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ASD-TR-71-46

INVESTIGATION OF PILOTS' TRACKING CAPABILITY USING A ROLL COMMAND DISPLAY

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FOREWORD

The work reported in this document was performed at the Crew Station Design Facility, Personnel Subsystems Branch of the Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. The work was conducted under system number 698DF and was accomplished during the period February 1970 through June 1970. Mr. Geiselhart, ASD/ENCCP, was the Air Force program director. This report was submitted by the authors 28 June 1971.

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The authors also acknowledge with gratitude the efforts of Major Kenneth Colson (USAF Reserve), who rendered valuable assistance in preparation of the final draft of the report.

This technical report has been reviewed and is approved.

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ABSTRACT

Ten Air Force pilots having current flying status flew a series of missions to establish baseline normative data for pilot tracking performance. An F-111A flight simulator was used as the test-bed for the experiment. The mission consisted of flying the aircraft simulator at 450 knots and 6000 feet to a designated target while tracking or keeping the bank steering needle centered. Various segments of the mission were designed to measure pilot tracking ability under perturbed and unperturbed conditions. Twenty-seven different evaluation scores were obtained to determine pilot tracking performance. From evaluation of the performance data, it was concluded that by employing a state-of-the-art avionics system an average tracking error of less than .4 milliradian is attainable by pilots when steering an aircraft about the vertical axis. Recommendations are made for further studies on tracking performance as a function of system and pilot constraints.

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SECTION I

INTRODUCTION

The operation of an aircraft in tracking and bombing a target can be and frequently is viewed as a closed-loop feedback control system, in which target position is the primary reference point for the error signal(s). As with all closed-loop feedback systems, specific functions must be accomplished in order to make the system operate effectively. These functions are (a) sensing the error; (b) interpreting the error; (c) correcting the error resulting in effective system output, namely, hitting the target. In essentially automatic feedback systems, e.g., long range missiles, the functions are performed by hardware. In manual feedback systems, e.g., aircraft, the functions are performed by hardware and/or by personnel depending on the function to be performed. For instance, sensing and correcting can be a hardware or operator function, but interpreting error is usually an operator function because of the abstract judgment frequently required. All the considerations described above must be taken into account by designers developing closed-loop control systems for aerospace vehicles. Once the functions of the closed-loop system are defined, based on mission requirements, the designer must allocate the functions to man or hardware. In the absence of adequate function allocation information, it is possible to design a system too complex for its intended user or unnecessarily develop costly hardware to fulfill a function that could be better assumed by the operator. This problem of defining the role of the man in the system has been encountered also by avionics research and development engineers who are interested in developing sophisticated new closed-loop systems and displays for improving bombing accuracy.

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This study is the first in a series of investigations to determine the man vs machine tradeoffs in developing an aircraft's precision bombing system based on the operator's ability to discriminate and correct angle rate errors in tracking.

While a significant portion of the scientific literature in the area of human engineering has been devoted to the study and discussion of man's performance and capability in tracking various kinds of dynamic systems, the usefulness of the available information for the design of Air Force weapon systems has been limited. This is because the majority of the studies have been conducted in a laboratory setting using inexperienced operators (mostly college students) interacting with rather uncomplicated machine dynamics. It is very difficult to take such data and generalize to a pilot flying a very complex high performance fighter or bomber. Also, most laboratory tracking data are not gathered under the conditions of high primary and secondary task loading that a pilot encounters in operating most Air Force weapon systems. This also makes extrapolation difficult. Even in those studies where data were gathered using experienced pilots in simulators, the state-of-the-art of simulation at the time was somewhat unsophisticated. On the other hand, those studies conducted in actual aircraft have been lacking in the precise measurement possible in a laboratory environment. Thus, with some few exceptions, there has been little or no data gathered on the pilot's tracking ability under operational conditions.

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The primary purpose of this study was to establish baseline normative data on the ability of trained pilots to track a command steering display using angle rate information for sensing deviation from a course to the target.

A secondary purpose of the study was to gather preliminary data on the effect on angle rate tracking of a step function update of target position.

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SECTION II

STUDY PROCEDURE

1. SIMULATION PROGRAM

Prior to conducting the present investigation, preliminary steps were necessary to determine the type of system to be simulated to establish baseline pilot tracking performance. Several assumptions were made in programming the simulation. These assumptions were as follows: (a) an errorless automatic TV tracker to provide angle rate error information, (b) an inertial navigation system, (c) straight-in approach to the target with no evasive action required, (d) altitude hold equipment, (e) augmented flight information to aid the pilot in tracking. The first four assumptions were easily incorporated into the simulation program; but the fifth assumption required development of a simulation program format that optimized the pilot/equipment relationship so that pilot tracking performance was not degraded due to equipment characteristics, thus making it possible to obtain a pure measure of pilot tracking ability. The analysis required to optimize the pilot/equipment relationship is discussed in the following paragraphs.

In earlier tracking studies (References 5, 6) it was found that, if heading error and angle of bank were summed and displayed to the pilot on the attitude director command needles, the pilot's track to the target was greatly improved; however, the effectiveness of the system was greatly reduced if needle gains were not optimized. A similar approach was selected for the present study except that only the roll command indicator on the ARU/11A (Figure 1) was used and more terms were added

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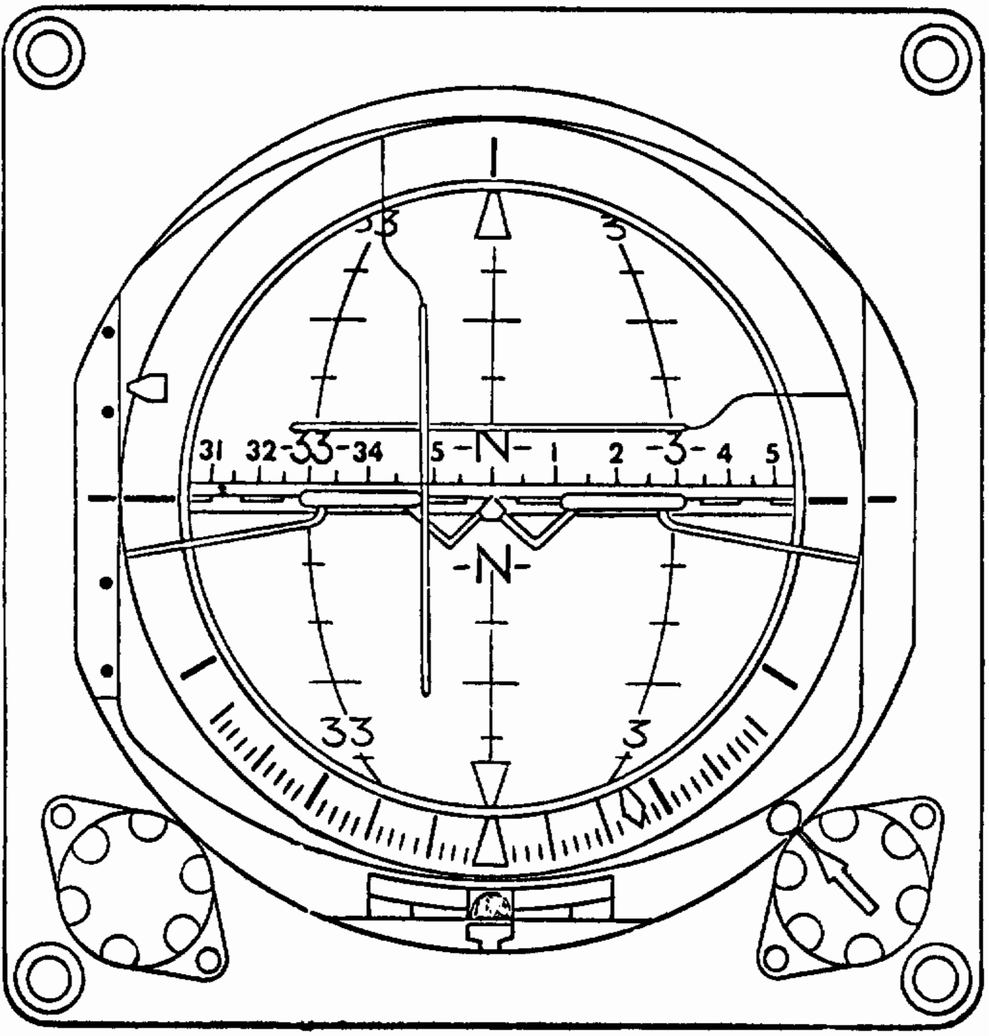

Figure 1. ARU/11A Attitude Director Indicator

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to the summation equation based on empirical data from a limited group of pilots who participated in a pretest of the system. The definitions and formula for determining the amount of displacement of the tracking needle, the underlying error functions, and scale factor value are described below.

Let X = Scale factor

ϕ = Bank angle (error)

Then Needle Displacement $D = F\phi \cdot X$

where further

$$\phi = \alpha_1 \psi_e + \alpha_2 \dot{\psi} + \alpha_3 \beta + \alpha_4 \delta_e$$

and

ψ_e = Course error (ground track minus bearing to the target)

$\dot{\psi}$ = Rate of change of course error

β = Aircraft yaw angle

δ_e = Lateral stick position

α_i = Coefficients (can be determined from Figures 2 through 6)

The scale factor (gain) X is given by:

$$X = \begin{cases} 1 \text{ for } |D| > \frac{5}{2} \\ -\frac{2}{5} \quad |D| + 2 \text{ for } |D| \leq \frac{5}{2} \end{cases}$$

where D is needle displacement measured in needle widths.

Bank Angle - The bank angle function is the angle between the earth horizon (right angle to the gravity vector) and the horizontal reference line of the aircraft, parallel to earth horizon in level flight. Figure 2 shows the relationship between bank angle and the amount of

