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CDI Sensitivity and Crosstrack Error on Nonprecision Approaches

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16. Abstract

This study was conducted to determine the influence of course deviation indicator (CDI) sensitivity on pilot tracking error during nonprecision approaches. Twelve pilots flew an instrumented single-engine airplane on 144 approaches at six different levels of CDI sensitivity. The sensitivities ranged from 15,190 feet (2.5 nautical miles) to 475 feet (0.08 nautical miles) for a full-scale deflection. Increases in sensitivity of this magnitude decreased crosstrack Root Mean Square (RMS) error from an average of 0.22 to 0.04 nautical miles. Magnitude of the error and the influence of sensitivity on that magnitude were affected by distance from the missed approach point. Pilots reported that increases in sensitivity increased their workload and changed their distribution of attention among the aircraft instruments used for navigation and directional control.

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PREFACE

This report is concerned with the influence of display needle sensitivity on the accuracy with which pilots can fly nonprecision approaches. Twelve private pilots flew an instrumented single engine airplane on 144 approaches at six different sensitivity levels. Increases in needle sensitivity produced decreases in racking error, but only at the cost of increases in pilot workload.

This report was prepared by the Operator Performance and Safety Analysis Division of the Office of Research and Analysis at the Volpe National Transportation Systems Center (VNTSC) for the FAA's Research and Development Service.

The research was directed by M. Stephen Huntley Jr. Data for the report were collected by Christopher J. Rourke and analyzed by Robert M. Disario.

METRIC / ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x - 32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES: 0 1 2 3 4 5 6 7 8 9 10

CENTIMETERS: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 | 25.40

QUICK FAHRENHEIT-CELCIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and/or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10 286.

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EXECUTIVE SUMMARY

This study was conducted to determine the influence of Course Deviation Indicator (CDI) sensitivity on pilot tracking error during nonprecision approaches. Twelve pilots flew an instrumented single-engine airplane on 144 approaches at six different levels of CDI sensitivity. The sensitivities ranged from 15,190 feet (2.5 nautical miles) to 475 feet (0.08 nautical miles) for a full-scale deflection. Increases in sensitivity of this magnitude decreased crosstrack Root Mean Square (RMS) error from an average of 0.22 to 0.04 nautical miles. Magnitude of the error and the influence of sensitivity on that magnitude were affected by distance from the missed approach point. Pilots reported that increases in sensitivity increased their workload and changed their distribution of attention among the aircraft instruments used for navigation and directional control.

1. INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

The FAA approves instrument approach procedures at all locations where the United States has jurisdiction over flight procedures in terminal areas. These procedures include the track and altitude profile that aircraft will be required to fly, as well as the depth, width, and horizontal dimensions of the involved airspace that must be guaranteed obstruction-free. The width of the path that must be cleared is determined by measuring sources of navigation system error. One of these is "Flight Technical Error" (FTE) or "crosstrack error," which refers to the accuracy with which the pilot controls the aircraft. This is measured by the discrepancy between the indicated command on the display and the actual aircraft position. The smaller the FTE, the narrower the path width that must be clear of obstruction.

The display often used to indicate the aircraft's position relative to the desired track is called the course deviation indicator (CDI). The principal objective of this study was to determine the influence of CDI sensitivity on FTE (an increase in CDI sensitivity results in greater deflections of the CDI needle for a given displacement of the aircraft from the desired track). Other study objectives included determining the influence of CDI sensitivity on pilot workload and aircraft handling.

1.2 METHODOLOGY

Data on flight performance was collected from twelve instrument-rated pilots who flew nonprecision instrument approaches at six different levels of CDI sensitivity into a local, uncontrolled airport. The approaches were flown in an instrumented Piper Archer airplane, equipped with a LORAN-C receiver. Each pilot flew all approaches wearing a hood and provided estimates of pilot workload during each approach. Safety pilots provided estimates of pilot effort.

The remainder of this section describes the characteristics of the pilots, the aircraft and instrumentation used, and the study procedures.

1.2.1 Pilot Characteristics

The twelve pilots who participated in this study were volunteers who responded to a sign-up sheet posted at the Minute Man Airfield in Stow, Massachusetts. They normally flew out of Minute Man and were familiar with the Piper Archer airplane. All volunteers were male, instrument-rated, and Instrument Flight Rule (IFR) current. The group characteristics included:

- Range of ages for pilots: 20 years to 51 years
  Mean: 36 years

- Range of total flight time: 325 hours to 2,900 hours
  Mean: 951 hours

- Range of total instrument time: 46 hours to 600 hours
  Mean: 146 hours

1.2.2 Aircraft and Instrumentation

All data collection flights were made in a Piper Archer. This light, single-engine airplane with a fixed gear was selected due to its simplicity and because it is familiar to many pilots.

In addition to being fully IFR-equipped, the airplane contained a Northstar M1 LORAN-C receiver and a second set of airplane instruments. The LORAN-C and the duplicate aircraft instruments were connected to a minicomputer used for data recording in flight.

The M1 LORAN-C receiver is a standard, commercially available unit that was modified for this experiment by Northstar so that the following CDI sensitivities could be selected in flight for any approach:

- 1/64 nautical miles (nm) per dot and 475 feet full scale, which is equivalent to Instrument Landing System (ILS) at middle marker

- 1/32 nm per dot and 950 ft. full scale

- 1/16 nm per dot and 1,900 ft. full scale

- 1/8 nm per dot and 3,800 ft. full scale

- 1/4 nm per dot and 7,600 ft. full scale

- 1/2 nm per dot and 15,190 ft. (2.5 nm) full scale

Information output from the LORAN-C included ground speed, distance to the next waypoint, the name of the next waypoint, and crosstrack error.

The second set of instruments, including directional gyro, attitude indicator, altimeter, and turn-and-slip indicator, were mounted together with a vacuum pump in a 12-inch square aluminum box located behind the pilot's seat.

1.2.3 Subjective Performance Measures

Subjective performance measures included estimates of pilot performance made by the pilot and the safety pilot during each instrument approach. At 1, 1.5, and 2.5 minutes inbound from the final approach fix, the pilot gave the "experimenter" (equipment operator) a verbal estimate of his present workload.

At the missed approach point, the safety pilot recorded his subjective estimate of how hard he thought the pilot worked during the approach. Both estimates were made on a seven-point scale, with "seven" indicating very high workload or effort.

1.2.4 Setup

Each pilot flew all approaches wearing a hood and, when cued, estimated his workload. A safety pilot operated the LORAN, monitored the safety of the flight, and provided estimates of pilot effort after each approach. A technician (also called the "experimenter"), in the rear of the airplane, operated the data recording equipment and cued the pilot three times during the approach for workload estimates.

The twelve instrument-rated pilots were divided into two groups. Six of these pilots constituted a high flying-time group (100 hours or above); the other six constituted a low flying-time group (below 100 hours). These flying times were based on total instrument time.

Within each group, the six men were further divided into groups of three:

	Number of pilots (high)	Number of pilots (low)
Group A	3	3
Group B	3	3

Groups A and B refer to CDI sensitivity levels as follows:

Group A	1/2 nm per dot 1/8 nm per dot 1/32 nm per dot
Group B	1/4 nm per dot 1/16 nm per dot 1/64 nm per dot

The order in which the pilots flew the three sensitivity levels was counterbalanced within each group of six pilots using the following sequences, with one sequence being assigned to a single pilot in the group (sequence reads from left to right):

123	312	231	321	132	213

Each pilot flew seven approaches each on two seperate days for a total of 168 nonprecision instrument approaches. The order in which he got the three sensitivity conditions was the same on each day.

The first approach of the day was always a practice approach at 1/4 nautical mile per dot. This value was selected because it is a common standard setting used with LORAN systems for operations within terminal areas. Data was recorded during the next six approaches. The pilot made two consecutive approaches at each of the three sensitivity levels assigned to him, in the assigned test order. The seven approaches took about two hours.

