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and Space Administration

Scientific and Technical
Information Branch

SUMMARY

A piloted-simulation study was conducted to evaluate the effect on instrument landing system (ILS) tracking performance of integrating localizer-error rate with raw localizer and glide-slope error. The display was named the pseudocommand tracking indicator (PCTI) because it provides an indication of the change of heading required to track the localizer center line without using all of the factors included in flight-director computations. Eight instrument-rated pilots each flew five instrument approaches with the PCTI and five instrument approaches with a conventional baseline course deviation indicator.

The results show good overall/pilot acceptance of the display, a significant improvement in localizer tracking error, and no significant changes in glide-slope tracking error or pilot workload. Pilot comments indicate that the PCTI is easy to use and that it greatly reduces the use of the directional gyro while tracking the localizer. The data also suggest that the task of tracking the localizer by using the PCTI approaches the task of maintaining a reference heading.

INTRODUCTION

General aviation activities involving instrument flight rules (IFR) currently involve approximately 15 million airport operations per year and are forecast by the Federal Aviation Administration (FAA) to come close to doubling by 1988 to about 29 million operations per year. (See ref. 1.) Most of these flights are flown by nonprofessional single-pilot crews. These single-pilot crews are expected to perform at the same level of competency as professional multipilot air-carrier crews. This level of competency may not be reached without improvements in aircraft handling qualities, avionics and automatic flight-control systems, training, and air-traffic control procedures. The high IFR accident rate in the landing phase of flight, as documented in reference 2, indicates a need for improvement in landing-phase displays.

The instrument landing system (ILS) approach can, at times, impose closed-loop control difficulties for the pilot. The ILS provides positive guidance to a runway, both in azimuth (localizer) and in elevation (glide slope). The localizer and glide slope must be tracked to within 2.5° and 0.7°, respectively, to avoid full-scale deflections of the course deviation indicator (CDI) needles. The heading required to track the localizer and the rate of descent needed to track the glide slope vary with aircraft speed and wind velocity and must be determined by trial and error. Since wind velocity usually varies with altitude, the reference heading and rate of descent are likely to change while tracking with the ILS. To complicate the ILS approach further, the increased sensitivity of the CDI near the runway can lead to pilot-induced oscillations. (See ref. 3.)

One experimental method used to improve localizer tracking (ref. 4) is supplying perspective runway symbology and relative track information to an electronic attitude director indicator (EADI). This display was well accepted by evaluation pilots and produced better tracking results than a baseline EADI. Another display used to improve localizer tracking is the "follow-me box" display. (See ref. 5.) This display draws a perspective box on a cathode-ray tube (CRT) to represent a box in space in front of the aircraft. The pilot simply follows the box when flying instrument approaches. These displays are not currently applicable to general aviation, however, since they require sensors, displays, and computation abilities not presently available in small general aviation aircraft. The relative track-angle information of the EADI is used by the pilot to control the closure of the aircraft with the runway extended center line. Localizer-error rate can also be used by the pilot to control the closure with the localizer center line. This error rate can be relatively easily determined from the localizer-error signal.

It was hypothesized that the addition of localizer-error rate to a conventional CDI display might significantly improve the pilot's perception of the aircraft's lateral situation, possibly reducing workload and tracking error. The low level of required computational and display abilities would give the rate concept a probable cost advantage over conventional flight directors and advanced EADI displays. The cost advantage and the lack of need for additional aircraft sensors would make the rate-enhanced display attractive for small general aviation aircraft.

A study was performed to evaluate a rate-enhanced ILS display. The goal was to determine the effect of the enhanced display on pilot workload and performance while flying with the ILS. The study was performed in the general aviation flight simulator at the Langley Research Center. Each of 8 instrument-rated pilots flew 10 ILS approaches. Five of the approaches were flown with a conventional CDI display format and five approaches used the enhanced display. Data collected included control inputs, pilot-estimated workload and performance, pilot comments, localizer-error and glide-slope-error time histories, and on-line calculations of root-mean-square (RMS) values of localizer and glide-slope error.

SYMBOLS AND ABBREVIATIONS

Values are given in both SI and U.S. Customary Units. The measurements were made in U.S. Customary Units.

Symbols

$F_{m,n}$ critical value of test statistic for (m,n) degrees of freedom

f calculated value of analysis-of-variance test statistic

GN angle that glide-slope needle makes with horizontal center line of display, positive below center, deg

K localizer rate gain

LN angle that localizer needle makes with vertical center line of display positive to right, deg

$\dot{LN}$ time derivative of LN, deg/sec

$\imath$ aircraft distance from localizer antenna, m (n. mi.)

RN angle that localizer rate needle makes with respect to vertical, positive to right, deg

V_a airspeed of aircraft, m/sec (knots)

V_g ground speed of aircraft, m/sec (knots)

V_w windspeed, m/sec (knots)

X,Y Earth axes (north and east, respectively)

$\dot{X}_T$ Earth-axis X (north) component of aircraft ground track, m/sec (knots)

$\dot{Y}_T$ Earth-axis Y (east) component of aircraft ground track, m/sec (knots)

α statistical level of significance

$\Delta\psi_g$ angle between line drawn to localizer source and ground track of aircraft, positive when δ_L is increasing, deg

$\Delta\psi_{g,i}$ intermediate value of $\Delta\psi_g$

δ_{gs} glide-slope deviation, positive above glide path, deg

δ_L localizer deviation, positive to right of course, deg

$\dot{\delta}_L$ time derivative of localizer deviation, deg/sec

ψ_a aircraft heading, deg, true

ψ_g aircraft ground track, deg, true

ψ_w direction that wind is blowing toward, deg, true

Abbreviations

ADF automatic direction finder

CDI course deviation indicator

CRT cathode-ray tube

DG directional gyro

DME distance measuring equipment

EADI electronic attitude director indicator

FAA Federal Aviation Administration

IFR instrument flight rules

ILS instrument landing system

NDB nondirectional beacon

OBS omnibearing selector

PCTI pseudocommand tracking indicator

RMS root mean square

VOR very-high-frequency omnirange

DISPLAY CONCEPT

A conventional CDI displays angular tracking error from the localizer and glide-slope center lines during an ILS approach. In one type of CKI (fig. 1), a vertical needle displays localizer error by swinging left and right while a horizontal needle indicates glide-slope error by swinging up and down. Centered needles indicate that the aircraft is on the localizer and glide-slope center line. A left localizer needle indicates that the localizer center line is to the left of the aircraft and a raised glide-slope needle indicates that the glide slope is above the aircraft. A general rule on an ILS approach, therefore, is to fly toward the needles.

The pilot cannot, however, simply turn, climb, or descend in the direction of needle deflection until the needle centers. Small changes in heading and vertical speed must be made and the effects of each change determined. These changes must be made frequently because of changing wind conditions and turbulence-induced tracking errors. The heading and vertical speed needed for proper tracking may/change as the approach progresses and must be determined by trial and error.

It was decided to enhance the CDI presentation with error-rate information. The enhanced CDI was made to resemble a conventional CDI as nearly as possible to reduce pilot learning time and to permit direct comparison between the two displays. Simple rate quickening was not desired since the pilot must have the raw ILS information in sight. (See ref. 6.)

The final design presented localizer data with two needles, one of which pivoted at the tip of the other needle. (See fig. 2.) The upper needle indicates localizer error and the lower needle indicates localizer-error rate. This display provides the effect of a rate-quickened indicator (the position of the tip of the rate needle is a function of error and error rate) while displaying the necessary raw-error data. The localizer was chosen to evaluate the rate concept, because the pilot is controlling a higher order system with the localizer than with the glide slope. The rate-display math model is described in appendix A.

The enhanced display was designed so that when a localizer error exists and the aircraft is moving back toward the localizer (see fig. 3), the rate needle will be deflected back toward the display center. When no error rate exists, the two needles would be in alignment; and when drifting farther from course, the rate needle would be deflected more than the error needle.

Changing the aircraft heading during an approach changes the localizer-error rate and the rate-needle position. An asymptotic return to the localizer is produced by changing the aircraft heading to keep the tip of the rate needle at the vertical center line of the display. Because the tip of the rate needle continuously shows the difference between actual aircraft heading and required heading, it was named the pseudocommand tracking indicator (PCTI). It was not considered a true command indicator such as a flight director since the PCTI does not include the bank-angle term in its calculations.

AIRCRAFT SIMULATION

The general aviation flight simulator at the Langley Research Center was used in this study. This simulator consists of an enclosed flight-quality cockpit (fig. 4) interfaced to a general-purpose digital computer.

The math model for a typical single-engine, high-wing, general aviation aircraft was used in the simulation. This math model included changes in flight-control effectiveness and force gradients as a function of airspeed, wing-flap-extension effects, a landing-gear model, a radio navigation-aid data base, and an atmospheric wind-turbulence model.

The simulator cockpit is fully enclosed by the cabin section of a light-aircraft fuselage. The simulator's instrumentation and avionics are typical of an IFR equipped high-performance single-engine or light twin-engine aircraft. This includes a horizontal-situation indicator, dual VOR receivers, ADF, DME, and a three-axis autopilot. An array of speakers provides realistic wind and engine noise up to volumes typical of general aviation aircraft. The control yoke (elevator and ailerons) is hydraulically loaded to provide the appropriate force gradients. Rudder-pedal force feel is supplied with springs.

The simulation navigation-aid data base (ref. 7) permits defining a real navigation environment so that a subject pilot may fly cross-country flights and instrument approaches by using standard instrument charts. This data base includes the location, Morse code audio identifier, and frequency of VOR, DME, NDB, marker beacon, localizer, and glide-slope transmitters.

The simulator can be initialized to any geographic and flight condition prior to operation. Each data run then begins at that condition with the aircraft trimmed. The simulator provides extensive data-recording capabilities. All parameters describing control positions, aircraft attitude and rates, geographic position, and position errors may be recorded in digital or analog format.

The PCTI display was presented in the cockpit on a 12.7-cm (5-in.) diagonal cathode-ray tube (CRT). The CRT was located immediately below the vertical-speed indicator in an instrument space normally used for an electromechanical course deviation indicator (CDI). The display was generated by an Adage graphics computer in stroke form and was converted to raster form for the cockpit CRT. This method of displaying the PCTI was chosen for its ease and speed of implementation. This method also allowed instantaneous switching between the PCTI and a conventional CDI display format between data runs. Appendix B shows possibilities for electromechanical implementations of the PCTI concept. Since the experimental tasks were to consist solely of localizer and glide-slope tracking, no omnibearing selector (OBS) knob or indicator was incorporated into the display.

DISPLAY OPTIMIZATION

The CRT implementation of the PCTI display was checked to ensure similarity with conventional electromechanical displays. Display sensitivity to localizer and glide-slope deviations and general display appearance were checked by initializing the simulator to various spatial coordinates and noting display indications. Flying ILS approaches verified smooth step-free movement of the displayed needles.

Examination of the PCTI math model given in appendix A shows a localizer rate gain K that governs the sensitivity of the rate needle. The rate gain was set during validation by varying K between runs as three pilots flew ILS approaches. Pilot opinion of workload and RMS tracking error was used to set K to produce good tracking performance without an excessive workload. The gain was varied from 60 to 200. Gains of about 125 to 200 provided for very close tracking but also produced a very high workload for the pilot. Lower gains produced a much lower workload but a tracking performance that was almost as good. A localizer rate gain of 90 was chosen for the experiment as a compromise between workload and improved tracking performance.

EXPERIMENT DESIGN

The experiment was designed to compare pilot performance with the PCTI display and the conventional CDI display. Half of the data runs were flown with the PCTI and half with the baseline CDI. The CDI was simulated by setting the localizer rate gain to zero. This caused the localizer needle and the rate needle to remain in line and move as one needle.

Each pilot was required to fly 10 ILS approaches. The starting conditions and weather conditions were identical for each of the approaches. Pilot learning effects were anticipated and compensated for by alternating the PCTI and CDI data runs. Starting conditions placed the aircraft to the left of the localizer on a 30° intercept heading. The aircraft was located so that the localizer intercept would occur about 4100 m (2.2 n. mi.) from the outer marker at an altitude that would give a glide-slope intercept just outside the outer marker. (See fig. 5.) The weather conditions provided light turbulence and winds that varied linearly with altitude. The winds varied from 6.2 m/sec (12 knots) from 28° left of the localizer course at the surface to 12.3 m/sec (24 knots) from 20° right of the localizer course at an altitude of 305 m (1000 ft). No outside visual display was used so that breakout and landing were not possible. The approaches were automatically terminated just prior to reaching the decision height.

