NASA - TM - 78771

NASA Technical Memorandum 78771

Description and Preliminary Studies of a Computer Drawn Instrument Landing Approach Display

James J. Adams and Frederick J. Lallman

NOVEMBER 1978

NASA

N78-18794

NASA Technical Memorandum 78771

Description and Preliminary Studies of a Computer Drawn Instrument Landing Approach Display

James J. Adams and Frederick J. Lallman
Langley Research Center
Hampton, Virginia

National Aeronautics
and Space Administration

Scientific and Technical
Information Office

1978

SUMMARY

An instrument landing approach display, which consists of the drawing of a three-dimensional box located on the desired path, alined with the path, and moving along the path at a selected distance ahead of the aircraft, has been examined. This display can be generated by using the landing system vertical- and lateral-displacement information and the aircraft attitude information as inputs to a computer and then using the computer to derive the information needed to draw the picture on a cathode-ray tube.

This display provides both raw displacement data and quickened command information in one well-integrated symbol with sensitivities that are well suited to the task. The range to the box, which is an important variable in the display geometry, is determined by a pilot-model analysis. A preliminary laboratory simulation study of the display has shown that pilot subjects find the display very easy to use, and they have achieved better performance scores with the box display than with a cross pointer and attitude instrument display.

INTRODUCTION

The execution of an instrument landing requires the display of the position of the aircraft with respect to the desired path. The control of this relative position (displacement) presents a difficult task to the pilot because the vehicle lag involved in displacement control is the largest amount that a pilot is asked to handle. For the pilot to control displacement properly, attitude information must also be displayed. The inner-loop compensation provided by the attitude information provides the assistance that the pilot needs to control the displacement. In the past these items of information have been displayed on separate meter needles or in simple combination on flight-director needles. The separation of this information on different needles, sometimes with different reference points, makes the instrument landing a difficult task. Advances in the technology of microprocessors and cathode-ray tubes have made it possible to consider complex combinations of the information provided by the landing system and aircraft attitude sensors to provide the pilot with displays that are more readily interpreted.

References 1 to 3 present examples of proposed advanced landing approach displays. Reference 1 suggests the use of a drawing of the landing strip and has shown that this display works very well. Reference 2 suggests the drawing of a path in the sky along with an elaborate aircraft reference symbol. Reference 3 suggests the use of a tube drawn along the desired path, called the star-and-circle display.

The present study examines a display format that has a combination of features that are not always present in displays of references 1 to 3. The display presents information in the same way that another airplane flying along the desired path would present. However, instead of another airplane, a box is drawn. The pilot's task is to follow the box. For this reason, the display is called the "follow me" box. By placing the box only a short distance ahead of the controlled aircraft, displacement sensitivity and useful lead information are provided in a manner that is not always provided by the landing strip symbol, the path in the sky, and the star-and-circle displays.

SYMBOLS

g acceleration due to gravity, m/sec^2 (1g = 9.8 m/sec^2)

h altitude, m

$K_\theta, K_\phi, K_\psi, K_h, K_y, K_n$ pilot-model gains, rad/m or dimensionless

p,q,r angular velocities of body-axis system about X-, Y-, and Z-axes, respectively, rad/sec or deg/sec

s Laplacian operator, sec^{-1}

T_R, T_S aircraft-roll and spiral-time constants, respectively, sec

u boxy-axis forward velocity, m/sec

V total velocity, m/sec

X,Y,Z body axes

X_i, Y_i, Z_i inertial axes

$X_{i,A}, Y_{i,A}, Z_{i,A}$ aircraft inertial positions, m

$X_{i,B}, Y_{i,B}, Z_{i,B}$ box inertial positions, m

y lateral displacement, m

α angle of attack, rad

β angle of sideslip, rad

γ flight-path angle, rad

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

θ, ϕ, ψ Eulerian angles, rad

$\lambda_\theta, \lambda_\psi$ pilot-model—aircraft system real roots, rad/sec

ρ, π aspect angles, rad (see fig. 7(a))

ω_{DR}, ξ_{DR} aircraft Dutch roll frequency, rad/sec, and damping ratio, respectively

ω_{sp}, ξ_{sp} aircraft short-period frequency, rad/sec, and damping ratio, respectively

$\left.\begin{array}{l}\omega_c, \xi_c \\ \omega_h, \xi_h \\ \omega_y, \xi_y \\ \omega_\alpha, \xi_\alpha \\ \omega_\phi, \xi_\phi \\ \omega_\psi, \xi_\psi\end{array}\right\}$ pilot-model—aircraft system frequencies, rad/sec, and damping ratios, respectively

Subscripts:

c command

ε error

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

THEORETICAL DEVELOPMENT

Control Task

A simplified block diagram of the pilot's task in controlling an aircraft to a glide-slope localizer path is shown in figure 1. In systems such as those which consist of a series of integrations, the output of each integrator must be included in the determination of the control signal to have a successful system. In order to control lateral displacement, the pilot must take into account not only lateral-displacement error but also heading angle, bank angle, and sometimes rolling velocity. Similarly for vertical displacement, he must take into account vertical error and either pitch angle or flight-path angle. All these quantities must be displayed to the pilot.

The present study examines a display which provides the basic information needed to make an instrument approach in a natural, well-integrated manner with the proper sensitivity for each variable. The display presents the picture of a box located on the desired path, alined with the path, and moving along the path at a fixed distance ahead of the controlled aircraft. A drawing of the display is shown in figure 2. A horizon and an aircraft reference symbol are also included in the display. The lateral and vertical displacements of the aircraft from the desired path are displayed by the aspect of the box. The fact that in figure 2 the bottom and side of the box are visible shows that the aircraft is below and to the right of the desired path. A small combined lateral and vertical displacement causes a very noticeable double line to appear on two edges of the box; this double line is a very sensitive indication of small displacement errors.

The lateral position of the box with respect to the aircraft reference symbol provides information on a combination of the lateral-displacement error of the aircraft with respect to the desired path and the deviation of the heading of the aircraft with respect to the heading of the desired path. A heading error alone (no displacement error) results in a display, as is shown in figure 3(a), with the box displaced from the aircraft reference symbol. Similarly, a displacement error alone (no heading error) also causes the box to be displaced from the aircraft reference symbol, as is shown in figure 3(b). The resulting combination for heading and displacement errors provides information that is similar to that provided by a flight director. By placing the aircraft reference symbol on the near face of the box, a heading angle that will reduce the displacement error is obtained. Keeping the aircraft reference symbol on the near face of the box results in a quick, well-damped displacement error correction. A quantitative definition of just how quick this response can be is discussed subsequently.

To reiterate, the distance between the aircraft reference symbol and the near face of the box in the display presents a signal which is a combination of the displacement of the aircraft from the desired path and the deviation of the heading of the aircraft from the heading of the desired path. The signal is, therefore, a weighted sum of the displacement and the rate of change of the displacement and meets the definition of a quickened, command signal. On the other hand, the aspect of the box is a function of displacement from the desired path only and therefore provides a raw displacement signal.

Bank-angle information is also provided by the roll orientation of the box. The horizon line emphasizes the bank-angle information and also provides information on the deviation of the flight path from level flight. The same comments that have been made regarding lateral information supplied by the display also apply to the vertical information.

The "follow me" box supplied all the information needed to guide the aircraft to the desired path. This information is supplied in a natural manner; that is, an orientation with respect to a three-dimensional object is required. The sensitivity of the different pieces of information (displacements and attitude angles) is presented in a desirable ratio if the box is located at the proper distance ahead of the aircraft. This distance can be determined with a pilot-model analysis.

Pilot-Model Analysis

Pilot response can be modeled in the manner shown in the pilot-aircraft system diagram presented in figure 4. A preferred pilot response, as defined in references 4 and 5, is shown. This response is called preferred in that the inner-loop closures θ and ϕ contain no lead and have a preferred lag time constant of 0.2 second.

The aircraft representation used in this analysis is linear with uncoupled longitudinal and lateral responses. The equations used for the aircraft are:

Longitudinal:

$$\dot{u} = 0$$

$$\dot{\alpha} = q - 0.6\alpha$$

$$\dot{q} = -3.70q - 15.2\alpha - 10\delta_e$$

$$\dot{h} = V(\theta - \alpha)$$

Lateral:

$$\dot{\beta} = -0.158\beta - r + 0.129\phi$$

$$\dot{p} = -42.14\beta - 2.79p + 2.06r - 10\delta_a$$

$$\dot{r} = 5.54\beta + 0.015p - 0.834r$$

$$\dot{\psi} = \frac{g\phi}{V}$$

$$\dot{y} = V\psi$$

$$V = 76.4 \text{ m/sec}$$

This aircraft has the following response characteristics:

Longitudinal: $\omega_{sp} = 4.11$ rad/sec, $\xi_{sp} = 0.52$

Lateral: $\omega_{DR} = 2.50$ rad/sec, $\xi_{DR} = 0.10$; $T_R = 0.33$ sec; $T_S = 6.25$ sec

In reference 6 these response characteristics indicate satisfactory handling qualities.

References 4 and 5 have indicated that if certain pilot-model—aircraft system response characteristics can be achieved, then the pilots will be satisfied. The required system characteristics for attitude control are:

Longitudinal: $\lambda_\theta \leqq -0.4$ rad/sec; $\omega_\alpha \geqq 2.5$ rad/sec, $\xi_\alpha \geqq 0$

Lateral: $\omega_{\phi} \geqq 1.9$ rad/sec, $\xi_{\phi} \geqq 0$; $\omega_{DR} \geqq 1.9$ rad/sec, $\xi_{DR} \geqq 0$

With the aircraft used in this study, these characteristics can be met with the preferred pilot model. The maximum gains (those gains which result in a damping ratio of zero or near zero) and the system characteristics are:

Longitudinal: $K_{\theta} = 3.0$; $\lambda_{\theta} = -0.42$ rad/sec; $\omega_{\alpha} = 4.20$ rad/sec, $\xi_{\alpha} = 0.007$;

$\omega_c = 7.80$ rad/sec, $\xi_c = 0.89$

Lateral: $K_{\phi} = 0.67$; $\omega_{\phi} = 1.87$ rad/sec, $\xi_{\phi} = 0.37$; $\omega_{DR} = 2.59$ rad/sec,

$\xi_{DR} = 0.001$; $\omega_c = 6.55$ rad/sec, $\xi_c = 0.94$

The value for $\omega_{\phi} = 1.87$ rad/sec is considered close enough to 1.9 rad/sec to be suitable. Since these gains for K_{θ} and K_{ϕ} result in meeting the required system characteristics, they are considered to be proper for making the computations.

With the inner-loop gains established, the h- and ψ-loops can be closed. The system response characteristics that are considered satisfactory are:

Longitudinal: $\omega_h \geqq 1.25$ rad/sec, $\xi_h \geqq 0$; $\omega_{\alpha} \geqq 2.5$ rad/sec, $\xi_{\alpha} \geqq 0$

Lateral: $\lambda_{\psi} \leqq -0.3$ rad/sec; $\omega_{\psi} \geqq 1.7$ rad/sec, $\xi_{\psi} \geqq 0$; $\omega_{DR} \geqq 1.7$ rad/sec,

$\xi_{DR} \geqq 0$

The maximum h- and ψ-loop gains and the system characteristics are:

Longitudinal: $K_h = 0.0525$ rad/m, $K_{\theta} = 3.0$; $\omega_h = 1.31$ rad/sec, $\xi_h = 0.002$;

$\omega_{\alpha} = 4.09$ rad/sec, $\xi_{\alpha} = 0.044$; $\omega_c = 7.85$ rad/sec, $\xi_c = 0.89$

Lateral: $K_{\psi} = 3.88$, $K_{\phi} = 0.60$; $\lambda_{\psi} = -0.60$ rad/sec; $\omega_{\psi} = 1.66$ rad/sec,

$\xi_{\psi} = 0.31$; $\omega_{DR} = 2.51$ rad/sec, $\xi_{DR} = 0.002$; $\omega_c = 6.40$ rad/sec,

$\xi_c = 0.95$

Again $\omega_\psi = 1.67$ rad/sec is considered close enough to 1.7 rad/sec to be suitable. Note that K_ϕ was reduced to 0.60 from 0.67 to allow the largest possible value for K_ψ to be obtained.

Lastly the lateral-displacement loop y is closed with the maximum allowable gain, and the following system response characteristics are obtained:

$$K_y = 0.017 \text{ rad/m}, \quad K_\psi = 3.88, \quad K_\phi = 0.60; \quad \omega_y = 0.91 \text{ rad/sec},$$

$$\xi_y = 0.02; \quad \omega_\psi = 1.59 \text{ rad/sec}, \quad \xi_\psi = 0.48; \quad \omega_{DR} = 2.50 \text{ rad/sec},$$

$$\xi_{DR} = 0.016; \quad \omega_c = 6.40 \text{ rad/sec}, \quad \xi_c = 0.95$$

Criteria for satisfactory system response with the lateral-displacement loop closed have not been examined previously. However, since the lateral ψ- and ϕ-systems were satisfactory, the lateral-displacement system response is also assumed to be satisfactory.

