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Flight-Test Verification of a Pictorial Display for General Aviation Instrument Approach

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SUMMARY

As an extension of the simulator studies of the pictorial "follow me" box display described in NASA TP-1963, flight tests have been conducted by using the Navion Avionics research aircraft of Princeton University. The pertinent display factors and elements used in the simulation study were also used in the flight tests. These factors are the value of the distance from the aircraft to the box in the direction of the desired path of 368 m, a field of view of ±45°, the size of the cathode-ray tube used for the display, the size of the box, and the presence of distance measuring equipment in the system. The flight-test results duplicate the results of the simulator study. The most important item of agreement was the frequency of the vertical and lateral modes of motion of the pilot-aircraft-display system, which was 0.4 rad/sec in each study. The flight tests also corroborated the simulator test in that they showed again that successful short, curved, descending approaches, such as are often suggested for use with microwave landing systems, can be executed with the "follow me" box display.

Variations of the value of distance from the aircraft to the box were also examined in the flight tests. Values of 736, 368, and 184 m were tested. The results show that successful approaches can be made with all of these values. A sharper final turn and greater precision of position control are obtained with the shorter distance.

Deletion of distance measuring equipment from the system was also examined in the flight tests. The results show that successful approaches can be made with no distance measures included in the system, but the values of distance from the aircraft to the box that can be used are restricted.

INTRODUCTION

Because of the aircraft lag involved in the control of lateral and vertical position, the execution of an instrument landing approach is a difficult control task. When conventional general aviation instruments are used, the task is extra difficult because of the unintegrated and decoupled manner in which the information required for the control of the aircraft is presented. Advances in the technology of microprocessors and cathode-ray tubes have made it possible to consider generating pictorial displays that are more readily interpreted by the pilot and which will reduce this difficulty. A computer drawing of a box that is located on the desired path and moves along the path ahead of the aircraft is a display format that meets these objectives. By following the box the pilot is able to control precisely the position of the aircraft. References 1 and 2 are simulator studies of such a display. It is established in these reports that the frequency of response of the pilot-aircraft-display system is much higher with the box display than it is with conventional displays, with the result that path following is much more precise with the box display. In addition to providing the means for more precise tracking, the box display also provides useful information when the position error is large. It is shown in reference 2 that the good situation awareness relative to the approach path provided by the display allows the display to be used for a short, curved, descending landing approach similar to the type of approach that is made in visual conditions. This type of approach is often suggested in conjunction with the use of a microwave landing system.

As an extension of the simulator studies of references 1 and 2, flight tests of the "follow me" box display have been conducted. The same type of short, curved, descending approaches performed in the study of reference 2 was also executed in the flight study. The flight-test study used a ground-based computer, a ground-based radar, and telemeter links between the aircraft and the ground. The test aircraft was also equipped with a cathode-ray-tube display device that exactly duplicated the one used in the simulator study.

Ground-track data and time histories of the approaches were obtained from the flight tests to verify the results of the simulator study of reference 2 and to corroborate that the short, curved, descending approaches can be precisely executed with the box display. The study also examines two variations in display parameters. The first is a variation in display sensitivity. The second is the presence or absence of distance measuring equipment in the system. The results show the effect of these variables on the radius of curvature of the final turn and the precision of control during the straight portion of the approach.

SYMBOLS

X,Y,Z   aircraft body-axis system

X_i,Y_i,Z_i inertial axis system

x,y,z   aircraft inertial position relative to touchdown point, n.mi.

$x_{iB} - x_{iA}$, $y_{iB} - y_{iA}$, $z_{iB} - z_{iA}$ distances from aircraft to box in inertial axis, m

ψ,θ,ϕ Euler angles, deg

Subscripts:

A   aircraft

B   box

Abbreviations:

DME   distance measuring equipment

G.S.   glide slope

Loc.   localizer

DESCRIPTION OF EXPERIMENT

The purpose of the flight tests was to cover the following three items:

(1) To verify the results of reference 2 for the final approach by comparing the pilot-aircraft-display system frequencies, and to determine if the short, curved, descending approach can be accomplished in flight.

(2) To examine the effect of varying the distance from the aircraft to the box in the direction of the commanded path ($x_{iB} - x_{iA}$) as was done in reference 1. The induced changes in pilot-aircraft-display system frequency and the radius of curvature of the curved part of the approach were to be determined.

(3) To examine the effect of deleting distance measuring equipment (DME) from the system.

In references 1 and 2 it was assumed that DME was available, and the display concept was examined on this basis. However, the display concept can be applied without DME. The following sections will review the display concept and the application as implemented in references 1 and 2, and they will explain the changes required in the application of the concept when DME is not included in the system. A description of the aircraft, the ground system, and the test procedures will also be given. Data related to the test subjects will be presented.

Box-Drawing Algorithm

The box-drawing algorithm is presented in references 1 and 2. The inputs required for the algorithm are the orthogonal distances from the aircraft to the box, the attitudes of the aircraft and the box, a specified size for the box, and a specified field of view. It is assumed that the vertical distance ($z_{iB} - z_{iA}$) and the lateral distance ($y_{iB} - y_{iA}$) of the aircraft from the desired path are obtained from the landing system. The third distance required ($x_{iB} - x_{iA}$) is a selected value that has a major influence on the displacement sensitivity of the display, and, therefore, on the precision of control of the aircraft during the straight portion of the approach, and on the radius of curvature (or bank angle) on the curved section of the approach.

Another variation that is of interest is the presence or absence of distance measuring equipment (DME) in the system. In references 1 and 2 a true geometric picture of the box was always displayed, based on an input of linear distance from the aircraft to the desired path. In those references it was assumed that these linear distances were obtained from a combination of the conventional angular-error signals supplied by the landing system and the DME signal. However, it is not necessary that a true geometric picture be displayed. The display can provide a useful signal if only the angular landing-system signal is used without the distance to the touchdown point being known. The box-drawing algorithm can use the angular signal as though it were a linear distance and draw a usable picture even though the picture would not be a true geometric representation.

In the interest of explaining exactly what was done in the test system, the following derivation is given. The radar system used in the test program (see the section entitled "Ground System") provided data on the position of the aircraft in an axis system that had its origin at the touchdown point and that was aligned with the runway. To obtain linear measures of the vertical and lateral distances of the aircraft to the box, the following relations were used:

From radar,

$$y_{iB} - y_{iA} = y$$

and where x and z are obtained from the radar,

$$z_{iB} - z_{iA} = x(\tan 3°) - z - (x_{iB} - x_{iA}) \tan 3°$$

The term $(x_{iB} - x_{iA}) \tan 3°$ is included to depress the box below horizontal along the glide slope. The attitude of the box is also pitched down 3°.

The flight-test system was used in the following manner to represent the deletion of DME:

$$y_{iB} - y_{iA} = \frac{915}{x} y$$

$$z_{iB} - z_{iA} = \frac{915}{x}(x \tan 3° - z) - (x_{iB} - x_{iA}) \tan 3°$$

The quotients $\frac{y}{x}$ and $\frac{x \tan 3° - z}{x}$ provide the glide-slope and localizer signals in radians, and the constant 915 is the proportional gain used to convert these angular glide-slope and localizer signals to usable values. The use of the value 915 means that the display will provide a true geometric picture only when the aircraft is 915 m from touchdown.

Use of the Display

A typical flight situation is shown in figure 1(a), where the aircraft is to the right and above the desired path and is banked to the left. The display as seen by the pilot for the typical flight situation is as shown in figure 1(b). A photograph of the display as generated by the computer is shown in figure 1(c); however, in this photograph the aircraft is below and to the left of the desired path.

This display provides a usable signal when the displacement error is very large, while at the same time providing a sufficiently sensitive signal so that very precise control can be obtained. If the aircraft were 3 n.mi. out from the touchdown point and 2 n.mi. to the side of the localizer (that is, a very large lateral error), at an altitude of 300 m, and pointed normal to the localizer, a sideview of the box would appear, very small, on the display. By pointing the aircraft at the box (putting the aircraft reference symbol on the box), a gradual turn to a position directly behind the box will occur. As the lateral error is reduced, the box will grow in size. Once behind the box, the display will provide a sensitive indication of position error, and precise position control of the aircraft will result. Assisting in obtaining this precise control is the quickened, or lead, information that is inherent in the display. This lead information comes about because the location of the box relative to the reference symbol is a combination of the position and attitude of the aircraft relative to the desired path. In the present study, these features of the display are used to generate a curved, descending, precisely controlled instrument approach.

The display provides the pilot with situation awareness with regard to the approach path. However, the box by itself does not provide any situation information with regard to the runway. In an operational system, additional information would have to be supplied. This additional information could be provided by the use of marker beacons, the display of the DME signal, or by the use of stationary boxes located at designated waypoints, such as was done in reference 2.

Aircraft

The aircraft used in the flight tests was the Navion Avionics research aircraft of Princeton University. (See fig. 2.) The left seat (the subject pilot's seat) was equipped with a fly-by-wire control system. In the present study, no stability augmentation was used. The control signal was a one-to-one correlation with the manual control signal. A small cathode-ray tube (7.6 cm by 10.16 cm) was mounted in the display panel for presenting the display. (See fig. 3.) Also included in the display panel was an airspeed indicator, an altimeter, and a horizontal-situation indicator. The glide-slope and localizer needles of the horizontal-situation indicator were not operative. A safety pilot rode in the right seat.

The flight-test aircraft was not the same aircraft that was modeled for the simulator tests of references 1 and 2. In spite of the differences that might exist in aircraft response, which may have some effect on the overall system frequency or damping, a decision was made to conduct the flight test. No attempt was made to identify the differences that might exist in the short-period longitudinal response and in the lateral response. One very noticeable difference in the aircraft used for the flight tests and the simulation studies was in the airspeed regulation. The flight-test aircraft operated at the beginning of a backside power-required variation in the approach condition, whereas the simulator aircraft did not contain this power-required problem. Therefore, the airspeed regulation task for the flight-test aircraft was a greater problem than for the simulator aircraft. The approach speed was approximately 80 knots in each case.

Ground System

The aircraft was equipped with a telemetry system that transmitted the aircraft attitude signals to the ground-based graphics computer. The ground-based radar system also sent aircraft-position data to the computer. The radar data were used to simulate the signal that otherwise would be obtained from the combination of the instrument landing system and the distance measuring equipment. The computer used these signals, along with given values for the attitude of the box, the size of the box, the value of $x_{iB} - x_{iA}$, and the field-of-view size to generate the display. The display was then video transmitted back to the aircraft. This system was also used to record data.

The display system included three computers in series (one in the aircraft, one associated with the radar, and the graphics computer). The delay involved in sending the display signals through each of these computers would naturally have some effect on the performance of the total system. However, a decision was made to conduct the flight tests regardless of any effect. No attempt was made to identify the magnitude of the effect of these delays.