The selection of a pilot for this study required that the pilot have at least an airplane instrument rating. Professional test pilots and both experienced and relatively inexperienced general aviation instrument pilots were used. (See table I.)

Each pilot was given an explanation of the PCTI display and a diagram showing PCTI indications in various situations. (See fig. 3.) Each pilot was required to fly a minimum of four familiarization approaches. More familiarization was allowed if desired by the pilot. Except for the absence of wind and turbulence the familiarization runs were identical to the data runs. For data collection each pilot flew five approaches with the PCTI display and five approaches with the CDI display. The data runs were alternated between the two displays. The pilots were asked to give, after each run, an estimate of their workload as well as any general comments regarding the display or the simulation. A variant of the rating scale described in reference 8 was used to collect the pilot-estimated workloads. The workload estimate was marked by the pilot on a horizontal line labeled "MIN" at one end and "MAX" at the other end. (See fig. 6.) Each pilot was given one workload estimate sheet with 10 lines, 1 for each run. The marks on the lines were later converted to percentages of the line length for analysis.

Statistical data, localizer and glide-slope deviation plots, and strip-chart time histories were recorded in addition to the pilot-provided data. The statistical data included RMS values of localizer deviation, localizer-deviation rate, and glide-slope deviation. The RMS data were collected for each run for the portion of the run beginning about 550 m (1800 ft) inside the glide-slope intercept point. This eliminated localizer intercept and glide-slope intercept from the statistical data. The localizer and glide-slope deviation graphs were plotted as angular deviation from the respective center line against distance from the glide-slope transmitter (located beside the runway about 300 m (1000 ft) from the threshold). These plots were made for each subject after that subject had completed all data runs. Five approaches are shown on each plot, either the five PCTI approaches or the five CDI approaches. Strip-chart time-history recordings were made for the entire duration of each run of the parameters listed for statistical-data collection and for yaw error and distance from runway. The yaw error was defined as the difference between the instantaneous heading and the instantaneous heading that would be required to track the localizer center line considering the wind.

RESULTS AND DISCUSSION

Performance Measures

The RMS errors of the three tracking measures (localizer, localizer rate, and glide-slope) for each data run are shown in table II. The average localizer error dropped 42 percent, from 0.3907° with the CDI display to 0.2261° with the PCTI display. The localizer-error rate also dropped 42 percent with the PCTI. The average glide-slope error fell 16 percent with the PCTI.

A two-way analysis of variance with the pilots and displays as the factors was used to test the significance of the improvements in the three tracking measures. The results are shown in table III. The localizer-error test is presented in table III(a). It can be seen that the performance both between the pilots and between the displays differs with a level of significance less than 0.001. The interaction factor, however, produces a level of significance between 0.05 and 0.025. Table III(b) shows similar results for the localizer-error-rate data. The glide-slope-error test in table III(c) shows that the pilot performances differ with a level of significance less than 0.001, the performances between the displays differ with a level of significance between 0.10 and 0.05, and the interaction factors produce a level of significance between 0.05 and 0.025. The three measures indicate that the performances of the pilots are not equal, the localizer-error RMS and localizer-error rate show highly significant differences between the two displays, and the two displays did not produce significant differences in glide-slope tracking.

Figure 7 shows the localizer-deviation plots for pilots 1 and 6. The differences between the plots of the approaches flown with the CDI and the approaches flown with the PCTI are typical of all the subject pilots. The right side of each plot shows the aircraft intercepting the localizer about 9.26 km (5 n. mi.) from the runway. The runs terminate at the left side of the plots about 1219 m (4000 ft) from the runway. Greater consistency is noted between the PCTI approaches than between the CDI approaches. By inspection of figure 7, localizer deviations are observed to have a shorter period and a smaller amplitude on the PCTI approaches, thus indicating tighter control.

The first derivative of localizer angular error with respect to time is shown in figure 8 as a function of time for each approach flown by pilot 6. The PCTI is seen to produce smaller amplitude oscillations and a higher system frequency in localizer-error rate than is produced by using the CDI display. In fact, the localizer-rate signal, while tracking the localizer with the PCTI, is similar in frequency to the signal obtained while the pilot is flying a constant heading prior to localizer intercept. This is especially evident in the charts for runs 6 and 10. The constant heading portion of each flight is at the left side of each chart where the signal is offset from zero by abut 0.1 deg/sec. This may suggest that the task of flying the PCTI is approaching the task of maintaining heading. In fact, the design of the PCTI is such that when the localizer error is nearly zero the display indication is almost solely localizer-error rate, which in turn is proportional to heading error. When the localizer error is large, the display indication is a combination of localizer-error rate and localizer error. This agrees with pilot comments reporting reduced use of the directonal gyro while using the PCTI.

Subjective Workload Estimates

The workload estimate provided by the pilots for each run is shown in table IV. The average estimated workload for all pilots with the CDI display was 62 percent and with the PCTI display was 60 percent. This represents only a 3-percent reduction in reported workload. The mean and standard deviations of the CDI runs and the PCTI runs are plotted in figure 9 for each pilot. Inspection of figure 9 shows that the variation in estimated workload is much greater between pilots than between displays. The large variation between pilots in the reported workloads could be due to differences in the way each pilot interprets the word "workload" and to varying levels of pilot skill.

Pilot Comments

Pilot comments were examined for information on the pilots' instrument scan with and without the display, pilot workload, learning to use the PCTI, flying techniques with the PCTI, and any other miscellaneous remarks. All but two pilots, pilots 1 and 6, either mentioned a learning effect during the runs or stated that they should have flown more familiarization approaches. Since each of the subjects was experienced in the use of the CDI display, this suggests that performance with the PCTI would eventually be more improved over CDI performance than is shown by this study.

All but pilots 3 and 5 noticed a decreased use of the directional gyro (DG) on final approach with the PCTI display. Pilot 2 reported using the DG much less, and pilot 4 reported not using the DG at all on final approach with the PCTI. Pilot 6 commented that the PCTI became almost a primary instrument as opposed to the normal use of the CDI as a secondary instrument. A similar comment was provided by pilot 8 who stated that he was spending much more time on the PCTI than on the standard CDI. This pilot commented that the CDI was used only for "quick looks" at the localizer errors.

Two of the pilots, pilot 3 and 7, reported using the PCTI rate needle less on their later runs than on earlier runs. Pilot 3 had memorized the heading required at various altitudes to track the localizer made possible by the winds being identical from run to run. Pilot 7 believed that he was using the rate indication too much and shifted his attention back to the DG. After all data runs were completed, pilot 7 was asked to fly an approach with the DG covered from sight. The approach was flown without difficulty. Pilot 6 commented that his scan of the glide slope and vertical speed deteriorated when using the PCTI but that he believed he could learn to scan properly. The glide-slope data for pilot 6 do show a 10-percent increase in glide-slope error with the PCTI in contrast to the overall improvement in glide-slope performance noted for all pilots.

Pilot comments regarding workload with the PCTI indicate that it is about the same as workload with the CDI. Pilot 6 commented that workload seemed to be the same with the two displays and that the PCTI involved less instrument scanning but tighter control of flight path. Pilot 1 indicated that the PCTI required the pilot to work harder, but pilot 4 felt that the PCTI resulted in less workload to control localizer error and, therefore, more time to devote to the glide slope. The glide-slope data for pilot 4 confirms the comment with a 52-percent reduction in glide-slope error with the PCTI. Pilot 5 indicated early in his set of approaches that the PCTI rate needle was too sensitive, that workload could be reduced with a lower rate gain, and that the PCTI workload was higher than the CDI workload. After gaining more experience, however, pilot 5 reduced the gain with which he was controlling localizer rate and reported less workload with the PCTI than with the CDI. The pilots generally believed that the PCTI was easy to interpret and to learn but that the learning process continued throughout the experiment.

Flying techniques with the PCTI seem to confirm that it can be used as a substitute for heading indications while on the localizer. Even though an asymptotic localizer capture can be made by keeping the rate-needle tip in the center, the rate needle was never used during localizer intercept. As with the CDI, pilots used the DG to maintain an intercept heading until reaching the localizer. After localizer intercept the pilots would use the rate needle of the PCTI in a manner similar to the use of the DG with the CDI display. Pilot 4 reported using bank angle to put the rate needle in a position that would center the localizer needle. He would then level the wings, wait for the localizer needle to center, and then use bank angle again to set the localizer rate to zero. This is analogous to the use of the DG and the CDI where the pilot turns to a heading that the pilot believes will center the localizer needle. Upon centering the needle the pilot turns to what is guessed to be the heading that will track the localizer. Pilot 6 commented that the PCTI solved the problem of finding the correct heading to track the localizer. These comments help explain the comments of pilots 6 and 8, where pilot 6 indicated using the PCTI almost as a primary instrument and pilot 8 reported spending much more time on the PCTI than on the CDI.

Once established on the localizer center line, keeping the rate needle of the PCTI centered will also tend to keep the localizer needle zeroed because of the way that the rate needle is integrated into the display. This was reflected by the comment of pilot 1 that concern shifted from the raw localizer error to the indication of the rate needle.

Pilot 7 remarked that he would tolerate localizer ad glide-slope errors early in the approach but aimed for a "window" near the end of the approach. This pilot believed the PCTI to be most beneficial near the end of the approach for bringing the errors to zero.

A few interesting miscellaneous comments were made. Pilot 3 rapidly memorized the headings required to fly the approach and to correct for winds. This pilot apparently derived little benefit from the rate information and commented that he would not buy one for his own aircraft, but at the same time he believed that adding a rate needle to the glide-slope error as well as to the localizer error would have made it possible to omit the attitude indicator from his scan. Pilot 7 commented that the PCTI provided lead information when the wind shifts or turbulence-induced attitude changes begin a departure from the localizer. Finally, pilot 8 suggested that bank angle somehow be integrated with the PCTI to provide even more lead. This would bring the PCTI calculations to include all of the terms used in flight-director lateral calculations.

CONCLUDING REMARKS

An evaluation of a pseudocommand tracking indicator (PCTI) concept to improve pilot tracking performance during instrument landing system (ILS) approaches was performed in the general aviation flight simulator at the Langley Research Center. The PCTI integrates localizer-error rate with the raw localizer-error display to indicate the difference between the heading required to track the localizer and the actual heading. Eight instrument-rated pilots flew five ILS approaches with the PCTI and five ILS approaches with a baseline course deviation indicator. The results showed a significant improvement in localizer tracking performance with no significant change in pilot workload when the PCTI was used. Pilot coments indicate good overall acceptance of the PCTI; the pilots felt that it is easy to interpret and learn and that it greatly reduces the use of the directional gyro on the localizer. Data analysis suggests that the task of tracking the localizer with the PCTI display approaches the task of maintaining a reference heading.

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APPENDIX A

PSEUDOCOMMAND TRACKING-INDICATOR MATH MODEL

The pseudocommand tracking indicator (PCTI) was presented on a cathode-ray-tube (CRT) display. The CRT was mounted in an instrument-panel location normally occupied by an electromechanical course deviation indicator.

The display consisted of fixed reference markings along the vertical and horizontal instrument center lines (fig. 10) with a moving glide-slope needle, a moving localizer needle, and a moving localizer rate needle (fig. 11). The glide-slope needle pivots from the left side of the display as it does on a conventional instrument. The localizer needle pivots from the top center of the display and terminates at the horizontal instrument center line. The localizer rate needle pivots from the lower end of the localizer needle and terminates at the bottom edge of the display.

Figure 12 shows the approach geometry used in the math model. This approach geometry and the equations that follow describe the deflections of the glide-slope needle, localizer needle, and localizer rate needle.

If localizer-needle deflection is limited to 45°, which occurs at a localizer deviation of 2.5°, the equation for LN can be expressed as

$$LN = \begin{cases} -18\left(\delta_L\right) & \left(\left|\delta_L\right| \leq 2.5^\circ\right) \\ -45\,\dfrac{\left|\delta_L\right|}{\delta_L} & \left(\left|\delta_L\right| > 2.5^\circ\right) \end{cases}$$

When localizer-rate-needle deflection is limited to ±90°, RN can be given as

$$RN = \begin{cases} LN + K(\dot{LN}) & \left(\left|LN + K(\dot{LN})\right| \leq 90^\circ\right) \\ 90\,\dfrac{\left|LN + K(\dot{LN})\right|}{LN + K(\dot{LN})} & \left(\left|LN + K(\dot{LN})\right| > 90^\circ\right) \end{cases}$$

where the rate gain K was set to 90 during display checkout.