The distance that the box can be placed ahead of the aircraft is related to these maximum allowable altitude and lateral-displacement gains. The maximum lateral-displacement gain of 0.017 rad/m indicates that if the aircraft were displaced 1 meter from the desired path, a heading angle of 0.017 radian would be commanded. This heading angle would result in the aircraft body axis intersecting the desired path at a point 59 meters ahead of the aircraft. Therefore, if the box were located at this point, the pilot would generate his maximum allowable gain if he pointed the aircraft at the box. Actually the box should be located at a slightly greater distance to allow the pilot to point at the box while a damped response is achieved.

A similar computation for the altitude gain shows that the box could be located at a distance of 19 meters to satisfy the same minimum distance for vertical control. However, since the lateral response determines the more critical distance, the lateral criterion is used to establish the distance to the box. In the experiments distances of 92 meters and greater were used to allow a margin for stability. In terms similar to those used to describe a flight director, varying the distance to the box varies the mix of heading command to lateral-displacement error.

A remnant term is also shown in the pilot model. This remnant is used in a postexperimental analysis to be described subsequently. The remnant is generated by passing a white noise through a second-order filter that is equivalent to the pilot-model lag $\dfrac{K_n}{(1 + 0.2s)^2}$.

COMPUTATIONAL AND EXPERIMENTAL FORMAT

Aircraft

The aircraft was represented by the linear equations given in the previous section, except that instead of using the linear kinematic relationships given previously, nonlinear kinematics were used. The complete aircraft representation is given in appendix A. Since the purpose of the investigation was to determine the accuracy with which the lateral and vertical position of the aircraft could be controlled, airspeed control was eliminated as a task by making the forward acceleration equal to zero. The aircraft was assumed to be traveling at a constant speed of 76 m/sec (148 knots). A sidearm controller that pivoted around the middle of the handle for pitch control and around the bottom of the handle for roll control was used. Rudder pedal control was also provided, but the subjects did not choose to use the rudder control. The sensitivity of the controls was fixed at values that were satisfactory for all the subjects.

Display

The equations needed to draw the "follow me" box were implemented with a digital computer, and the display was presented on a 28-cm-square laboratory cathode-ray tube. This exercise was conducted to gain experience with these equations and to obtain preliminary data on pilot acceptance of the display. Root-mean-square performance data were also obtained. In order to add more meaning to these performance measures, similar data were obtained with a raw data, cross pointer instrument mounted on an all-attitude indicator. In this way a direct comparison could be made of the performance obtained with the box display and that obtained with an instrument that has been used in actual practice. A photograph of the simulator is shown in figure 5. The cathode-ray tube was positioned just to the left of a standard instrument panel. The cross pointer instrument is shown in figure 6.

<u>Box display</u>.- The equations used to draw the box are listed in appendix B. A heuristic description of these calculations is as follows. The aircraft is located in an axis system (X_i,Y_i,Z_i) that is alined with the sides of the box, as shown in figure 7(a). The dimensions to the aircraft define the angles ρ and π, which in turn define the aspect of the box that is seen when the aircraft is not on the desired path. Also, the box is located in an axis system (X,Y,Z) that is alined with the aircraft. Dimensions Y and Z (shown in fig. 7(b)) define the location of the center of the box in the aircraft display. Length vectors are also alined with the box and define the size of the box. These vectors are transformed into aircraft-axis components through the angles ψ, θ, and ϕ and are also transformed through the box aspect angles ρ and π to supply the information needed to draw the box around its center position. The direction cosines that result from the axis transformations are used to locate three of the visible corners of the box and to draw the sides of the box from these corners. In the simulation, the position of the box is updated 26 times per second, and the lines are refreshed at approximately 100 times a second.

In the simulation computations, the inertial positions of the box and the aircraft were determined, and the differences in positions were used as inputs to the box drawing computations. In an operational system, these differences in position would be determined from the landing system measurements. As an example, these distances might be determined as follows:

$$X_{i,A} - X_{i,B} = \text{Selected range}$$

$$Y_{i,A} - Y_{i,B} = \text{(Localizer signal)(Range to localizer station)}$$

$$Z_{i,A} - Z_{i,B} = \text{(Glide-slope signal)(Range to glide-slope station)}$$

$$- \text{(Selected range)(Glide-slope angle)}$$

The display was scaled so that the field of view presented was 25° both vertically and horizontally. The cathode-ray tube was located 90 cm from the subject's eye so that the display device presented a 17° field of view. As a result the magnification factor was 0.68. The box was tested at ranges (the X_i distance to the box) of 550, 368, 184, and 92 meters. The size of the box was varied as a function of range so that the box always subtended the same visual angle. The box sizes are given in the following table along with the display displacement of the center of the box for a 12-meter aircraft displacement error to indicate the sensitivity of the display:

Range, m	Box dimensions			Display sensitivity
	Depth, m	Width, m	Height, m	Display displacement for a 12-m error, cm
550	92	46	23	0.91
368	61	31	15	1.5
184	31	15	7.6	2.9
92	15	7.6	3.8	5.8

Cross pointer display.- A cross pointer instrument landing display, shown in figure 6, was also used to provide comparison data. A 7.6-cm-diameter all-attitude indicator was used along with two cross pointer needles mounted in the same instrument case. The information of ψ, θ, and ϕ was provided by the attitude indicator, and the vertical and lateral raw displacement data were presented by the cross pointers. The sensitivity of the cross pointers was adjusted so that a 12-meter displacement error moved the needles 1.8 cm; therefore, the displacement sensitivity was approximately the same as that for the box at a range of 368 meters.

Atmospheric Turbulence

Some tests were run with atmospheric turbulence. A Dryden spectrum was used to represent the turbulence. The scale of turbulence was chosen to be 305 meters. Two random white noise generators were used in conjunction with two first-order filters with time constants of 4 seconds. The amplitude of the filtered signals was adjusted to provide a 1.5-m/sec root-mean-square turbulence level. These random signals were added to the aerodynamic angles α and β.

Subjects

The subjects used in the study were the author, subject G, two general aviation pilots, subjects H and S, who had a small amount of instrument flying experience, and two research pilots, subjects E and K. One of the general aviation pilots, subject S, was in the process of obtaining his instrument license. The other, subject H, had more instrument experience, had taken part in many pilot-response laboratory experiments, and was known to do well in experiments in which performance scores were obtained. The two research pilots, subjects E and K, were project pilots for the Terminal Configured Vehicle Program and were very interested in display proposals. The flight experience of the subjects is given in the following table:

Subject	Age	Flight time, hr	Aircraft
E	45	6500	All types
K	43	6250	All types
H	41	2500	Cessna 172, Cessna 182, Cessna 206, Cherokee Six
S	38	200	Cessna 152, Cherokee Six
G	51	0	--------------------------

The following test procedures were used. The box display was demonstrated to the subjects, and they were given an opportunity to practice with the simulator until they had become accustomed to the nature and sensitivities of the display and controls. Then they performed 3 minutes of straight and level tracking, both with and without turbulence, at several values of range to the box. The root-mean-square values of the displacement error were obtained during these runs. The longest range to the box was tested first; then the testing progressed to the shortest range. These tests with the box display were followed by similar tests with the cross pointer display. After the continuous tracking tests, tests with initial errors in either vertical or lateral displacement were conducted. Repeat runs were obtained with the initial errors.

RESULTS

Continuous Tracking Results

Root-mean-square values of vertical- and horizontal-displacement errors are presented in table I, where data obtained with the cross pointer display are given along with data obtained with the "follow me" box display for several values of box range.

All subjects reported that using the cross pointer and attitude indicator display required all of their attention, whereas the box display was very comfortable to use. Nevertheless, the table shows that better scores were obtained with the box display at a range of 368 meters than with the cross pointer. The one exception was with subject K for vertical error with turbulence. In all other cases an improvement in score was obtained. In half the cases an improvement of 40 percent or better was obtained. Also, except for two cases, further improvement was obtained when the range to the box was reduced from 368 meters to 184 meters.

The data present evidence that a range of 92 meters is near the minimum useful range. From the theoretical analysis, it was expected that as a 59-meter range was approached, system lateral-stability problems would be encountered. For subject E better scores were obtained at a range of 184 meters than at 92 meters, thereby indicating that for this subject, a range of 92 meters was definitely too short. Also for subject G the lateral scores with turbulence did not show an improvement when the range was reduced to 92 meters. The theoretical analysis also indicated that a shorter range would be acceptable for vertical control than for lateral control. The data are in agreement with this conclusion in that the vertical scores showed continued improvement with reduction in range. The subjects did note that as the range was reduced with the box display and the pilot-aircraft system frequencies increased, more attention was required on their part.

In this preliminary investigation only single data points were obtained for each test condition, and therefore the results must be reviewed with caution. However, the data and the subject opinions show that the "follow me" box display is worthy of further consideration.

Step Input Tests

In addition to the continuous tracking, the subjects were asked to correct initial displacement errors. They were presented with an initial 12-meter error in either the lateral or vertical direction, and time-history records were taken of their corrective action. These records were then matched with a pilot-model—aircraft system using a trial-and-error adjustment of the pilot-model gains. The pilot model was combined with either the nonlinear representation of the aircraft used in the simulation study or the linear representation discussed in the section entitled "Pilot-Model Analysis." When the lateral response with the simulation aircraft was examined, a coordinated turn was insured by leaving the longitudinal pilot model in operation. The same type of response was obtained with both nonlinear and linear aircraft representation; however, because use of the linear representation was more convenient, a finer adjustment of the pilot-model gains was achieved. The gains that the pilots used were thereby determined.

Time histories obtained with subject K are shown in figures 8 to 11. The corresponding model matches for these runs are also shown. The outer-loop gains K_h and K_y used in the model indicate whether or not the pilot is pointing at the box. The inverse of the gain is the static pointing distance that the pilot is using. For example, at ranges of 184 and 368 meters both longitudinal and lateral gains show that the pilot is using the box as a pointing reference. At a range of 92 meters the longitudinal gain shows that the box is used as a reference point for vertical control, but that the pointing reference for lateral control is slightly beyond the box at 128 meters. These results again show that a range of 92 meters is too short for the pilot to make optimum use of the heading command information provided by the display for lateral control, but this range is very comfortable for longitudinal control.

The runs shown in figures 8 to 11 agreed well with the theory that the pilot would point at the box. These data, plus some additional data for subject K, and model matching data for subject G are presented in table II. When more than one set of data are given in this table, they represent different characteristics that were obtained in repeated runs at the given condition. All these data taken together indicated more scatter in the pointing reference for lateral control than was indicated previously by the runs selected for the time-history figures. A very liberal interpretation of all the data would be that two conflicting tendencies are being shown. One tendency is to use the box as a pointing reference. The other tendency is to keep the system lateral-displacement mode frequency at about 0.45 rad/sec, which would correspond to using a pointing reference at 300 meters.

The closed-loop system, pilot model plus aircraft, characteristics given in table II show the quickness with which displacement is controlled. At a box range of 92 meters, the displacement modes of motion frequencies ω_h and ω_y are approximately 0.6 rad/sec for ω_h and 0.7 rad/sec for ω_y and are well damped. The time histories also show the same system characteristics with periods of about 10 seconds being very prominent. These results illustrate how quickly displacement errors can be corrected with the "follow me" box display.

Another point brought out by the model matching analysis concerns the remnant generated by the pilot. The analysis showed that a large remnant had to be added to the model to duplicate the cross pointer data. The displacement records for y and h obtained when the subjects were using the "follow me" box display were matched very well with no remnant added to the model. A small amount of remnant was added in box display cases to provide a better match of the inner-loop variables θ, ψ, and ϕ, but the amount of remnant added had only a very small effect on the displacements y and h. In order to match the time histories obtained with the cross pointer display, enough remnant had to be added to the pilot model so that a noticeable effect occurred in the displacement records. Apparently one detrimental effect of the cross pointer display, which separates the needed information into different needles, is that it causes more pilot-generated noise than does the box display.

In addition to the continuous tracking and the step corrections, tests relating to the acquisition of the "follow me" box were conducted. If the landing system defined a straight path out from the landing strip and the aircraft were a great distance to the side of this path, then the box would appear as a very small object on the display. As long as the aircraft flies on a path perpendicular to the approach path, the box will remain stationary on the approach path. As the aircraft moves close to the approach path, a turn could be initiated to bring the aircraft behind the box. The box would then proceed down the approach path at the selected range ahead of the aircraft. This situation was simulated, and the subjects had no difficulty in performing this acquisition maneuver. If the landing system defined a curved path, the box could be used to lead the aircraft around this curve. This situation was also simulated, and again the subjects had no difficulty in performing this maneuver.

