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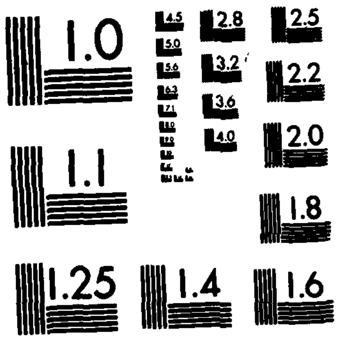

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Simulation Study of Traffic-Sensor Noise Effects on Utilization of Traffic Situation Display for Self-Spacing Task

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Simulation Study of Traffic-Sensor Noise Effects on Utilization of Traffic Situation Display for Self-Spacing Task

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SUMMARY

A simulation study was undertaken to determine the effect of traffic-sensor noise on the ability of a pilot to perform an in-trail spacing task. The tests were conducted in a fixed-base cockpit simulator configured as a current-generation transport aircraft, with an electronic traffic display provided in the weather-radarscope location. The true positions of the traffic were perturbed in both relative range and azimuth by random errors to simulate traffic-sensor noise associated with an onboard sensor. The evaluation task involved simulated instrument approaches into a terminal area while maintaining self-separation on a lead aircraft. Separation performance data and pilot subjective ratings and comments were obtained during the study.

The results of the separation data indicate that displayed traffic position errors, having standard-deviation values up to 0.3-n.mi. range and 8° azimuth, had negligible effect on the spacing performance achieved by the pilots. Speed profiles of the lead aircraft, display of the lead aircraft groundspeed, and individual pilot techniques were found to significantly affect the mean spacing performance. Pilot comments and ratings indicated that despite the ability to successfully use the traffic position data with high sensor noise levels, the pilots objected to even small errors in the displayed traffic location. Position errors with standard deviations of 0.1-n.mi. range and 2° azimuth were rated as the maximum noise values which were acceptable to the pilots for performing the self-spacing task. High mental workload and confusion over the true traffic location were cited as the reasons for objecting to the displayed traffic position errors.

INTRODUCTION

Future growth of air transportation is dependent on the ability of the air-traffic control (ATC) system to accommodate the increasing demand for capacity at the major high-density terminal airports. Currently, many airports are capacity-limited during peak operating periods, resulting in costly aircraft delays and high workload levels for air-traffic controllers. One method that has been proposed to reduce controller workload and increase airport capacity is to provide traffic information in the cockpit to allow greater pilot participation in the ATC process and, possibly, permit the use of more efficient procedures. This concept was first proposed in the 1940's (ref. 1); however, early efforts involving TV broadcast of the controllers' radarscope were abandoned because of numerous technical deficiencies. Recent advances in computer technology, digital data links, and electronic flight displays have resulted in renewed interest in the concept.

Numerous simulation studies, most notably the efforts by the Massachusetts Institute of Technology in the early 1970's (ref. 2), have demonstrated pilot acceptance of traffic information and have identified several possible benefits associated with active use of traffic-situation displays. Currently, the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) have undertaken a joint program to explore potential cockpit display of traffic information (CDTI) applications under realistic environmental and workload conditions. As a part of this program, NASA Langley Research Center is investigating CDTI applications in the operation of current, conventionally equipped transport aircraft through the use of piloted simulation studies. An important consideration in these studies is the impact of traffic-sensor characteristics on the ability of pilots to effectively utilize the CDTI.

The primary objective of this study was to determine the effect of traffic-sensor errors on the ability of a pilot to perform an in-trail spacing task. The tests were conducted in a fixed-based cockpit simulator configured as a current-generation transport aircraft with an electronic traffic display provided in the weather-radarscope location (fig. 1). The true positions of the traffic were perturbed in both range and azimuth by random errors to simulate traffic-sensor noise associated with an onboard sensor. Range noise errors (with standard-deviation values of up to 0.3 n.mi.) and azimuth noise errors (with standard-deviation values up to 8°) were evaluated.

The primary pilot task for this study was to achieve and maintain specified spacing intervals behind a cockpit-displayed lead aircraft while conducting a simulated approach. Two pilots each flew 54 approaches into a simulated Denver-Stapleton environment (fig. 2) with varying error levels present in the traffic display. Data were taken in the form of quantitative performance measures as well as subjective pilot ratings and comments.

RESEARCH SYSTEM

Simulator Description

This study was conducted utilizing a fixed-base cockpit simulator configured as a conventional, two-engine jet transport aircraft (fig. 1). The four throttle controls present in the cockpit were mechanically pinned together in pairs to represent the two-engine configuration. The aircraft dynamics modeled for the simulation were those of a Boeing 737. Nonlinear aerodynamic data and atmospheric effects were included in the simulation model. The host computer for the simulation was a Control Data CYBER 175 system, which contained the aircraft dynamics, navigation, and flight director algorithms. Conventional navigation instruments, which included horizontal situation indicators, flight director, and distance measuring equipment (DME), were provided in the cockpit. Flight instrumentation consisted of standard instruments required for manual flight control; however, no autopilot or automatic flight control systems were provided to the pilot. In addition, no attempt was made to duplicate any specific aircraft cockpit configuration or control-force feel characteristics.

Traffic Generation Scheme

The displayed traffic was generated from data previously recorded using the Langley Real-Time Simulation System. Specifically, the traffic data were created by using a piloted simulation capability wherein flights were made along each of the routes that corresponded to the airway structure prescribed by the test scenarios. These individual flights were recorded and then merged into a set of data that was position and time correlated. The output of these merged data was the representation of numerous airplanes following several flight paths. This traffic-generation technique was developed for use in the study described in reference 3. A description of the actual traffic scenarios used in this study is contained in the section of this report entitled "Traffic Profiles."

EXPERIMENT DESIGN

CDTI Display

The display used as the CDTI for this study was a monochrome cathode-ray tube (CRT) located behind the throttle quadrant as shown in figure 1. This location corresponds to the normal location for a weather-radar display on most conventionally equipped transport aircraft. Although the CRT measured 10 in. across the diagonal, an opaque mask was used to reduce the display size to 5 in. high by 4 in. wide, which is a more representative size for a standard weather-radar display.

The display format used in this study is illustrated in figures 3 and 4. The own-ship symbol representing the location of own-aircraft was centered horizontally and was offset vertically one-third up from the bottom. Map information provided on the display gave route structure and waypoints for the instrument landing system (ILS) approach to runway 35R. The display was oriented "track up" with apparent continuous movement of the map information about the fixed own-ship symbol. Six map scales, ranging from 1.0 to 32.0 n.mi./in., were available to, and controllable by, the test subjects.

A straight-line vector extended from the own-ship symbol projecting a scaled distance of 5 n.mi. directly ahead. Range arcs were displayed on the vector at scaled ranges of 3 n.mi. and 5 n.mi., which were the prescribed spacing intervals for the test.

Traffic aircraft were displayed on the CDTI referenced to the map display. Unlike the map, however, the traffic data were not updated continuously but at 4-sec intervals. Between updates, the traffic symbology would remain fixed to the moving map and then jump to its new position at the update.

The traffic symbology was obtained from reference 4 and was the same as in reference 5. Figure 5 illustrates the symbology and the information provided the pilot concerning the aircraft traffic. Aircraft within ±500-ft altitude were considered "at" own-ship altitude. The trend vector on the traffic indicated where the traffic would move in 60 sec at its current groundspeed and heading. The past-position dots showed where the traffic had been, relative to the map, on the previous three position updates. The alphanumeric data tags provided identification, absolute altitude, and groundspeed information for the traffic (fig. 5). The trend vectors, past-position dots, and data tags were independently selectable by the test subject at any time during a run. Selection of a display option resulted in that option appearing for all the displayed traffic. The alphanumeric characters and the symbols were of constant size, independent of map scale.

Sensor Noise Model

For the purposes of this study, sensor noise is defined as the random inaccuracies in the measurement of the horizontal location of aircraft traffic. This measurement is assumed to be performed by some type of traffic sensor located onboard the aircraft. Airborne radars and active or passive collision avoidance systems with directional capability are examples of airborne traffic sensors.

The measured traffic location consists of a distance component of range and a directional component of bearing. These components are measured separately and have essentially independent errors associated with them. Figure 6 illustrates the geometry of range and bearing measurements of traffic location with errors in both range and bearing. The errors are assumed to be normally distributed, high-frequency random noise. Actual measurement of the location of a particular aircraft occurs at discrete intervals. Depending on the particular traffic sensor, the length of time between actual measurements is quite variable. For the purposes of this study, the measurement interval was chosen to be 4 sec, which is the approximate interrogation rate of terminal-area secondary surveillance radars.

The sensor noise model implemented in this study functioned as follows. The standard-deviation values for both range and bearing components of sensor noise were predefined at the start of each simulated approach. Using these standard-deviation values, the components of range and bearing error were calculated at 1-sec intervals by a random number generation routine. These error components were sampled every 4 sec and added to the actual range and bearing values for each of the aircraft. This technique produced an apparent low-frequency random error in the traffic location presented on the cockpit traffic display with standard deviations equal to the preselected values of sensor noise.

Traffic Profiles

The traffic scenario utilized in this study was taken directly from reference 5. The scenario contained aircraft that were landing, departing, and flying over the Denver terminal area. The flight paths of the background traffic simulated published instrument procedures and hypothetical radar vectoring for take-off and landing, utilizing runways 35L (left) and 35R (right) in a parallel, but not simultaneous, operational manner.

Three new aircraft profiles were generated for this study to be used as substitutes for the lead aircraft from reference 5. The initial conditions for each of these aircraft were the same. The initial position was at the Kiowa VORTAC (IOC), with a heading of 253°, an indicated airspeed of 250 knots, and an altitude of 14 000 ft. Each aircraft flew the same published approach to runway 35R (fig. 2); however, there were significant differences in the speed profiles of the three aircraft. The speed profiles as a function of distance to runway threshold are shown in figure 7. On the base leg of the approach, aircraft 1 maintained a fairly constant indicated airspeed of 250 knots. Aircraft 2 and aircraft 3 flew at indicated airspeeds of approximately 240 and 260 knots, respectively. These airspeed variations represent the ±10-knot tolerance which could accompany an ATC instructed airspeed of 250 knots. After the turn to final, the three aircraft followed different deceleration patterns, arriving at the final approach speed of 130 knots at approximately the same location on the approach path. The three deceleration patterns were considered suitable for airline operations with flap and gear extensions within appropriate speed limits, and accomplished without the use of speed brakes. The initial position of own-ship was 7 n.mi. behind the lead aircraft at the same heading and altitude with an indicated airspeed of 290 knots. The traffic identifier for the lead aircraft was the same for all conditions, and the test subjects were not informed of the variations in speed profiles or the number of lead aircraft being used in the study.

Task Description

The basic piloting task in this study was a manual instrument approach in a terminal-area environment utilizing conventional navigation information. Additionally, the test subjects were asked to utilize the CDTI display to establish and maintain specified separation intervals on a preceding aircraft following the same approach path.

The description of initial conditions, piloting task, and performance variables to be measured were given the test subjects prior to participating in the test. (See the appendix.) The test subjects were further instructed to fly the simulator in a manner they deemed acceptable for airline-type operations and to avoid radical maneuvers. Besides being NASA research pilots, the test subjects had attended an airline training school and were experienced in flying the Boeing 737 aircraft.

As described previously, the simulator used for this study was a fixed-base partial-workload cockpit. It was, therefore, impossible to simulate the full-workload environment associated with "real-world" operations. Previous experience had indicated that utilizing the standard two-man crew in part-task simulations of this nature resulted in unrealistically low workload levels. For this reason, each test subject in this study was required to function essentially as a single pilot performing all decision-making functions and traffic-display monitoring while exercising total manual control of the simulated aircraft. The only tasks not required of the test subjects were manual operation of landing gear and flaps, tuning of radios to proper navigation frequencies, and changes in traffic display formats. These functions were performed by the test engineer at verbal requests of the subject pilot.

It should be noted that the pilots were instructed to "fly" the flight director roll and pitch command bars as precisely as possible throughout each approach. This was done to further limit the amount of time the pilots had to focus on the traffic display which was located outside the primary instrument scan area.

Test Conditions

A total of 18 unique combinations of test variables were devised for this study. Two NASA research pilots flying 3 replications of each test condition resulted in a total of 108 simulator runs. Table I presents the matrix of test conditions used for both test subjects. The test-sequence number given in the table indicates the order in which the runs were made. This order was randomized with respect to the sensor noise level and traffic set used for the lead aircraft. The entire matrix of 18 test conditions was completed prior to any replications.

The primary independent variables of interest for this study were the range and azimuth components of the sensor noise. Six values of azimuth noise were tested with no range noise, and four values of range noise were tested at two constant azimuth noise levels. This setup allowed independent evaluation of each component of sensor noise while also permitting combinations of range and azimuth sensor noise to be tested.