If the glide-slope-needle deflection is limited to ±45°, which occurs at glide-slope deviations of ±0.7°, GN can be expressed as

$$GN = \begin{cases} 64.29\left(\delta_{gs}\right) & \left(\left|\delta_{gs}\right| \leq 0.7^\circ\right) \\ 45\,\dfrac{\left|\delta_{gs}\right|}{\delta_{gs}} & \left(\left|\delta_{gs}\right| > 0.7^\circ\right) \end{cases}$$

where the glide-slope needle has a fixed length of 3.81 cm (1.5 in.).

The time derivative of LN is calculated from aircraft speed, ground track, and position relative to the localizer. This permitted display validation with the simulator in a hold mode at a preset point in space. The equation for $\dot{LN}$ is written as

$$L\dot{N} = \begin{cases} -18\dot{\delta}_L & (\delta_L < 2.5^\circ) \\ 0 & (\delta_L > 2.5^\circ) \end{cases}$$

where

$$\dot{\delta}_L = \frac{V_g}{\iota} \cos \delta_L \sin \Delta\phi_g$$

Since $\delta_L < 2.5°$ in the area of interest, $\dot{\delta}_L$ can be approximated by

$$\dot{\delta}_L = \frac{V_g}{\iota} \sin \Delta\phi_g$$

In the calculation of $\Delta\phi_g$, consider

$$\dot{X}_T = V_a \cos \phi_a + V_w \cos \phi_w$$

$$\dot{Y}_T = V_a \sin \phi_a + V_w \sin \phi_w$$

and

$$\phi_g = \tan^{-1}\left(\dot{Y}_T / \dot{X}_T\right) \qquad \left(-180^\circ \leq \phi_g \leq 180^\circ\right)$$

$$\Delta\phi_{g,i} = \phi_g - 57.9^\circ + \delta_L$$

where 57.9° is the course of the localizer used. Therefore,

$$\Delta\phi_g = \begin{cases} \Delta\phi_{g,i} & \left(\Delta\phi_{g,i} \geq -180^\circ\right) \\ \Delta\phi_{g,i} + 360 & \left(\Delta\phi_{g,i} < -180^\circ\right) \end{cases}$$

APPENDIX B

ALTERNATE PCTI IMPLEMENTATIONS

In this appendix, which discusses alternate PCTI implementation concepts, first examine figure 13 which shows an electronic display that uses illuminated segments to form light bars. The localizer deviation would be displayed as on commercially available electronic course-deviation displays. Additional light bars would originate from the end of the localizer bar to indicate localizer-error rate. The display of figure 14 would move the zero-reference indicator of the display to indicate localizer-error rate. The zero reference would be at the display center when the localizer rate is zero. If the aircraft track was deflected to the right, then the zero reference would also move to the right. The pilot could track the localizer by turning the aircraft to keep the zero reference under the localizer needle. Figure 15 shows a hybrid display consisting of both a conventional display and a rate-quickened display. The needle and pointer could be driven several different ways. As shown, the needle could display localizer deviation while the pointer would sum deviation and deviation rate. Alternatively, the rate-quickened data could be shown on the needle while raw data would be put on the pointer. Lastly, the raw data could be put on the needle while localizer rate alone would be presented on the pointer. In the last configuration the pointer would provide the same data as the relative track information on the EADI of reference 3.

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TABLE I.- RECORD OF SUBJECT-PILOT EXPERIENCE

Pilot number	Flight time, hr	Instrument flight time, hr
1	250	60
2	1500	100
3	2500	400
4	1300	240
5	6000	3000
6	3500	400
7	1400	70
8	2500	200

TABLE II.- RMS ERRORS FOR LOCALIZER, LOCALIZER RATE,

AND GLIDE SLOPE FOR EACH RUN

Pilot with mean and std. dev.	Run number		Localizer error		Localizer-error rate		Glide-slope error	
	CDI	PCTI	CDI	PCTI	CDI	PCTI	CDI	PCTI
Pilot 1	2	1	0.1620	0.1092	0.01563	0.01510	0.0556	0.0821
	4	3	.4779	.1998	.05028	.01990	.1017	.0640
	6	5	.2409	.2275	.02768	.01999	.1041	.1468
	8	7	.3282	.0847	.03179	.01624	.0930	.1055
	10	9	.1120	.1087	.01886	.01315	.0563	.0601
Mean			0.2642	0.1460	0.02885	0.01688	0.0821	0.0917
Std. dev.			0.145	0.063	0.0136	0.0030	0.024	0.036
Pilot 2	1	2	1.371	0.3318	0.07502	0.03246	0.3114	0.1731
	3	4	.6105	.2491	.08205	.02898	.1743	.2363
	5	6	.2821	.1241	.04555	.02392	.1692	.2685
	7	8	.6410	.2180	.04139	.04622	.3297	.1990
	9	10	.1943	.0822	.03128	.01912	.0566	.0843
Mean			0.6198	0.2010	0.05506	0.03014	0.2082	0.1922
Std. dev.			0.464	0.100	0.0222	0.0103	0.113	0.070

TABLE II.- Continued

Pilot with mean and std. dev.	Run number		Localizer error		Localizer-error rate		Glide-slope error	
	CDI	PCTI	CDI	PCTI	CDI	PCTI	CDI	PCTI
Pilot 3	2	1	0.4062	0.05326	0.05948	0.04369	0.0800	0.1791
	4	3	.4150	.1364	.02690	.01528	.0638	.0797
	6	5	.1952	.5126	.02620	.03523	.1368	.0645
	8	7	.5027	.2412	.03846	.02411	.1014	.1159
	10	9	.4609	.0979	.04591	.01649	.1243	.0927
Mean			0.3960	0.3041	0.03939	0.02696	0.1013	0.1064
Std. dev.			0.119	0.206	0.0139	0.0123	0.030	0.045
Pilot 4	1	2	0.5948	0.3305	0.06510	0.03093	0.1316	0.1137
	3	4	1.042	.1822	.08928	.01705	.3793	.1087
	5	6	.3764	.3809	.05835	.04111	.2245	.1132
	7	8	1.236	.1650	.07833	.02051	.3116	.1463
	9	10	.7223	.4962	.07578	.06017	.1908	.1152
Mean			0.7943	0.3110	0.07337	0.03395	0.2476	0.1194
Std. dev			0.345	0.139	0.0120	0.0174	0.098	0.015

TABLE II.- Continued

Pilot with mean and std. dev.	Run number		Localizer error		Localizer-error rate		Glide-slope error	
	CDI	PCTI	CDI	PCTI	CDI	PCTI	CDI	PCTI
Pilot 5	2	1	0.2824	0.1078	0.04003	0.02166	0.0708	0.0595
	4	3	.2556	.3268	.03830	.03333	.1120	.1012
	6	5	.1732	.3448	.03439	.02488	.1092	.1030
	8	7	.4027	.1390	.05486	.02719	.1488	.0459
	10	9	.4810	.1989	.04702	.01985	.0530	.0757
Mean			0.3190	0.2235	0.04292	0.02538	0.0988	0.0771
Std. dev.			0.122	0.108	0.0081	0.0053	0.038	0.025
Pilot 6	1	2	0.1621	0.1623	0.03348	0.01245	0.0443	0.0567
	3	4	.1189	.1157	.02810	.01754	.0643	.0789
	5	6	.1192	.0488	.03122	.01135	.0391	.0462
	7	8	.1632	.0586	.03372	.01634	.0762	.0489
	9	10	.1025	.0609	.02315	.01141	.0491	.0685
Mean			0.1332	0.0893	0.02993	0.01382	0.0546	0.0598
Std. dev.			0.028	0.049	0.0044	0.0029	0.015	0.014

TABLE II.- Concluded

Pilot with mean and std. dev.	Run number		Localizer error		Localizer-error rate		Glide-slope error	
	CDI	PCTI	CDI	PCTI	CDI	PCTI	CDI	PCTI
Pilot 7	2	1	0.2668	0.2228	0.03686	0.02848	0.0813	0.0737
	4	3	.4138	.3097	.04508	.02894	.2005	.1061
	6	5	.5907	.2216	.04584	.03038	.0910	.1133
	8	7	.3455	.8053	.03759	.03504	.1287	.1125
	10	9	.3472	.2846	.03214	.02618	.0984	.0662
Mean			0.3928	0.3688	0.03950	0.02980	0.1200	0.0944
Std. dev.			0.122	0.247	0.0058	0.0033	0.048	0.023
Pilot 8	1	2	0.2372	0.1631	0.02377	0.01441	0.0889	0.1058
	3	4	.2052	.1622	.01987	.01800	.0634	.0786
	5	6	.1846	.1804	.02775	.02297	.0713	.0825
	7	8	.1379	.1608	.01908	.01795	.0727	.0770
	9	10	.2684	.1587	.04474	.02023	.0830	.0958
Mean			0.2067	0.1650	0.02704	0.01871	0.0759	0.0879
Std. dev.			0.050	0.009	0.0105	0.0032	0.010	0.012
Overall:								
Mean			0.3907	0.2261	0.04201	0.02446	0.1235	0.1036
Std. dev.			0.291	0.154	0.0186	0.0105	0.084	0.050

TABLE III.- TWO-WAY ANALYSIS OF VARIANCE OF THREE TRACKING MEASURES

(a) The localizer-error test

Factor	Sum of squares	Degrees of freedom	Mean square	f-ratio	α
Pilots	1.4299	7	0.2043	5.908	<0.001
Displays	0.5422	1	0.5422	15.68	<0.001
Interaction	0.5696	7	0.08137	2.353	$0.025 < \alpha < 0.05$
Error	2.2129	64	0.03458		
Total	4.7546	79			

$F_{m,n}$	Critical F-ratios at levels of significance α of -				
	0.05	0.025	0.01	0.005	0.001
$F_{1,64}$	3.99	5.27	7.05	8.45	11.93
$F_{7,64}$	2.16	2.50	2.93	3.27	4.05

TABLE III.- Continued

(b) The localizer-error-rate test

Factor	Sum of squares	Degrees of freedom	Mean square	f-ratio	α
Pilots	0.00852	7	0.00122	10.4	<0.001
Displays	0.00616	1	0.00616	52.6	<0.001
Interaction	0.00185	7	0.000264	2.26	$0.025 < \alpha < 0.05$
Error	0.00749	64	0.000117		
Total	0.02402	79			

$F_{m,n}$	Critical F-ratios at levels of significance α of -				
	0.05	0.025	0.01	0.005	0.001
$F_{1,64}$	3.99	5.27	7.05	8.45	11.93
$F_{7,64}$	2.16	2.50	2.93	3.27	4.05

TABLE III.- Concluded

(c) The glide-slope-error test

Factor	Sum of squares	Degrees of freedom	Mean square	f-ratio	α
Pilots	0.1809	7	0.02584	10.89	<0.001
Displays	0.00794	1	0.00794	3.35	0.05 < α < 0.10
Interaction	0.03727	7	0.005324	2.244	0.025 < α < 0.05
Error	0.1519	64	0.002373		
Total	0.37801	79			

$F_{m,n}$	Critical F-ratios at levels of significance α of –					
	0.10	0.05	0.025	0.01	0.005	0.001
$F_{1,64}$	2.79	3.99	5.27	7.05	8.45	11.93
$F_{7,64}$		2.16	2.50	2.93	3.27	4.05

TABLE IV.- PILOT-ESTIMATED WORKLOAD FOR EACH RUN

Pilot number	Run number		Estimated workload, percent	
	CDI	PCTI	CDI	PCTI
1	2	1	63	59
	4	3	73	60
	6	5	63	66
	8	7	67	70
	10	9	64	60
2	1	2	91	90
	3	4	86	88
	5	6	89	91
	7	8	92	93
	9	10	90	90
3	2	1	41	47
	4	3	35	30
	6	5	30	32
	8	7	29	30
	10	9	33	29
4	1	2	47	36
	3	4	62	28
	5	6	44	47
	7	8	65	31
	9	10	55	51
5	2	1	69	76
	4	3	64	68
	6	5	72	68
	8	7	75	66
	10	9	68	57
6	1	2	52	53
	3	4	55	49
	5	6	60	54
	7	8	55	69
	9	10	56	56
7	2	1	66	63
	4	3	73	63
	6	5	64	56
	8	7	57	57
	10	9	47	43
8	1	2	76	80
	3	4	69	74
	5	6	66	79
	7	8	59	55
	9	10	61	66
Mean ...			62	60