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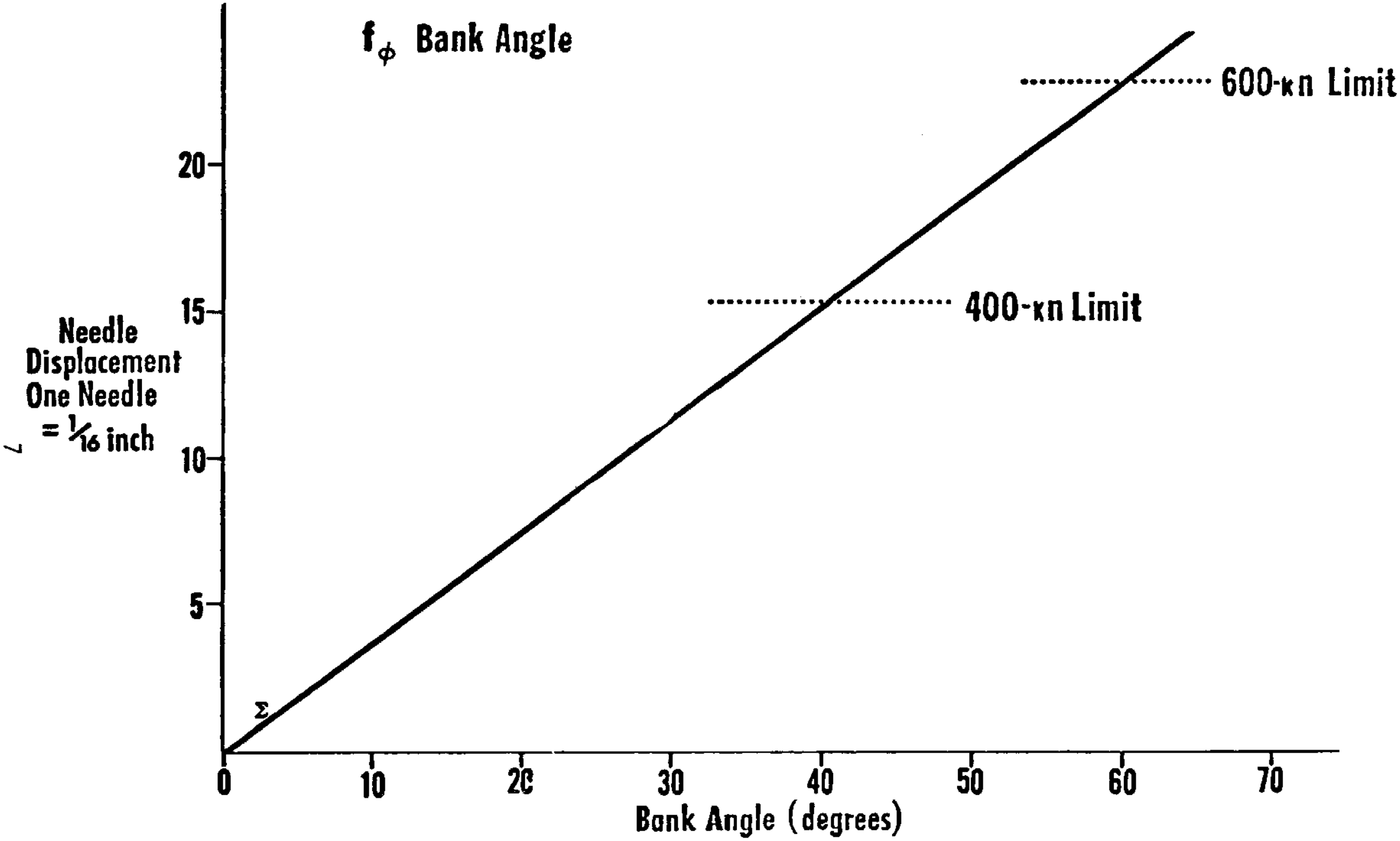

Figure 2. Relationship Between Bank Angle and Vertical Needle Displacement

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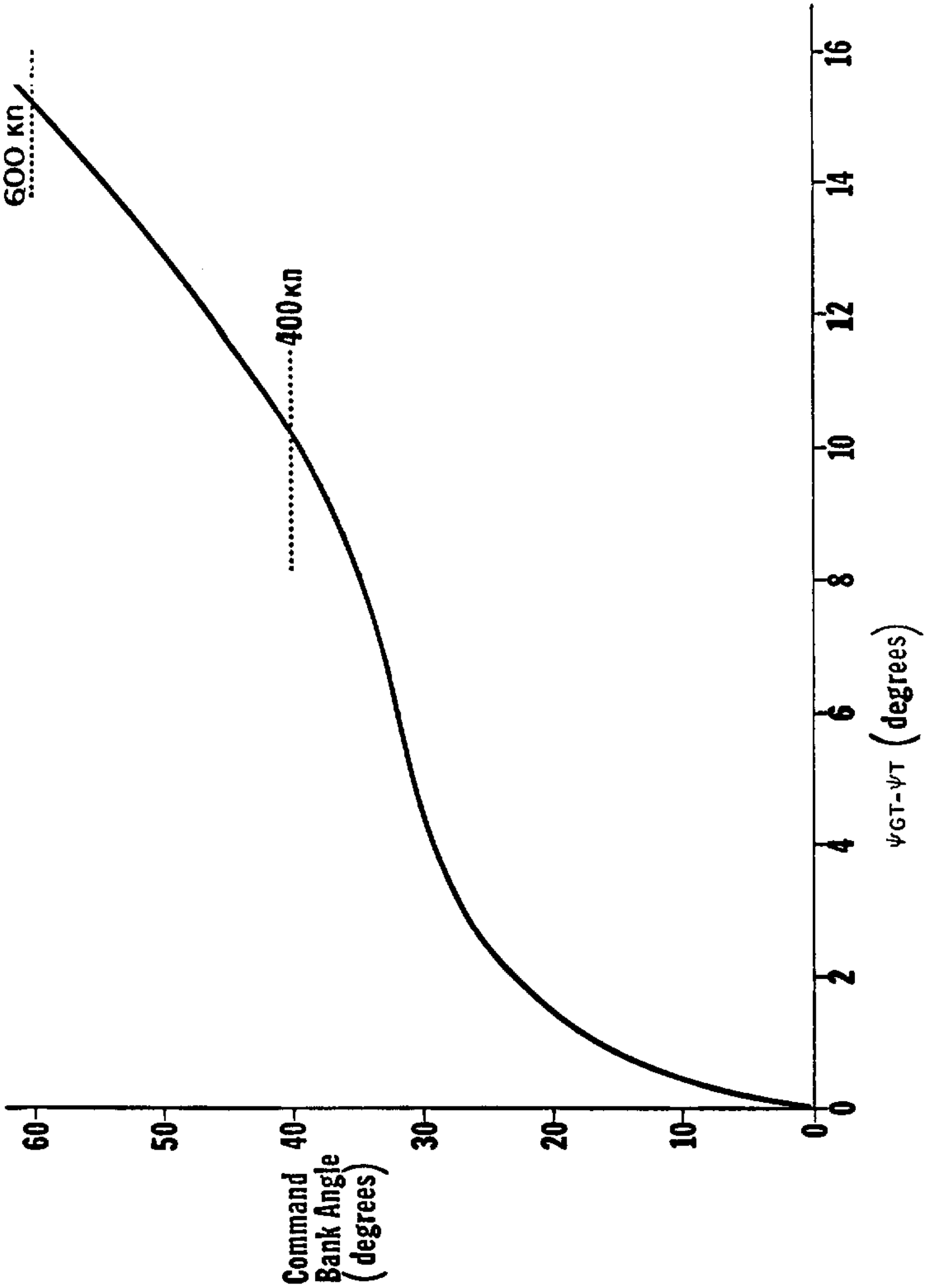

Figure 3. Course Error Function

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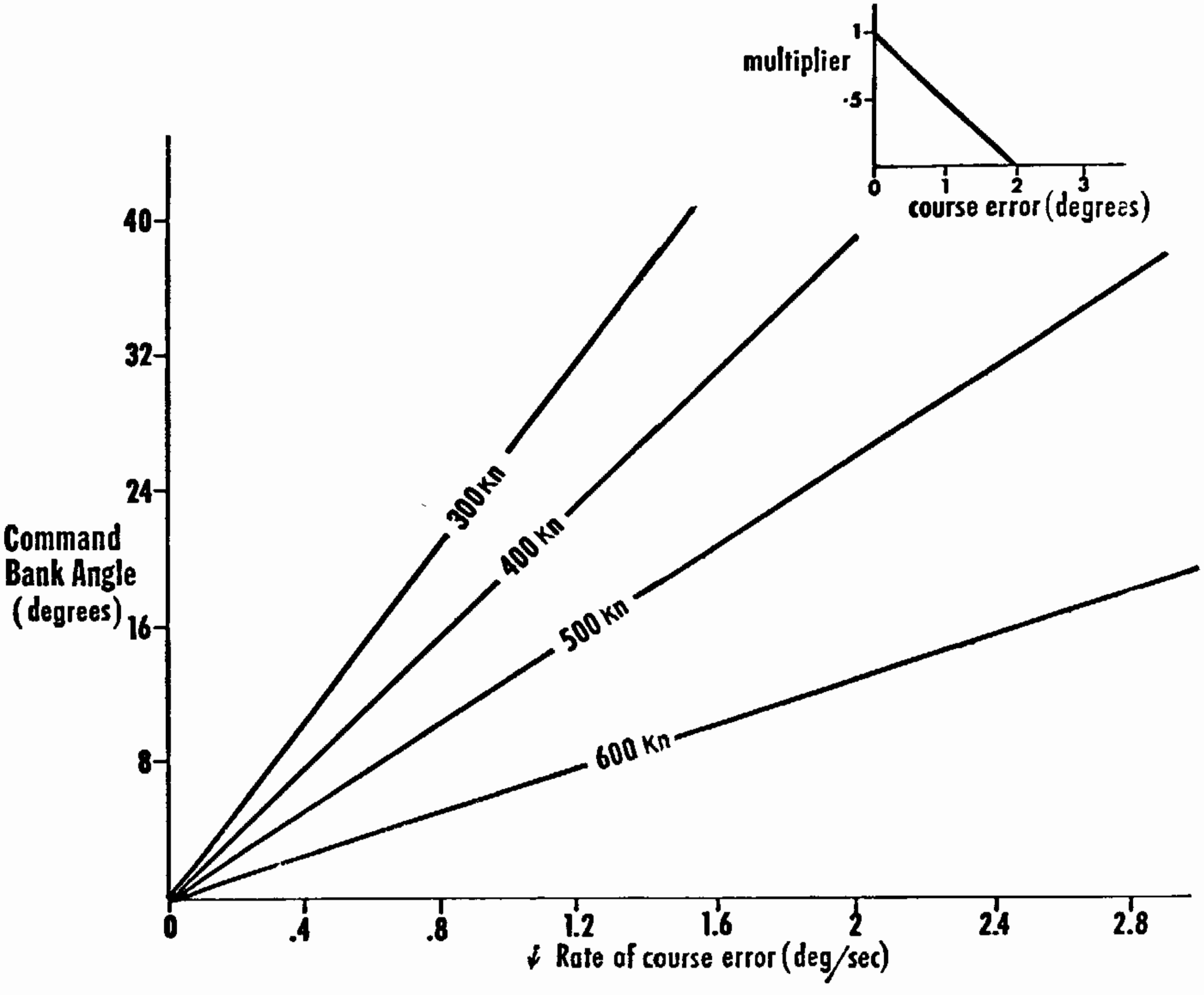