Three independent variables of secondary interest were the provision of traffic groundspeed data tags, the traffic profile used as lead aircraft, and the pilot. The test matrix was set up such that a subset could be used in a 2 × 2 × 2 full factorial analysis of variance on these three variables. The conditions used for this analysis are indicated in table I and detailed in table II. The additional lead-aircraft traffic profile (traffic set 1), which was not used in the analysis of variance, was included in the study to help minimize pilot anticipation of lead-aircraft speed changes.

Data obtained during the study consisted of qualitative opinion in the form of a pilot questionnaire as well as quantitative performance measures. The approach ground track flown by the simulated aircraft was divided into segments and gates as illustrated in figure 8. Essentially, the gates indicated on the figure correspond to the locations on the approach path where the pilots were instructed to achieve or maintain a specific spacing condition.

RESULTS AND DISCUSSION

Effects of Sensor Noise

Spacing performance.- The horizontal spacing between own-aircraft and lead-aircraft was recorded throughout each data run. The spacing values at each of the five gates were used as performance measures to evaluate the effect of increasing sensor noise levels on pilot ability to establish and maintain a specified separation distance. The hypothesis prior to undertaking the simulation was that increasing noise levels in the displayed traffic position would degrade the pilot spacing performance to a noticeable degree. The noise component in the longitudinal (range) direction was considered to be the most critical for the in-trail spacing task.

Figures 9 to 13 present the spacing performance achieved by the test subjects at each of the five gates along the approach path. In part (a) of each figure, aircraft separation is plotted versus azimuth noise with no range noise for target 1; in part (b), aircraft separation is plotted versus range noise with 1° azimuth noise for target 2; in part (c), aircraft separation is plotted versus range noise with 3° azimuth noise for target 3. These data are presented in this manner to isolate the effects of the range and azimuth noise components on spacing performance. However, this test design did not allow for a comparison of traffic types. The data points on the figures represent the average of the spacing values from six data runs (two pilots with three replications). The dispersion in the spacing performance at each data point is represented by the 1σ standard-deviation bars shown in figures 9 to 13. Also included on the plots is a dashed line representing the spacing which the test subjects were instructed to achieve or maintain at that location on the approach path. Note that no spacing was specified for gate 3 and no reference line is presented on the data plots for that gate (fig. 11).

As can be seen in figures 9(a) to 13(a), the plots of spacing versus azimuth noise at all the data gates reveal nearly constant mean spacing values with increasing azimuth noise for a particular plot. In addition, the dispersion about the data points is also fairly constant with increasing azimuth noise. These results indicate that sensor noise in the azimuthal direction had negligible effect on the spacing performance achieved by the test subjects during the in-trail following task. This is not surprising since spacing is a longitudinal task, and the test subjects were provided with spacing arcs on the traffic display to compensate for azimuthal offsets as great as 15°.

The data presented in parts (b) and (c) of figures 9 to 13 indicate no clear trend in spacing performance as a function of the range component of sensor noise. In general, the mean and standard-deviation spacing values show negligible degradation in spacing performance with increasing levels of range noise. This result is contrary to the subjective pilot opinion concerning the effects of sensor noise as obtained in the form of pilot ratings. Following each simulated approach, the test subjects were asked to rate the effect of display noise on their spacing performance during the run. The results of this rating (fig. 14) indicated a consistent trend of increasing effect with increasing noise level, with the greatest effect corresponding to the highest level of range noise. Despite these ratings, the spacing data indicate no trend in spacing performance as a function of range noise. The most reasonable explanation for this apparent discrepancy is the spacing accuracy which the pilots were trying to achieve. Pilot comments indicated that when they were within approximately 0.25 n.mi. of the desired spacing they would minimize the effort to improve the spacing. The relatively long time period required to change spacing and the increased pilot workload associated with "fine-tuning" the spacing interval were cited as factors contributing to this tolerance level in the spacing error. This spacing-error tolerance resulted in greater spacing errors at the low sensor noise levels than would have been possible had the pilots strived for more accurate performance. It is possible that the spacing data would have indicated a trend of degraded spacing performance with increasing range noise if the pilots had been instructed to reduce their spacing tolerance. It is significant to note, however, that a tolerance on spacing is highly desirable from a workload standpoint as well as to dampen possible chain instabilities for multiple in-trail following conditions. It would, therefore, appear that actual spacing performance, given a modest spacing tolerance, is essentially unaffected by range noise levels up to the maximum tested in this study.

Flight director tracking performance.- Deviation of the flight director command bars from the centered location was recorded at 1-sec intervals during two segments of the approach. The first segment extended along the base leg of the approach. During this segment, the navigation radio was tuned to the Kiowa VORTAC, and the roll command deviation on the flight director was recorded. The second segment extended for 10 n.mi. on final approach, with both roll and pitch command deviations on the flight director being recorded. The command deviation data during segments were analyzed to obtain a mean and standard-deviation value for each run for both the roll and pitch command basis. Since both the mean and standard-deviation values are indications of flight director command-bar tracking performance, the absolute value of the mean was added to the standard deviation to obtain a single number, referred to here as simply command-bar deviation, to quantify the performance of a test subject during a particular run. The smaller the command-bar-deviation value, therefore, the more accurate was the command-bar tracking performance achieved by the test subject. This method of quantifying command-bar tracking performance was chosen since it provides an equal weighting to both offsets in command-bar position as well as the standard deviation of command-bar errors. It should be noted that these data are not normally distributed. Standard analysis techniques (t-test, analysis of variance, etc.) may not be applicable.

Figures 15 and 16 present the roll and pitch tracking performance as a function of azimuth and range sensor noise. Once again, each data point represents the average of six runs with the dispersion represented by the 1σ standard deviation bars. The dashed line on each plot represents the average flight director tracking performance that the test subjects were able to achieve when they flew the identical approach without the addition of the CDTI self-separation task. As can be seen, the addition of the CDTI task degraded the flight director tracking performance of the test subjects. The addition of sensor noise to traffic display, however, did not further degrade the tracking performance as might have been expected. Pilot ratings of the effect of sensor noise on flight director tracking performance (fig. 17) indicate a slight effect of the sensor noise; however, pilot comments confirmed that the addition of the CDTI spacing task was the major workload increase and accounted for the bulk of the tracking performance degradation. It would appear that any increase in workload caused by the increase in sensor noise level is minor in comparison with the addition of the CDTI self-separation task itself. Pilot comments indicated that mental workload and confusion were very much affected by the display noise level even though it was not necessarily reflected in the flight director tracking performance.

Pilot acceptance.- A subjective evaluation of acceptable levels of displayed sensor noise was obtained through pilot comments and ratings. At the conclusion of each simulated approach, the test subjects were asked to rate the level of noise they detected in the traffic display using the following scale:

Pilot rating	Noise level
1	None
2	Small
3	Moderate
4	Heavy
5	Extreme

The pilots were given no guidelines as to the maximum levels of noise they would encounter; however, they were instructed to assign a noise-level rating which they considered to be the maximum acceptable noise they would tolerate for operational use of the CDTI. At the conclusion of the tests, one of the pilots chose rating 2 (small amount of noise), while the other pilot chose rating 3 (moderate noise) as the maximum tolerable noise level.

The ratings assigned by both pilots for all runs at the same actual sensor noise level were averaged and are presented on a plot of azimuth noise versus range noise in figure 18. The pilots had no trouble detecting the relative magnitudes of the display noise, as is evident by increasing trend in the ratings with increasing noise level. The region marked "satisfactory" on figure 18 represents the sensor noise levels which received an average rating equal to or less than the rating the pilots had assigned as the maximum acceptable noise level (an average of 2.5 for both pilots). The region marked "unsatisfactory" represents the noise levels that received ratings in excess of the maximum acceptable rating.

Both pilots agreed that despite the unfavorable ratings, even the highest noise levels tested did not prevent them from accomplishing the in-trail spacing task. The primary objection to the higher noise levels was the increased mental workload associated with visually averaging the mean position of the target aircraft over several position updates. The unsatisfactory ratings given the higher noise levels indicated the pilots felt that such levels of display noise required an unacceptable amount of effort on the part of the pilot to discern the correct position of the traffic. The ratings were limited to the in-trail spacing task, and both pilots indicated that other tasks might well have higher or lower threshold levels of maximum acceptable display noise.

Effects of Groundspeed Display and Traffic Profiles

The effects on mean spacing performance of different lead aircraft speed profiles, different pilots, and the displ·v of grour speed information were evaluated using an analysis-of-variance test for significance at each of the data gates along the approach (ref. 6). The data from 8 of the 18 test conditions provided a 2 × 2 × 2 full-factorial matrix with 6 replications as indicated in table II. It should be noted that test conditions used in this matrix contained sensor noise errors which are not included as factors in the analysis of variance. The pooling of data incorporating different sensor noise levels is felt to be justified, since sensor noise was found to have a negligible effect on spacing performance in the previous analysis. In addition, the limited number of pilots and traffic profiles used in this study do not permit a rigorous analysis of the effects of these factors on spacing performance. The results from the current study must, therefore, be viewed as providing trends and insight into the importance of the variables in conducting CDTI self-spacing experiments, and care must be taken in extrapolating these results to more general conditions.

Table III presents the computed F-values for the analysis-of-variance tests at each of the five data gates. The results in terms of significant factors at each gate are presented as follows:

Gate	Factor (at least 5-percent significance level)
1	Pilot Traffic set Groundspeed tag and traffic set interaction
2	Pilot
3	Groundspeed tag
4	Pilot Pilot and groundspeed tag interaction Pilot and traffic set interaction
5	Pilot Groundspeed tag Pilot and groundspeed tag interaction Pilot and traffic set interaction

As might have been expected, the factor which consistently appears as having a significant effect on the spacing performance is the pilot. The manual nature of the self-spacing task in this study places a high demand on the pilot, and the resulting spacing performance is, therefore, pilot dependent to a great extent. The significance of this result should not be minimized. The values of the spacing performance achieved by the test subjects in this study, or any study involving a small sample of test subjects, should not be used to extrapolate to absolute performance of the general population of pilots. Care must be observed in selecting an adequate, random group of test subjects if such extrapolation is desired.

The traffic set factor is seen to have a significant effect on spacing performance at gate 1. In figure 7, the speed profiles of the two target aircraft used in the analysis of variance (targets 2 and 3) are seen to be approximately 20 knots different during the base leg of the approach. At gate 1, where the test subjects were to initially establish a 5-n.mi. spacing, this difference in speed between the two target aircraft has a significant effect on the ability of the test subjects to achieve the desired spacing. At gate 2, where the test subjects were to maintain the 5-mile spacing achieved at gate 1, there is little effect of the different target speed profiles on the pilot spacing performance. On final approach, where the speed profiles of the two target aircraft exhibit only minor differences, the only significant traffic set effect noted at gates 4 and 5 is pilot and traffic set interaction. These results indicate that differences in lead-aircraft speed profiles can significantly influence self-spacing performance, depending on the tactical nature of the self-spacing task, the amount of time available to accomplish the task, and individual pilot response to variations in traffic speed profiles. While these results are far from conclusive, they do point out the necessity to include the traffic mix and speed profile variations when evaluating CDTI self-spacing tasks.

Providing the pilots with groundspeed information is also seen to be a significant factor at several of the data gates. At gate 1, where there is a significant traffic set effect, there is also a significant traffic set and groundspeed interaction. On final approach, at gates 4 and 5, groundspeed and/or pilot and groundspeed interaction is a significant factor. Of particular interest is gate 3, where groundspeed is the only significant factor to affect spacing performance. At this gate, the test subjects had no spacing interval specified but were in the process of closing the spacing from 5 n.mi. to 3 n.mi. Pilot comments indicated that without groundspeed information on the lead aircraft, the pilots would have a tendency to "overshoot" the desired spacing and get closer than the minimum 3-n.mi. interval. The test subjects would compensate for this factor by exercising more caution in closing the spacing when groundspeed information was not provided on the lead aircraft. As a result, the conditions without groundspeed data tags had a significantly greater mean spacing at gate 3. Figure 19 presents the spacing performance with and without groundspeed at the three gates. As can be seen, the greater spacing interval at gate 3 without target groundspeed is clearly evident. Despite this pilot compensation, the tendency for less than desired spacing when target groundspeed is not provided is still evident when the target crosses the runway threshold (gate 5).

CONCLUSIONS

A piloted simulation was conducted to determine the effect of traffic-sensor noise on the use of an airborne traffic display for in-trail self-separation during approach to landing operations. The following conclusions are based on the results of this study:

1. Displayed traffic position errors with standard-deviation values up to 0.3-n.mi. range and 8° azimuth had negligible effect on the ability of the pilots to perform the self-spacing task.