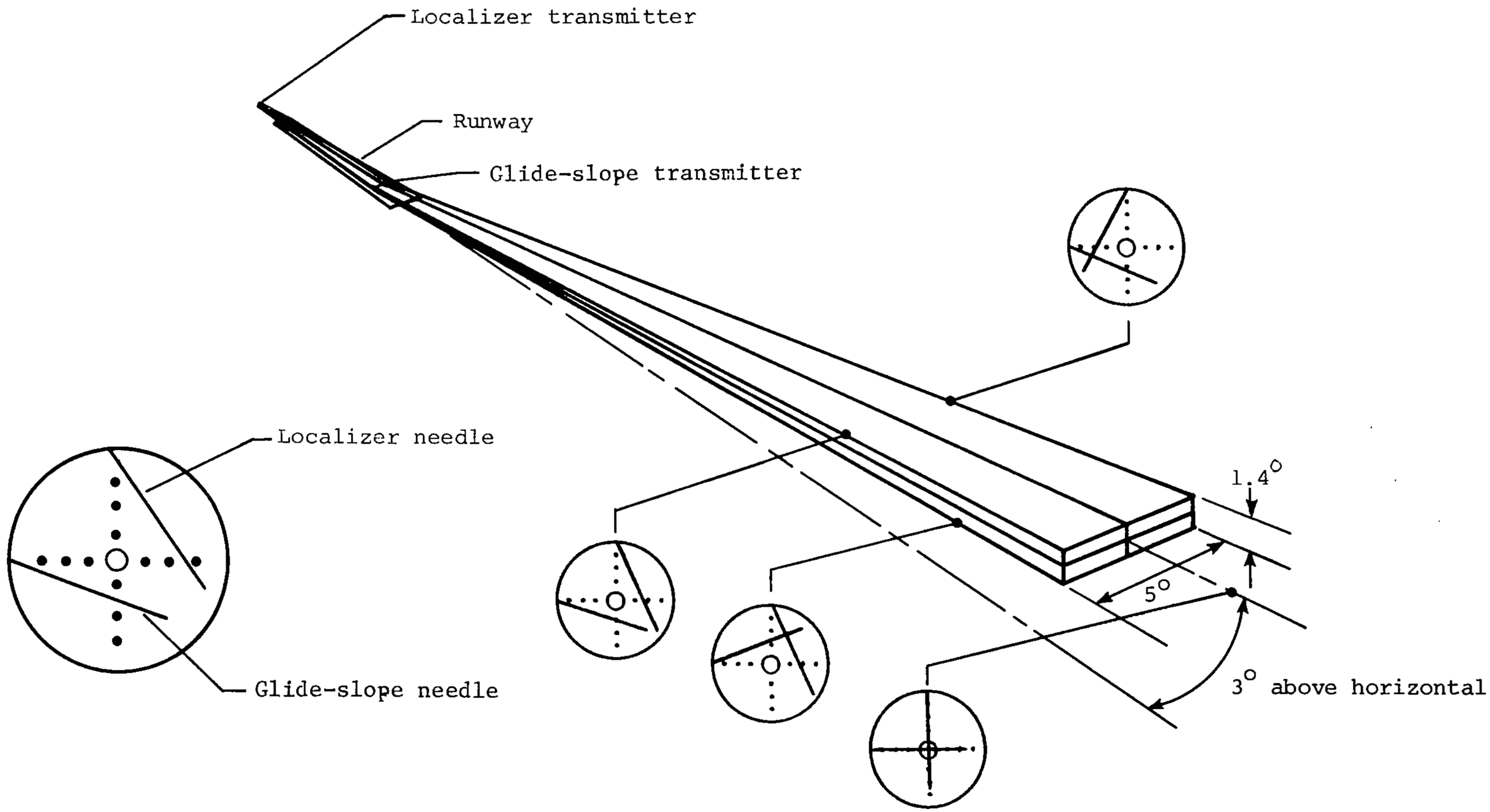


Figure 1.- Conventional CDI indications during an ILS approach.

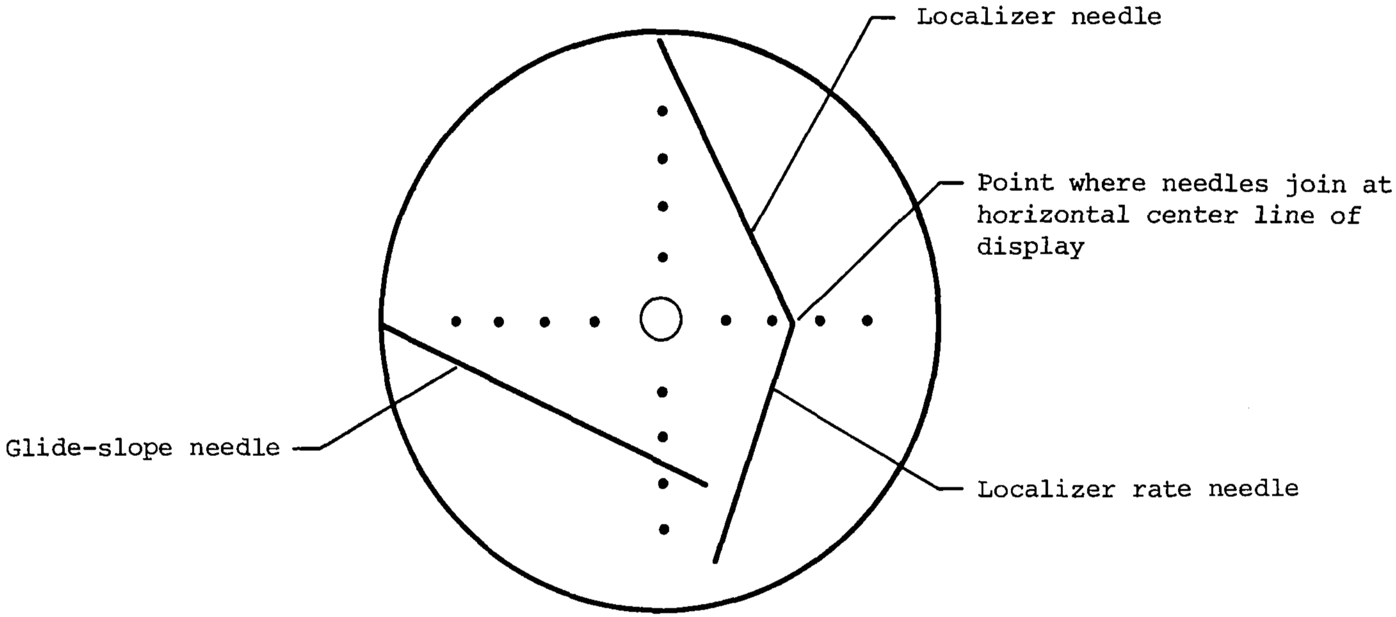
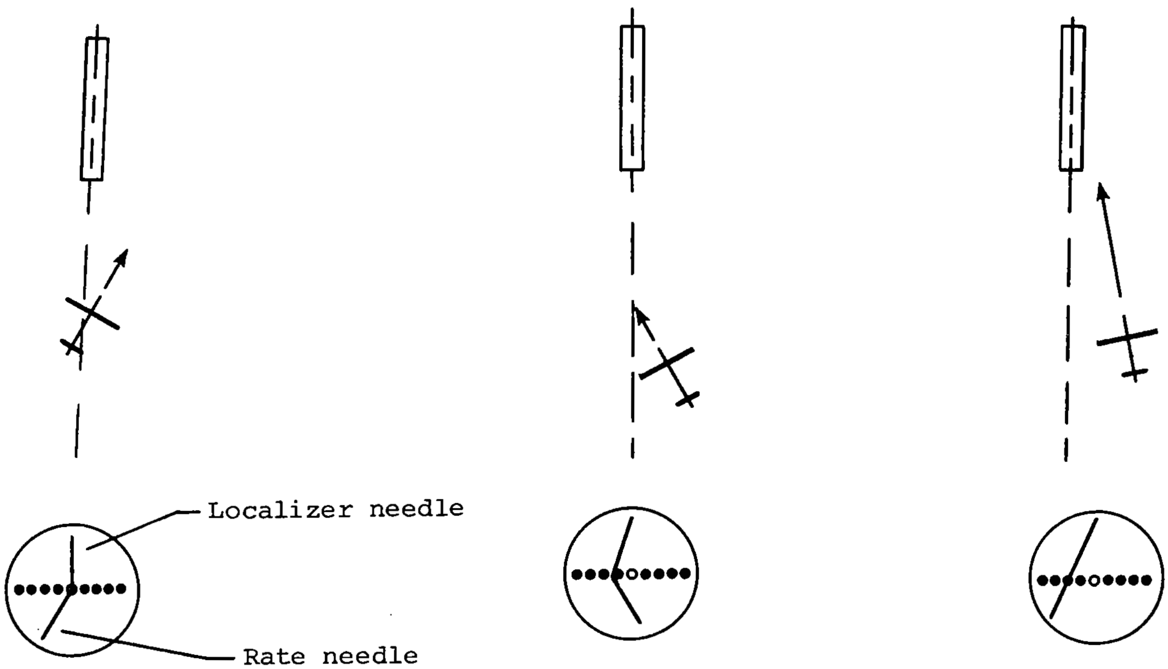


Figure 2.- Components of pseudocommand tracking indicator.

TYPICAL RATE-NEEDLE INDICATIONS

Rule of thumb: Bank toward the rate-needle tip

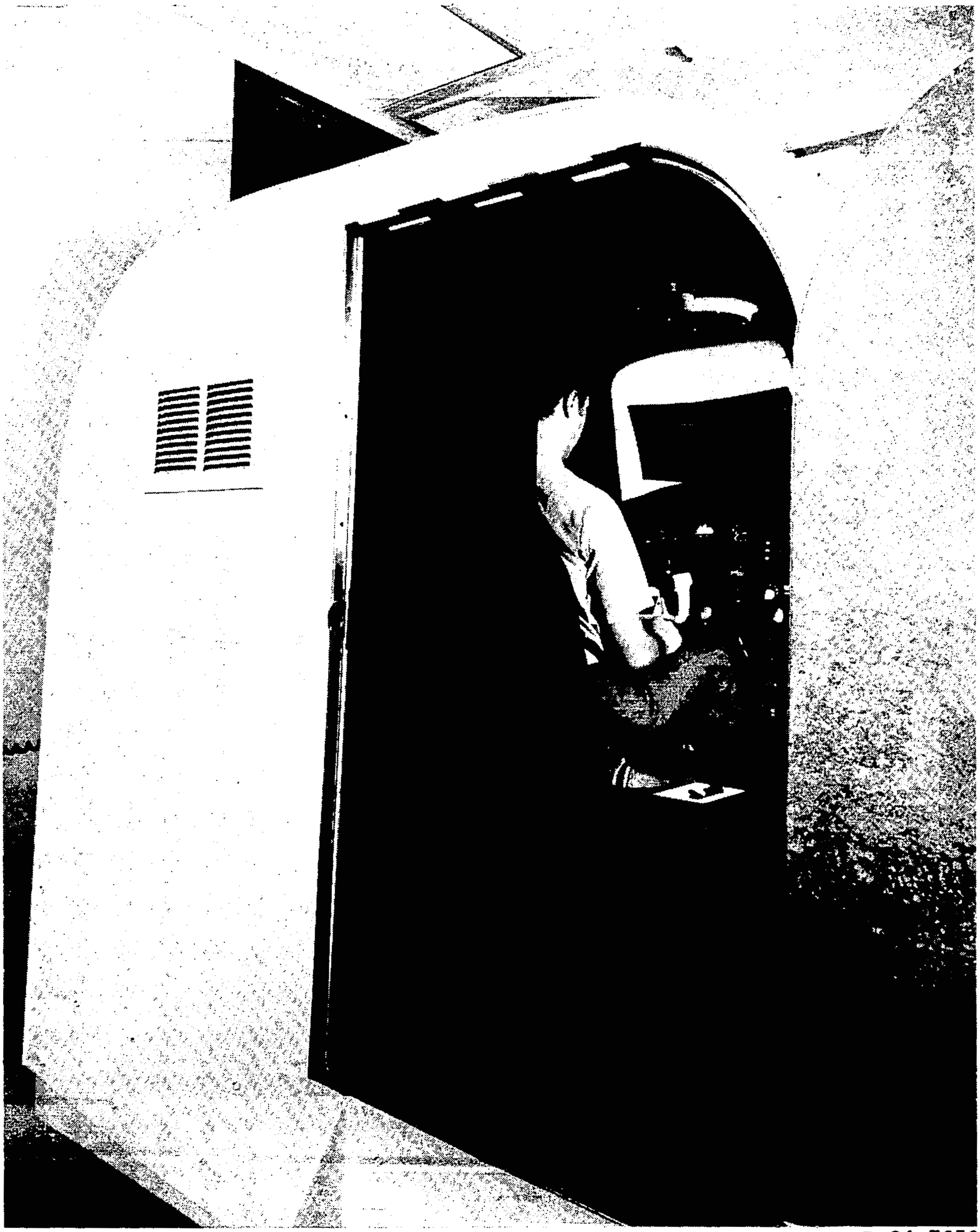


On course, drifting to right

To right of course, correcting

To right of course, constant localizer deviation

Figure 3.- Sample of PCTI explanation diagram provided to the subject pilots.



