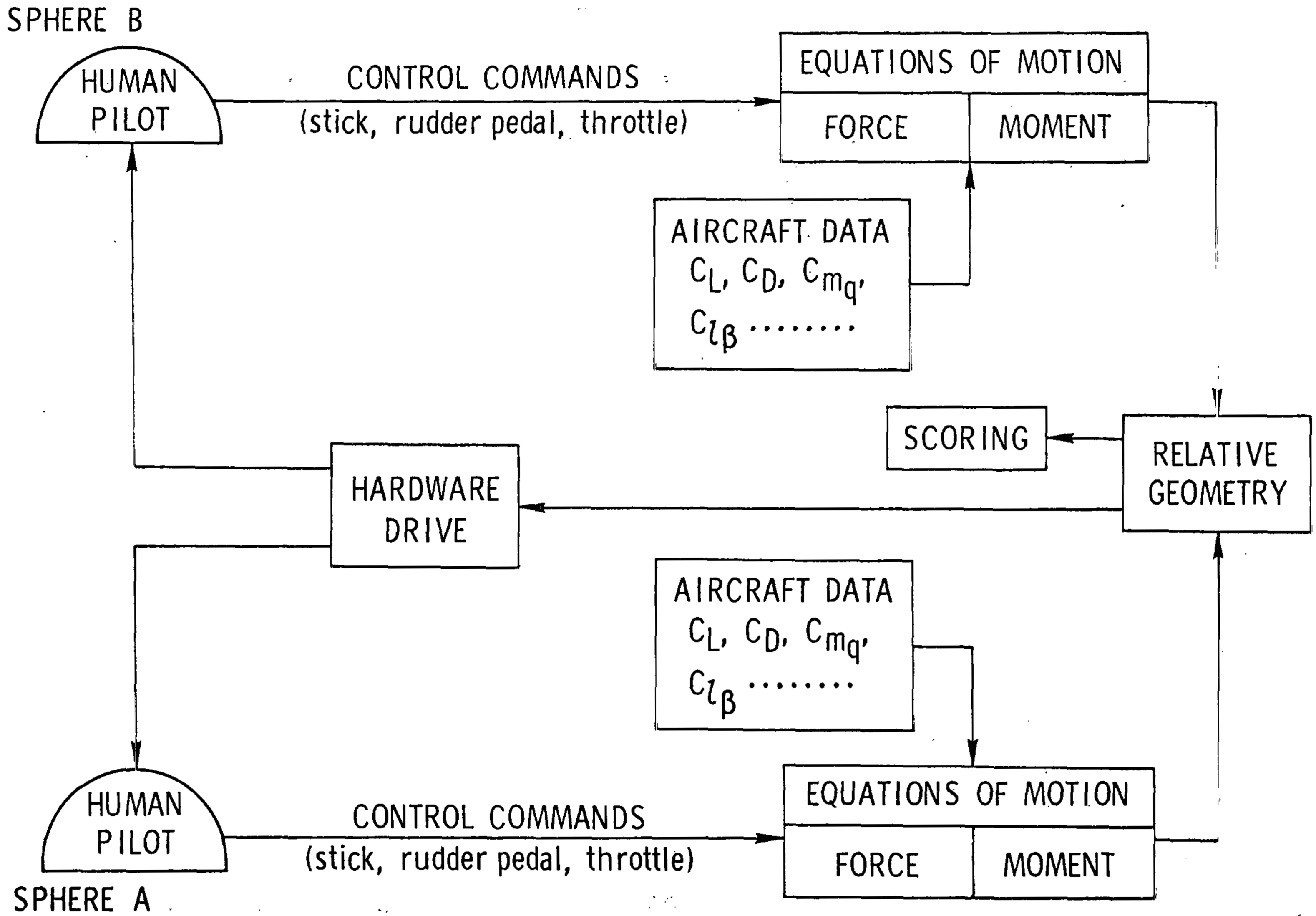


Figure 2.- Block diagram of two-sphere Langley differential maneuvering simulator.

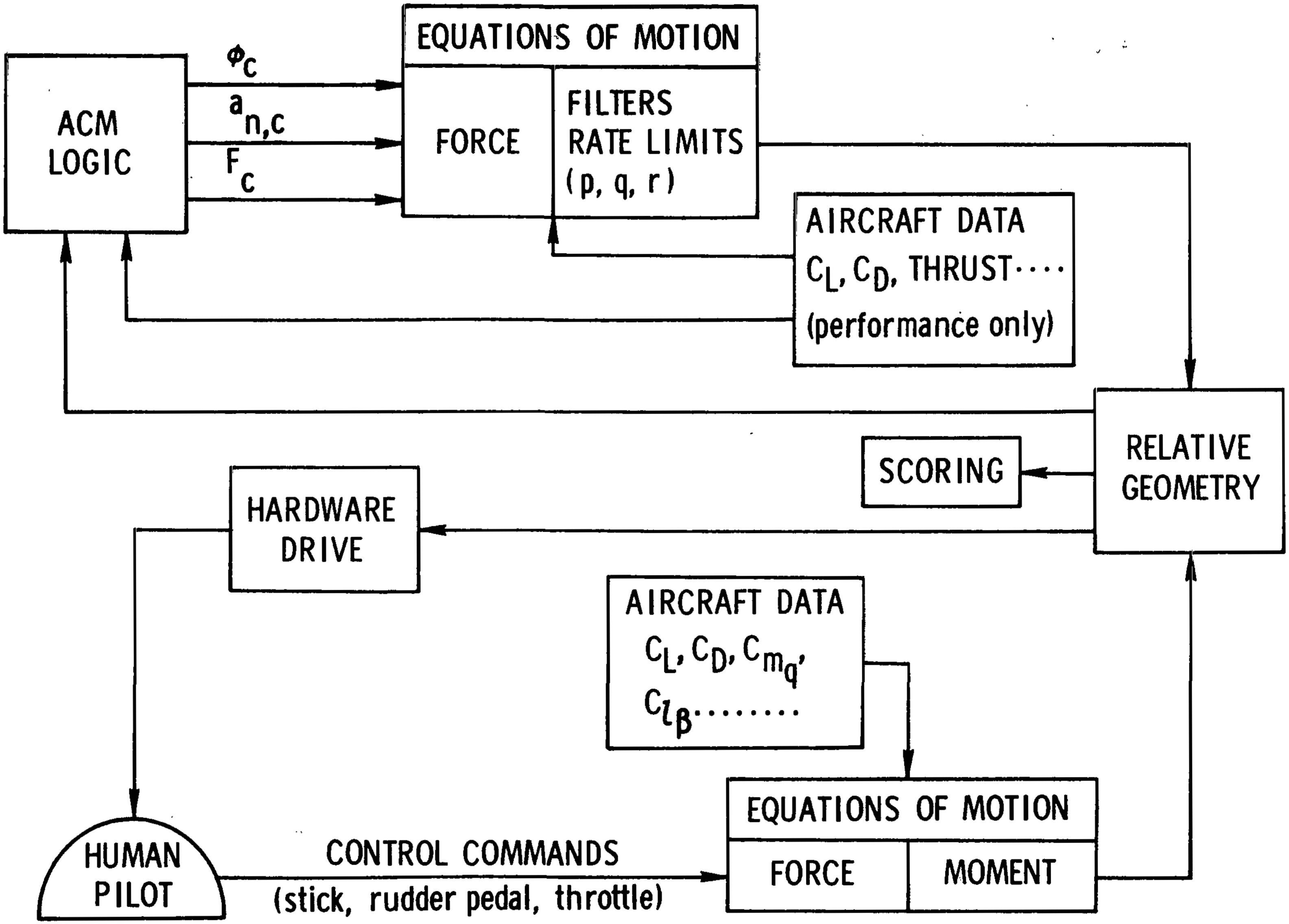


Figure 3.- DMS-AML performance model.

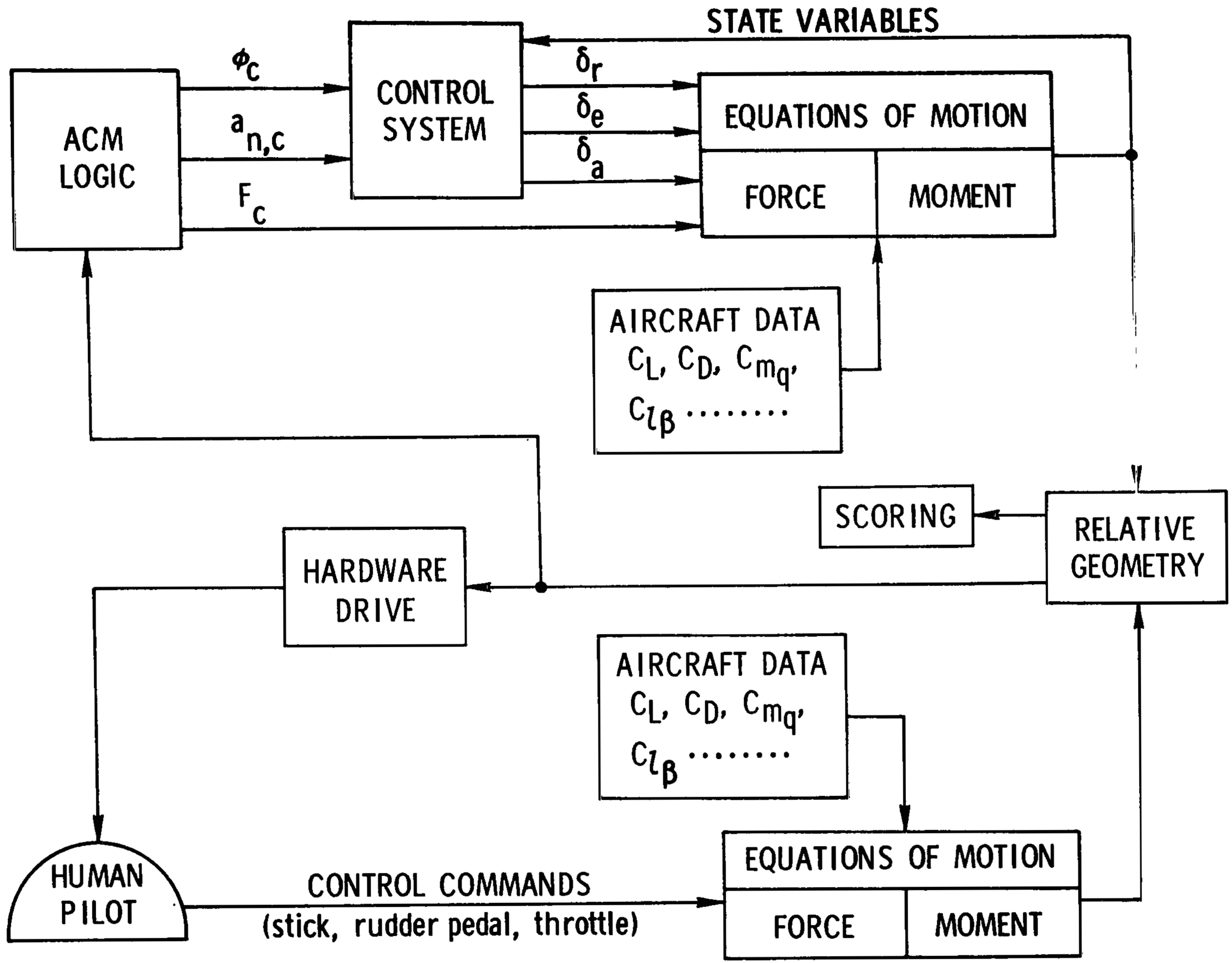


Figure 4.- DMS-AML control model.

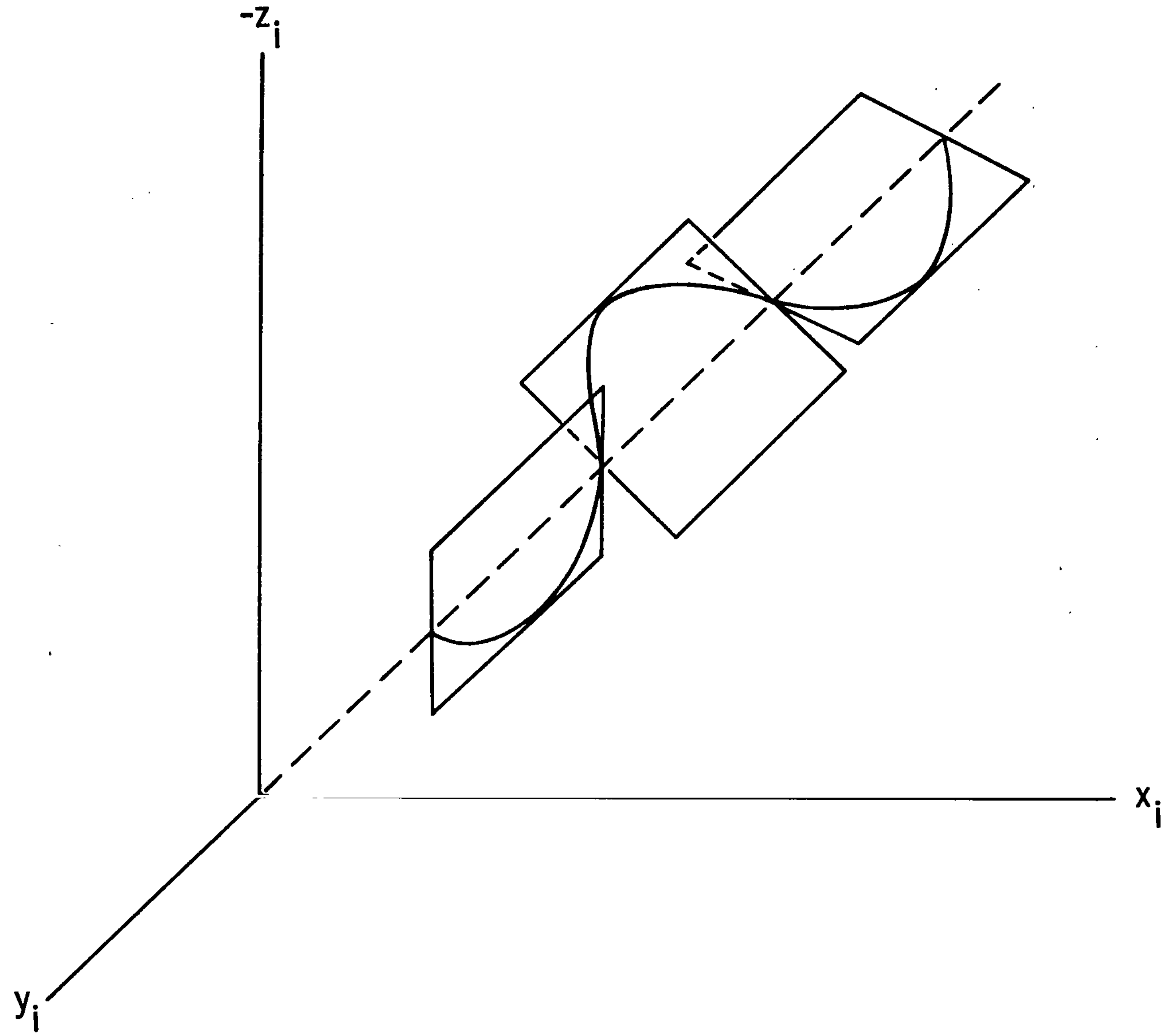


Figure 5.- Segmented flight path.

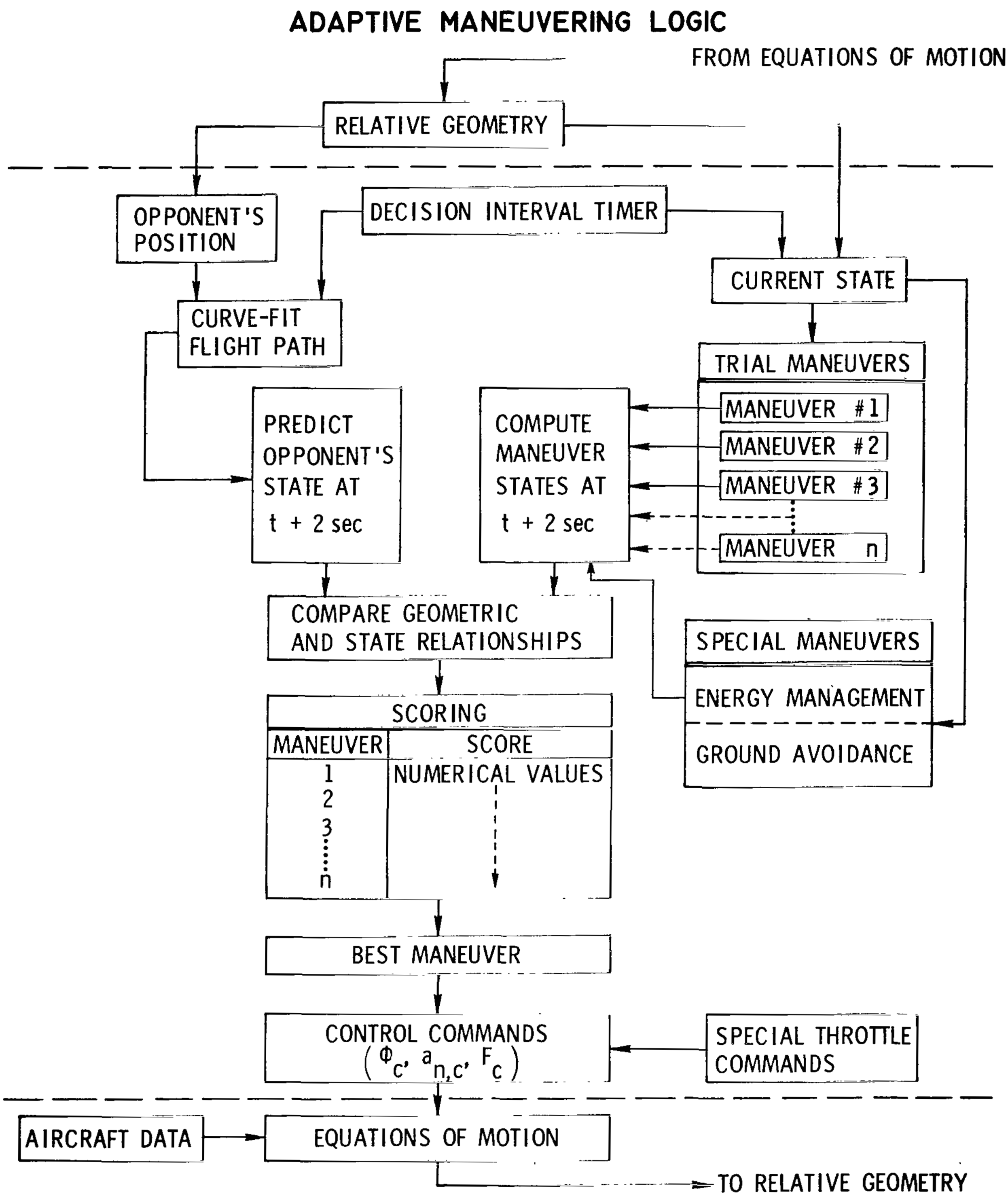


Figure 6.- Adaptive maneuvering logic.

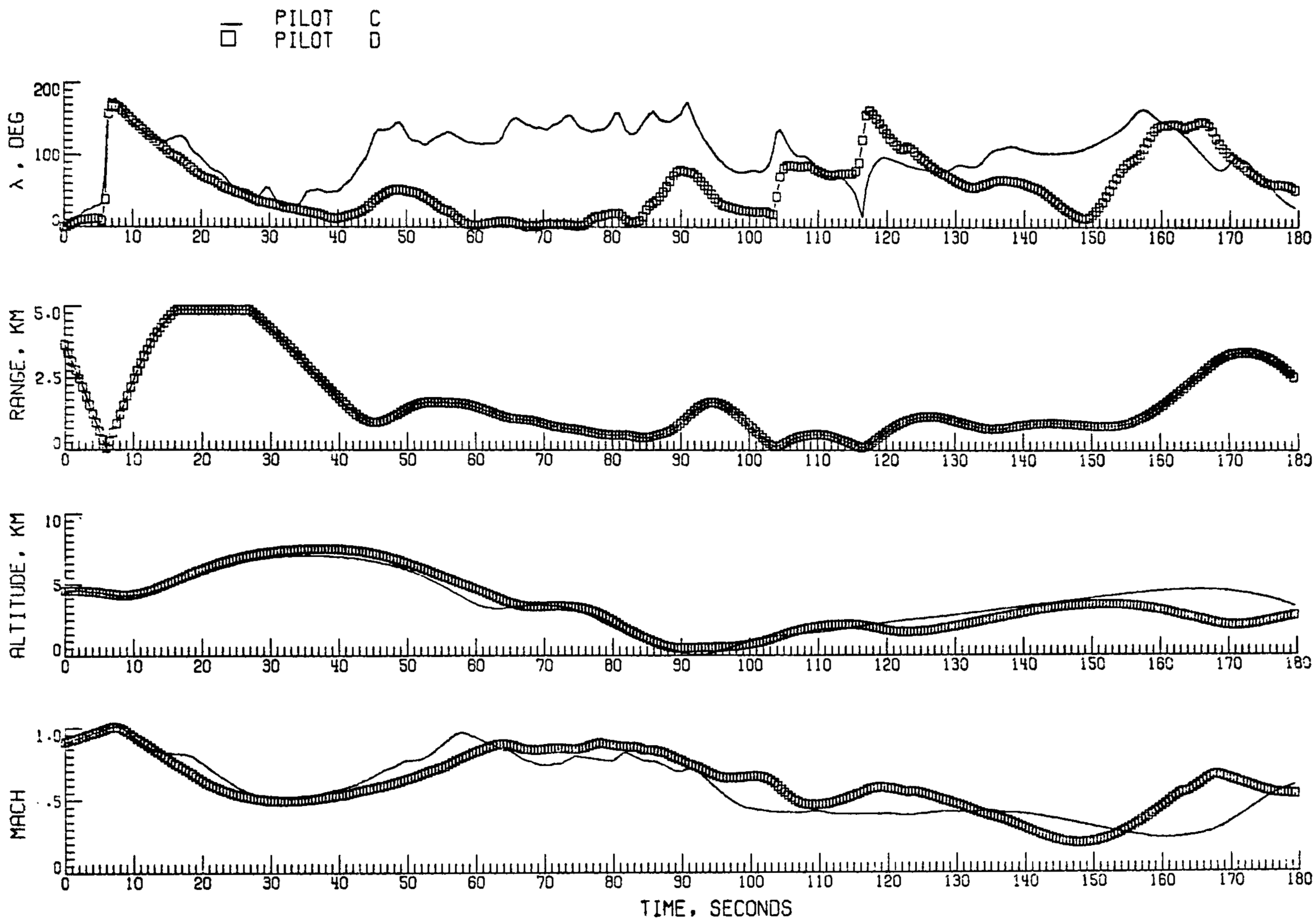


Figure 7.- Pilot-versus-pilot data set for run 1.

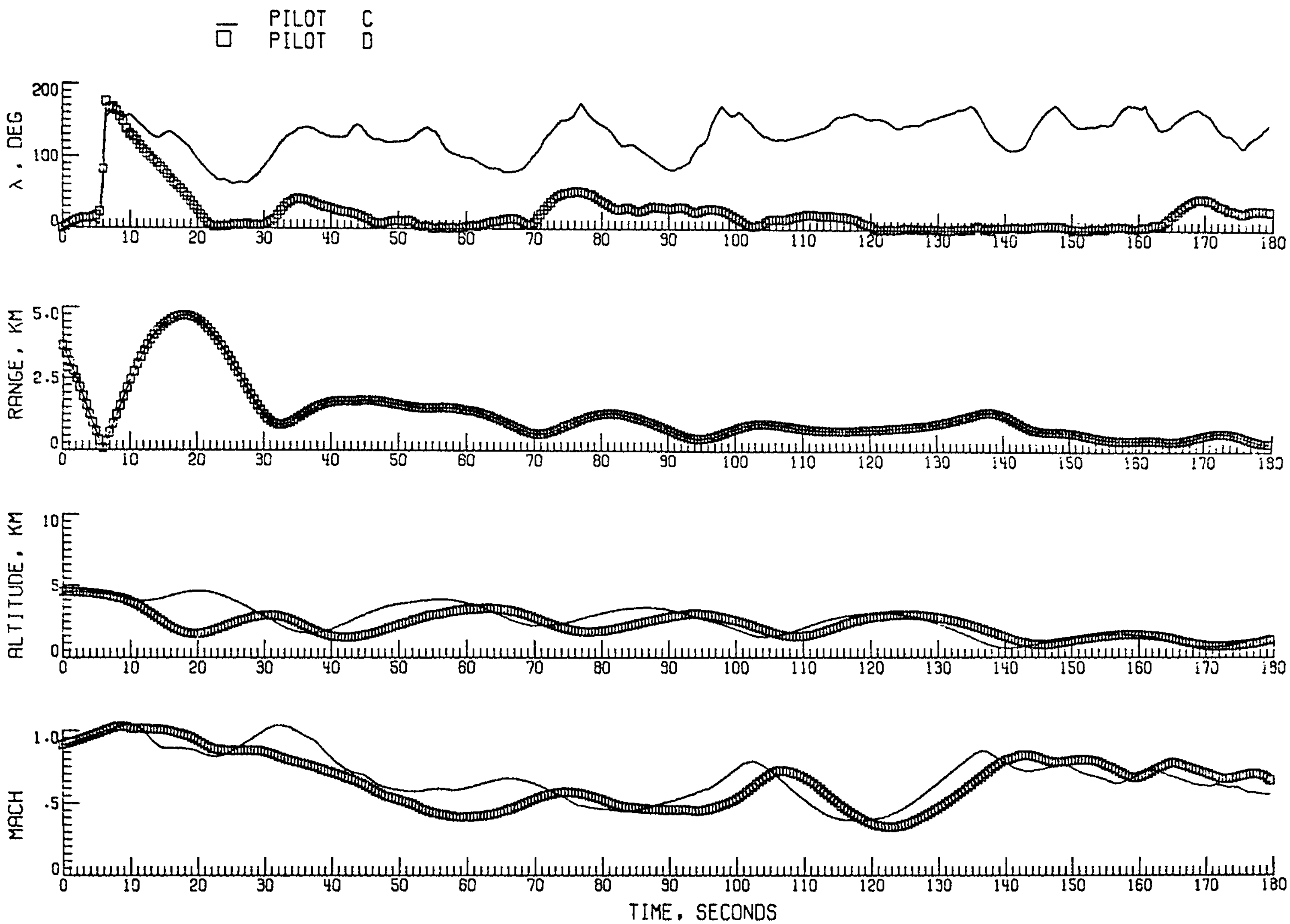


Figure 8.- Pilot-versus-pilot data set for run 2.

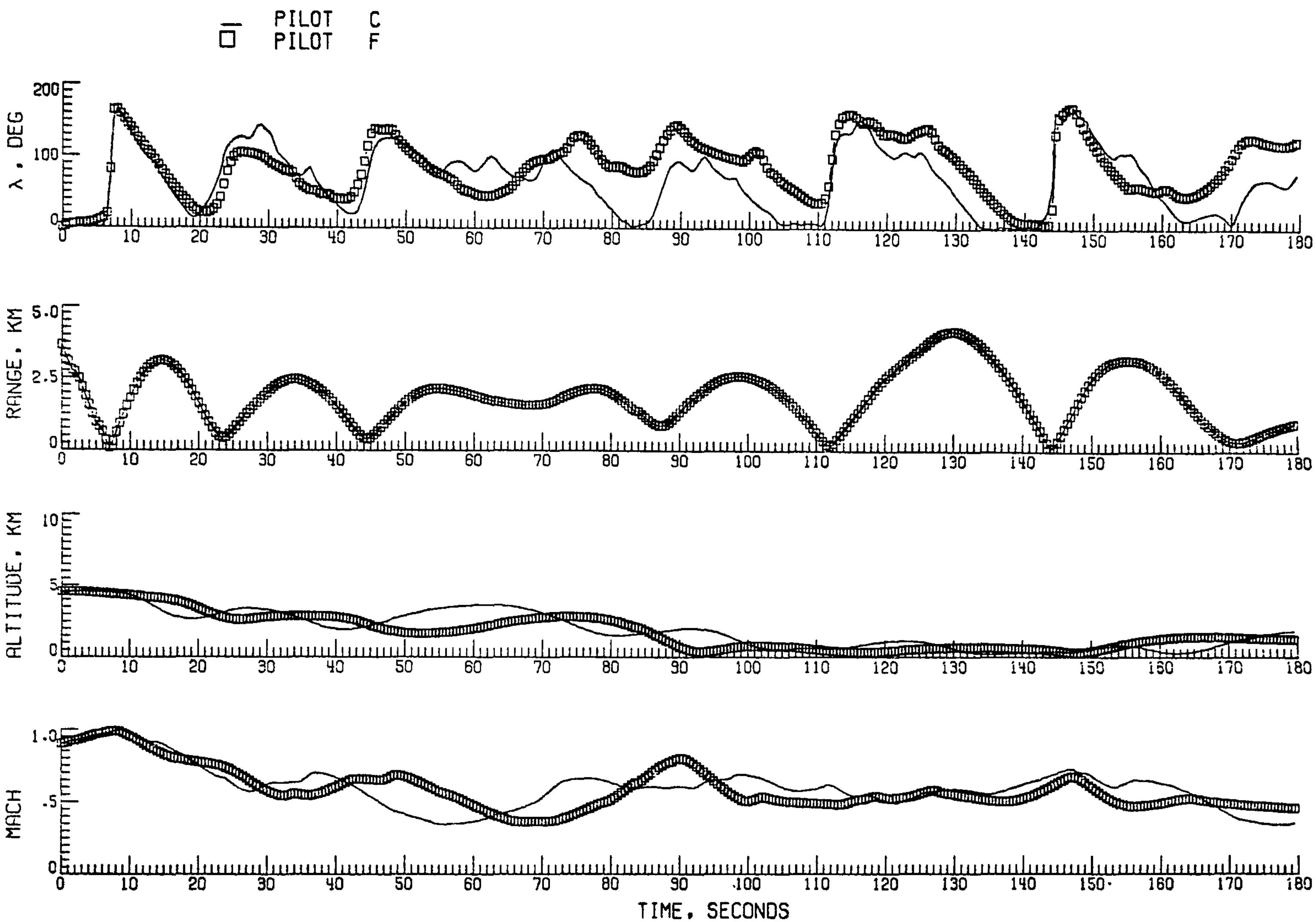


Figure 9.- Pilot-versus-pilot data set for run 3.

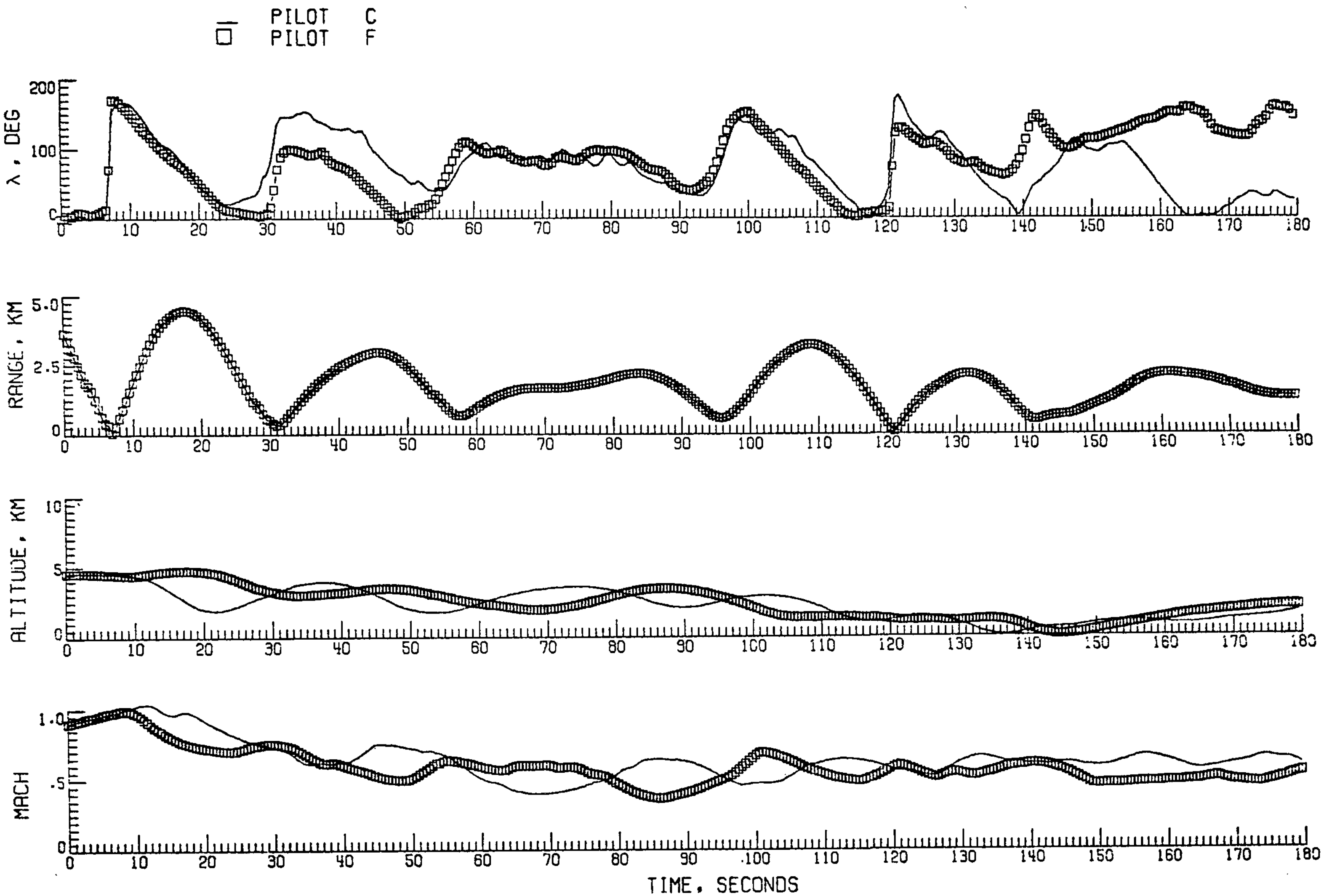


Figure 10.- Pilot-versus-pilot data set for run 4.

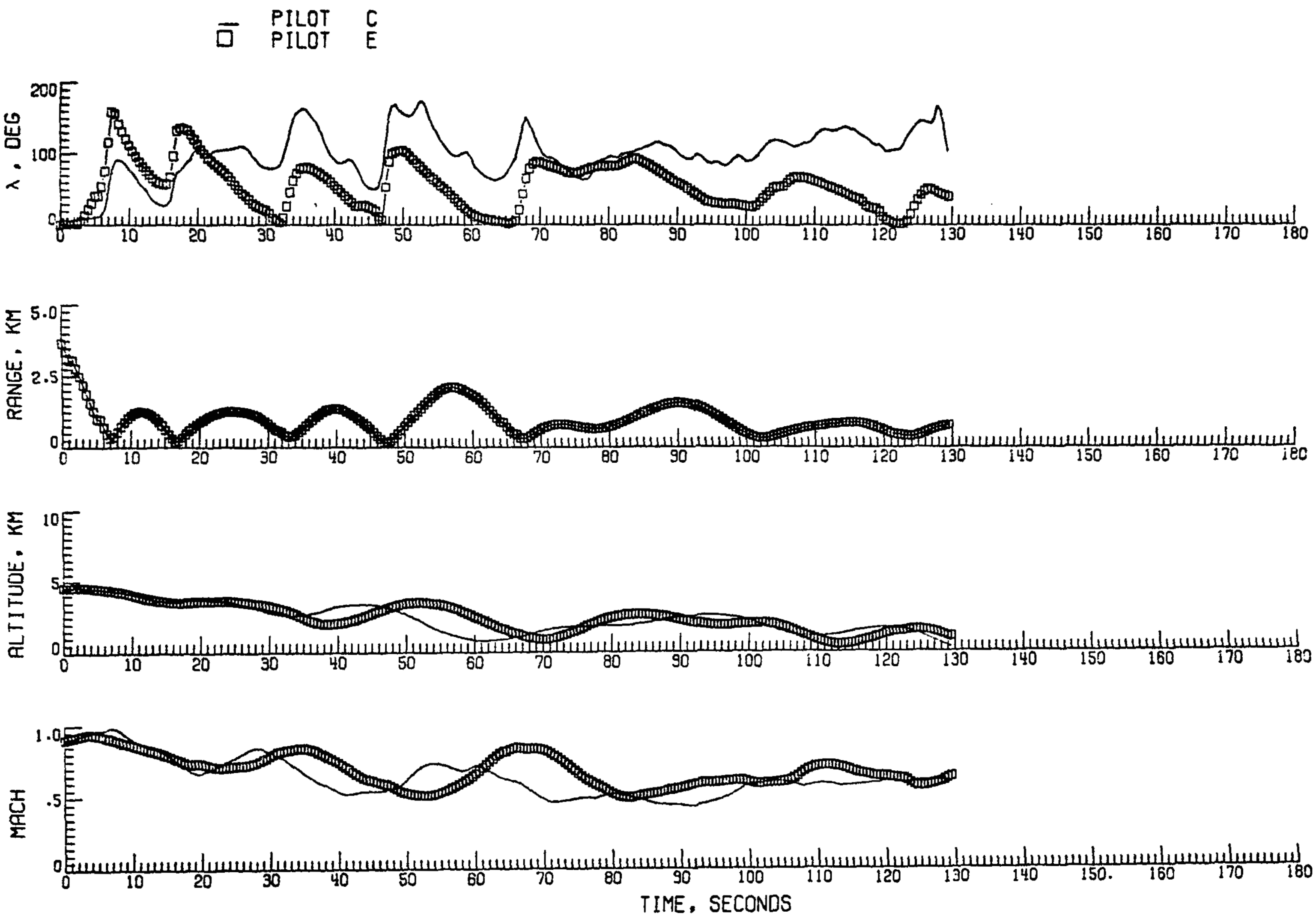


Figure 11.- Pilot-versus-pilot data set for run 5.

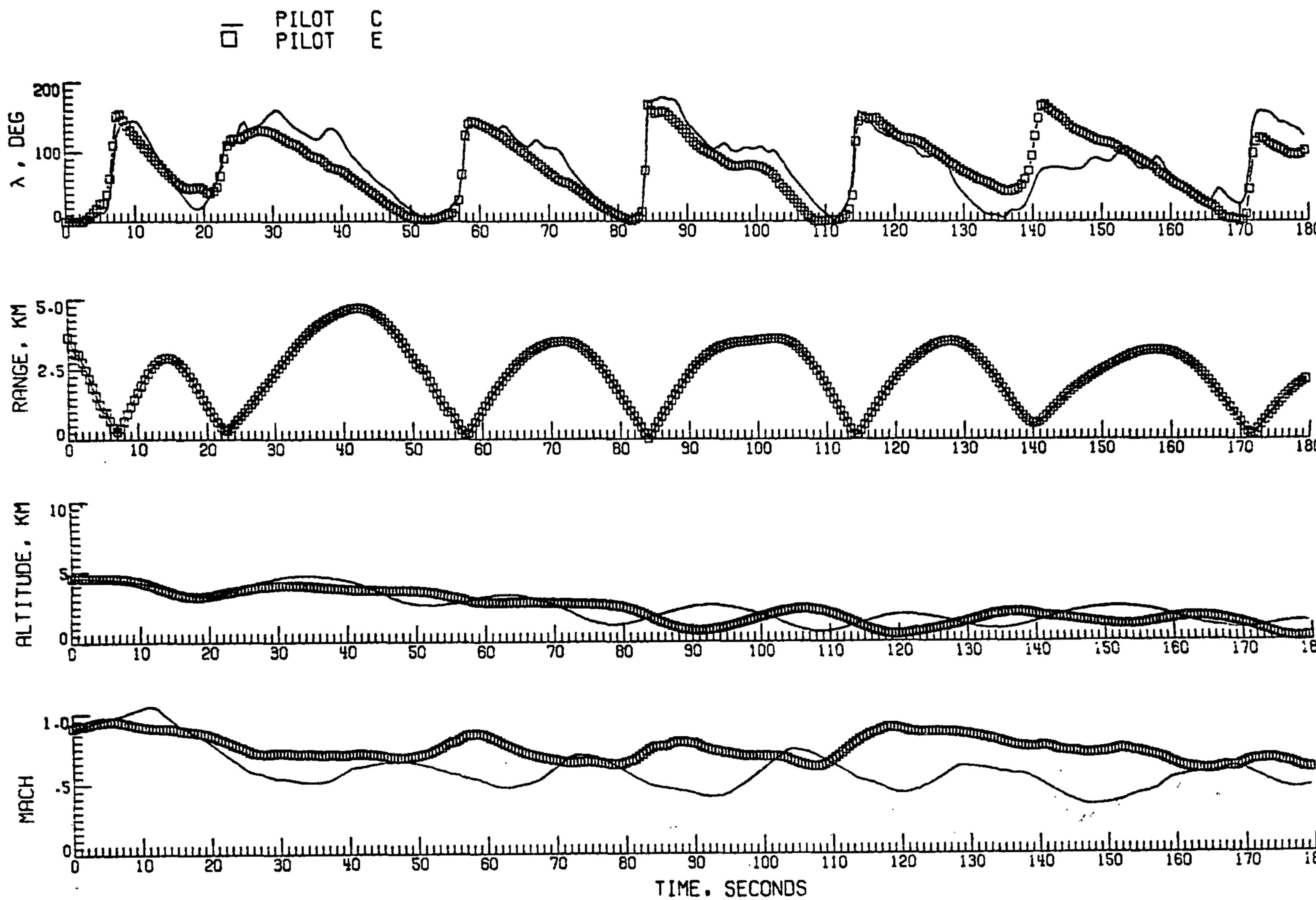


Figure 12.- Pilot-versus-pilot data set for run 6.