2. The test pilots objected to displayed traffic position errors with standard-deviation values greater than approximately 0.1-n.mi. range and 2° azimuth. Mental workload and confusion over true traffic position were cited as the basis for objection to the higher display errors.

3. Display of the lead aircraft groundspeed was found to affect the mean spacing performance, especially during periods of speed or spacing changes. Pilot comments cited the groundspeed information as a definite aid in performing the spacing task.

4. The speed profile of the lead aircraft was found to be a significant factor in the mean spacing performance achieved by the test subjects. The magnitude of this effect was a function of the time available to accomplish the spacing task and individual pilot response to the variations in traffic speed profiles.

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APPENDIX

INSTRUCTIONS TO PILOT

Initial Conditions

1. Your aircraft is a Boeing 737 located 7 n.mi. east of the Kiowa VORTAC at an altitude of 14 000 ft and an indicated airspeed of 290 knots at a heading of 253° toward Kiowa.

2. The target aircraft is another 737 located over Kiowa at an altitude of 14 000 ft following the same 253 radial from Kiowa.

Pilot Task

1. You have been instructed by Denver ATC to cross Kiowa at 14 000 ft and follow radial 253 from Kiowa and intercept localizer and glide slope for landing on runway 35R. You are cleared to descend from 14 000 ft to 10 000 ft once you have crossed Kiowa.

2. The target aircraft is flying the same approach. You have been instructed to self-space on the traffic by ATC. You are to close to a spacing interval of 5 n.mi. on the target aircraft by the time you are 10 n.mi. past Kiowa. You are to maintain the 5-mile spacing until the target begins its turn to final. Once you have turned to final, you should close your spacing on the target in order to obtain a 3-mile spacing when you cross the outer marker. You are to maintain the 3-mile spacing until the target crosses the runway threshold.

3. Maximum landing gear and flap extension speeds for the 737 aircraft must be observed.

Performance Measures

1. Your ability to acquire and maintain the separation interval will be measured and used as a performance parameter.

2. Throughout the approach, the flight director should be flown as precisely as possible. Deviations from centered command bars on the flight director will be recorded and used as a measure of your performance.

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TABLE I.- TEST CONDITIONS

Test-condition number	Test-sequence number (a)	Sensor noise level		Traffic set	Traffic groundspeed provided
		Range, n.mi.	Azimuth, deg		
1	1,33,47	0	0	1	Yes
2	9,26,51	0	.5	1	Yes
3	17,20,43	0	1.0	1	Yes
4	5,30,54	0	2.0	1	Yes
5	11,22,41	0	4.0	1	Yes
6	13,35,37	0	8.0	1	Yes
[b]7	15,36,39	0	1.0	2	Yes
8	2,27,42	.1	1.0	2	Yes
9	10,29,46	.2	1.0	2	Yes
[b]10	4,32,53	.3	1.0	2	Yes
[b]11	7,24,49	.0	1.0	2	No
[b]12	12,19,44	.3	1.0	2	No
[b]13	18,28,45	.0	4.0	3	Yes
14	6,21,38	.1	4.0	3	Yes
15	8,25,48	.2	4.0	3	Yes
[b]16	14,23,50	.3	4.0	3	Yes
[b]17	3,31,52	.0	4.0	3	No
[b]18	16,34,40	.3	4.0	3	No

[a]Indicates order in which runs were made.
[b]Used in statistical analysis to test significance of traffic set, groundspeed, and pilot effects.

TABLE II.- TEST CONDITIONS FOR THREE-FACTOR ANALYSIS OF VARIANCE

Test-condition number (a)	Factor A	Factor B	Factor C
7 and 10	Pilot 1	With groundspeed display	Traffic set 2
13 and 16	Pilot 1	With groundspeed display	Traffic set 3
11 and 12	Pilot 1	Without groundspeed display	Traffic set 2
17 and 18	Pilot 1	Without groundspeed display	Traffic set 3
7 and 10	Pilot 2	With groundspeed display	Traffic set 2
13 and 16	Pilot 2	With groundspeed display	Traffic set 3
11 and 12	Pilot 2	Without groundspeed display	Traffic set 2
17 and 18	Pilot 2	Without groundspeed display	Traffic set 3

[a]From table I.

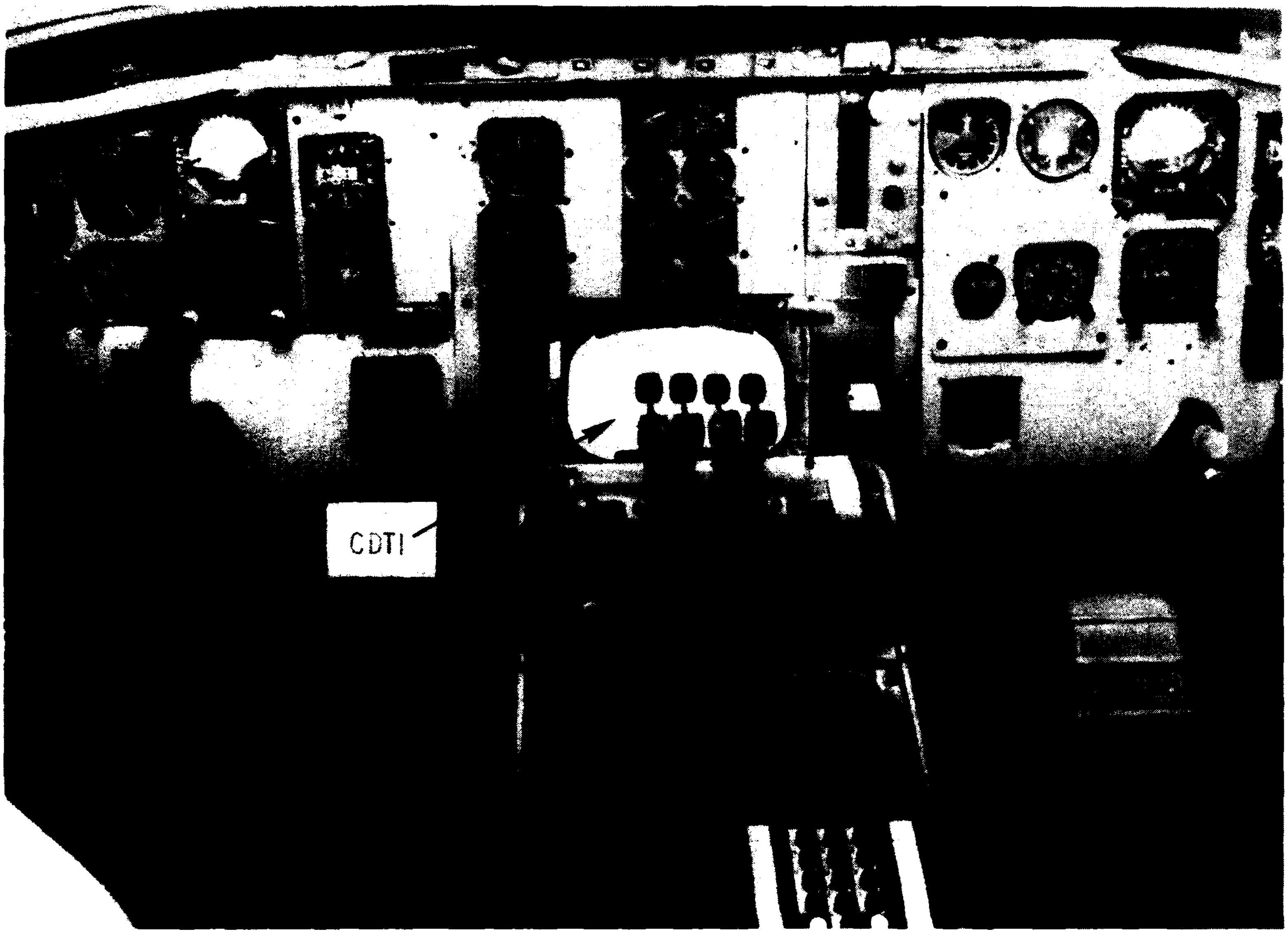
TABLE III.- COMPUTED F-VALUES FOR ANALYSIS OF VARIANCE

[Location of gates 1 to 5 are defined in figure 8]

Factors	Degrees of freedom	Sum of squares, (n.mi.)^2	Mean square, (n.mi.)^2	Computed F-value
Gate 1				
Pilot, A	1	0.44	0.44	[a]17.83
Groundspeed, B	1	.01	.01	.58
Traffic profile, C	1	2.35	2.35	[a]94.68
AB	1	.00	.00	.16
AC	1	.02	.02	.91
BC	1	.39	.39	[a]15.55
ABC	1	.07	.07	2.65
Error	40	.99	.02	
Total	47	4.27		
Gate 2				
Pilot, A	1	1.15	1.15	[a]22.48
Groundspeed, B	1	.00	.00	.00
Traffic profile, C	1	.17	.17	3.38
AB	1	.01	.01	.20
AC	1	.01	.01	.25
BC	1	.06	.06	1.13
ABC	1	.00	.00	.01
Error	40	2.04	.05	
Total	47	3.44		
Gate 3				
Pilot, A	1	0.02	0.02	0.12
Groundspeed, B	1	1.28	1.28	[a]8.49
Traffic profile, C	1	.52	.52	3.46
AB	1	.00	.00	.03
AC	1	.02	.02	.15
BC	1	.03	.03	.19
ABC	1	.16	.16	1.07
Error	40	6.05	.15	
Total	47	8.09		
Gate 4				
Pilot, A	1	0.85	0.85	[a]12.35
Groundspeed, B	1	.00	.00	.04
Traffic profile, C	1	.14	.14	2.03
AB	1	.46	.46	[b]6.70
AC	1	.32	.32	[b]4.61
BC	1	.13	.13	1.95
ABC	1	.01	.01	.19
Error	40	2.74	.07	
Total	47	4.66		
Gate 5				
Pilot, A	1	0.24	0.24	[b]5.47
Groundspeed, B	1	.18	.18	[b]4.24
Traffic profile, C	1	.08	.08	1.74
AB	1	.38	.38	[a]8.85
AC	1	.42	.42	[a]9.80
BC	1	.08	.08	1.91
ABC	1	.00	.00	.00
Error	40	1.73	.04	
Total	47	3.12		

[a]Indicates 1-percent significance level.
[b]Indicates 5-percent significance level:

Significance level	Tabulated F-value
0.05	4.08
.01	7.31



L-80-7799.1

Figure 1.- Simulator cockpit with cockpit display of traffic information (CDTI).

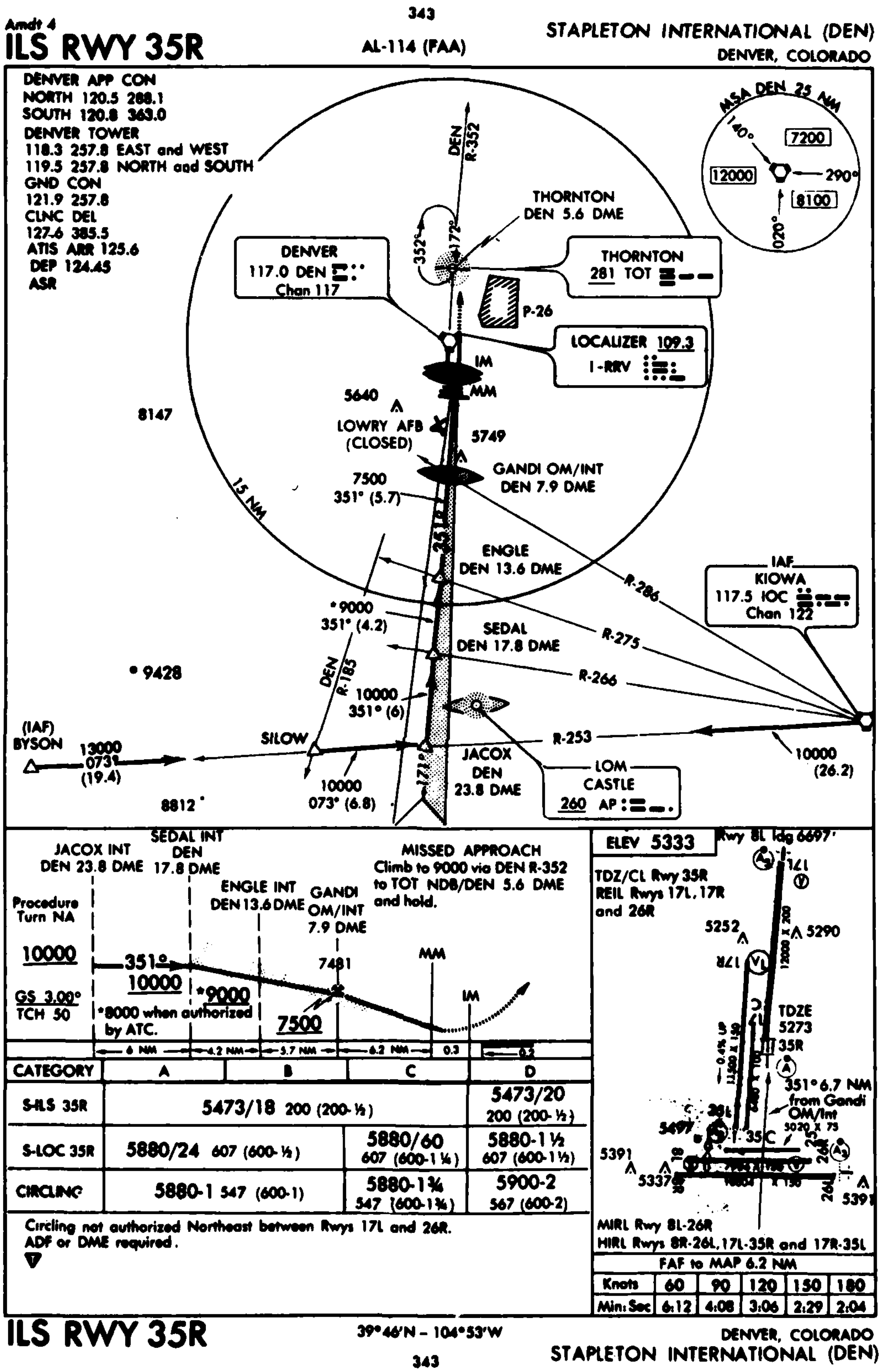


Figure 2.- Approach chart.