L-81-7650

Figure 4.- General aviation flight simulator at the Langley Research Center.

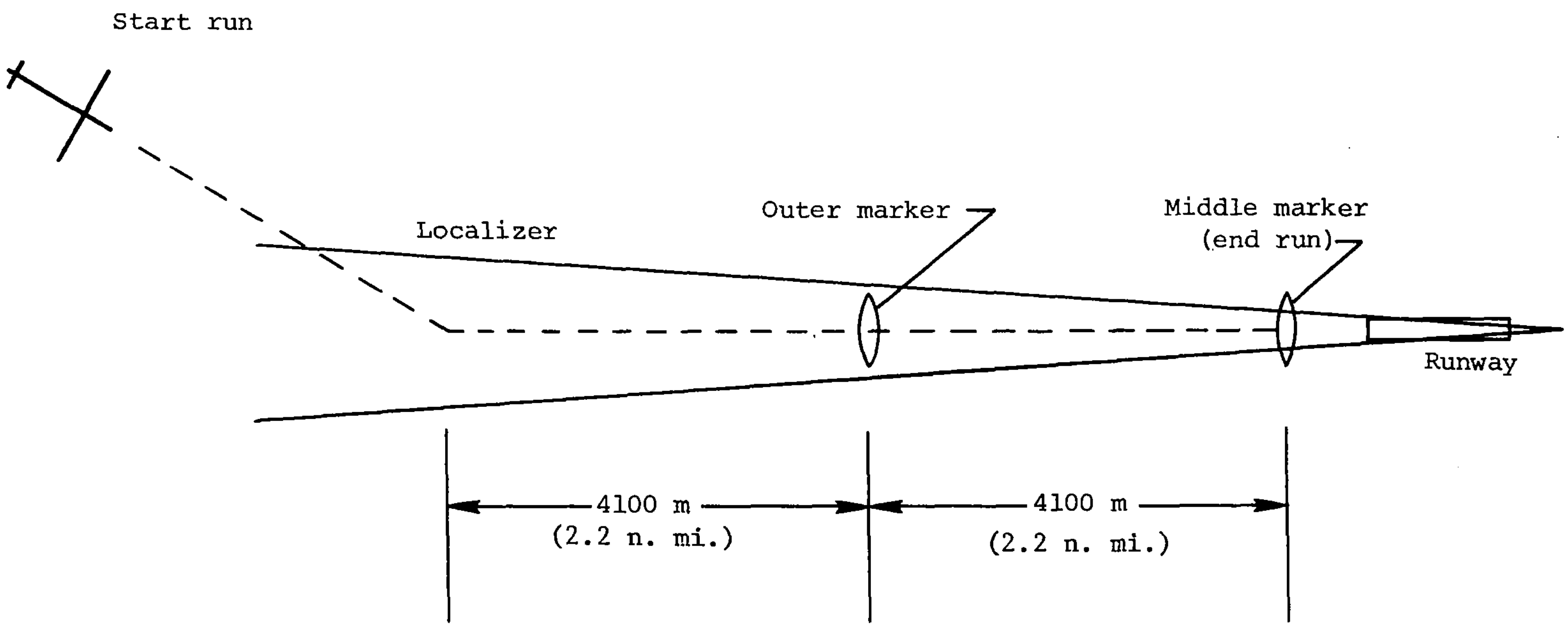


Figure 5.- Flight path of experiment.

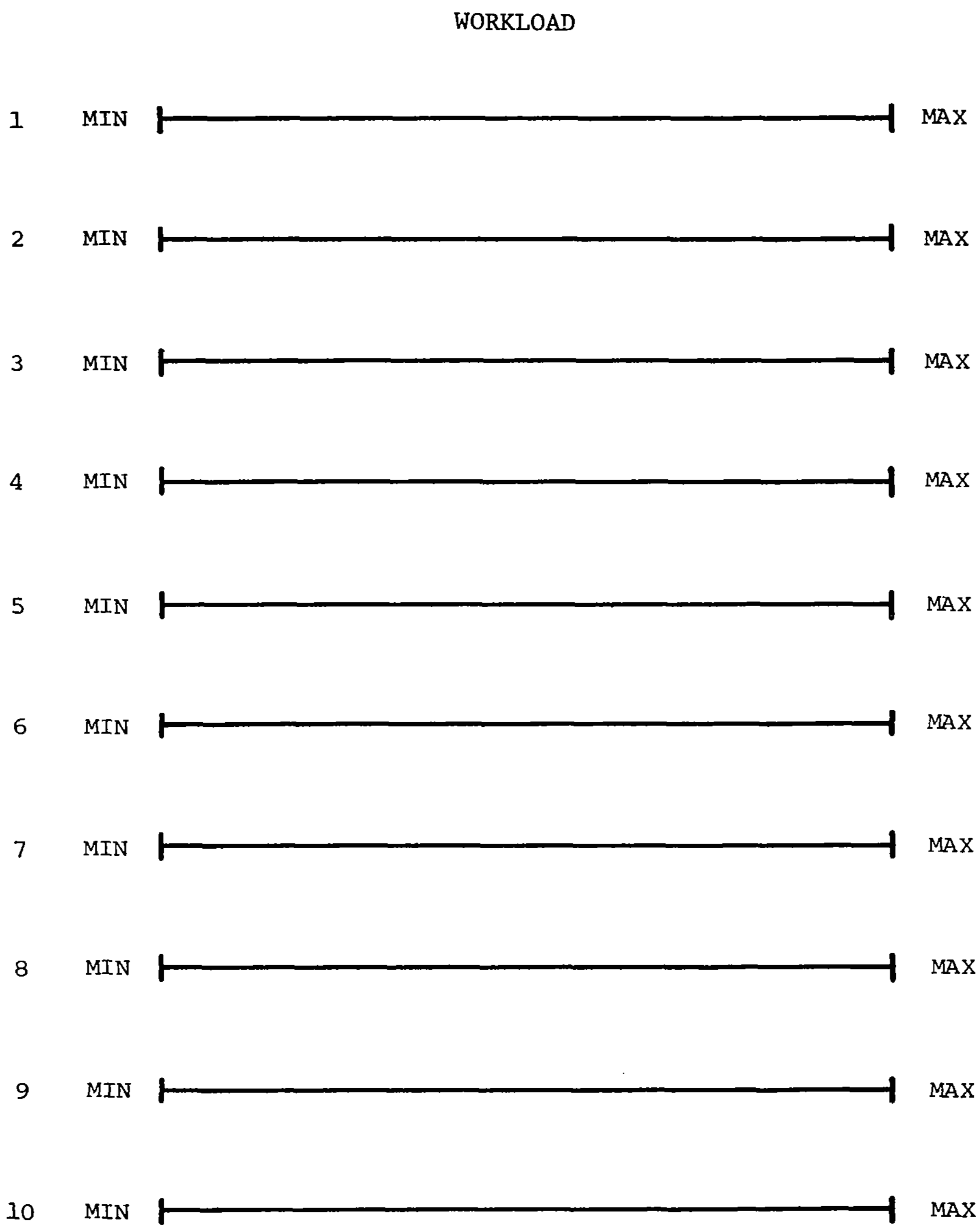
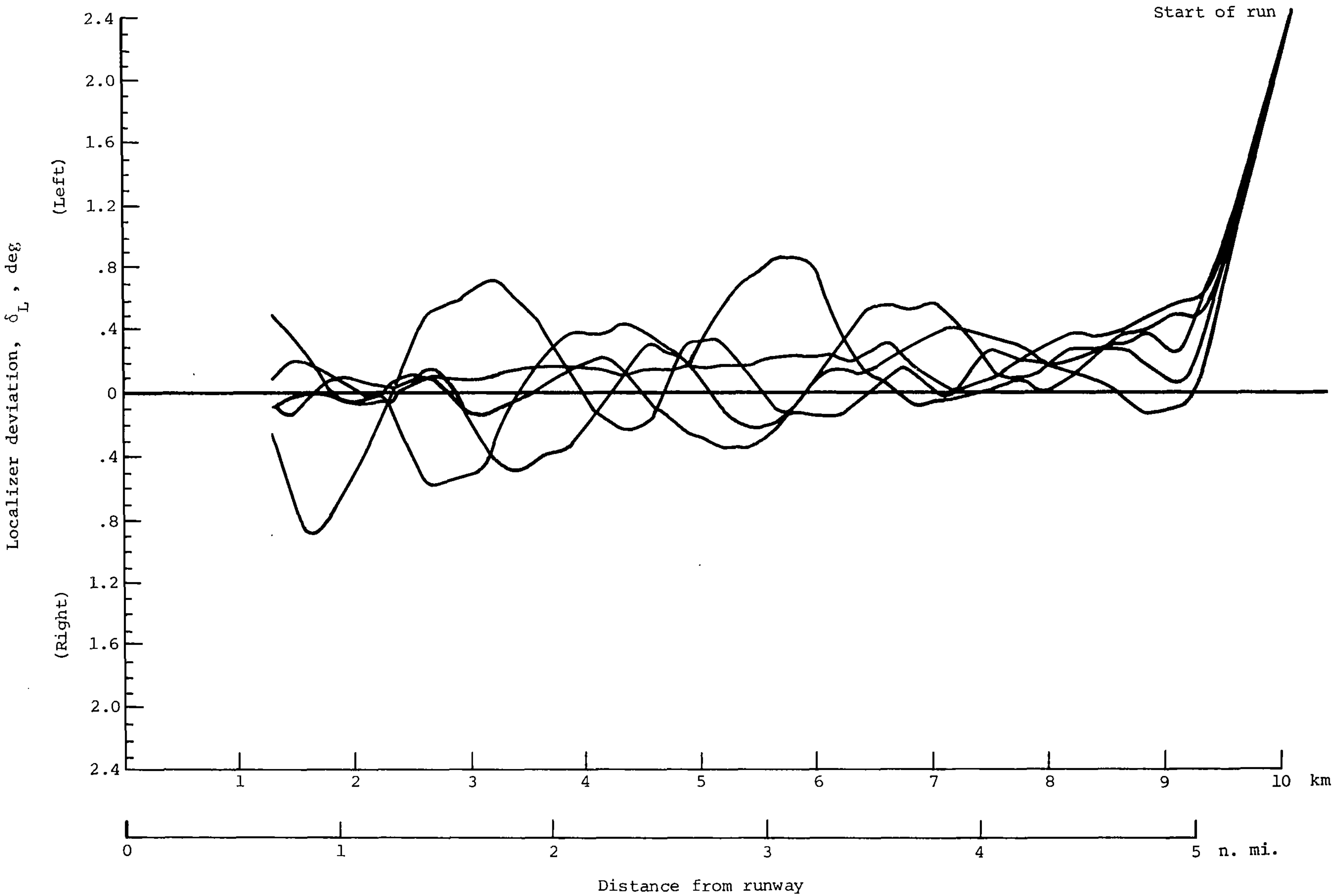
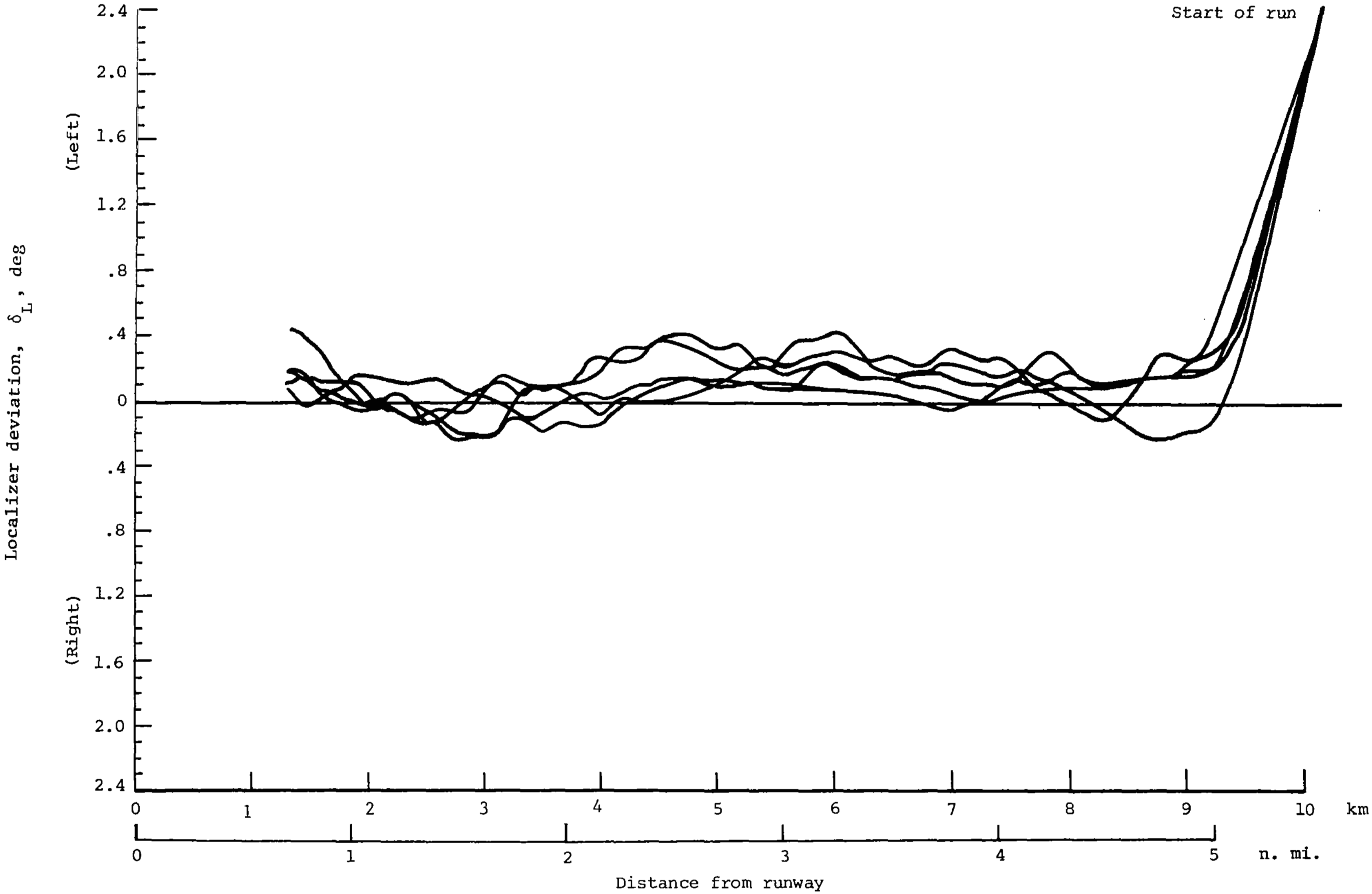