Verification of Test Results of Reference 2

The first purpose of the flight tests was to verify the results of simulator study of reference 2 for the short, curved, descending final-approach segment of the flight. The important display parameters used for the final approach in the simulator were, therefore, duplicated for the flight tests. These parameters were the value of $x_{iB} - x_{iA}$ of 368 m and the field of view of ±45°, and they had the greatest influence on the results. In the simulator study, other values of $x_{iB} - x_{iA}$ were used for the en route and terminal-area segments of the flight. In the flight tests, only the final-approach segment of the flight task was examined. Other parameters of less importance are the size of the cathode-ray tube, the size of the box, and the response of the aircraft. The size of the cathode-ray tube was the same in both studies. The size of the box was approximately the same in each case.

In most cases, the pilot-aircraft-display system frequency can be determined from time histories of the glide-slope and localizer errors. Those system frequencies are fundamental indicators of the usefulness of the system. In the study of reference 2, the time histories of the final approach show system frequencies of approximately 0.4 rad/sec (periods ranging from 11 sec to 18 sec). The time histories obtained in the flight tests were examined to see if the same system frequencies were obtained.

Variations in $x_{iB} - x_{iA}$

Reference 1 examines variations in $x_{iB} - x_{iA}$. In addition, reference 1 contains a pilot-model analysis to establish the pilot-aircraft-display system frequencies and an error analysis to establish the root-mean-square performance scores. The study, therefore, shows the correlation between system frequency and performance. In the present study, these same relationships are established by using visual inspection of the time histories. Values of $x_{iB} - x_{iA}$ of 736, 368, and 184 m are examined.

Deletion of DME

Because distance measures may not always be available for use in the system, the effect of deleting this quantity from the system was examined. If DME is not available, then it becomes necessary to use the angular measures for aircraft glide-slope and localizer errors instead of linear measures. The angular-error signals must be adjusted for use in the box-drawing algorithm. By using a constant gain in the angular-error signals, the signal can be adjusted so that the display will present a true geometric view of the box at one point in the approach. Then, at distances farther from touchdown than this selected point, the displacement errors will appear smaller than if linear displacement errors were used. The change in displacement-error sensitivity along the approach will affect the pilot-aircraft-display system frequency. (A continual increase in frequency along the approach could be expected.)

Also, the use of angular signals for $z_{iB} - z_{iA}$ and $y_{iB} - y_{iA}$ changes the meaning of the linear value of $x_{iB} - x_{iA}$. The new combinations of angular signals for $z_{iB} - z_{iA}$ and $y_{iB} - y_{iA}$ and the linear value for $x_{iB} - x_{iA}$ will have an effect on the turn rate of the final turn onto the approach.

As was indicated in an earlier section, the constant gain used on the angular-error signals was 915. Other values were not examined. This constant gain was used in combination with values of $x_{iB} - x_{iA}$ of 368, 184, and 92 m. It was noted in reference 1 that when a value of $x_{iB} - x_{iA}$ of 92 m was used in the system with DME, a noticeable reduction in pilot-aircraft-display system damping was encountered in one case. In the present study, it can be expected that a similar result may occur as the aircraft approaches a point 915 m from touchdown. (The experiment ends before the 915-m point is reached.) The effect of eliminating DME from the system will be examined for effects on the radius of turn and on system frequency and damping.

Subjects

The test subjects were all NASA test pilots. Four subjects took part in the study. Two of these subjects had also taken part in the study of reference 2, and they are labeled "subject 8" and "subject 9" in both the present study and in reference 2. Subject 10 took part in the study of reference 1 and, therefore, was familiar with the use of the display. Subject 11 had no previous experience with the display. Subjects 8, 9, and 11 had no previous experience with the test aircraft, and subject 10 had only a small amount of experience with the aircraft.

Test Procedures

The safety pilot flew the aircraft to a position 3 n.mi. out from touchdown, 2 n.mi. to the left of center line, at an altitude of 300 m with a heading normal to the center line. The safety pilot used vectors supplied by the radar crew to assist him in setting up this initial condition. The subject pilot would then verify that the display symbol was present on the cathode-ray tube and take over control of the aircraft. Data recording was started at this point. The subject pilot would then maneuver the aircraft through the approach down to an altitude of 60 m. At this point, the safety pilot would resume control. Data recording was stopped shortly after the safety pilot started the pull-up.

An instrument hood was used to prevent any view of the outside. All testing was done on 1 day for each of the subjects. All flights were made on clear days at Wallops Flight Center. Winds were generally light to moderate. The surface wind conditions at the time of the tests are given in the following table:

Pilot	Runway	Wind condition at -	
		Surface	300 m
8	35	300 at 6 knots	326 at 16 knots
9	28	260 at 8 to 11 knots	275 at 5 knots
10	28	300 to 308 at 6 knots	325 at 15 knots
11	28	220 at 4 knots	275 at 13 knots

RESULTS

Verification of Simulator Tests Results

Comparisons of pilot-aircraft-display system response for the simulation study of reference 2 and the flight tests for subjects 8 and 9 are shown in figures 4 to 7. Each figure contains one run from the simulation study and one run from the flight study. One of the runs from the simulation study has no wind input, and the other is with a wind input of moderate strength (a random component with root-mean-square velocity of 2.4 knots and a crosswind shear that varies from 10 to -10 knots). These runs were all made with values of $x_{iB} - x_{iA}$ of 368 m and a field of view of +45°. It can be seen that good agreement exists in the system frequencies (about 0.4 rad/sec) and in the general amplitude of the glide-slope and localizer errors. The places in the time histories where these system frequencies are estimated are shown in the figures. These comparisons verify the simulation-test results.

The safety pilot noted on several occasions that the aircraft always lined up very well with the runway at the completion of the turn. On some occasions the subject pilot looked up at the completion of the run and reported that the aircraft was lined up on the runway center line. Negative comments were made during the flight tests about the small size of the display and the small size of the box symbol, just as they were made during the simulation study. There were no comments made related to the fact that the flight environment raised any additional problems. Subject 9 commented that the motion associated with the flight tests improved his performance over what he felt he had done in the simulator.

Variations of Values for $x_{iB} - x_{iA}$

Subjects 9, 10, and 11 made runs with values of $x_{iB} - x_{iA}$ of 736, 368, and 184 m. Sample time histories of approaches made with each of these values are shown in figures 8 to 10. The variations in system frequencies and precision of control are apparent from these figures. The highest system frequencies (about 0.5 rad/sec, or a period of about 13 sec) and the tightest control occur with the shortest distance to the box. The lowest frequencies (about 0.18 rad/sec) occur with the longest distance to the box. These frequencies refer to the dominant mode of motion in the glide-slope and localizer outputs. The higher the system frequency, the more attention must be paid to the display; and the pilots commented that their workload was increased when the shortest distance to the box (184 m) was used. In exchange for this increase in work load, better precision in aircraft position control is obtained.

Plots of the ground tracks of all runs made by subjects 10 and 11 are shown in figures 11 and 12. These plots show the effect of the parameter $x_{iB} - x_{iA}$ on the radius of the final turn. When using the longest distance to the box ($x_{iB} - x_{iA} = 736$ m), a very gentle turn is created. In the case of subject 10, a fairly strong crosswind applied almost all of the turning force required. Figure 9(a), which is a time history of one of the runs made by subject 10 for the longest distance to the box, shows that the bank angle used is at most 5° and that a substantial crab angle has to be maintained to stay on the localizer. With the shortest distance to the box ($x_{iB} - x_{iA} = 184$ m), an abrupt turn, as shown in figures 11 and 12, is generated. These turns were all generated by keeping the reference mark on the box. The pilots called these turns abrupt. Subject 10 called the turns abrupt, and subject 11 called the turns too abrupt. Bank angles greater than 20° were used in making these turns. Thus, a trade-off or compromise between the desire for precise control (although with increased work load) and the acceptability of the final turn would be required in selecting a value of $x_{iB} - x_{iA}$. The abruptness of these turns can be alleviated by pointing ahead of the box, but these piloting techniques were not used in these tests.

Deleting Distance Measurements

All the runs shown in figures 4 to 12 were made by using linear-distance sures for the vertical and lateral aircraft-position errors in the box-drawin algorithm. Because DME may not always be available, there is interest in determining the use of the display concept without the aid of distance measurements, when using only the angular landing-system signals. This method, implemented as described in a previous section of the paper, was used in conjunction with values of $x_{iB} - x_{iA}$ of 368, 184, and 92 m. Ground tracks of the runs made by subjects 10 and 11 are shown in figures 13 and 14, respectively. With the value of $x_{iB} - x_{iA}$ of 368 m, an extremely slow turn is generated. The localizer is just barely acquired by the time that decision height is reached. This display configuration is probably usable, but it is not practical at 3 n.mi. from touchdown starting point.

A more realistic approach is made with a value of $x_{iB} - x_{iA}$ of 92 m. In this case, the final turn is very similar to that made when distance measurements are used in conjunction with a value of $x_{iB} - x_{iA}$ of 368 m. However, as the displacement indication of the display undergoes a change in sensitivity (and, therefore, in system frequency), as the aircraft nears the decision height (60 m), with the value of $x_{iB} - x_{iA}$ of 92 m, the pilot-aircraft-display system response can approach a condition of low damping.

Time histories of the final approach using the display configuration with no distance measurement are shown in figures 15 and 16. It can be seen from these figures that the position control of the aircraft is very lax at the beginning of close acquisition of the glide-slope—localizer path with a value of $x_{iB} - x_{iA}$ of 184 m. The initial overshoot of the glide slope reaches a value of 25 m, and this error is reduced very slowly. The lateral errors are quite reasonable.

With a value of $x_{iB} - x_{iA}$ of 92 m, the glide-slope overshoot is less than 15 m, and the errors at decision height are near zero. However, with subject 10 there is an indication of a lateral instability developing near the end of the approach. These results indicate that although successful approaches can be made with a wide variety of values of $x_{iB} - x_{iA}$ when distance measuring equipment is assured to be present in the system, the values of $x_{iB} - x_{iA}$ that can be used with no distance measurements are restricted to values between 184 and 92 m. The compromise that must be made is similar to the compromise that must be made with conventional instruments.

CONCLUDING REMARKS

Flight tests of the pictorial "follow me" box display have been conducted at the Wallops Flight Center under simulated-instrument meteorological conditions by using the Navion Avionics research aircraft of Princeton University. Short, curved, descending approaches, such as those performed in the simulator study of NASA TP-1963, were also performed in the flight tests. The flight-test results corroborated the simulation-study results very closely. The pilot-aircraft-display system frequencies of the vertical and lateral displacement modes of motion (frequencies of 0.4 rad/sec, or a period of 16 sec) were the same in each study. The principal display characteristics involved in these verification tests were values of distance from aircraft to box ($x_{iB} - x_{iA}$) of 368 m, a field of view of ±45°, and the presence of distance measuring equipment in the system.