Figure 4. Rate of Change of Course Error

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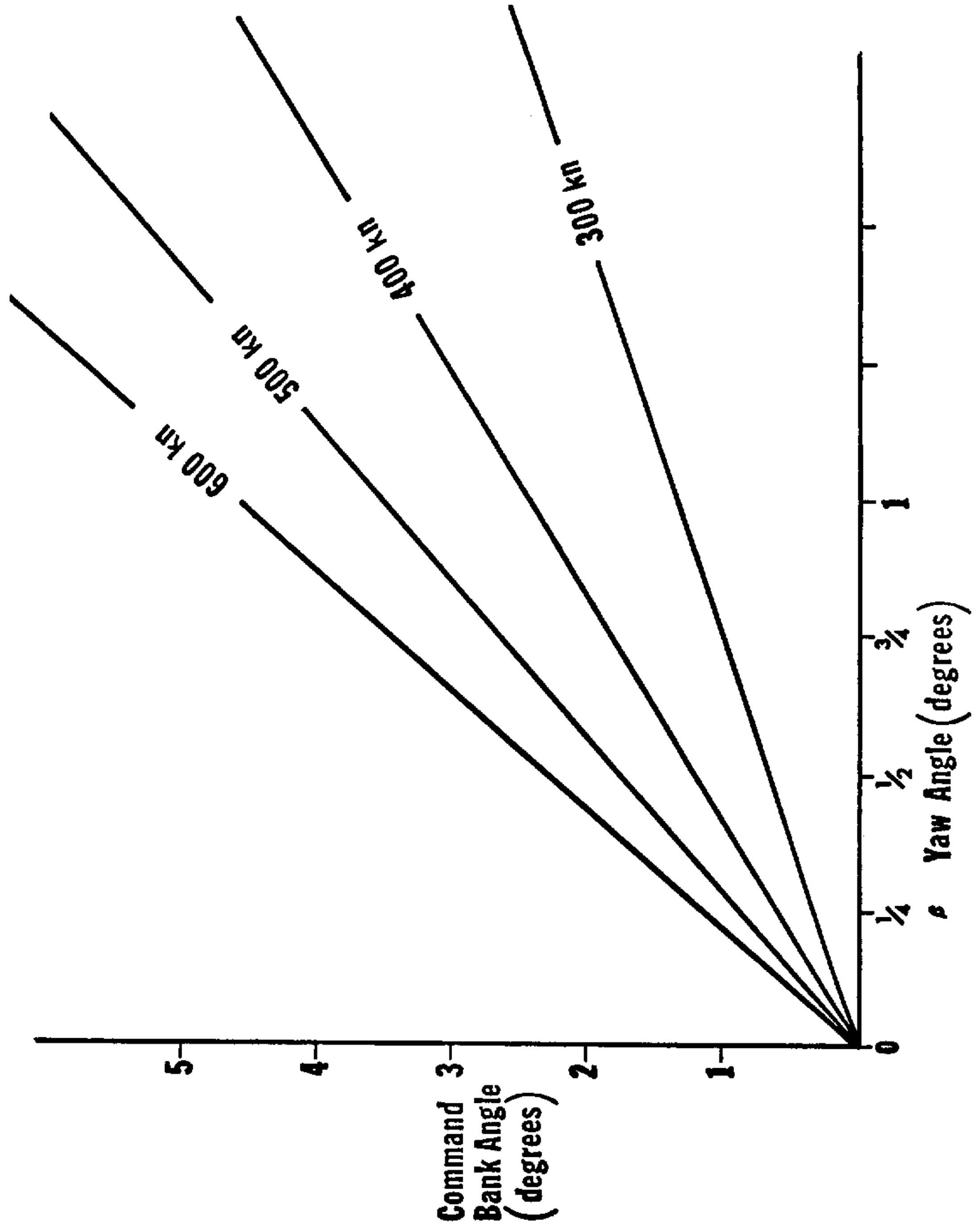

Figure 5. Aircraft Yaw Angle

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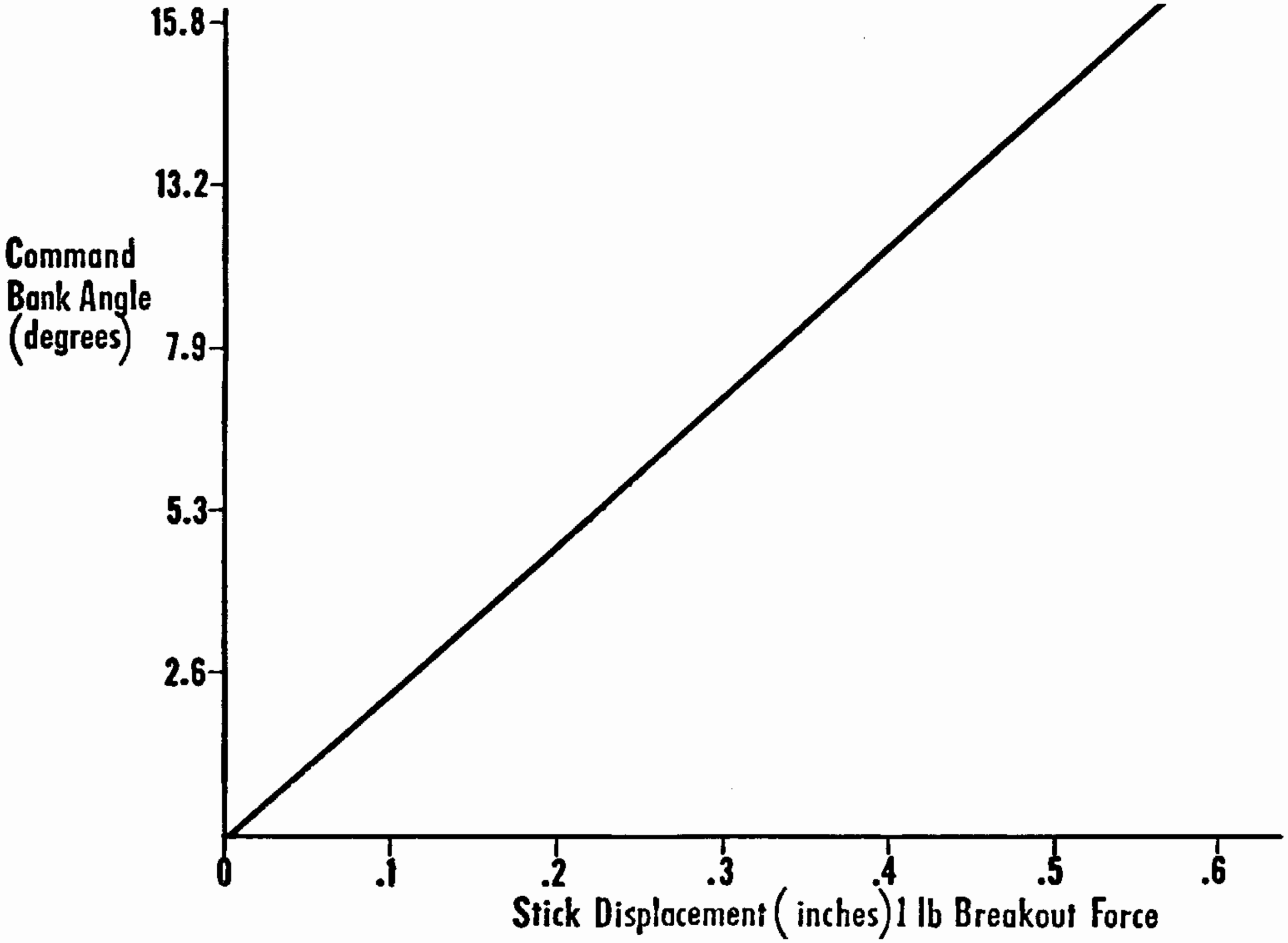

Figure 6. Lateral Stick Position

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bank steering command needle displacement that is displayed to the pilot on the attitude director indicator. All error terms were related to bank angle since corrections in this aircraft axis are required to maintain an accurate angle track to the desired path to the target. The dotted lines at 400 and 600 knots true airspeed are system limitations, i.e., the pilot could not exceed 40 degrees bank and 60 degrees bank at 400 and 600 knots, respectively, and remain in stable flight.

Course Error (ψ_e) - The course error function (Figure 3) is the angle between true north and the aircraft ground track minus the angle between true north and bearing to the target. This error term was added to provide primary error information, and directed a constant bank angle to bring the pilot back on course as quickly as possible. The term also tended to prevent the pilot from rolling out too soon. Instrumentation for sensing this error term is somewhat complex in that ψGT requires an inertial platform and the ψT would use an automatic TV tracker; however, the two could be combined in an inertially stabilized TV tracker.

Rate of Change of Course Error ($\dot{\psi}$) - The rate of change of course error (Figure 4) acted as a stabilizing force in conjunction with the course error function, i.e., the course error function was used to prevent undershooting while the rate function was designed to preclude overshooting or overcontrolling. Since rate functions tend to reduce time on target when attempting larger corrections, the rate function was eliminated for course errors greater than 2 degrees. Between 0 and 2 degrees the gain of the rate function was changed in a linear fashion from 0 to 1. Thus, as the pilot approaches a desired heading, his

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larger corrections are attenuated and once he is on target the system becomes most sensitive, causing a commanded correction at the slightest error. To further stabilize the rate function, it was modified by airspeed, so that as airspeed increased the slope of the function decreased. This function would also rely on the TV tracker, which would provide angle rate error.

Aircraft Yaw Angle (β) - The aircraft yaw angle (Figure 5) was included as the only predictive term in ϕ. In the preliminary phase of this study it was found that small but rapid maneuvers of the aircraft such as inadvertent stick movements or rough air gusts caused uncoordinated flight. To overcome this anomaly very small yaw angles would command some bank angle. The yaw function is a measure of instantaneous side forces on the aircraft. Since the resulting rate of turn of a given yaw angle is a function of dynamic pressure this function was also speed-compensated - the higher the speed, the greater correction required. The yaw angle function would probably require a specialized device such as an accelerometer or other similar sensor. This may require some research and development of hardware.

Side Force - As the steering equation was developed, it was found that the pilot had the tendency to overcontrol the aircraft. To maximize time on target, it was necessary to find some way of indicating to the pilot exactly the magnitude of the control input required without awaiting the aerodynamic feedback. To accomplish this, lateral stick position was selected to indicate side force. The side force is measured between the vertical reference line of the aircraft (parallel to the

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gravity vector in level flight) and the force vector at any instant on the aircraft lateral axis. This angle was measured between the neutral position of the control stick and the lateral stick displacement at any instant. This error can be sensed either by force sensors in the control system or, in the case of an adaptive gain-control system, this term can be sensed in the control stick computer. Figure 6 depicts the graph for determining this function.

The method of determining the value of the scale factor used is shown in Figure 7. As needle displacement approaches zero, the scale factor increases linearly. This function makes the system more sensitive the closer the pilot approaches zero. The function tends to hold a pilot on course once he nulls the needle. Beyond 2.5 needle widths, the gain is reduced to one to one. Since a larger control input is required for correction at values greater than 2.5, a gain greater than one could easily cause the pilot to overcontrol the aircraft. The weighting of the summed values varies depending on size of error and the particular performance envelope within which the aircraft is being operated.

In addition to the above terms, side slip acceleration and roll acceleration were investigated but were eliminated from the equation; the former was deleted as superfluous and the latter because the term tended to steer the pilot off target.

Following definition of the aiding equations, these were programmed into the Mark I computer for display on an ARU/11A Attitude Director Indicator (Figure 1) installed in the F-111A simulator.