Figure 6.- Sample of workload estimate sheet provided to the subject pilots.



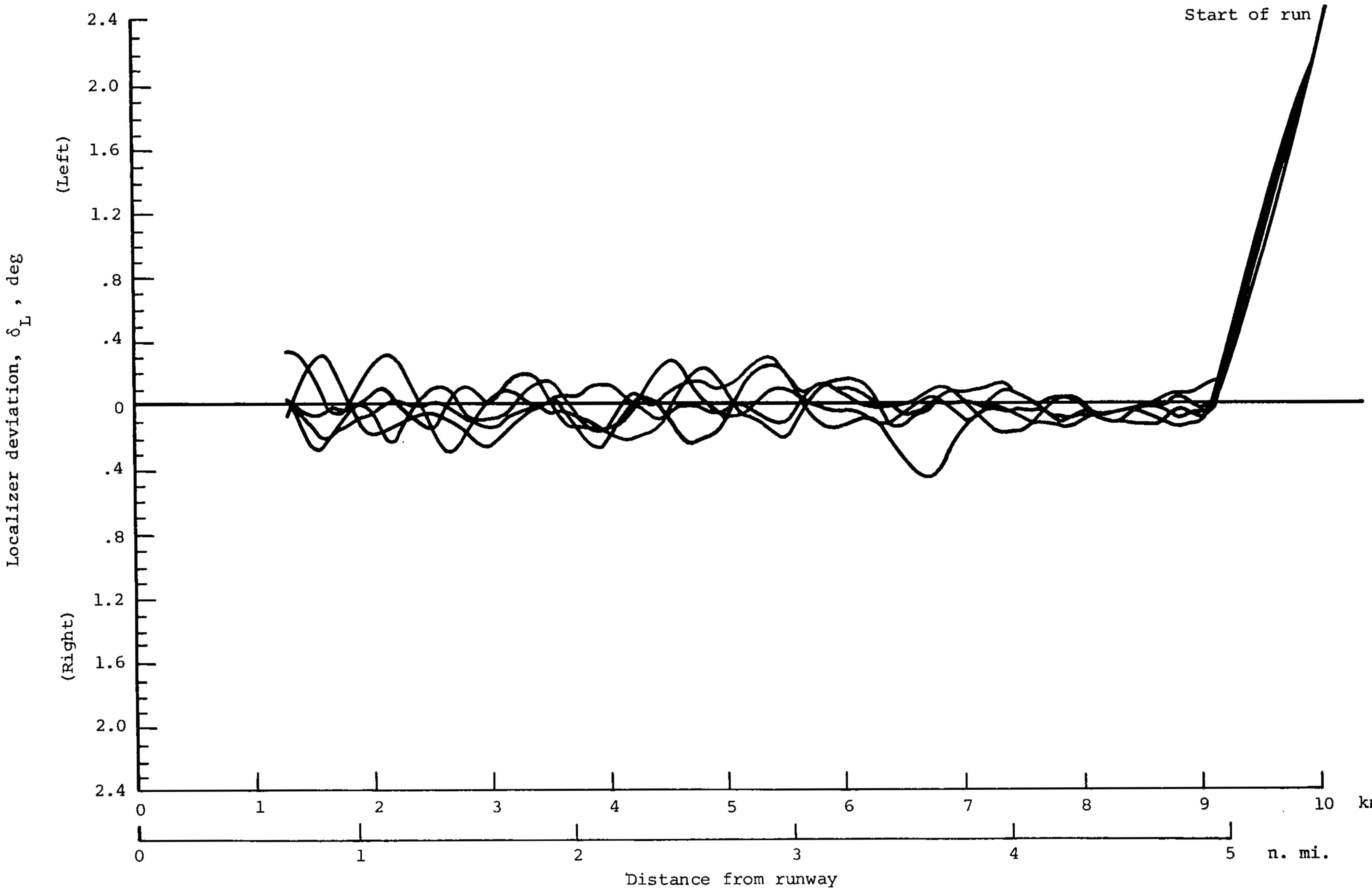
(a) Pilot 1 with CDI.

Figure 7.- Localizer-deviation plots for pilots 1 and 6 with CDI and PCTI.



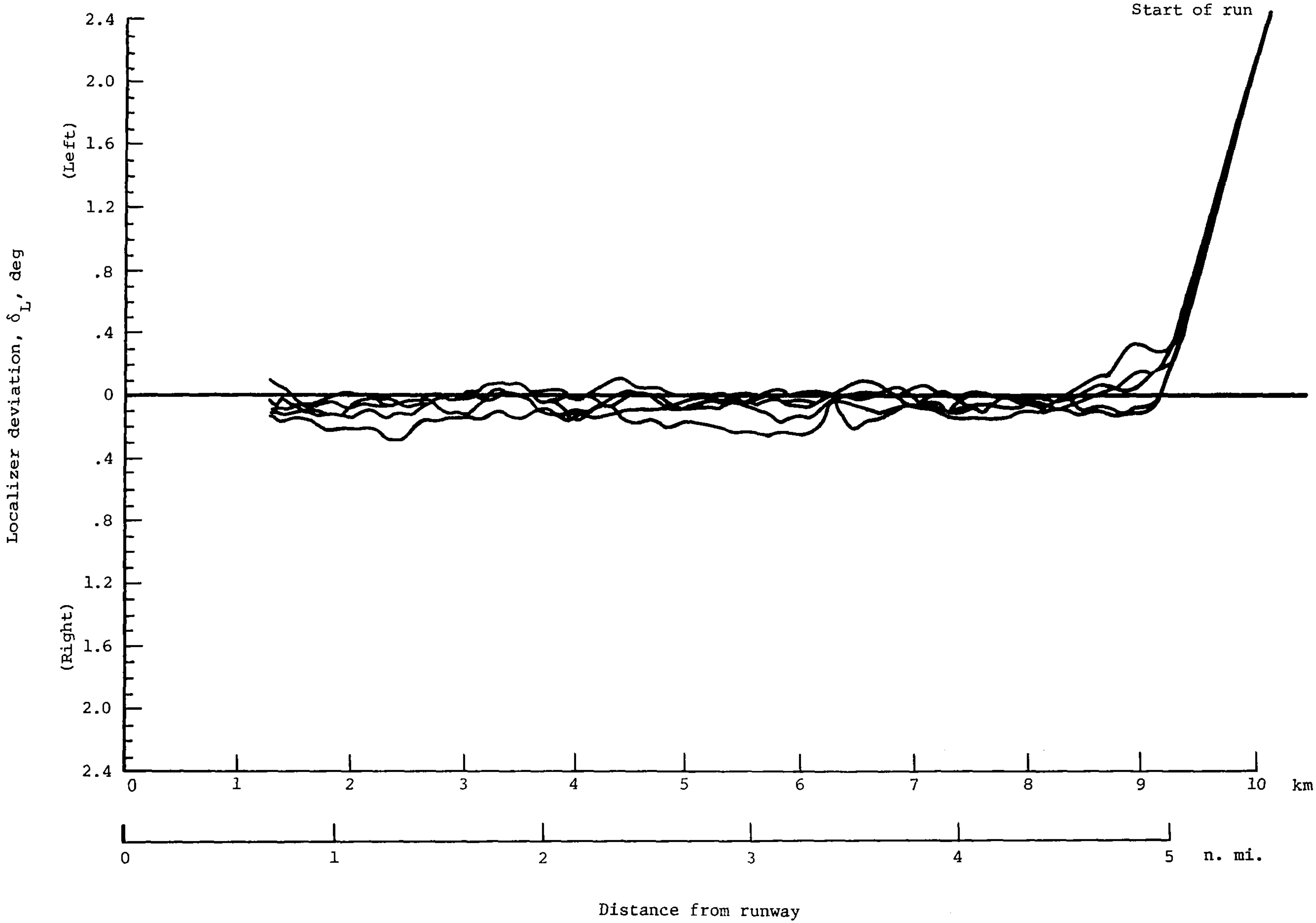
(b) Pilot 1 with PCTI.

Figure 7.- Continued.