Variations in the value of $x_{iB} - x_{iA}$ were examined in the flight-test studies. Values of 736, 368, and 184 m were tested. It was shown that system frequencies of 0.5 rad/sec and more precise position control were obtained with the shortest distance (184 m). In contrast, the system frequency obtained with the longest distance (736 m) was 0.18 rad/sec. Also, the final turn was abrupt with the shortest distance and was very slow with the longest distance. In all cases, the approaches were judged to be successful. The data show the choices that can be implemented by varying $x_{iB} - x_{iA}$.

The deletion of distance measuring equipment was simulated in the flight tests, and approaches were made with values of $x_{iB} - x_{iA}$ of 368, 184, and 94 m. With no distance measurements in the system, the final turn generated while using the value of $x_{iB} - x_{iA}$ of 368 m was too gentle to be used for short approaches. Also, with no distance measurements, the sensitivity of the displacement indication of the display becomes greater as the aircraft approaches the decision height. With a value of $x_{iB} - x_{iA}$ of 94 m, a noticeable loss of pilot-aircraft-display system damping was detected in one case. It is concluded that although successful approaches can be made when no distance measuring equipment is included, the values of $x_{iB} - x_{iA}$ that can be used are more restricted than when distance measurements are included in the system.

As is the case with conventional instruments, compromises exist in selecting the characteristics of a display. A thorough understanding of the effects of the various choices is, therefore, required. The results of the flight tests reported here contribute toward the understanding of the "follow me" box display.

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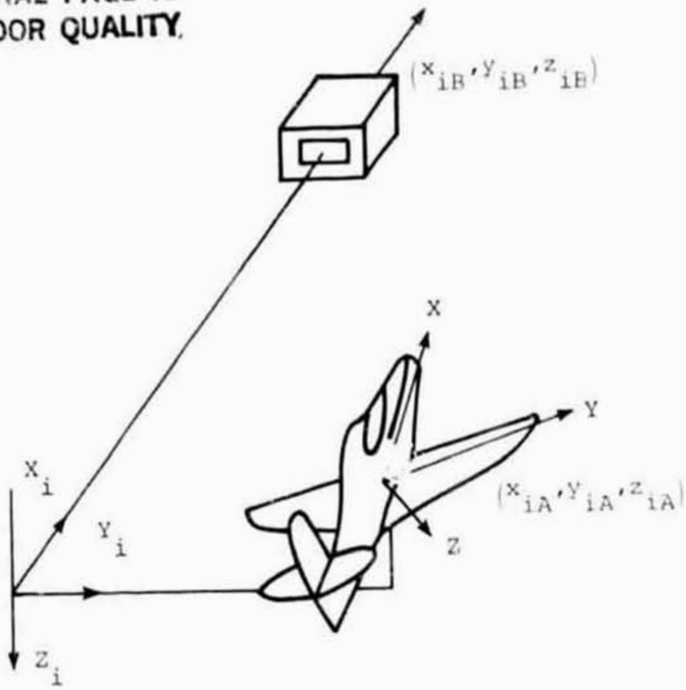
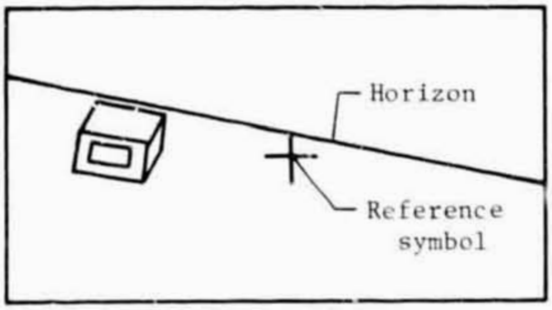
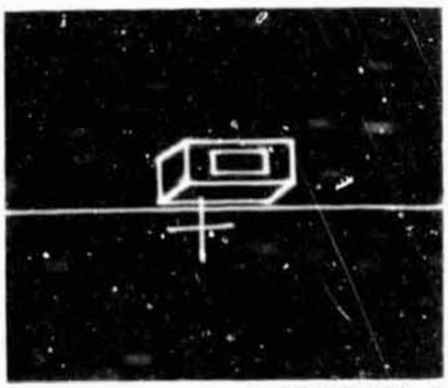
2. Adams, James J.: Simulator Study of a Pictorial Display for General Aviation Instrument Flight. NASA TP-1963, 1982.



(a) Typical flight situation.



(b) Display for typical flight situation.



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(c) Photograph of actual display.

Figure 1.- Display concept.

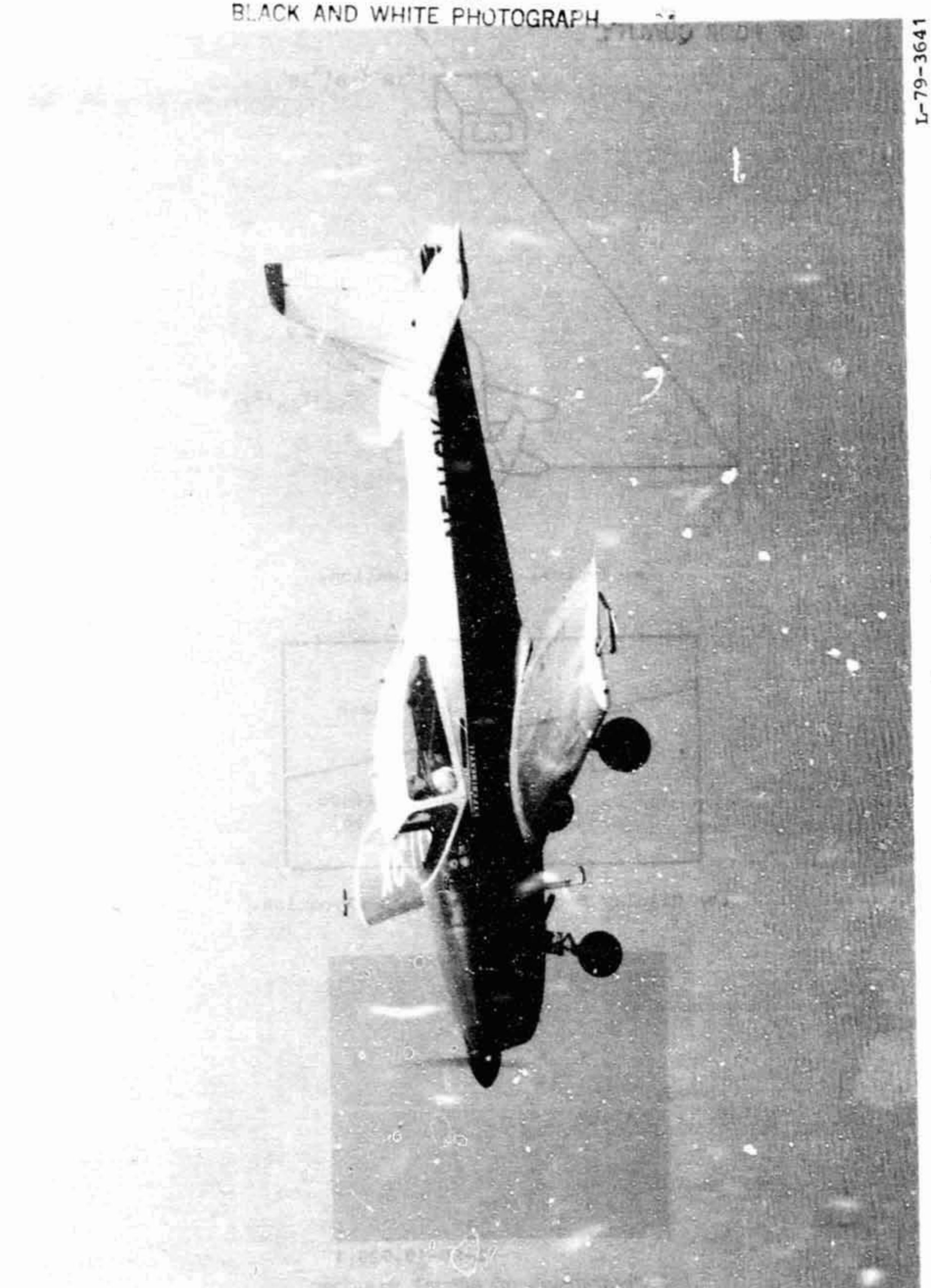

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Figure 2.- Photograph of test aircraft.

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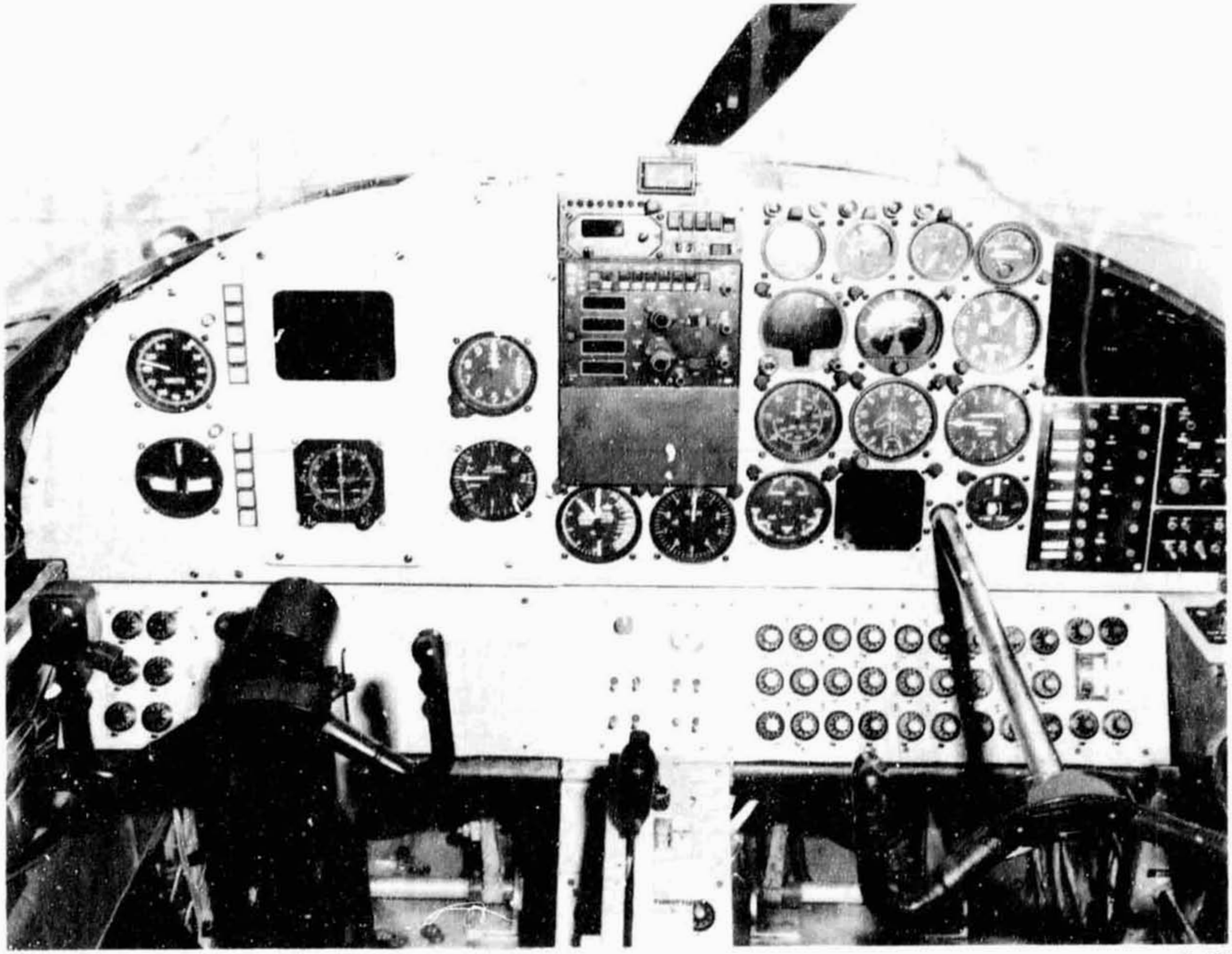

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Figure 3.- Photograph of instrument panel of test aircraft.