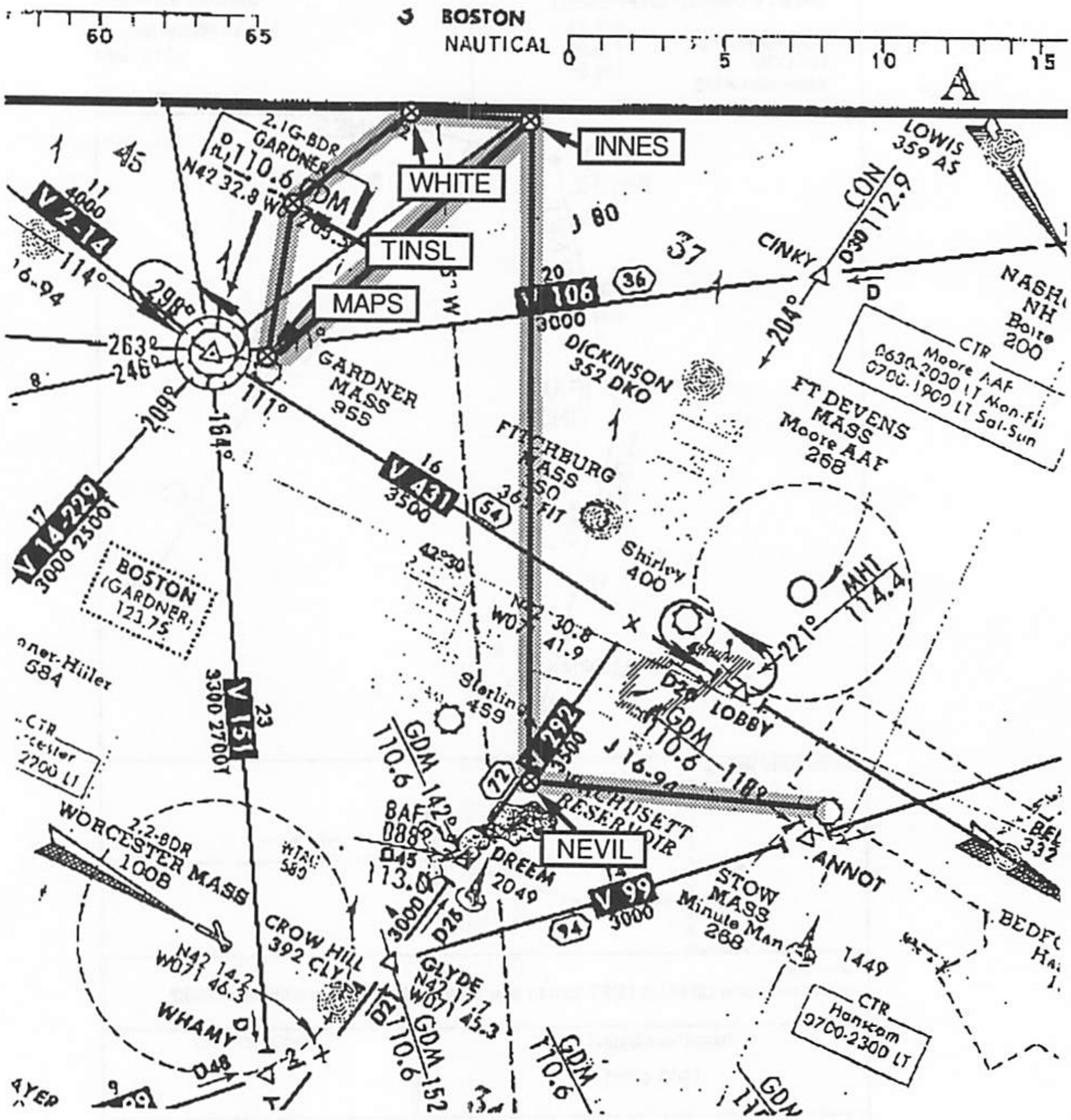
1.2.5 Procedure

Before each day's flight, the pilot was verbally briefed and given written material that described the test procedures. He was further provided with the appropriate sectional chart and approach plate (Figures 1-1, 1-2, and 1-3). The pilot was encouraged to make notes on the plate if desired. In addition, he was told how the seven-point workload scale was to be used:

- A "1" on the scale represented very low workload. It indicated that all phases of the approach could easily be accomplished and that there was time to spare to attend to other aspects of the flight.
- A "7" on the scale represented very high workload. It indicated that there was insufficient time to attend to all of the approach procedures and that no time could be spared for planning, or for unanticipated events.

The pilot was also given a description of how the LORAN-C operated, so that the automatic waypoint sequencing in the LORAN-C's flight plan mode was understood. Finally, the volunteer was reminded of the importance of keeping the CDI needle as close to the center as possible while flying the approach procedure, especially at the course intercept.

All test flights were flown between Minute Man Airfield in Stow and the Gardner Municipal Airport in Gardner, a distance of about 25 miles (Figure 1-1). The flight from Stow to Gardner and the seven approaches took more than two hours of continuous flying.



Note: NEVIL, INNES, WHITE, TINSL, and MAPS are LORAN waypoints.

FIGURE 1-1. MINUTE MAN AND GARDNER AIRPORTS AND ORIENTATION OF INSTRUMENT APPROACH TO RUNWAY 18 (GARDNER)