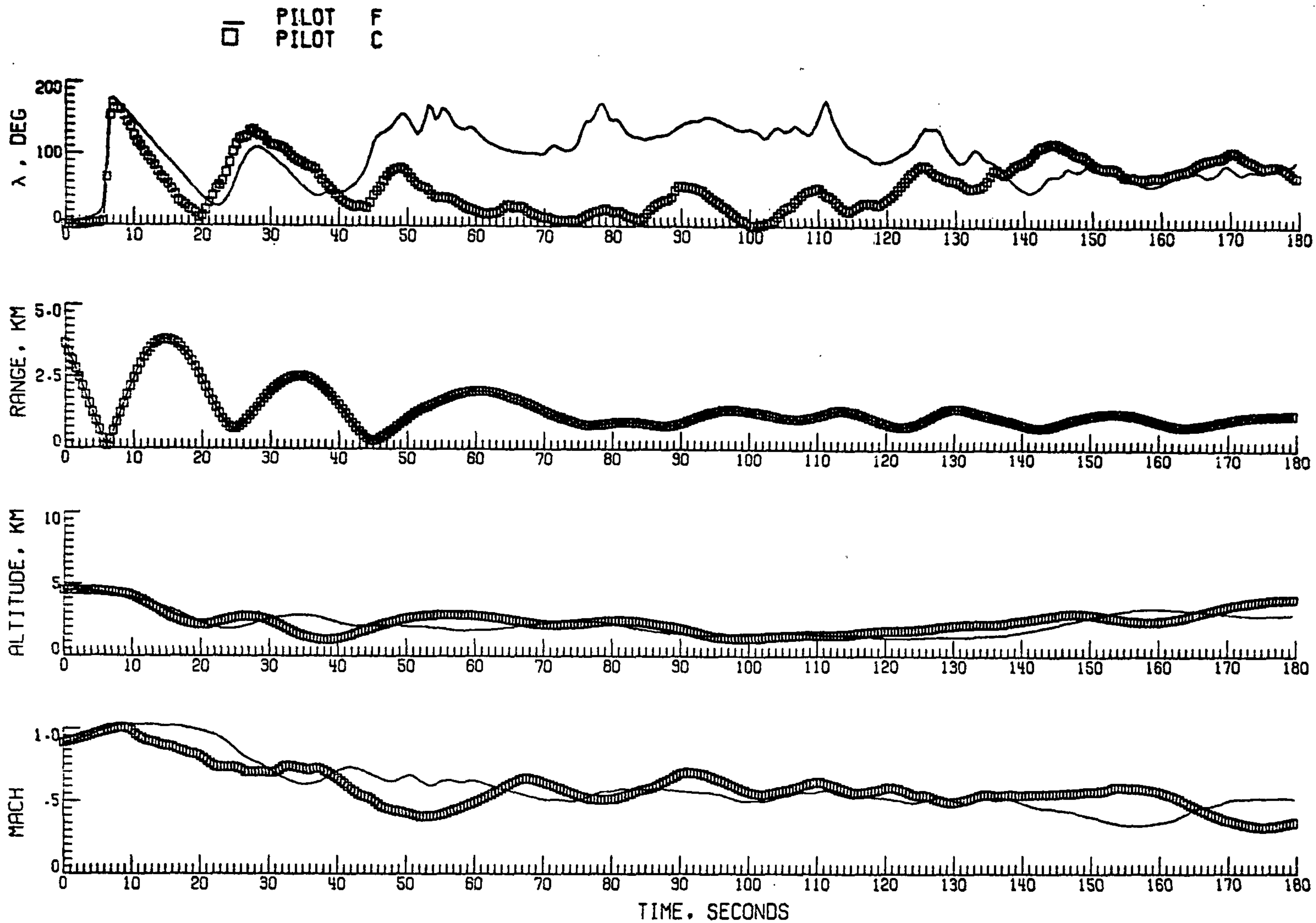


Figure 13.- Pilot-versus-pilot data set for run 7.

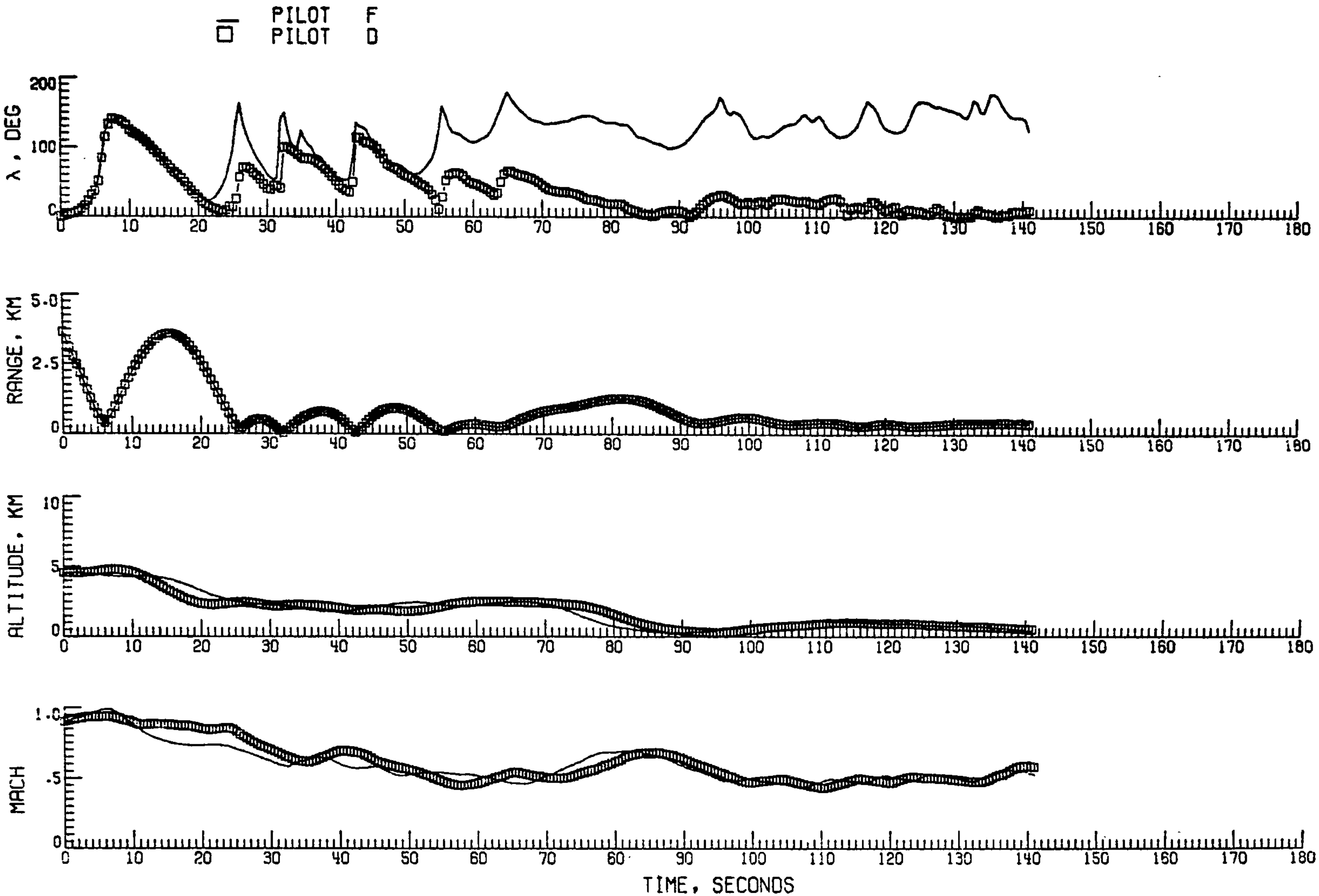


Figure 14.- Pilot-versus-pilot data set for run 8.

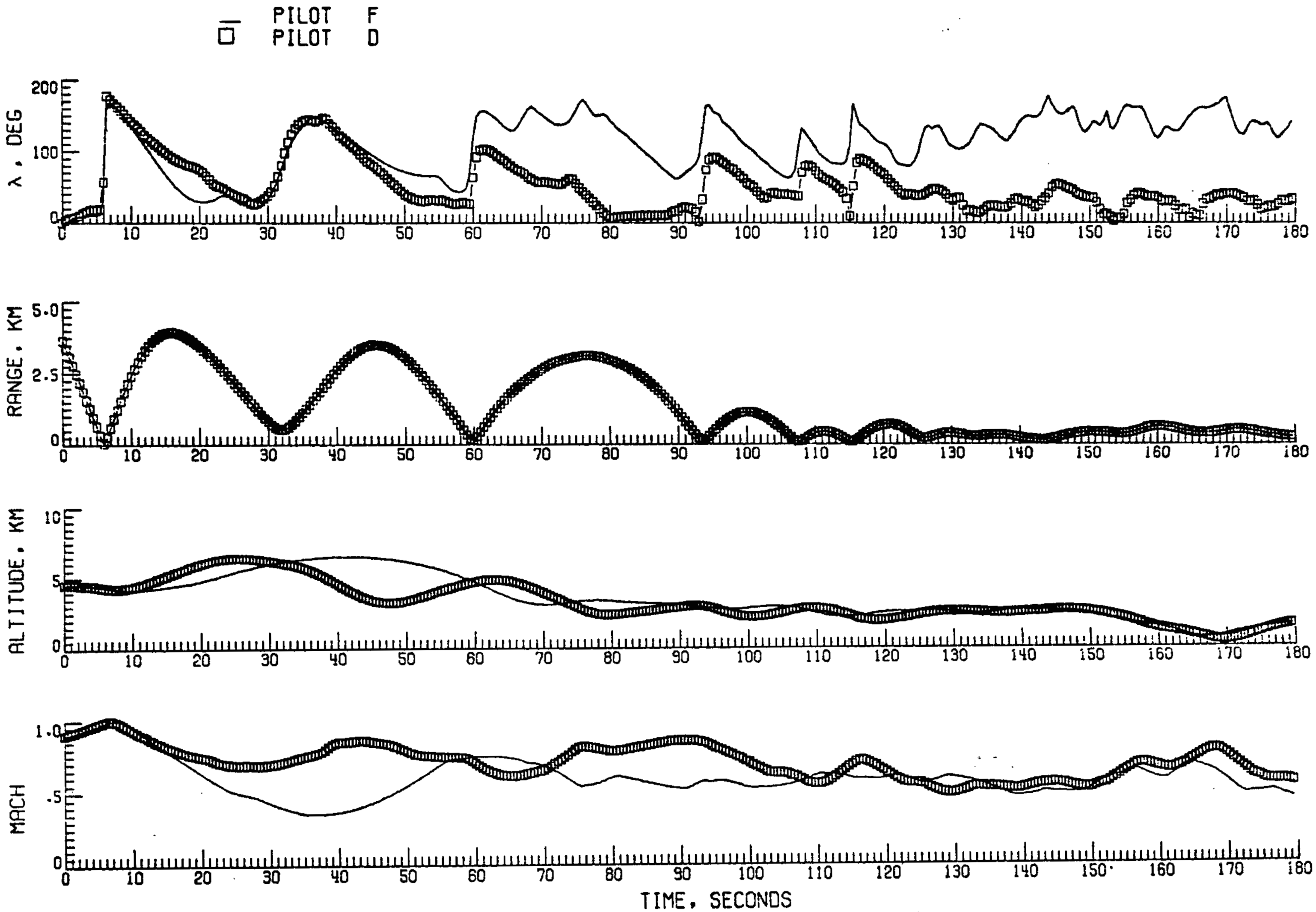


Figure 15.- Pilot-versus-pilot data set for run 9.

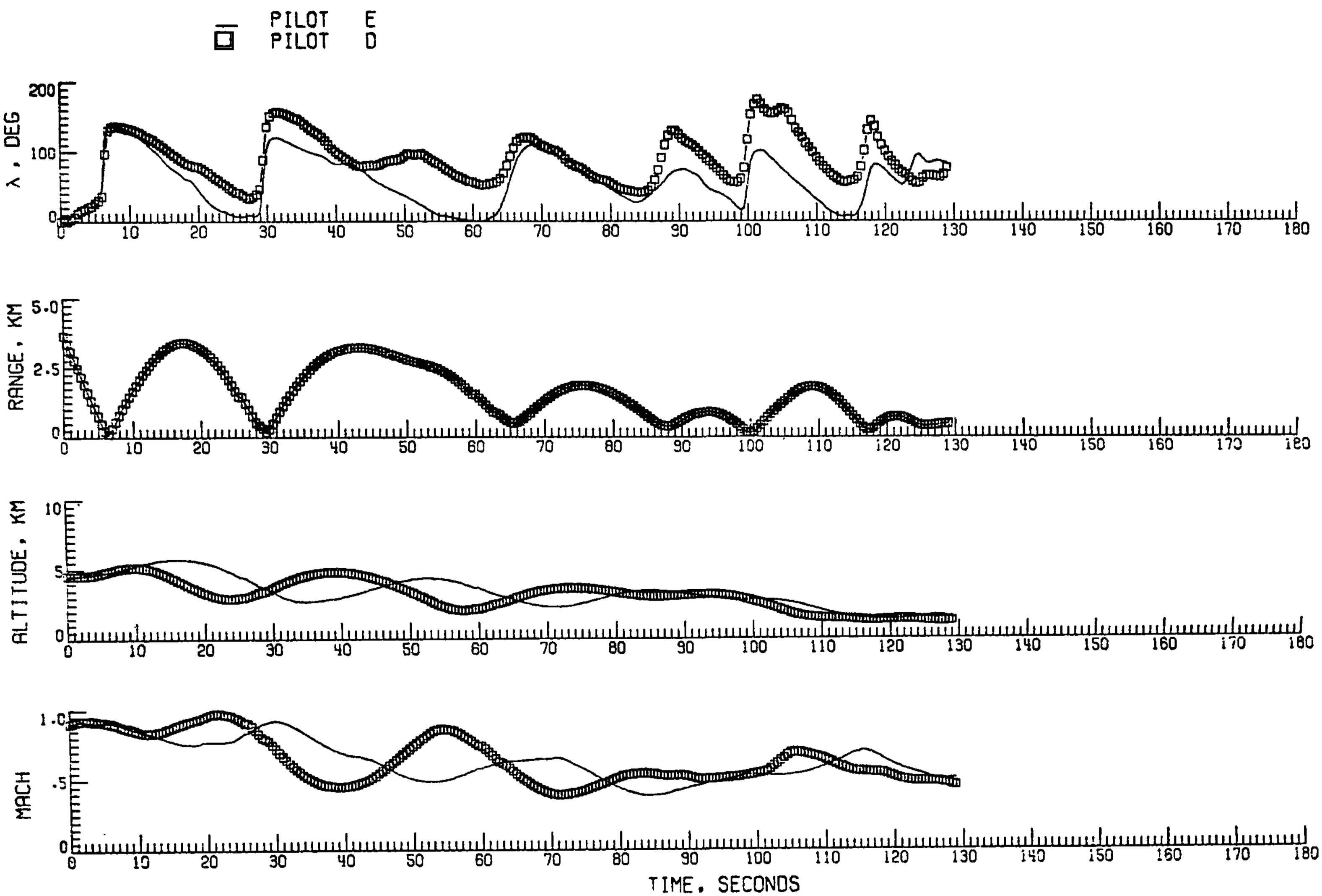


Figure 16.- Pilot-versus-pilot data set for run 10.

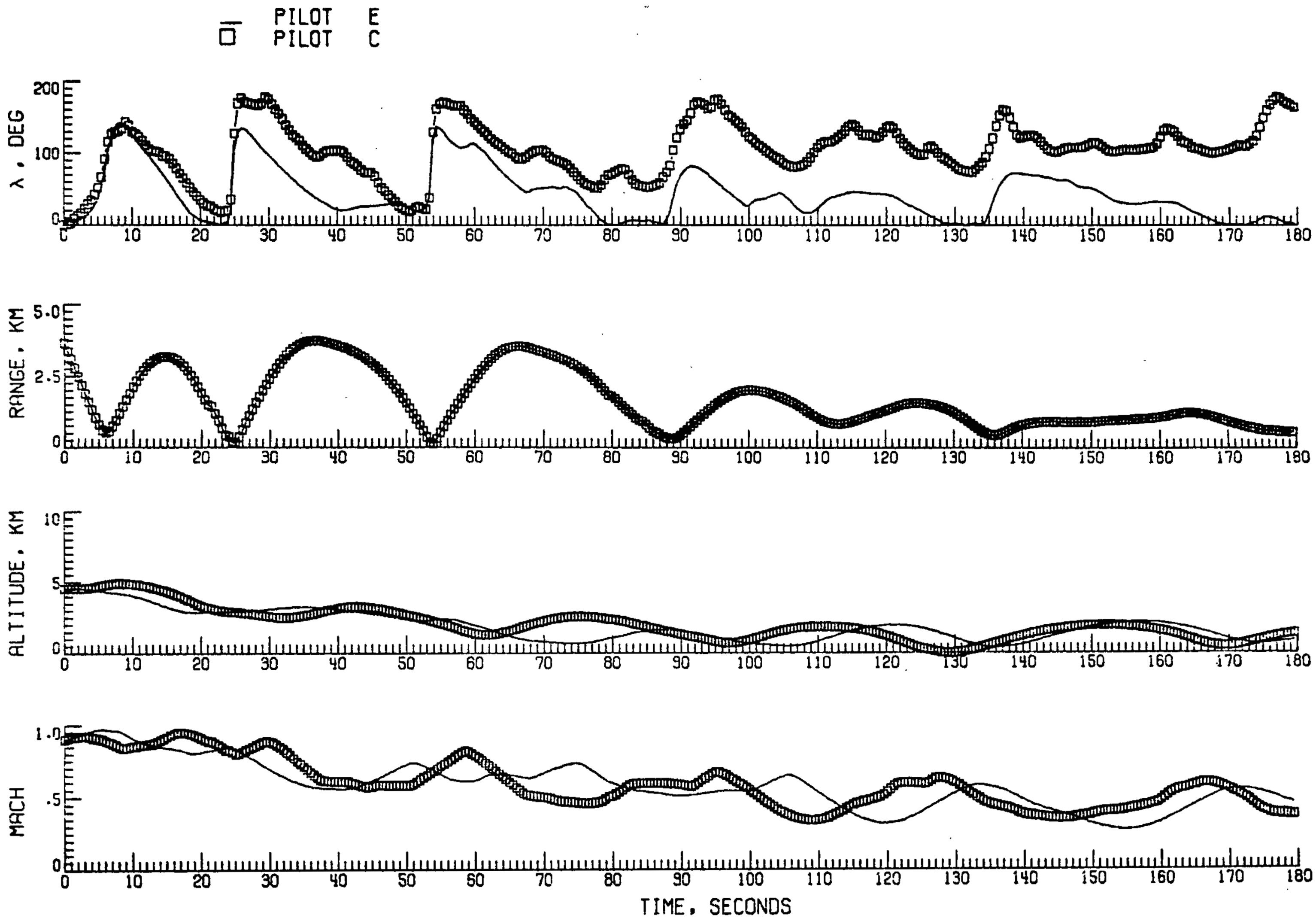


Figure 17.- Pilot-versus-pilot data set for run 11.

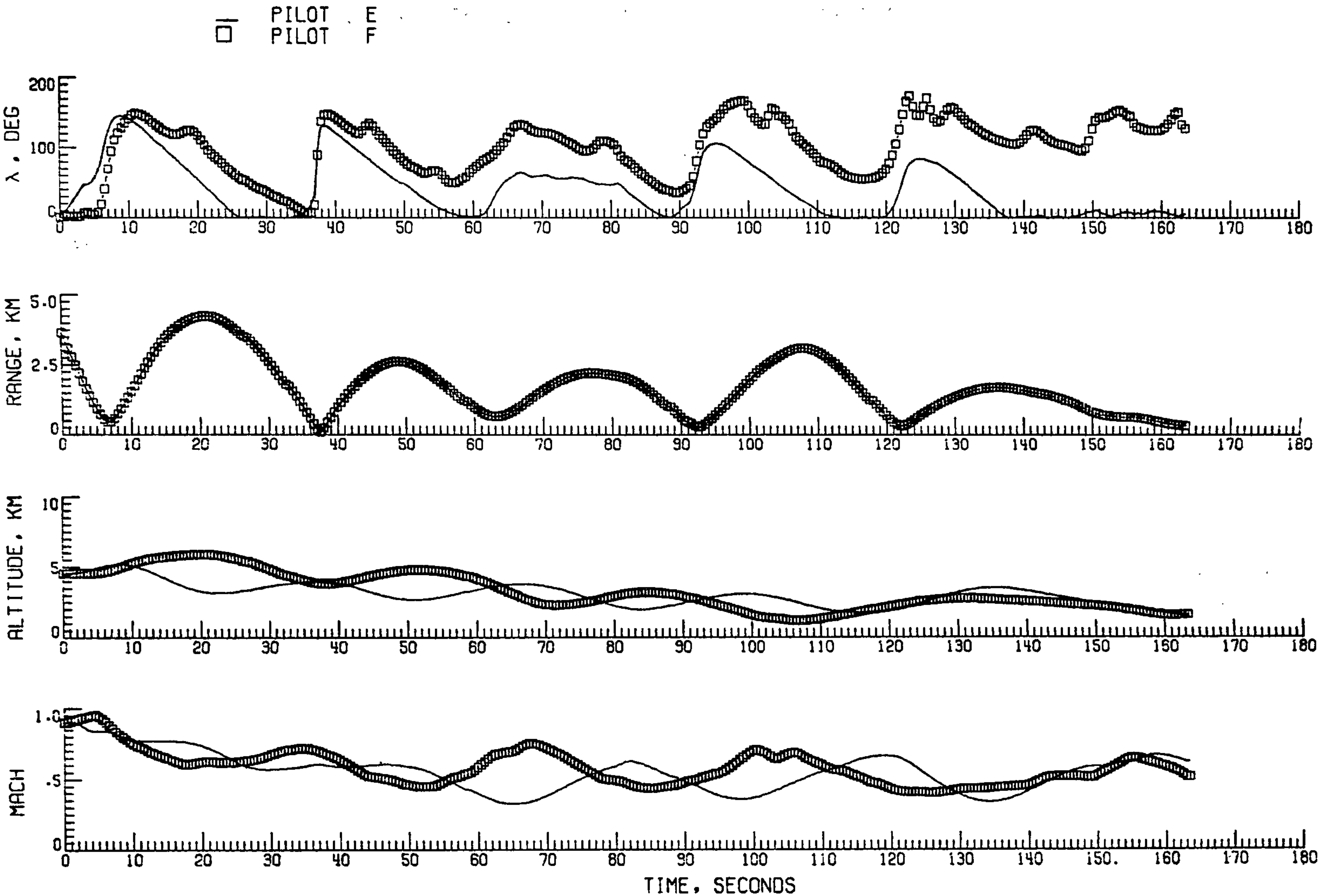


Figure 18.- Pilot-versus-pilot data set for run 12.

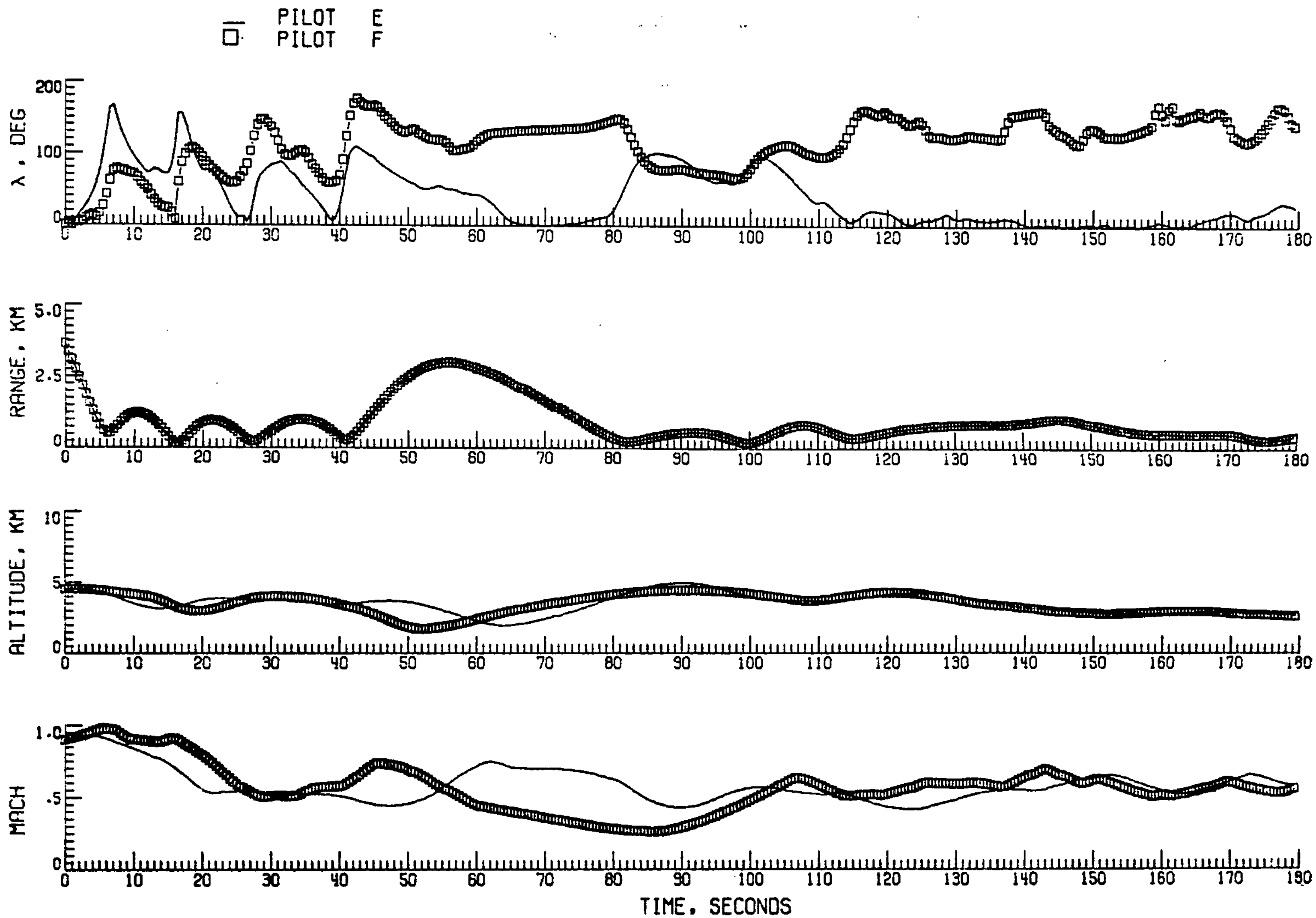


Figure 19.- Pilot-versus-pilot data set for run 13.

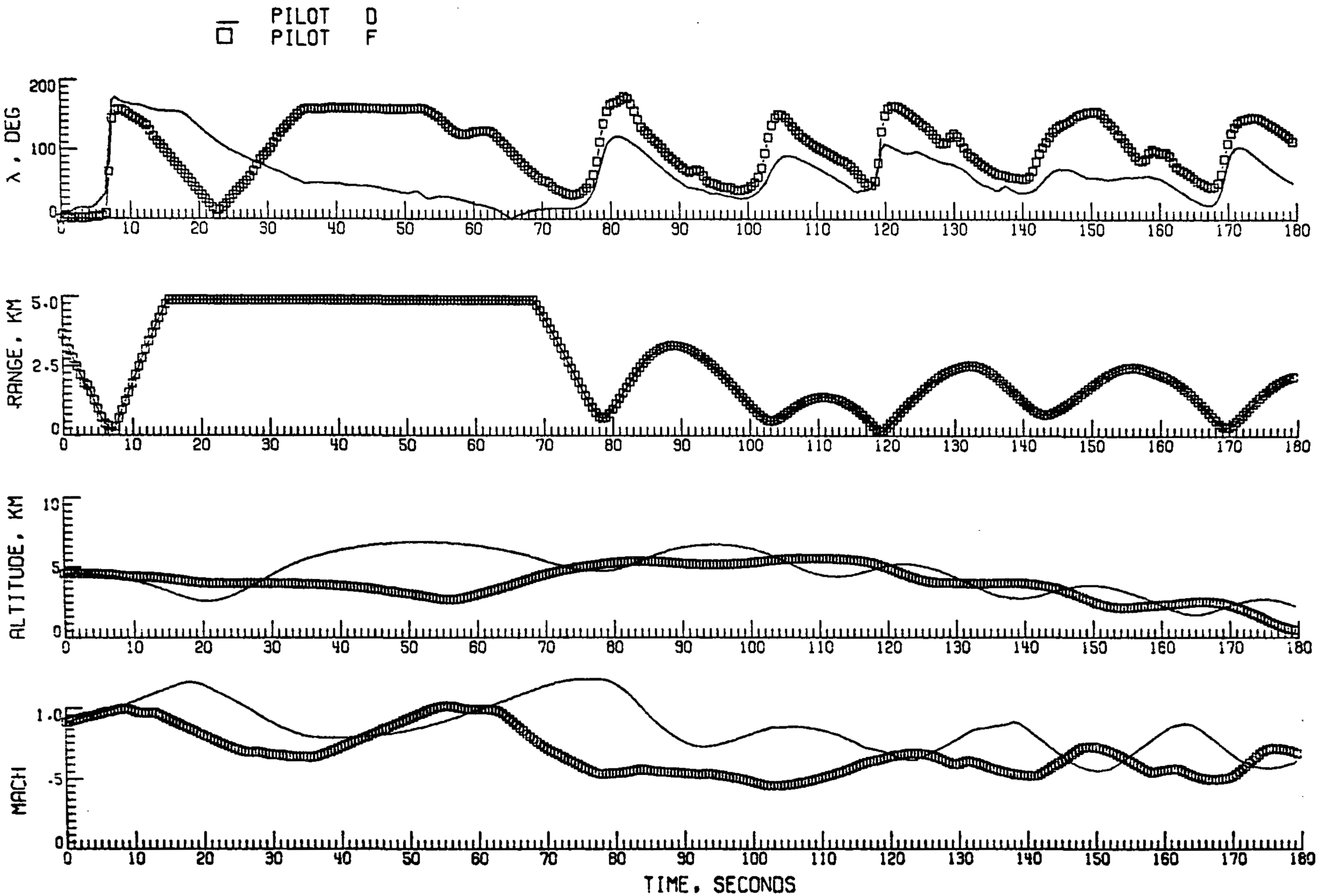


Figure 20.- Pilot-versus-pilot data set for run 14.

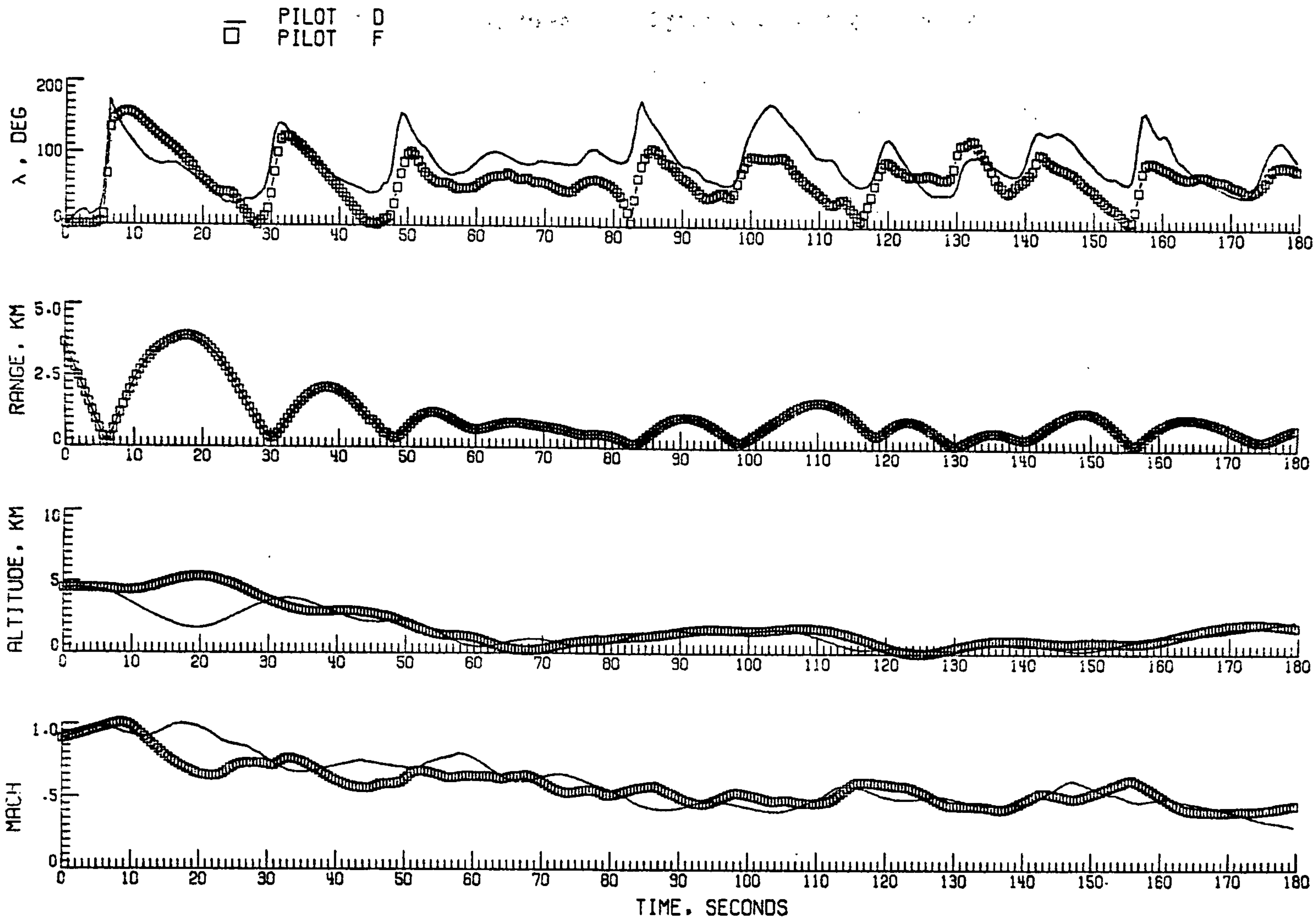


Figure 21.- Pilot-versus-pilot data set for run 15.

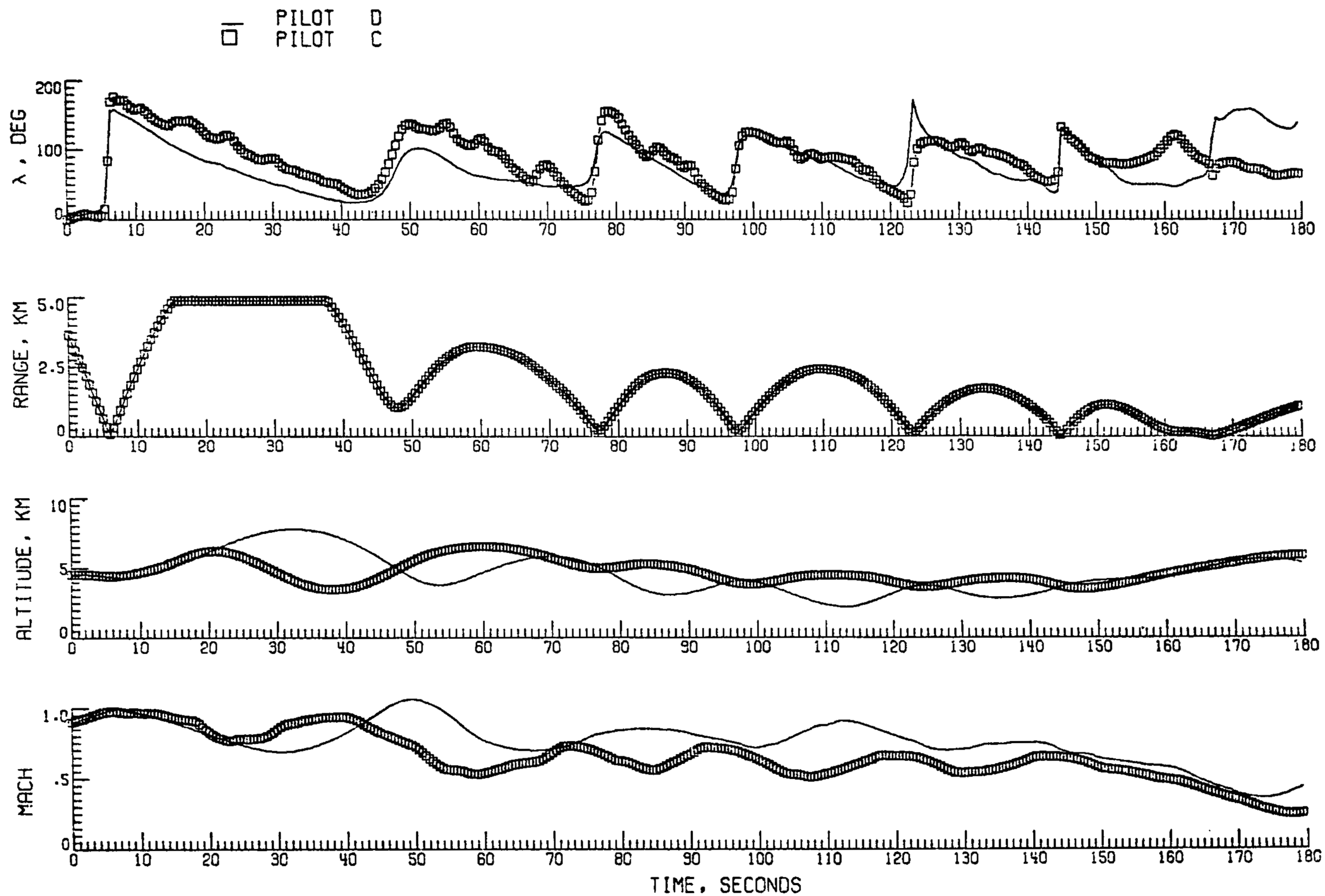


Figure 22.- Pilot-versus pilot data set for run 16.

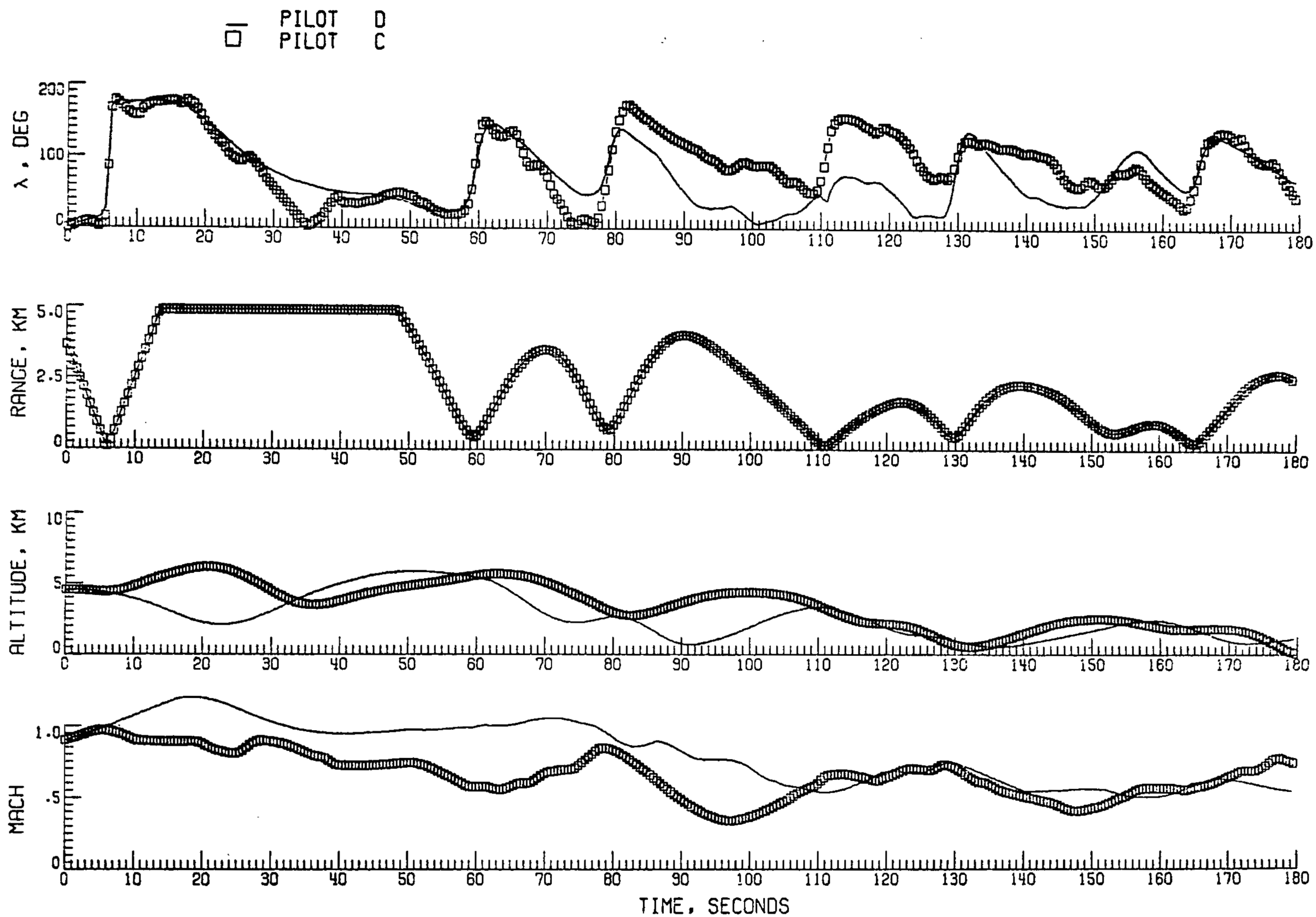


Figure 23.- Pilot-versus-pilot data set for run 17.

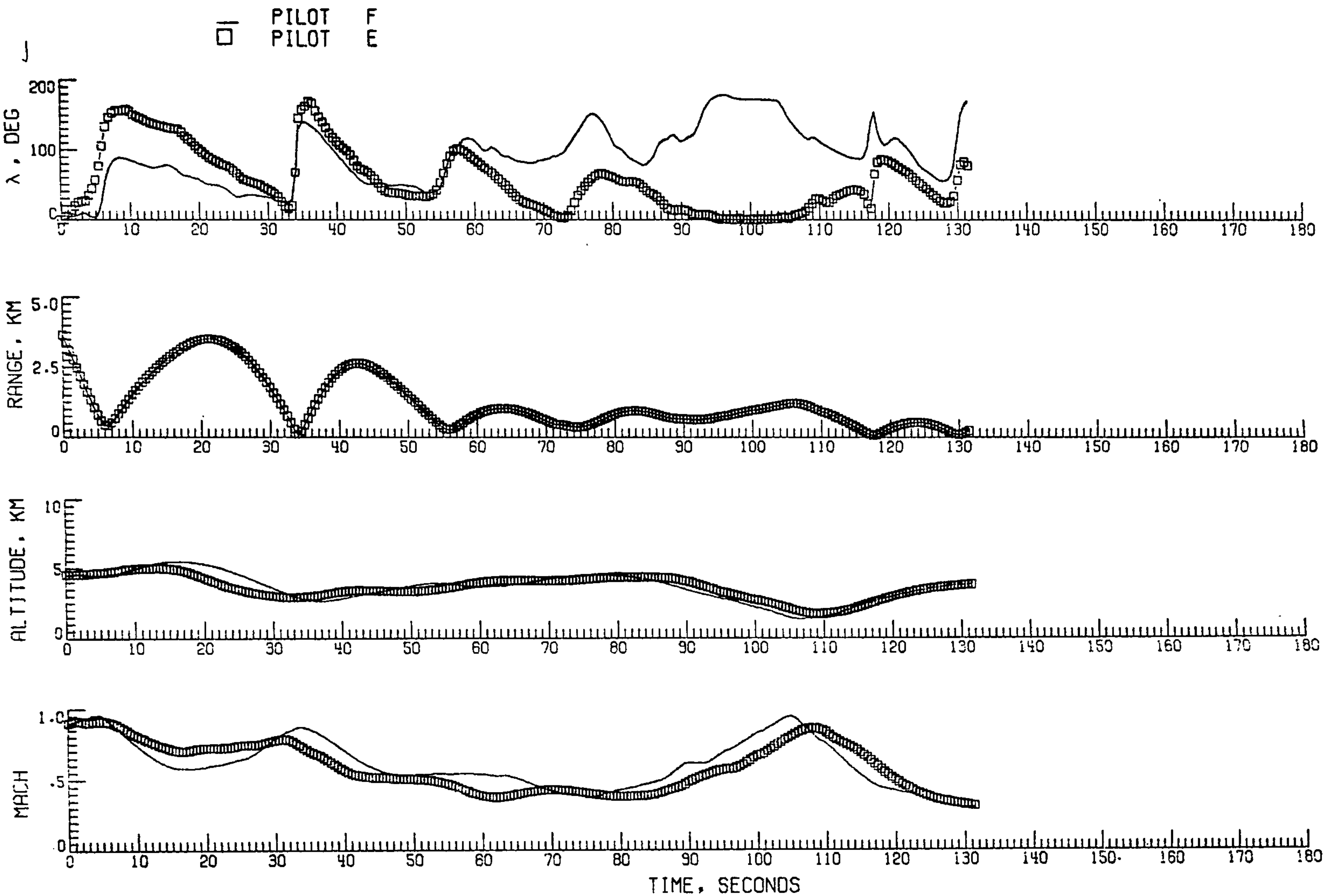


Figure 24.- Pilot-versus-pilot data set for run 18.