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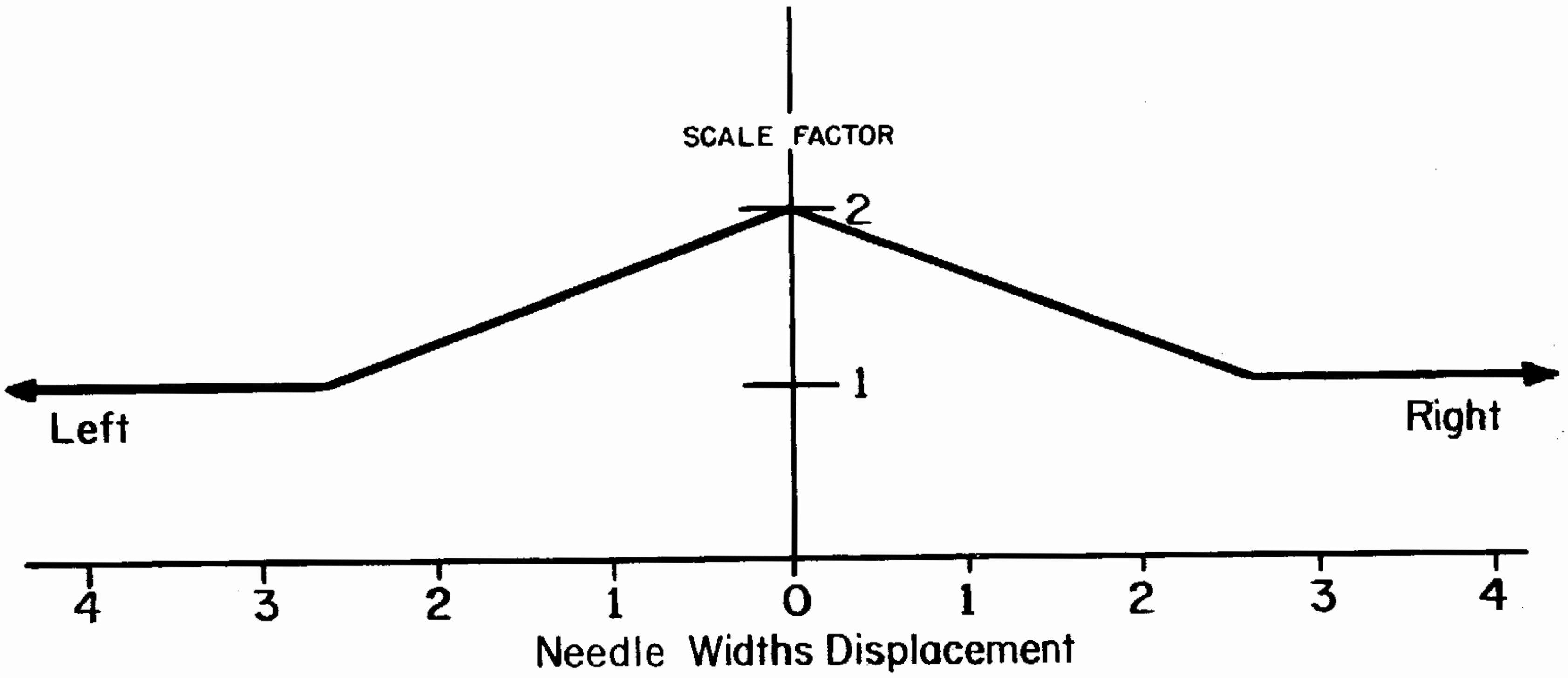

Figure 7. ADI Vertical Needle Gain

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2. APPARATUS

The apparatus for conducting this experiment was the Crew Station Design Facility, which has the capability to dynamically simulate a complete flight regime under a variety of controlled conditions. The facility consists of six basic components:

1. Three crew station shells mounted on motion bases
    a. F-111A
    b. C-135B/C5
    c. F-4D
2. Two Link Mark I digital computers
3. A visual system
4. Radar simulation equipment
5. Monitors and recording equipment

For this study only the F-111A cockpit was used. The crew station shell configured as an F-111A is mounted on a motion platform having three types of motion - 15 degrees down and 25 degrees up in pitch, 9 to 20 degrees roll depending on pitch angle, and ±12 inches of vertical displacement. The digital computer interacts with and controls all systems involved in simulation of a total mission. With the magnetic tape unit, up to 500 separate parameters can be recorded every .2 seconds for later data analysis. The visual simulation equipment was not used in this study. A drawing and block diagram of the facility are shown in Figures 8 and 9.

3. TRACKING TASK

The tracking task consisted of flying the aircraft simulator at 450 knots and 6000 feet while tracking the bank steering needle (keeping

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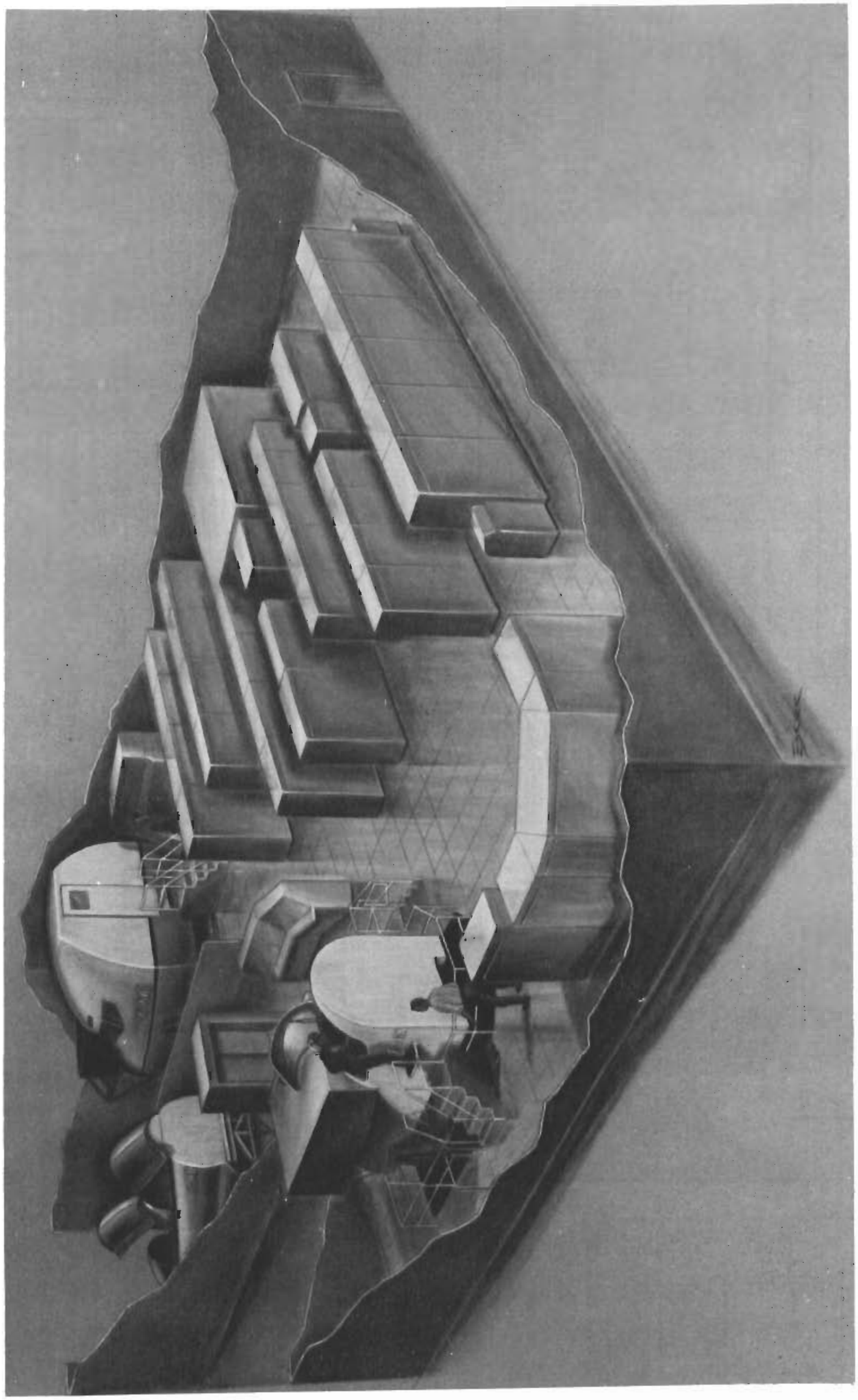

Figure 8. Crew Station Design Facility

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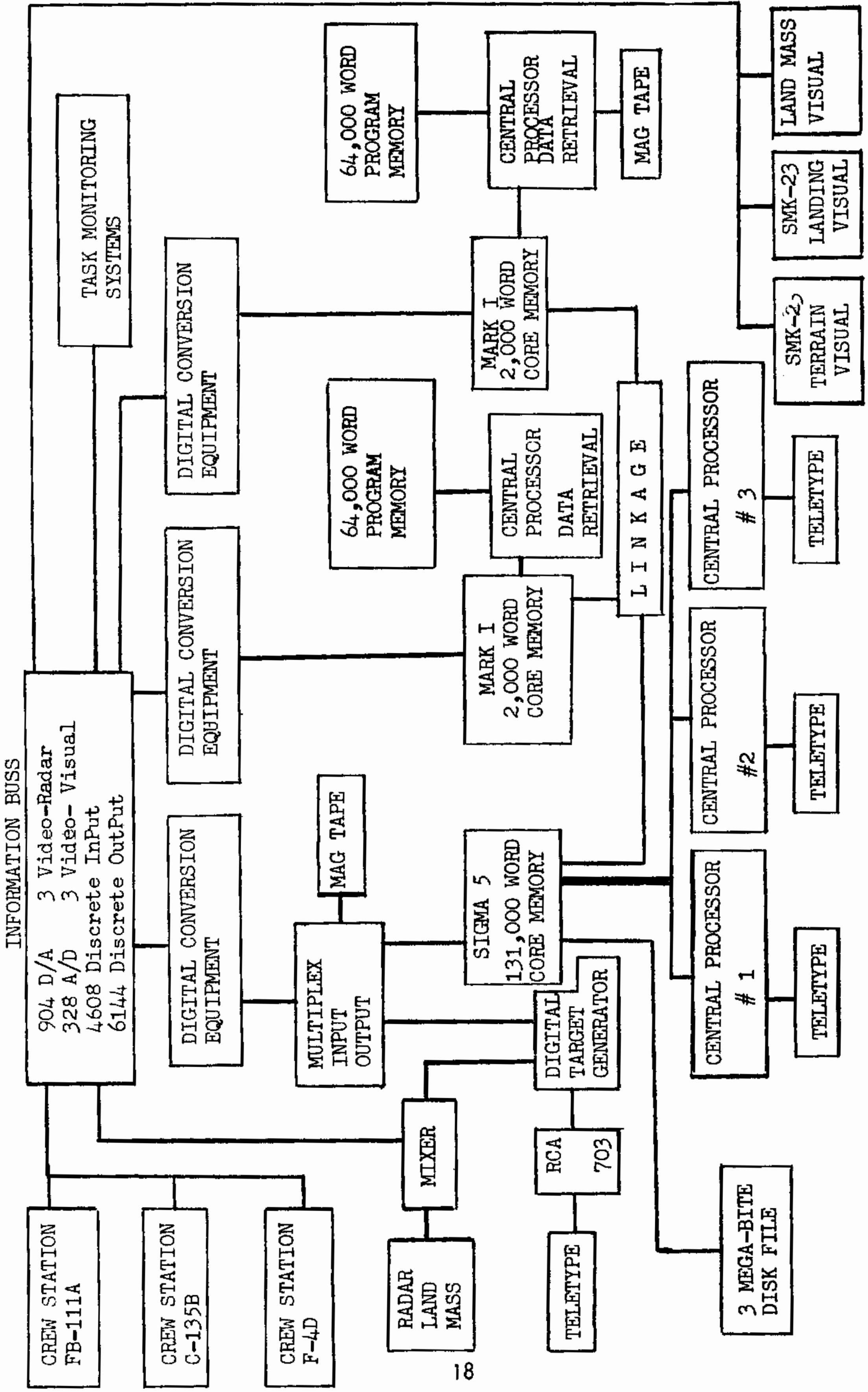

Figure 9. Block Diagram of Crew Station Design Facility

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it centered). During the unperturbed runs, the pilot was required to keep the needle centered; during the perturbed runs the steering needle was deliberately offset 5 milliradians and the pilot had to recenter it as rapidly as possible. The perturbation was introduced four miles from the target. Each tracking run had a duration of approximately 45 seconds and data were recorded every .2 of a second from 6 miles out to the target. An eight-channel recorder was run continuously (6 miles to target) as a backup data-collection technique.