CONCLUDING REMARKS

An approach to landing display, which consists of the drawing of a three-dimensional box located on the desired path, alined with the path, and moving along the path a selected distance ahead of the aircraft, has been examined. This display can be generated by using the landing-system vertical- and lateral-displacement information and the aircraft attitude information as inputs to a computer and then using the computer to derive the information necessary to draw the picture on a cathode-ray tube.

This display provides both raw displacement data and quickened, command information in one well-integrated symbol with sensitivities that are well suited to the task. A preliminary laboratory simulation of the display has shown that pilot subjects find the display very easy to use and have achieved better performance scores with the box display than with a cross pointer and attitude instrument display.

It is recommended that the box display format be considered for computer-augmented instrument landing approach displays.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
September 18, 1978

APPENDIX A

AIRCRAFT EQUATIONS OF MOTION

The equations of motion for the aircraft simulation used in the study are

$$\dot{\alpha} = q - 0.6\alpha - 0.129(1 - \cos\theta\cos\phi)$$

$$\dot{q} = -3.70q - 15.2\alpha - 10\delta_e$$

$$\dot{p} = -2.79p + 2.06r - 42.14\beta - 10\delta_a$$

$$\dot{r} = 0.015p - 0.834r + 5.54\beta - 10\delta_r$$

$$\dot{\beta} = -r - 0.158\beta + 0.129\sin\phi\cos\theta$$

$$\dot{\phi} = p + \dot{\psi}\sin\theta$$

$$\dot{\theta} = q\cos\phi - r\sin\phi$$

$$\dot{\psi} = \frac{r\cos\phi + q\sin\phi}{\cos\theta}$$

$$\dot{X}_1 = (\ell_1 + m_1\beta + n_1\alpha)V$$

$$\dot{Y}_1 = (\ell_2 + m_2\beta + n_2\alpha)V$$

$$\dot{Z}_1 = (\ell_3 + m_3\beta + n_3\alpha)V$$

where

$$\ell_1 = \cos\psi\cos\theta$$

$$m_1 = \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi$$

$$n_1 = \cos\psi\sin\theta\cos\phi + \sin\psi\sin\phi$$

$$\ell_2 = \sin\psi \cos\theta$$

$$m_2 = \sin\psi \sin\theta \sin\phi + \cos\psi \cos\phi$$

$$n_2 = \sin\psi \sin\theta \cos\phi - \cos\psi \sin\phi$$

$$\ell_3 = -\sin\theta$$

$$m_3 = \cos\theta \sin\phi$$

$$n_3 = \cos\theta \cos\phi$$

APPENDIX B

DISPLAY EQUATIONS

The equations used to define the display image used in the study are presented. Additional symbols used in this appendix and figures are given.

SYMBOLS

C	box center position
i,j,k	unit vectors
ℓ,m,n	direction cosines
l_x, l_y, l_z	box dimensions, m
T_A	aircraft Eulerian angle transformation matrix
T_V	visual axis-system transformation matrix
η,μ	aspect angles in body axis, rad

Subscripts:

A	aircraft
B	box
BA	box minus aircraft
p	picture
V	visual axis system
w	window

Superscripts:

x,y,z	associated with designated axis

DERIVATION OF EQUATIONS

An imaginary rectangular box shaped object is located in space in the vicinity of the airplane as shown in figure 12. Given that the pilot could see such an object through a window, a mathematical description of the projection of the object upon the window can be derived. This mathematical description can then be used to form an image on an electronic display device which would reproduce the view that the pilot had above.

APPENDIX B

The center of the box is located at a position designated by $(X_{i,B}, Y_{i,B}, Z_{i,B})$ in inertial coordinates. Length vectors that define the size of the box are obtained by multiplying semilengths l_x, l_y, and l_z by orthogonal unit vectors i, j, and k.

$$i_B = i l_x$$

$$j_B = j l_y$$

$$k_B = k l_z$$

If the box is at an attitude ψ_B, θ_B, and ϕ_B to the reference inertial-axis system, then the inertial components of the box vectors are

$$i_i = \begin{bmatrix} i_i^x \\ i_i^y \\ i_i^z \end{bmatrix} = \begin{bmatrix} i_B(\cos\theta_B \cos\psi_B) \\ i_B(\cos\theta_B \sin\psi_B) \\ i_B(-\sin\theta_B) \end{bmatrix}$$

$$j_i = \begin{bmatrix} j_i^x \\ j_i^y \\ j_i^z \end{bmatrix} = \begin{bmatrix} j_B(\sin\phi_B \sin\theta_B \cos\psi_B - \cos\phi_B \sin\psi_B) \\ j_B(\sin\phi_B \sin\theta_B \sin\psi_B + \cos\phi_B \cos\psi_B) \\ j_B(\sin\phi_B \cos\theta_B) \end{bmatrix}$$

$$k_i = \begin{bmatrix} k_i^x \\ k_i^y \\ k_i^z \end{bmatrix} = \begin{bmatrix} k_B(\cos\phi_B \sin\theta_B \cos\psi_B + \sin\phi_B \sin\psi_B) \\ k_B(\cos\phi_B \sin\theta_B \sin\psi_B - \sin\phi_B \cos\psi_B) \\ k_B(\cos\phi_B \cos\theta_B) \end{bmatrix}$$

These nine vector components are the quantities needed to draw the box when the aircraft is on the desired path and alined with the path and the box is at an angle to the desired path. Whereas this is a logical first step in the development of the equations needed to draw the box, it is not used extensively and was not mentioned in the body of the paper. The steps that are needed to account for the attitudes and displacements of the aircraft from the desired path are now given.

The transformation matrix which converts vectors from inertial coordinates to airplane body-fixed coordinates is

$$T_A = \begin{bmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \\ n_1 & n_2 & n_3 \end{bmatrix}$$

where ℓ, m, and n are the airplane direction cosines defined in appendix A.

Multiplying the vector difference between the box location and the airplane location by the transformation matrix T_A gives the location of the box in airplane coordinates as

$$\begin{bmatrix} X_{BA} \\ Y_{BA} \\ Z_{BA} \end{bmatrix} = T_A \begin{bmatrix} X_{i,B} - X_{i,A} \\ Y_{i,B} - Y_{i,A} \\ Z_{i,B} - Z_{i,A} \end{bmatrix}$$

Multiplying the box specification vectors by the transformation matrix T_A gives these vectors in airplane coordinates

$$i_A = T_A i_i$$

$$j_A = T_A j_i$$

$$k_A = T_A k_i$$

In order to obtain the correct aspect of the display image of the box, the vectors (i_A, j_A, k_A) must be transformed to a visual coordinate system which is alined with the pilot's line of sight. The visual coordinate system is defined by a rotation of angle η about the airplane Y-axis and a rotation of angle μ about the airplane Z-axis so that the resultant visual X-axis is alined with the vector from the airplane to the box as shown in figure 13. The transformation matrix from airplane coordinates to visual coordinates is

$$T_V = \begin{bmatrix} \dfrac{X_{BA}}{\sqrt{X_{BA}^2 + Y_{BA}^2 + Z_{BA}^2}} & \dfrac{Y_{BA}}{\sqrt{X_{BA}^2 + Y_{BA}^2 + Z_{BA}^2}} & \dfrac{Z_{BA}}{\sqrt{X_{BA}^2 + Y_{BA}^2 + Z_{BA}^2}} \\ -\dfrac{X_{BA}}{\sqrt{X_{BA}^2 + Z_{BA}^2}} \dfrac{Y_{BA}}{\sqrt{X_{BA}^2 + Y_{BA}^2 + Z_{BA}^2}} & \dfrac{\sqrt{X_{BA}^2 + Z_{BA}^2}}{\sqrt{X_{BA}^2 + Y_{BA}^2 + Z_{BA}^2}} & -\dfrac{Z_{BA}}{\sqrt{X_{BA}^2 + Z_{BA}^2}} \dfrac{Y_{BA}}{\sqrt{X_{BA}^2 + Y_{BA}^2 + Z_{BA}^2}} \\ -\dfrac{Z_{BA}}{\sqrt{X_{BA}^2 + Z_{BA}^2}} & 0 & \dfrac{X_{BA}}{\sqrt{X_{BA}^2 + Z_{BA}^2}} \end{bmatrix}$$

Multiplying the vectors (i_A,j_A,k_A) by the matrix T_V gives the box specification vectors in visual coordinates as

$$i_V = T_V i_A$$

$$j_V = T_V j_A$$

$$k_V = T_V k_A$$

Consider a flat rectangular window in the airplane cockpit located so that the vector from the pilot's eye(s) to the center of the window is parallel with the airplane X-axis as shown in figure 14. The distance from the pilot to the window is X_w meters. From simple geometric relations, a point in space, as seen by the pilot, can be projected to a point on the window that is the intersection of the pilot's line of sight with the window. The center of the box, which is located at (X_{BA},Y_{BA},Z_{BA}) in airplane coordinates, projects to the point $C = \left(\dfrac{X_w}{X_{BA}} Y_{BA}, \dfrac{X_w}{X_{BA}} Z_{BA}\right)$ in window coordinates.

The line of sight to the center of the box is alined with the visual X-axis. The calculations to project the visible edges of the box to the window are performed relative to the projection of the center of the box with no corrections for the changing distance from the pilot; that is, the parallel edges of the box will project parallel to and have twice the length as the projections of the vectors (i_V,j_V,k_V). The projections of the vectors (i_V,j_V,k_V) relative to the center of the box are

$$i_w = \begin{pmatrix} i_w^y \\ \\ i_w^z \end{pmatrix} = \begin{pmatrix} \frac{X_W}{X_{BA}} i_V^y \\ \\ \frac{X_W}{X_{BA}} i_V^z \end{pmatrix}$$

$$j_w = \begin{pmatrix} j_w^y \\ \\ j_w^z \end{pmatrix} = \begin{pmatrix} \frac{X_W}{X_{BA}} j_V^y \\ \\ \frac{X_W}{X_{BA}} j_V^z \end{pmatrix}$$

$$k_w = \begin{pmatrix} k_w^y \\ \\ k_w^z \end{pmatrix} = \begin{pmatrix} \frac{X_W}{X_{BA}} k_V^y \\ \\ \frac{X_W}{X_{BA}} k_V^z \end{pmatrix}$$

where the superscripts x, y, and z identify the components of the vectors.

Of the six surfaces of the box, only three are visible to the pilot. Therefore, only 9 of the 12 edges of the box are projected onto the window. The vectors (i_w, j_w, k_w) point to the center of one of the surfaces as shown in figure 15(a). Also, the vectors $(-i_w, -j_w, -k_w)$ point to the center of one of the remaining surfaces.

Since the box is symmetric about each axis, an altered set of specification vectors may be defined as

$$i_p = \begin{cases} i_w, & i_V^x \leqq 0 \\ \\ -i_w, & i_V^x > 0 \end{cases}$$

$$j_p = \begin{cases} j_w, & j_V^x \leqq 0 \\ \\ -j_w, & j_V^x > 0 \end{cases}$$

$$k_p = \begin{cases} k_w, & k_V^x \leqq 0 \\ -k_w, & k_V^x > 0 \end{cases}$$

The altered set of specification vectors (i_p, j_p, k_p) point to one of the visible sides of the box, as shown in figure 15(b).

The projections of each of the nine visible edges may be defined by specifying an origin and a vector (direction and length) as given in the following table:

Line	Vector	Origin
1	$2i_p$	$C_1 = C - i_p + j_p + k_p$
2	$-2j_p$	
3	$-2k_p$	
4	$-2i_p$	$C_2 = C + i_p - j_p + k_p$
5	$2j_p$	
6	$-2k_p$	
7	$-2i_p$	$C_3 = C + i_p + j_p - k_p$
8	$-2j_p$	
9	$2k_p$	

Although the box may be specified with different length edges, at some orientations the image may be confusing and difficult to interpret. In order to alleviate this problem, a rectangular figure is drawn on the end face (the face perpendicular to the vector i_p), as is shown in figure 16. The lengths of the edges of this figure are chosen to be a fraction f of the lengths of the edges of the end of the box. Each of these edges is defined by an origin and a vector as given in the following table:

Line	Vector	Origin
10	$2fj_p$	$C_4 = C + i_p - fj_p + fk_p$
11	$-2fk_p$	
12	$-2fj_p$	$C_5 = C + i_p + fj_p - fk_p$
13	$-2fk_p$	

The projection of the Earth's horizon (using the flat Earth assumption) is the distance $X_w \tan\theta$ from the center of the window and is rotated by the angle ϕ about the center of the window, as is shown in figure 17(a), where θ is the pitch angle of the airplane and ϕ is the roll angle of the airplane. The symbology used to depict the horizon is given in figure 17(b). The two lines are defined by the origins and vectors given in the following table:

Line	Vector	Origin
14	C_6	$(h_2 \cos\phi,\ -h_2 \sin\phi)$
15	C_7	$(-h_2 \cos\phi,\ h_2 \sin\phi)$

where

$$C_6 = (X_w \tan\theta \sin\phi + h_1 \cos\phi,\ X_w \tan\theta \cos\phi - h_1 \sin\phi)$$

$$C_7 = (X_w \tan\theta \sin\phi - h_1 \cos\phi,\ X_w \tan\theta \cos\phi + h_1 \sin\phi)$$

and where h_1 and h_2 are arbitrarily chosen constants. A cross is placed at the center of the display to provide a reference which makes flying the airplane toward the target box more precise. A typical display scene is shown in figure 18.