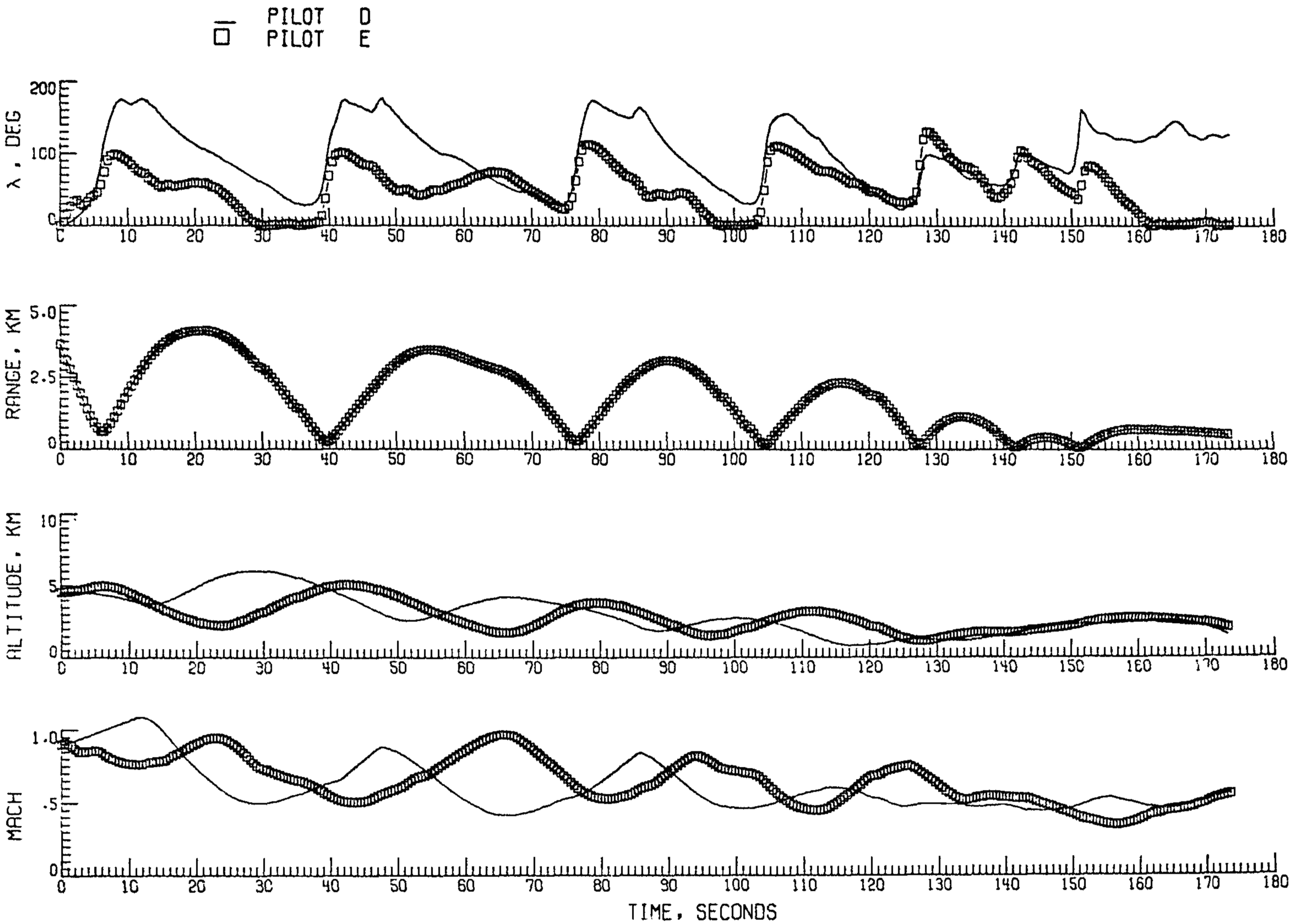


Figure 25.- Pilot-versus-pilot data set for run 19.

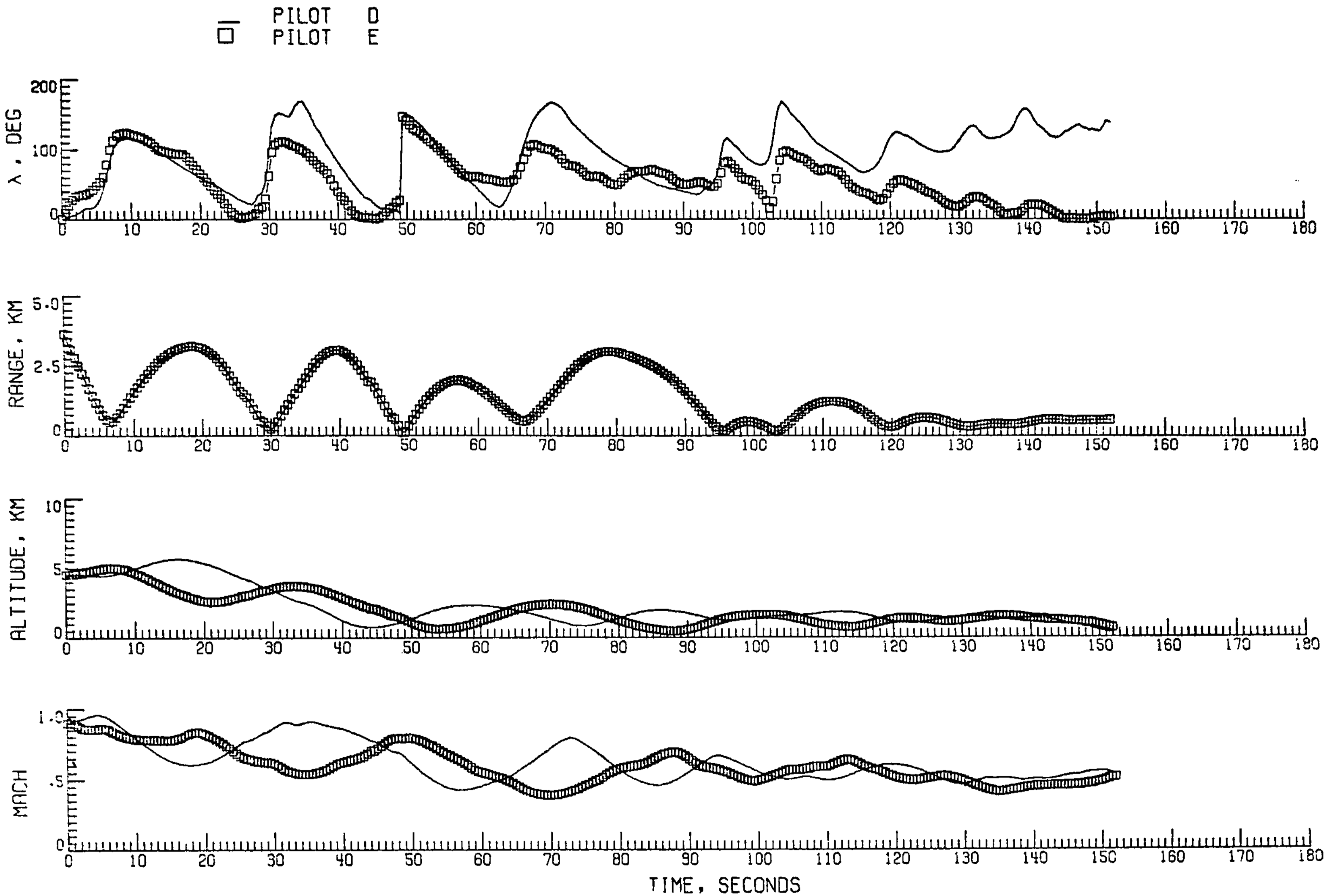


Figure 26.- Pilot-versus pilot data set for run 20.

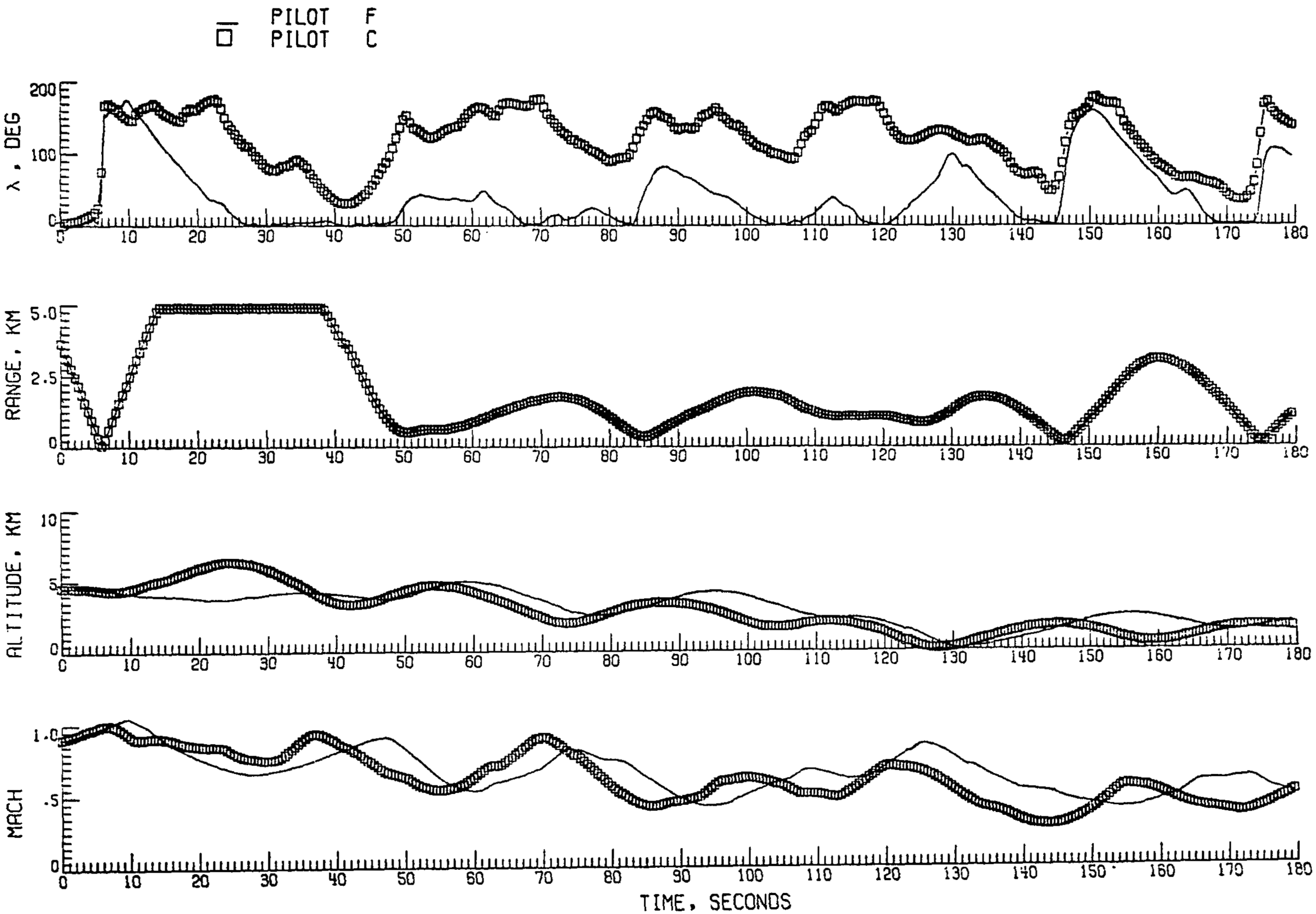


Figure 27.- Pilot-versus-pilot data set for run 21.

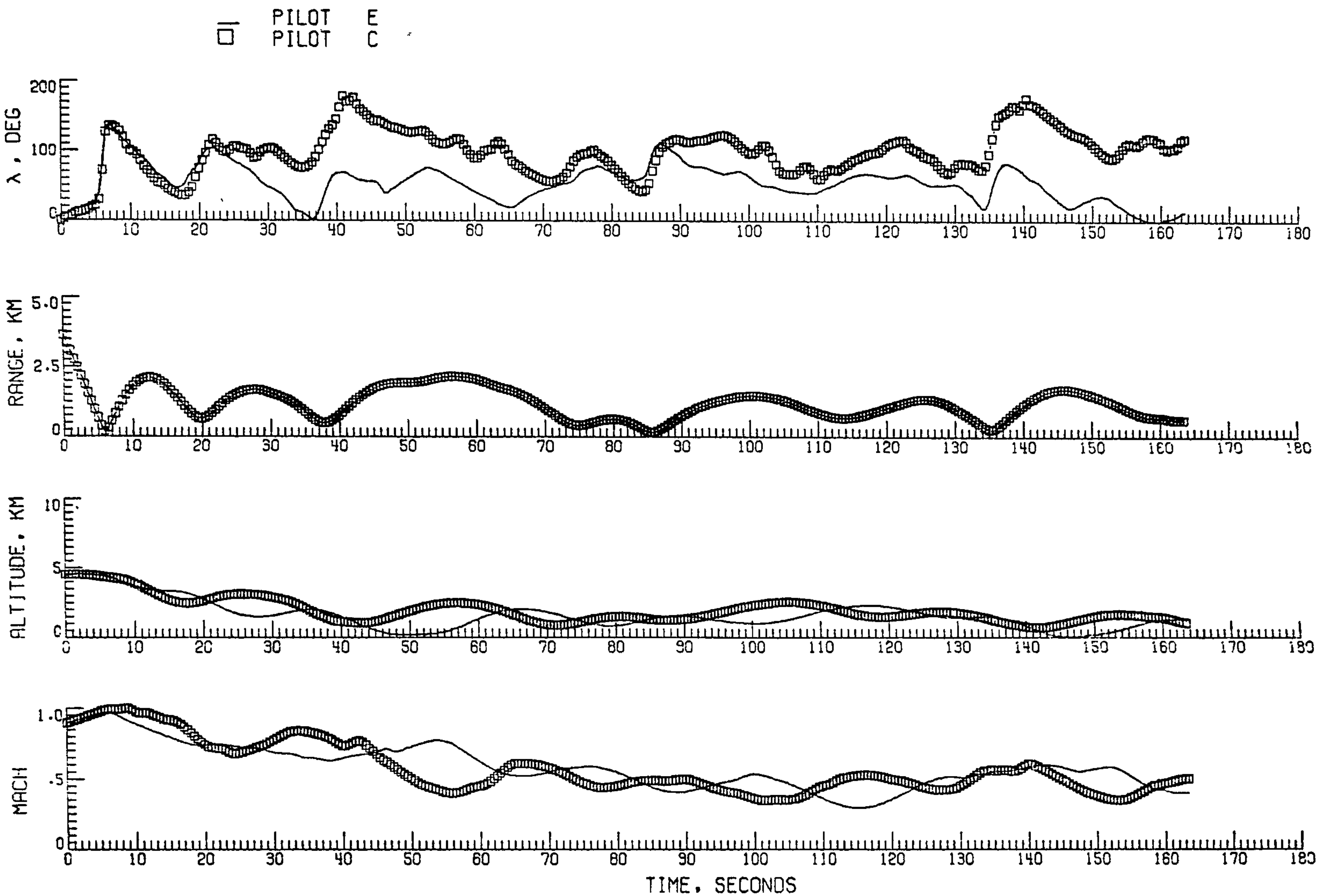


Figure 28.- Pilot-versus-pilot data set for run 22.

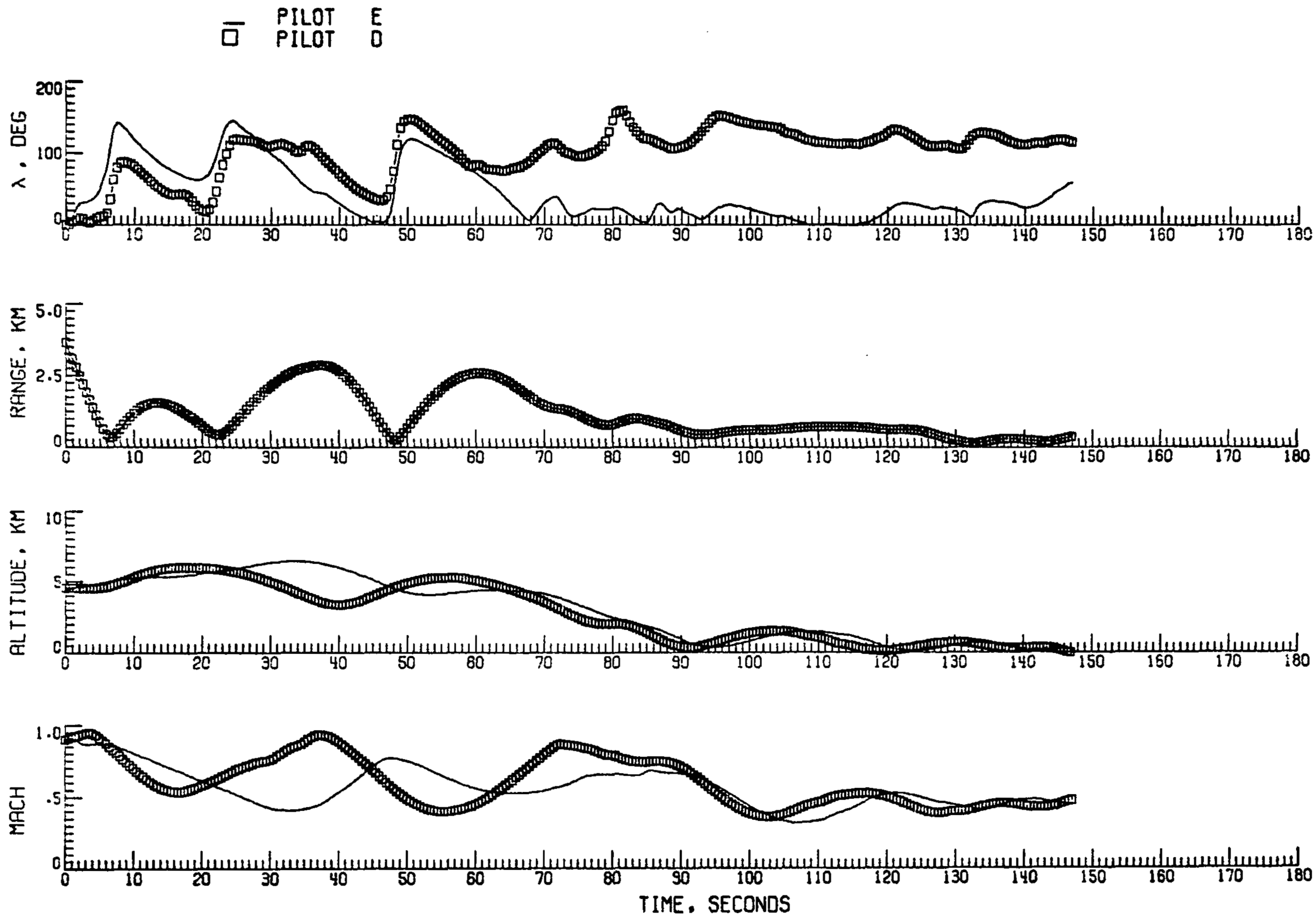


Figure 29.- Pilot-versus-pilot data set for run 23.

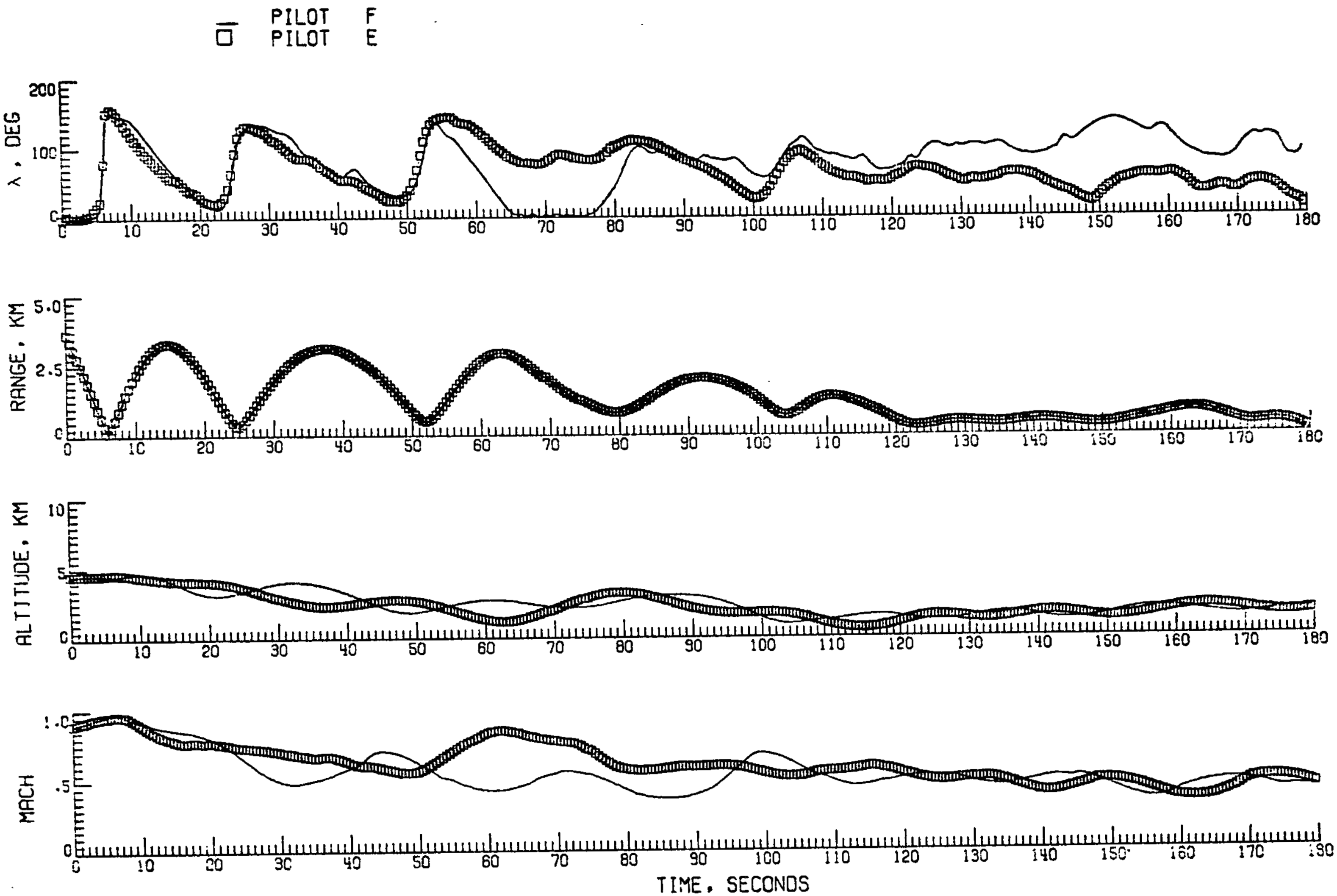


Figure 30.- Pilot-versus pilot data set for run 24.

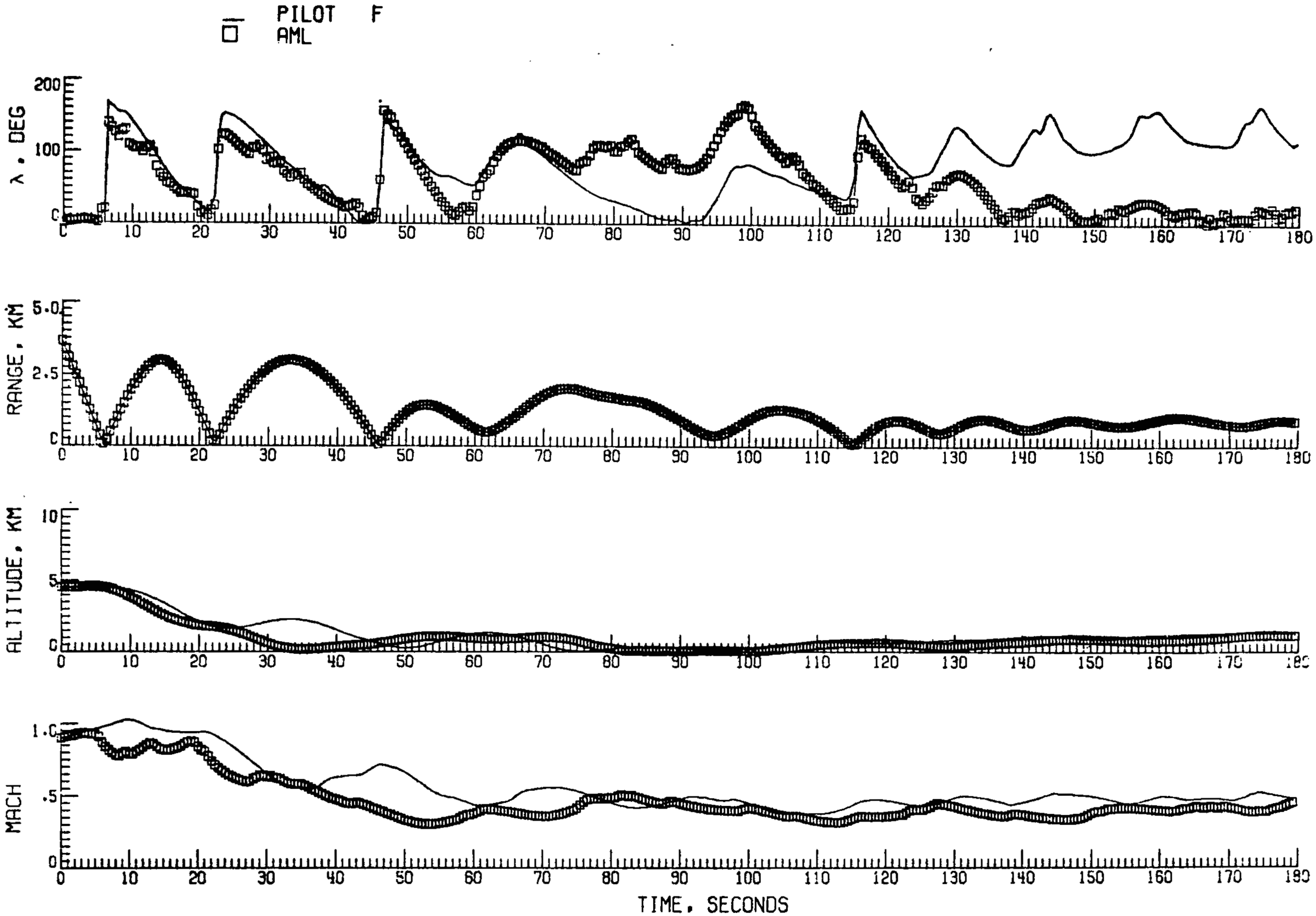


Figure 31.- Pilot-versus-AML-control-model data set for run 1.

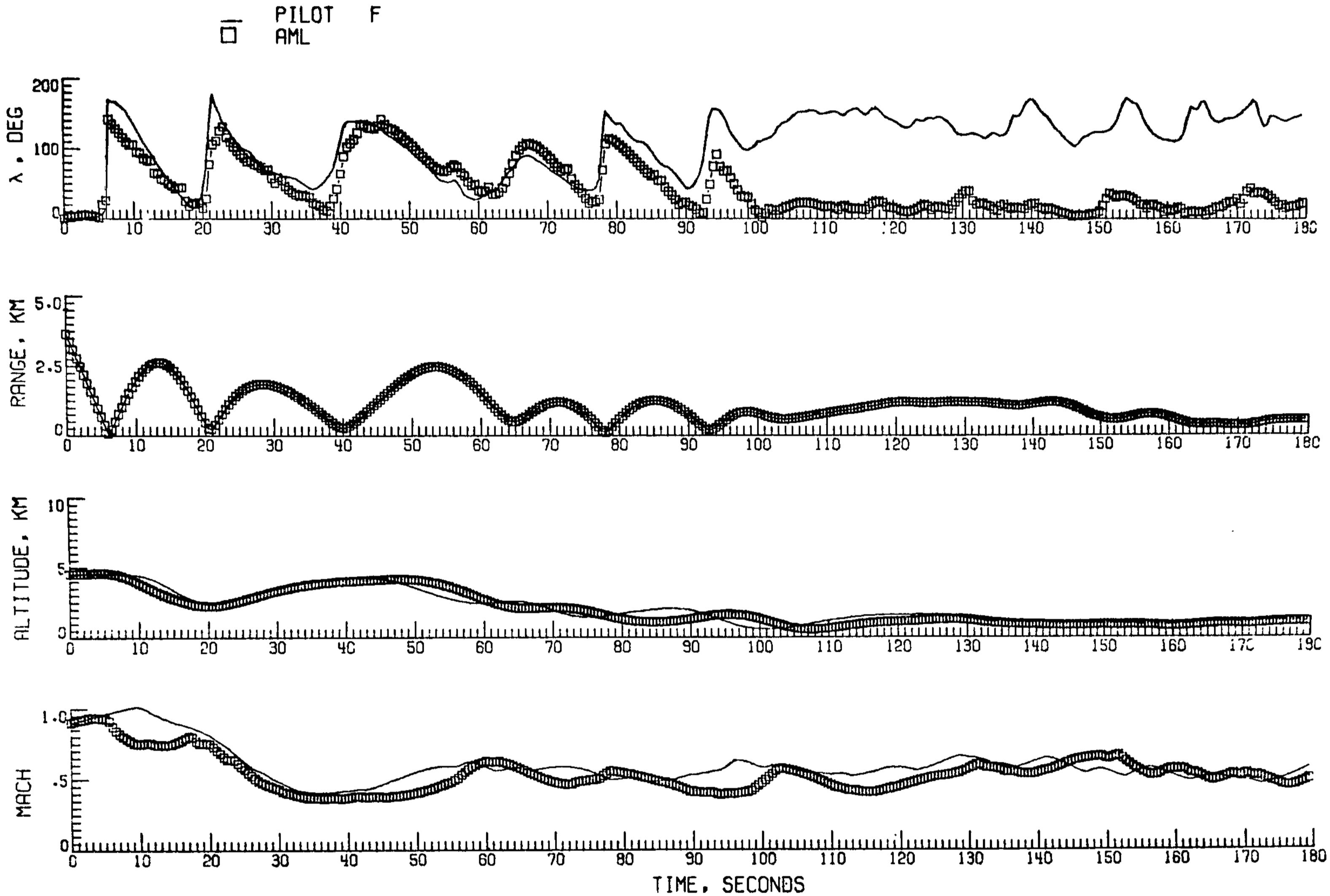


Figure 32.- Pilot-versus-AML-control-model data set for run 2.

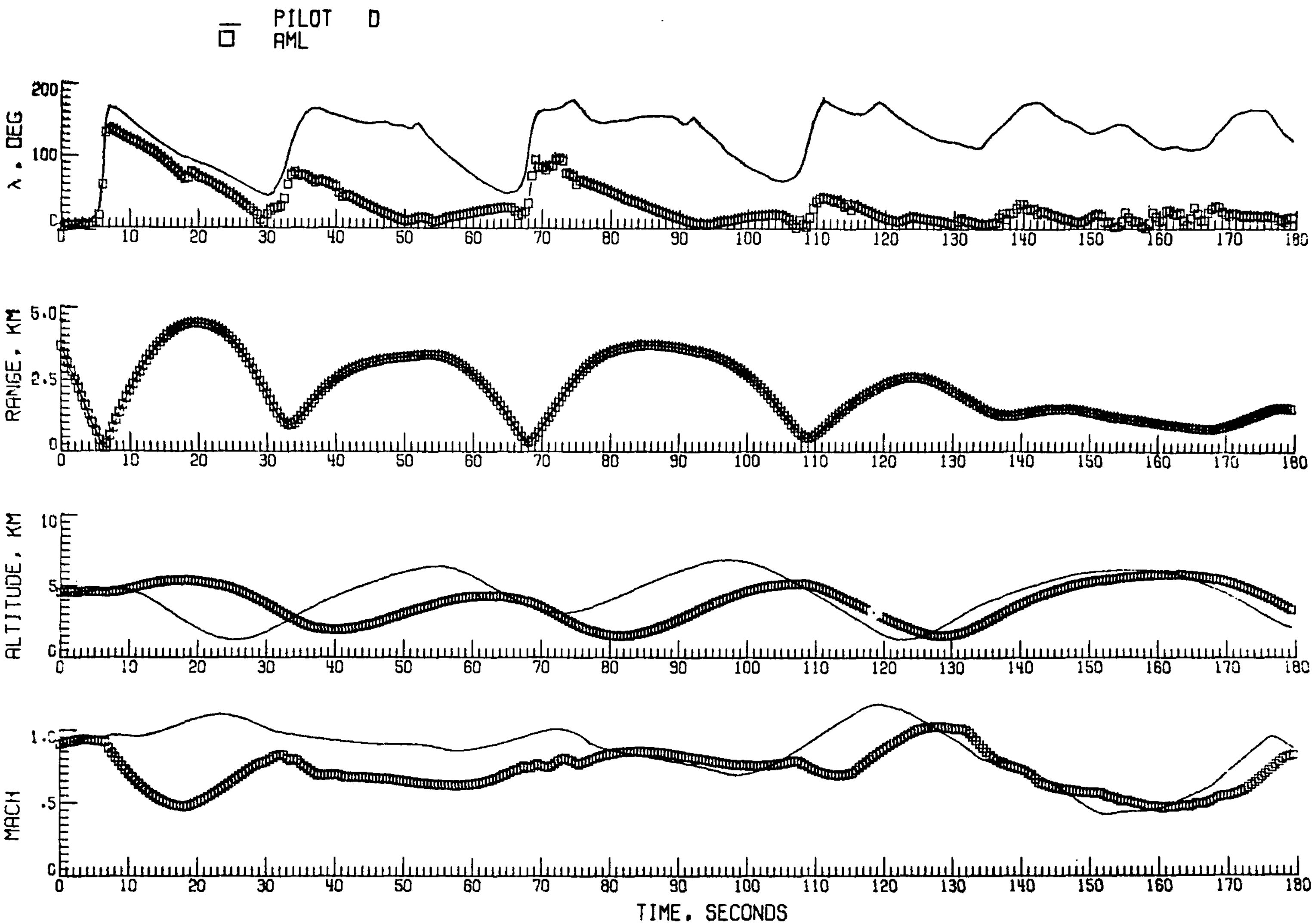


Figure 33.- Pilot-versus-AML-control-model data set for run 3.

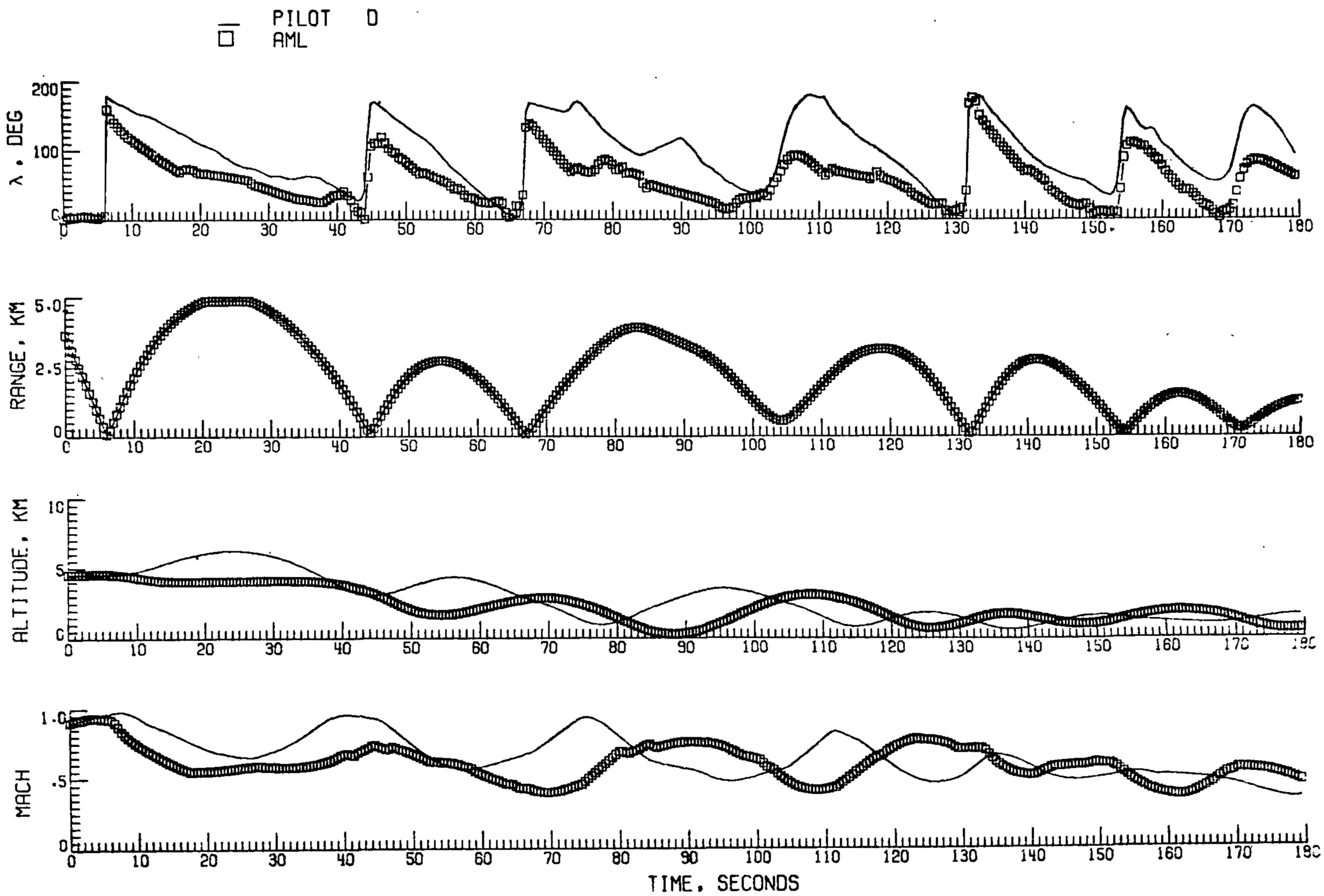


Figure 34.- Pilot-versus-AML-control-model data set for run 4.

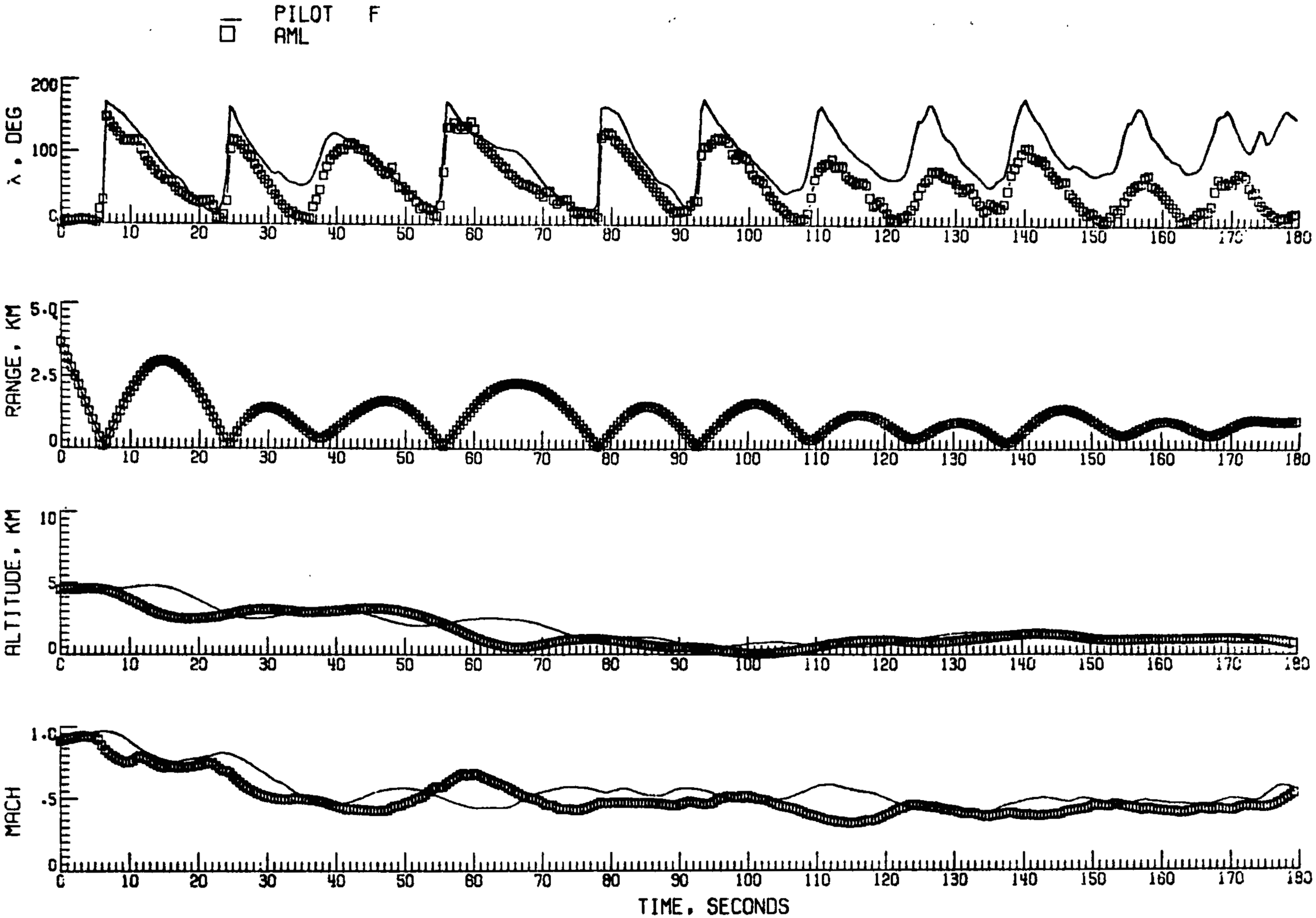


Figure 35.- Pilot-versus-AML-control-model data set for run 5.