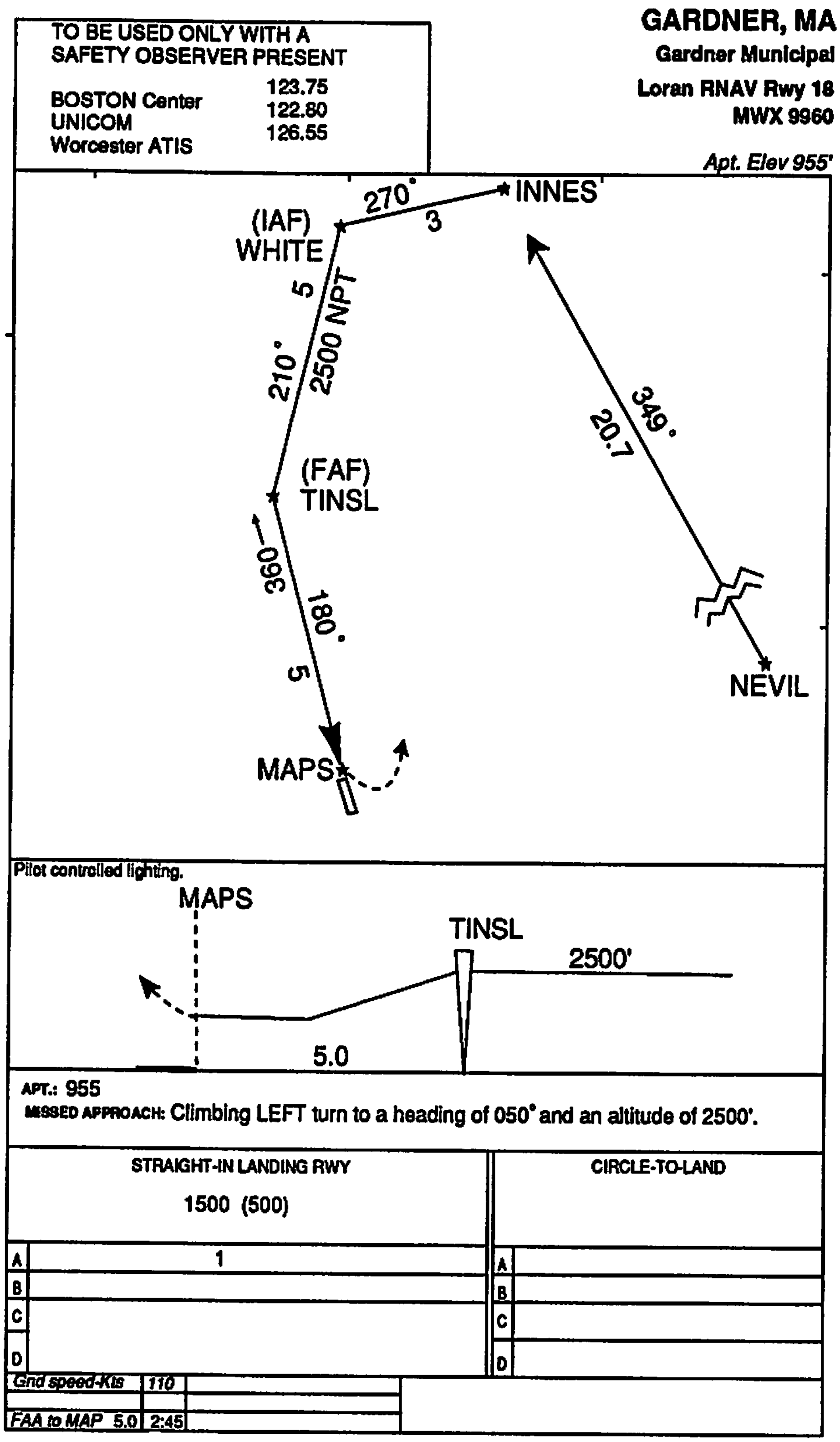


FIGURE 1-2. INSTRUMENT PROCEDURE CHART FOR RUNWAY 18 APPROACHES

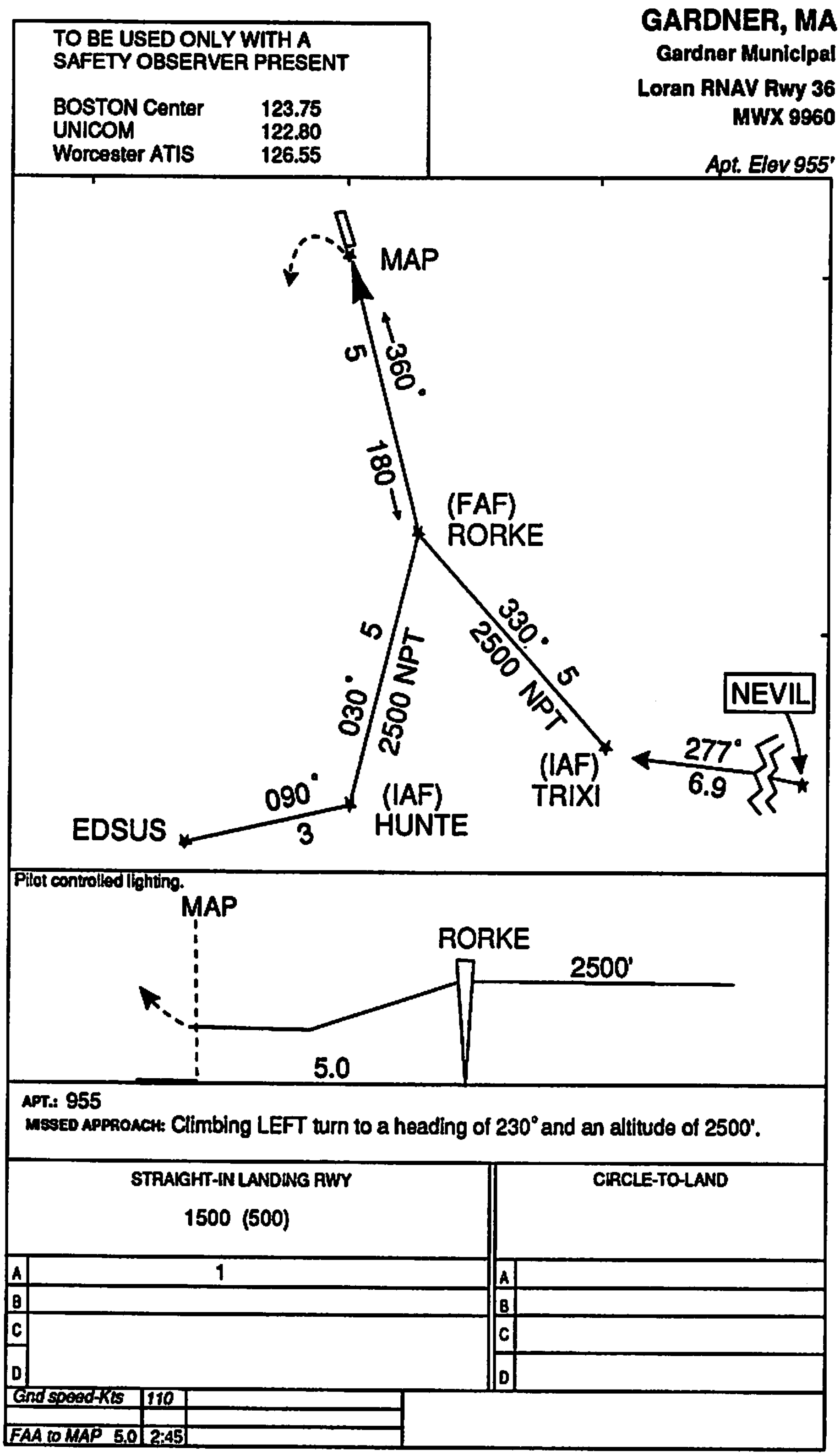


FIGURE 1-3. INSTRUMENT PROCEDURE CHART FOR RUNWAY 36 APPROACHES

Depending on the prevailing winds, the pilot flew one of two possible approach courses for all seven approaches of the day (see Figures 1-2 and 1-3). The pilot was informed of the sensitivity of the CDI setting before each approach.

The first of the seven consecutive approaches was a practice run and was flown from the initial approach fix (WHITE in Figure 1-2 or TRIXI in Figure 1-3) with a CDI sensitivity of 1/4 nm per dot. When the missed approach point (MAPS) was reached, the safety pilot instructed the pilot to execute the missed approach procedure and to return to INNES (EDSUS) for another approach. The flight from the missed approach point to INNES or EDSUS could be flown without the hood if the pilot wished.

The pilot was required to maintain an air speed of 110 knots during the entire approach and an altitude of 2,500 feet until the final approach fix. He could then descend to 1,500 feet as indicated on the approach plate.

The pilot decided when to initiate each turn by referencing the distance-to-waypoint readout on the LORAN-C. He was asked to perform standard procedures at specific points in the approach to maintain workload at a realistic level, and to duplicate the activities required during an actual instrument approach at an uncontrolled airport, including:

- Monitoring the Automated Terminal Information Service (ATIS) frequency of a nearby airport at the Initial Approach Fix (IAF) to obtain the altimeter setting.

- Calling the Common Traffic Advisory Frequency (CTAF) to notify area traffic of the approach at one and two minutes inbound from the Final Approach Fix (FAF).

The pilot was debriefed at Minute Man Airport after the seven approaches had been completed. Debriefing discussions included obtaining:

- The pilot's perception of CDI sensitivity's influence on workload.

- The percentage of time on the approach that the pilot spent monitoring the CDI and the directional gyro.

2. RESULTS

2.1 CDI SENSITIVITY'S INFLUENCE ON CROSSTRACK ERROR

The primary measure of pilot performance was crosstrack error. The crosstrack error was sampled by the minicomputer once per second from the LORAN receiver. The sampled crosstrack error was stored together with the distance of the airplane from the MAP at the time of the sample.

This positional information is represented in Figure 2-1. The matrix in Figure 2-2 shows how the crosstrack error data in Figure 2-1 is organized. The dashed line in the center of Figure 2-2 represents the centerline of the approach course, and the MAP is represented by a zero on the ordinate at the left of the figure. The numbers above the zero on the ordinate represent distances in nautical miles from the MAP.

The three rows, labeled 1, 2, and 3, are called "windows" in this report and are defined by the four distances indicated on the left. For example, Window 1 is between three and five nautical miles from the missed approach point. The seven columns in the matrix are called "zones." The numbers on the abscissa indicate the centerline in the zones and correspond to the numbers on the abscissa of Figure 2-1.

Figure 2-1 shows the crosstrack error performance of the twelve pilots as a function of window and CDI sensitivity. Each data point represents the percentage of time that the pilots spent in that zone for the window and sensitivity indicated. The percentage of time that each pilot spent in each zone was calculated independently for each window. The calculation was made from the crosstrack error data collected on each approach. Summed across zones, the seven percentages represented for a particular sensitivity add up to 100% for each window. Each data point represents data from approximately 24 approaches.

Figure 2-1 also indicates that, as pilots progressed from Window 1 to Window 3, they spent more time in the more central zones, and that the time spent in the more central zones increased with CDI sensitivity. The curves representing the three lower sensitivities are skewed to the right. Pilot performance using the 1/32-mile and 1/64-mile sensitivities is good immediately following the intercept and stays good or improves as the pilot continues along the approach course. Performance at the three lower sensitivities starts out poorly in Window 1 but improves somewhat as the pilots get closer to the MAP.