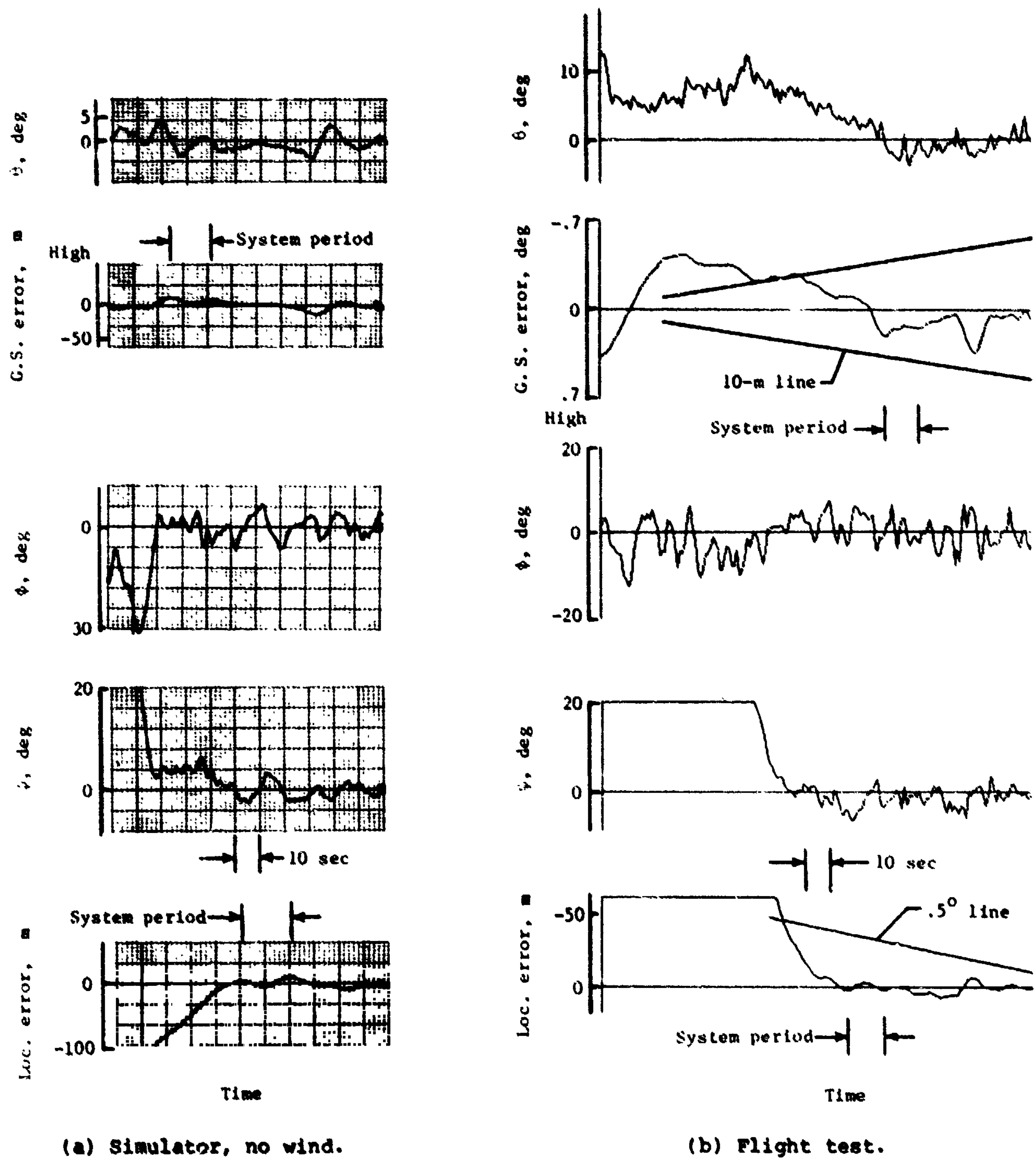

Figure 4.- Approaches made by subject 8. $x_{iB} - x_{iA}$ = 368 m; field of view, ±45°.

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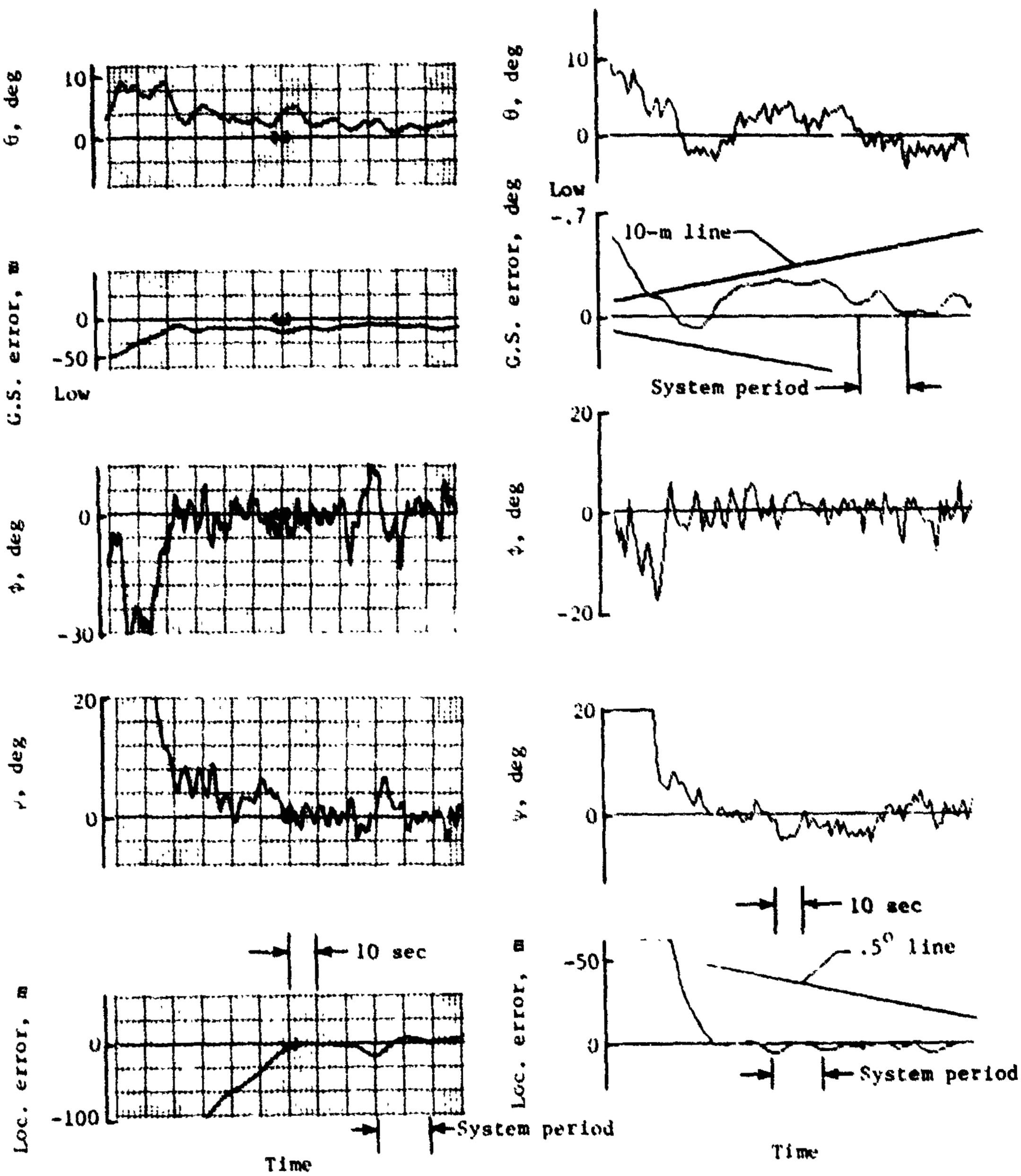
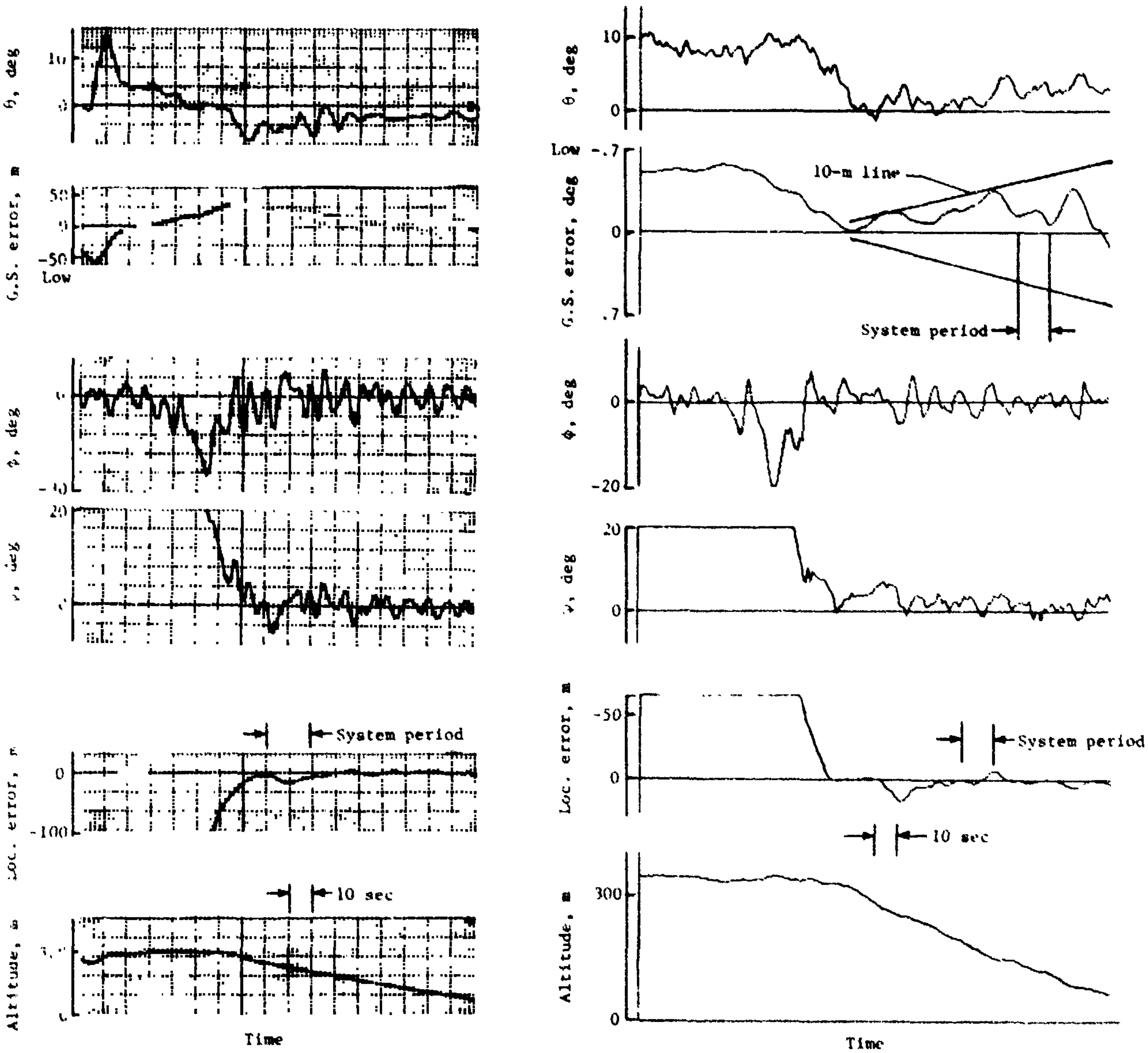