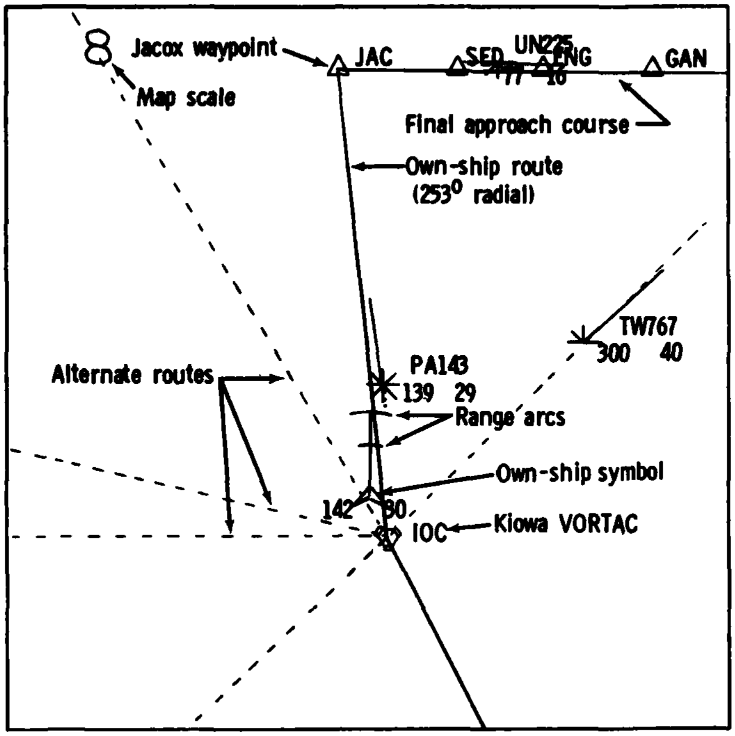


Figure 3.- CDTI format, map scale 8.

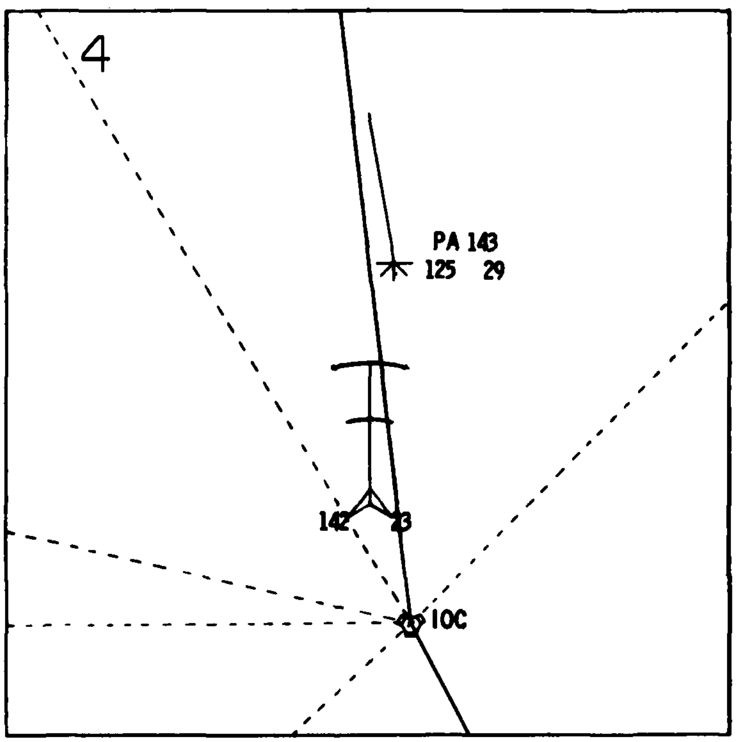
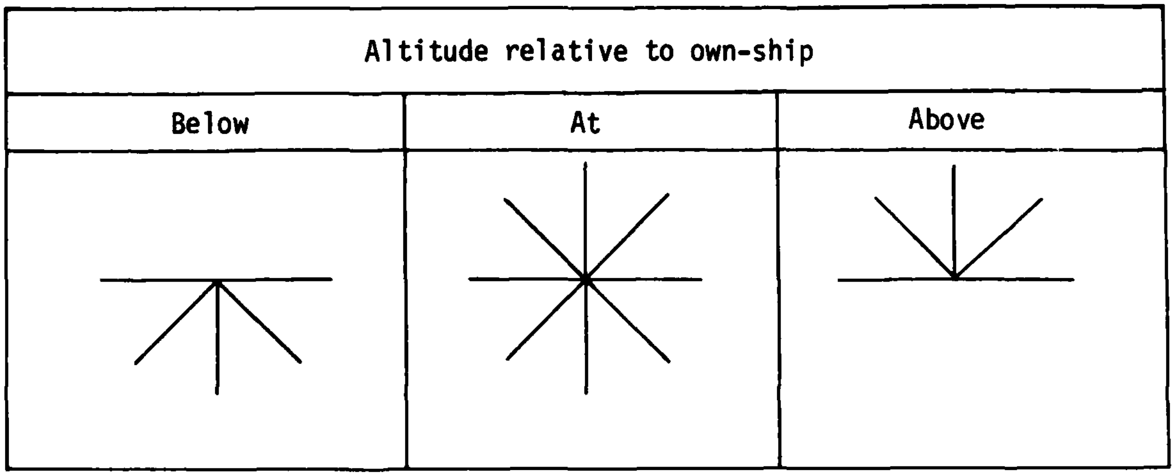
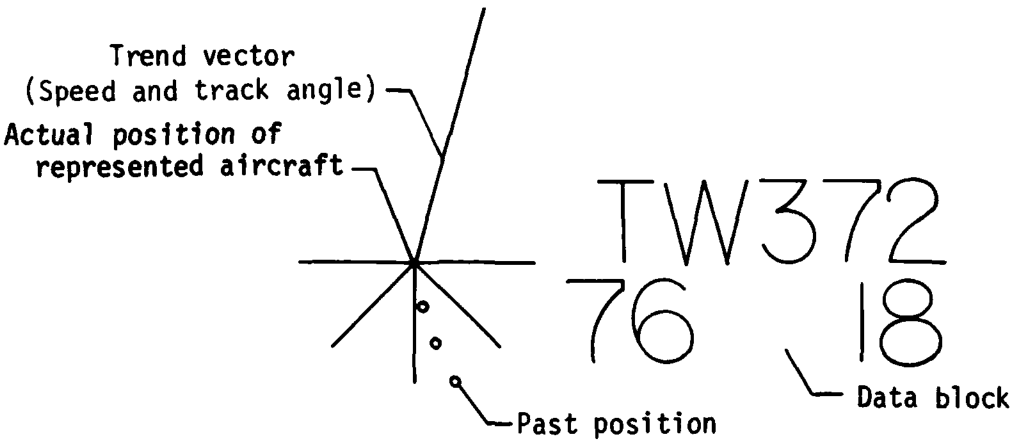


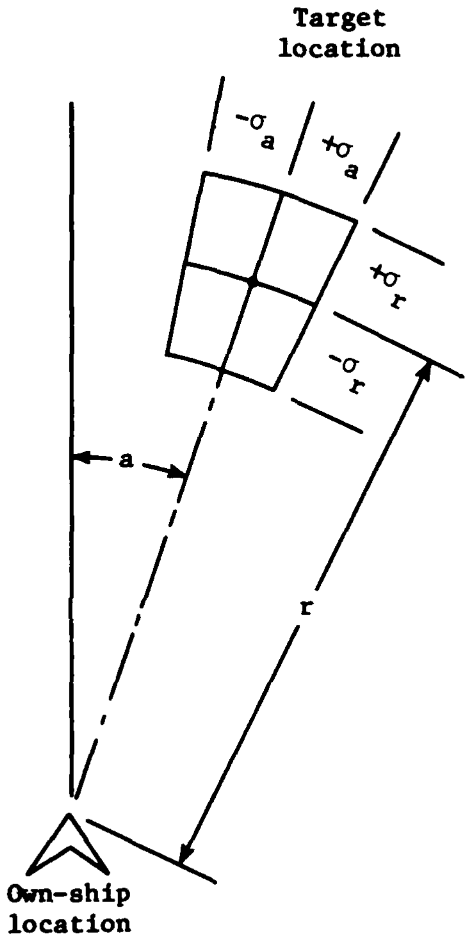
Figure 4.- CDTI format, map scale 4.





Data-block format	
Identifier	
Altitude/100	Speed/10

Figure 5.- Traffic symbology.



a	Azimuthal bearing
r	Horizontal range
σ_a	Azimuthal error standard deviation
σ_r	Range error standard deviation

Figure 6.- Error geometry associated with range and azimuth measurements.