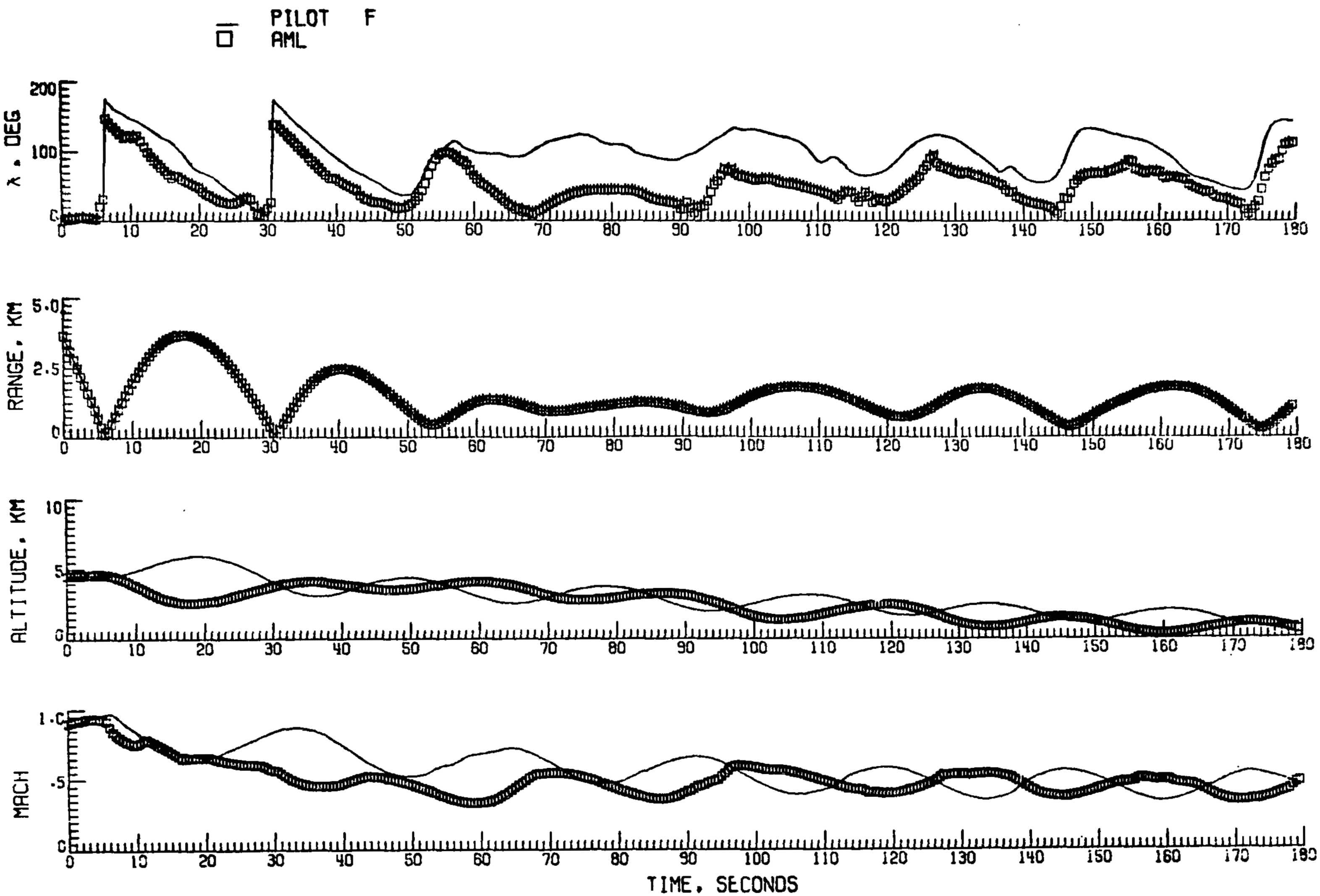


Figure 36.- Pilot-versus-AML-control-model data set for run 6.

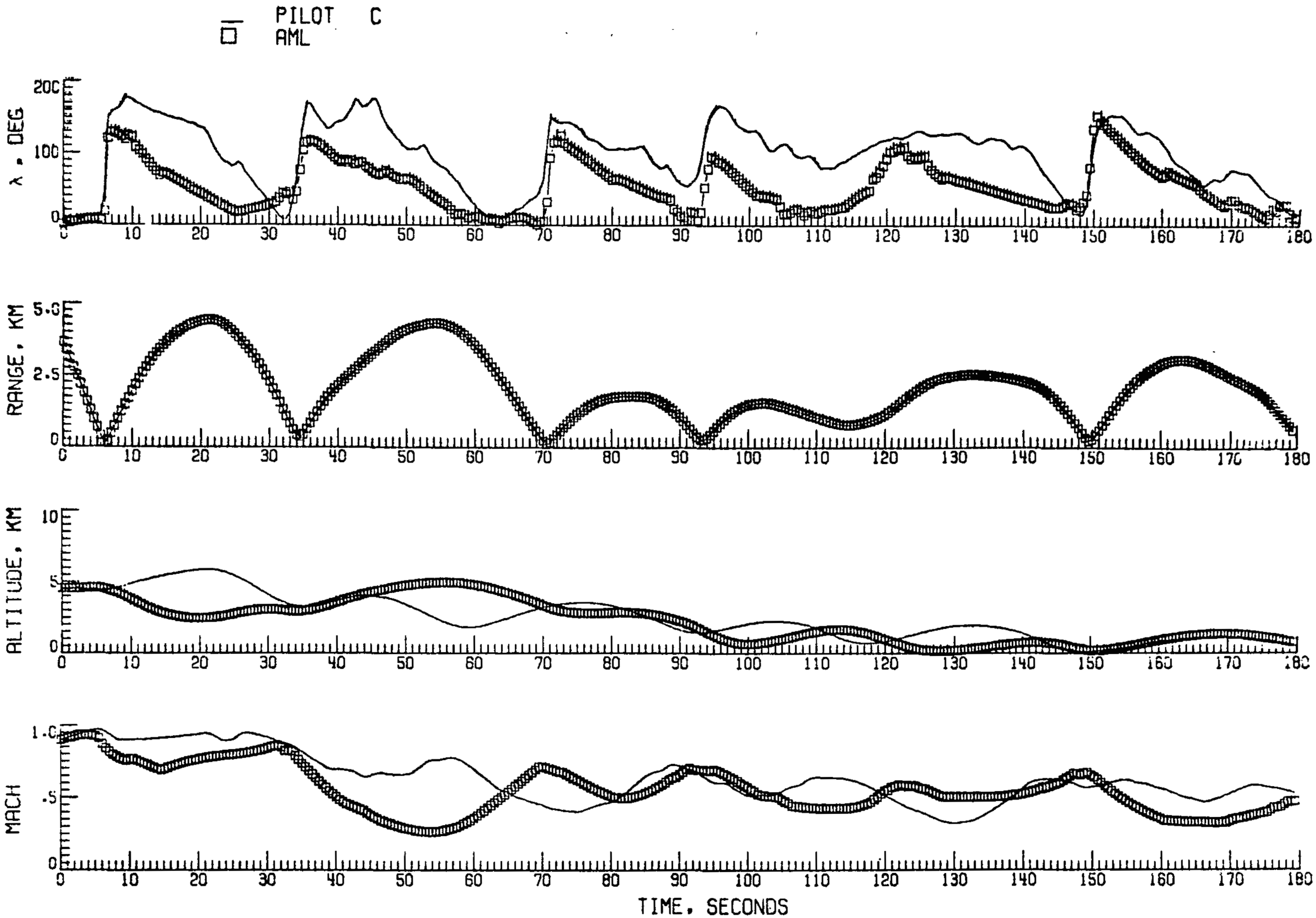


Figure 37.- Pilot-versus-AML-control-model data set for run 7.

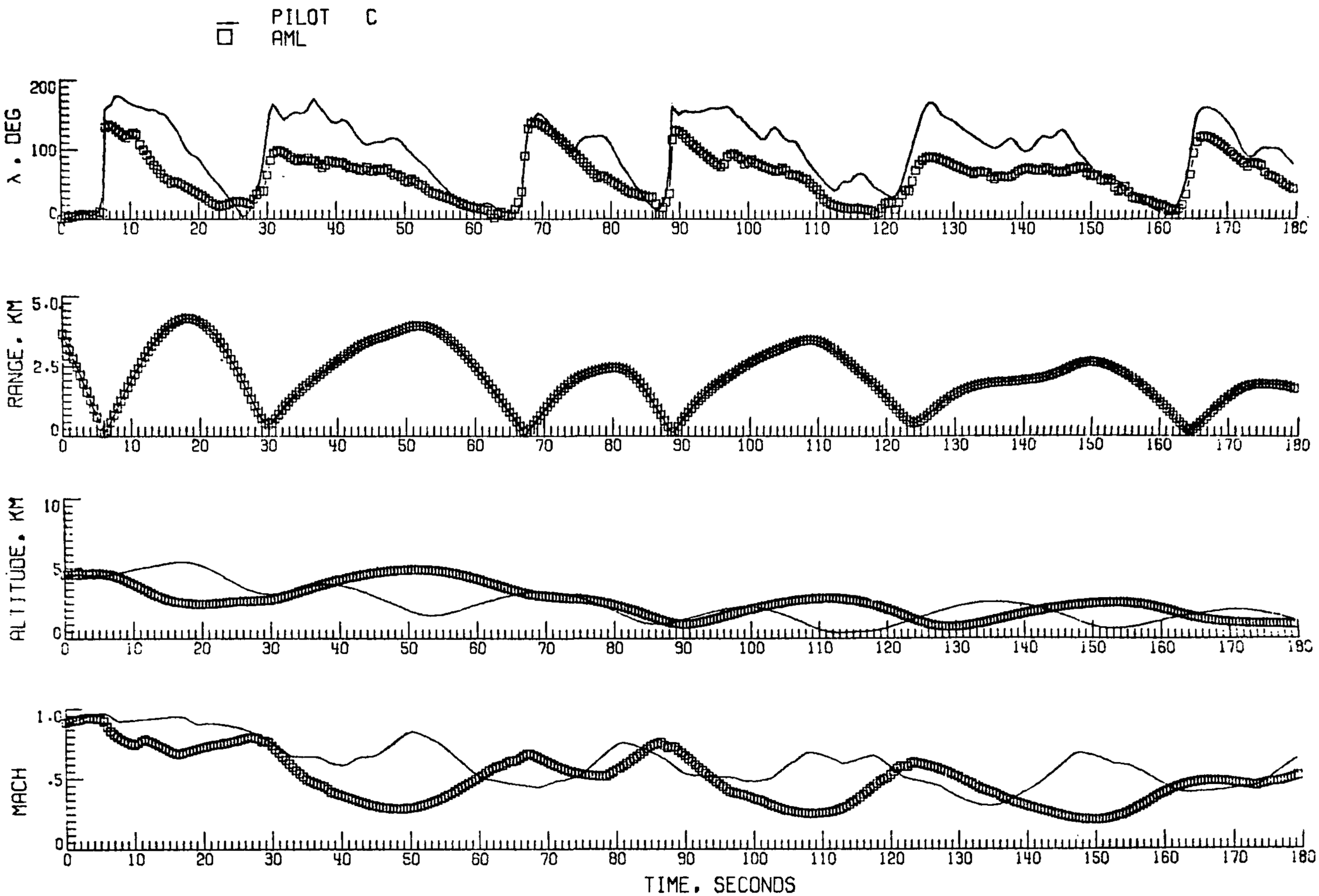


Figure 38.- Pilot-versus-AML-control-model data set for run 8.

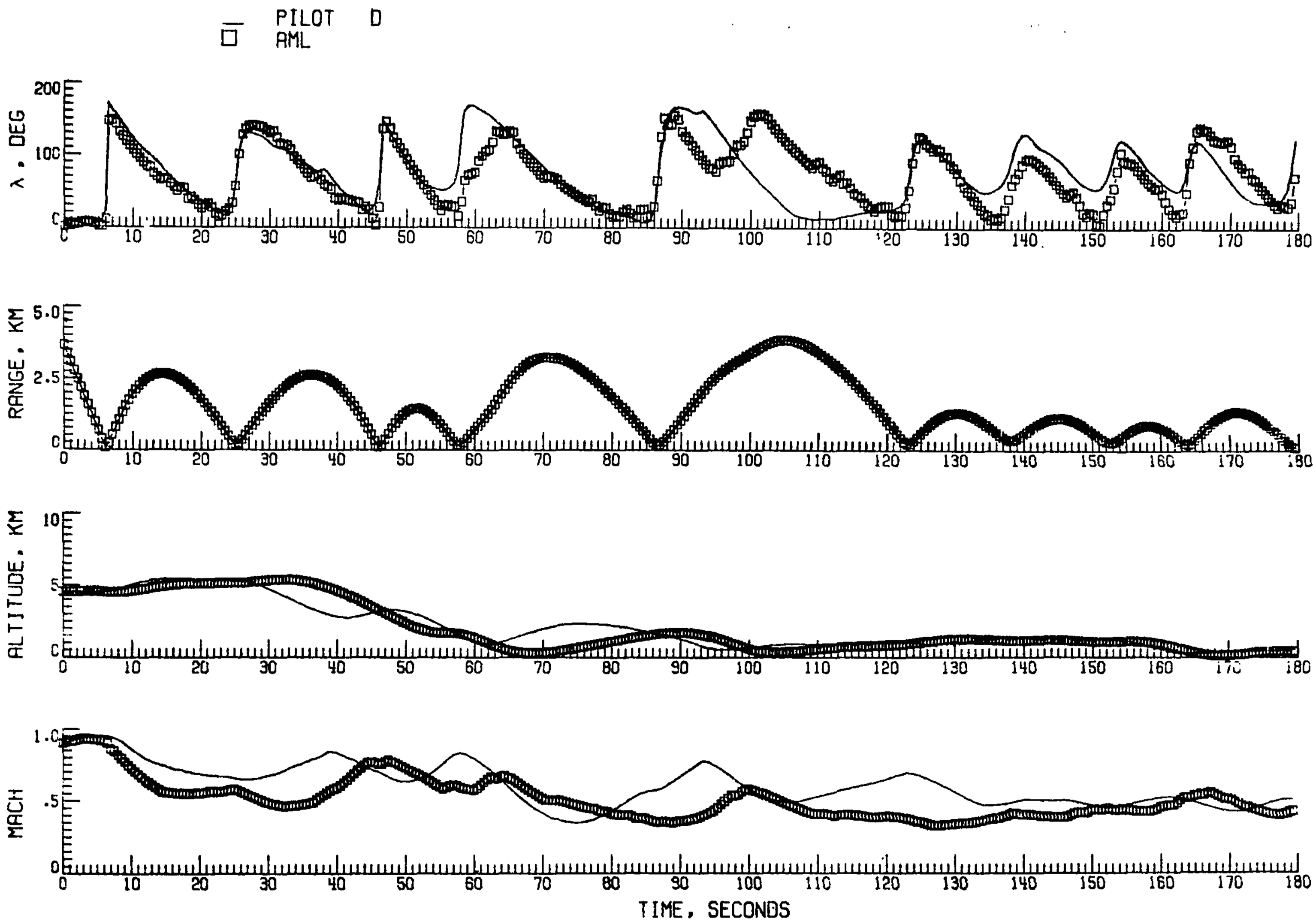


Figure 39.- Pilot-versus-AML-control-model data set for run 9.

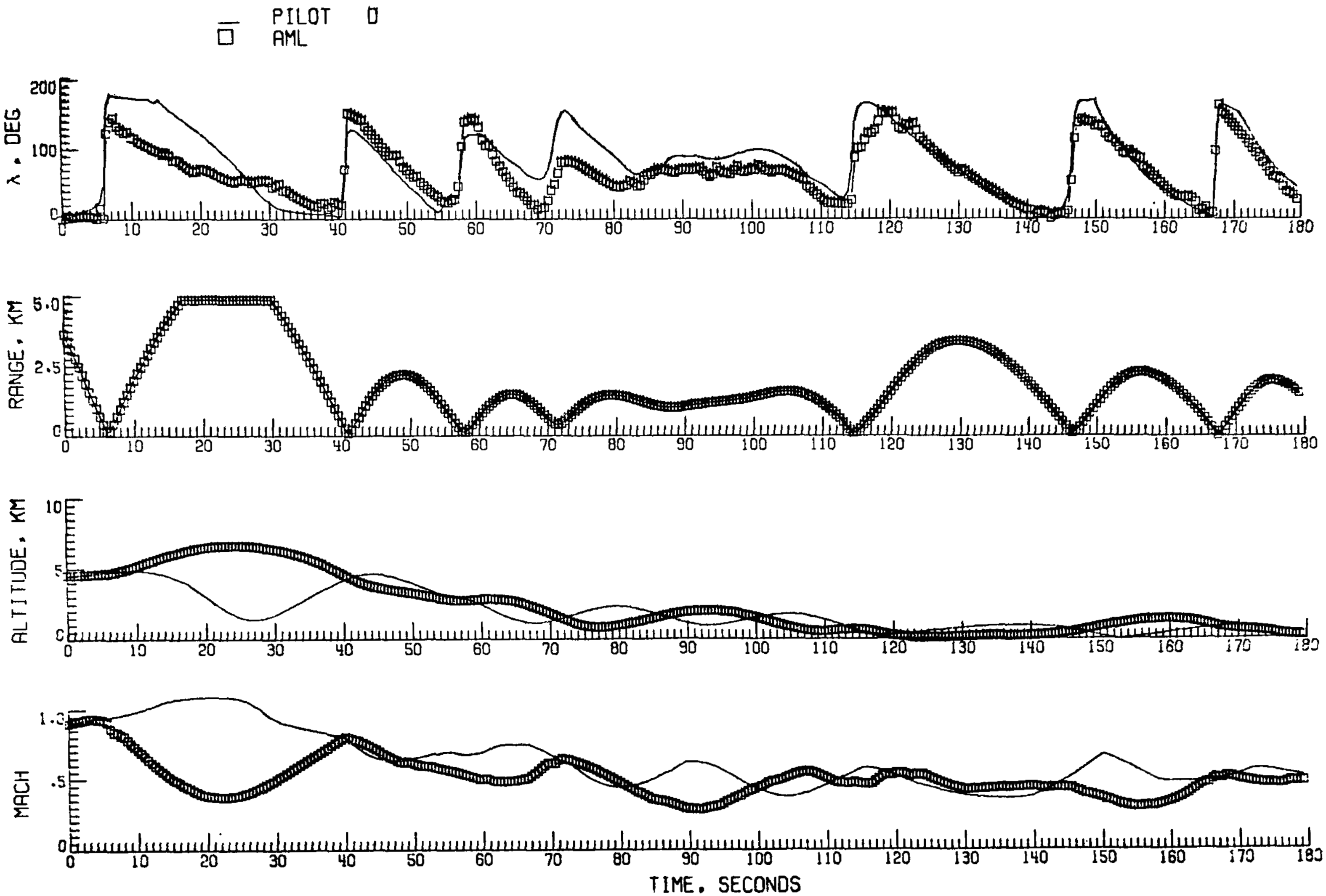


Figure 40.- Pilot-versus-AML-control-model data set for run 10.

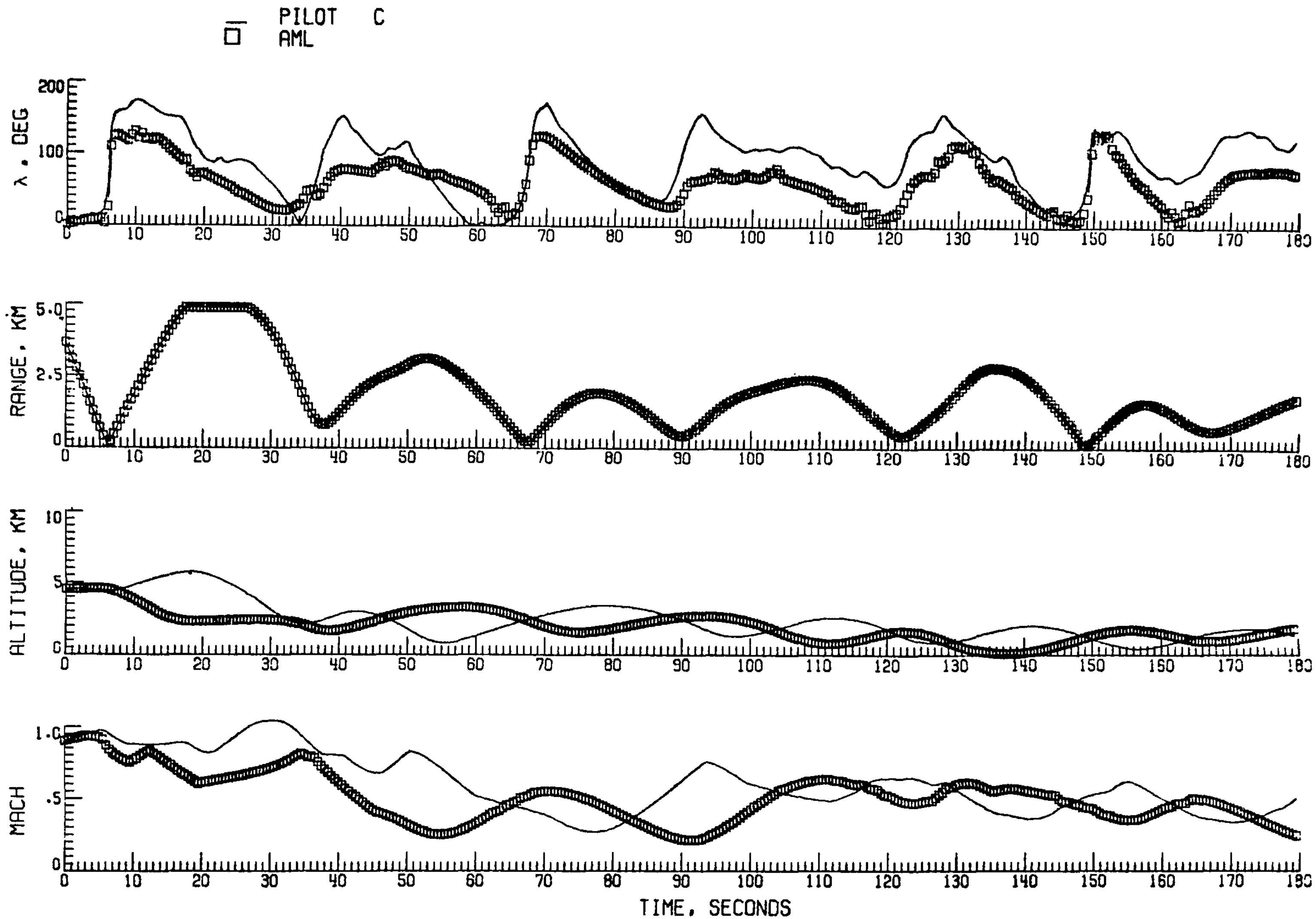


Figure 41.- Pilot-versus-AML-control-model data set for run 11.

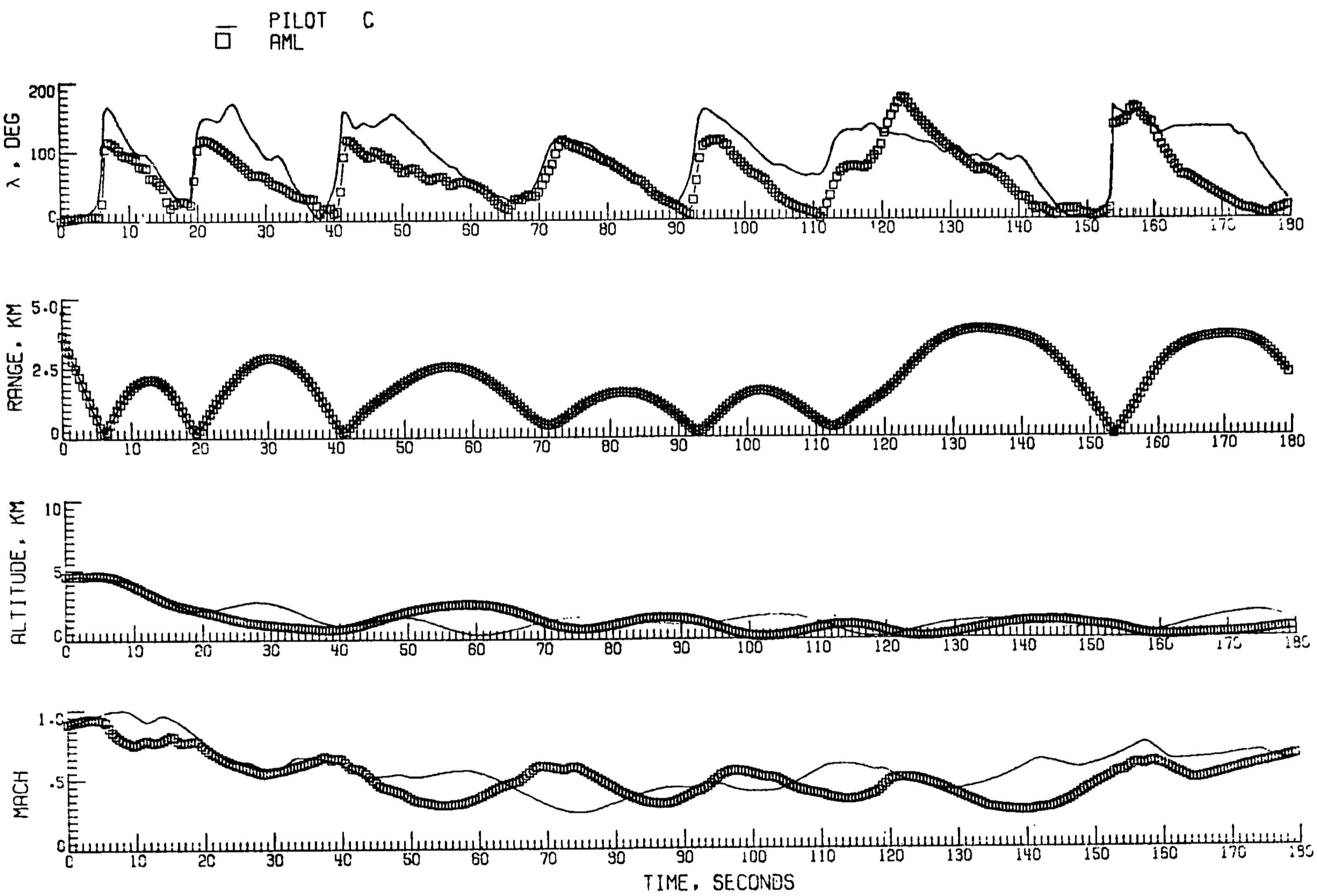


Figure 42.- Pilot-versus-AML-control-model data set for run 12.

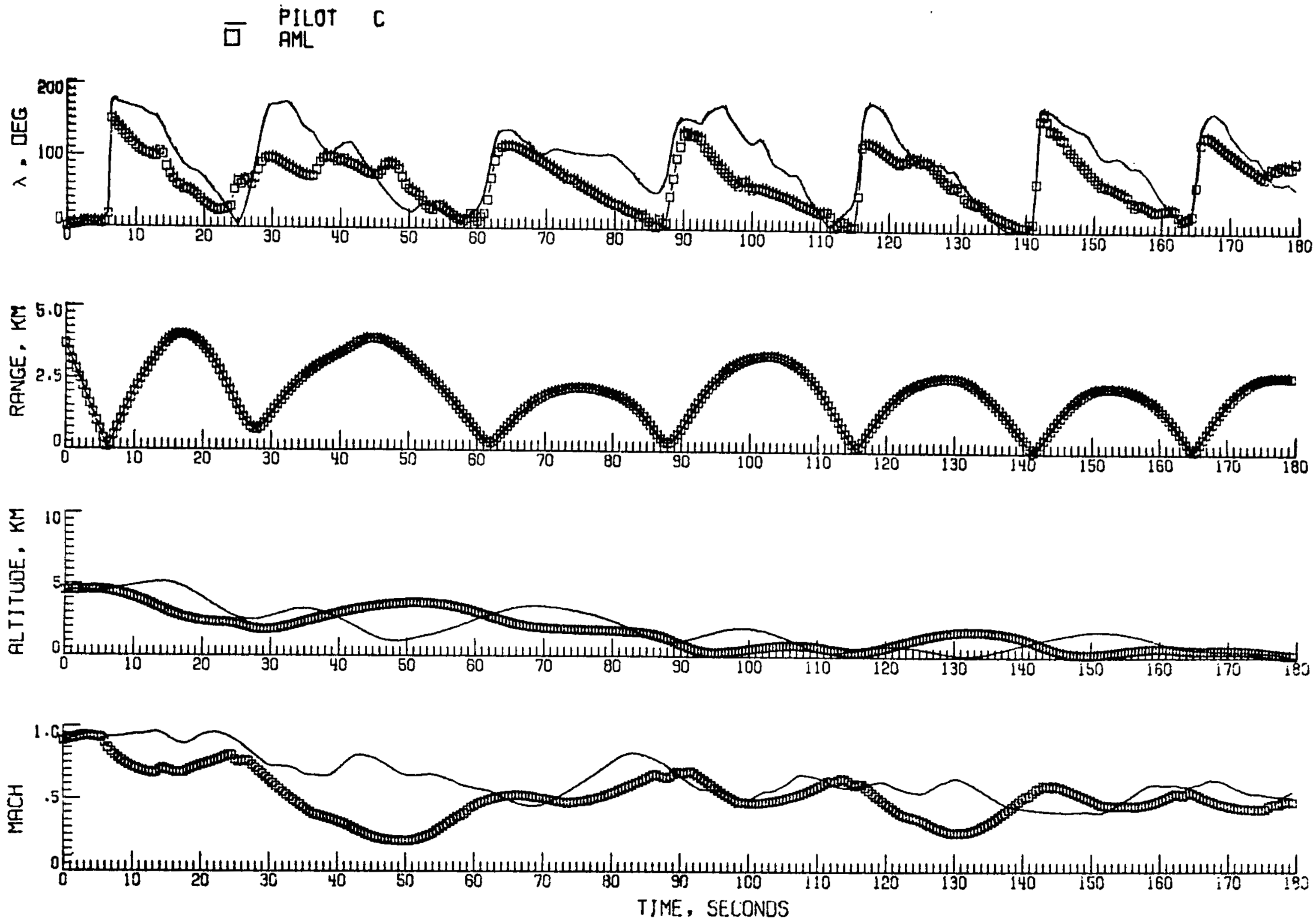


Figure 43.- Pilot-versus-AML-control-model data set for run 13.

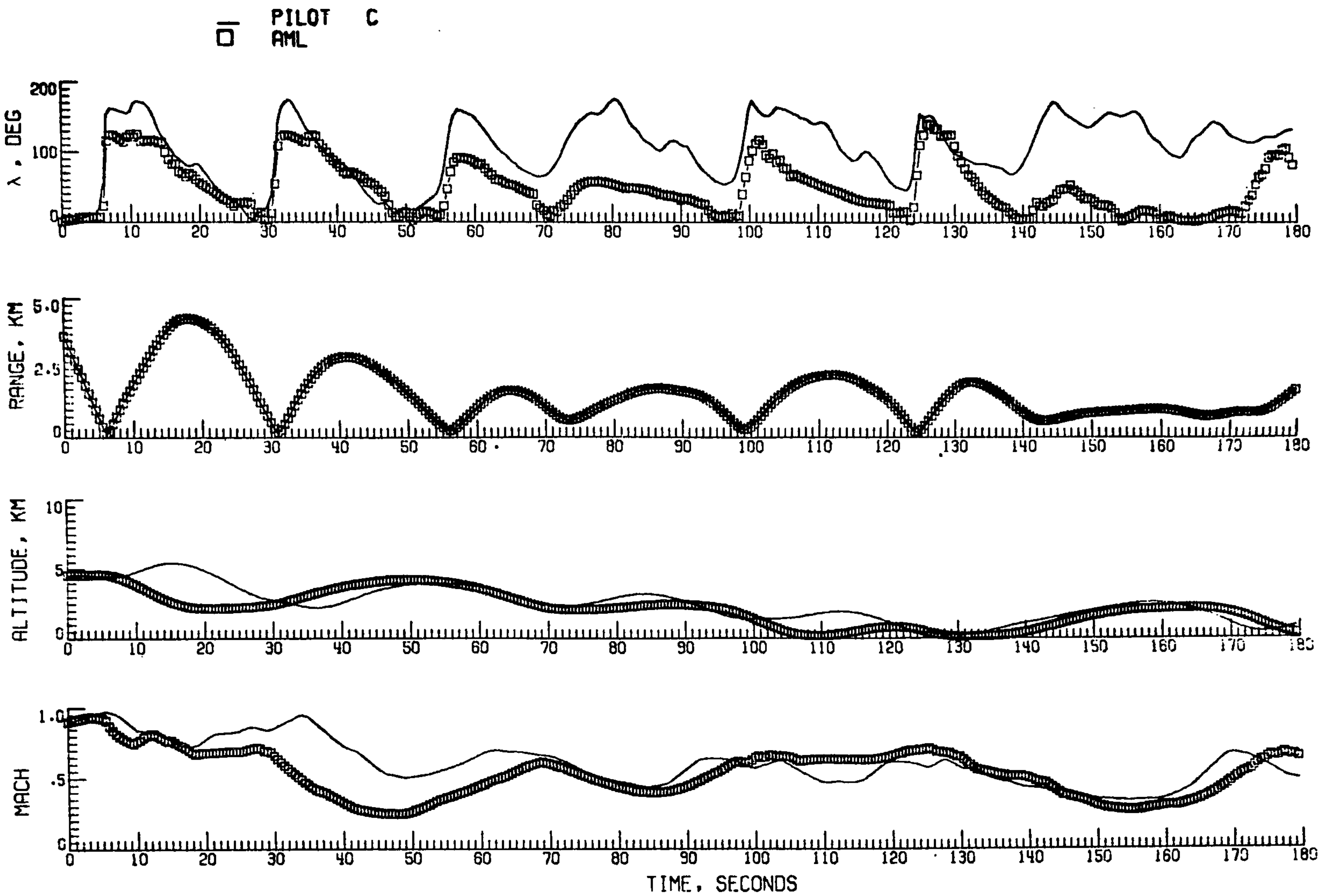


Figure 44.- Pilot-versus-AML-control-model data set for run 14.

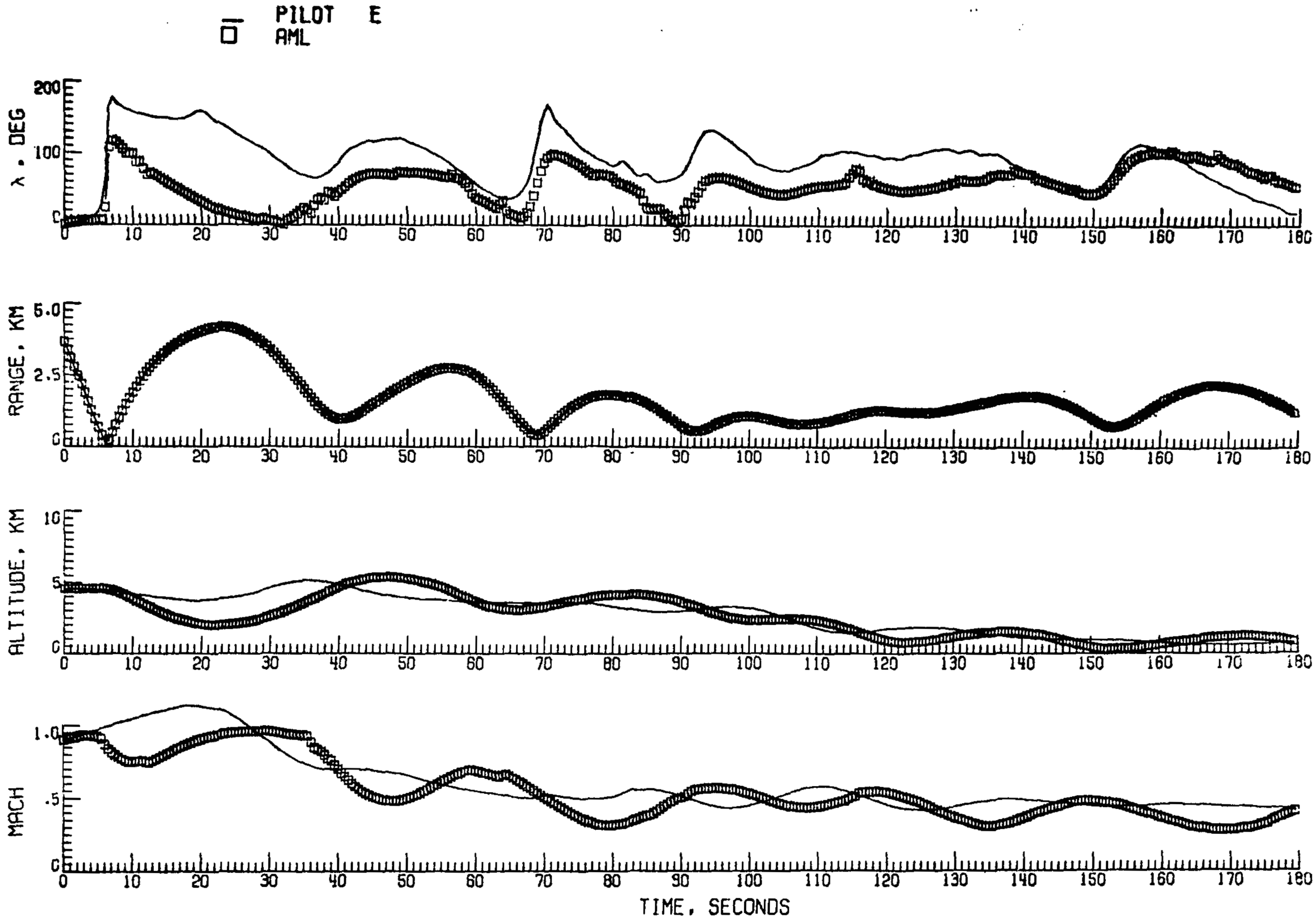


Figure 45.- Pilot-versus-AML-control-model data set for run 15.

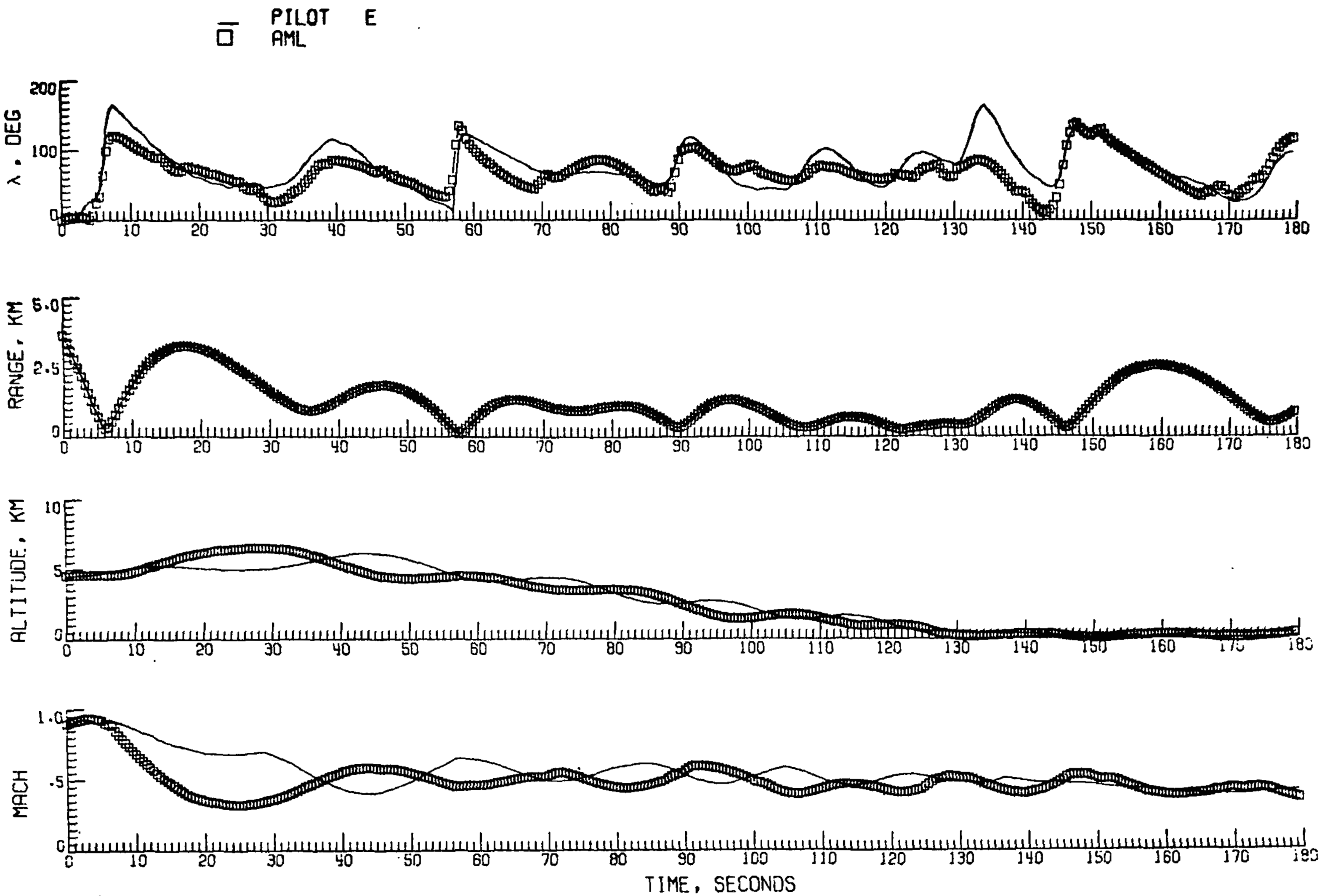


Figure 46.- Pilot-versus-AML-control-model data set for run 16.

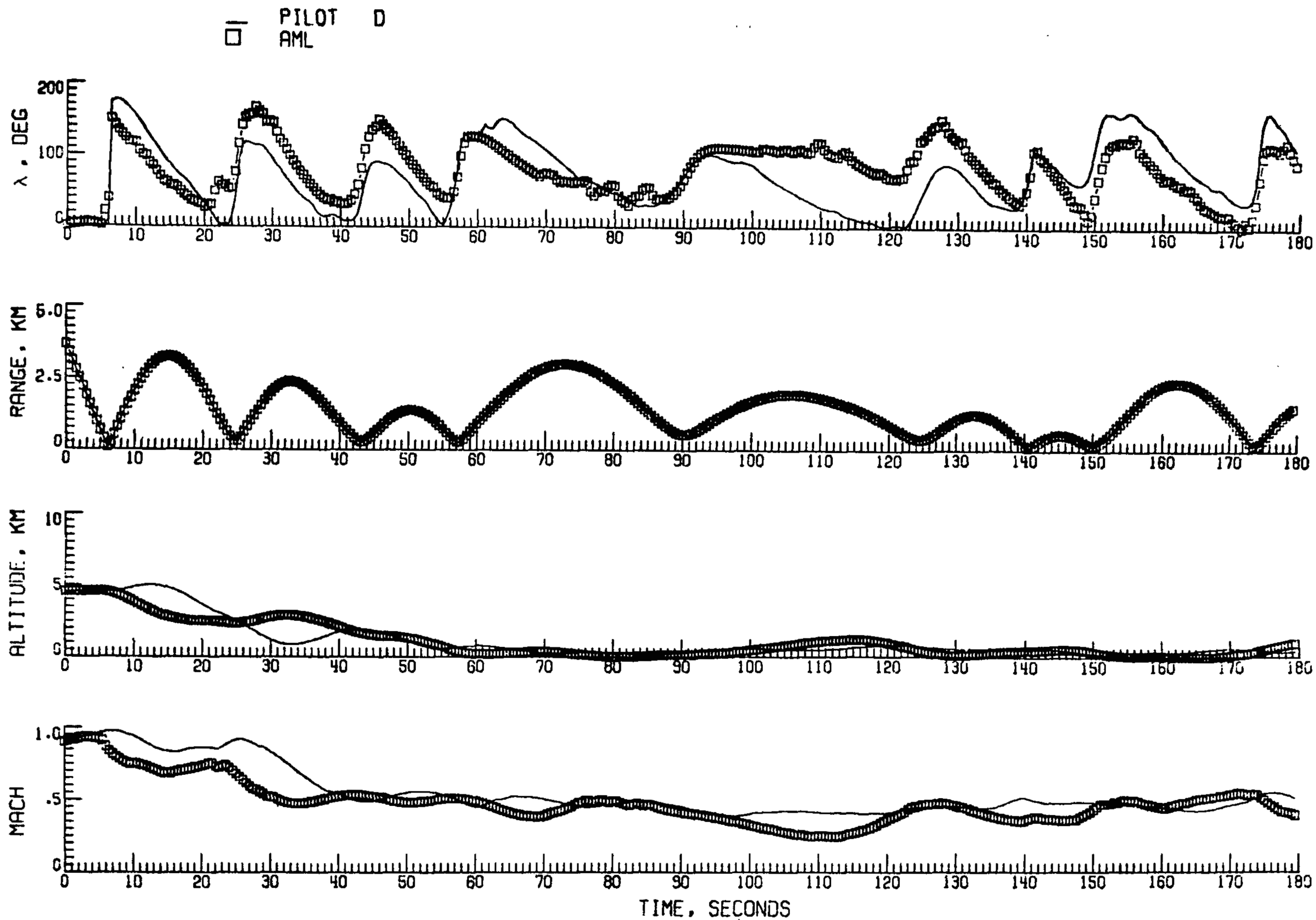


Figure 47.- Pilot-versus-AML-control-model data set for run 17.