(a) Simulator, with wind.

(b) Flight test.

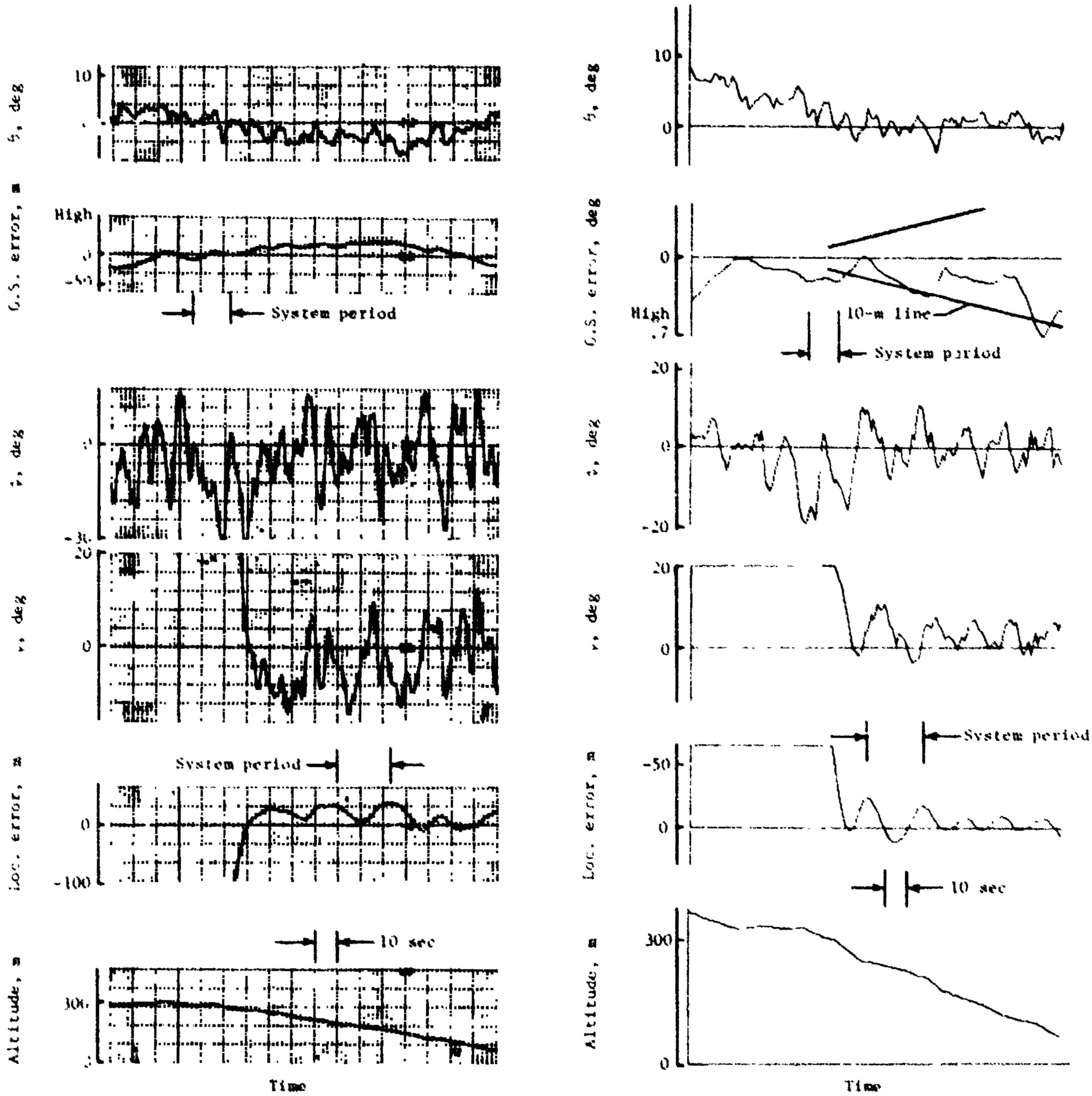
Figure 5.- Approaches made by subject 8. $x_{iB} - x_{iA}$ = 368 m; field of view, ±45°.



(a) Simulator, no wind.

(b) Flight test.

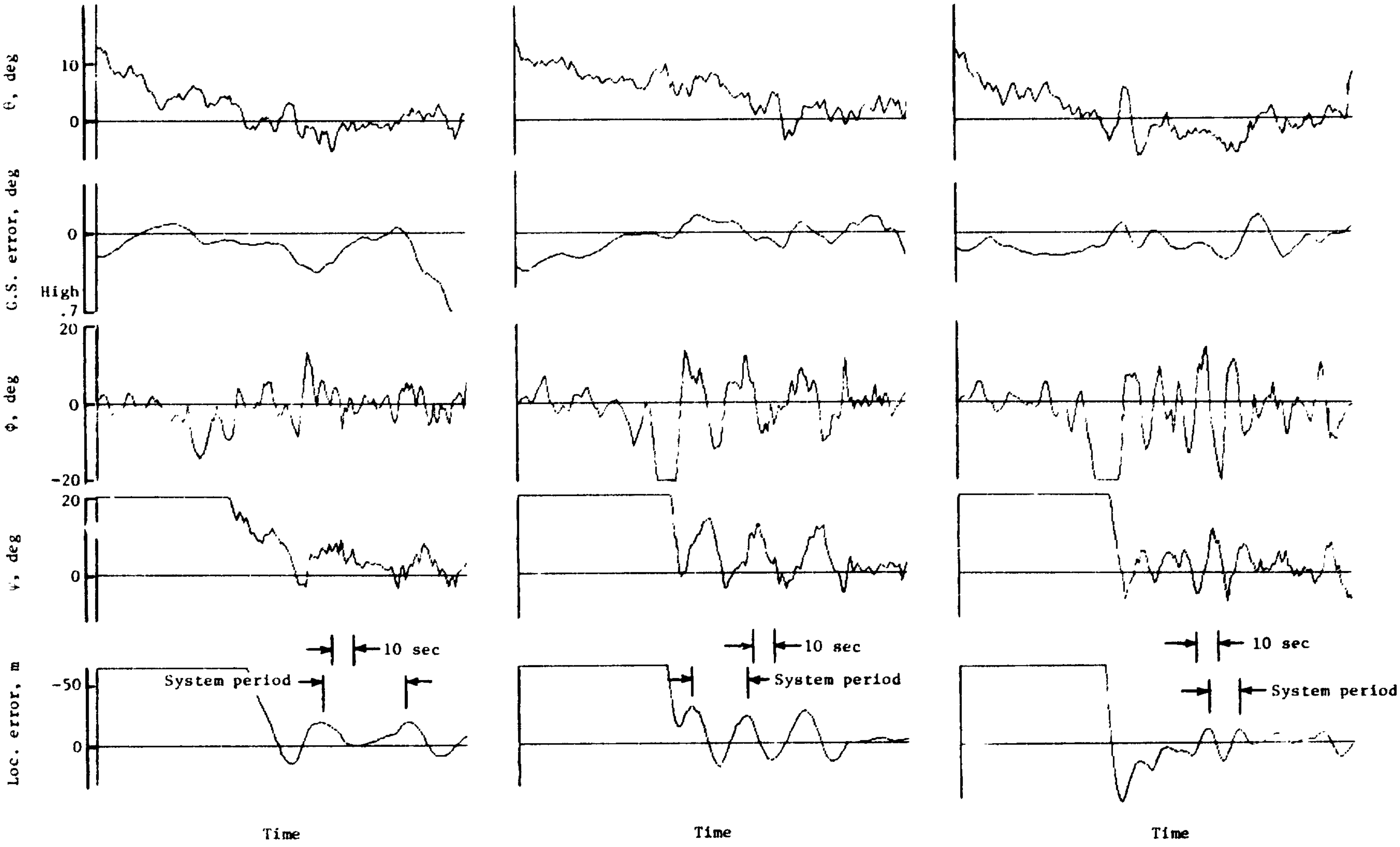
Figure 6.- Approaches made by subject 9. $x_{iB} - x_{iA} = 368$ m; field of view, ±45°.



(a) Simulator, with wind.

(b) Flight test.

Figure 7.- Approaches made by subject 9. $x_{iB} - x_{iA}$ = 368 m; field of view, ±45°.