REFERENCES

1. Steinmetz, George G.; Morello, Samuel A.; Knox, Charles E.; and Person, Lee H., Jr.: A Piloted-Simulation Evaluation of Two Electronic Display Formats for Approach and Landing. NASA TN D-8183, 1976.

2. Knox, Charles E.; and Leavitt, John: Description of Path-in-the-Sky Contact Analog Piloting Display. NASA TM-74057, 1977.

3. Martin, A. J.; and Cosley, D. H.: ADEDS Functional/Software Requirements. FAA-SS-73-19, Dec. 1973.

4. Adams, James J.; and Hatch, Howard G., Jr.: An Approach to the Determination of Aircraft Handling Qualities by Using Pilot Transfer Functions. NASA TN D-6104, 1971.

5. Adams, James J.; and Moore, Frederick L.: An Analytical Study of Aircraft Lateral-Directional Handling Qualities Using Pilot Models. NASA TN D-8103, 1976.

6. Flying Qualities of Piloted Airplanes. Mil. Specif. MIL-F-8785B(ASG), Aug. 7, 1969.

TABLE I.- ROOT-MEAN-SQUARE SCORES

Display configuration	No gust		With gust	
	Y, m	Z, m	Y, m	Z, m
Subject G				
Cross pointer	9.60	6.85	13.00	16.90
Box at 550 m	2.04	1.19	6.48	4.85
Box at 368 m	2.56	1.25	5.51	4.30
Box at 184 m	1.74	1.31	4.15	2.84
Box at 92 m	1.62	1.04	4.19	2.47
Subject H				
Cross pointer	2.16	2.08	11.40	5.96
Box at 368 m	1.65	2.04	4.55	4.75
Box at 184 m	.88	.88	3.02	3.17
Subject S				
Cross pointer	3.60	2.38	9.29	7.45
Box at 368 m	1.98	2.16	5.50	4.49
Box at 184 m	1.31	1.53	6.00	4.05
Subject E				
Cross pointer	3.02	3.18	-----	-----
Box at 368 m	1.95	.95	7.15	4.70
Box at 184 m	1.52	.80	4.65	3.60
Box at 92 m	2.26	1.31	7.65	3.96
Subject K				
Cross pointer	5.28	1.98	11.20	2.98
Box at 368 m	3.20	1.43	7.90	6.22
Box at 184 m	----	----	5.70	4.15
Box at 92 m	2.53	1.31	2.80	2.07

TABLE II.- PILOT-MODEL GAINS USED TO MATCH PILOTED STEP CORRECTIONS AND PILOT-MODEL—AIRCRAFT SYSTEM RESPONSE CHARACTERISTICS

(a) Longitudinal

Display configuration	Pilot-model gains		Closed-loop system response characteristics					
	K_h, rad/m	K_θ	ω_h, rad/sec	ξ_h	ω_α, rad/sec	ξ_α	ω_c, rad/sec	ξ_c
Subject G								
Box at 92 m	0.0105	2.0	0.533	0.25	3.97	0.11	7.30	0.90
Box at 92 m	.0130	2.5	.625	.23	4.78	.52	7.60	.89
Subject K								
Cross pointer	0.00525	1.0	0.310	0.32	3.80	0.27	6.55	0.92
Box at 368 m	.0026	1.0	.218	.50	3.80	.27	6.55	.91
Box at 184 m	.00525	2.0	.386	.40	3.97	.11	7.30	.90
Box at 184 m	.0066	.7	.304	.23	3.80	.34	6.25	.92
Box at 92 m	.0105	2.0	.533	.25	3.96	.12	7.05	.93
Box at 92 m	.0130	1.4	.541	.17	3.85	.20	6.90	.91

TABLE II.- Concluded

(b) Lateral

Display configuration	Pilot-model gains			Closed-loop system response characteristics							
	K_y, rad/m	K_ψ	K_ϕ	ω_y, rad/sec	ξ_y	ω_ψ, rad/sec	ξ_ψ	ω_{DR}, rad/sec	ξ_{DR}	ω_c, rad/sec	ξ_c
Subject G											
Cross pointer	0.0079	2.34	0.5	0.45	0.21	1.58	0.45	2.52	0.030	6.30	0.95
Box at 368 m	.0039	7.00	.5	.66	.96	1.36	.19	2.45	.026	6.23	.95
Box at 368 m	.0053	2.34	.5	.37	.33	1.58	.44	2.52	.030	6.30	.95
Box at 184 m	.0026	7.00	.5	.52	1.20	1.41	.20	2.46	.024	6.20	.95
Box at 184 m	.0039	3.90	.5	.44	.59	1.47	.40	2.50	.020	6.30	.95
Box at 92 m	.0079	3.90	.5	.64	.29	1.45	.45	2.50	.030	6.28	.95
Box at 92 m	.0053	7.00	.5	.795	.82	1.31	.18	2.46	.028	6.20	.95
Subject K											
Cross pointer	0.0079	2.34	0.5	0.45	0.21	1.58	0.45	2.52	0.030	6.30	0.95
Box at 368 m	.0026	3.90	.5	.36	.78	1.48	.38	2.50	.027	6.30	.95
Box at 368 m	.0053	2.34	.5	.37	.33	1.58	.44	2.52	.030	6.30	.95
Box at 184 m	.0053	2.34	.5	.37	.33	1.58	.44	2.52	.030	6.30	.95
Box at 92 m	.0079	3.90	.5	.64	.29	1.45	.45	2.50	.030	6.28	.95

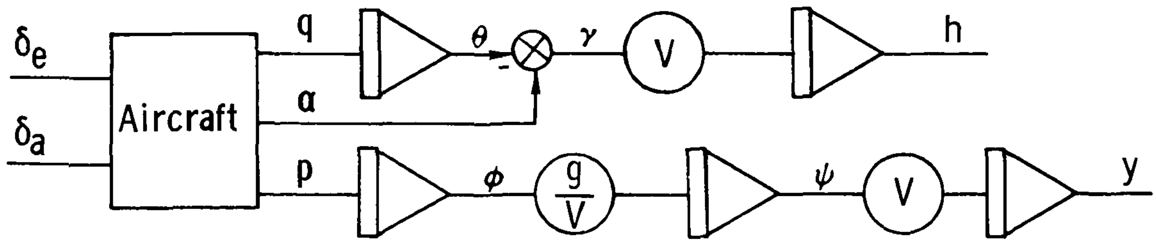


Figure 1.- Block diagram of landing approach control task.

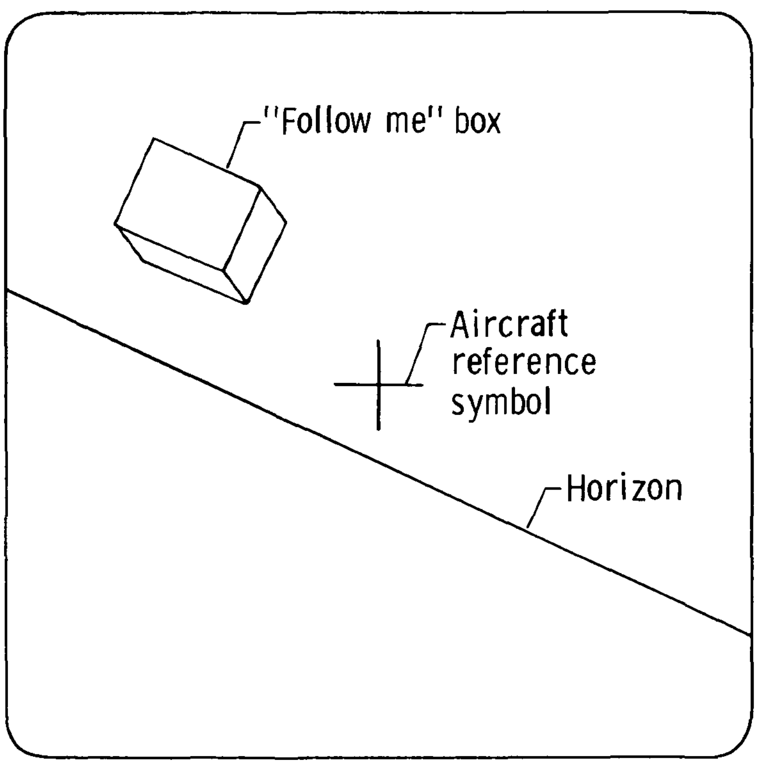
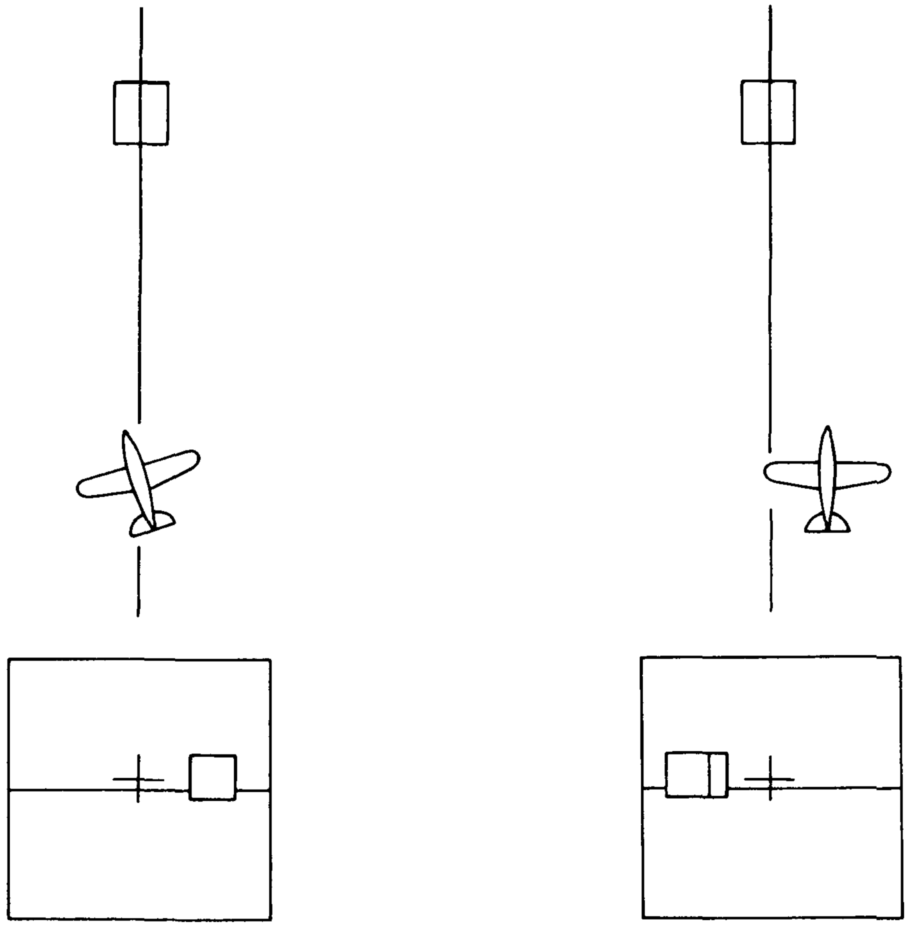


Figure 2.- "Follow me" display format.



(a) Heading error only.

(b) Displacement error only.

Figure 3.- Display scene for heading and displacement errors.