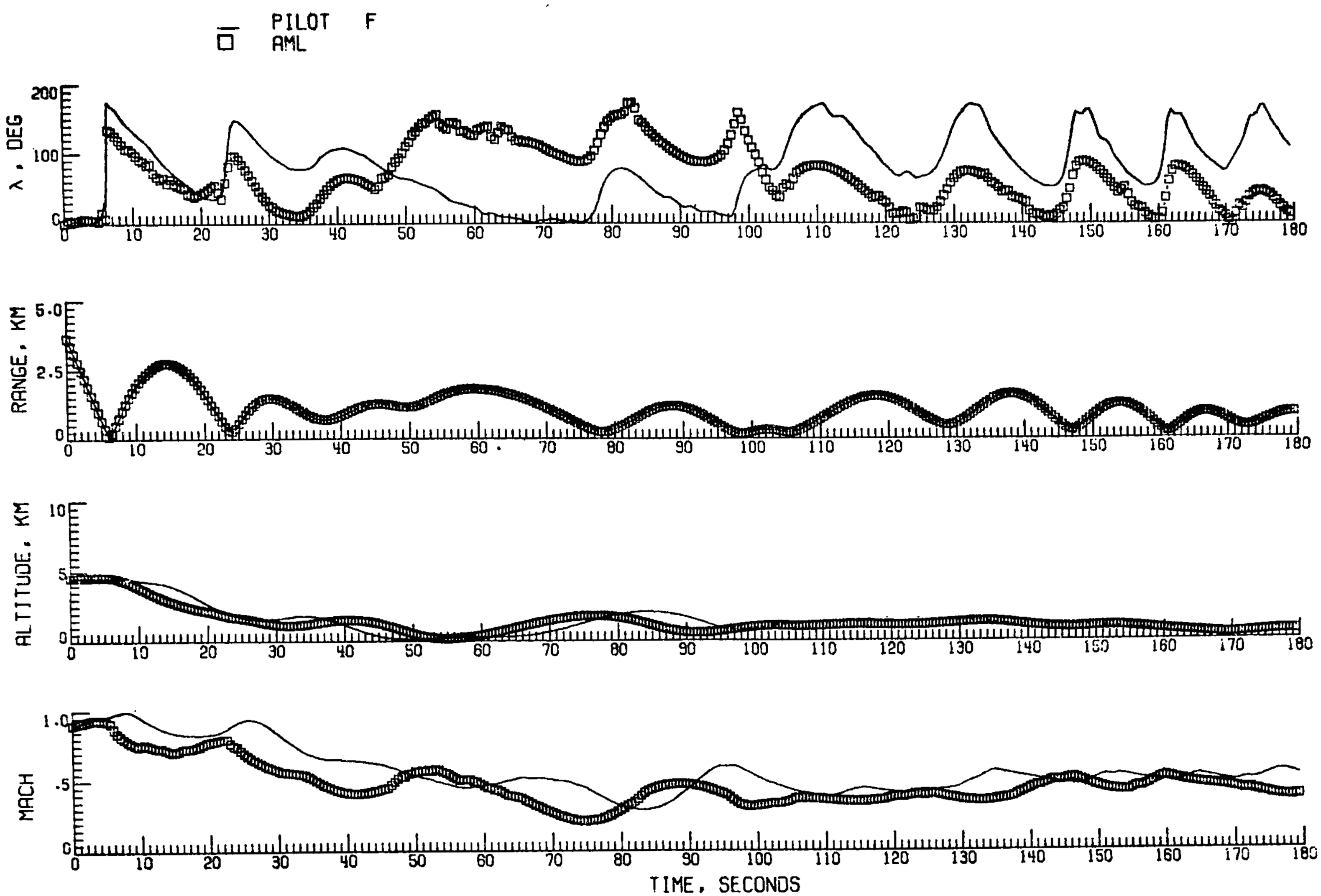


Figure 48.- Pilot-versus-AML-control-model data set for run 18.

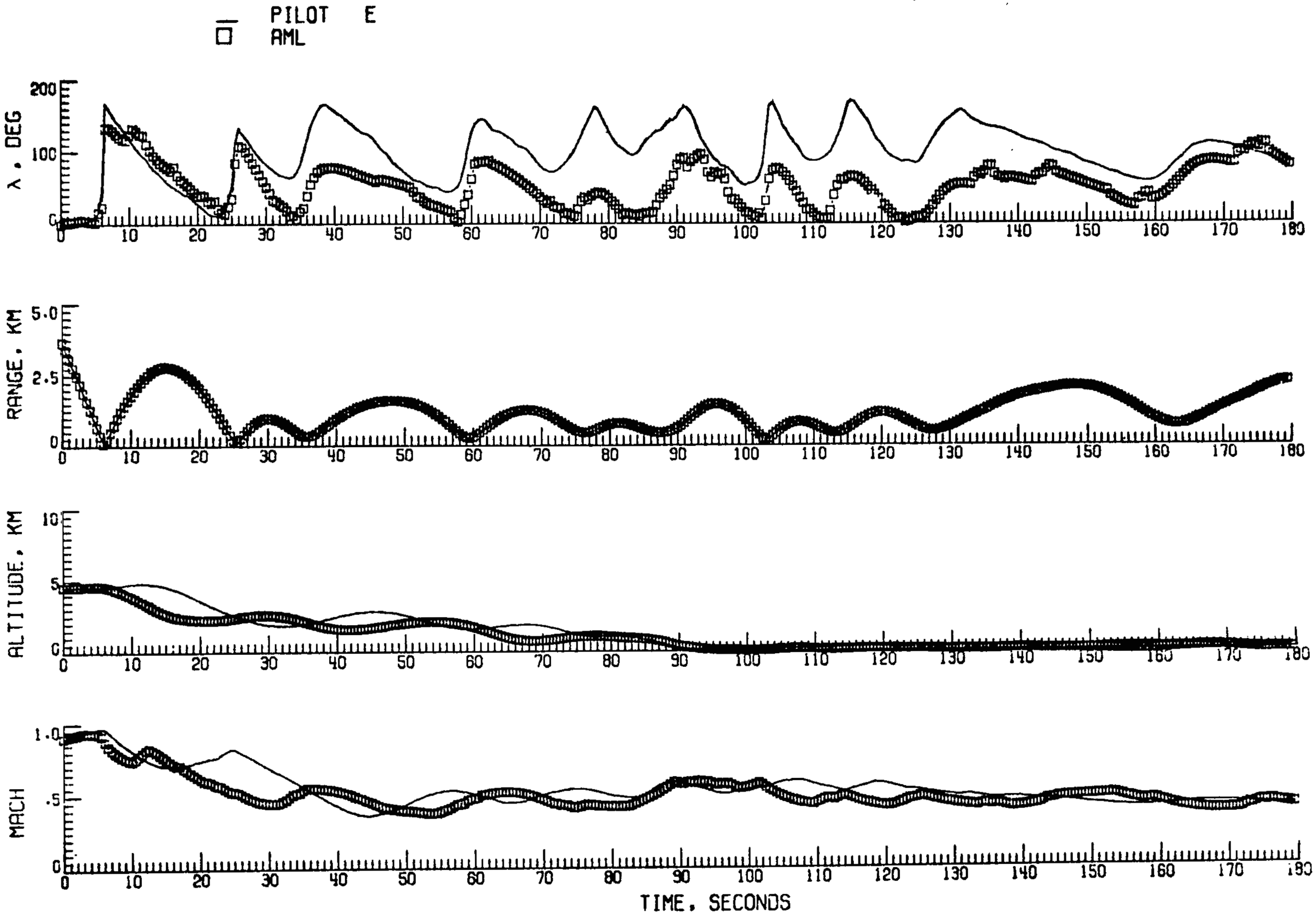


Figure 49.- Pilot-versus-AML-control-model data set for run 19.

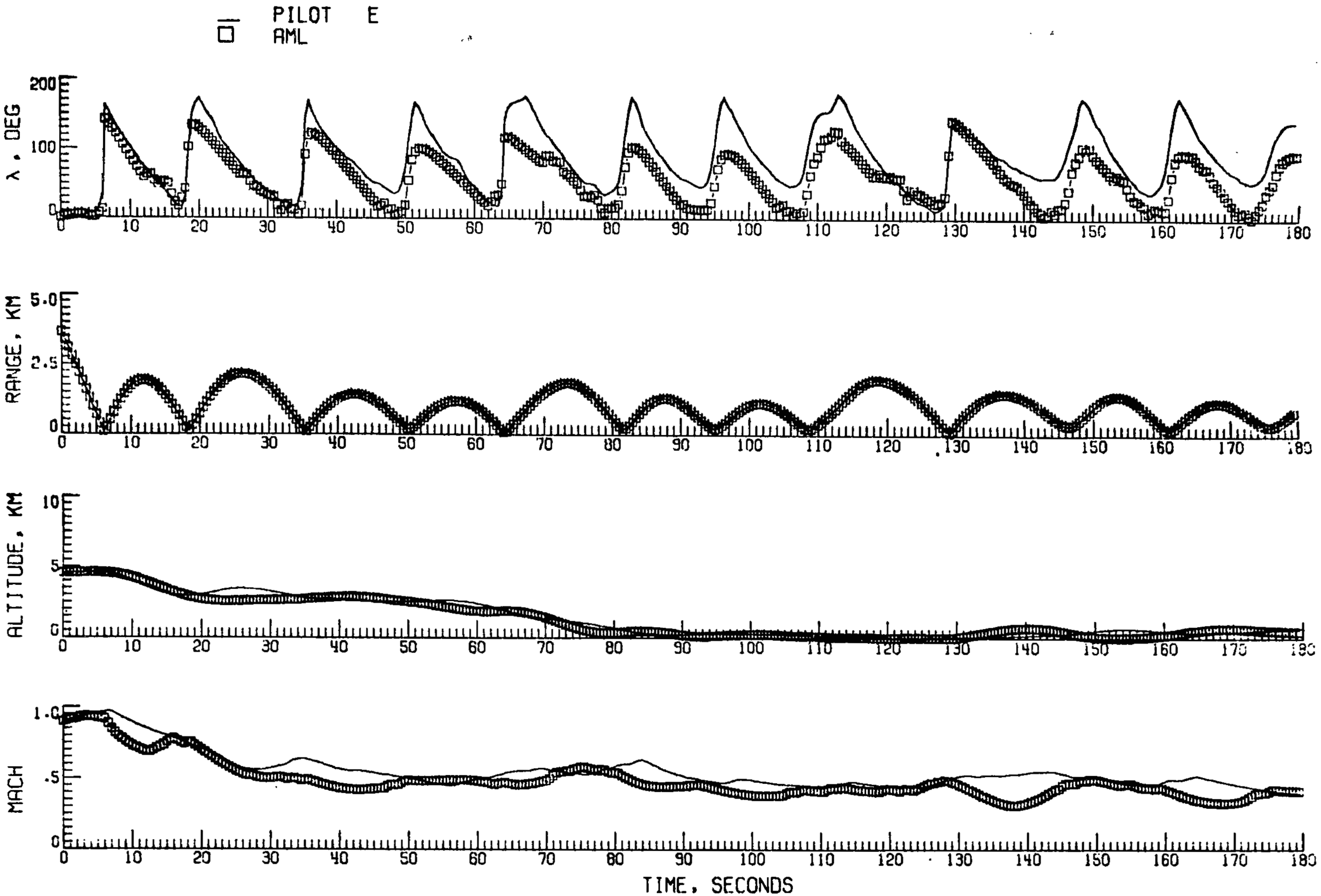


Figure 50.- Pilot-versus-AML-control-model data set for run 20.

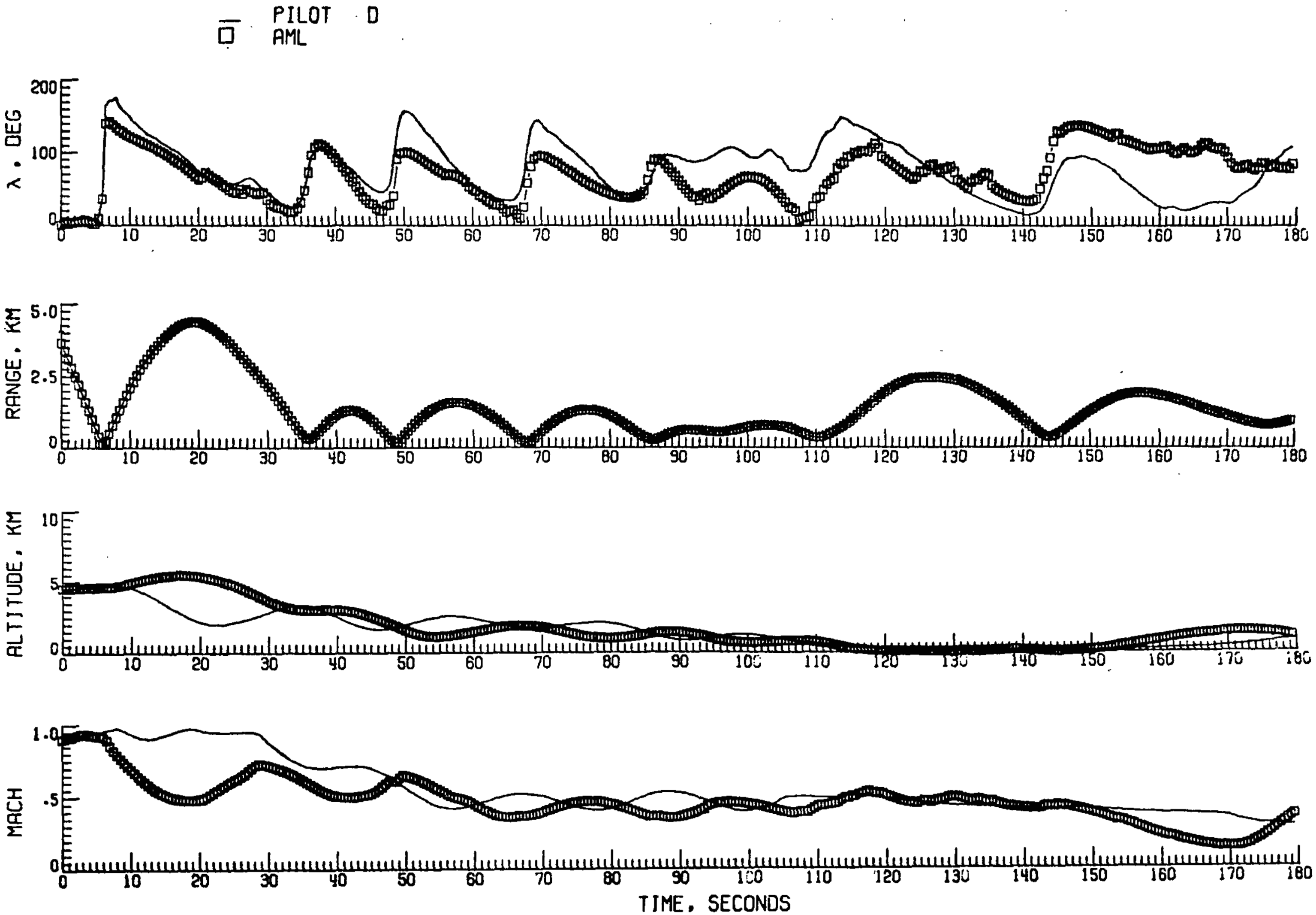


Figure 51.- Pilot-versus-AML-control-model data set for run 21.

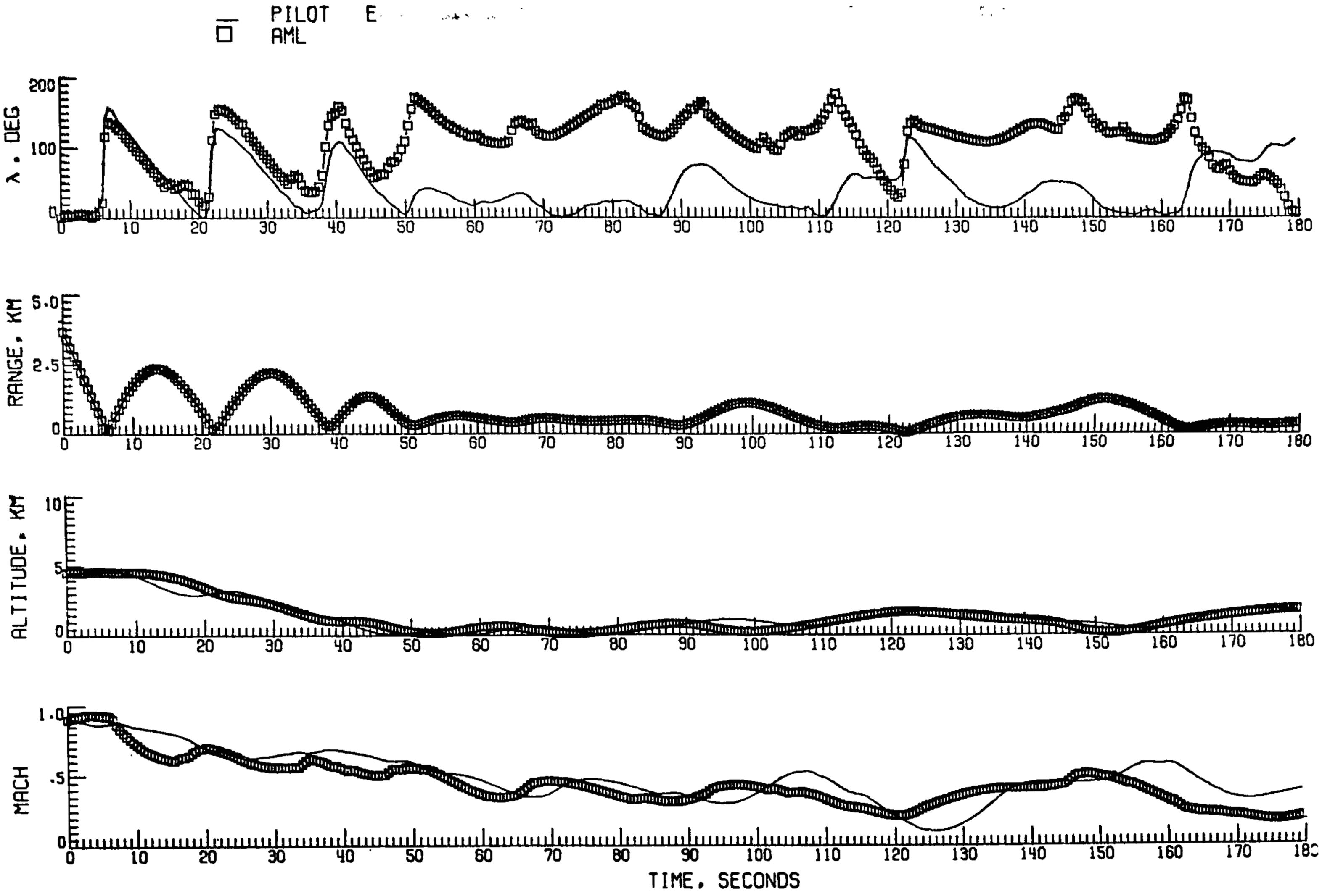


Figure 52.- Pilot-versus-AML-control-model data set for run 22.

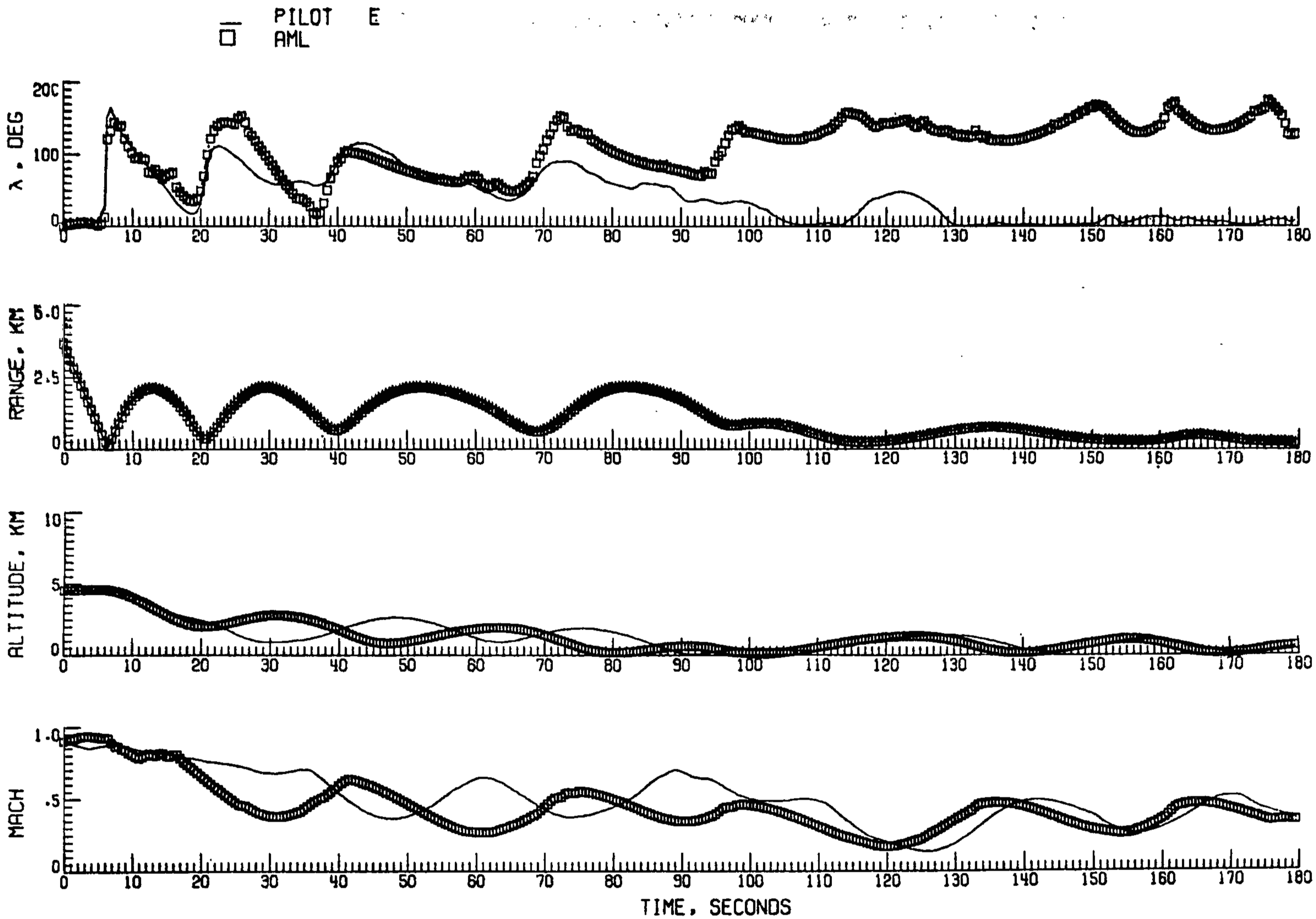


Figure 53.- Pilot-versus-AML-control-model data set for run 23.

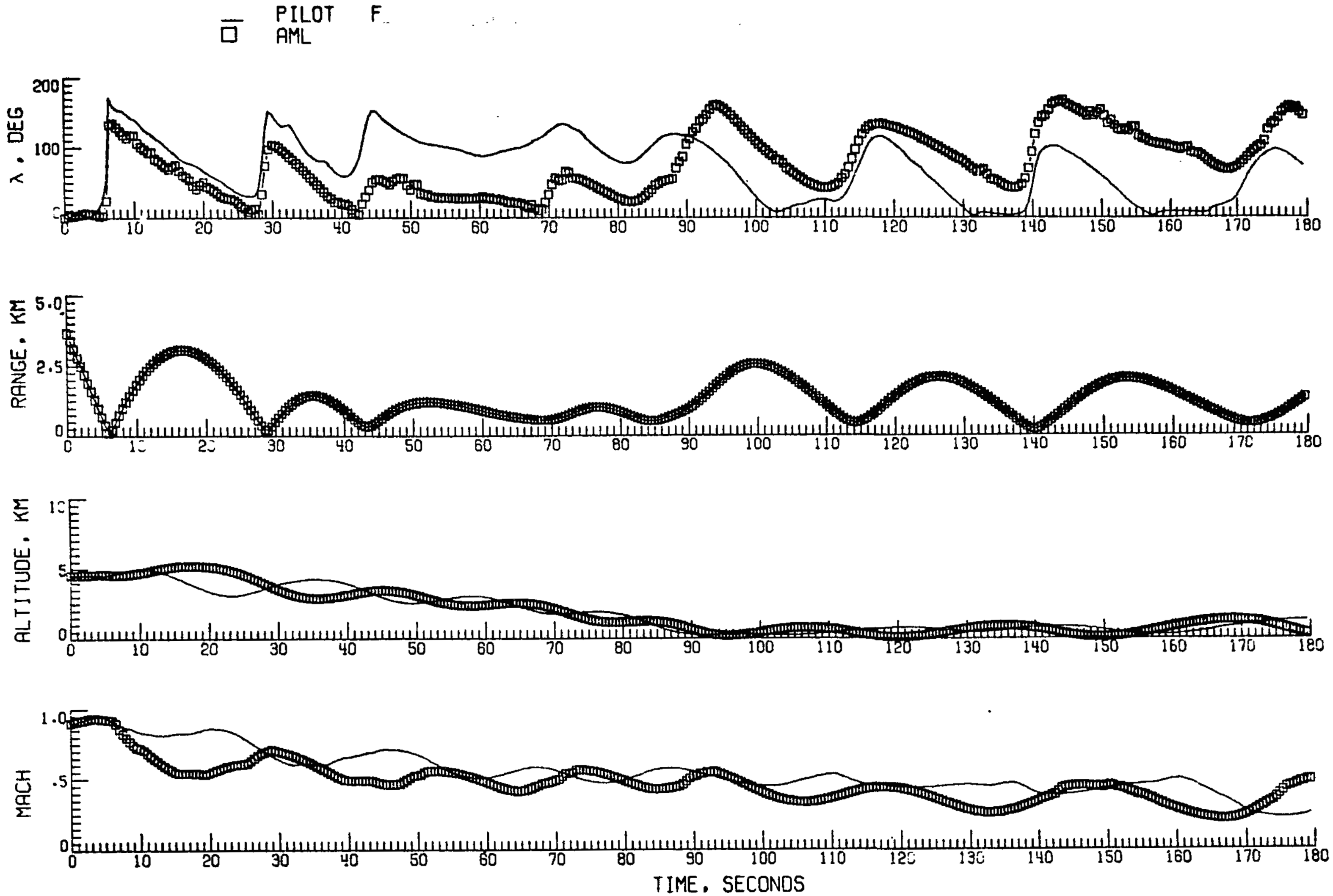


Figure 54.- Pilot-versus-AML-control-model data set for run 24.

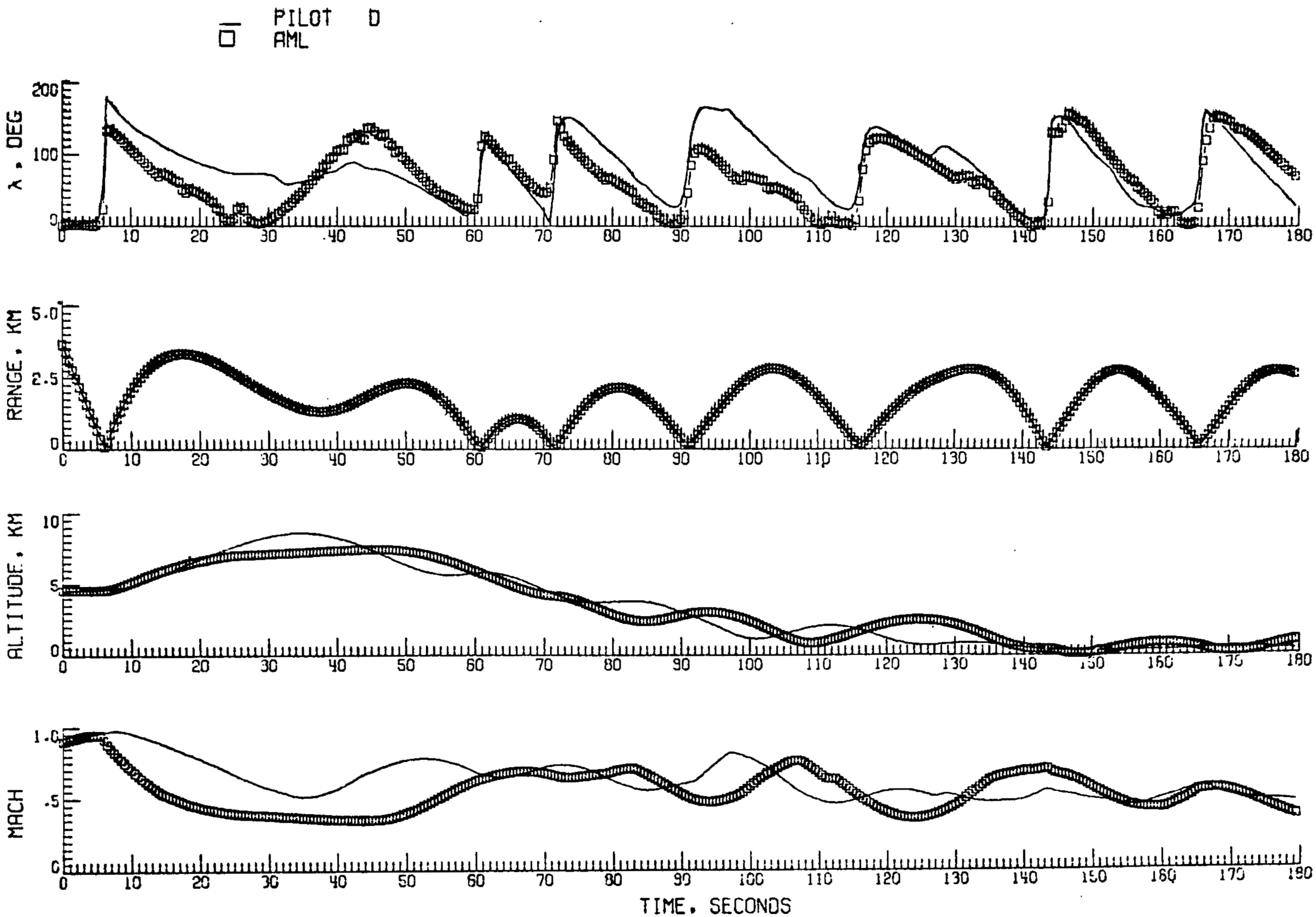
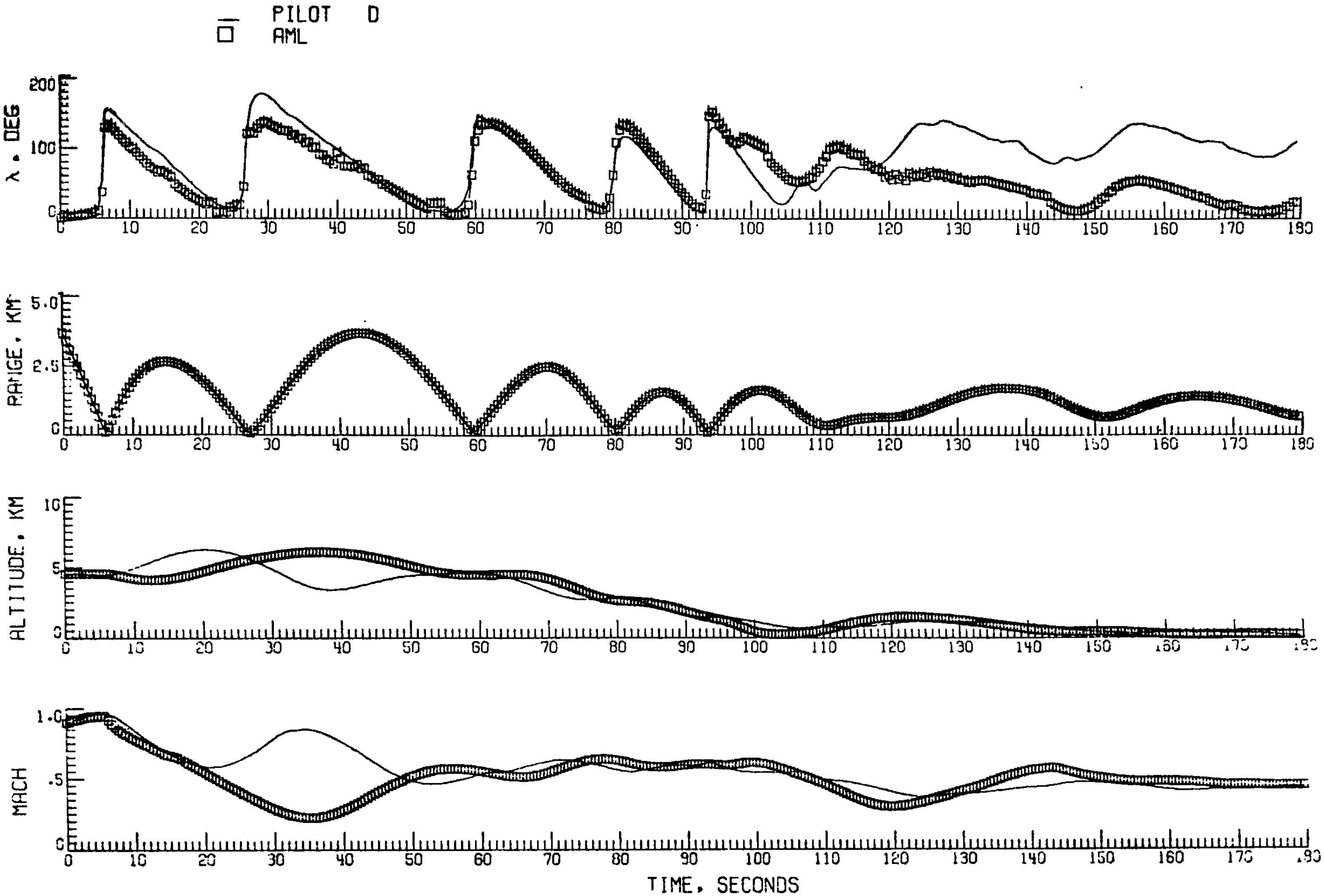


Figure 55.- Pilot-versus-AML-performance-model data set for run 1.



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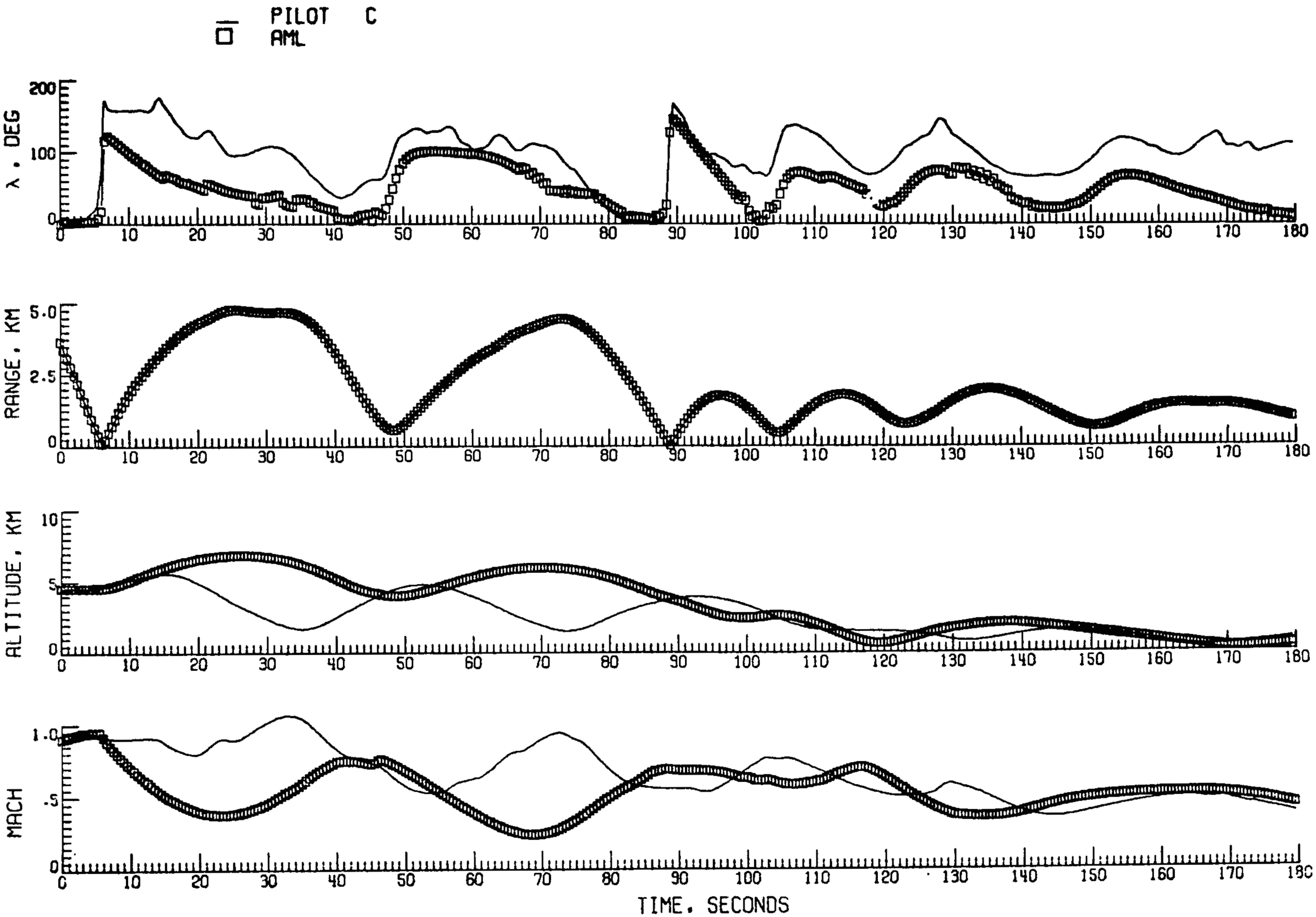

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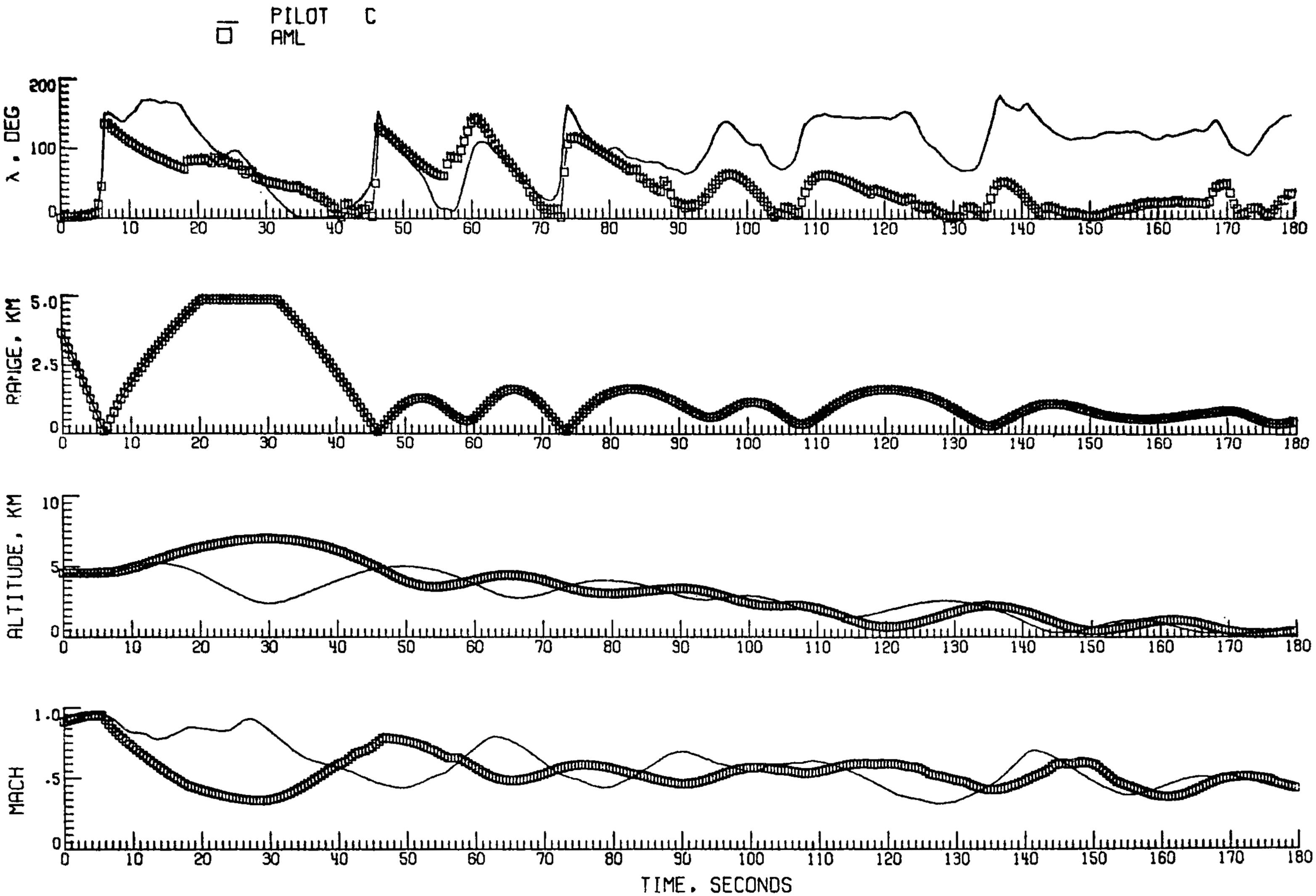