After the briefing, the pilots were each given a practice session of approximately 15 minutes. If more time was required for any pilot to feel confident in task performance, he was allowed more practice. When the practice was completed a 20 minute break was given (at this time the other subject got his practice), and after the break Session I was begun. After each run (pass over the target) the simulator was reset geographically within the computer and, when the pilot indicated over the intercom that he was ready, he was released for the next run. Three runs for each of three missions made up Session I. After this session another break of 20 minutes was given and then Session II was "flown." The methodology during both sessions was similar except that the perturbed vs unperturbed runs were counterbalanced.

4. SUBJECTS

Twelve subjects were used in the experiment and all were rated USAF pilots. Four of these pilots had completed the USAF Aerospace Research Pilots' Course and all but two of the subjects had flown the F-111A simulator in previous studies. These latter two were dropped since

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they were unable to learn the task to a sufficient degree to follow the display. The subjects mean age was 35 with an average flying time of 3120 hours. Overall summary by individual subject is presented in Table I.

5. EXPERIMENTAL DESIGN

The experimental design was an AxBxS design described in Lindquist's Design and Analysis of Experiments in Psychology and Education (Reference 3).

The analysis regarded the flight condition (perturbed or unperturbed) as the "A" variable, number of trials the "B" variable, and number of subjects the "S" variable. Each subject went through all experimental conditions, thus acting as his own control and thereby increasing the efficiency and precision of the experiment. A graphic outline of the study is shown in Figure 10.

6. PERFORMANCE MEASURES

Statistical data on 27 parameters selected to measure pilots' tracking performance (See Table II) were obtained using the computer output on magnetic tape to record them. From these 27 parameters, the six parameters listed below - considered most relevant to pilot tracking performance - were analyzed extensively, employing absolute average error (AAE), average error (AE), root mean square (RMS), and percent time on target as the scoring measures.

1. Milliradian deviation from desired course
2. ADI steering command (needle displacement)

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TABLE I

PERSONAL QUESTIONNAIRE DATA

Subject	Age	Qualification	Type Duty	Flying Time (hr)
1	34	Senior Pilot	Test Pilot	2200
2	37	Senior Pilot	Fighter	3500
3	31	Pilot	Test Pilot	1800
4	33	Senior Pilot	Fighter Pilot	2500
5	38	Senior Pilot	Fighter Pilot	3100
6	33	Senior Pilot	Fighter Pilot	3500
7	34	Pilot	T-39 Pilot	2100
8	43	Command Pilot	Fighter Pilot	5500
9	34	Pilot	Test Pilot	4500
10	37	Senior Pilot	T-39 Pilot	3000
Avg	35.5		Avg	3170

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Practice

Run	
1	
2	
3	

BREAK

Session I

1	2	3
A	B	A
B	A	B
A	B	A

BREAK

Session II

4	5	6
B	A	B
A	B	A
B	A	B

NOTES: A = Unperturbed Track
B = Perturbed (Step Input) Track
N = 12 Pilots (Two pilots dropped in data analyses)

The design was counterbalanced where possible, i.e., if subject 1 started with an unperturbed run, subject 2 started with a perturbed run.

Thus, each pilot flew 9 perturbed and 9 unperturbed runs for a total of 18 passes at the target.

Figure 10. Experimental Design

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TABLE II

PARAMETERS MEASURED IN TRACKING STUDY

Parameter

Problem Clock
Distance Latitude
Distance Longitude
True Airspeed
Indicator Airspeed
Sine Yaw
Lateral Stick Position
Lateral Stick Forces
Sine Bank
ADI Steering Command (Hor)
Course Error Command
Pressure Altitude
Mach
Sine Pitch

Parameter(Contd)

Angle of Attack
Sine Flight Path Azimuth Angle
Cos Flight Path Azimuth Angle
Aircraft Displacement
Amount of Longitude Displacement
Amount of Latitude Displacement
Geometric Aircraft Above Field
North Computed of Wind
East Computed of Wind
Longitudinal Velocity of Wind
Lateral Velocity of Wind
Vertical Velocity of Wind
Vertical Velocity

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3. Milliradian error times steering command measures
4. Lateral error in feet
5. Lateral stick position
6. Lateral stick forces

The definition of the measures used to score pilot tracking performance is as follows:

Absolute Average Error - This error score is obtained by sampling displacement from an ideal value every .2 second and summing it over the entire distance of the track to the target. Specifically, this score describes an off-the-target error at any given instant along the pilot's track. This measure has been used on previous studies conducted on the Crew Station Design Facility and is quite effective in describing performance. The error is in actual rather than arbitrary units as is frequently the case with this measure. The formula for this measure is:

$$AAE = \frac{1}{N} \sum_{i=1}^{N} |e_i|$$

where N = Number of iterations

e = Absolute value of error

Average Error - This error score is derived in the same manner as AAE except that sign of error is taken into account. This score measures and detects constant error if the subject consistently errs to right or left of course. This value is normally near zero if a typical track is maintained. Formula for this measure is:

$$AE = \frac{1}{N} \sum_{i=1}^{N} e_i$$

where N = Number of iteration

e = Sign and magnitude of error

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Root Mean Square (RMS) - RMS is the standard deviation of the error amplitude distribution and is obtained by integrating the squared error signal and taking the square root of the summation measured over the entire track. The formula is:

$$\mathrm{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} e_i^2}$$

where N = Number of iterations

e = Error score

Percent Time on Target - This score represents the percent of time the track is within limits predetermined by the experimenter. The formula is:

$$\%\,\mathrm{OT} = \frac{\sum_{i=1}^{N} P_i}{N}$$

where P = 1 when within tolerance

0 when outside limits

N = Number of iterations

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SECTION III

RESULTS

1. UNPERTURBED TRACKING RESULTS

A frequency distribution of the pilots' tracking performance, as measured by AAE milliradian error score, across all experimental sessions where no target displacement occurred is shown in Figure 11. (See Appendix for a discussion on the method used in developing the frequency distributions.) This curve was slightly smoothed from the frequency polygon of the data. The distribution is essentially a bell-shaped or normal distribution with a range of .565 (.167 to .690 milliradians), a mean milliradian error of .363, and a standard deviation of .124. A very interesting trend regarding pilot tracking ability appears in these data - 87% of all target passes (76 of 87) were flown with an average error at any given point along the track of less than .50 milliradian. The accuracy of rate tracking demonstrated in this investigation surpasses that previously assumed possible by many design engineers. Of course, these data were collected simulating an ideal system that provides more complex feedback to the operator than is provided in present operational flight instruments. However, the system simulated is assumed to be within the present state-of-the-art and is considered a reasonable starting point for providing baseline normative data on pilot tracking ability.

2. PERTURBED TRACKING RESULTS

Figure 12 depicts the performance curve of the group on those trials where the target location was displaced, requiring the pilot to make a

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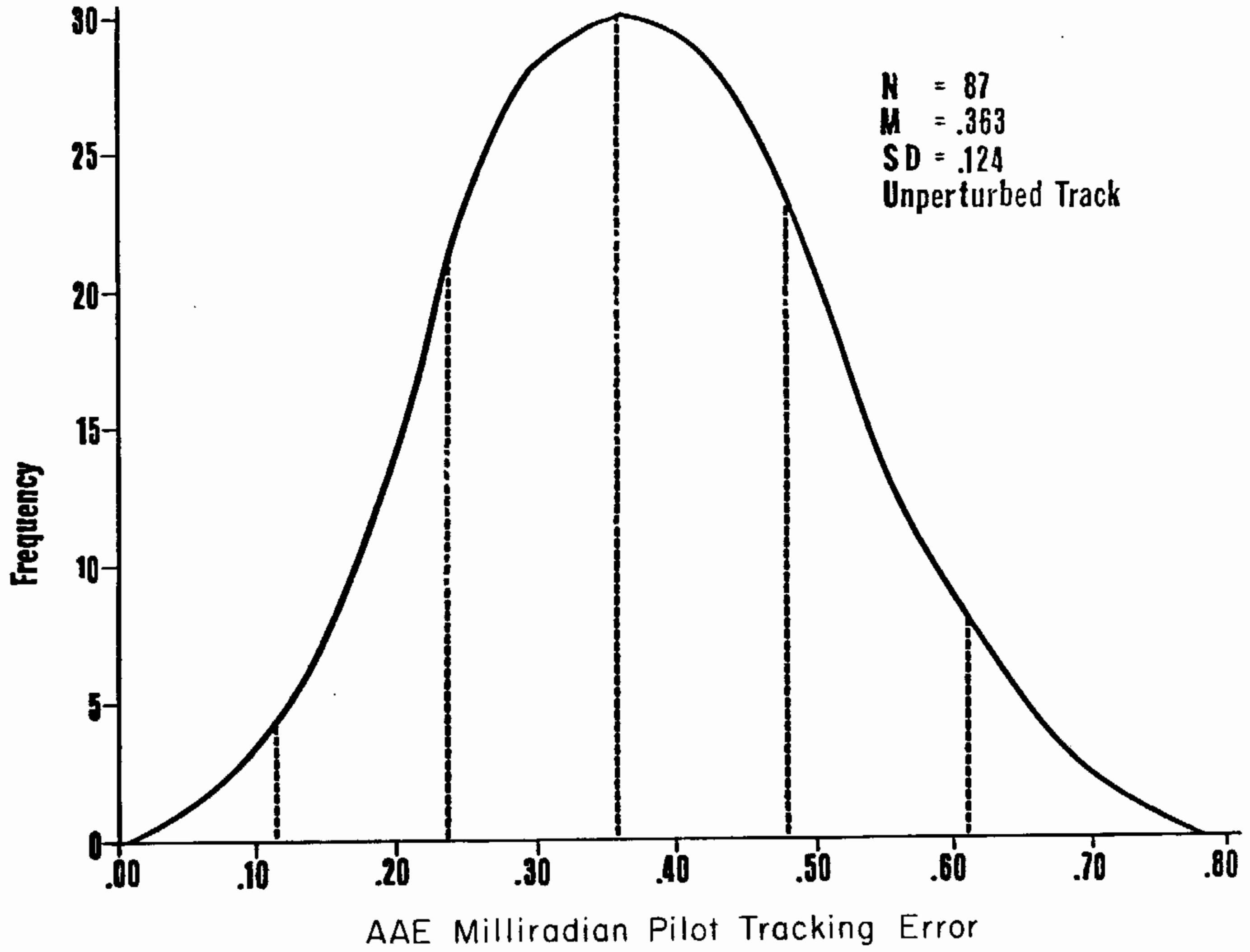