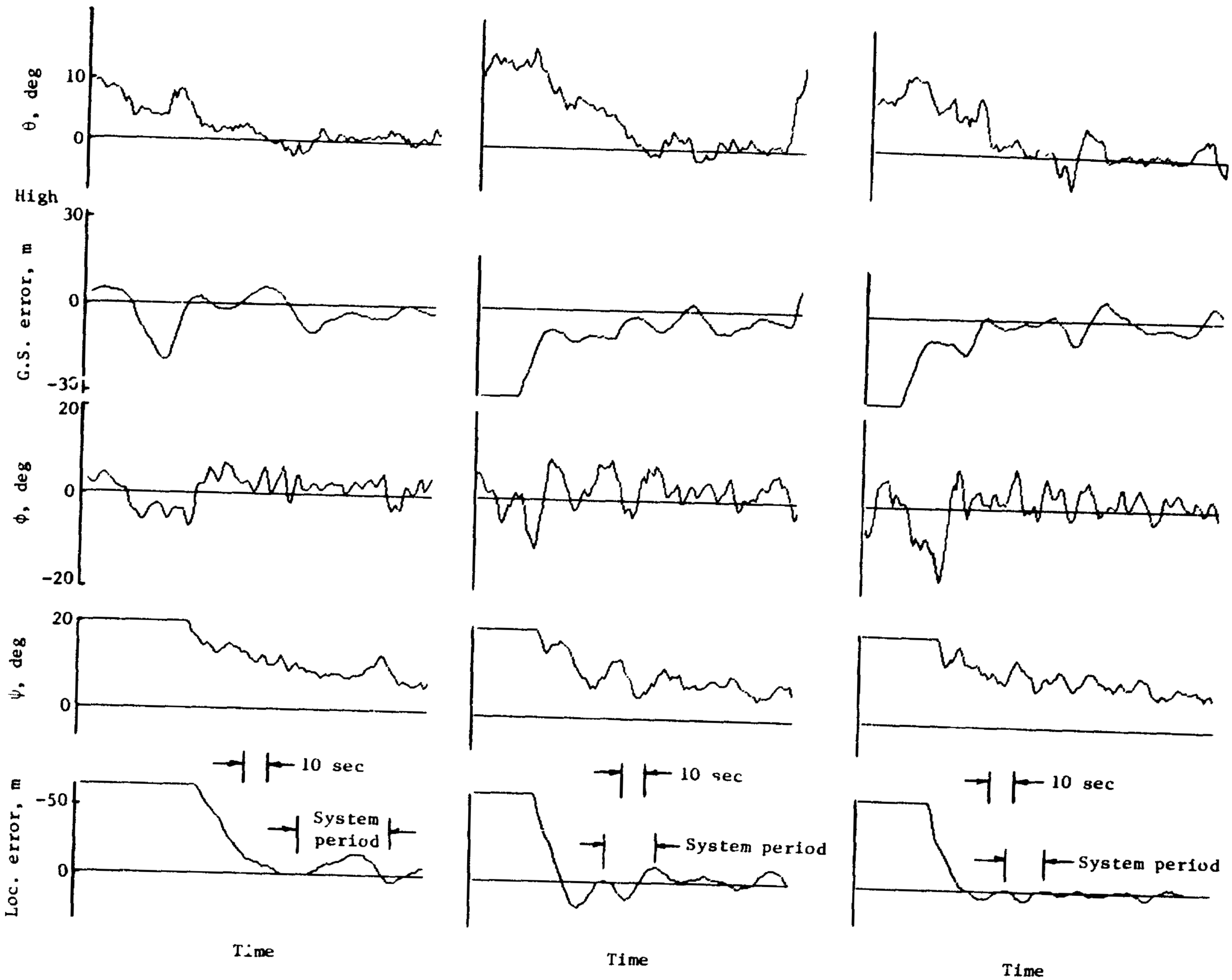


(a) $x_{iB} - x_{iA} = 736$ m.

(b) $x_{iB} - x_{iA} = 368$ m.

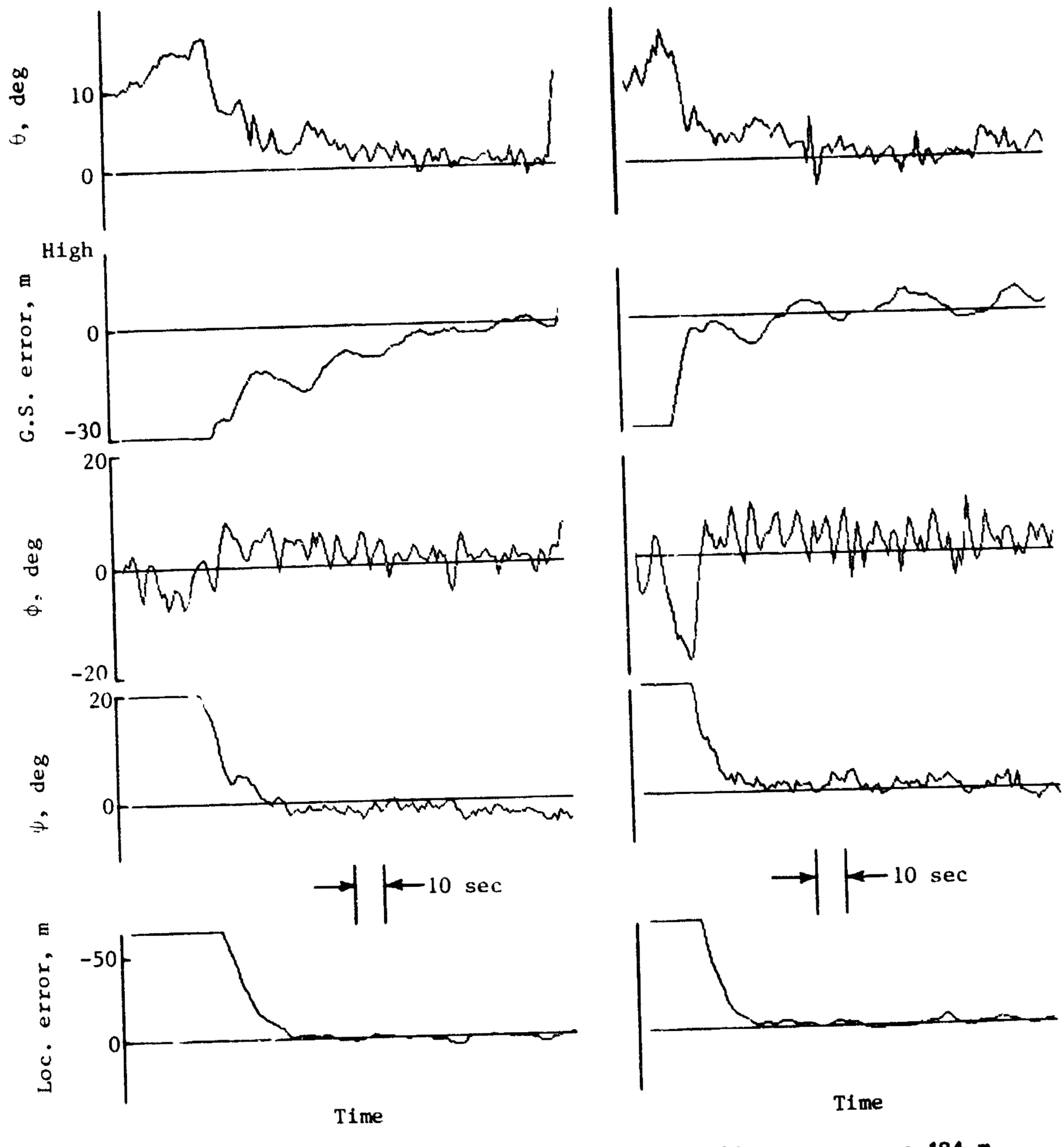
(c) $x_{iB} - x_{iA} = 184$ m.

Figure 8.- Approaches made by subject 9.



(a) $x_{iB} - x_{iA} = 736$ m. (b) $x_{iB} - x_{iA} = 368$ m. (c) $x_{iB} - x_{iA} = 184$ m.

Figure 9.- Approaches made by subject 10.



(a) $x_{iB} - x_{iA} = 368$ m.

(b) $x_{iB} - x_{iA} = 184$ m.

Figure 10.- Approaches made by subject 11.

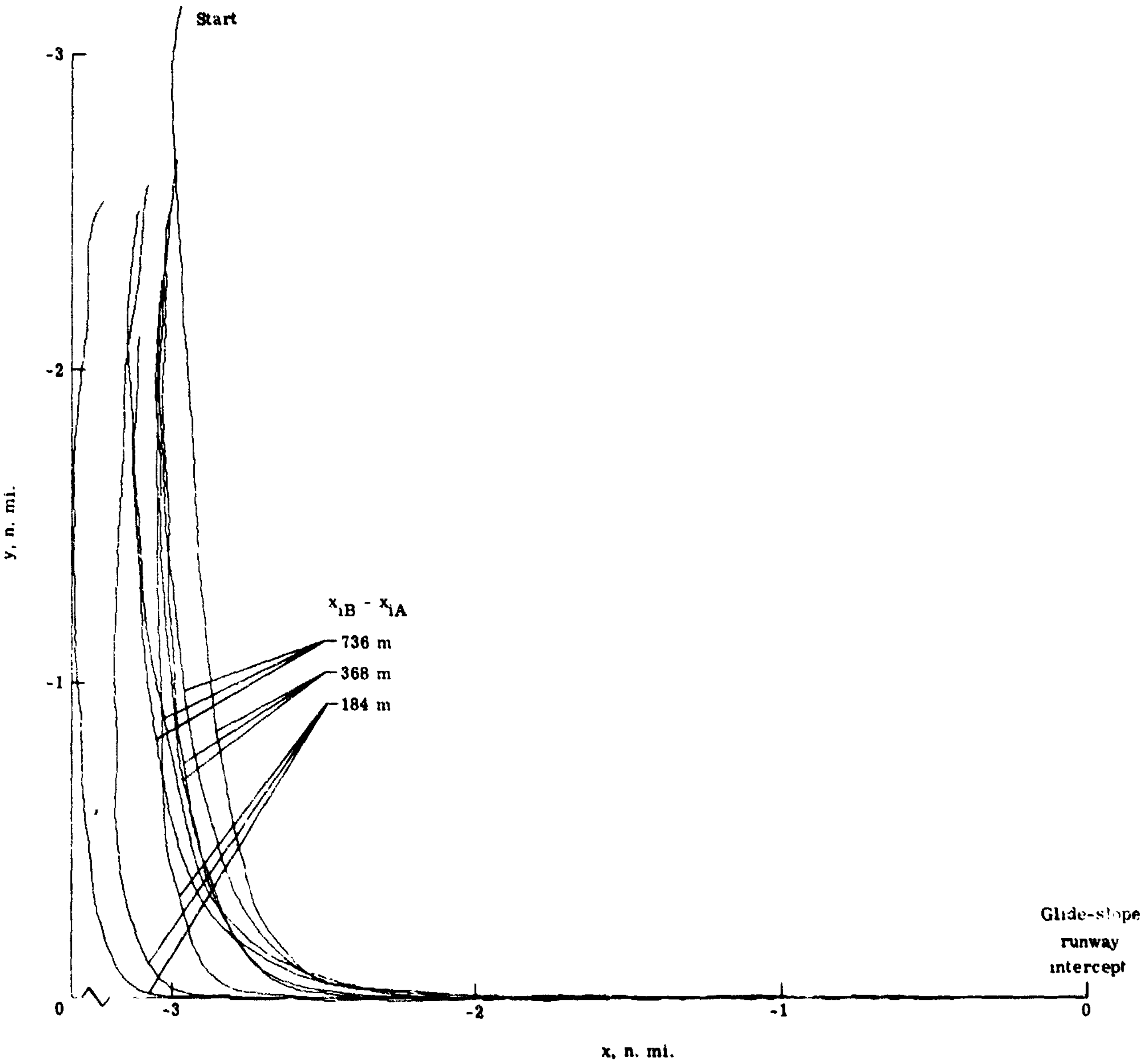


Figure 11.- Ground tracks of approaches made by subject 10.