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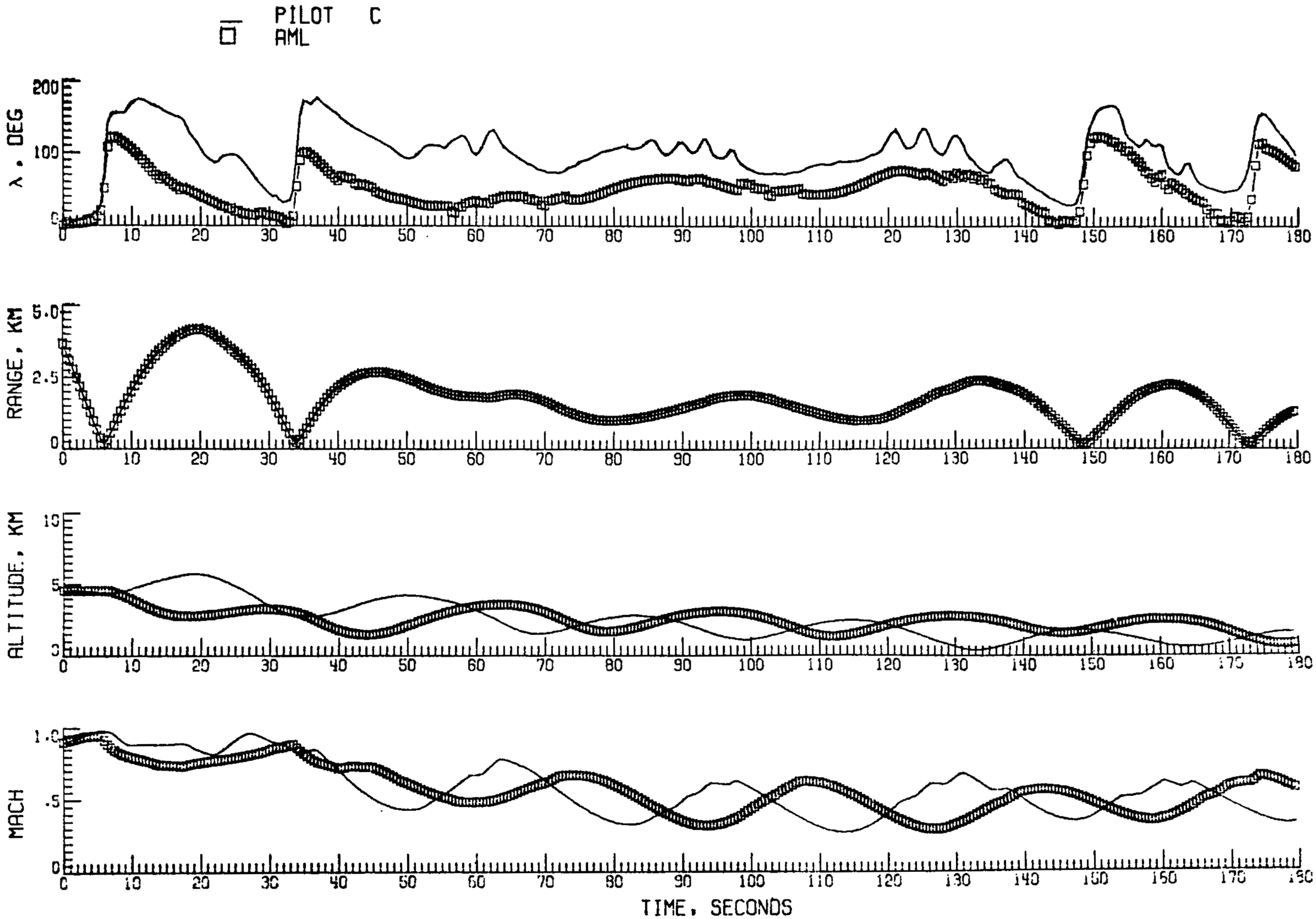

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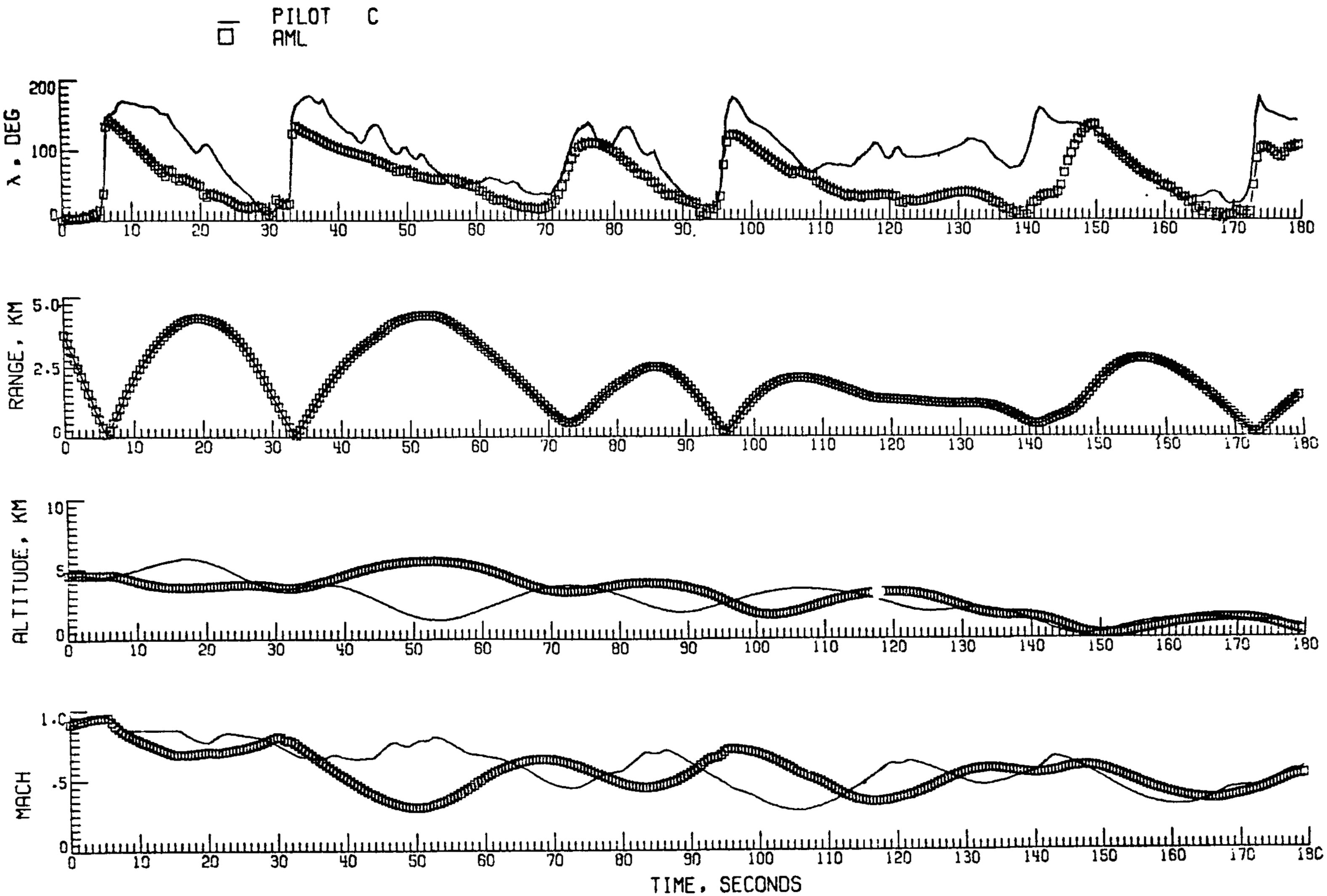

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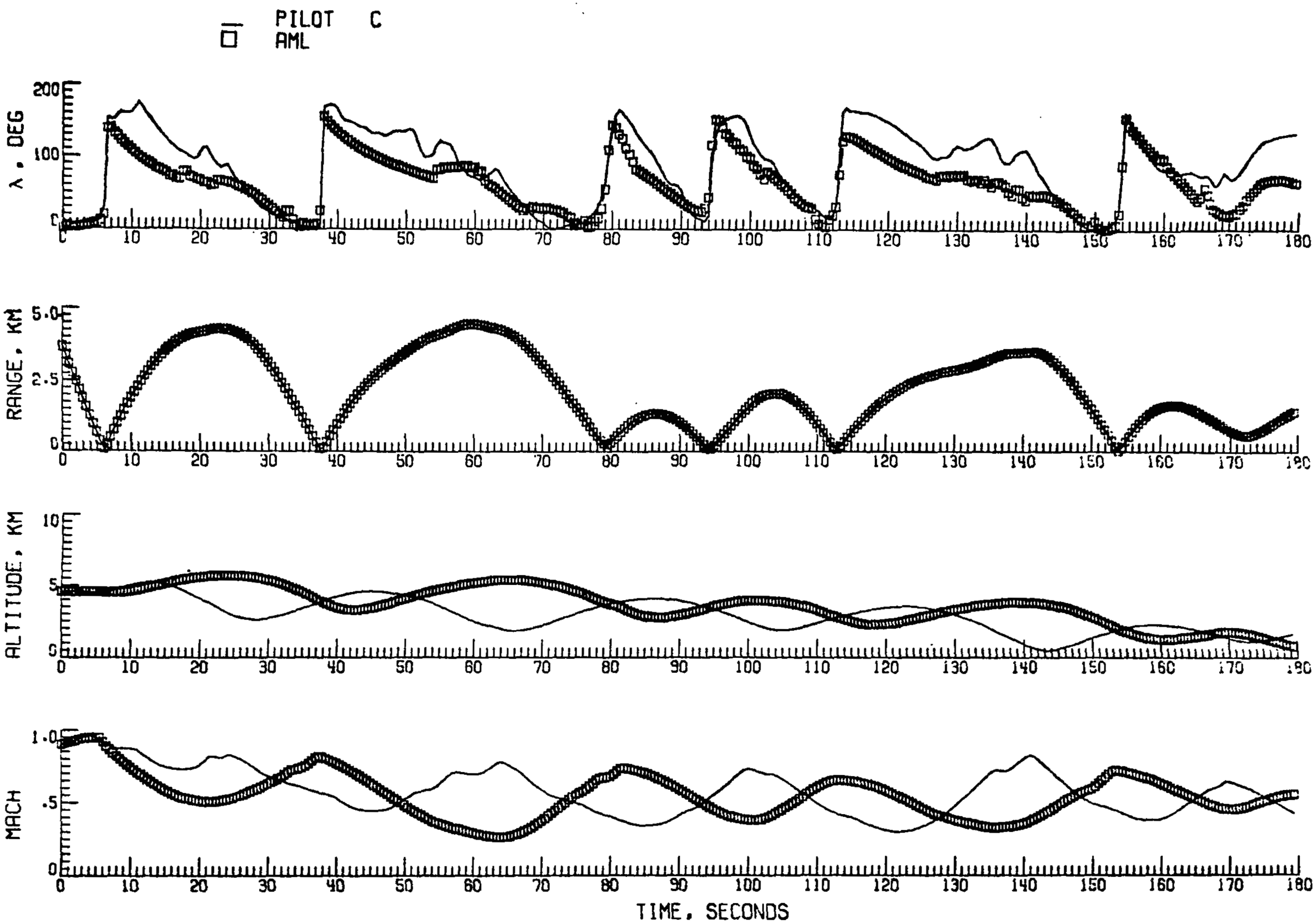

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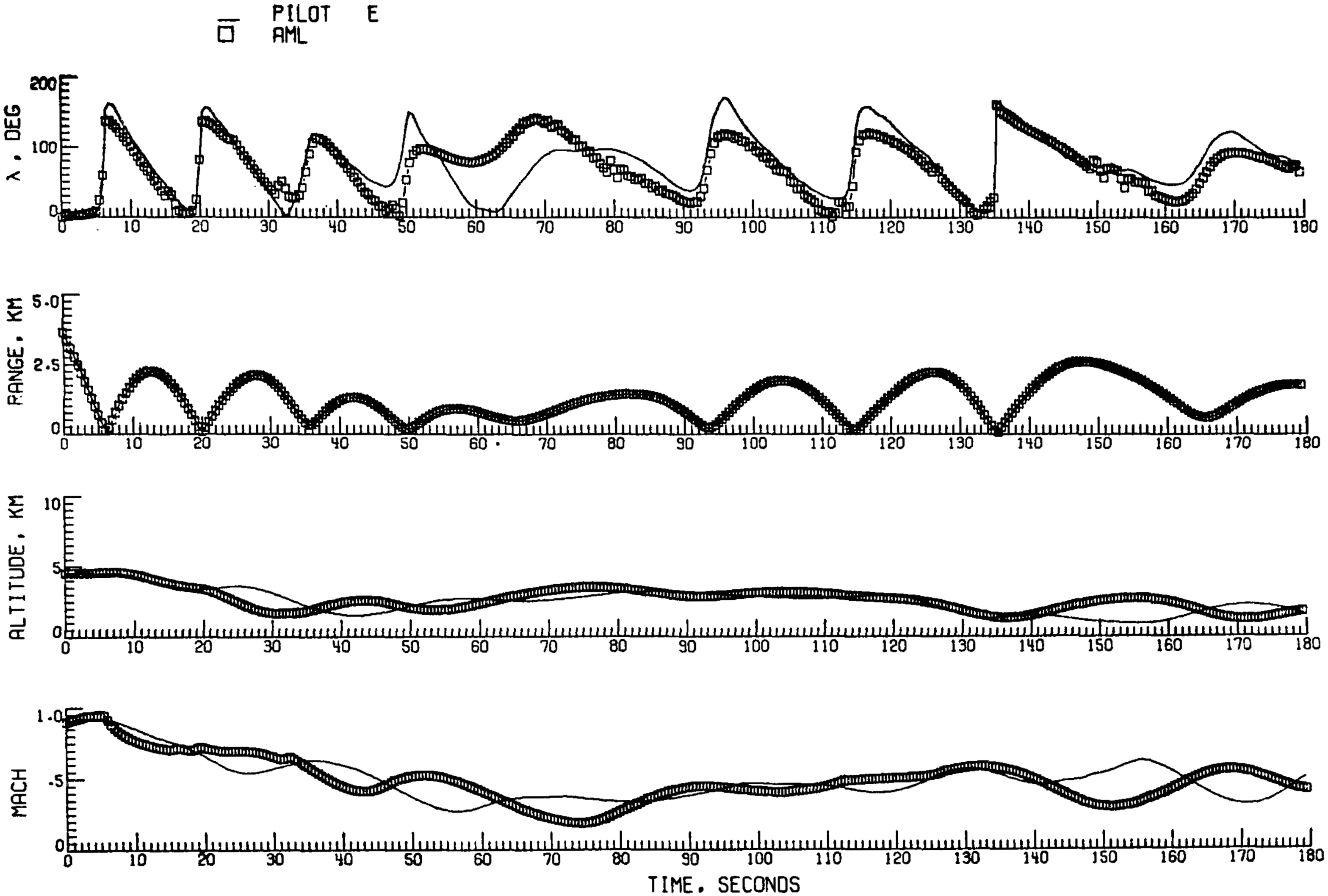

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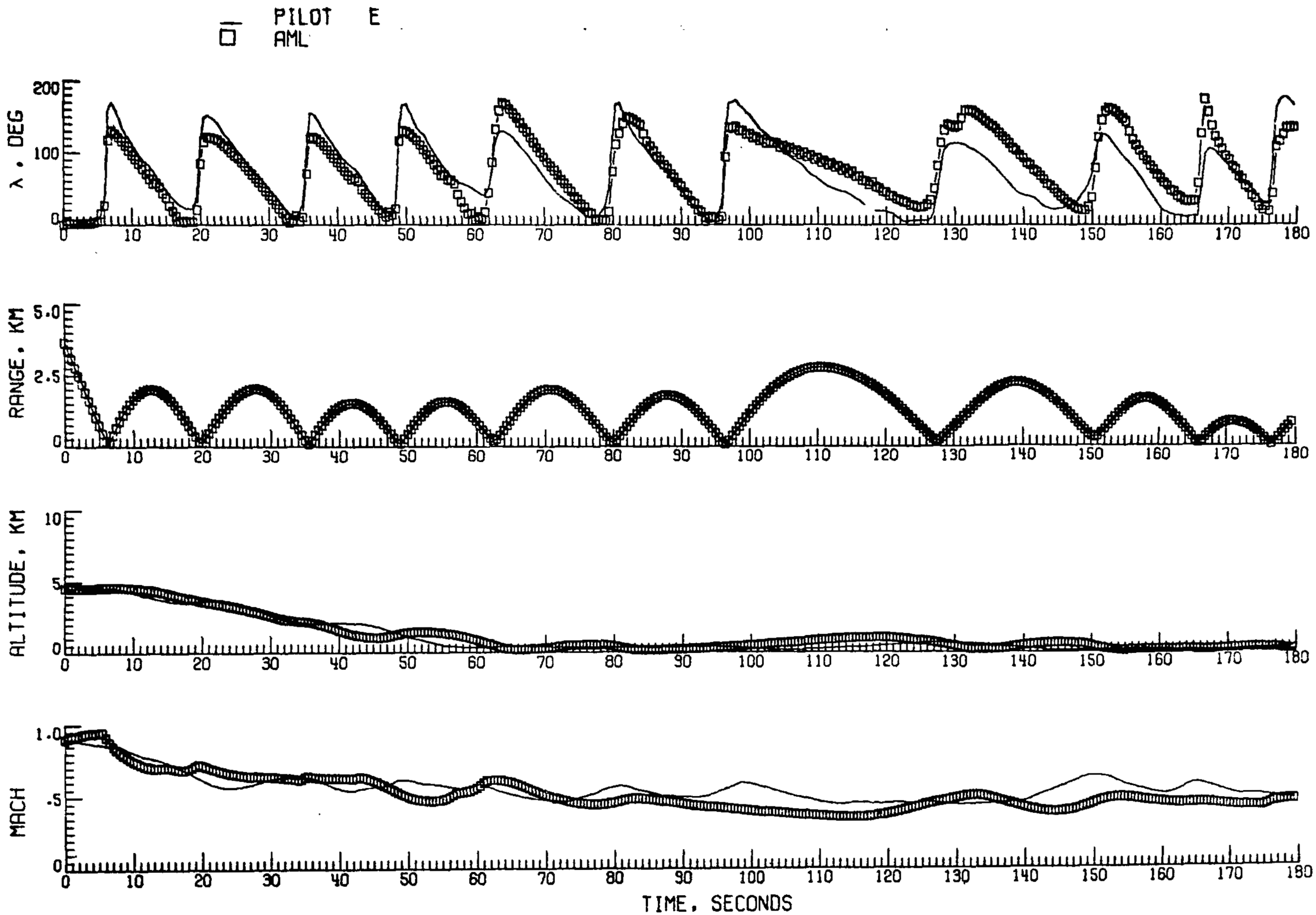


Figure 63.- Pilot-versus-AML-performance-model data set for run 9.

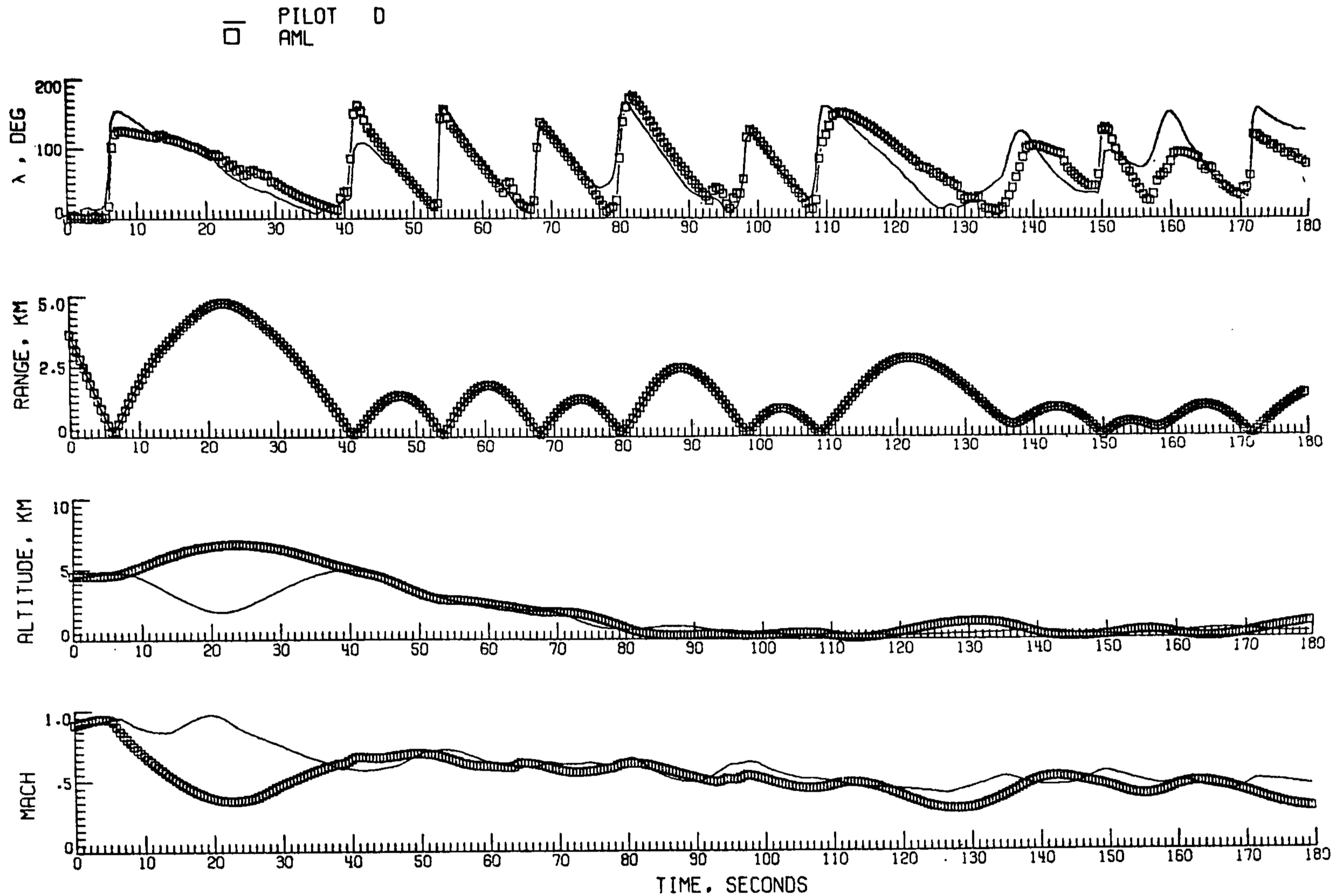


Figure 64.- Pilot-versus-AML-performance-model data set for run 10.

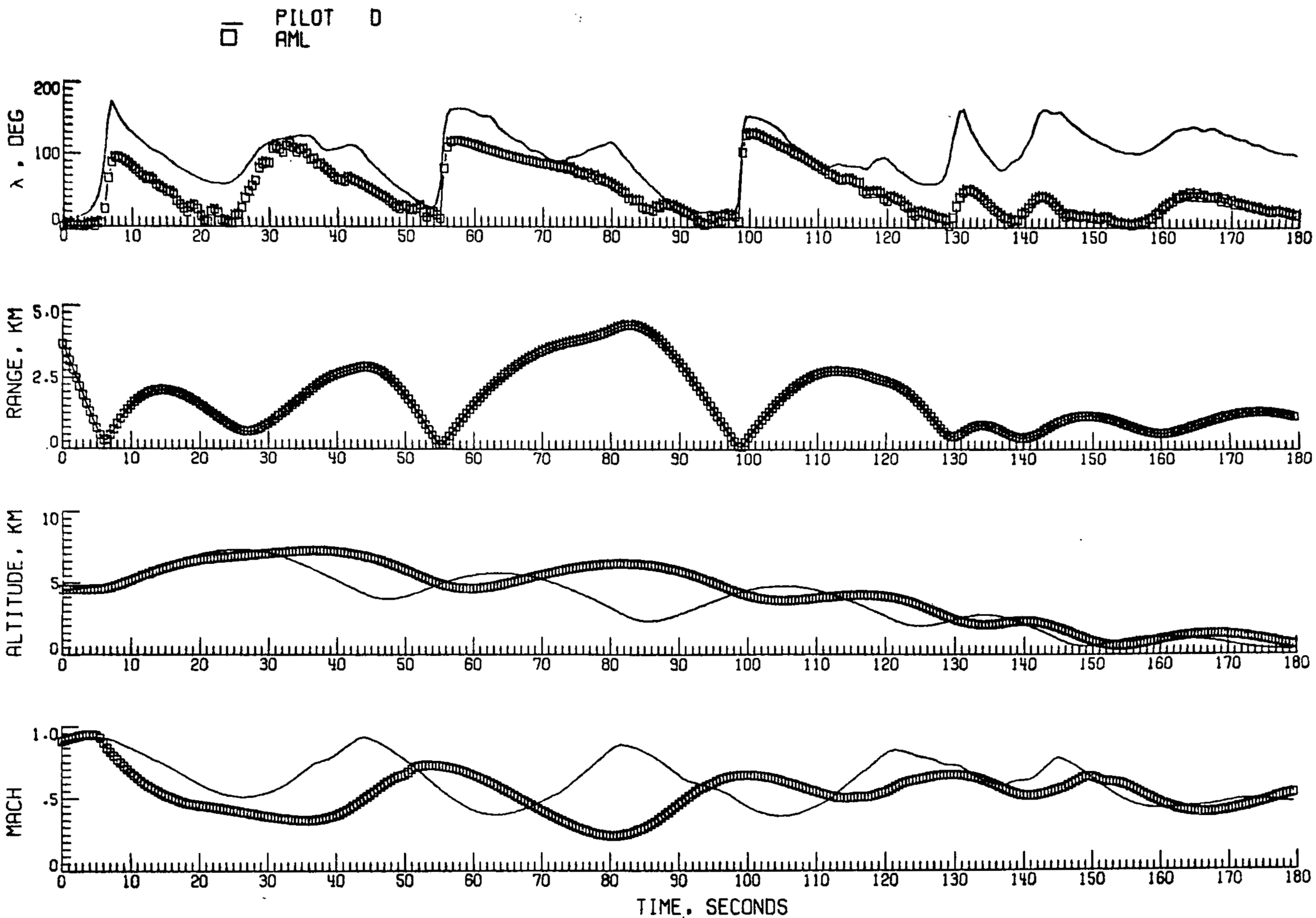


Figure 65.- Pilot-versus-AML-performance-model data set for run 11.

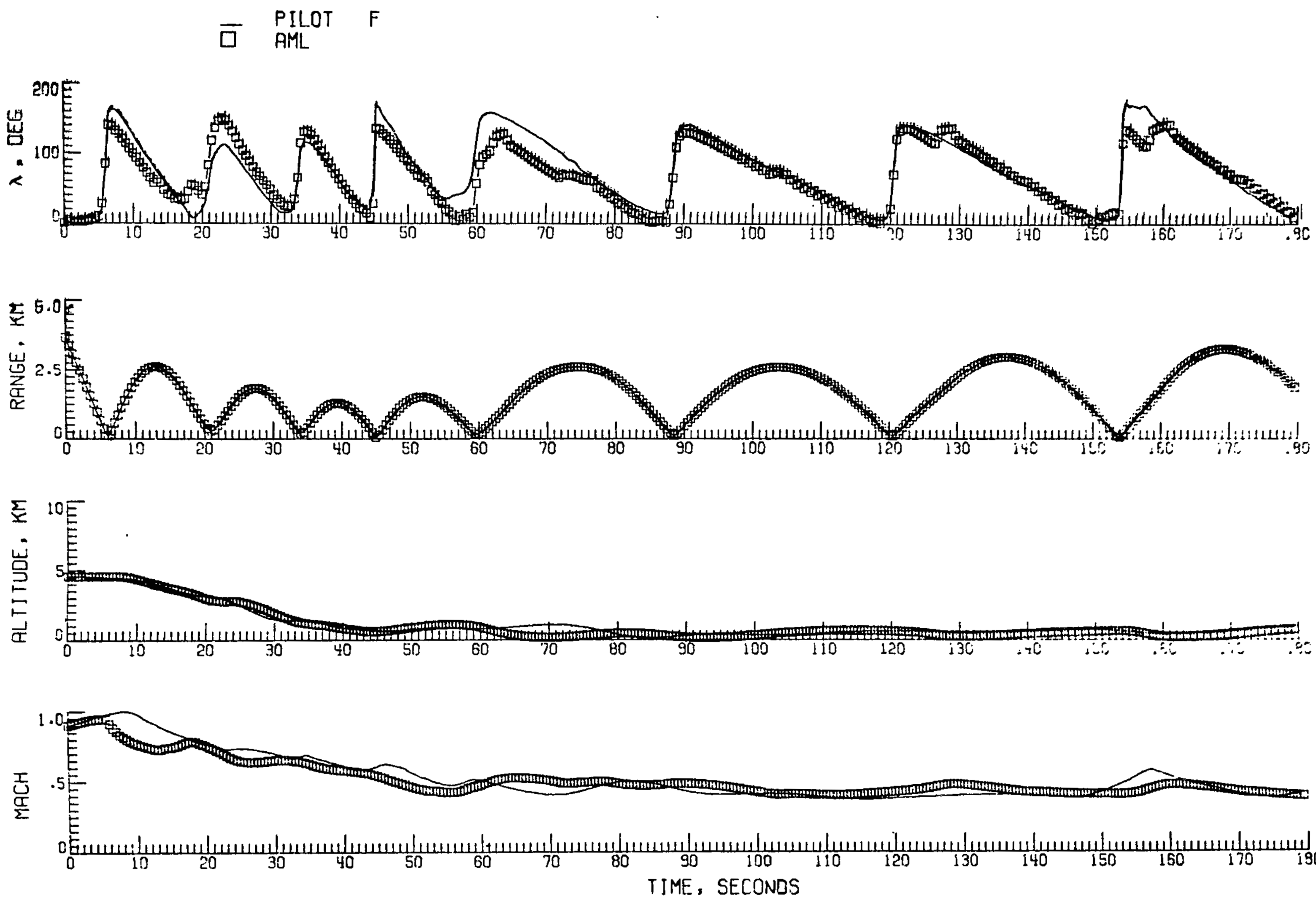


Figure 66.- Pilot-versus-AML-performance-model data set for run 12.

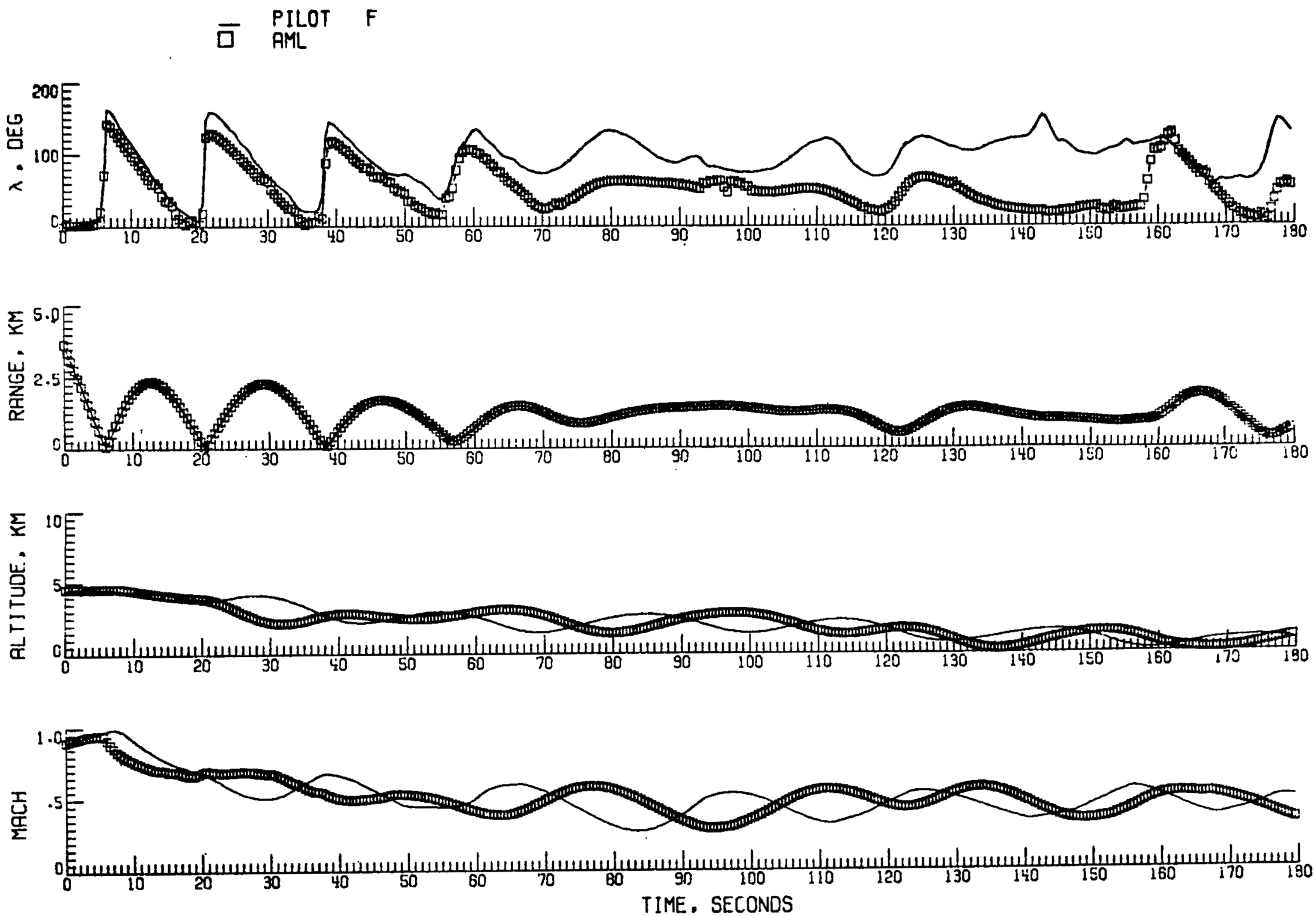


Figure 67.- Pilot-versus-AML-performance-model data set for run 13.

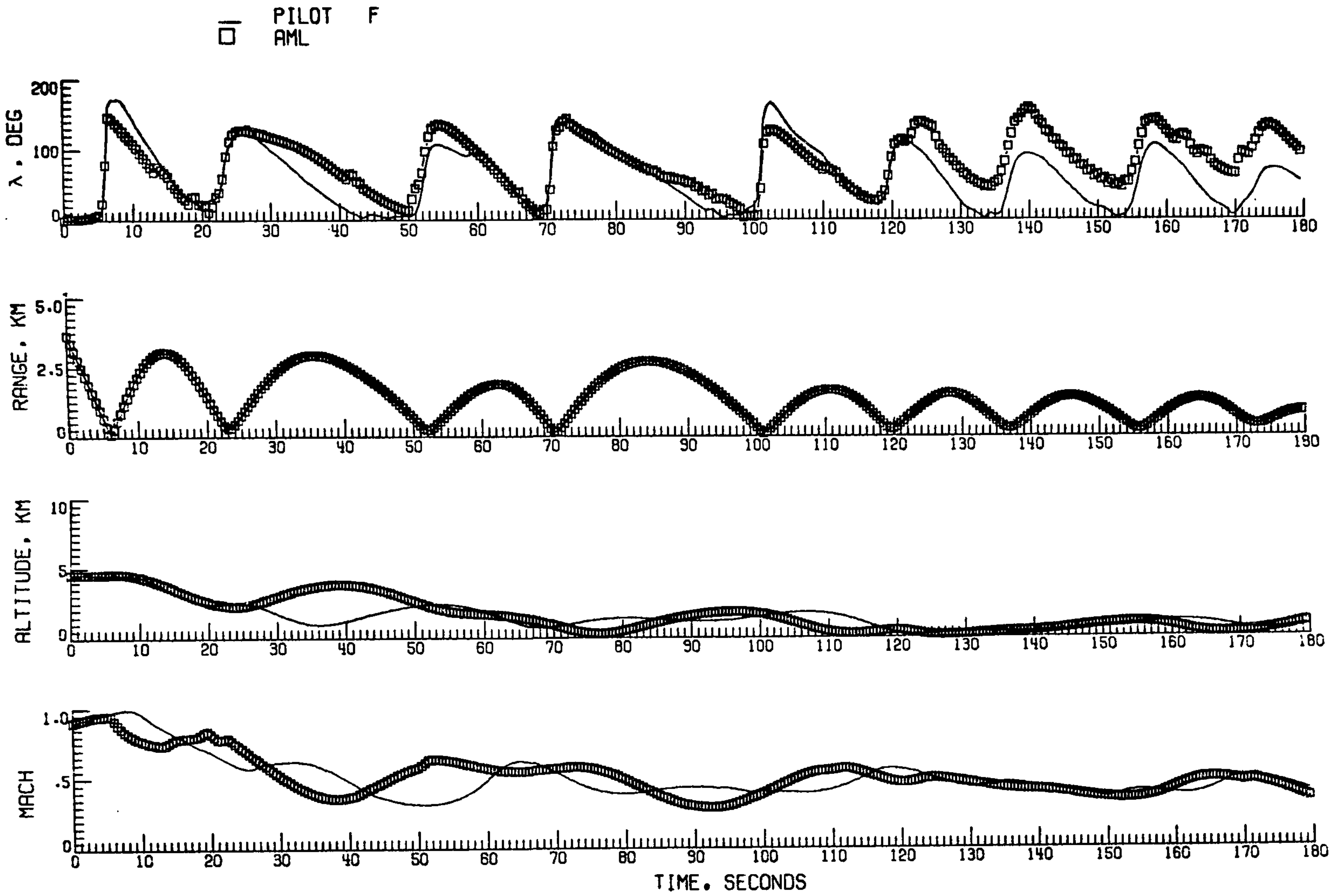
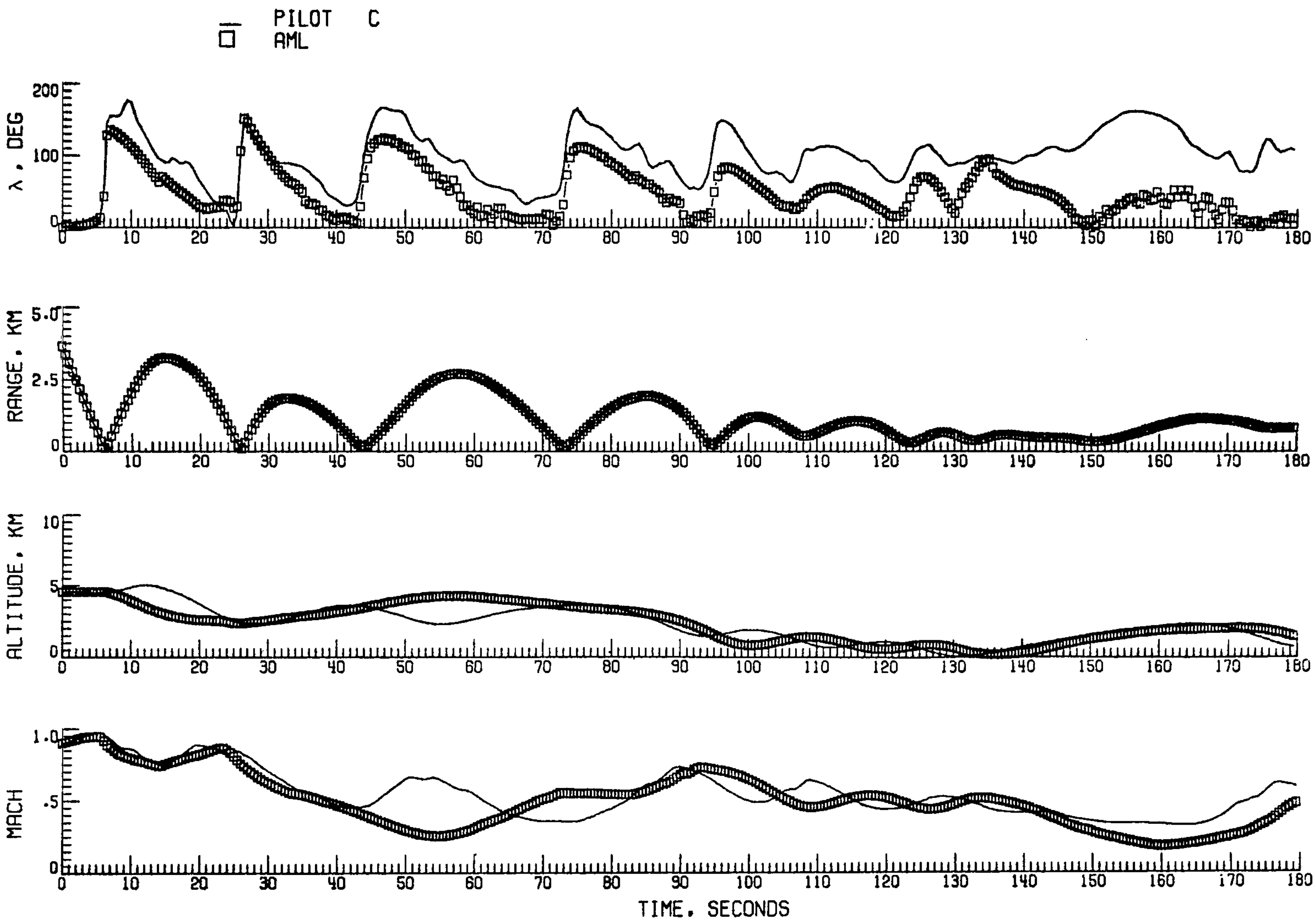


Figure 68.- Pilot-versus-AML-performance-model data set for run 14.