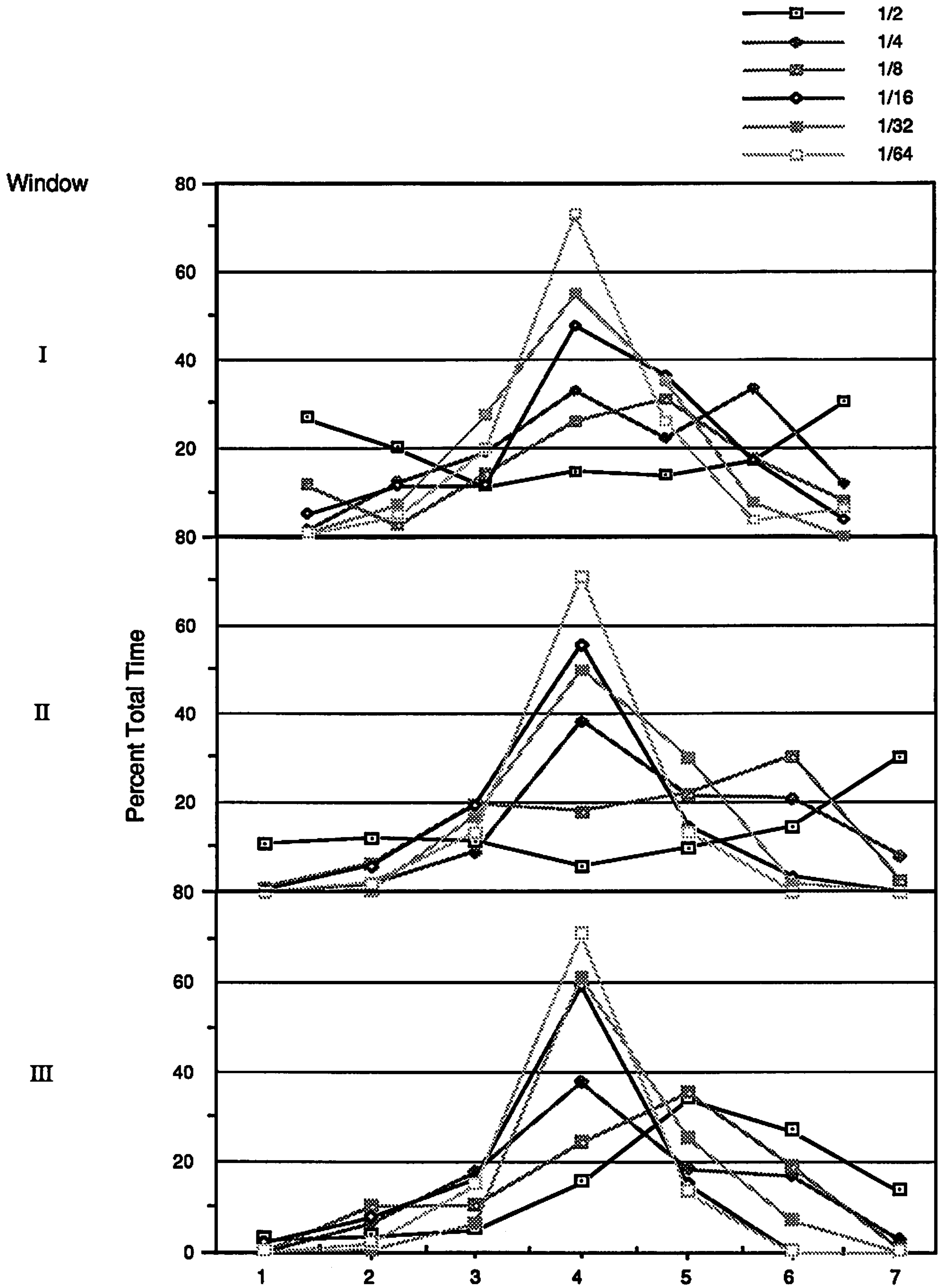


FIGURE 2-1. PERCENTAGE OF TOTAL PILOT TIME SPENT IN EACH OF SEVEN ZONES FOR EACH OF THREE WINDOWS UNDER SIX CONDITIONS OF CDI SENSITIVITY

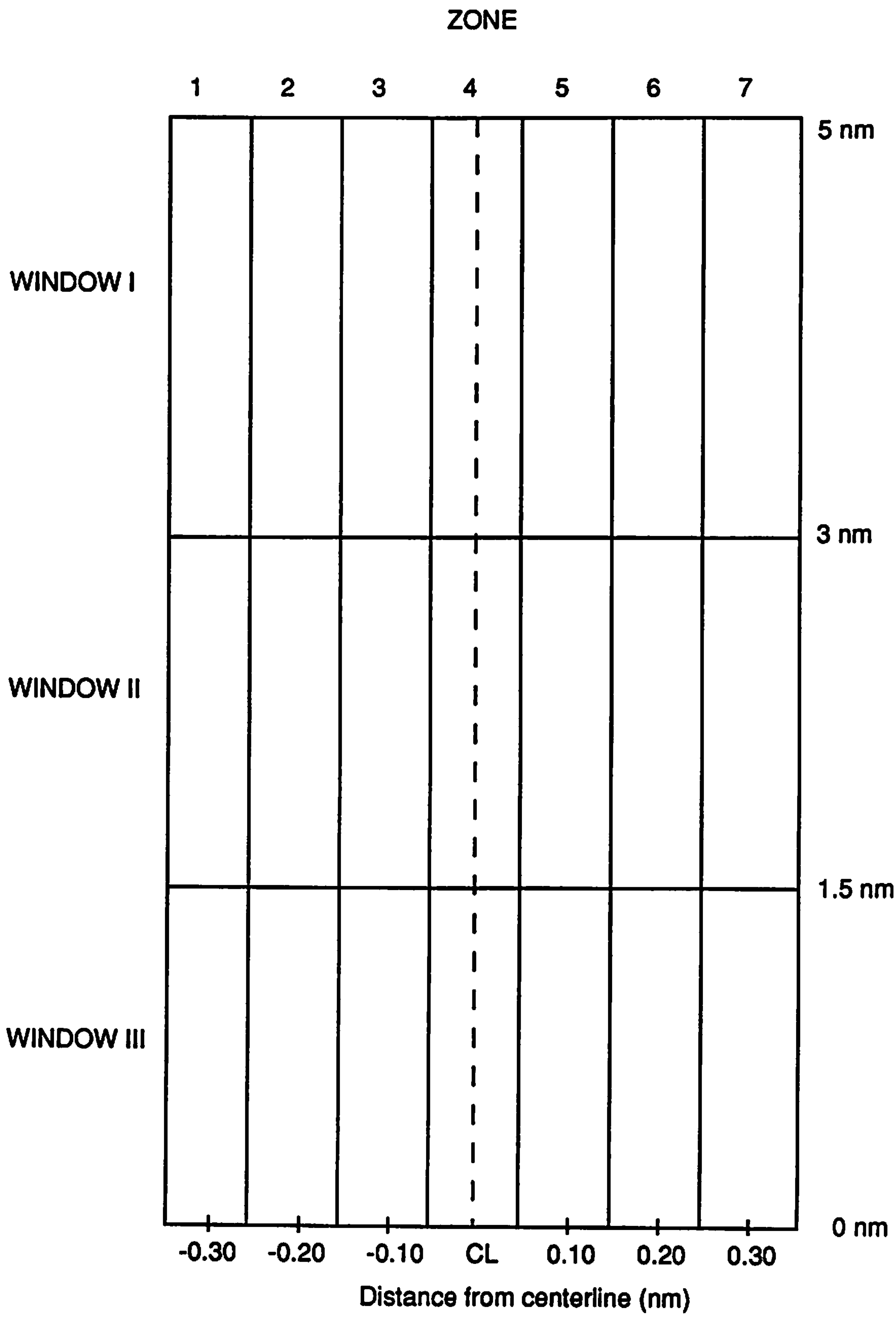


FIGURE 2-2. SCORING MATRIX FOR CROSSTRACK ERROR

The distribution of airplane positions across the zones at the lower sensitivity levels appears to be largely the result of the pilot's inaccurately intercepting the approach course, and the initial overcorrections back to the left (from the pilot's point of view) to compensate for such errors. (In the test trials, the approach course was intercepted from the left.)

To determine if tracking performance is reliably related to CDI sensitivity and longitudinal position on the approach course, the crosstrack error data was converted to root mean square values. This conversion changed negative to positive scores (airplane locations to the left of the approach course produced negative scores) and amplified the effects of large errors. The resulting RMS scores appear in Table 2-1 for each sensitivity and the three windows. The score in each cell is the mean of the six pilots' performance.