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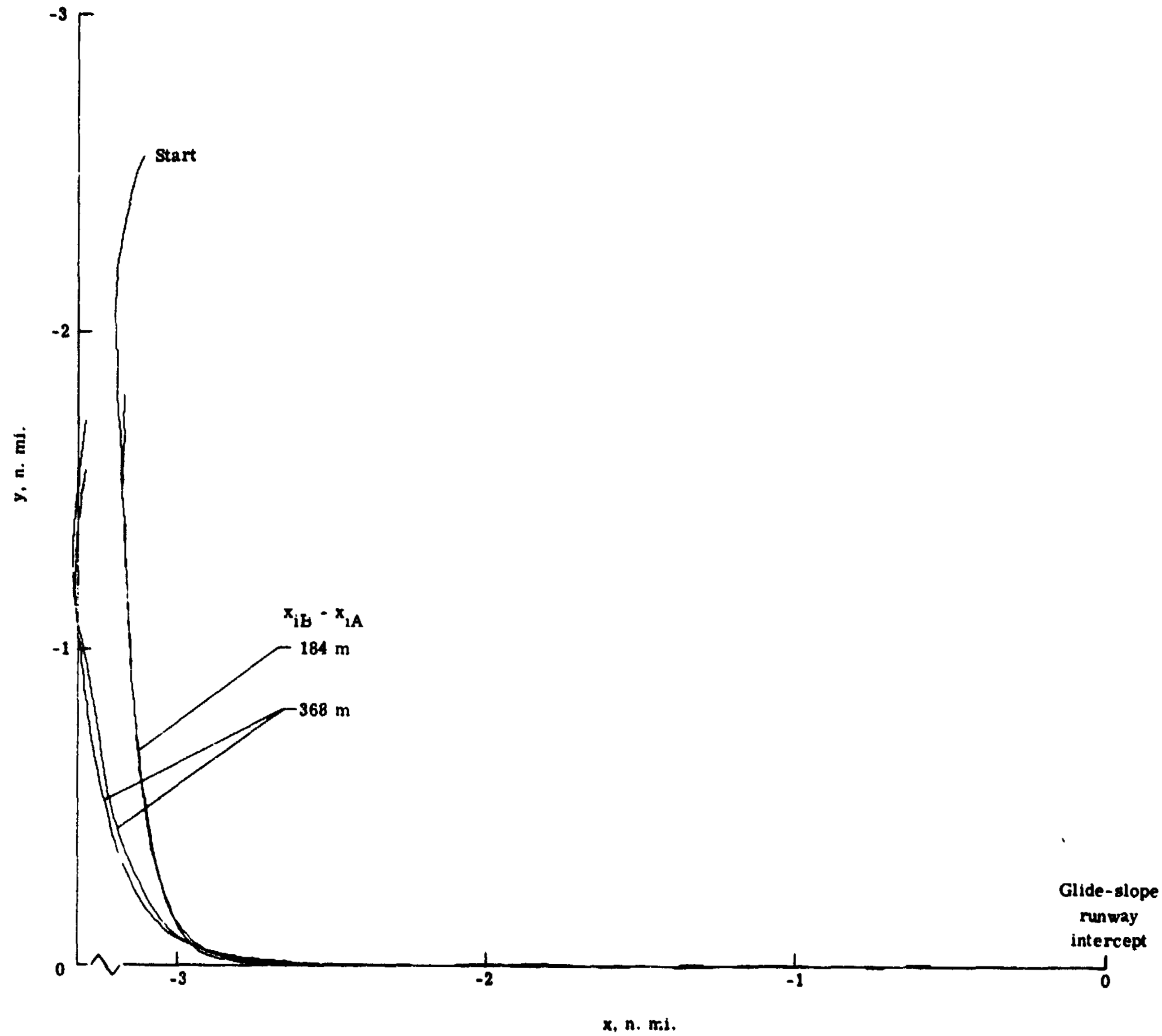

Figure 12.- Ground tracks of approaches by subject 11.

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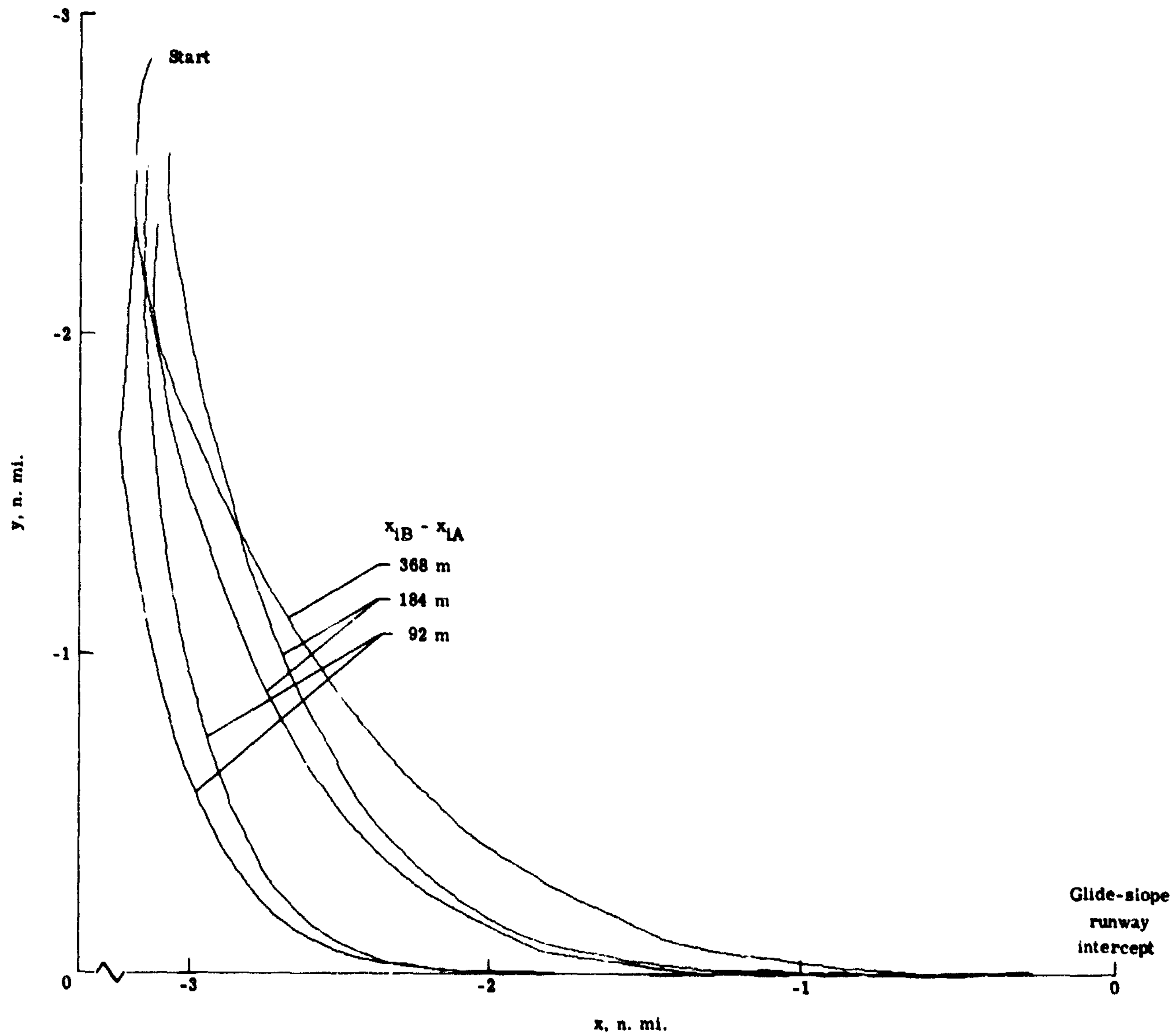

Figure 13.- Ground tracks of approaches made by subject 10 with no distance measurements.