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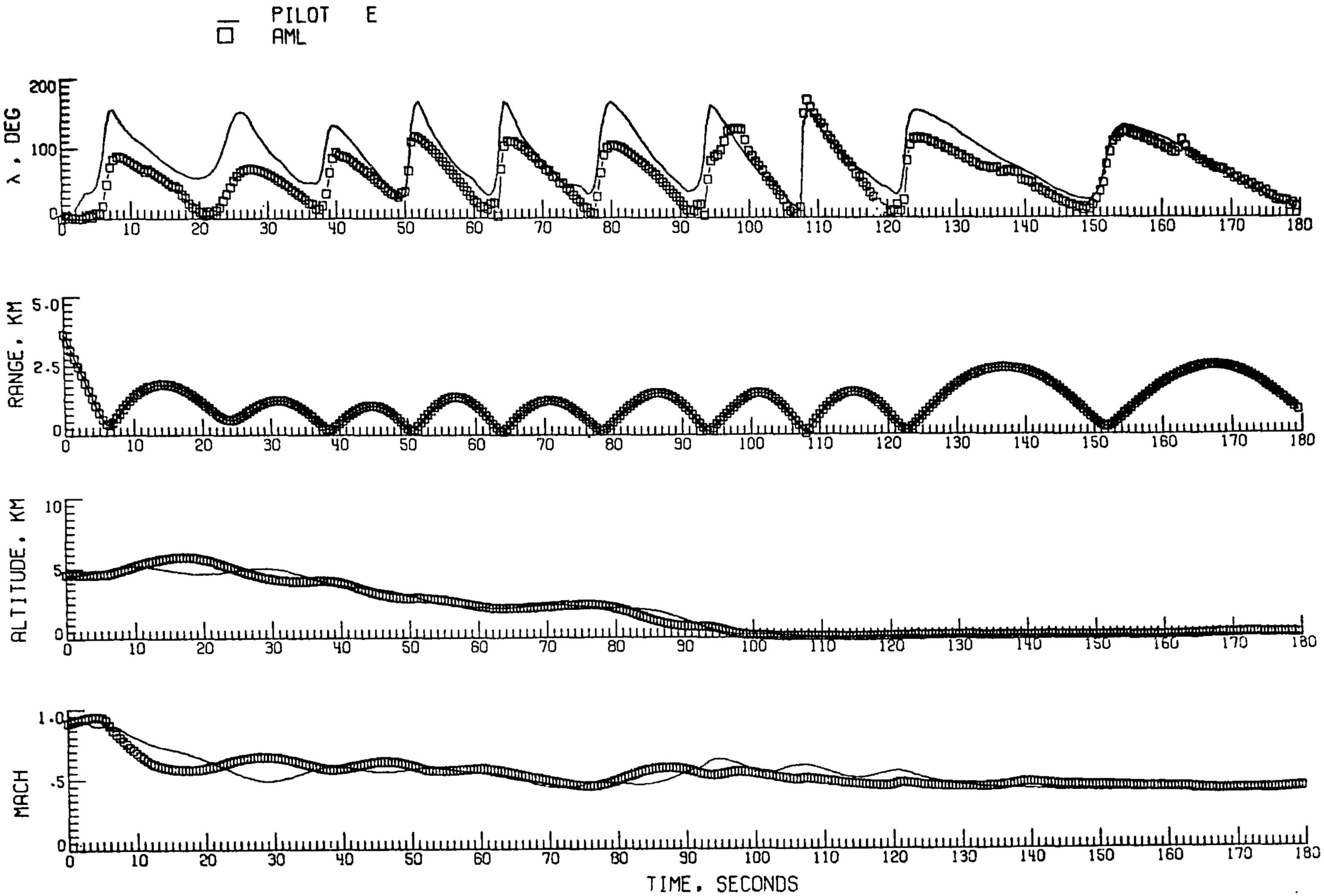

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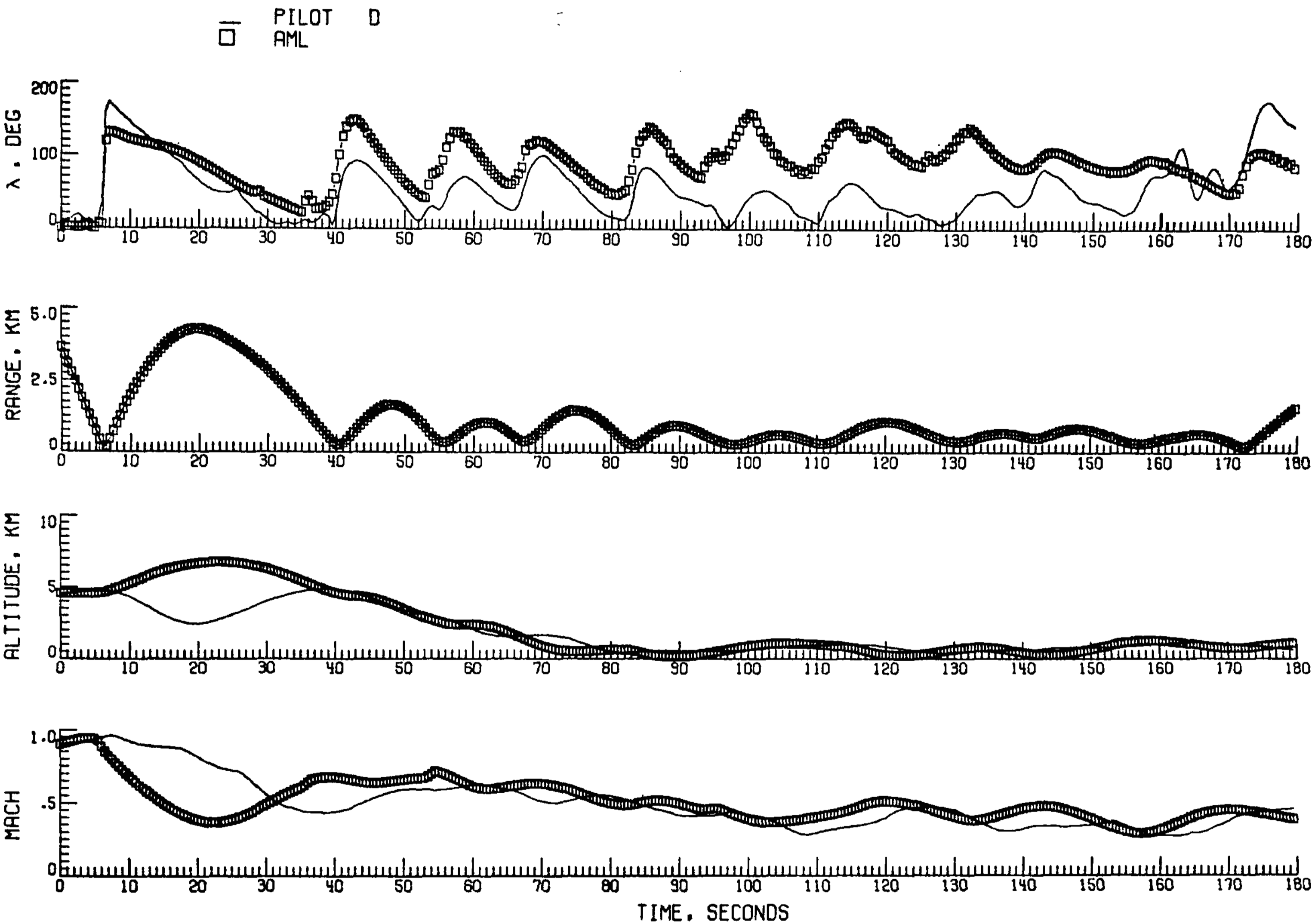

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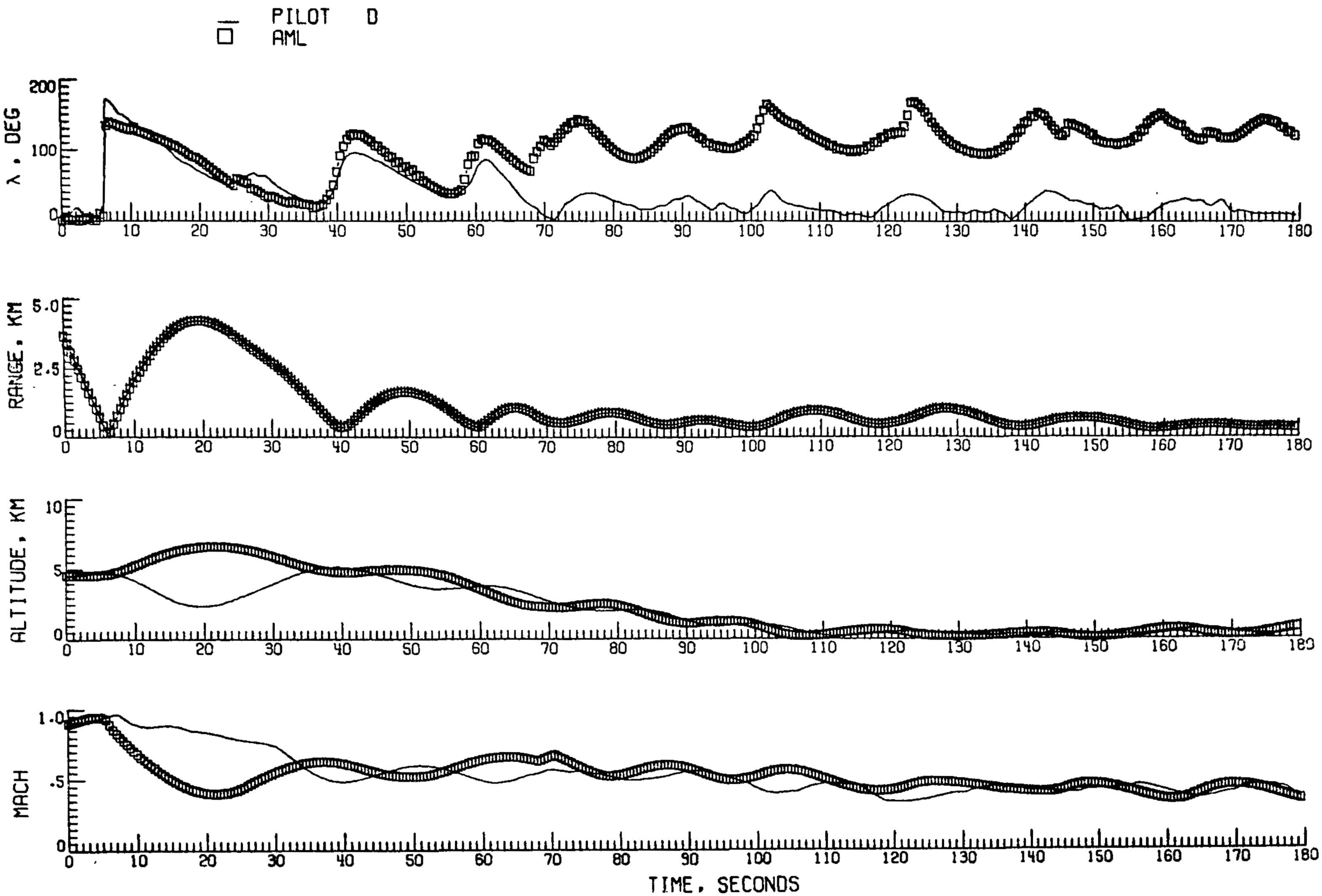

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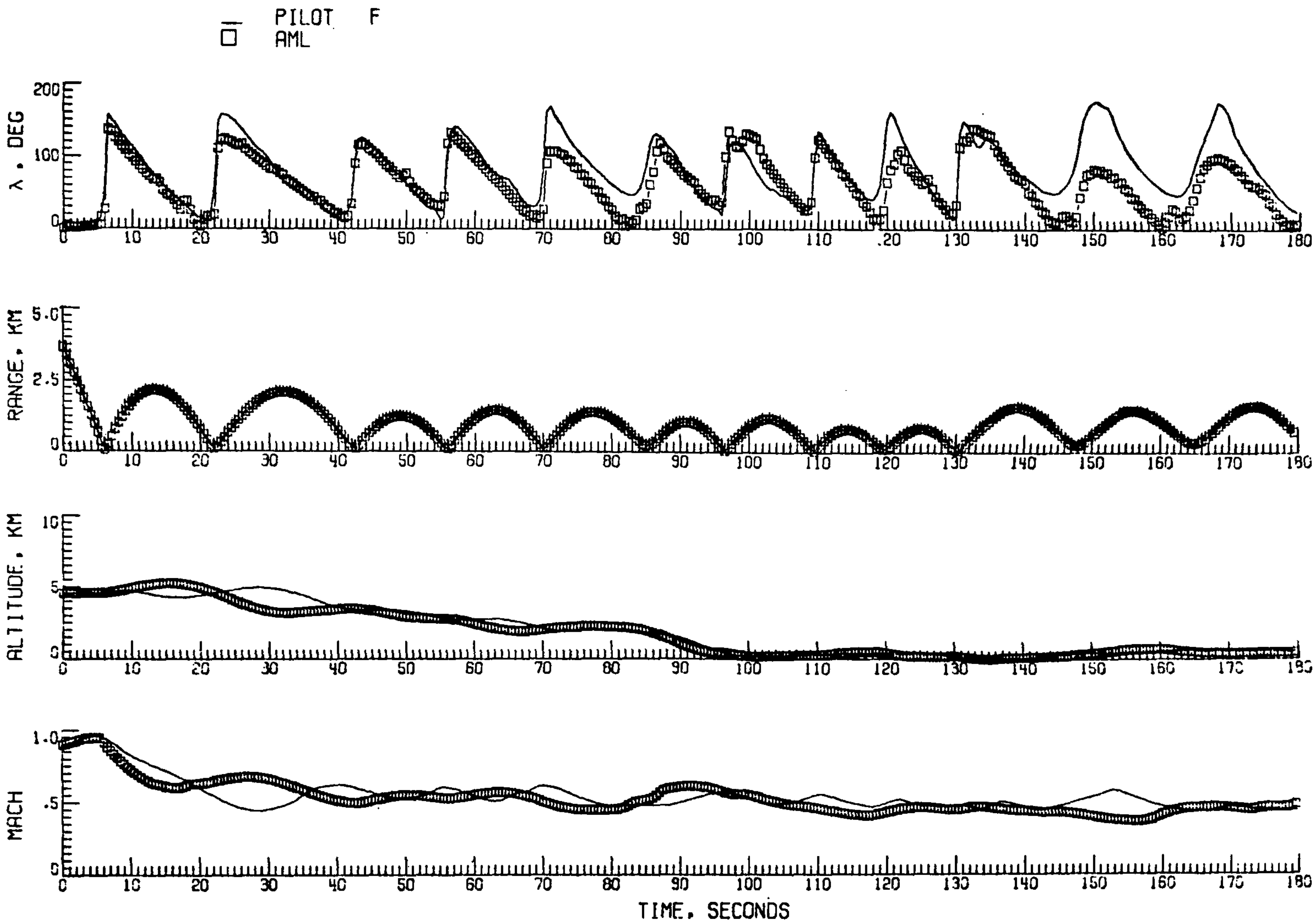

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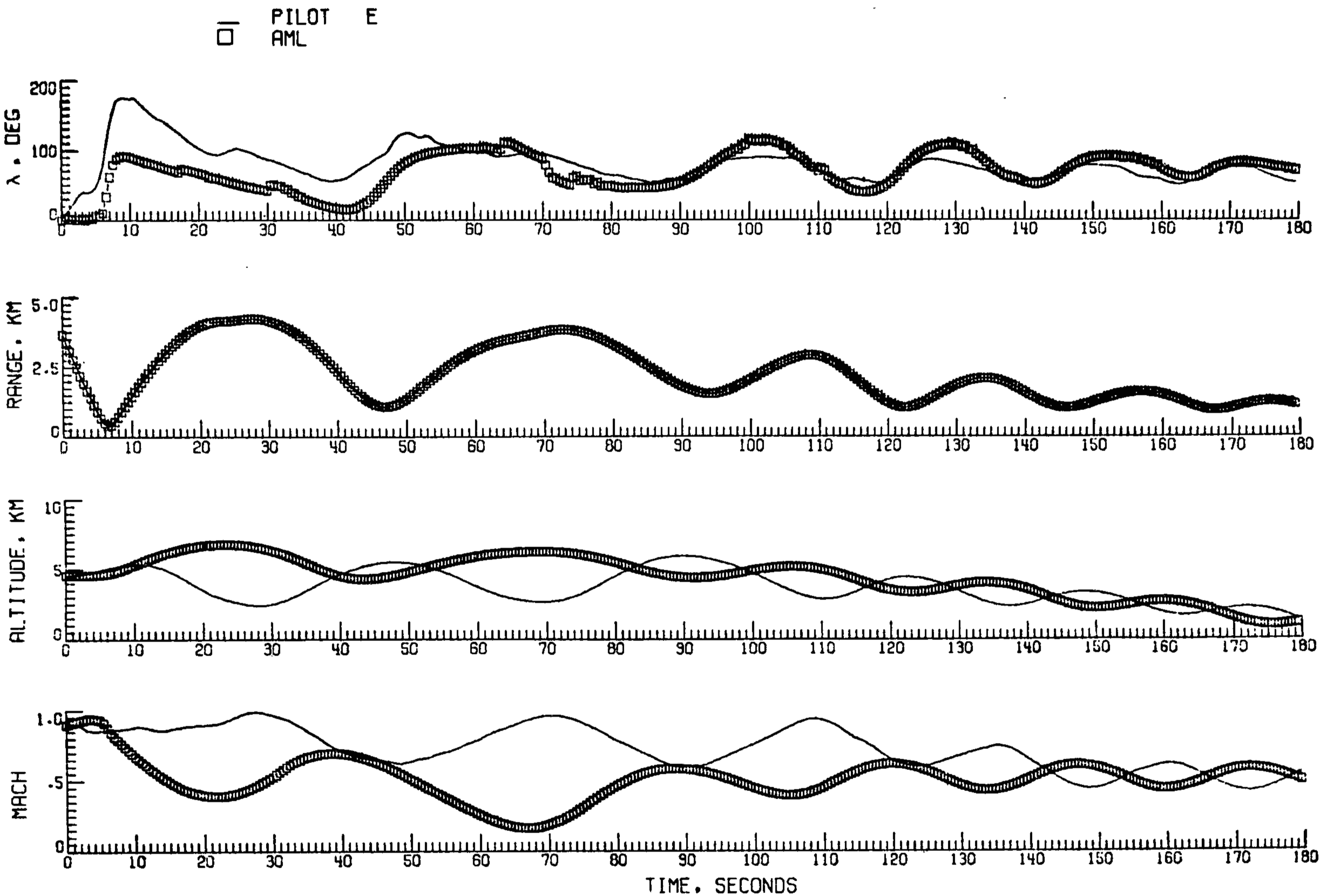

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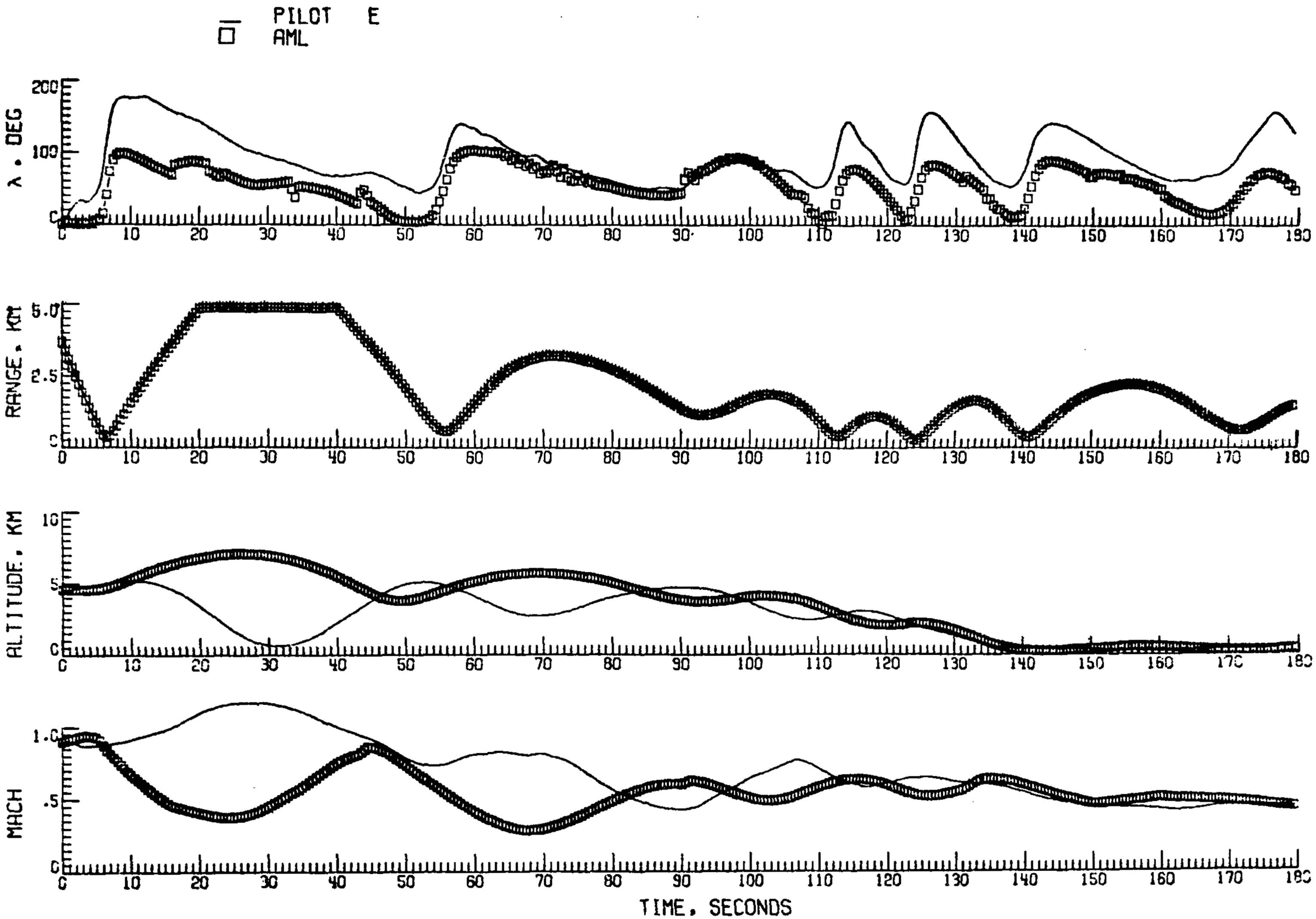


Figure 75.- Pilot-versus-AML-performance-model data set for run 21.

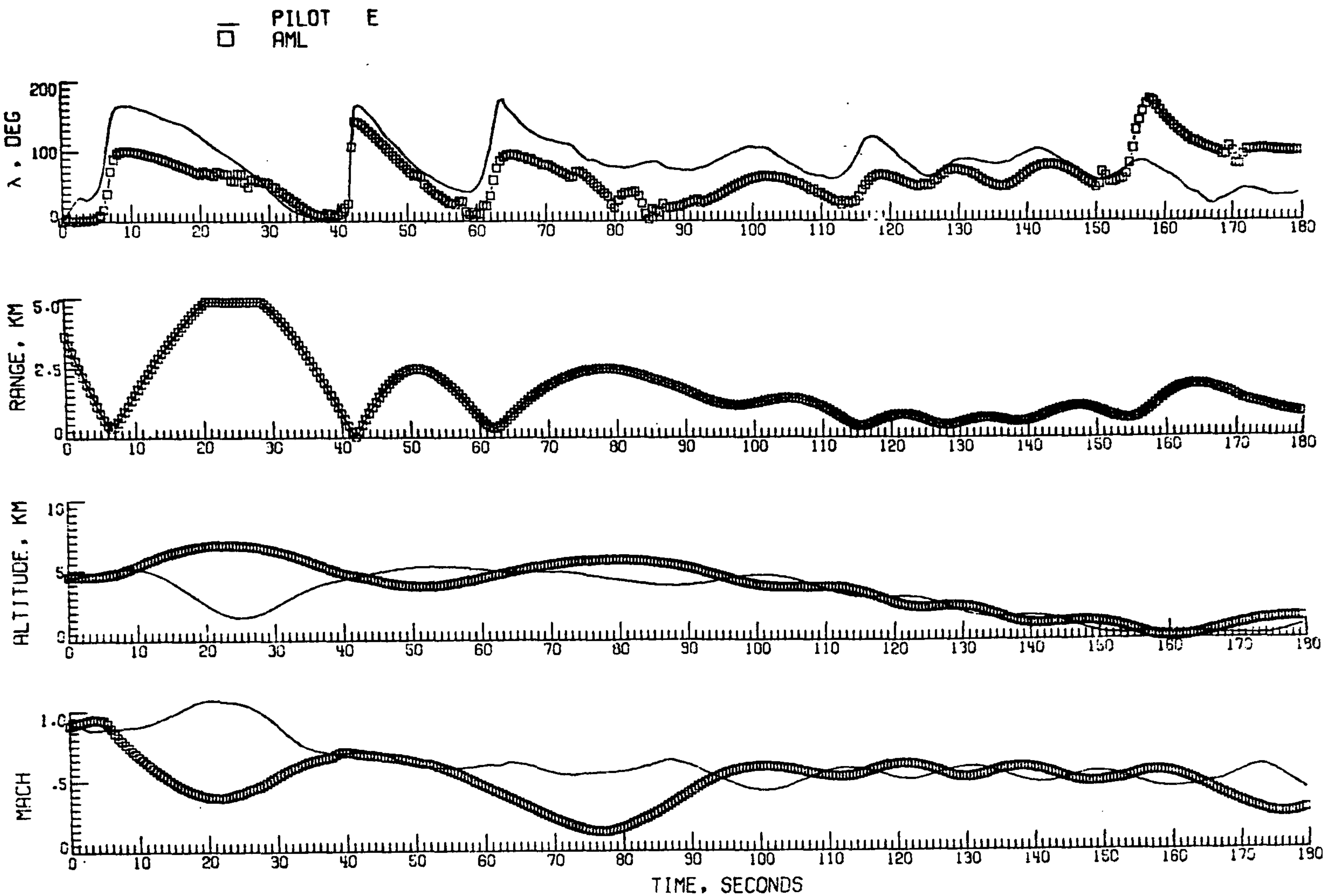
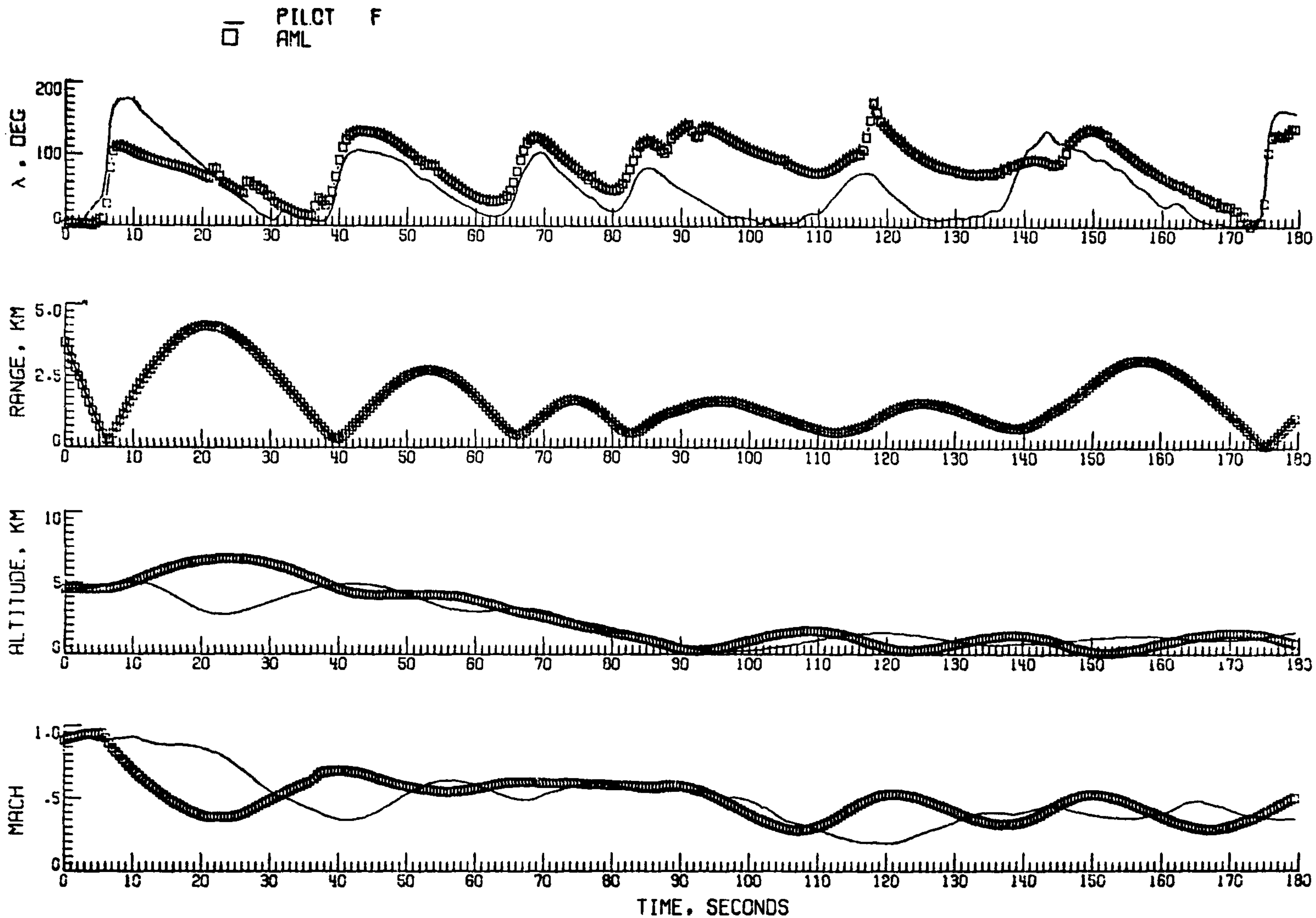


Figure 76.- Pilot-versus-AML-performance-model data set for run 22.



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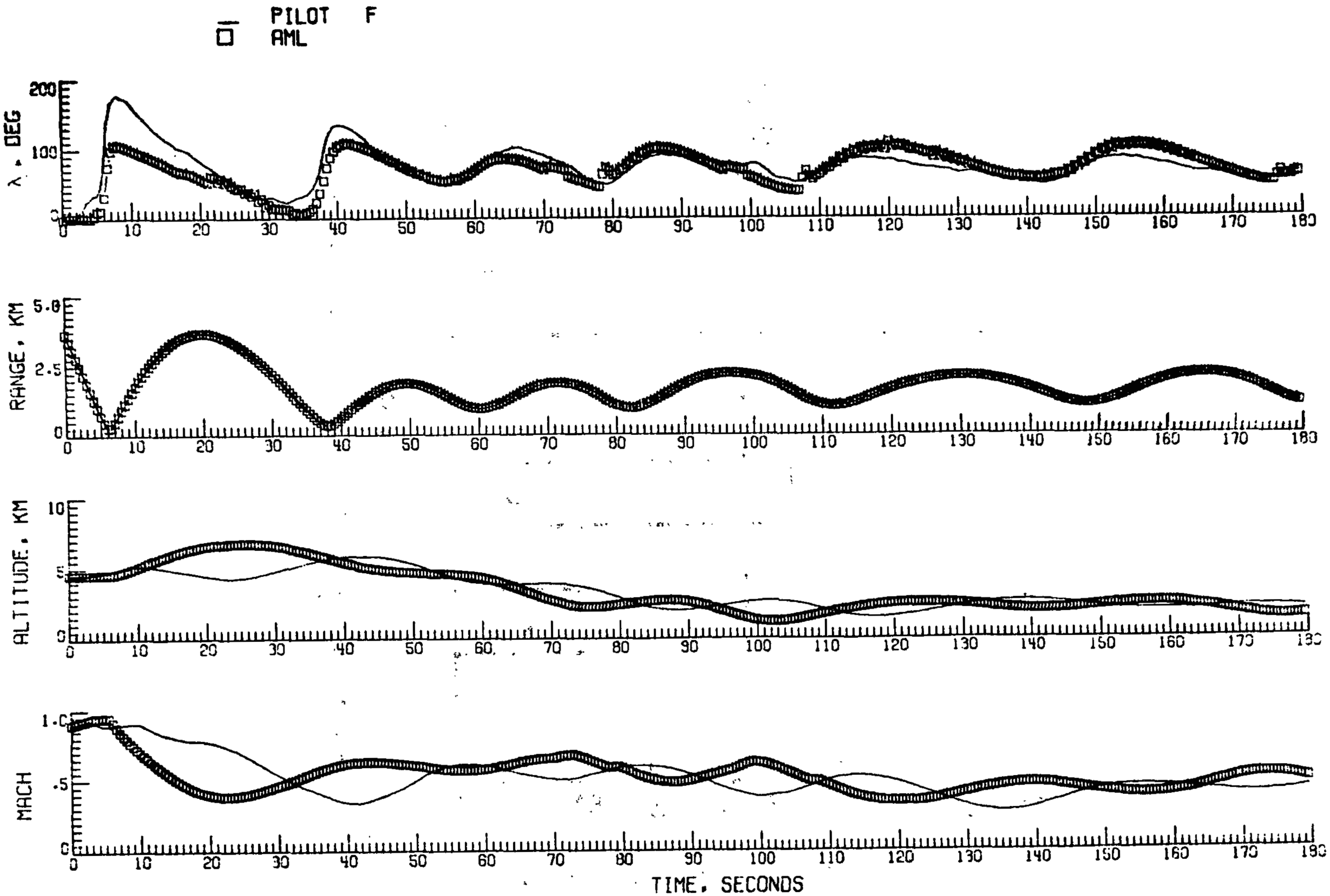

Figure 78.- Pilot-versus-AML-performance-model data set for run 24.

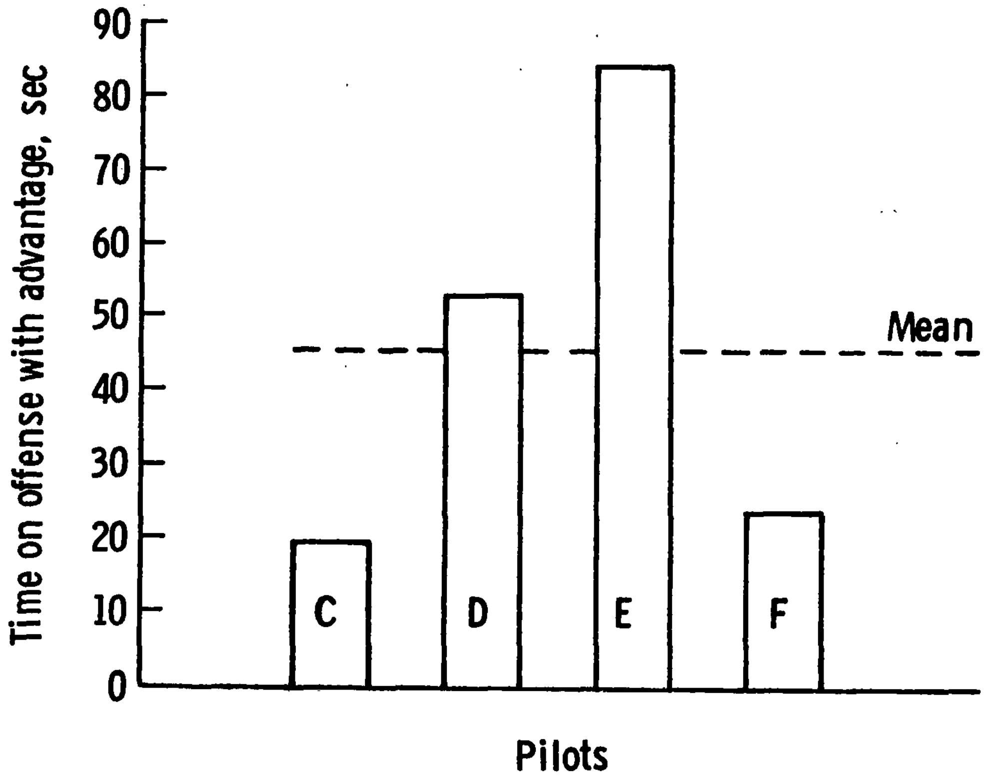

Figure 79.- Comparisons of time on offense with advantage for pilots versus pilots.

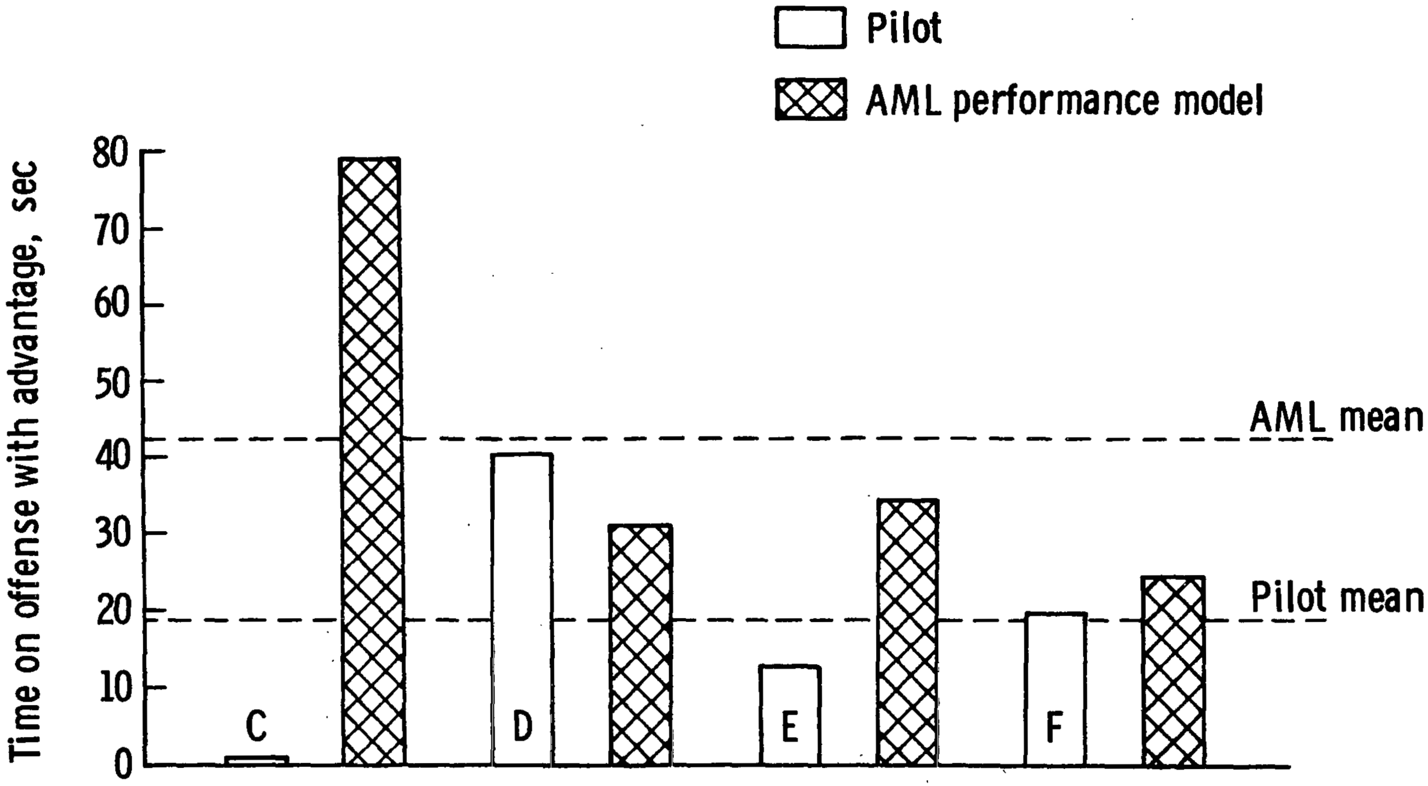

Figure 80.- Time on offense with advantage for individual pilots versus AML performance model.

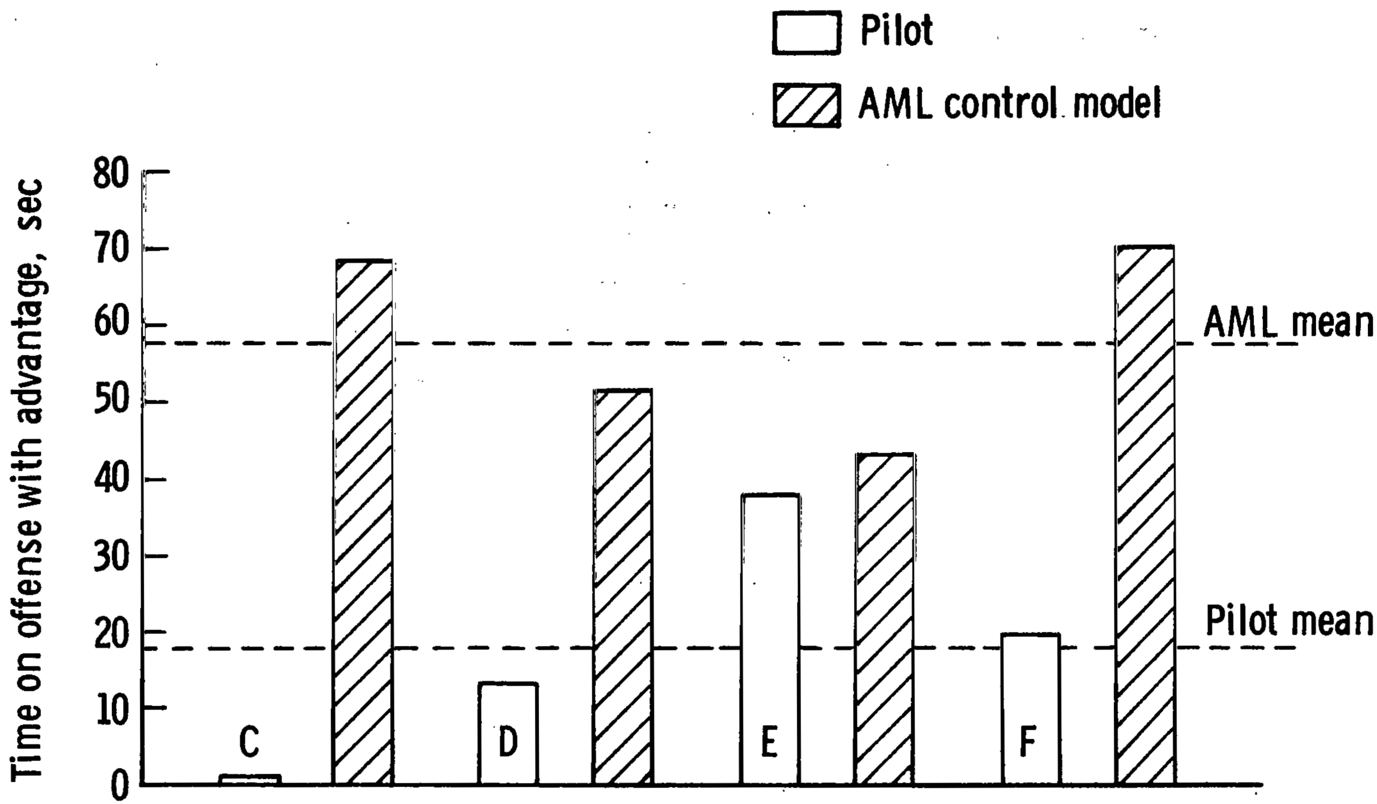

Figure 81.- Time on offense with advantage for individual pilots versus AML control model.

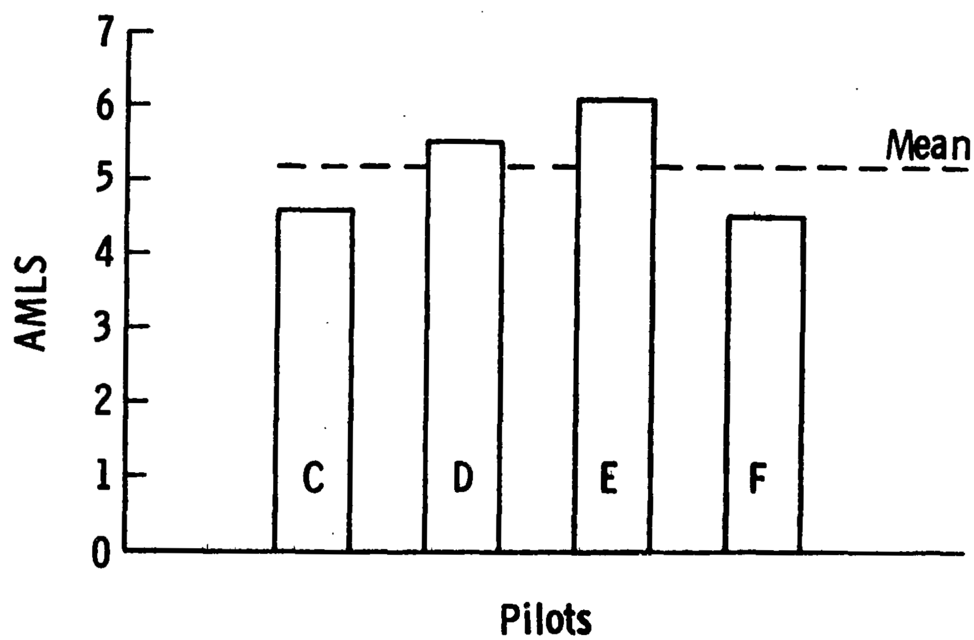

Figure 82.- Comparisons of AML scores for pilots versus pilots.