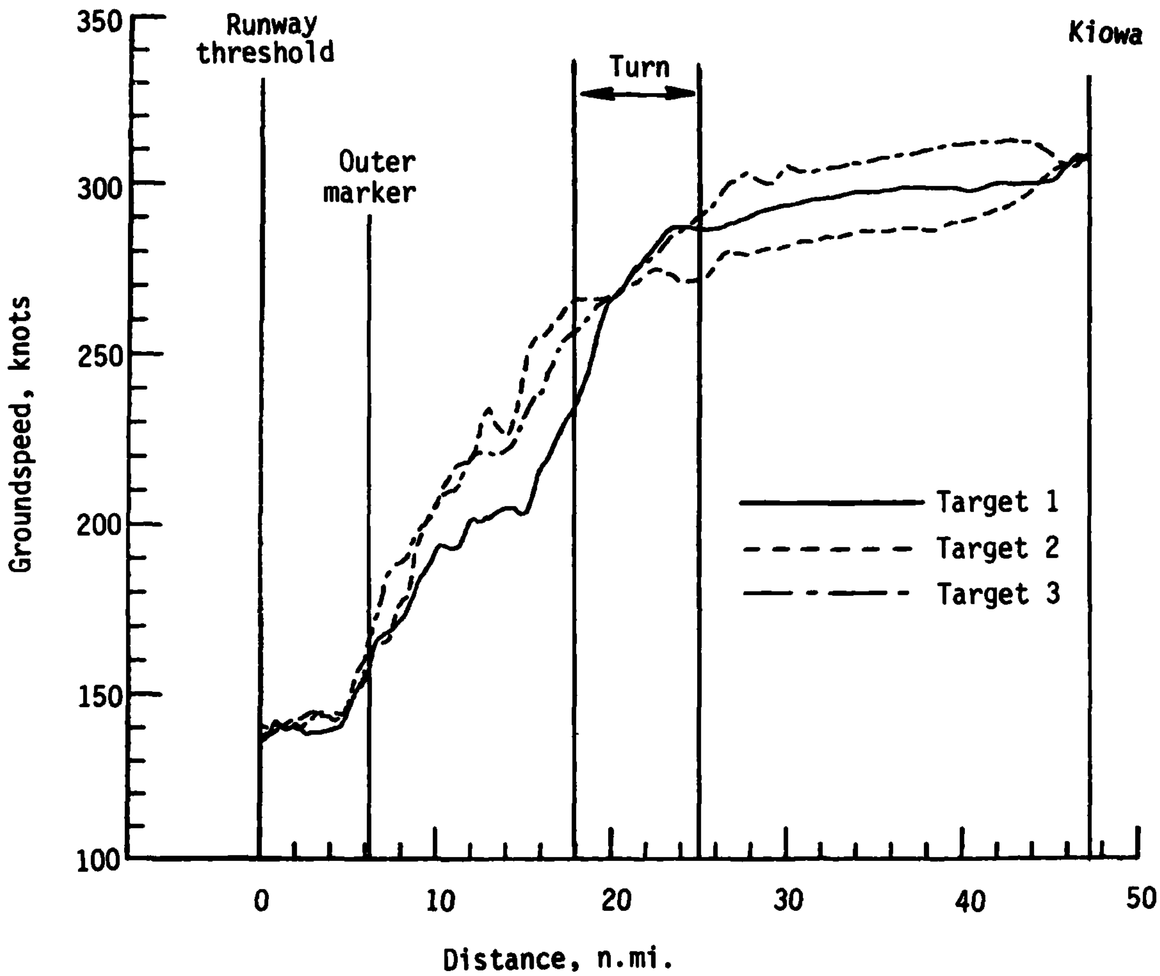
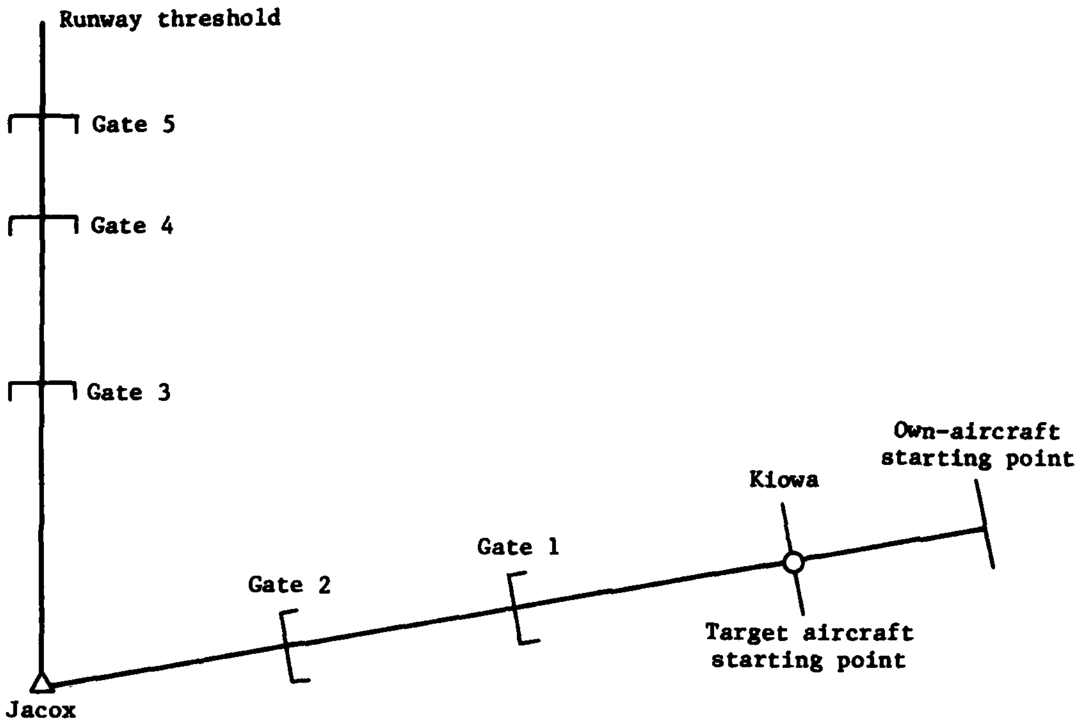


Figure 7.- Groundspeed versus distance to runway threshold for three target aircraft.



Gate	Location	Pilot instructions
1	10 n.mi. past Kiowa VORTAC	Establish 5-n.mi. spacing on target aircraft
2	18 n.mi. past Kiowa VORTAC	Maintain 5-n.mi. spacing on target aircraft
3	13 n.mi. from runway threshold	None
4	Outer marker	Establish 3-n.mi. spacing on target aircraft
5	Approximately 3 n.mi. from runway threshold (target crossing threshold)	Maintain 3-n.mi. spacing on target aircraft

Figure 8.- Locations along approach path used in analysis of pilot self-spacing performance.

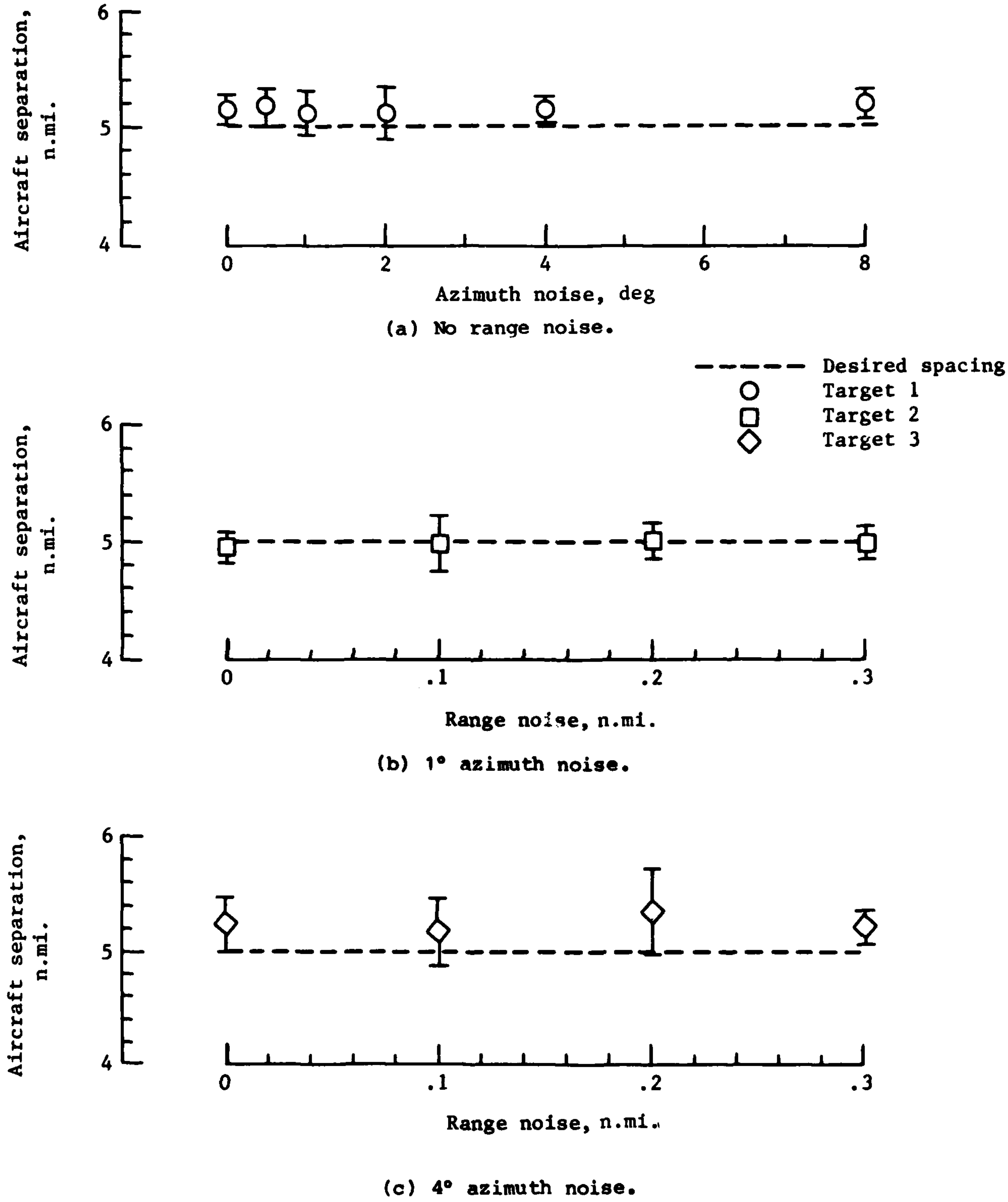


Figure 9.- Effect of sensor noise on spacing performance at gate 1.

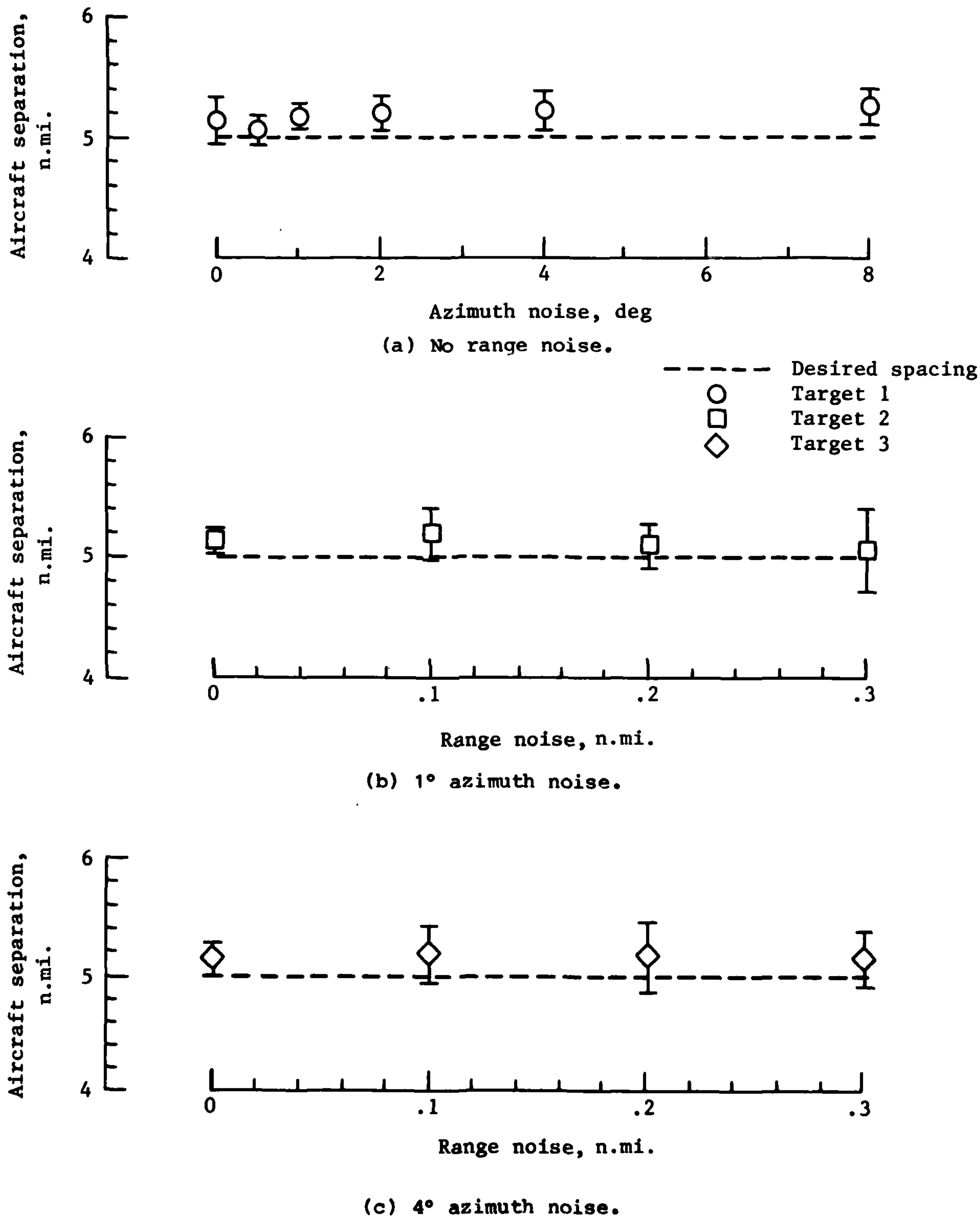
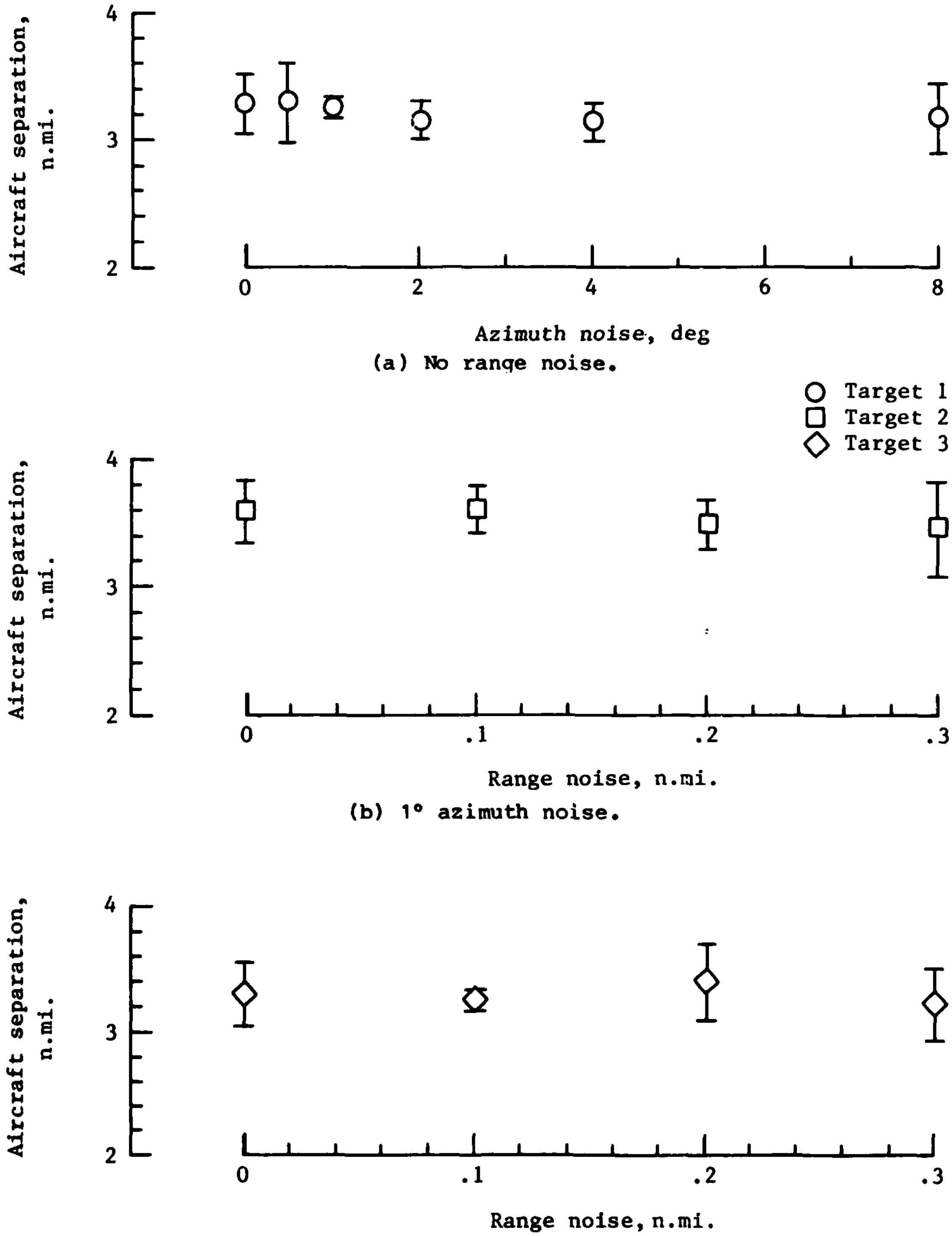