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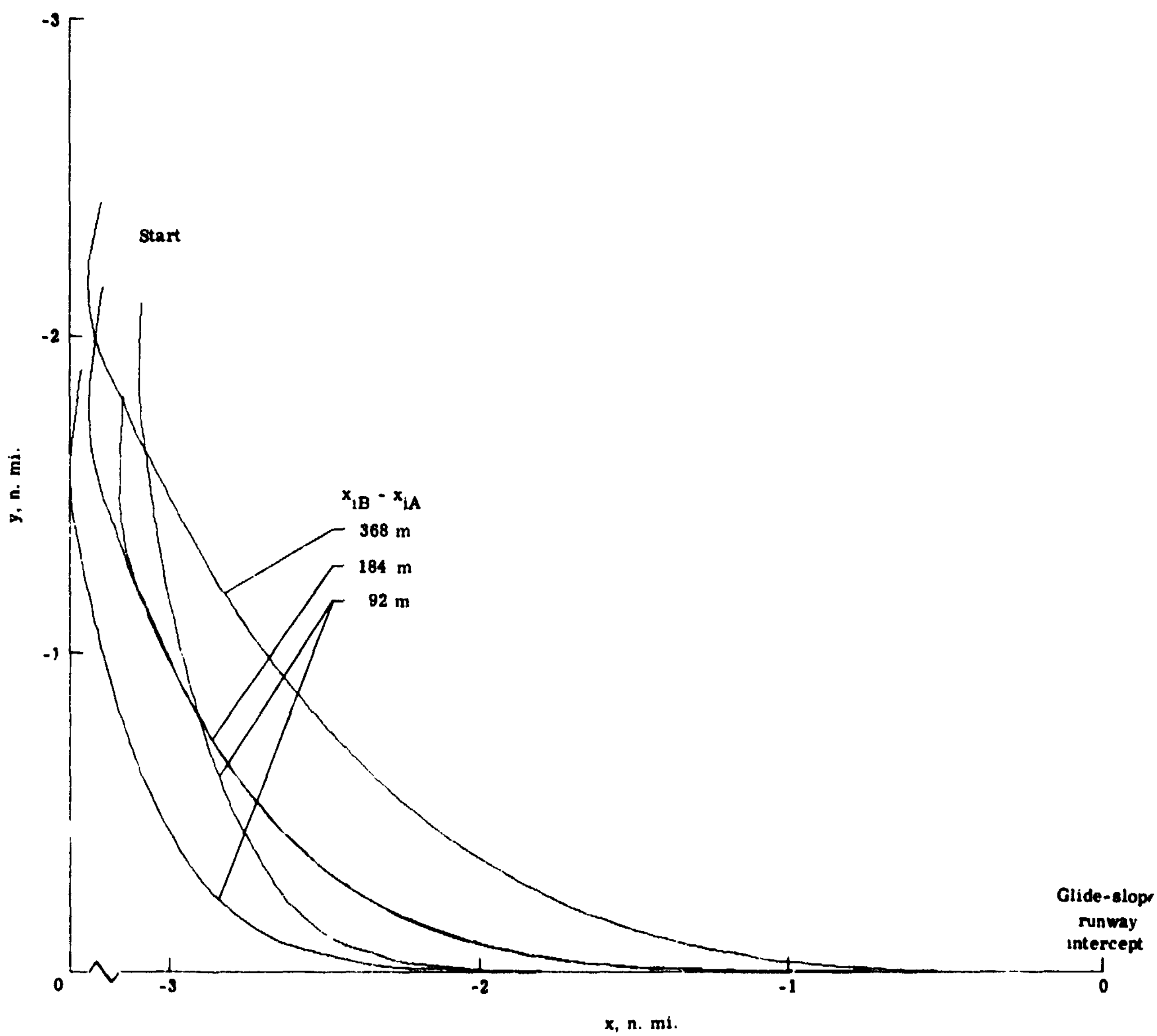
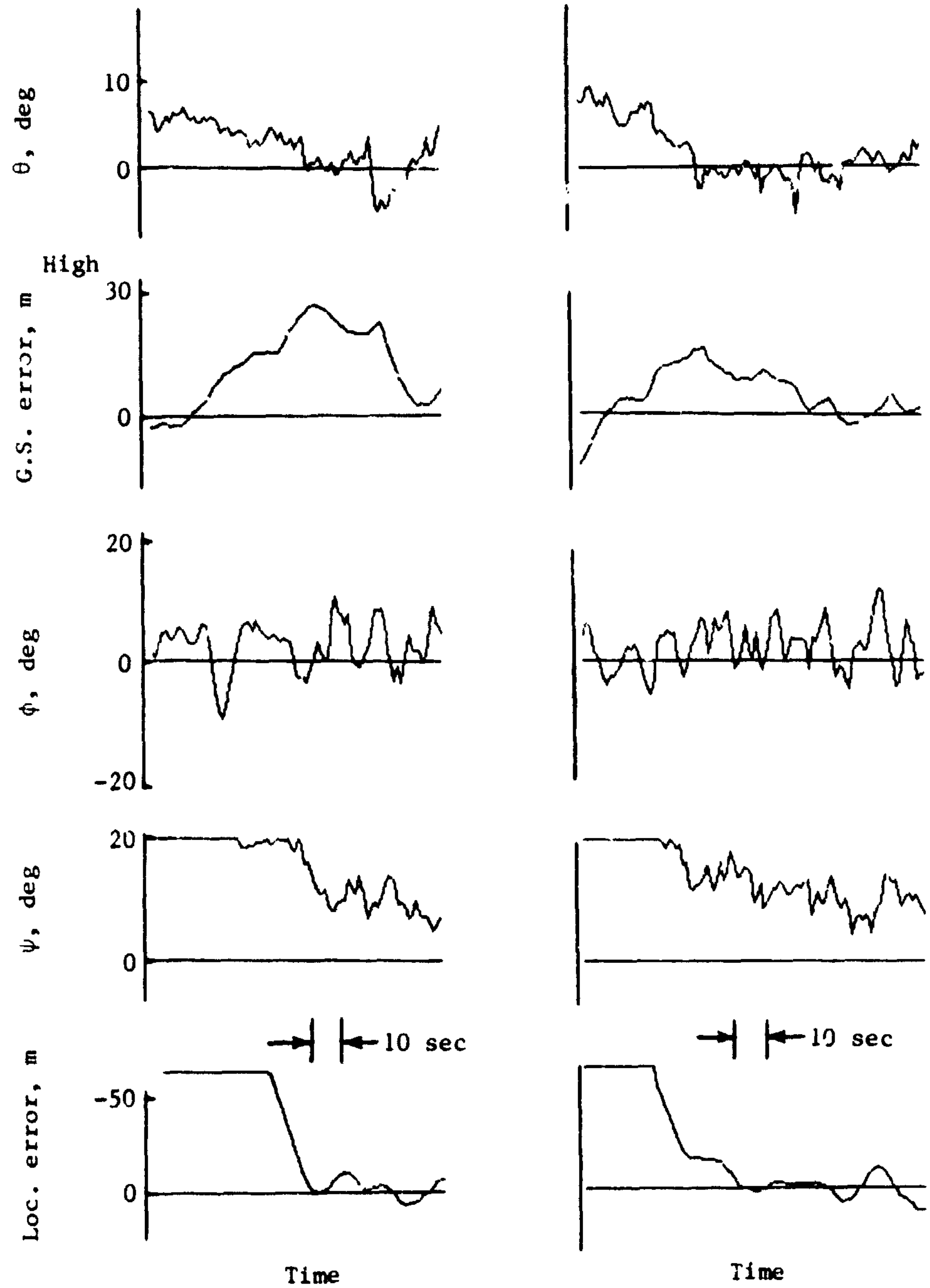


Figure 14.- Ground tracks of approaches made by subject 11 with no distance measurements.



(a) $x_{iB} - x_{iA} = 184$ m. (b) $x_{iB} - x_{iA} = 92$ m.

Figure 15.- Approaches made by subject 10 with no distance measurements.

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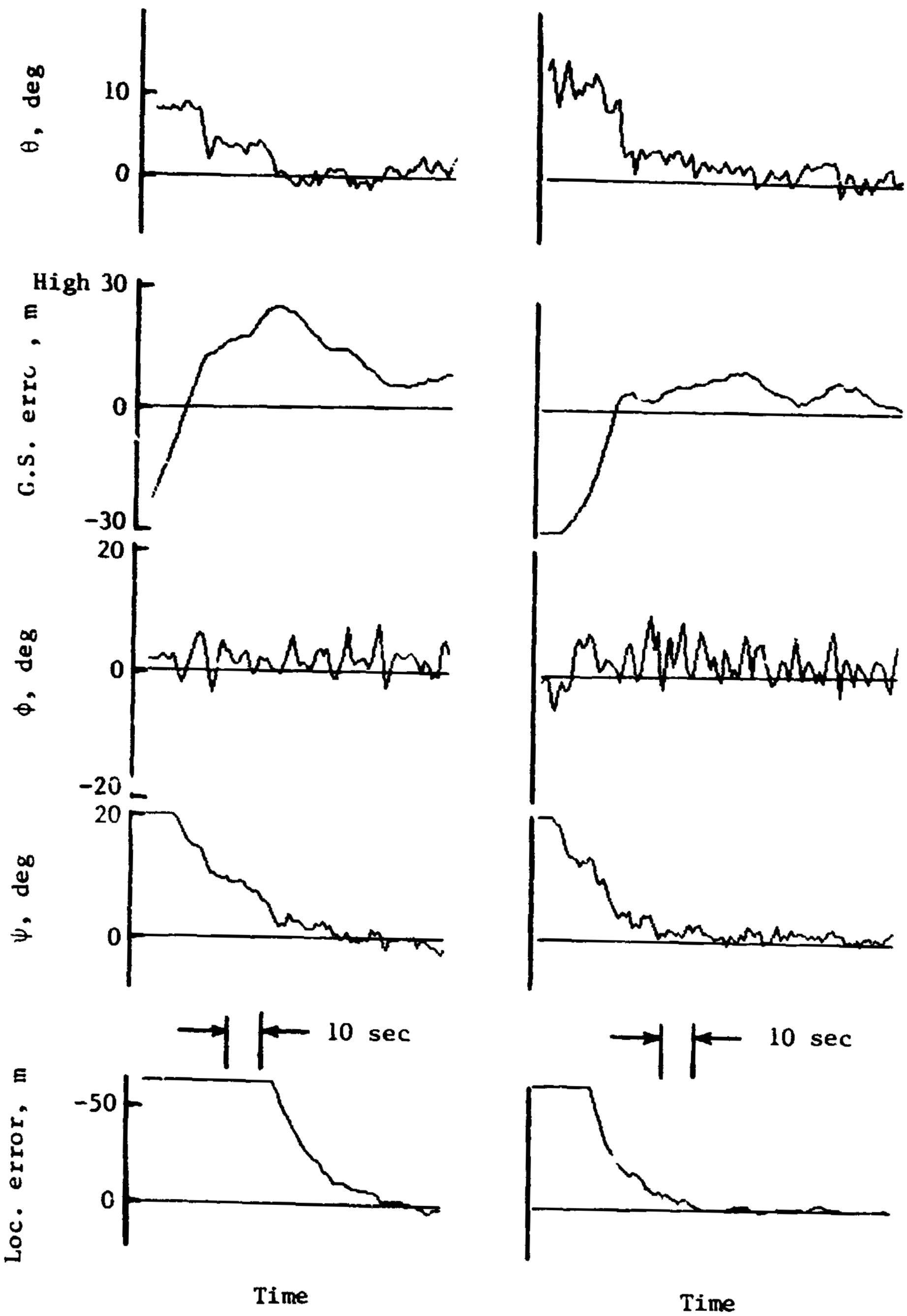

(a) $x_{iB} - x_{iA}$ = 184 m. (b) $x_{iB} - x_{iA}$ = 92 m.

Figure 16.- Approaches made by subject 11 with no distance measurements.

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15. Supplementary Notes

16. Abstract

As an extension of the simulator studies of the pictorial "follow me" box display, flight tests have been conducted by using the Navion Avionics research aircraft of Princeton University. The pertinent display factors and elements used in the simulation study were also used in the flight tests. The flight-test results duplicate the results of the simulator study. The most important item of agreement was the frequency of the vertical and lateral modes of motion of the pilot-aircraft-display system, which was 0.4 rad/sec in each study. The flight tests showed again that successful short, curved, descending approaches, such as are often suggested for use with microwave landing systems, can be executed with the "follow me" box display. Variations of the value of distance from the aircraft to the box were also examined in the flight tests. Values of 736, 368, and 184 m were tested. The results show that successful approaches can be made with all of these values. A sharper final turn and greater precision of position control are obtained with the shorter distance. Deletion of distance measuring equipment from the system was also examined in the flight tests. The results show that successful approaches can be made with no distance measures included in the system, but the values of distance from the aircraft to the box that can be used are restricted.

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