Figure 11. AAE Milliradian Pilot Tracking Error Score - Unperturbed

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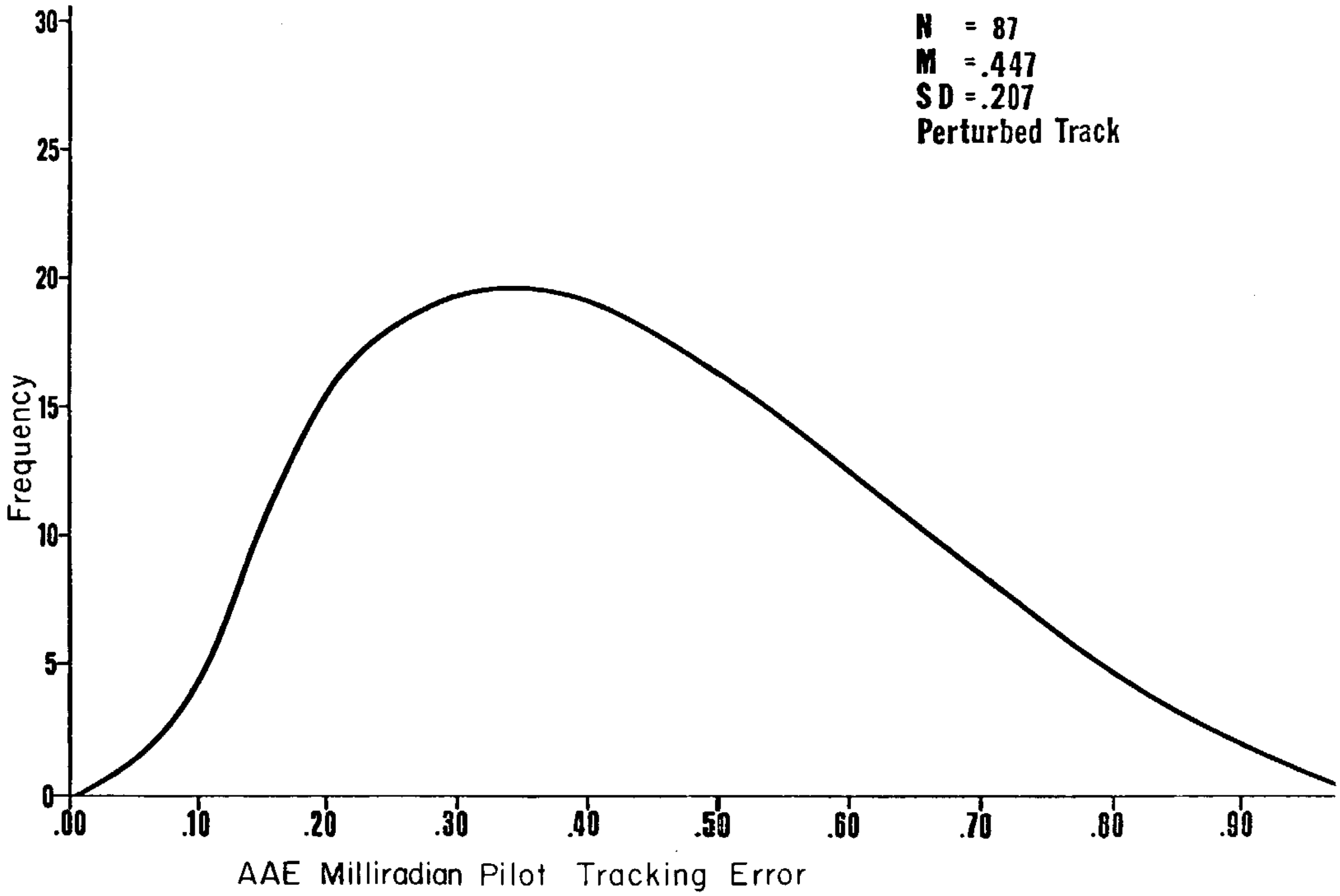

Figure 12. AAE Milliradian Pilot Tracking Error Score - Perturbed

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correction back to course. As mentioned in Experimental Design Section II, this experimental condition was introduced to determine how well and in what manner an operator compensates for a step "update" of tracking information. These data were obtained to study the effect of a continuous update involving both pilot and systems operator. Figure 12 is a frequency distribution of the pilots' performance at a range between three nautical miles and one nautical mile from target, and shows what effect the large course correction required at four nautical miles might have on the pilots' subsequent track. In comparison to the "unperturbed" tracking, the "perturbed" tracking distribution has a larger range of scores (between .162 and 1.15 milliradians error score), a higher mean error score (.447 vs .363), and greater variability (a score of .207 vs .124). The principal difference between Figures 11 and 12 is that 13% of the scores during "perturbed" runs exceed the highest value in the "unperturbed" runs. However, 67% of the error scores on "perturbed" runs are less than .50 milliradians which is only slightly below the percentage (12% difference) demonstrated by the group that had an undisturbed pass at the target. This indicates that pilots, in most cases, recover quite well from a single update during a tracking run. A curve across all trials comparing the data in the two distributions is shown in Figure 13.

3. LEARNING RESULTS

Another result of this study which is of interest is milliradian error over trials, which reflects the learning curve, if any, in acquiring tracking skill. Referring again to Figure 13, one can determine that there is no significant slope of either curve although in both the

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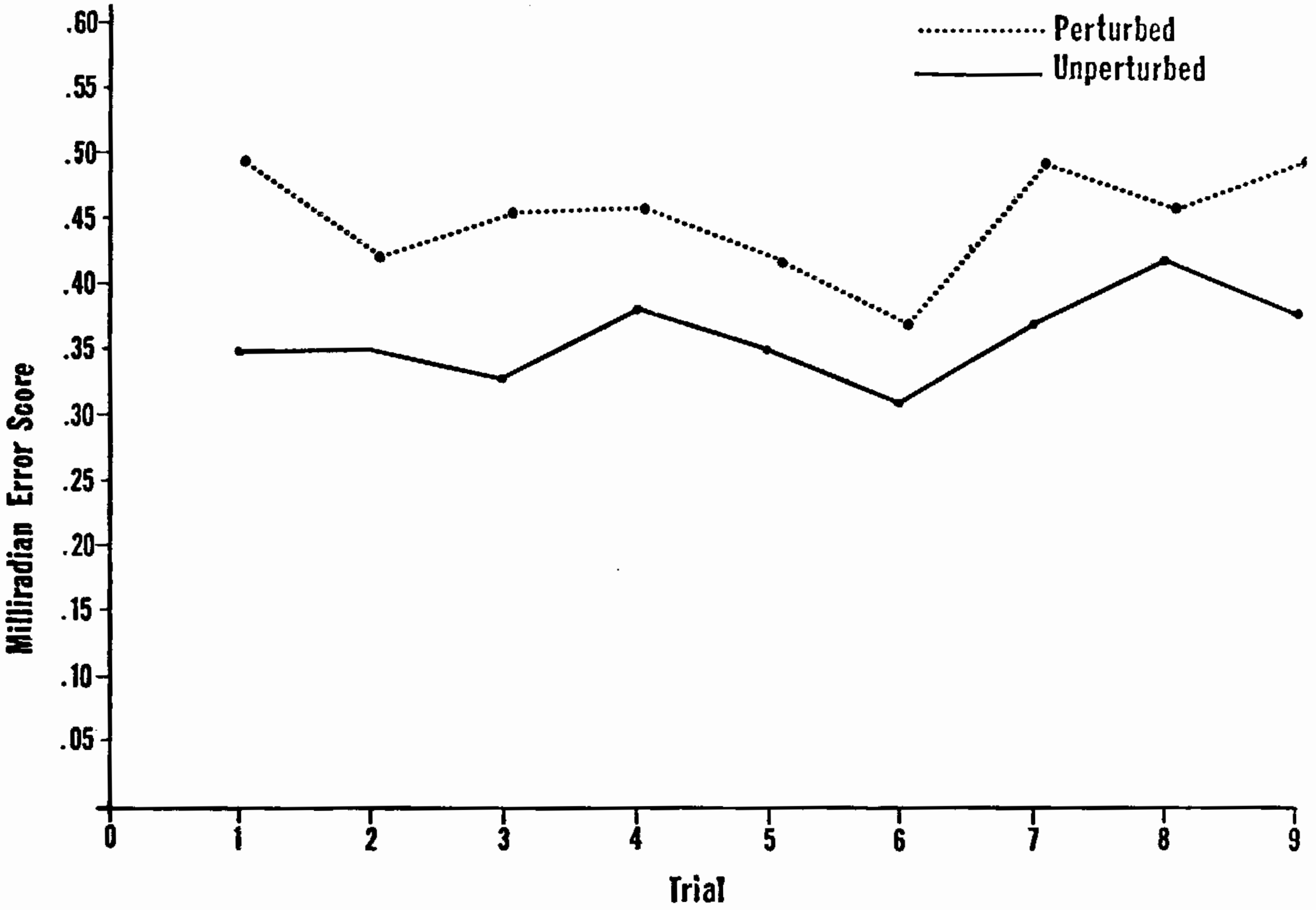

Figure 13. Milliradian Error Over Trials

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"perturbed" and "unperturbed" data there is a slight increase in the slope of the curves over trials 7, 8, and 9. This could be a fatigue effect, but it certainly does not reflect any trend of significant proportions.

In summary, an overall review of the tracking curves indicates that the tracking performance of the pilots was practically identical across the two flight conditions (perturbed vs unperturbed) and learning was not a factor in assessing baseline pilot tracking performance. This is verified in Table III where the analysis of variance shows no significance for any of the variables depicted.

TABLE III

ANALYSIS OF VARIANCE OF PILOT PERFORMANCE SCORES

Source	Degree of Freedom (df)	Mean Square	F Ratio
Flight Condition (A)	1	.200	4.50*
Trials (B)	8	.037	1.76*
Subjects (S)	9	.066	
A X B	8	.013	.568*
A X S	9	.044	
B X S	72	.021	
A X B X S	72	.019	
Total df	179		

*Note: Not significant.

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4. AAE MILLIRADIAN ERROR TIMES STEERING COMMAND RESULTS

Pilots' tracking performance expressed in terms of AAE milliradian error times steering command is shown in Figure 14. This performance measure was derived by taking the AAE milliradian error score for each run and multiplying it by a scale factor whose value was directly proportional to the amount of command needle displacement up to 2 needle widths. For values beyond 2 needle widths displacement, the scale factor was 1; for values equal to and less than 2 needle widths displacement, the scale factor decreased linearly from 1 at 2 widths displacement to 0 when the needles were centered. Thus, the measure is a direct assessment of how well the pilots followed the commanded bank angles. The J shape of the distribution indicates that the subjects tracked the needles very well. These data further suggest that the pilot's tracking ability was limited by the system rather than by his own ability. In other words tracking to the tolerances required for precision bombing, using a system similar to that simulated, is well within the capability of the pilot.

A frequency plot of ADI steering command (AAE) (Figure 15) indicates a near normal distribution and is an expected result in the light of data which is directly derived from steering command. The lateral error in feet shows a distribution (Figure 16) similar to that in Figure 11, which also is not surprising since it is measuring the same error and expressing it in feet off desired track. Presentation of data in these units is of course superfluous except directly prior to bomb release or for calculation of circular probable error (CEP). Learning curves for AAE milliradian error times steering command, ADI steering command, and