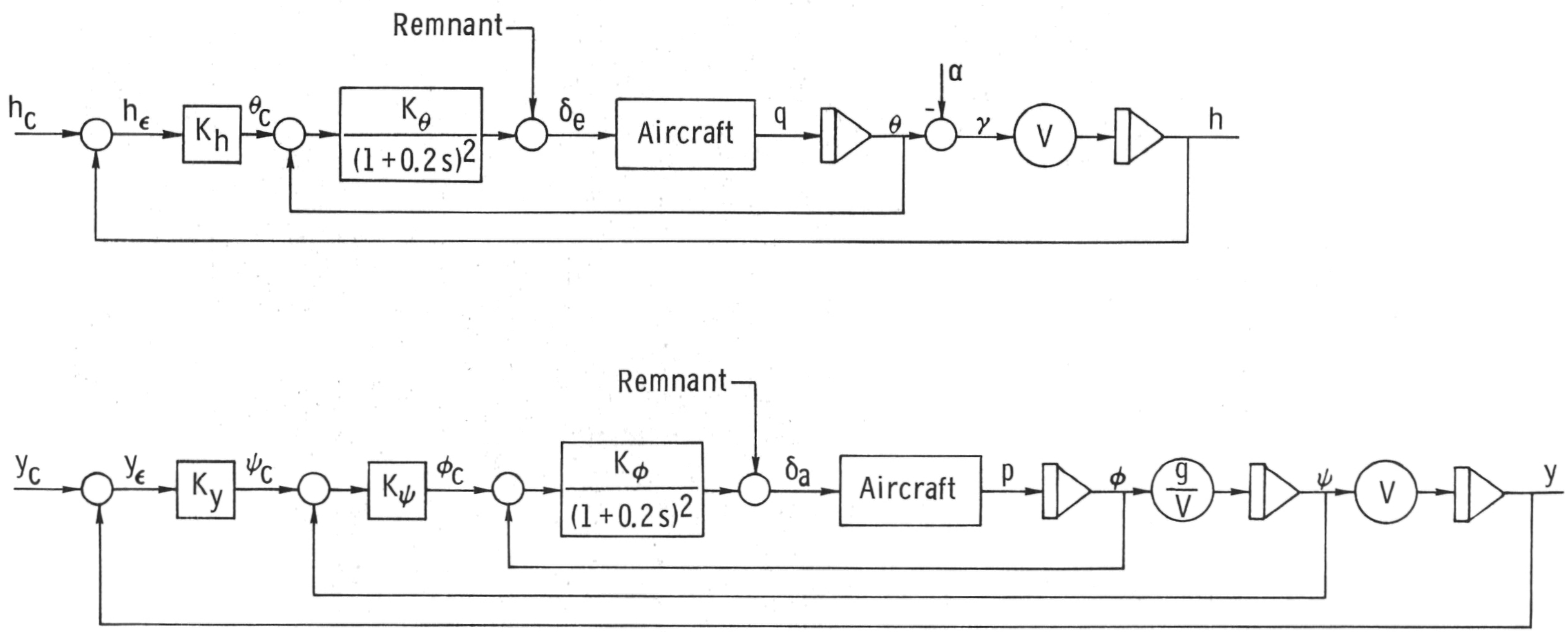
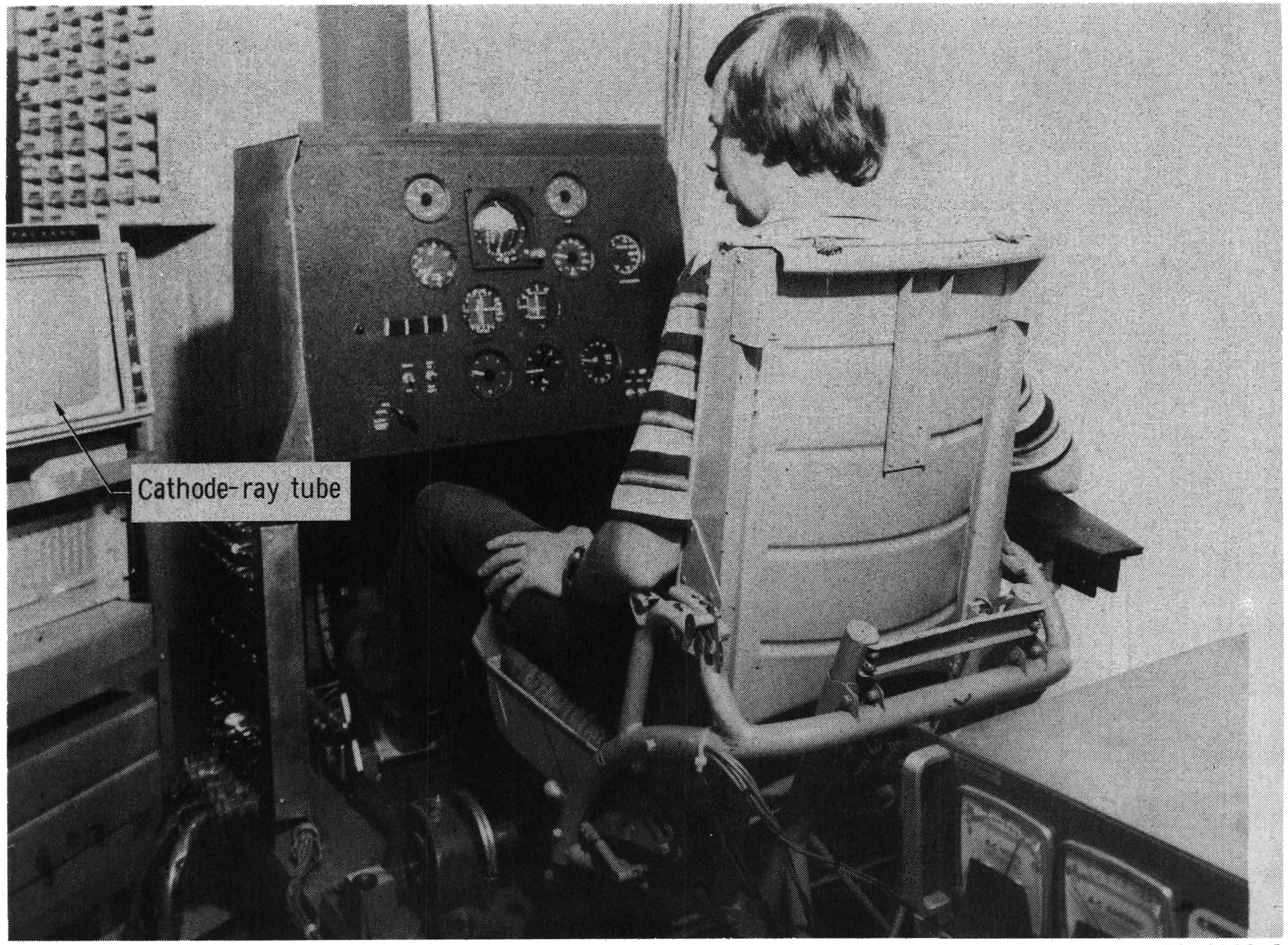
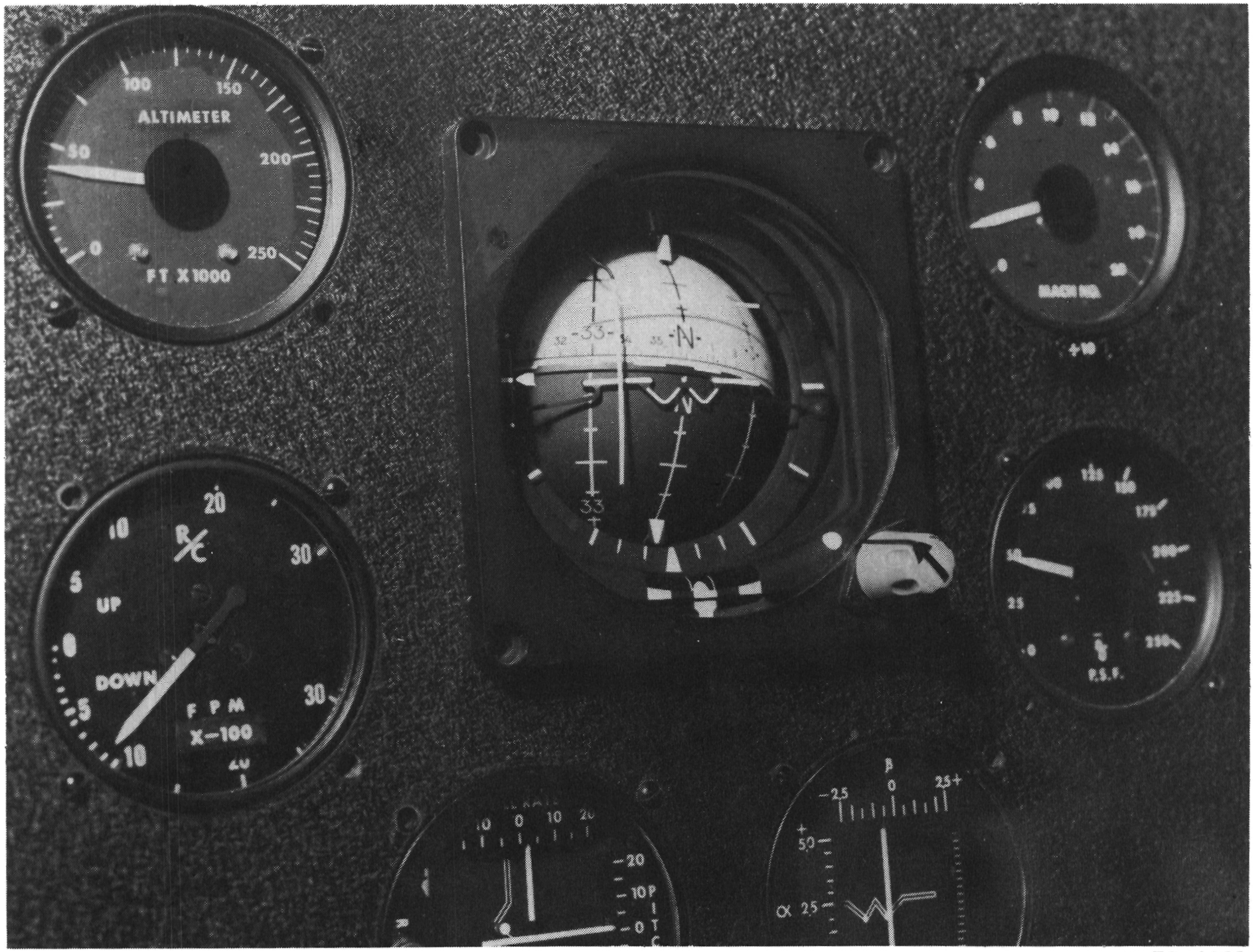


Figure 4.- Pilot-model—aircraft system.



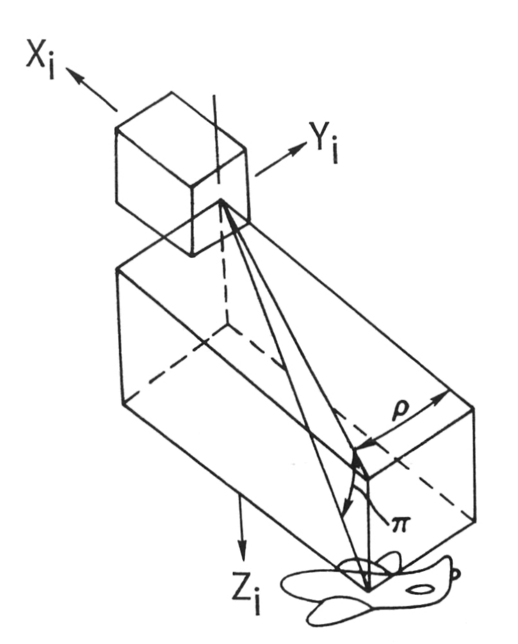
L-78-4222.1

Figure 5.- Simulator used in experiment.

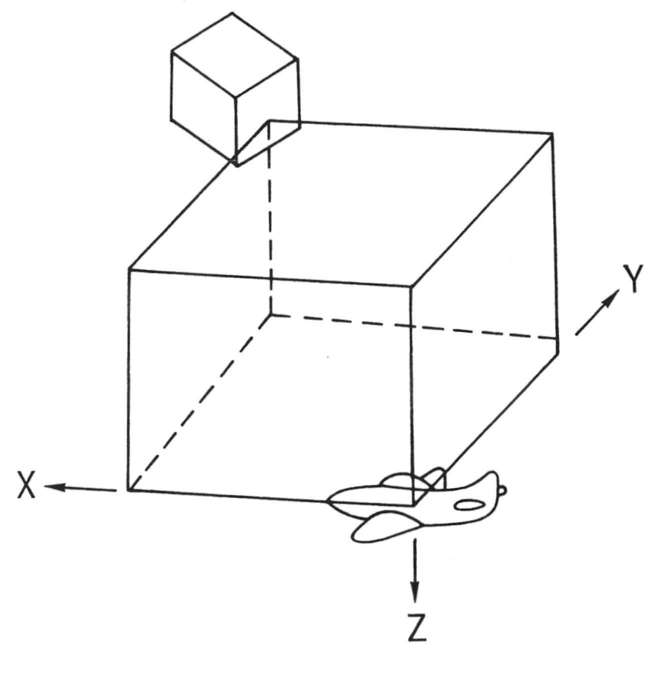


L-78-4221

Figure 6.- Cross pointer and altitude indicator used in experiment.



(a) X_i-, Y_i-, Z_i-axis system.



(b) X-, Y-, Z-axis system.

Figure 7.- Axis systems used in computation for box.