The statistical significance of the differences among the data was examined with the use of the Statistical Analysis System Procedure for General Linear Models (SAS PROC GLM) computer package for statistical analysis. The effects of window and sensitivity were statistically significant ($F = 10\ 26$, $df = 2$, $p < 0.01$) and ($F = 152.21$, $df = 1$, $p < 0.01$), respectively. Also significant was the window by sensitivity interaction ($F = 3.57$, $df = 2$, $p < 0.05$).

Table 2-1 illustrates these three effects:

- The size of the error decreases as the pilot flies from Window 1 to Window 3.

- The size of the error decreases as sensitivity is increased from 1/2 to 1/64 mile per dot.

- The higher degrees of accuracy that resulted from increases in sensitivity were greater for Windows 1 and 2 than they were for Window 3. This indicates that, with higher sensitivity levels, pilots were quicker in establishing the airplane on the approach course, and they were more accurate in flying the course.

Typical approach path tracks of pilots flying a very sensitive (1/64) and a very insensitive (1/2) needle appear in Figure 2-3. Notice that pilots have smaller maximum deviations from the centerline and make more centerline crossings when flying with the more sensitive CDIs. Center crossings require a heading change to get back on centerline and thus are a source of increased workload.

TABLE 2-1. RMS CROSSTRACK ERROR IN NAUTICAL MILES FOR APPROACH WINDOW CDI SENSITIVITY

Approach Window	CDI Sensitivity 1/2	1/4	1/8	1/16	1/32	1/64	$\bar{X}$
I	0.26	0.15	0.14	0.09	0.06	0.06	0.13
II	0.23	0.11	0.08	0.05	0.03	0.03	0.09
III	0.14	0.08	0.08	0.05	0.05	0.03	0.08
$\bar{X}$	0.21	0.11	0.10	0.07	0.05	0.04	0.10

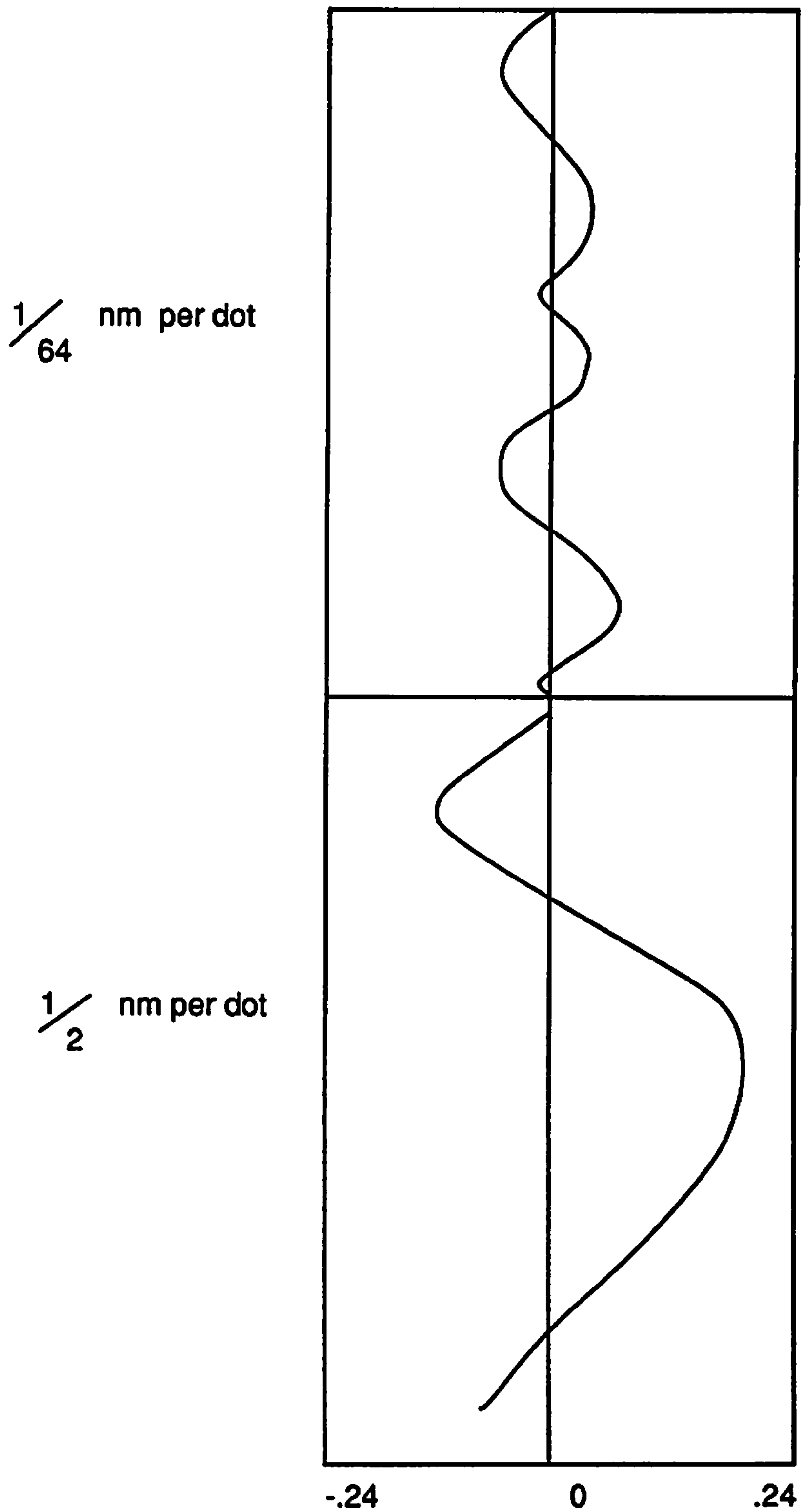


FIGURE 2-3. TYPICAL APPROACH PATH TRACKS FLOWN WITH SENSITIVE (1/64) AND INSENSITIVE (1/2) CDI SETTINGS

Figure 2-4 illustrates the course width required to contain 95% of the maximum course deviations to be expected with each of the six CDI sensitivity levels in each of the three windows. The limits of each of the course widths are represented by the 18 horizontal lines. The limits of these lines were derived from the crosstrack performance measured on approximately 24 approaches. (In some cases, only 22 approaches were available for calculation due to missing data.) In order to determine the limits of these lines, standard deviations of the maximum distances traveled from the centerline on each of the 22 to 24 runs were calculated. The limits of the horizontal lines illustrating course width represent the mean of the 24 maximums plus two standard deviations from the centerline. The lines are asymmetrical because the calculations were done independently for excursions to each side of the centerline.

This figure is another way of showing the same relations illustrated in Figure 2-1, but it presents the data in a way that is easier to relate to requirements for approach course width. Again, the higher sensitivity levels produce narrower course width requirements. For example, at a distance of 1.5 to 3 miles out from the threshold, the approach course must be 0.63 of a nautical mile to include approximately 95% of all maximum excursions from the centerline if a 1/4-mile CDI sensitivity were used, whereas approximately 1/2 that width (0.32 of a nautical mile) would be required if the 1/16-mile sensitivity level were used.

2.2 SEQUENCE EFFECTS

Several pilots reported that their flying became easier as they became more familiar with the approach procedures; however, toward the end of the seven consecutive approaches they began to tire. Since the test conditions were counterbalanced among pilots, these sequences would not be expected to influence the pattern of test results that we obtained. However, we were curious about the influence of the long test sessions on flying performance.

Figure 2-5 illustrates the RMS crosstrack error scores for each of the six daily test runs averaged across all other test conditions. Performance was worst on the first trial and was best during the second, third, and fourth trials. Performance also tended to tail off after the fourth trial, confirming the pilots' comments about getting tired.

Furthermore, performance was never as good on the odd trials as it was on the following even ones. This seemed to be the result of practice. The pilots had their first experience with a new sensitivity level on the odd trials, and their second experience on the even trials.