Figure 10.- Effect of sensor noise on spacing performance at gate 2.

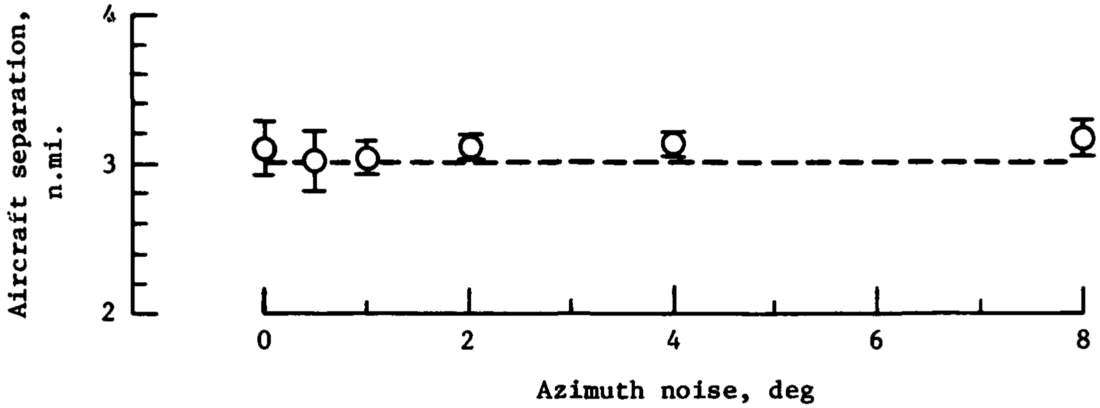


(a) No range noise.

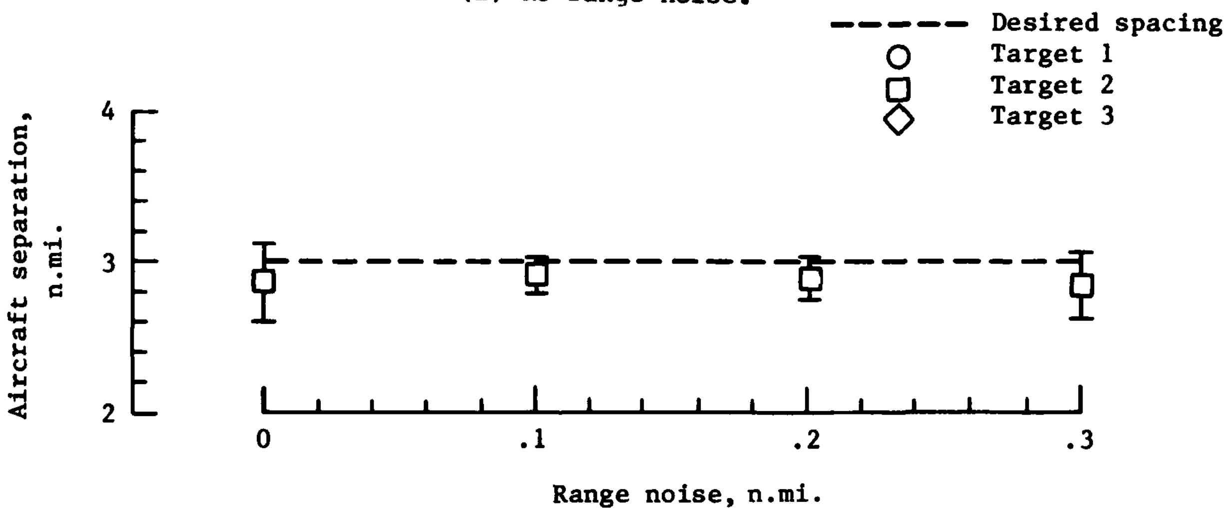
(b) 1° azimuth noise.

(c) 4° azimuth noise.

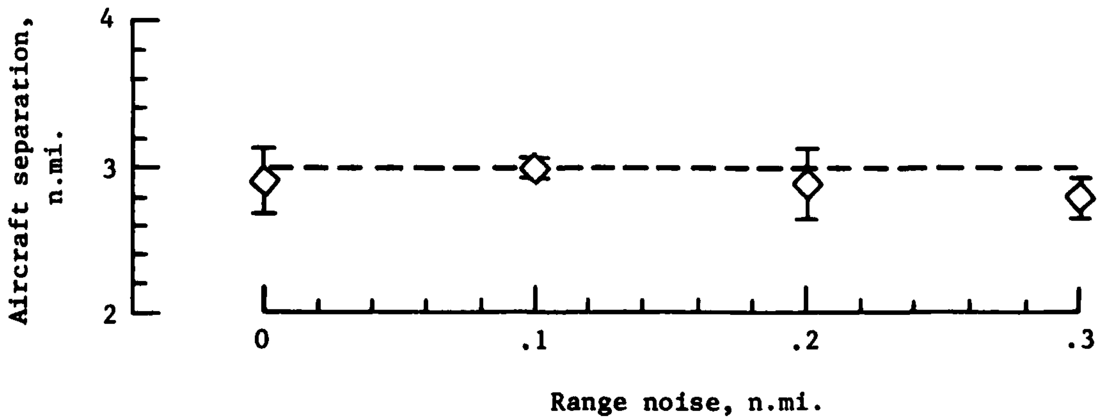
Figure 11.- Effect of sensor noise on spacing performance at gate 3.



(a) No range noise.

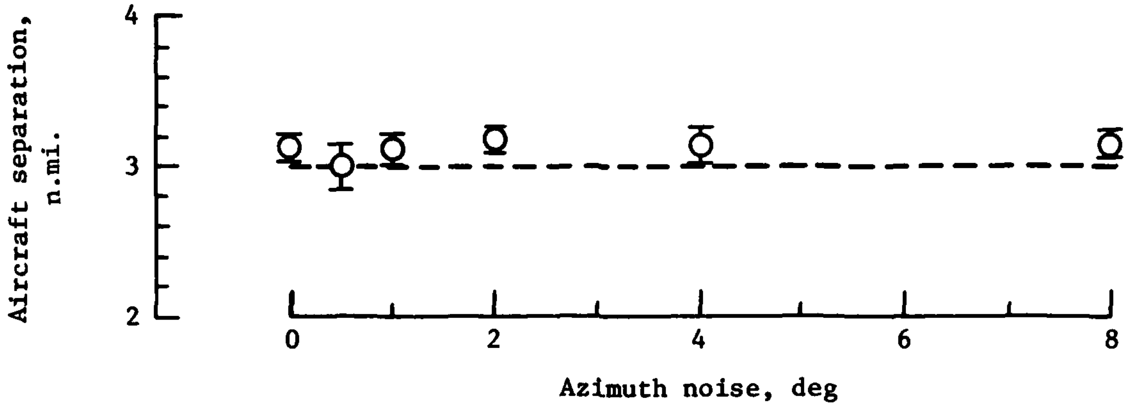


(b) 1° azimuth noise.

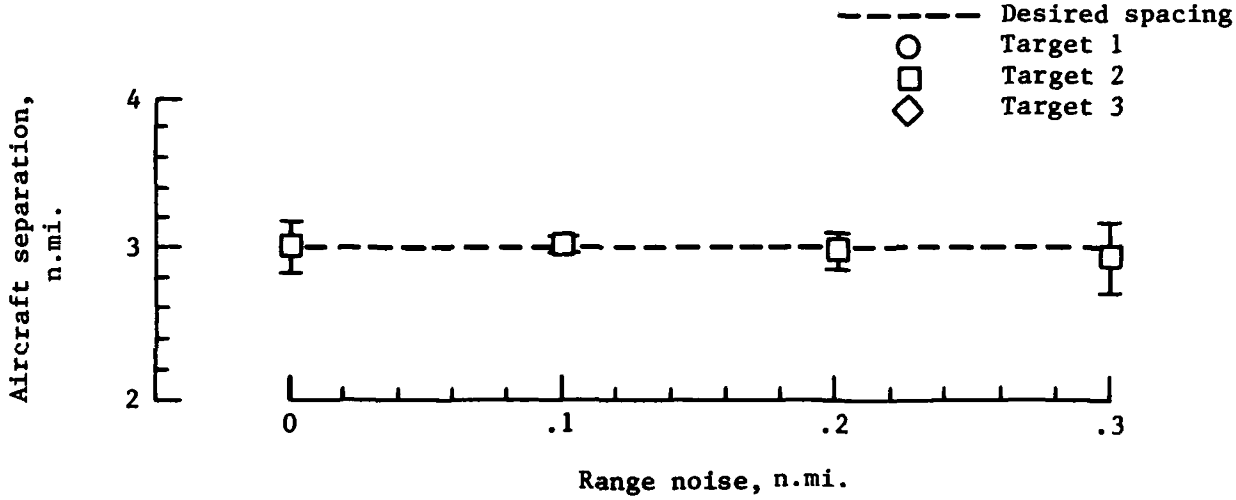


(c) 4° azimuth noise.