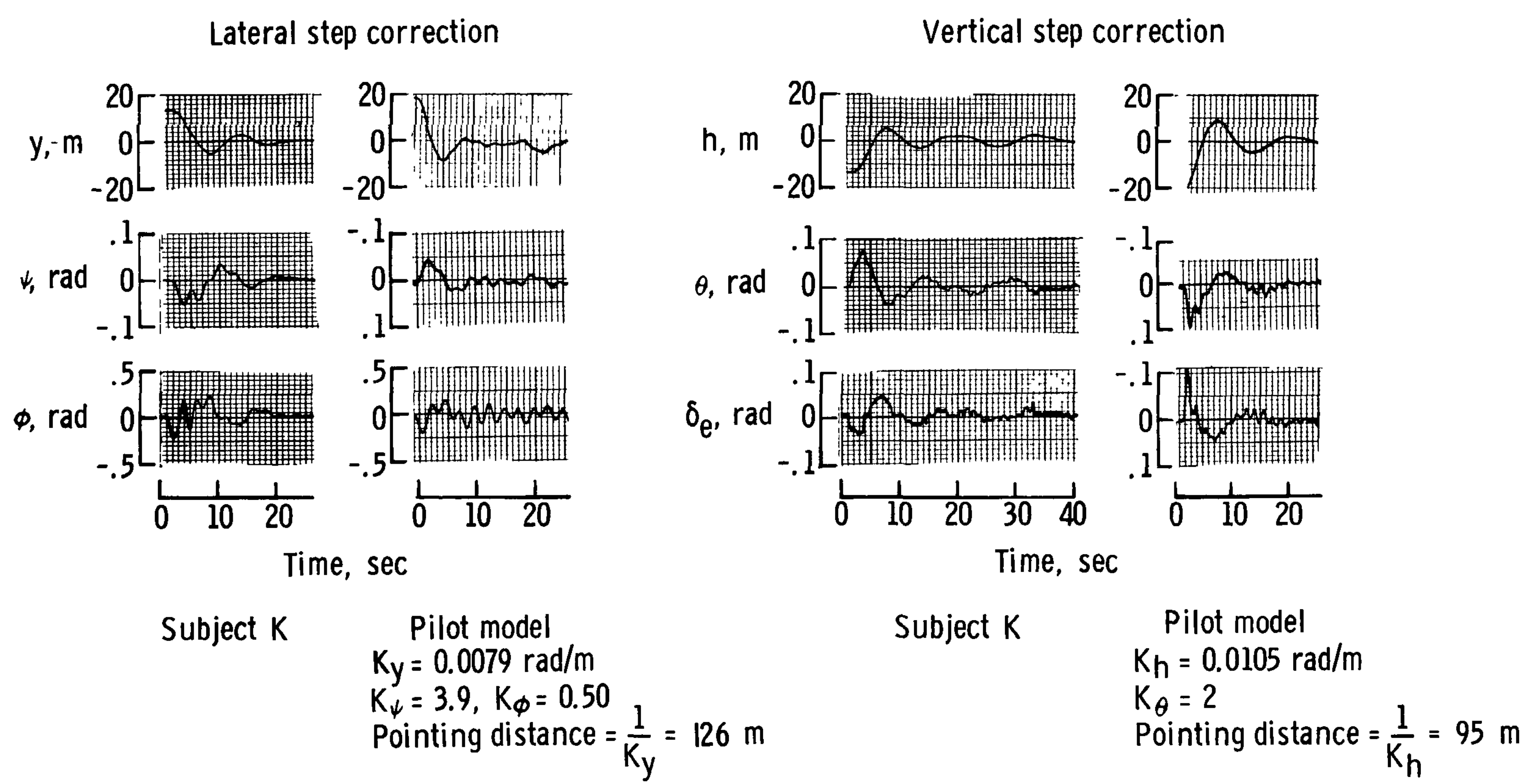


Figure 8.- Time histories of lateral and vertical step corrections obtained with subject K with box at 92-m X_i distance and corresponding pilot-model—aircraft system match.

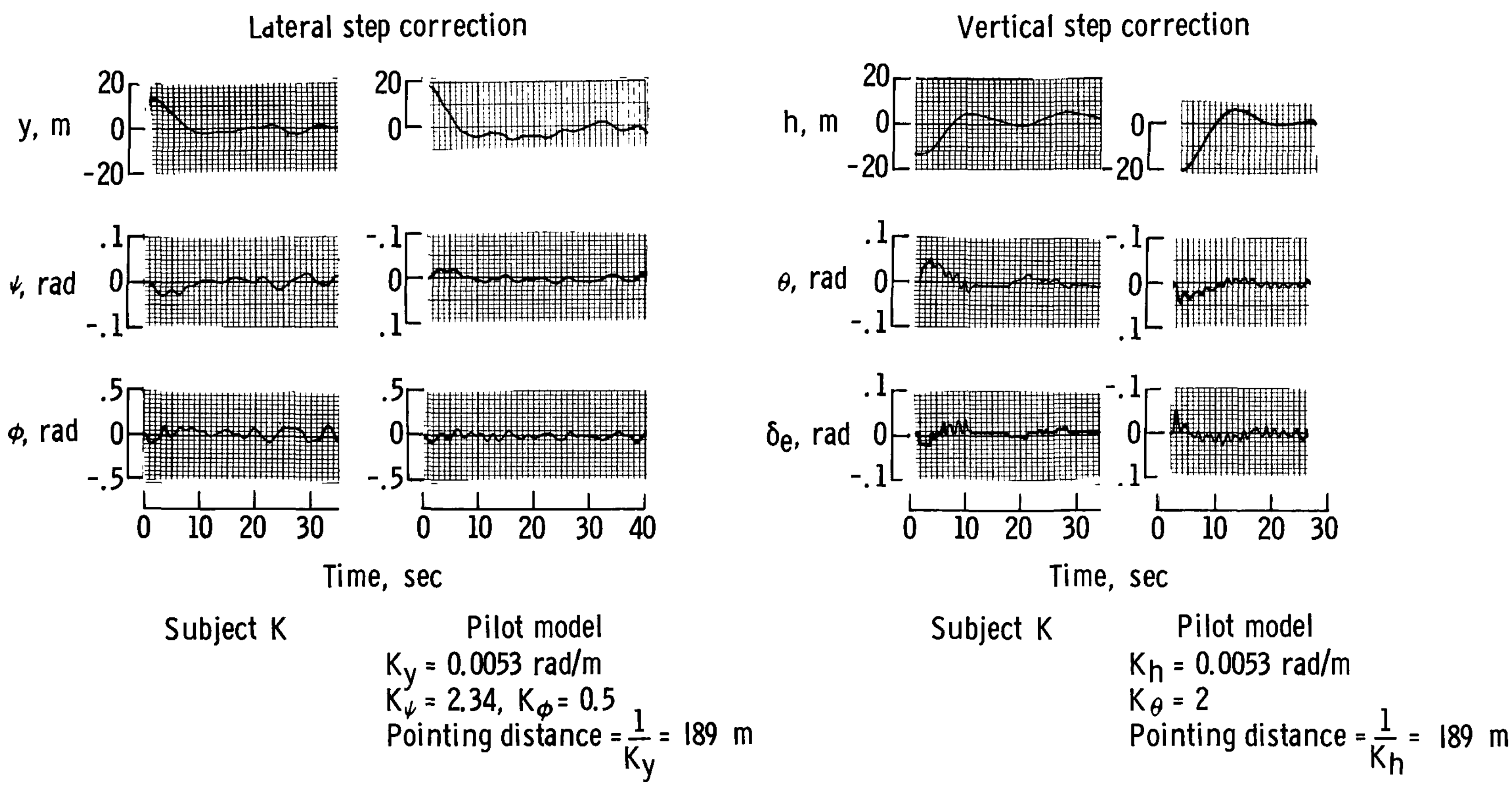


Figure 9.- Time histories of lateral and vertical step corrections obtained with subject K with box at 184-m X_1 distance and corresponding pilot-model—aircraft system match.

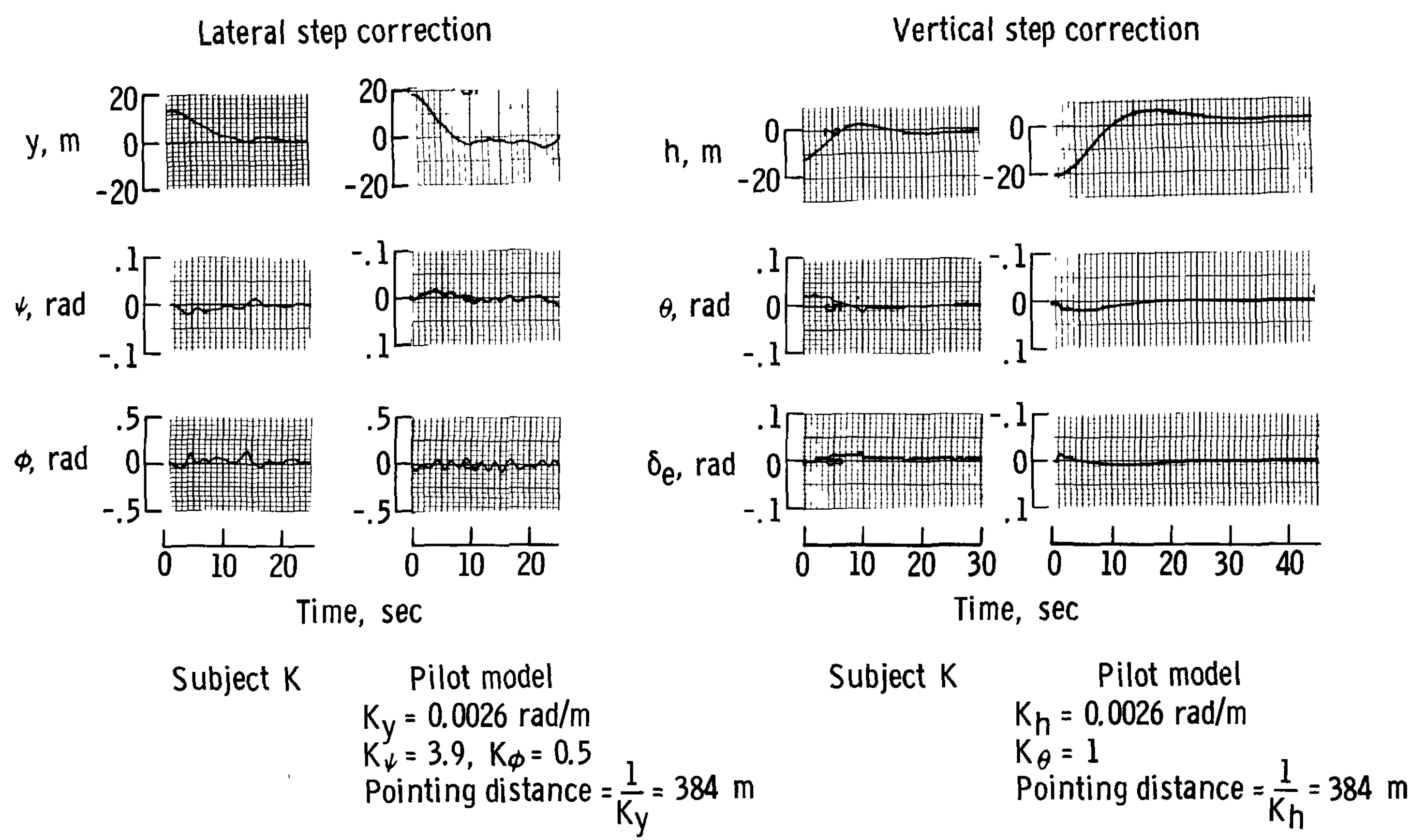


Figure 10.- Time histories of lateral and vertical step corrections obtained with subject K with box at 368-m X_1 distance and corresponding pilot-model—aircraft system match.