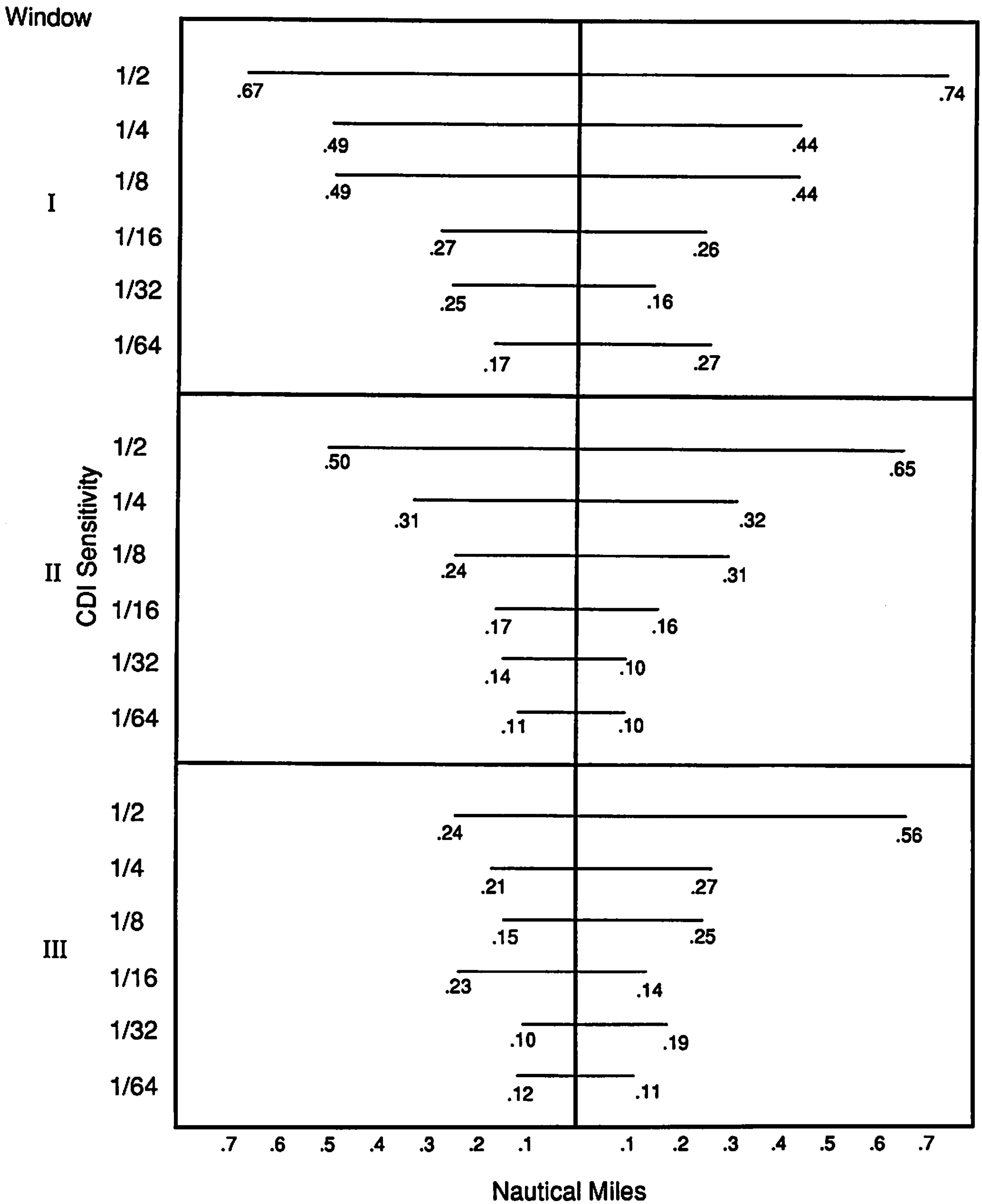
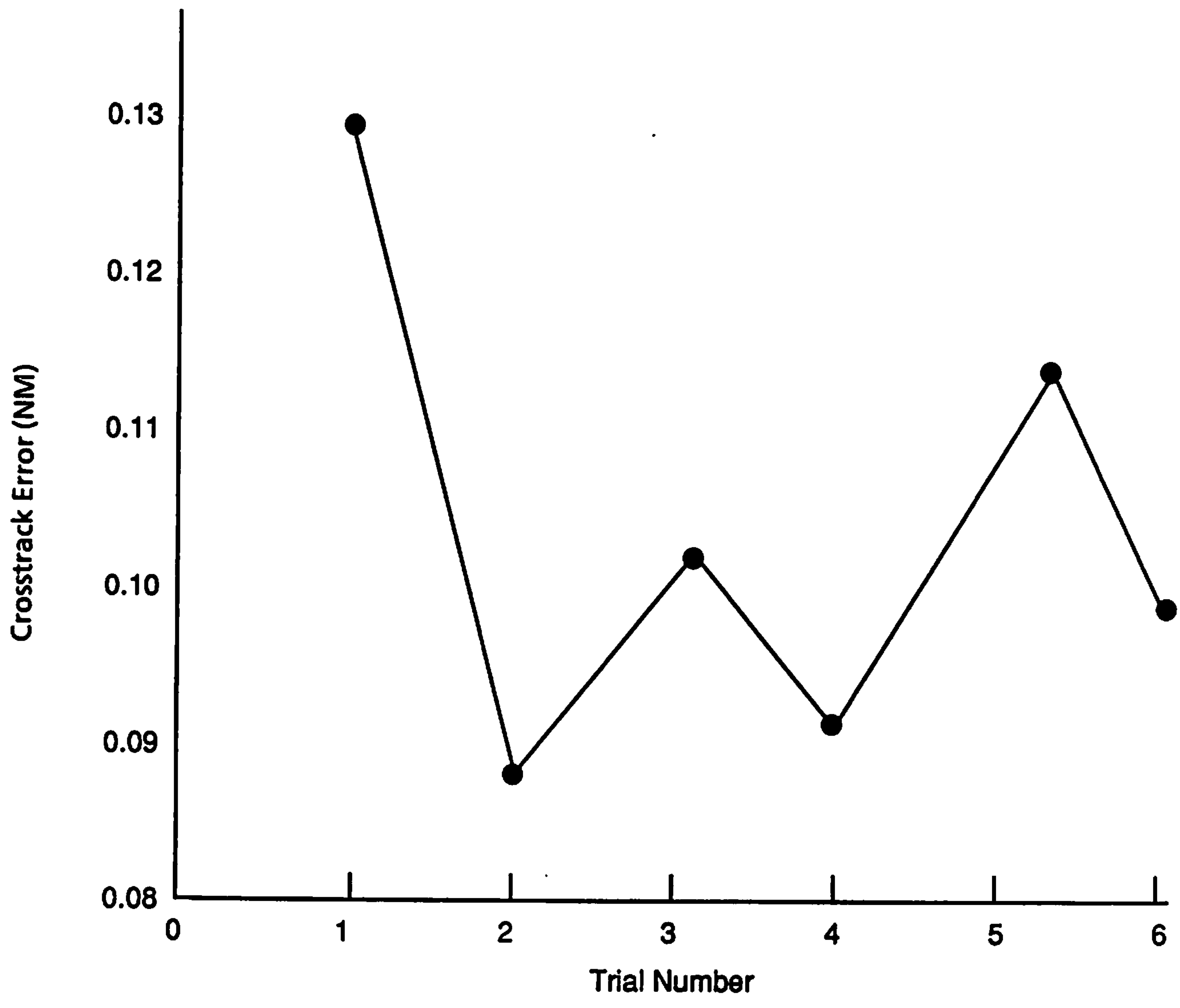


FIGURE 2-4. COURSE WIDTH EXPECTED TO CONTAIN 95 PERCENT OF MAXIMUM DEVIATIONS FROM CENTERLINE AS A FUNCTION OF WINDOW AND CDI SENSITIVITY



Note: Scores are averaged across pilots, test day, and CDI conditions.

FIGURE 2-5. RMS CROSSTRACK ERROR FOR EACH CONSECUTIVE DAILY TEST TRIAL

A multi-regression (SAS PROC GLM) analysis of the data revealed that the difference between odd and even trials was statistically significant ($F = 7.27$, $df = 1$, $p < 0.01$). No significant interaction was found between the odd/even approaches and sensitivity.

2.3 THE COST OF HIGHER APPROACH PRECISION: VISUAL SCAN

During the debriefing, each pilot was asked to estimate the percentage of time spent monitoring the CDI and the directional gyro (DG) during each of the three pairs of approaches of the day.

Table 2-2 shows the pilot estimates of time spent monitoring the DG and course deviation (CD) for each of the six sensitivity levels. Each of the twelve averages shown in the body of the table is the mean of approximately twelve estimates.