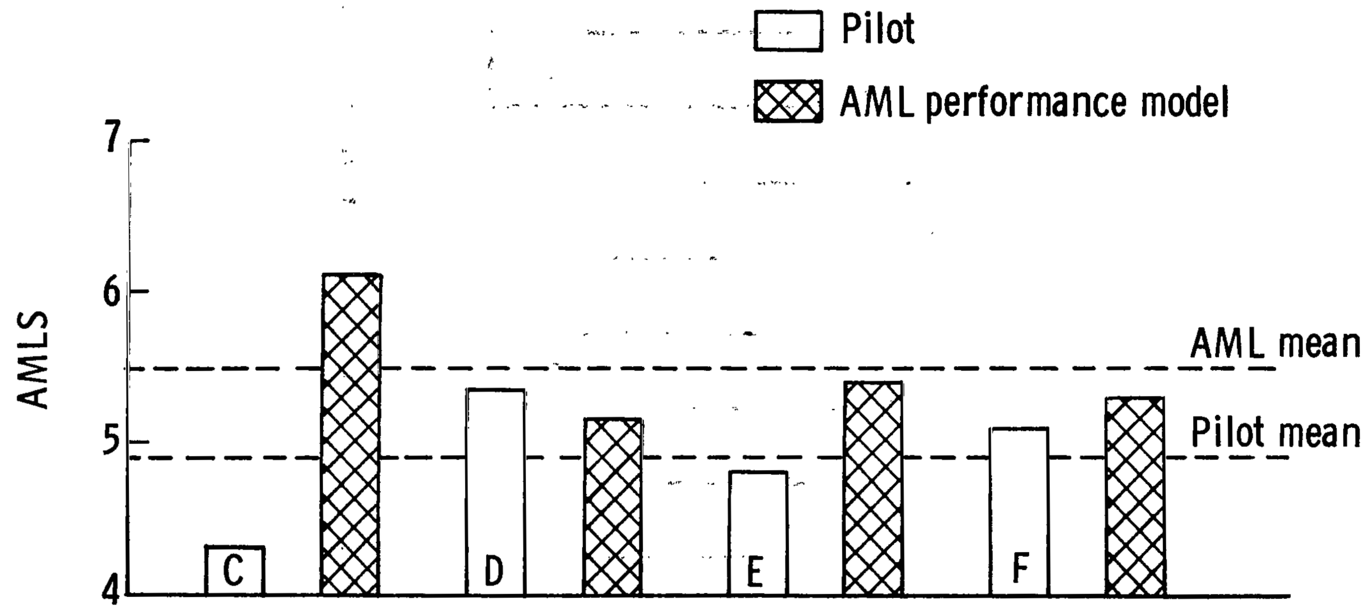

Figure 83.- AML score of individual pilots versus AML performance model.

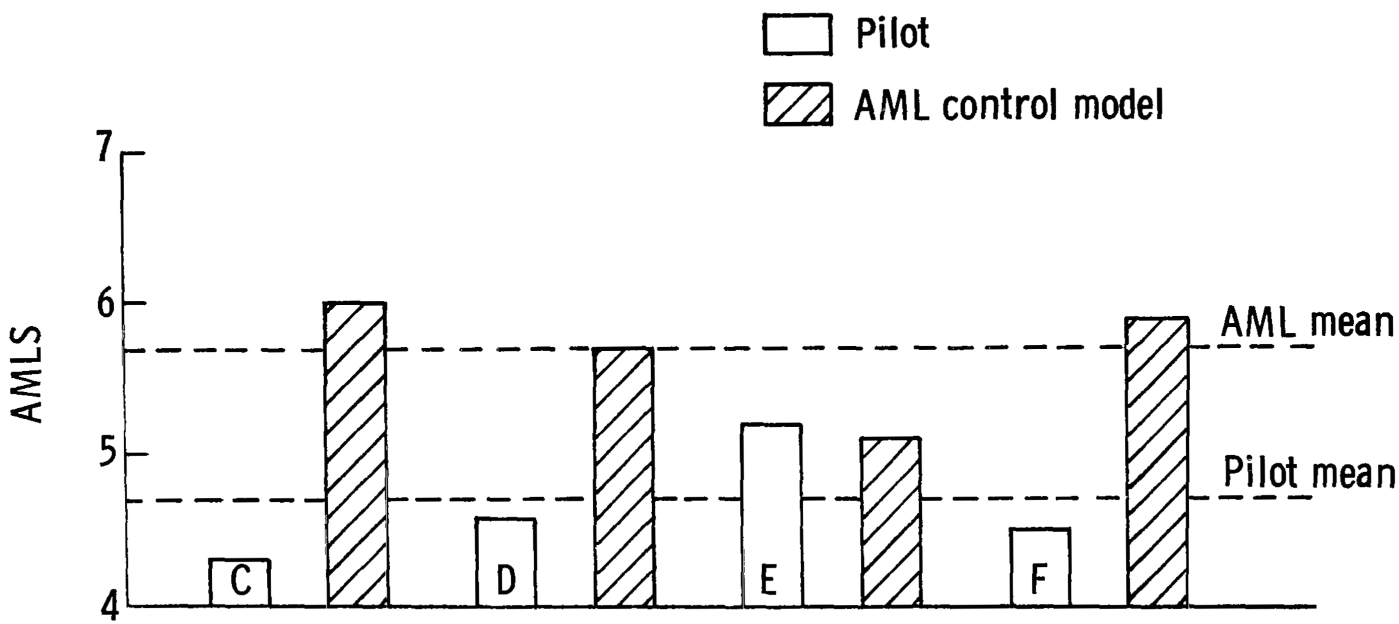

Figure 84.- AML score of individual pilots versus AML control model.

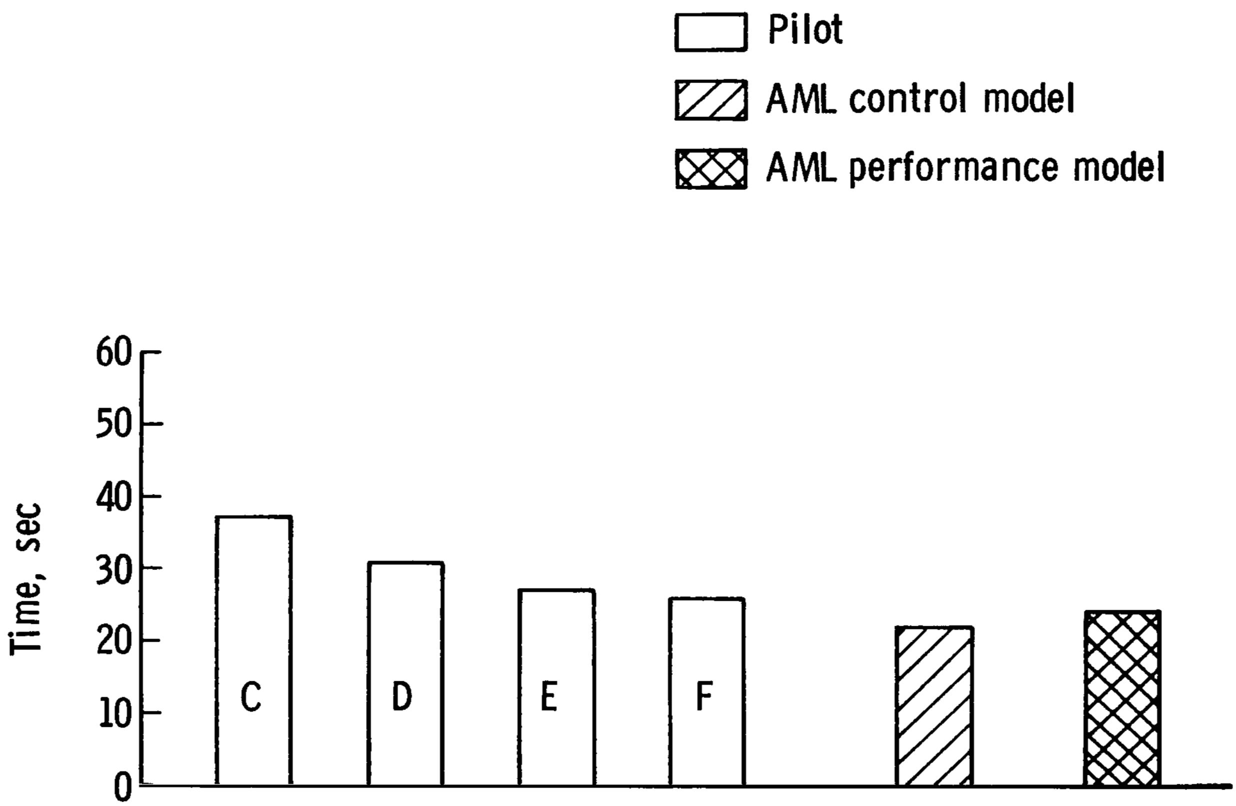

Figure 85.- Average time of first entry into zone A for individual pilots and AML against common opponent.

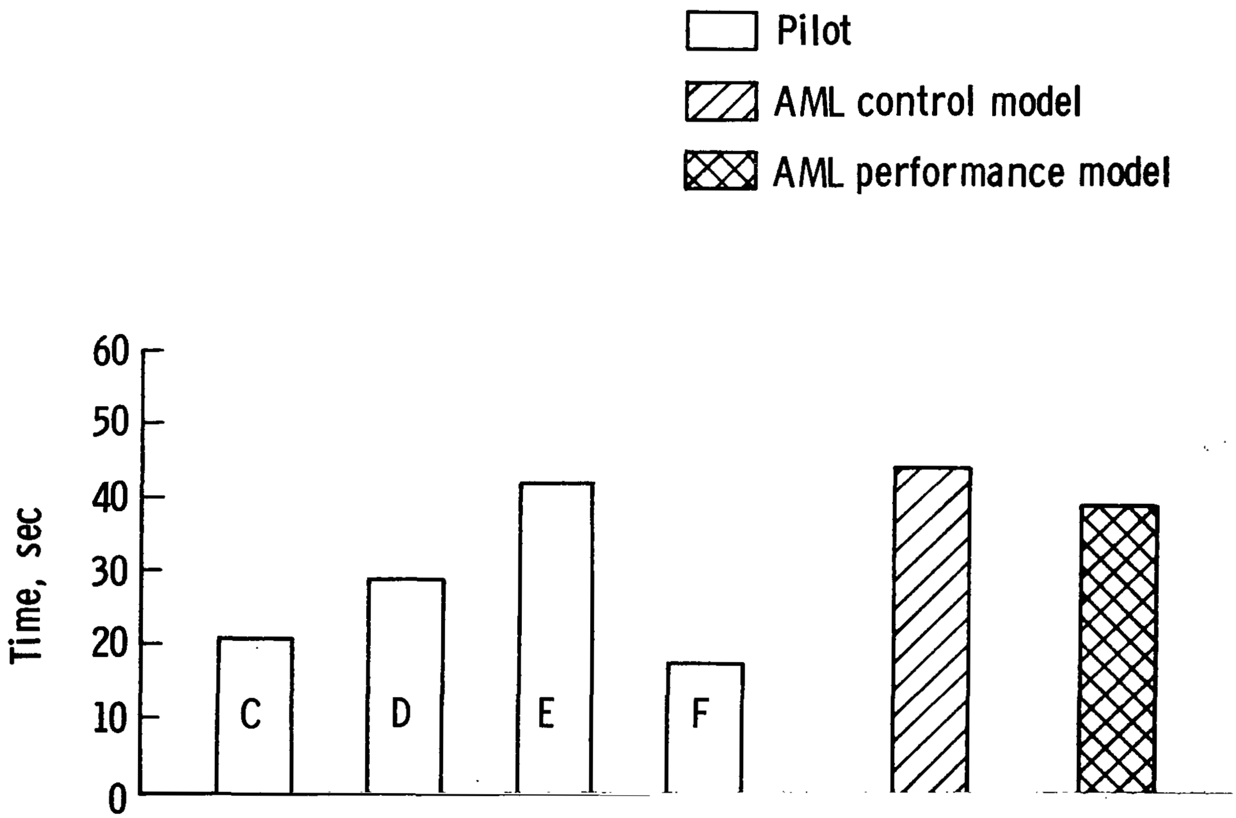

Figure 86.- Average time in zone A for individual pilots and AML against common opponent.

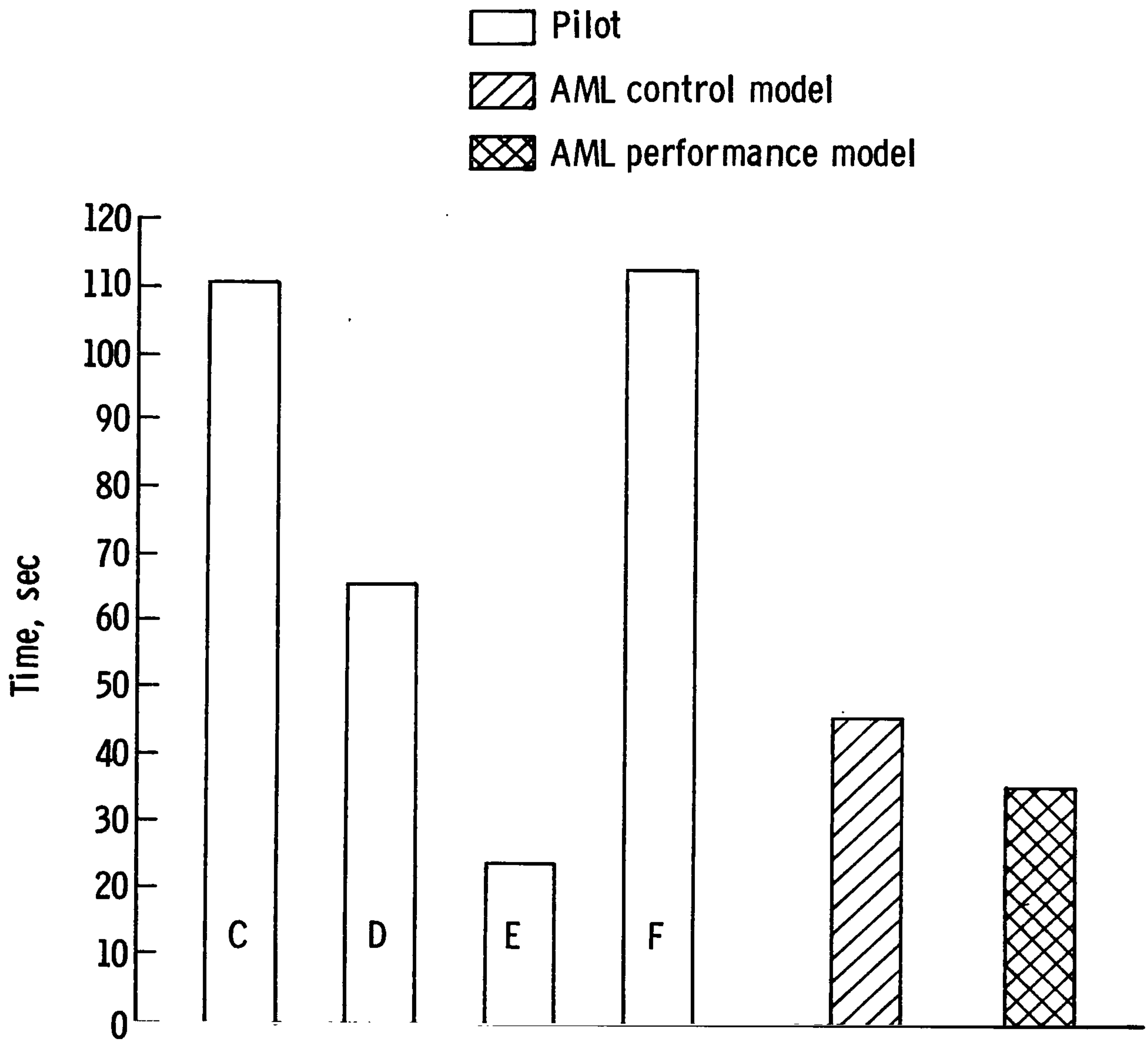

Figure 87.- Average time of first entry into zone B for individual pilots and AML against common opponent.

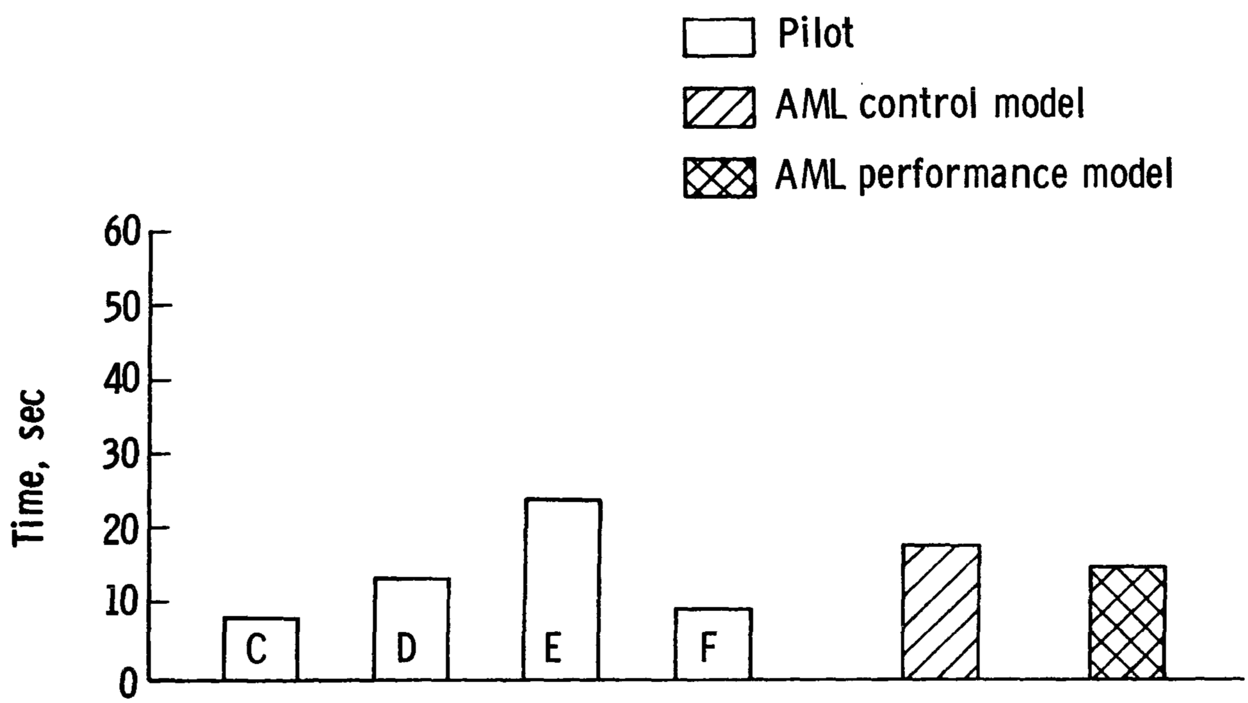

Figure 88.- Average time in zone B for individual pilots and AML against common opponent.

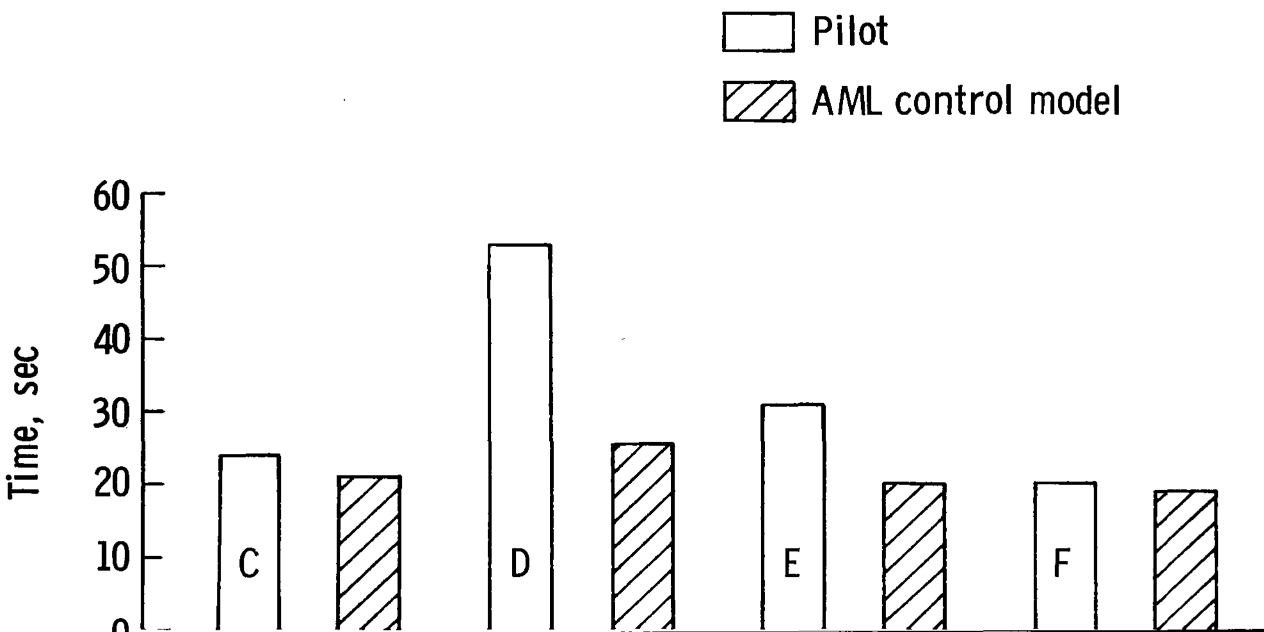

Figure 89.- Average time of first entry into zone A for individual pilots versus AML control model.

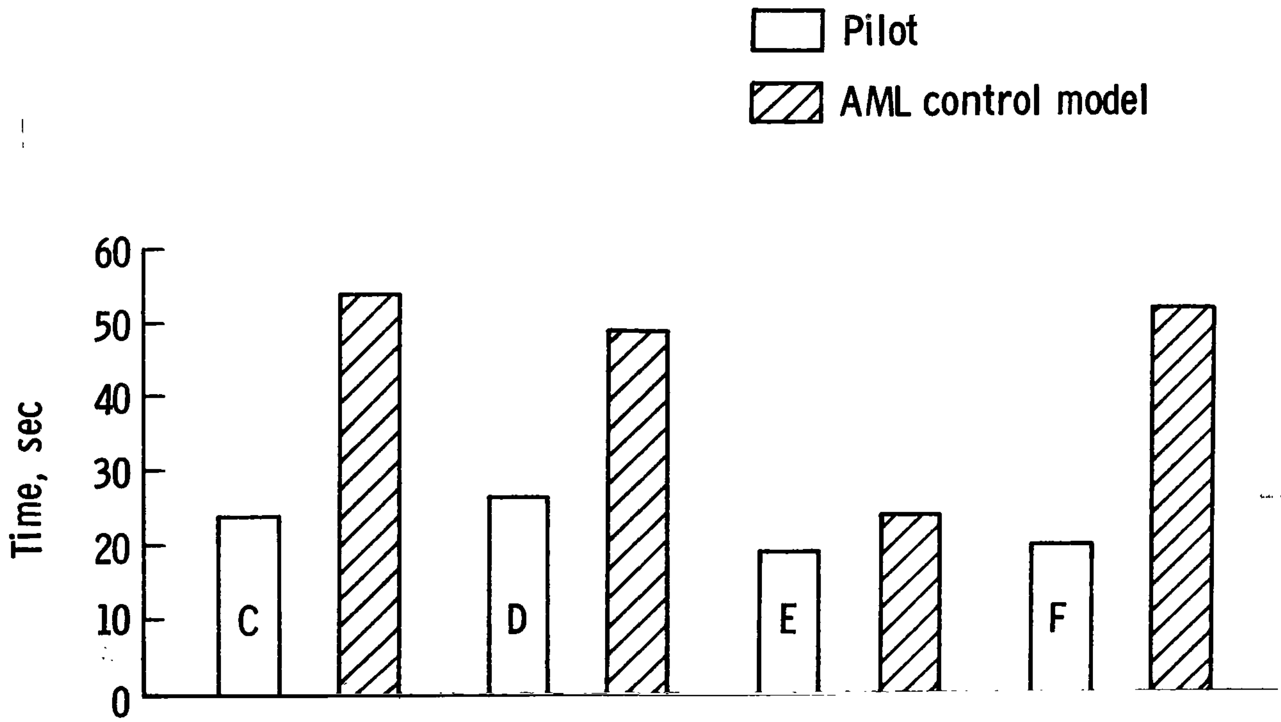

Figure 90.- Average time in zone A for individual pilots versus AML control model.

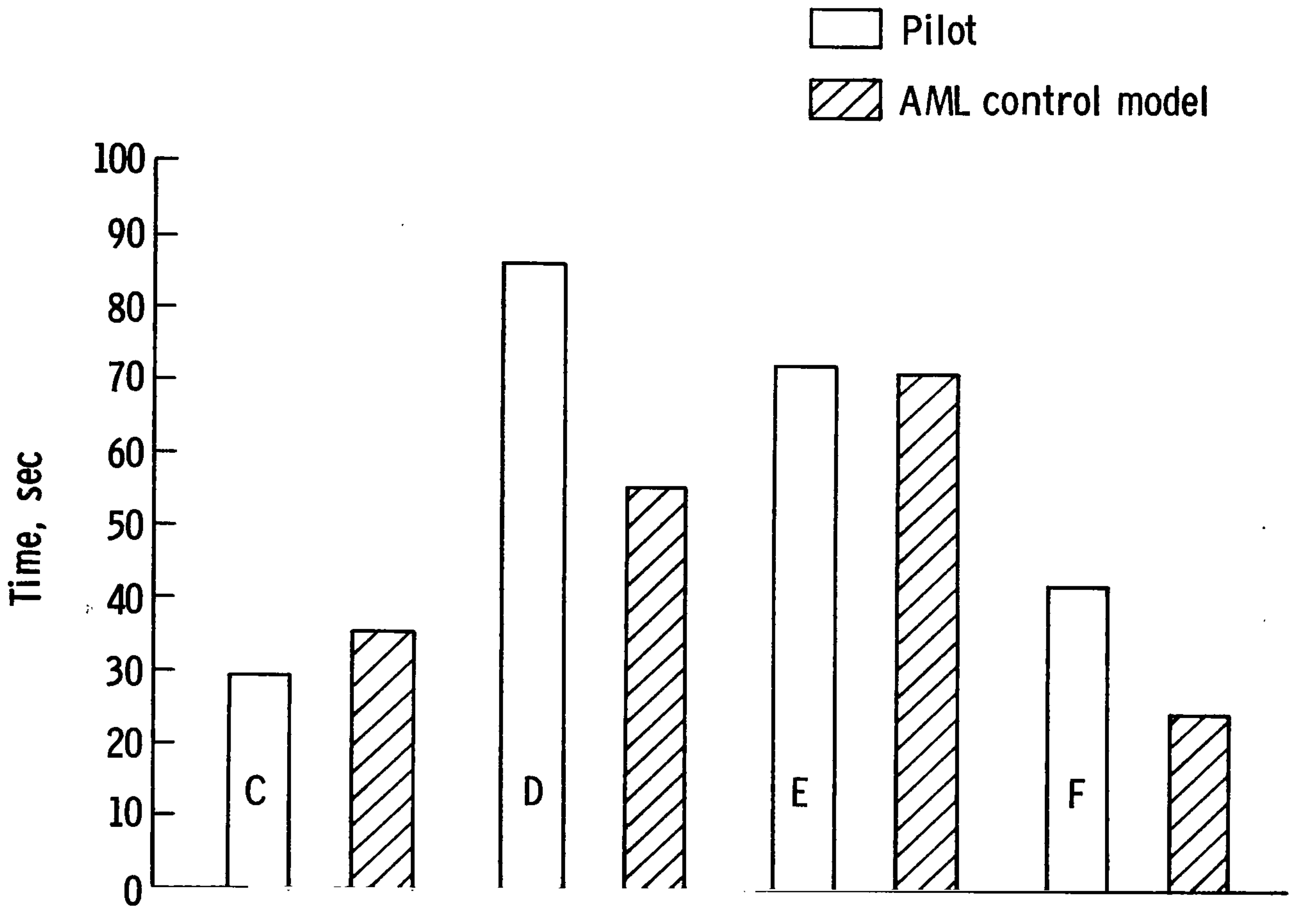

Figure 91.- Average time of first entry into zone B for individual pilots versus AML control model.

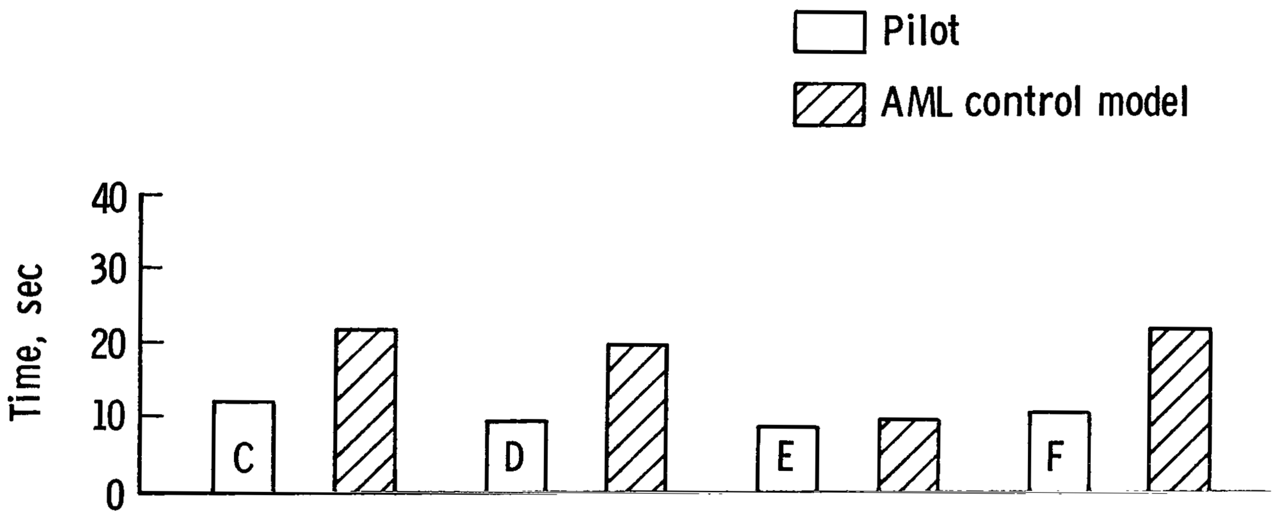

Figure 92.- Average time in zone B for individual pilots versus AML control model.

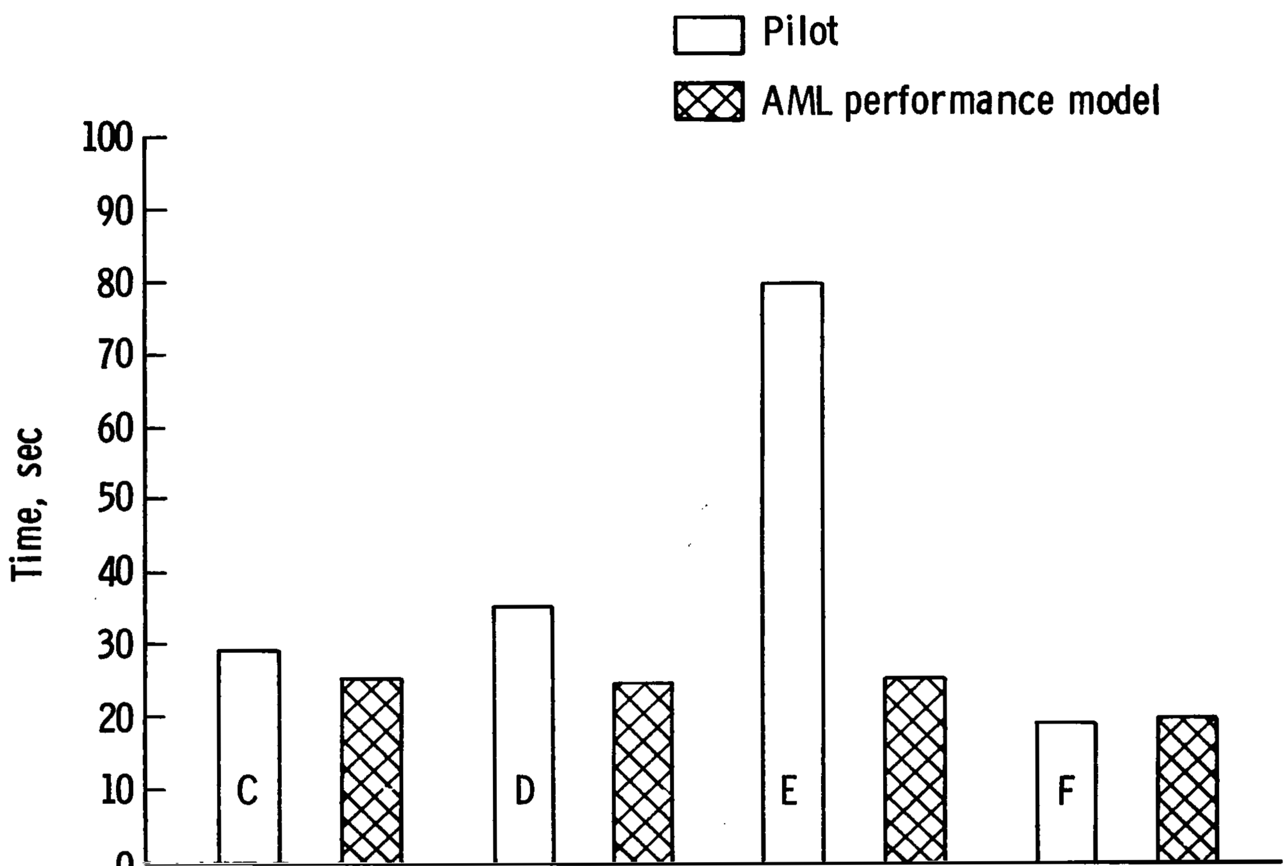

Figure 93.- Average time of first entry into zone A for individual pilots versus AML performance model.

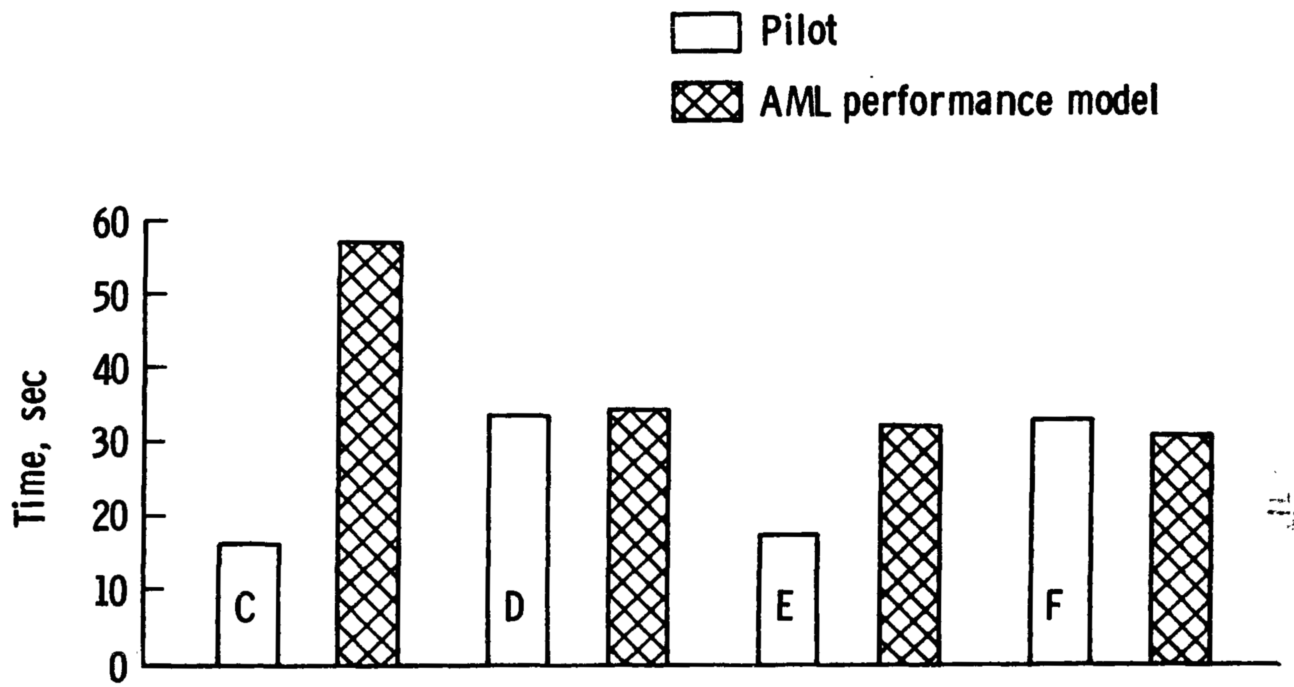

Figure 94.- Average time in zone A for individual pilots versus AML performance model.

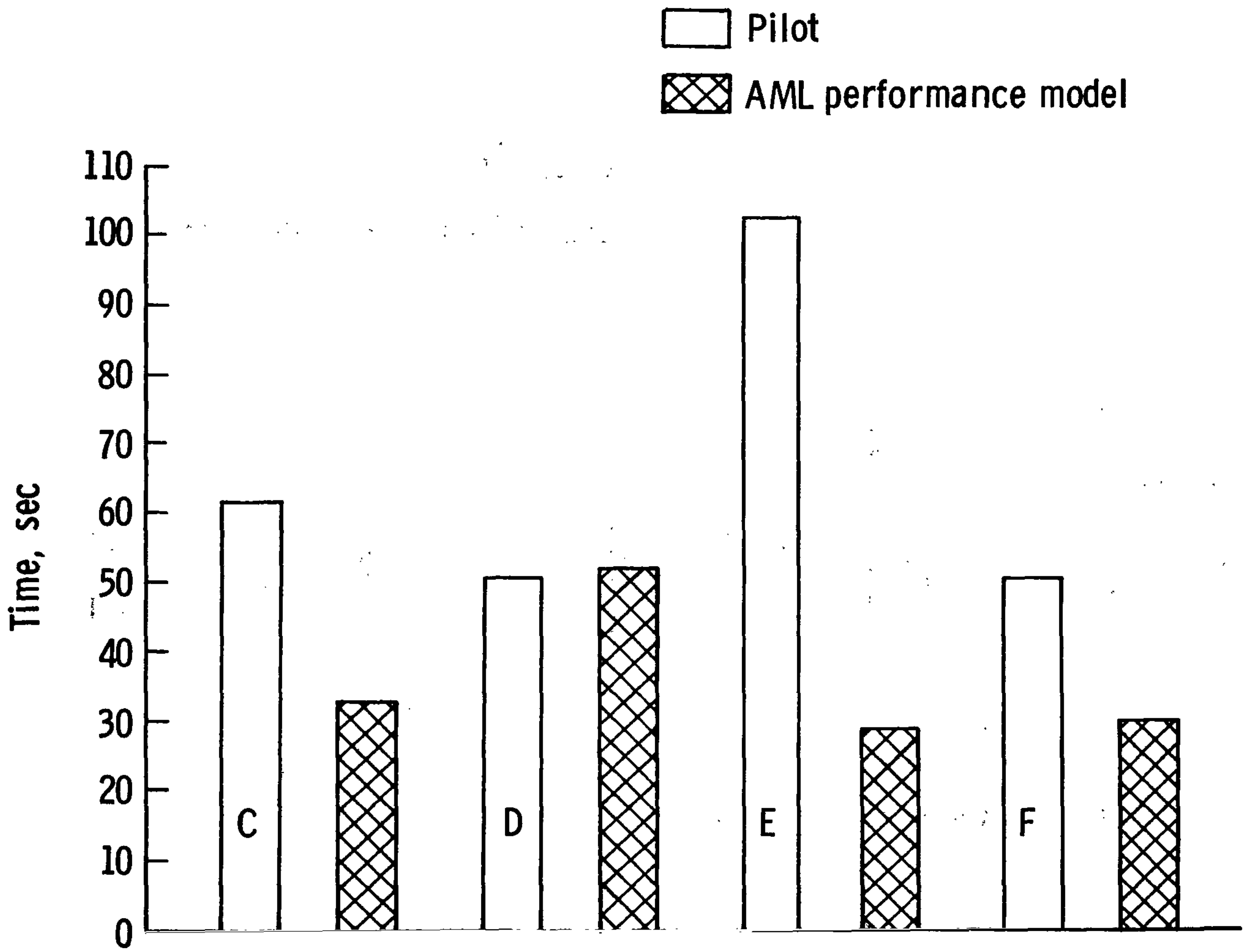

Figure 95.- Average time of first entry into zone B for individual pilots versus AML performance model.

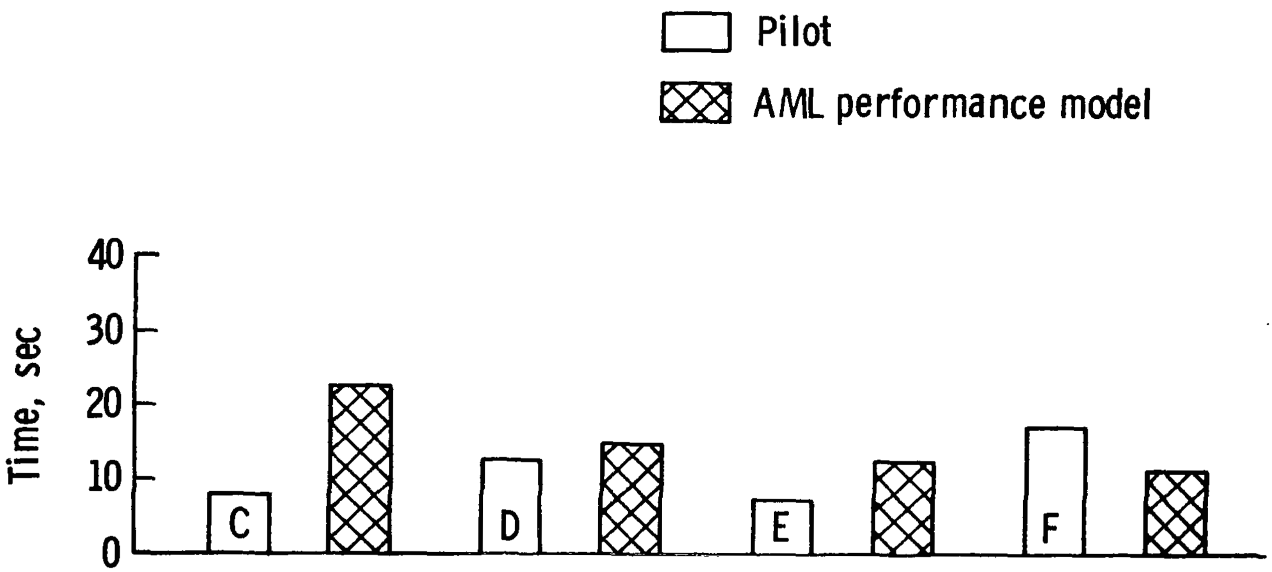

Figure 96.- Average time in zone B for individual pilots versus AML performance model.

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15. Supplementary Notes

Appendix A by Bobby J. Glover, Kentron International, Inc.

16. Abstract

Two versions of a real-time digital-computer program that operates a fighter airplane interactively against a human pilot in simulated air combat have been evaluated. They function by replacing one of two pilots in the Langley differential maneuvering simulator. Both versions make maneuvering decisions from identical information and logic; they differ essentially in the aerodynamic models that they control. One is very complete, but the other is much simpler, primarily characterizing the airplane's performance (lift, drag, and thrust). Both models competed extremely well against highly trained U.S. fighter pilots.

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