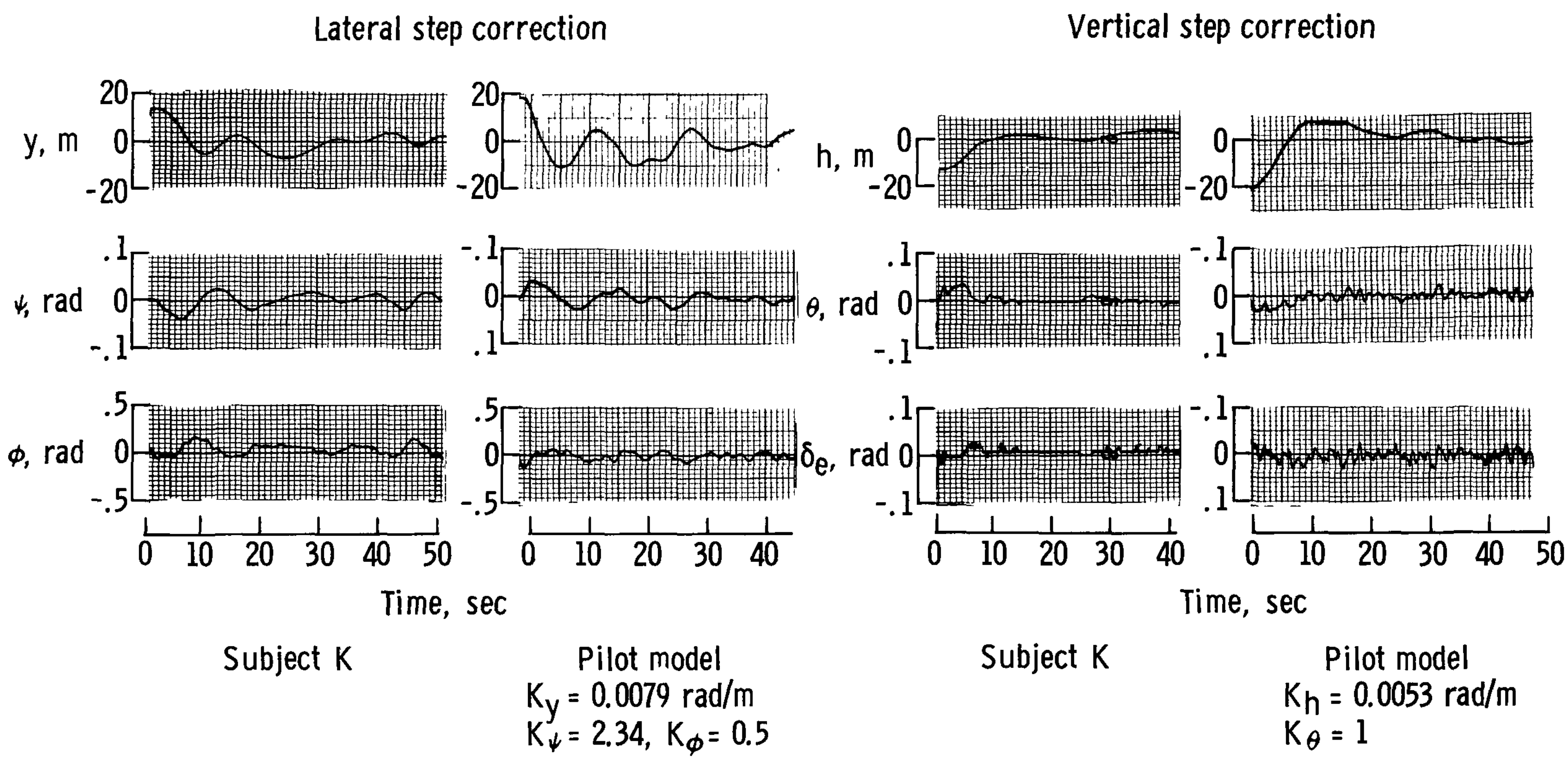


Figure 11.- Time histories of lateral and vertical step corrections obtained with subject K using cross pointer display and corresponding pilot-model—aircraft system match.

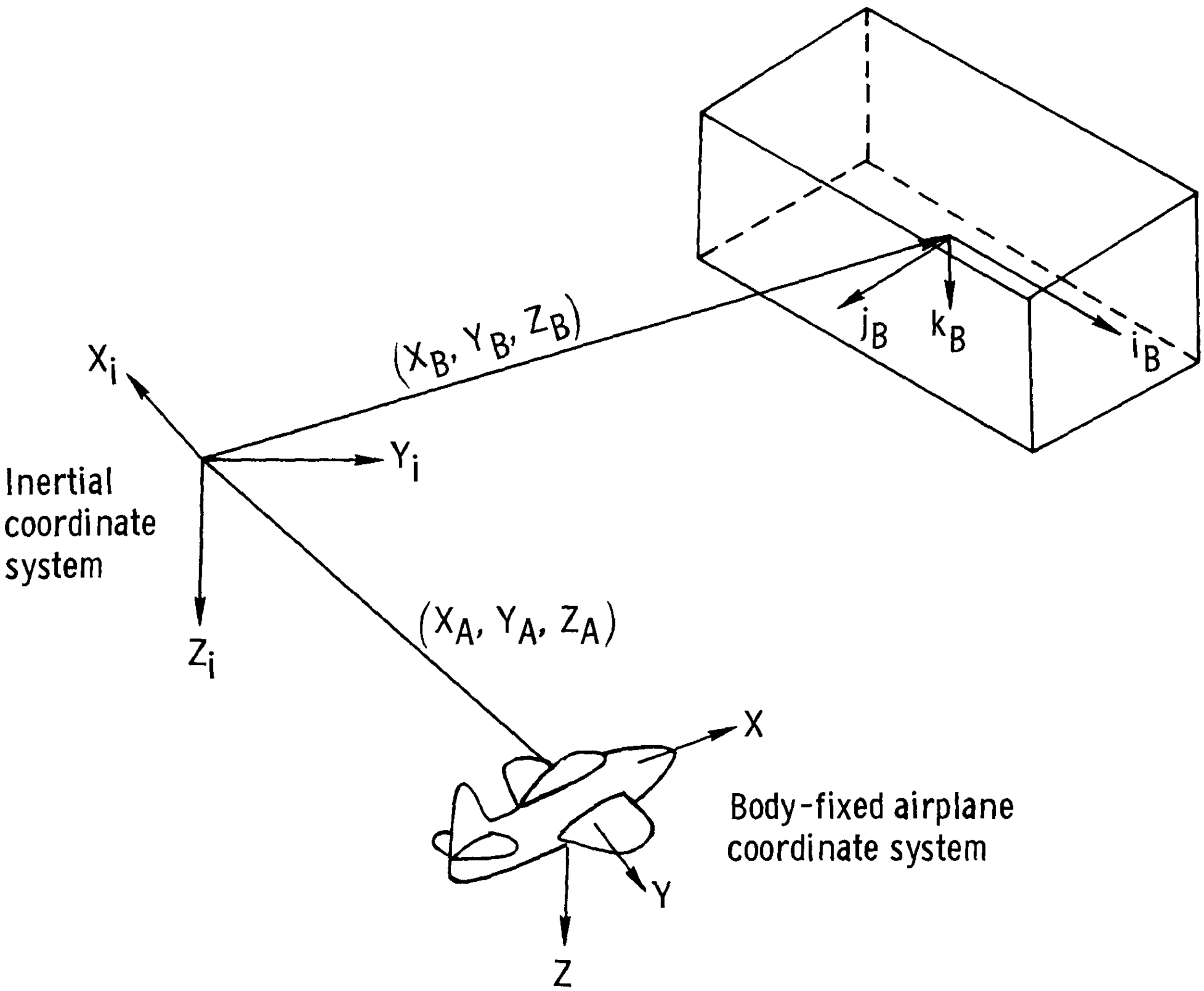


Figure 12.- Axis system.

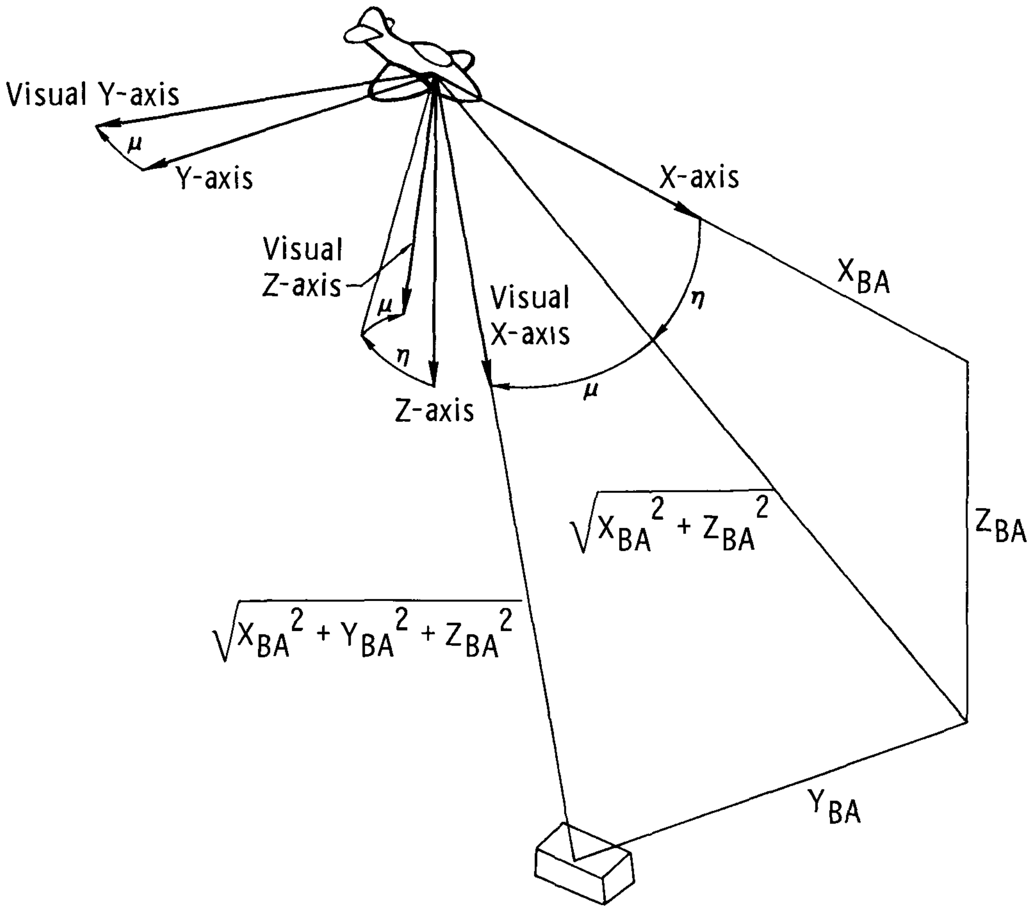


Figure 13.- Visual axis system.

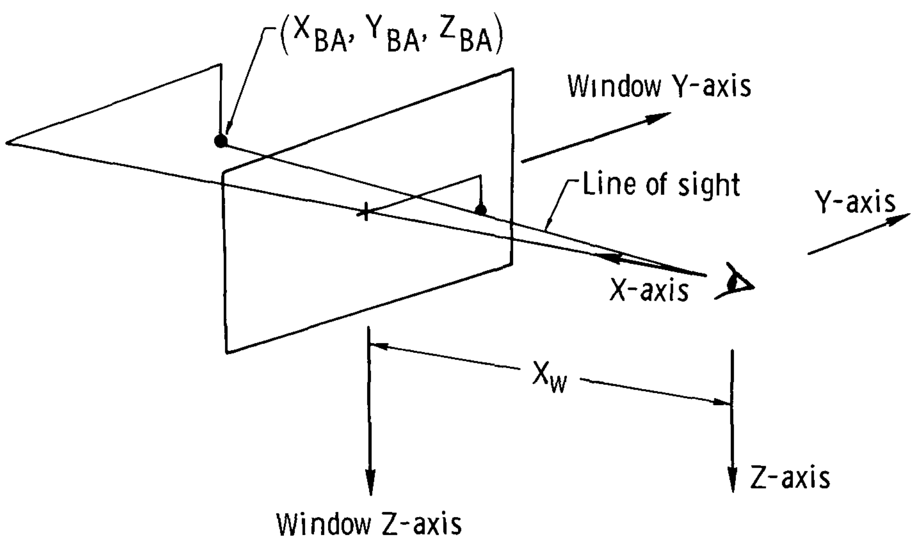
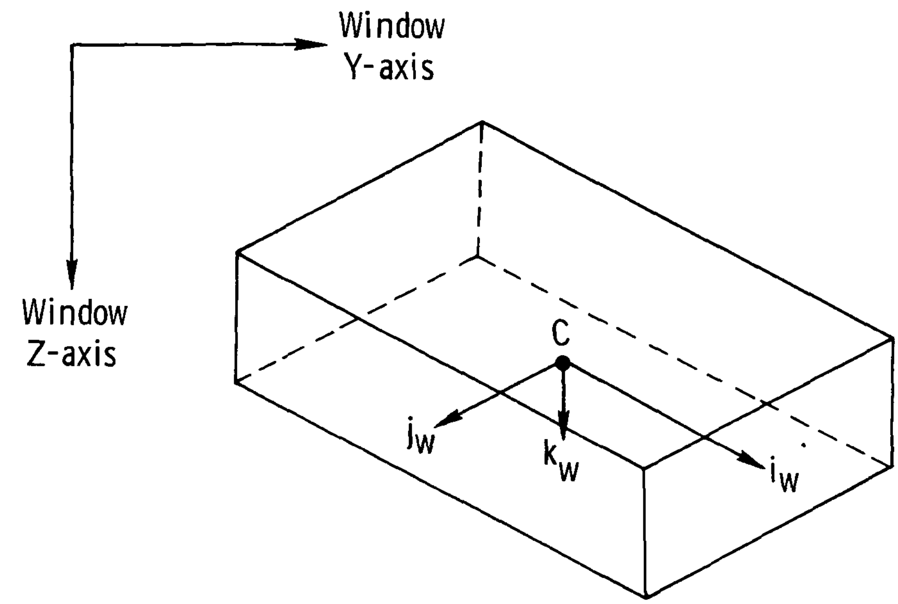
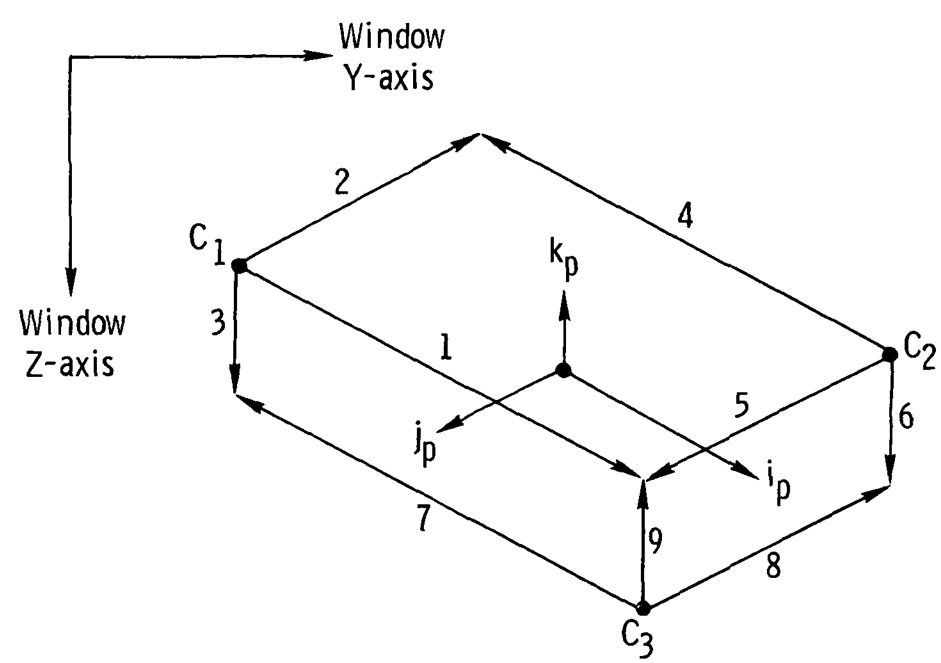


Figure 14.- Window projection system.