The table shows three particularly interesting influences of CDI sensitivity on the pilots' reported distribution of attention. At lower sensitivity levels, they spent more than twice as much time watching the DG as they did the CDI. But at the highest levels that relationship was reversed, indicating that the higher levels of sensitivity caused them to "fly the needle" rather than a heading.

Pilots spent more time monitoring the CDI as sensitivity increased. Consequently, they spent less time monitoring the DG and other instruments in the airplane. The biggest jumps in the monitoring time for the CDI were between the 1/4 and 1/8 and the 1/16 and 1/32 sensitivity levels. Data indicates that the ideal CDI sensitivity for instrument approaches is somewhere between 1/4 and 1/32 mile per dot. These shifts of attention are potentially important indicators of pilot workload and should be verified using measures that are more objective than pilot opinion.

2.4 THE COST OF HIGHER APPROACH PRECISION: WORKLOAD

Each pilot made an estimate of his workload during each window of the approach.

Table 2-3 shows the average of pilot workload estimates for each sensitivity level in each window. The number in each cell is the mean of 19 to 24 workload estimates.

TABLE 2-2. PILOT ESTIMATES OF PERCENTAGE OF APPROACH TIME SPENT MONITORING THE CD AND DG FOR THE SIX LEVELS OF CDI SENSITIVITY

	CDI Sensitivity					
Flight Instrument	**1/2**	**1/4**	**1/8**	**1/16**	**1/32**	**1/64**
CDI	15	17	28	28	43	47
Gyro	37	33	31	30	29	21
Total	52	50	59	58	72	68

TABLE 2-3. PILOT ESTIMATES OF WORKLOAD OBTAINED IN THE THREE APPROACH WINDOWS FOR THE SIX LEVELS OF CDI SENSITIVITY

	CDI Sensitivity						
Window	**1/2**	**1/4**	**1/8**	**1/16**	**1/32**	**1/64**	$\bar{X}$
I	2.3	3.1	3.1	3.8	4.3	5.5	3.7
II	2.5	3.2	3.0	4.0	4.2	5.6	3.8
III	2.5	3.3	3.2	4.1	4.3	5.6	3.8
$\bar{X}$	2.4	3.2	3.1	3.8	4.3	5.6	3.8

Workload was judged to increase with increases in CDI sensitivity. It was approximately the same for each of the three windows. An analysis of these data with Scheffee's multiple comparison procedure (Kirk, 1982, pp. 121-122) revealed that the differences in workload among the six sensitivity levels were statistically significant ($P = 0.05$) for all except the differences between the 1/4 and 1/8 levels and between the 1/16 and 1/32 levels. Each of the two pilot groups was exposed to only three of the six sensitivity levels. No pilot had both the 1/4 and 1/8 or 1/16 and 1/32 levels. Thus the pilots thought increases in sensitivity caused increases in workload, but did not think workload varied from window to window.

At the completion of each approach, the safety pilot estimated on a scale of 1 to 7 how hard the pilot appeared to be working during that approach. Table 2-4 shows the average of the safety pilot estimates of pilot effort for each sensitivity level. The value in each cell is the mean of approximately twelve independent estimates. The table indicates that pilot effort was judged to increase with increases in sensitivity. Scheffee's test revealed that the differences between all pairs except 1/4 and 1/8 and 1/16 and 1/33 were statistically significant.

Figure 2-6 shows the relation between pilot workload and crosstrack error. Clearly, increases in CDI sensitivity cause systematic decreases in crosstrack error and an increase in workload.

A positive correlation of 0.66 ($p < 0.01$) was produced by a Pearson product moment correlation coefficient calculated between the effort ratings of the safety pilot and the workload estimates of the pilots.

2.5 THE COST OF HIGHER APPROACH PRECISION: FLIGHT SMOOTHNESS

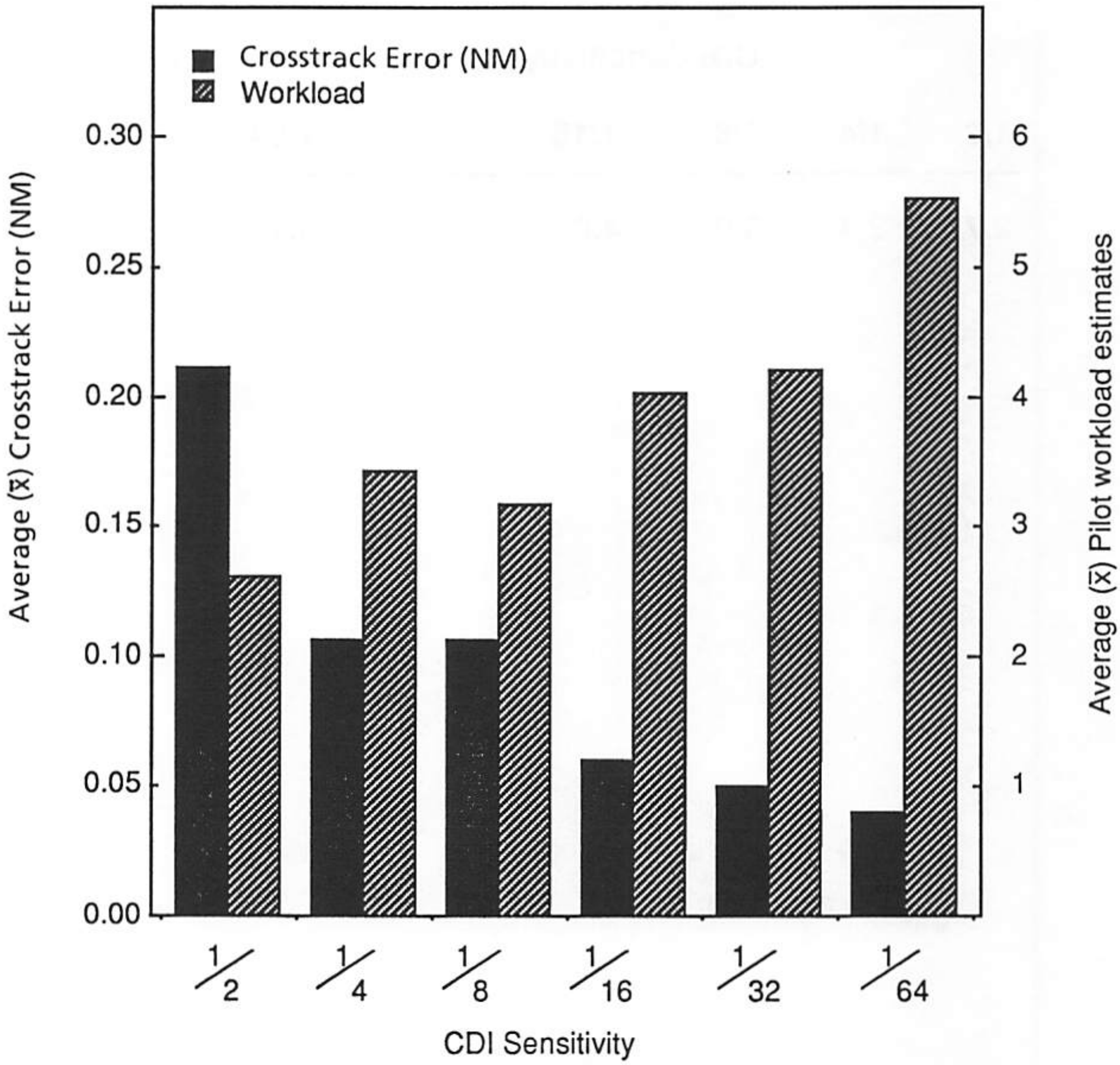
We examined the statistical significance of the influences of CDI sensitivity, pilot, and window on the seven objective performance measures (turn rate and altitude variation, etc.). To do this, we used the SAS PROC GLM computer package for statistical analysis.

The analyses were performed primarily on RMS difference scores of the objective measures. Difference scores were calculated as roughness indicators in handling the airplane. RMS transformations were done to increase the sensitivity of the analysis. Second differences were calculated for altitude as indicators of variation around the normal descent path that was required for the approach.