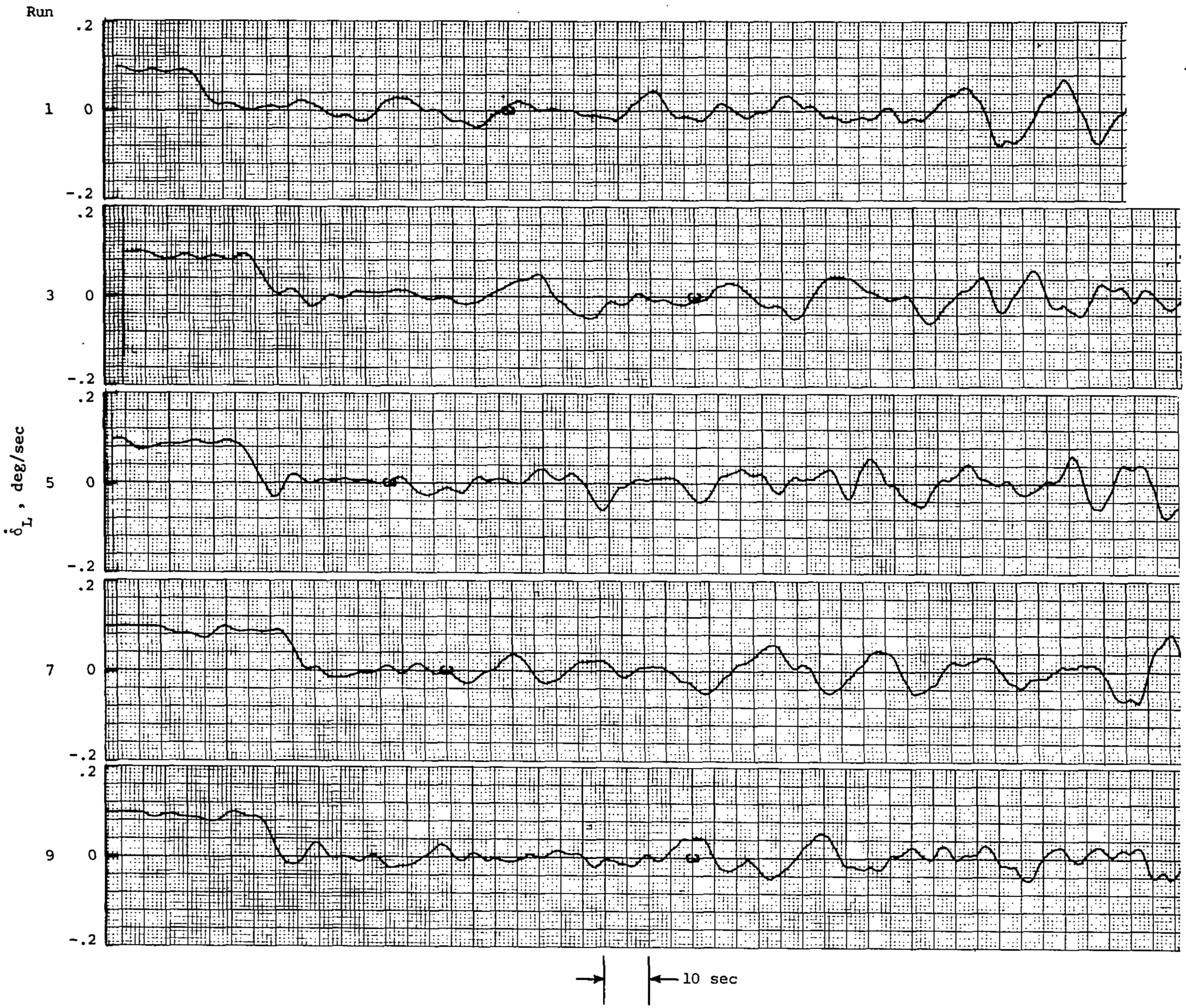
(c) Pilot 6 with CDI.

Figure 7.- Continued.



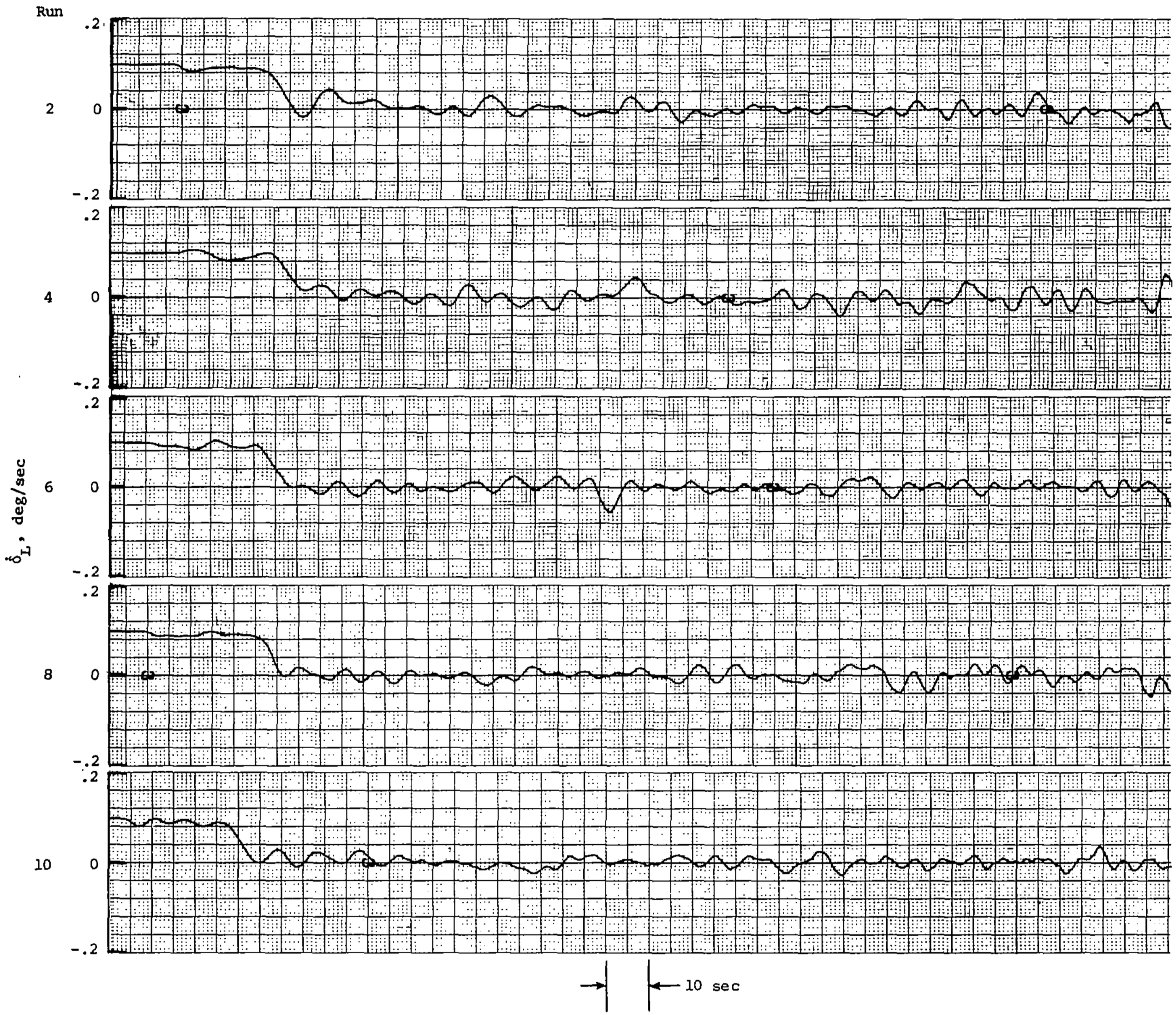
(d) Pilot 6 with PCTI.

Figure 7.- Concluded.



(a) CDI runs by pilot 6.

Figure 8.- Localizer-error rate plotted against time for all CDI and PCTI runs by pilot 6.



(b) PCTI runs by pilot 6.

Figure 8.- Concluded.

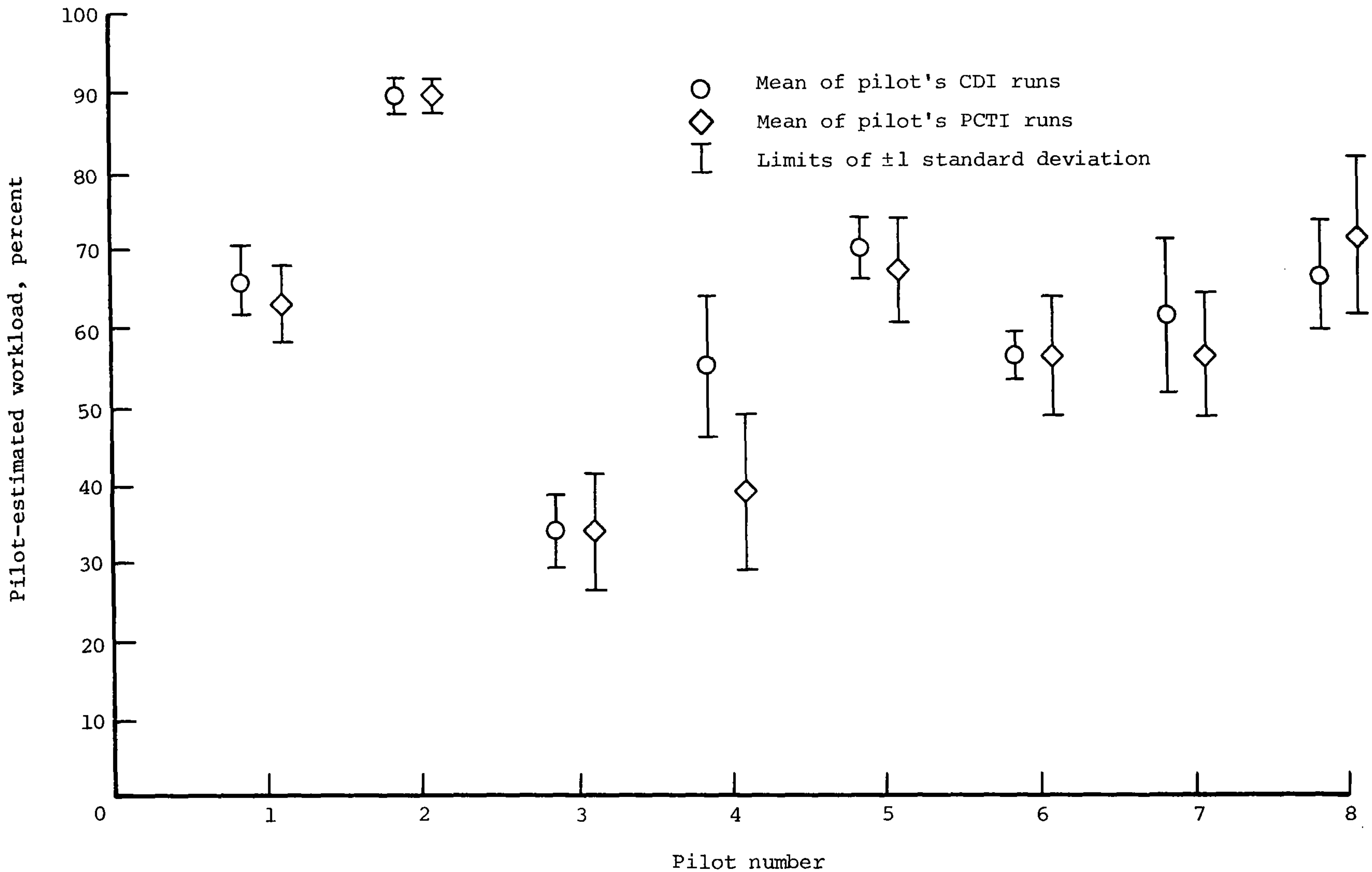


Figure 9.- Mean and standard deviations of pilot-estimated workload for each pilot and display.

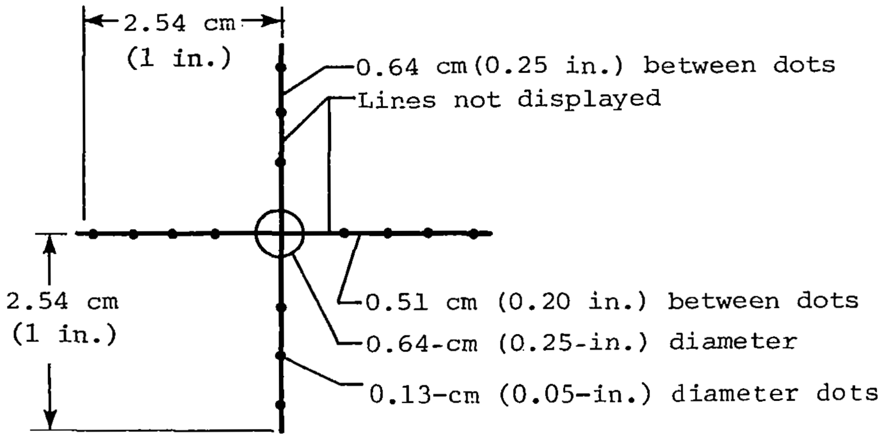


Figure 10.- Fixed reference markings on PCTI display.