(a) Original specification vectors.



(b) Altered specification vectors.

Figure 15.- Box drawing diagram.

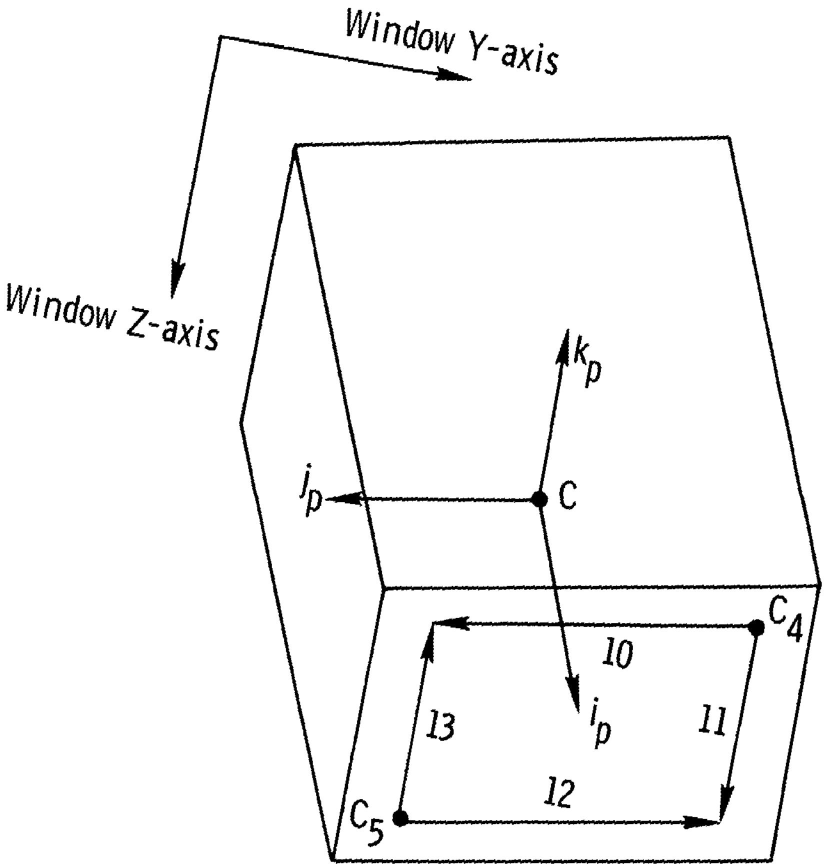
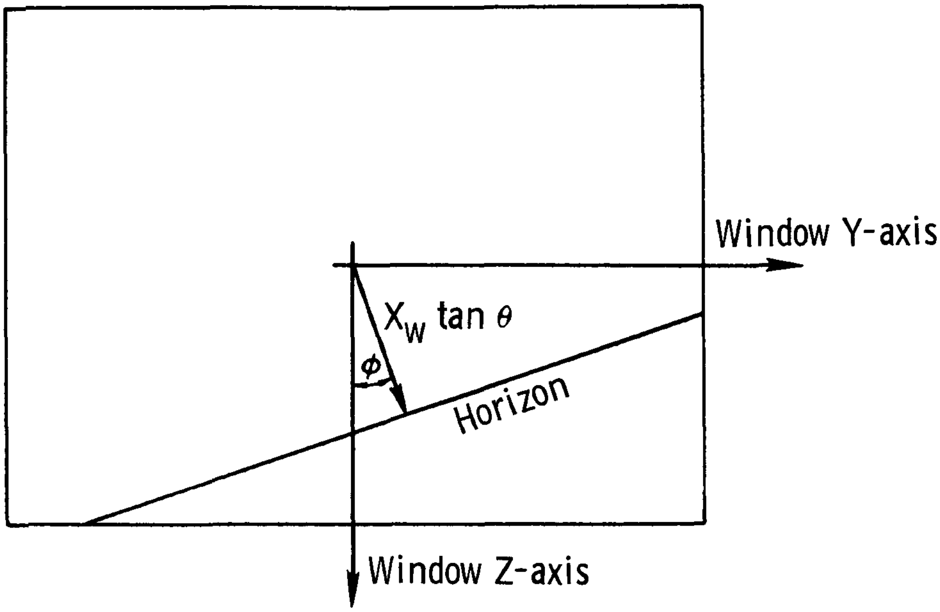
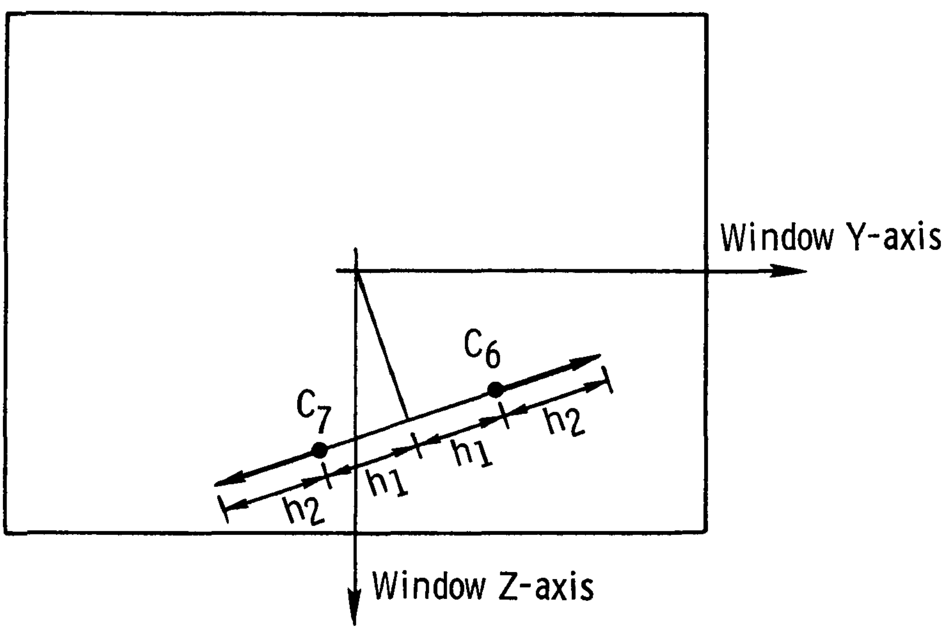


Figure 16.- End-face figure.



(a) As seen through window.



(b) As drawn on display.

Figure 17.- Horizon drawing.

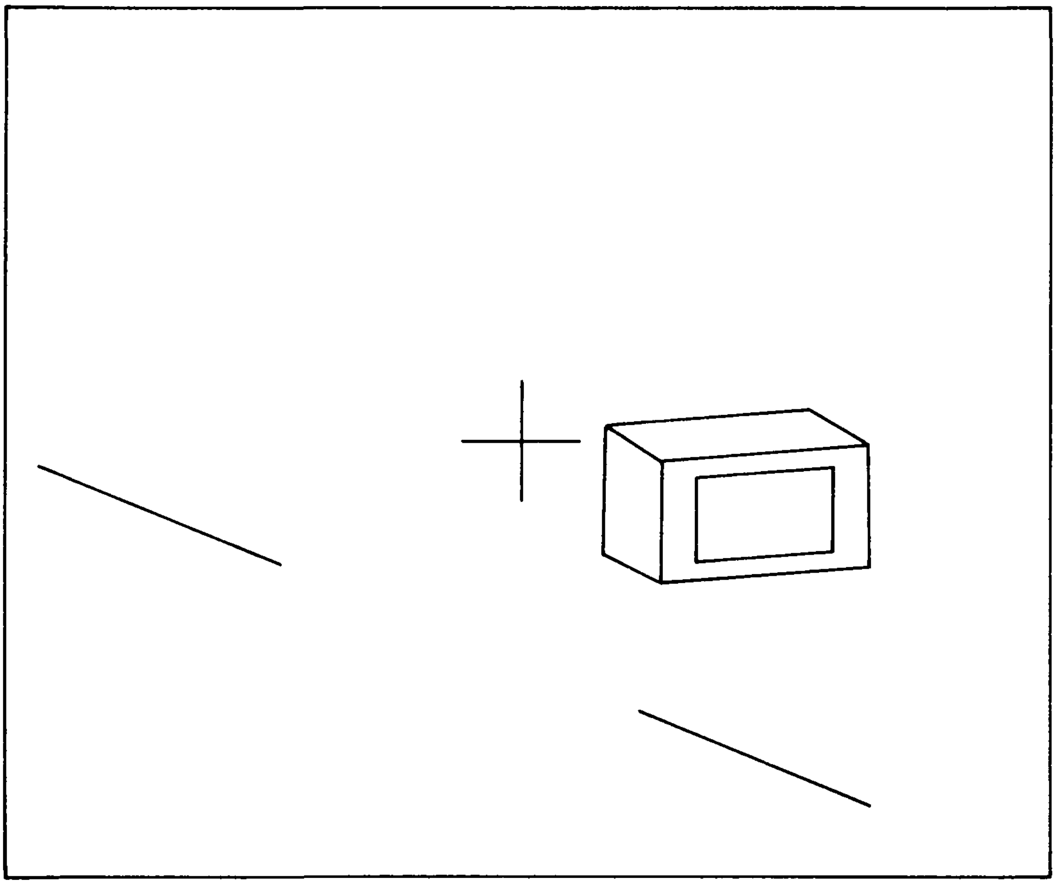


Figure 18.- Typical display scene.

1 Report No	2 Government Accession No	3 Recipient's Catalog No
NASA TM-78771		

4 Title and Subtitle	5 Report Date
DESCRIPTION AND PRELIMINARY STUDIES OF A COMPUTER DRAWN INSTRUMENT LANDING APPROACH DISPLAY	November 1978
	6 Performing Organization Code

7 Author(s)	8 Performing Organization Report No
James J. Adams and Frederick J. Lallman	L-12269
	10 Work Unit No 505-07-13-02
9 Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665	11 Contract or Grant No
	13 Type of Report and Period Covered Technical Memorandum
12 Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14 Sponsoring Agency Code

15 Supplementary Notes

16 Abstract

A computer drawn instrument landing approach display, which shows a box located on the desired path, alined with the path, and moving along the path at a selected distance ahead of the aircraft, has been examined. Vertical and lateral displacements from the desired path and aircraft attitude information are used as inputs to the computer. A preliminary simulation study with pilot subjects has shown that the pilots find the display very easy to use, and they achieved better performance scores with the box display than with a cross pointer instrument landing display.

17 Key Words (Suggested by Author(s))	18 Distribution Statement
Instrument landing display Computer-derived display Flight-director display	Unclassified - Unlimited Subject Category 06

19 Security Classif (of this report)	20 Security Classif (of this page)	21 No of Pages	22 Price*
Unclassified	Unclassified	42	$4.50

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1978

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business

Penalty for Private Use, $300

THIRD-CLASS BULK RATE

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

U.S.MAIL

7 2 1U,A, 102078 S90844HU
MCDONNELL DOUGLAS CORP
ATTN: PUBLICATIONS GROUP PR 15246-A
P O BOX 516
ST LOUIS MO 63166

NASA

POSTMASTER. If Undeliverable (Section 158 Postal Manual) Do Not Return

~~J. H. Bunny E422/74/G5/21347~~