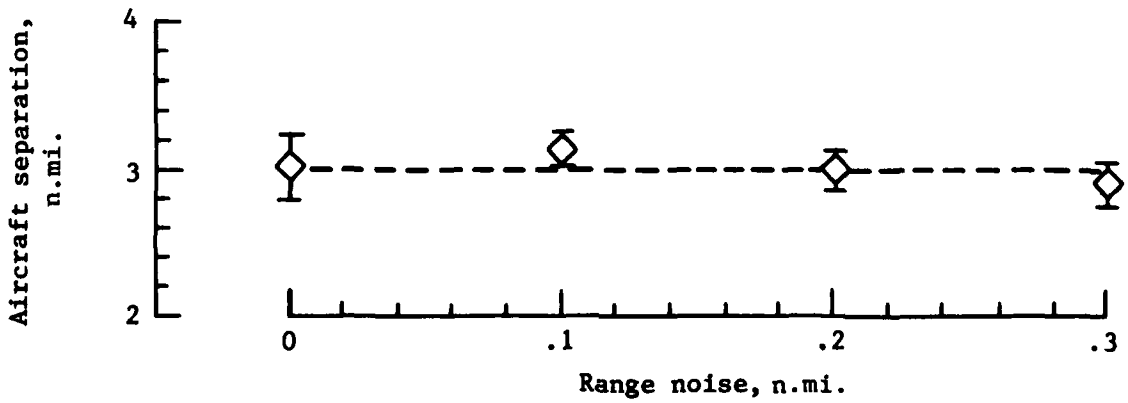
Figure 12.- Effect of sensor noise on spacing performance at gate 4.



(a) No range noise.



(b) 1° azimuth noise.



(c) 4° azimuth noise.

Figure 13.- Effect of sensor noise on spacing performance at gate 5.

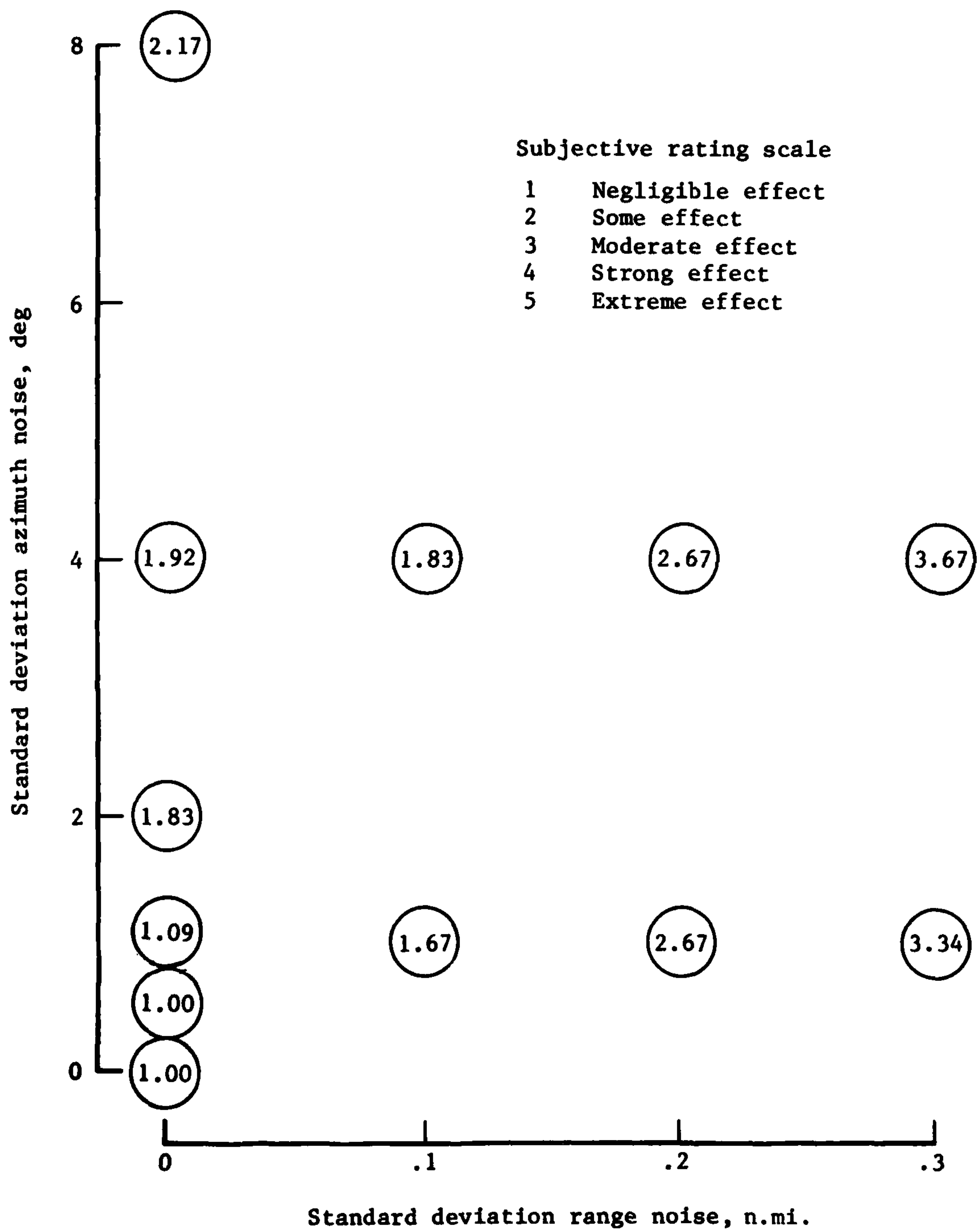


Figure 14.- Pilot average subjective rating of noise effect on spacing performance.

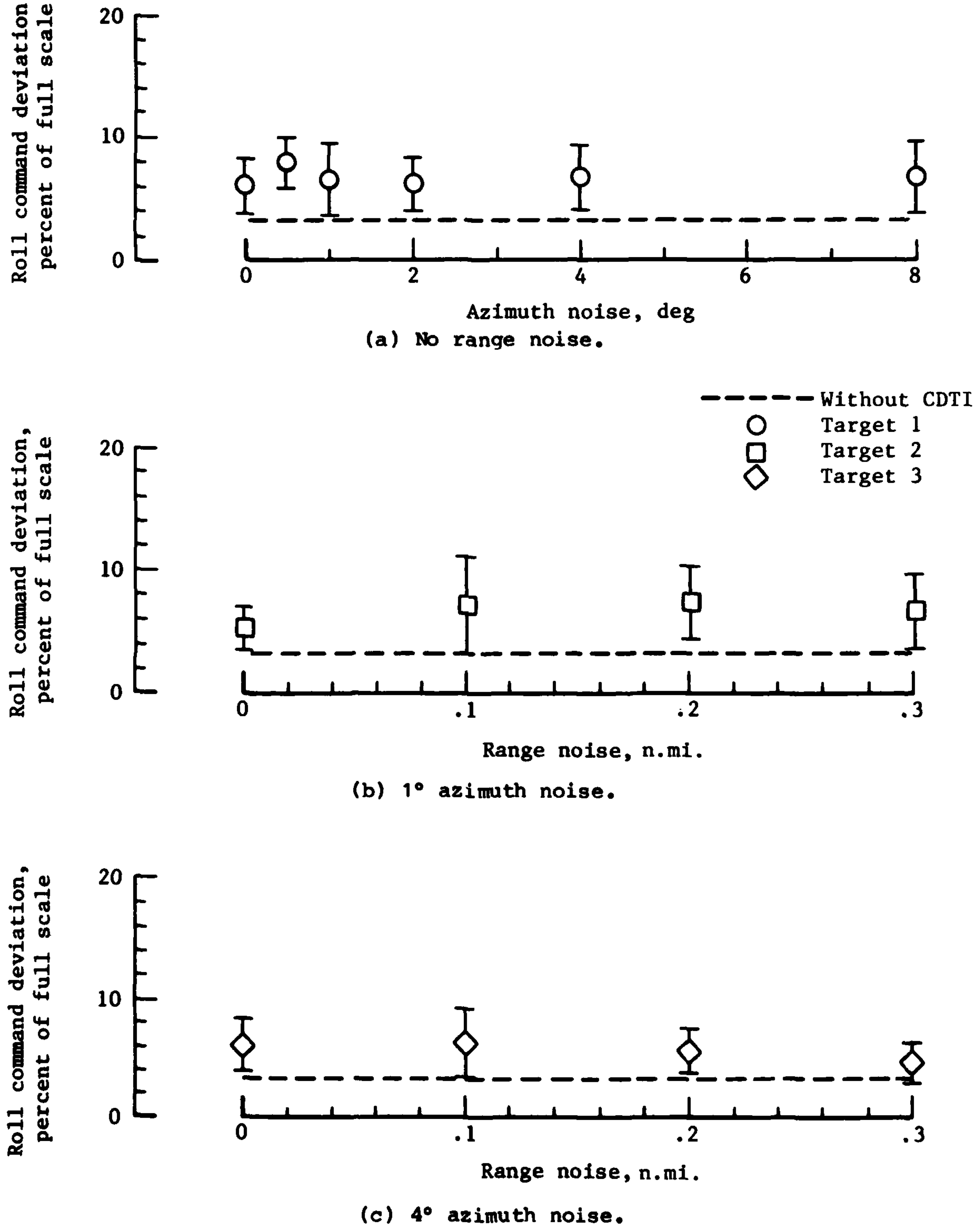


Figure 15.- Effect of sensor noise on flight director roll command tracking performance.

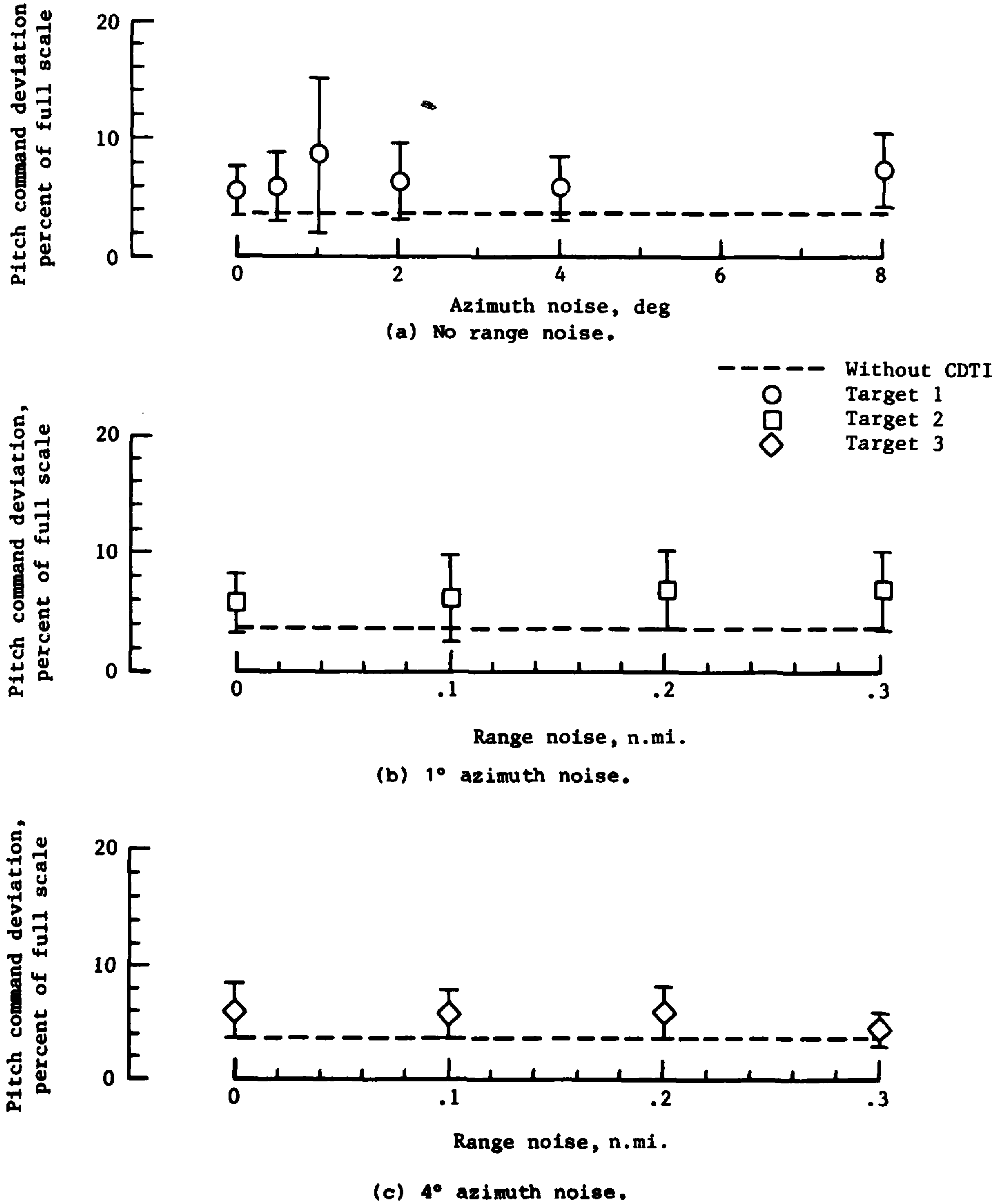


Figure 16.- Effect of sensor noise on flight director pitch command tracking performance.