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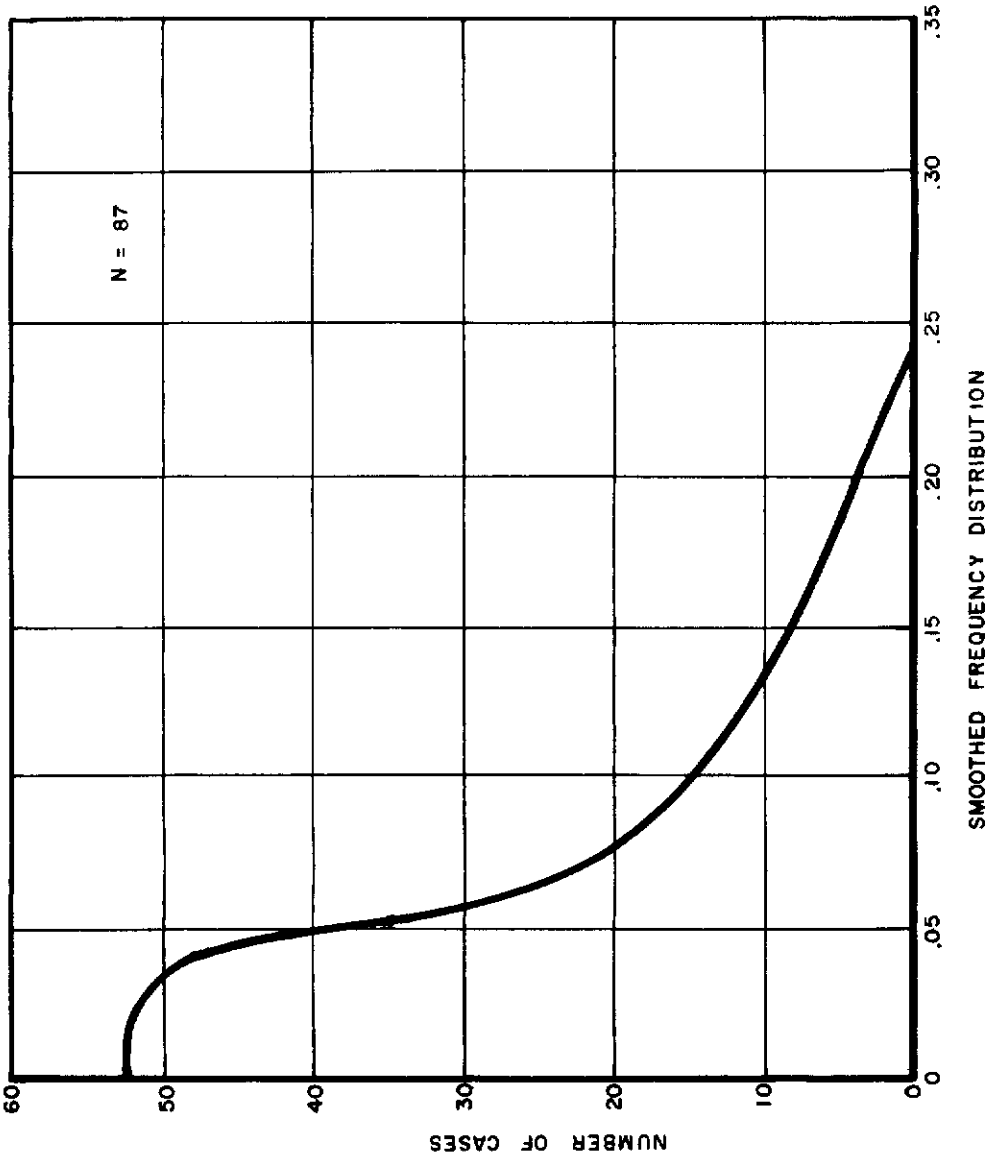

Figure 14. Frequency Plot of AAE Milliradian Error Times Steering Command

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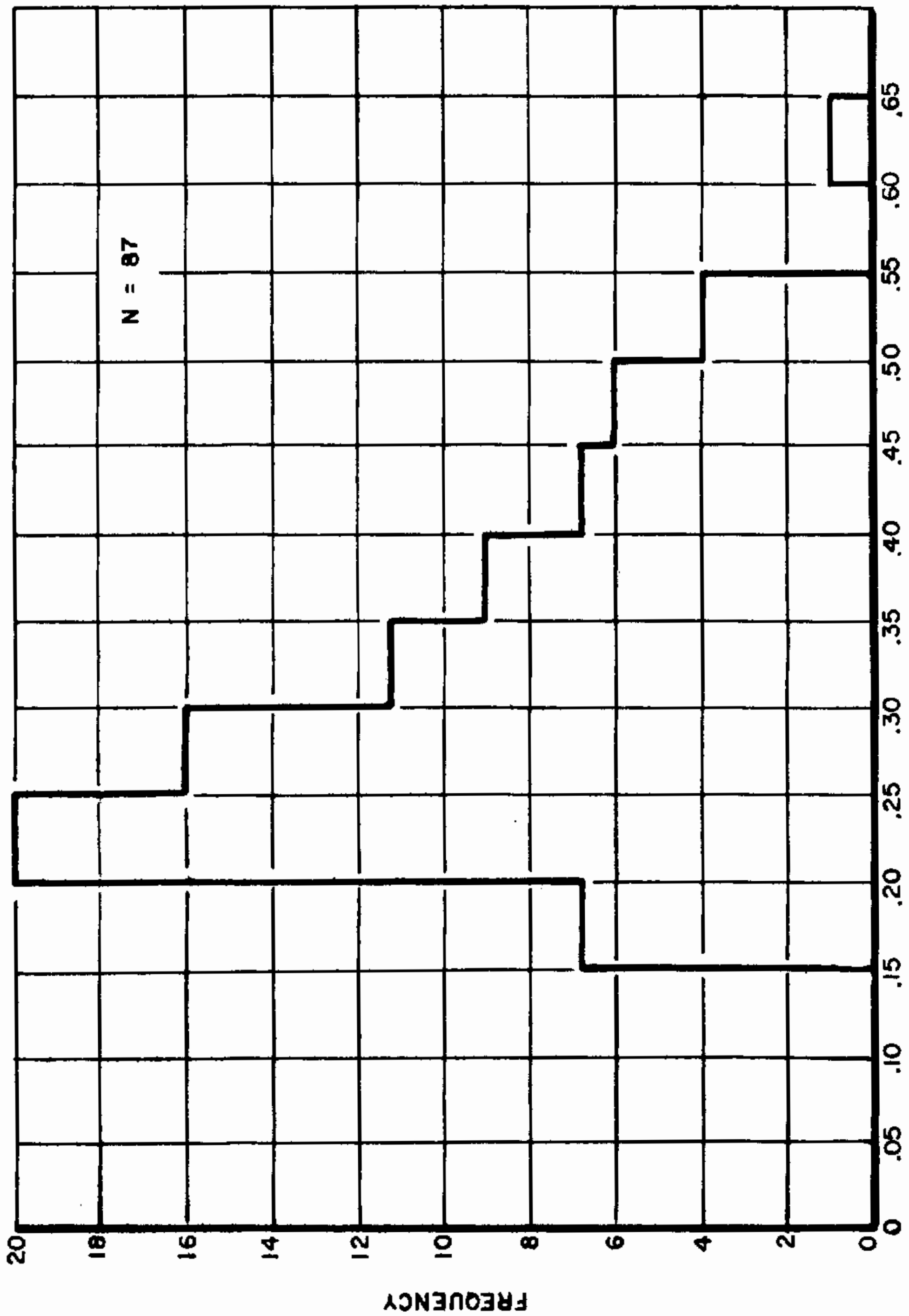

Figure 15. Frequency Plot of ADI Steering Command

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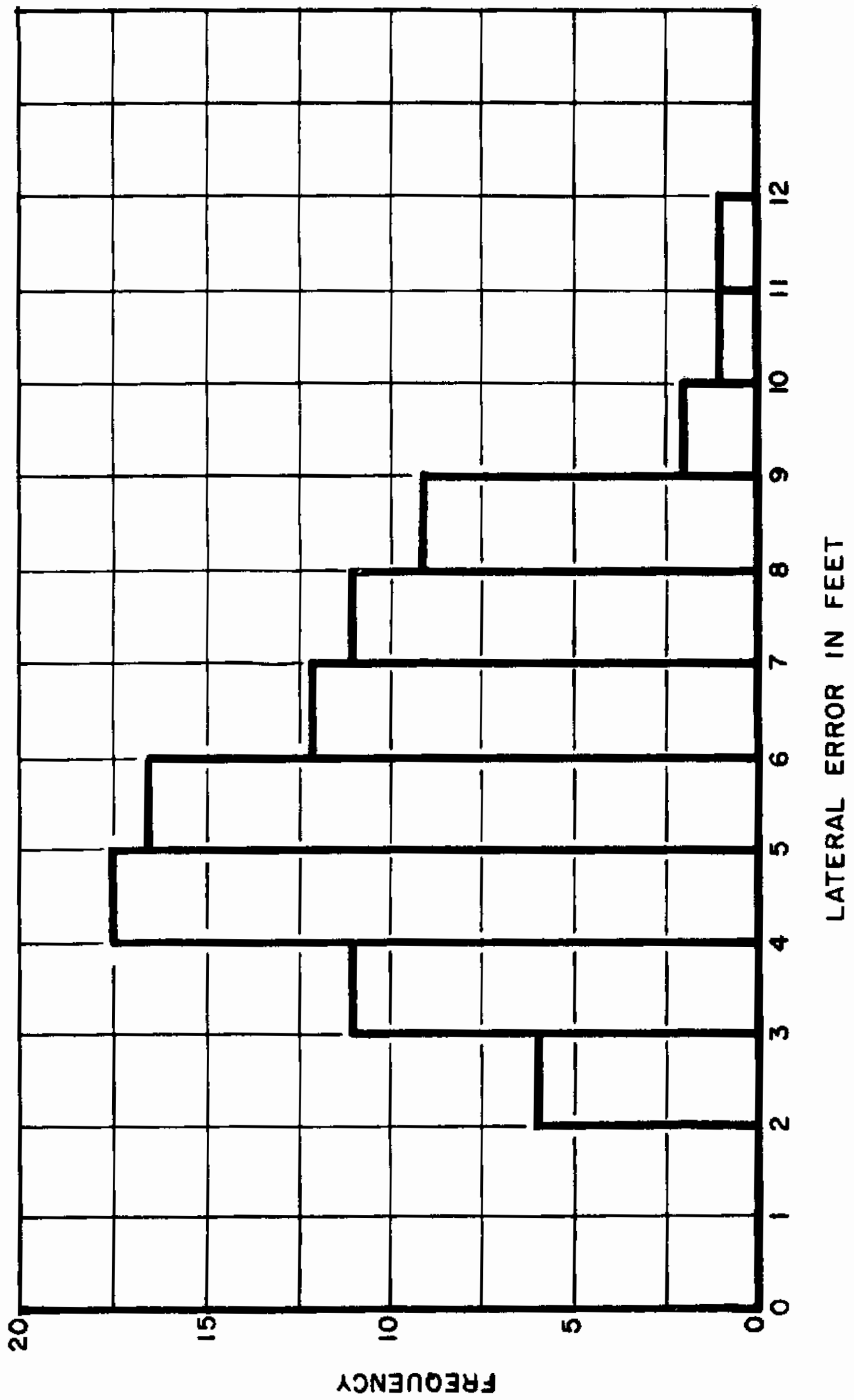

Figure 16. Frequency Plot of Lateral Error in Feet

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lateral error are depicted in Figures 17, 18, and 19. All these curves indicate little or no practice effect and are consistent with other curves shown.

5. COURSE REVERSAL RESULTS

The performance of the pilots was also evaluated in terms of time between course reversals (Figure 20). This measure had a mean of 4.42 seconds between reversals and a SD of 1.44. Inspection of the data indicates that the lower frequency runs tend to yield better error scores, which is not surprising. Better tracking performance is usually characterized by consistent responses requiring few adjustments. Figure 21 indicates that the time between reversals undergoes practically no change across trials.

It is interesting to note that the majority of the performance measures are all good predictors of deviations from desired course (milliradian error). The correlation coefficients between these individual performance measures and milliradian error are depicted in Table IV.

There is a high correlation between AAE milliradian error and ADI steering command, which is reasonable since the terms are indirectly related in the system, only being attenuated by summing of other error terms and some scaling factors. Lateral error also shows a high correlation with milliradian error, since it is an alternate measure of the same parameter. The measure, AAE milliradian error vs AAE milliradian error times steering command, shows a lower correlation probably because of the restricted range on one of the variables (see Figure 14).