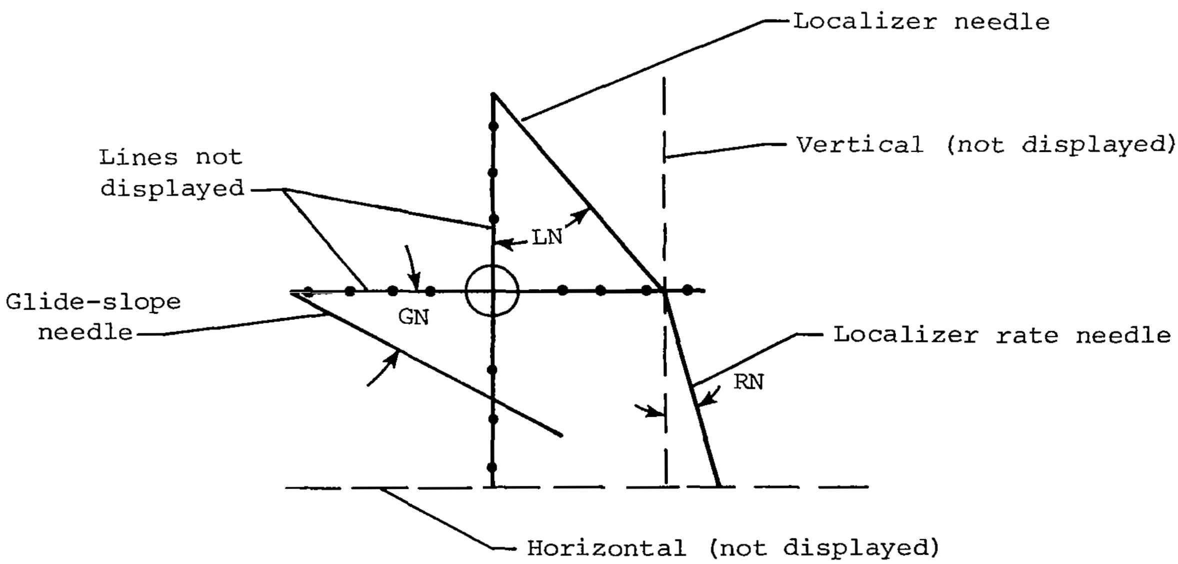


Figure 11.- PCTI display with movable components.

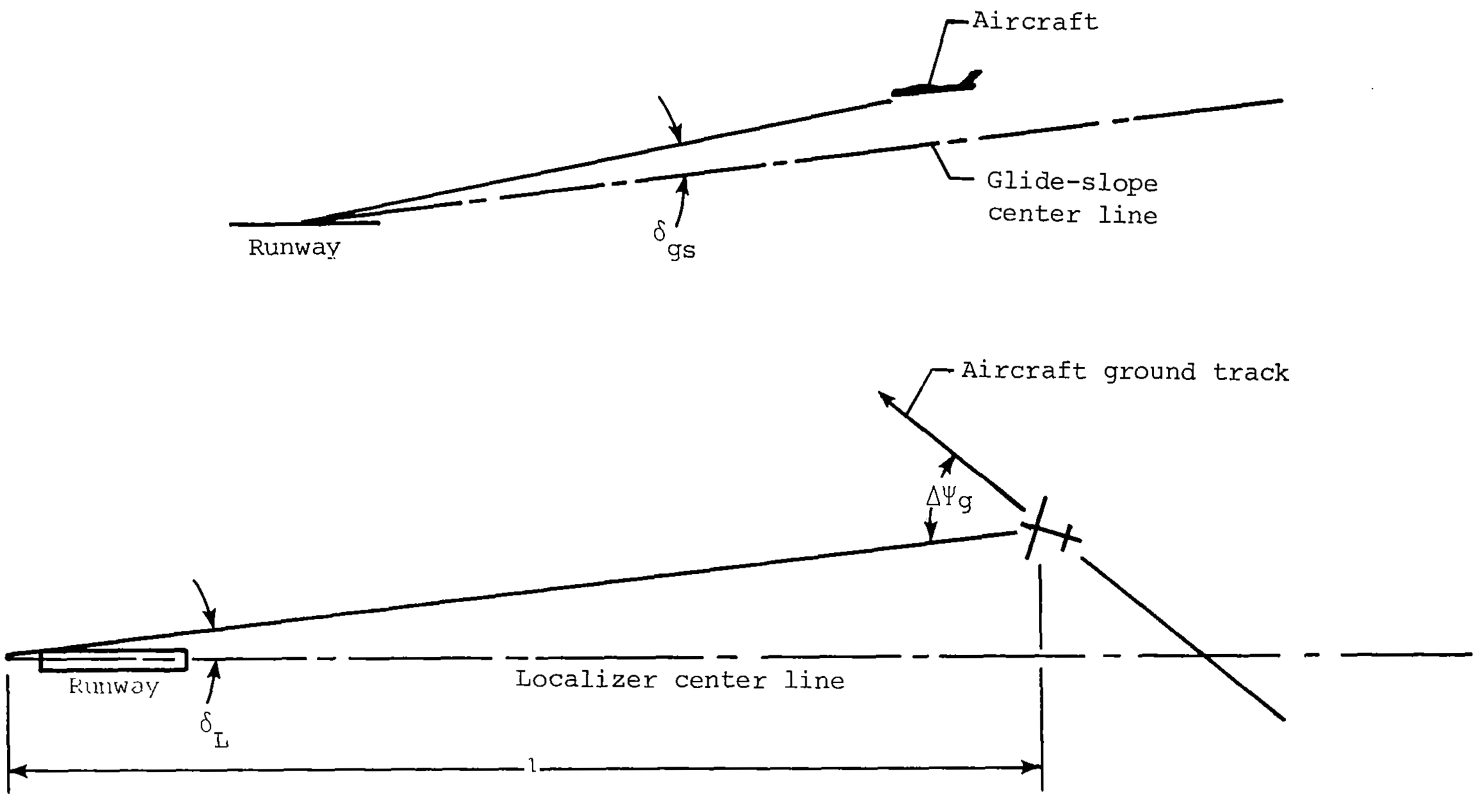
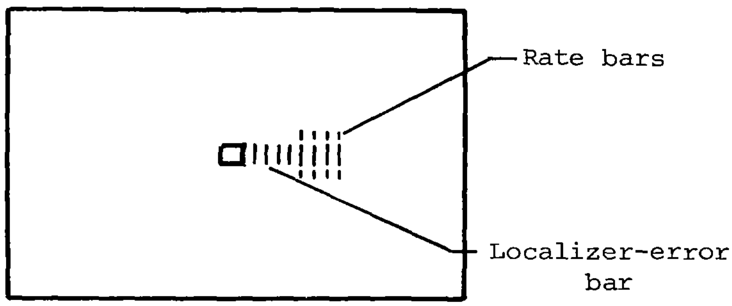
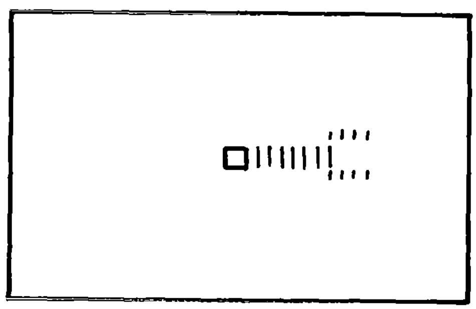


Figure 12.- Instrument landing system geometry used in PCTI math model. All angles are positive as shown.

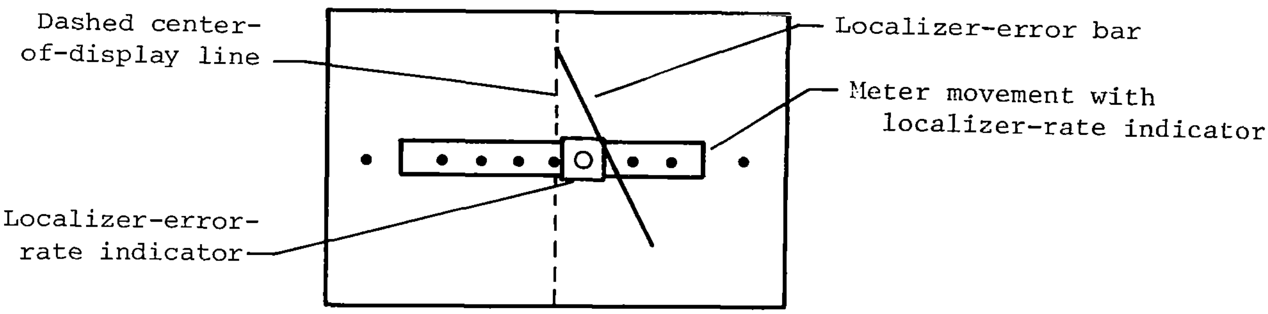


(a) Light-bar display showing localizer to right of aircraft and aircraft returning to localizer center line.

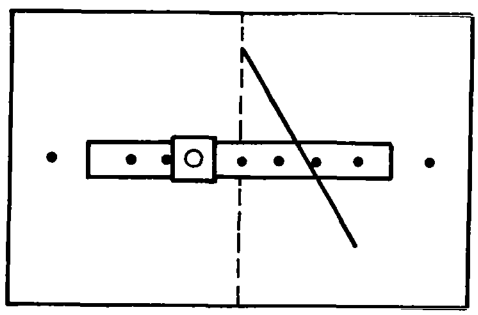


(b) Light-bar display showing localizer to right of aircraft and aircraft drifting farther to left.

Figure 13.- Light-bar implementation.

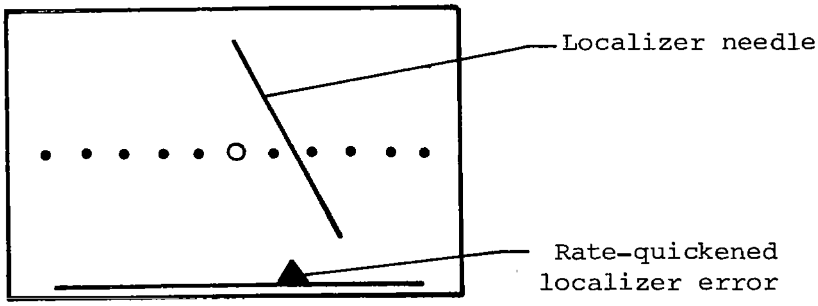


(a) Moving-zero indicator display showing localizer to right of aircraft and aircraft slowly returning to localizer center line.

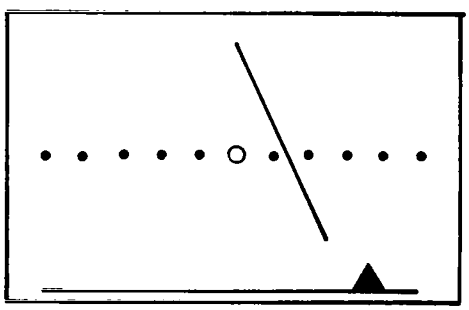


(b) Display showing localizer to right of aircraft and aircraft drifting farther to left.

Figure 14.- Moving-zero reference implementation.



(a) Hybrid display showing localizer to right of aircraft and aircraft slowly returning to localizer center line.



(b) Hybrid display showing localizer to right of aircraft and aircraft drifting farther to left.

Figure 15.- Hybrid display of raw data and rate-quickened data.

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16. Abstract

A piloted-simulation study was conducted to evaluate the effect on instrument landing system (ILS) tracking performance of integrating localizer-error rate with raw localizer and glide-slope error. The display was named the pseudocommand tracking indicator (PCTI) because it provides an indication of the change of heading required to track the localizer center line. Eight instrument-rated pilots each flew five instrument approaches with the PCTI and five instrument approaches with a conventional course deviation indicator. The results show good overall pilot acceptance of the display, a significant improvement in localizer tracking error, and no significant changes in glide-slope tracking error or pilot workload.

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