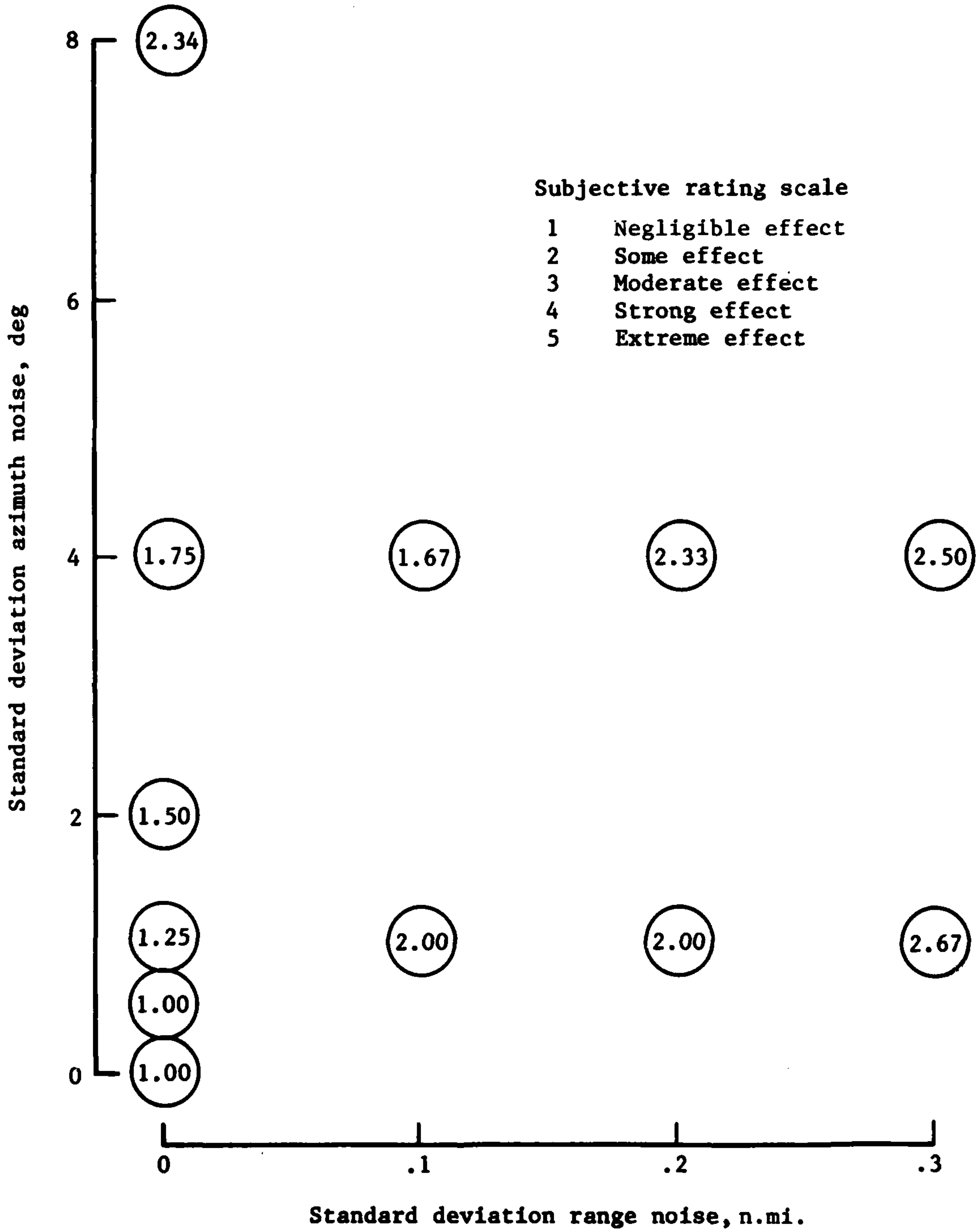


Figure 17.- Pilot average subjective rating of noise effect on flight director tracking performance.

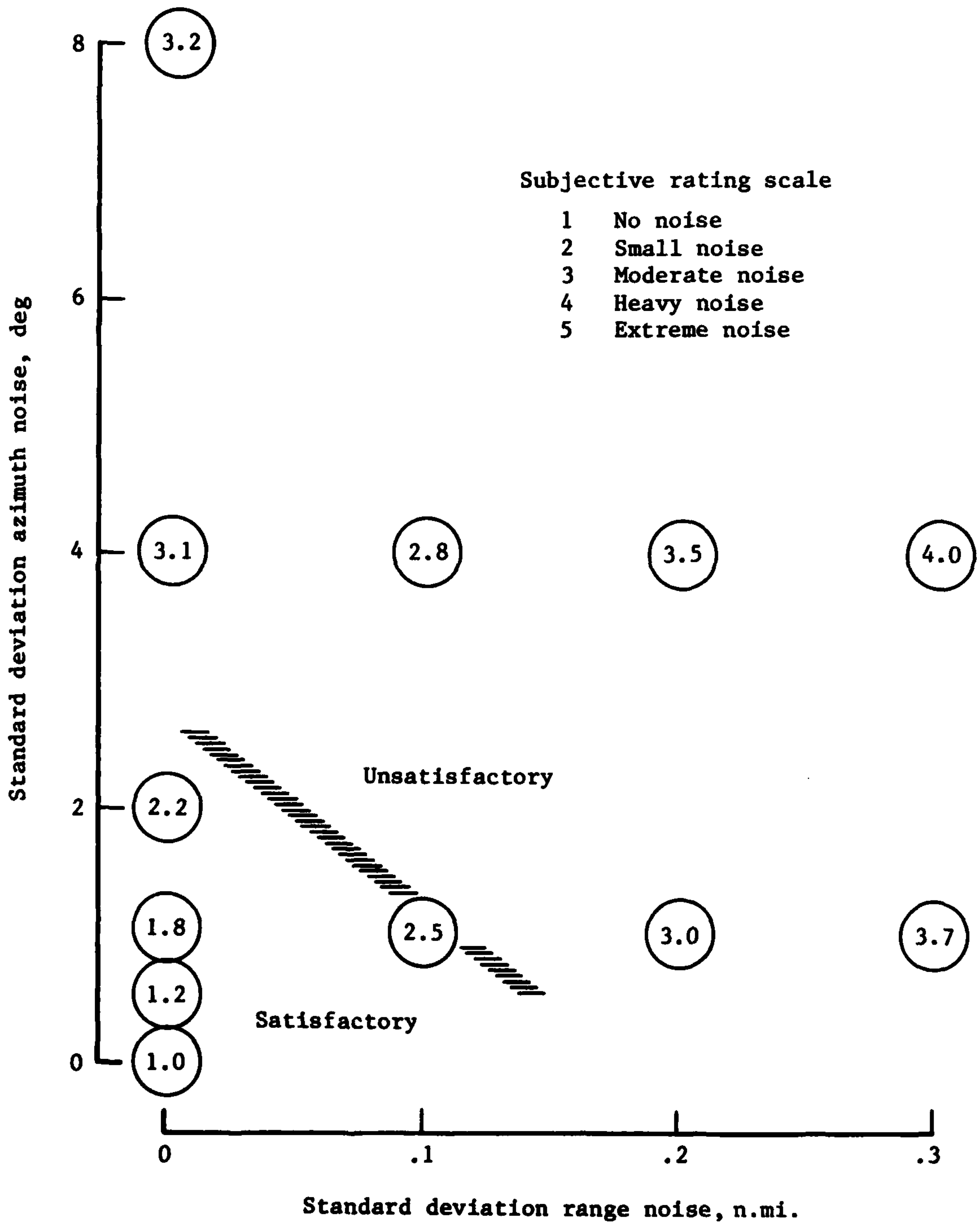


Figure 18.- Pilot average subjective rating of displayed noise level.

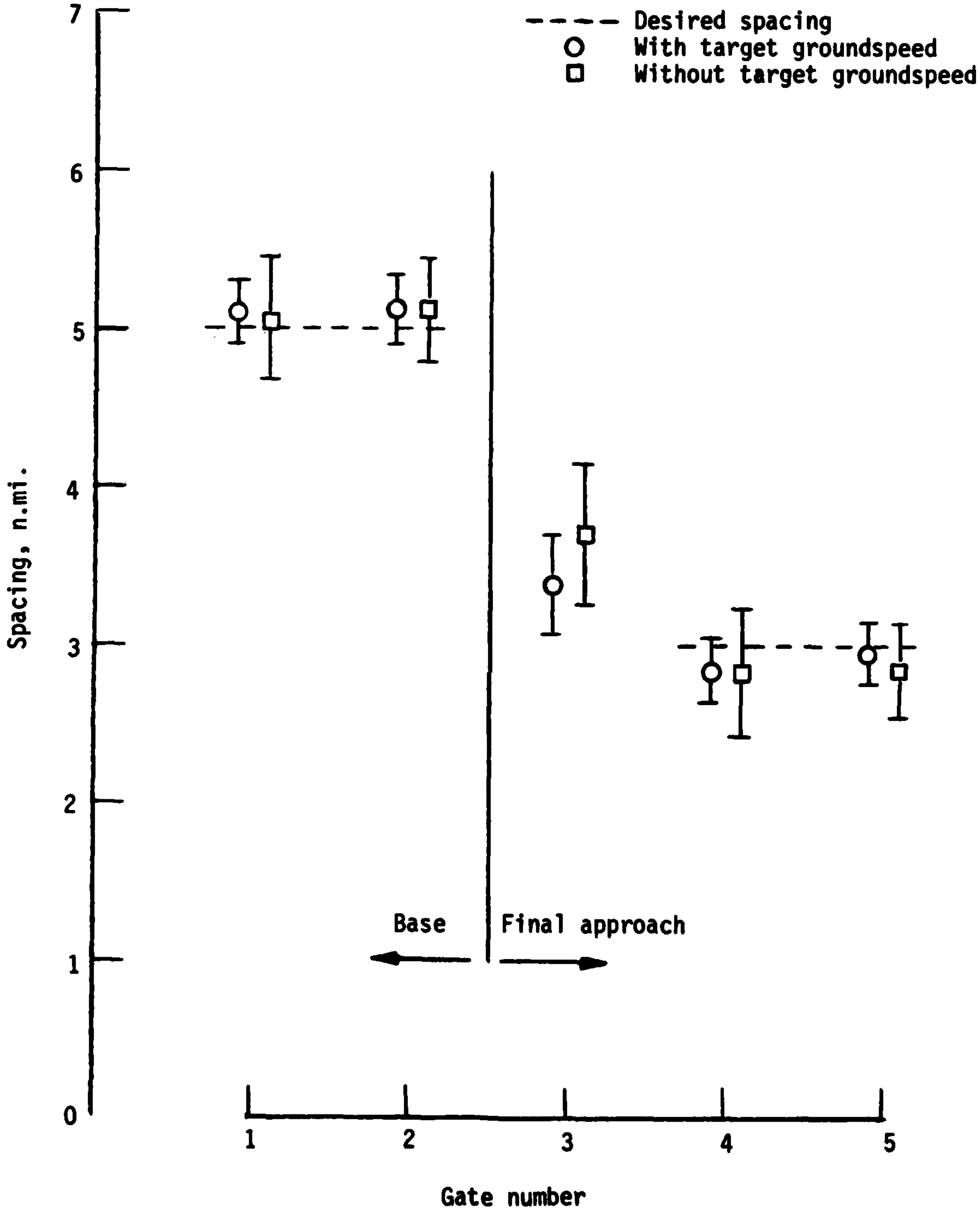


Figure 19.- Spacing performance on final approach with and without target groundspeed tags.

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15. Supplementary Notes

David H. Williams: Langley Research Center.
Gene C. Moen: Structures Laboratory, AVRADCOM Research and Technology Laboratories.

16. Abstract

A simulation study was undertaken to determine the effect of traffic-sensor noise on the ability of a pilot to perform an in-trail spacing task. The tests were conducted in a fixed-base cockpit simulator configured as a current-generation transport aircraft, with an electronic traffic display provided in the weather-radarscope location. The true positions of the traffic were perturbed in both relative range and azimuth by random errors to simulate traffic-sensor noise associated with an onboard sensor. Separation performance data and pilot subjective ratings and comments were obtained during the study. The results of the separation data indicate that displayed traffic position errors, having standard deviation values up to 0.3-n.mi. range and 8° azimuth, had negligible effect on the spacing performance achieved by the pilots. Speed profiles of the lead aircraft, display of the lead aircraft groundspeed, and individual pilot techniques were found to significantly affect the mean spacing performance. Pilot comments and ratings indicated that despite the ability to successfully use the traffic position data with high sensor noise levels, the pilots objected to even small errors in the displayed traffic location.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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