TABLE 2-4. SAFETY PILOT ESTIMATES OF PILOT EFFORT DURING THE APPROACH FOR SIX LEVELS OF CDI SENSITIVITY

CDI Sensitivity

1/2	1/4	1/8	1/16	1/32	1/64
2.7	3.4	3.0	4.0	3.6	5.1



Note: The results of analysis for differences among pilots are not shown.

FIGURE 2-6. CROSSTRACK ERROR AND PILOT WORKLOAD ESTIMATES FOR THE SIX CDI SENSITIVITY LEVELS

Table 2-5 shows the results of the analysis for window and sensitivity on flight quality as follows:

- o Window affected groundspeed and altitude variation. Groundspeed variation was highest in Window 1, which is where the pilots initiated their descent to the minimum descent altitude. Altitude variation was least in Window 3, where most pilots leveled out at the MDA prior to reaching the missed approach point. This was insignificant except for crosstrack error (see Table 2-1).

- o Turn rate differences were the least for Window 1.

- o Sensitivity produced significant effects in heading and roll rate variation. In both cases, variation was highest for the higher sensitivity levels, probably because the higher levels were associated with more centerline crossings.

- o No statistically significant window by sensitivity interactions were found.

- o Significant ($p<0.01$) differences were found among pilots for all six measures.

These results indicate that increases in CDI sensitivity do influence flight smoothness. However, other than as possible indicators of pilot workload, the practical significance of these findings is unclear.

2.6 FLIGHT SMOOTHNESS AS A MEASURE OF WORKLOAD

Table 2-6 shows the results of multiple regression analyses (PROC GLM; Pcorr2) that were conducted. These analyses were conducted between the measures of flight smoothness and the subjective measures (pilot estimates of workload and safety pilots' estimates of pilot effort). The objective measures recorded during each approach are listed in the left column of the table.

Workload and pilot effort are represented as column headings. The cells of the table contain the correlation of the corresponding row and column variables and the level of statistical significance of that correlation. The "Pcorr2" option of PROC GLM was used to partial out the influence of CDI sensitivity on these correlations. This was done to control the fact that both the pilot and the safety pilot knew the CDI conditions under which they were flying during each approach. That knowledge might have influenced their workload and effort estimates.

TABLE 2-5. INFLUENCE OF WINDOW AND CDI SENSITIVITY ON FLIGHT SMOOTHNESS

Flight Quality Measure	Window			Sensitivity					
	I	II	III	1/2	1/4	1/8	1/16	1/32	1/64
Ground speed/d (kts)	*0.4	0.2	0.2	0.3	0.2	0.3	0.4	0.3	0.3
Altitude/2d (ft)	*56.0	55.3	47.6	47.9	53.7	44.9	64.6	49.5	58.7
Heading/d (deg)	1.8	1.8	1.8	*1.7	1.6	1.9	1.8	1.9	2.1
Pitch/d (deg)	1.2	1.3	1.4	1.4	1.3	1.2	1.5	1.0	1.6
Roll/d (deg)	2.6	2.6	2.7	*2.4	2.2	2.6	2.5	3.0	3.1
Turn rate/d (deg/sec)	*2.2	2.4	2.6	2.4	2.3	2.5	2.2	2.4	2.5

*$p < 0.01$

TABLE 2-6. PARTIAL CORRELATION OF FLIGHT QUALITY MEASURES WITH PILOT EFFORT AND PILOT WORKLOAD ESTIMATES

Flight Quality Measure	Pilot Effort	Pilot Workload
Cross Track Error	+0.06	*+0.19
Ground Speed/d	+0.11	+0.10
Altitude/2d	+0.02	+0.11
Heading/d	*+0.28	*+0.15
Pitch/d	*+0.14	-0.04
Roll/d	*+0.29	+0.06
Turn rate/d	*+0.21	+0.06

*$p < 0.01$

The table indicates that heading, pitch, roll, and turn rate differences were significantly related ($p<0.01$) to safety pilots' effort estimates. Crosstrack error, heading, roll, and turn rate differences were significantly related to workload estimates of the pilot. These relationships indicate that certain measures of flight quality, as related to pitch and turning, should be further examined as potential measures of pilot workload on instrument approaches.

It is generally accepted that the best estimate of pilot workload is the pilot's own report. This is believed true even if (as is generally believed) the pilot's memory limits, ego, and expectations may influence such estimates. It is possible, however, that the safety pilot, with less ego involvement and more time to attend to details, could provide more useful estimates of pilot workload.

Heading, pitch, roll, and turn rate differences were associated significantly with the safety pilots' estimates of pilot effort. Only crosstrack error and heading differences are significantly associated with pilot estimates of workload. This indicates that - to the extent that workload is reflected in how the pilot handles the airplane - an observer may be a better judge of pilot workload than the pilot himself.

2.7 CONCLUSION

Tables 2-1, 2-2, 2-3, 2-4, and 2-5 indicate that the increase in CDI sensitivity resulted in more accurate flying of the final approach course. This accuracy was accomplished at the cost of a narrowing of visual scan in the cockpit, increased pilot workload, and some decrease in flight smoothness.

Further, observations by a cockpit observer of pilot behavior during instrument approaches appeared to be a useful source of information on pilot workload.

3. SUMMARY AND DISCUSSION

Recordings from the LORAN-C indicated that:

- o Crosstrack error decreased systematically with increases in CDI sensitivity.
- o Pilot estimates of workload, instrument scan, and CDI "flyability" indicated that the workload increased and the extent of instrument scan decreased with increases in CDI sensitivity.
- o CDI sensitivity did cause a significant change in the quality of the pilot's handling of the airplane. Pilot and safety pilot estimates of workload were significantly correlated. However, the estimates of the safety pilot appeared more highly correlated with objective measures of flight quality, such as variations in pitch, roll, and turn rate, than were the pilot estimates.

Our study indicates that for certain instrument approach conditions, a more sensitive CDI than the standard currently used may be advantageous. For these airports, which cannot have wide approach courses due to terrain, a CDI sensitivity of 1 1/4 mile off course for full-scale deflection is most often used. This sensitivity is also recommended by the Radio Technical Commission for Aeronautics (RTCA) for LORAN-C instrument approaches. However, we found that using a more sensitive needle, which deflected to full scale when only one-quarter of this distance off course (1,900 ft.), would decrease crosstrack error by 40% to 30%.

Crosstrack error accounts for a major proportion of system error budget used by procedure design specialists for designing LORAN-C instrument approaches. Reducing the value of the crosstrack error (flight technical error) component of this budget could narrow the path that needs to be cleared for LORAN-C approaches, thus making such approaches possible in locations where currently they are not.

The problem with an increase in CDI sensitivity is uncertainty about the workload that may accompany it. Our results indicate that althougth a measurable increase in workload is likely with such an increase, large changes in pilot control of the aircraft would not occur.

4. RECOMMENDATIONS

Our results indicate that further research is needed. A reliable and valid means of measuring pilot workload during instrument approaches needs to be developed. Present research indicates three potentially fruitful avenues for further study that involves judgment of an observer and measurement of visual scan:

- Much time and effort have been spent on developing procedures for structuring pilot judgment for better estimating pilot workload. Similar efforts concerning the judgment of an observer in the right seat should be taken.

- Research is needed on the impact of cockpit workload on pilot visual scan. Changes in visual scan could provide an objective measure of workload that has both operational and face validity. Techniques should be developed for measuring the pilot's visual scan in the cockpit. The more difficult the task is, the more visual scan is reduced. This phenomenon has been demonstrated in the laboratory and in automobile tests on the highways. However, such demonstrations use equipment and data analysis procedures that are impractical for cockpit use.

- Logically, workload would influence how the pilot handles his aircraft, and we have some data to support this notion. This relationship should be researched directly by examining the influence of workload on pilots' use of the yoke.

APPENDIX A

ACRONYMS

A

ATIS	Automated Terminal Information Service

B

C

CD	Course Deviation
CDI	Course Deviation Indicator
CTAF	Common Traffic Advisory Frequency

D

DG	Directional Gyro

E
F

FAF	Final Approach Fix
FTE	Flight Technical Error

G
H
I

IAF	Initial Approach Fix
IFR	Instrument Flight Rule
ILS	Instrument Landing System

J
K
L

LORAN	Long-range Navigation

M
N

NM	Nautical Mile

O
P
Q
R

RMS	Root Mean Square
RTCA	Radio Technical Commission for Aeronautics

S

SAS PROC GLM	Statistical Analysis System Procedure for General Linear Models

T
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V
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