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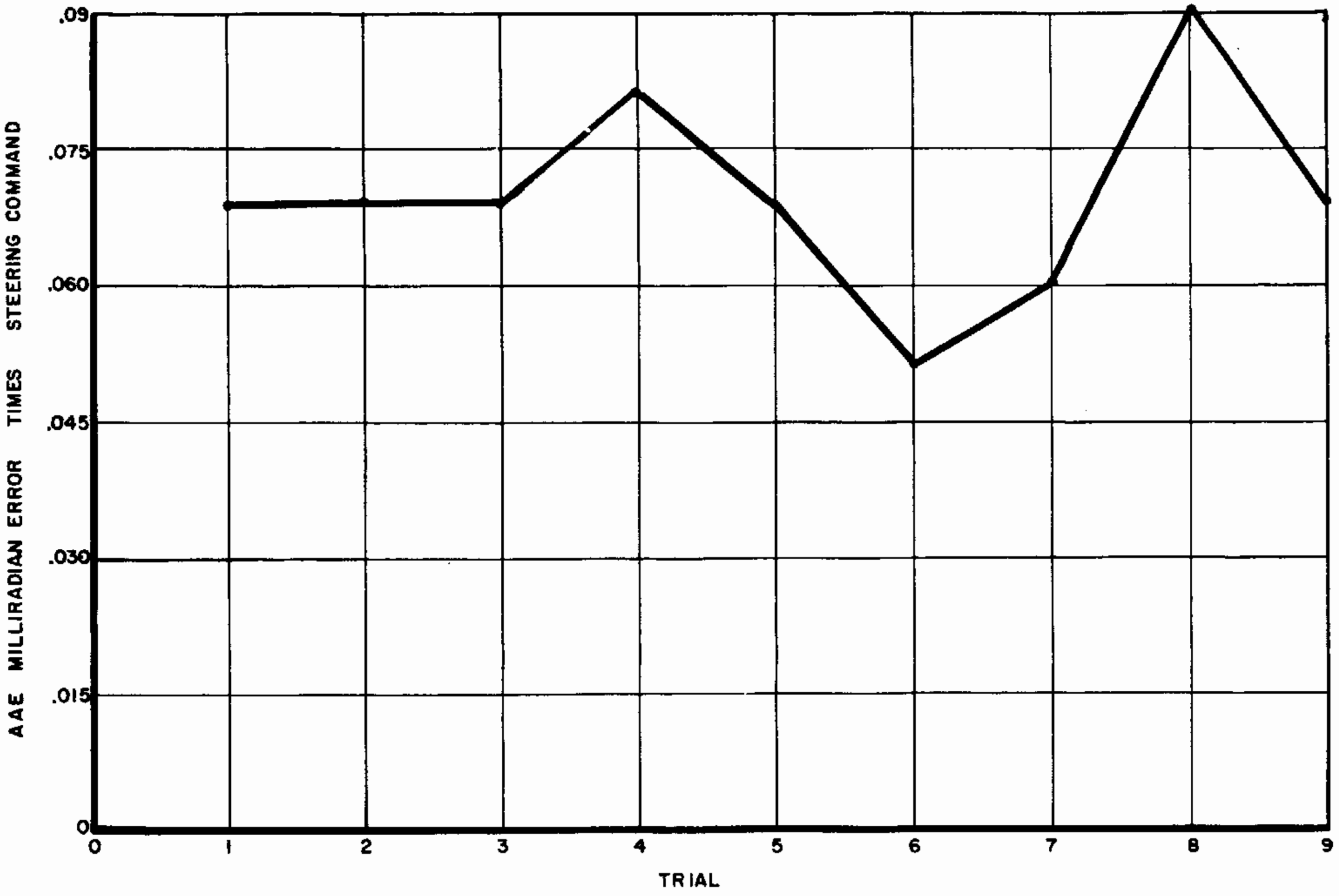

Figure 17. Learning Curve for AAE Milliradian Error Times Steering Command

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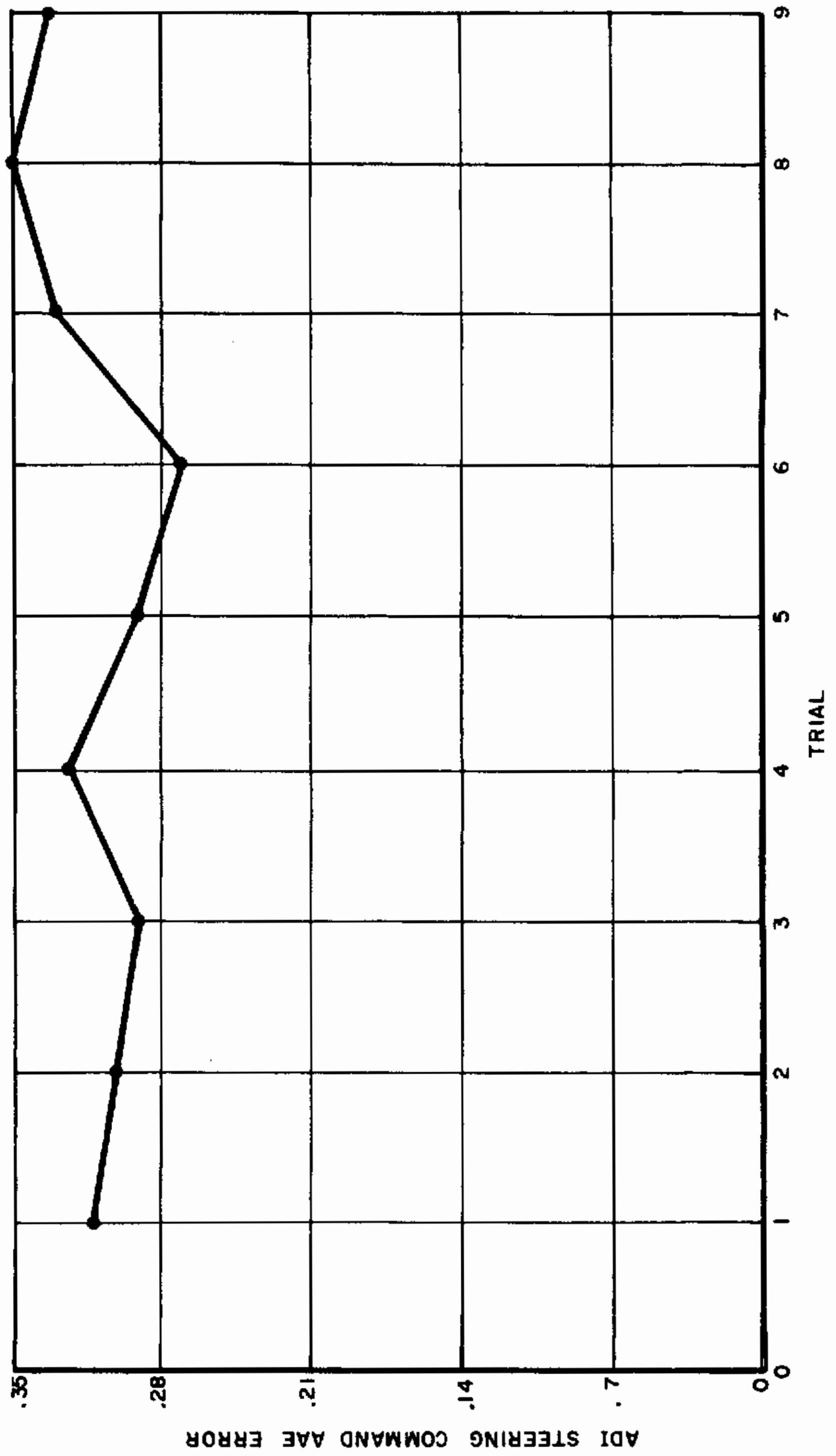

Figure 18. Learning Curve for ADI Steering Command

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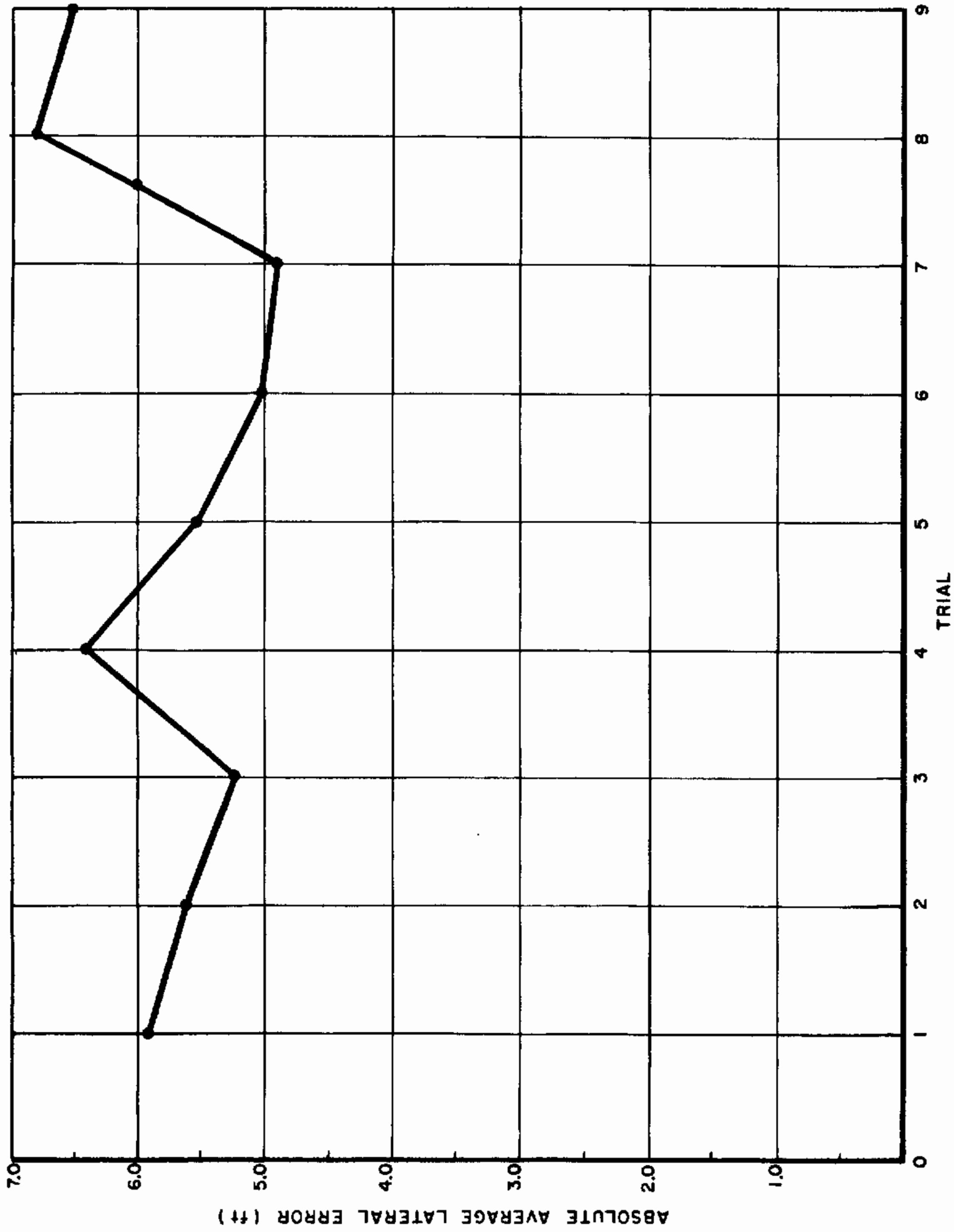

Figure 19. Learning Curve for Lateral Error

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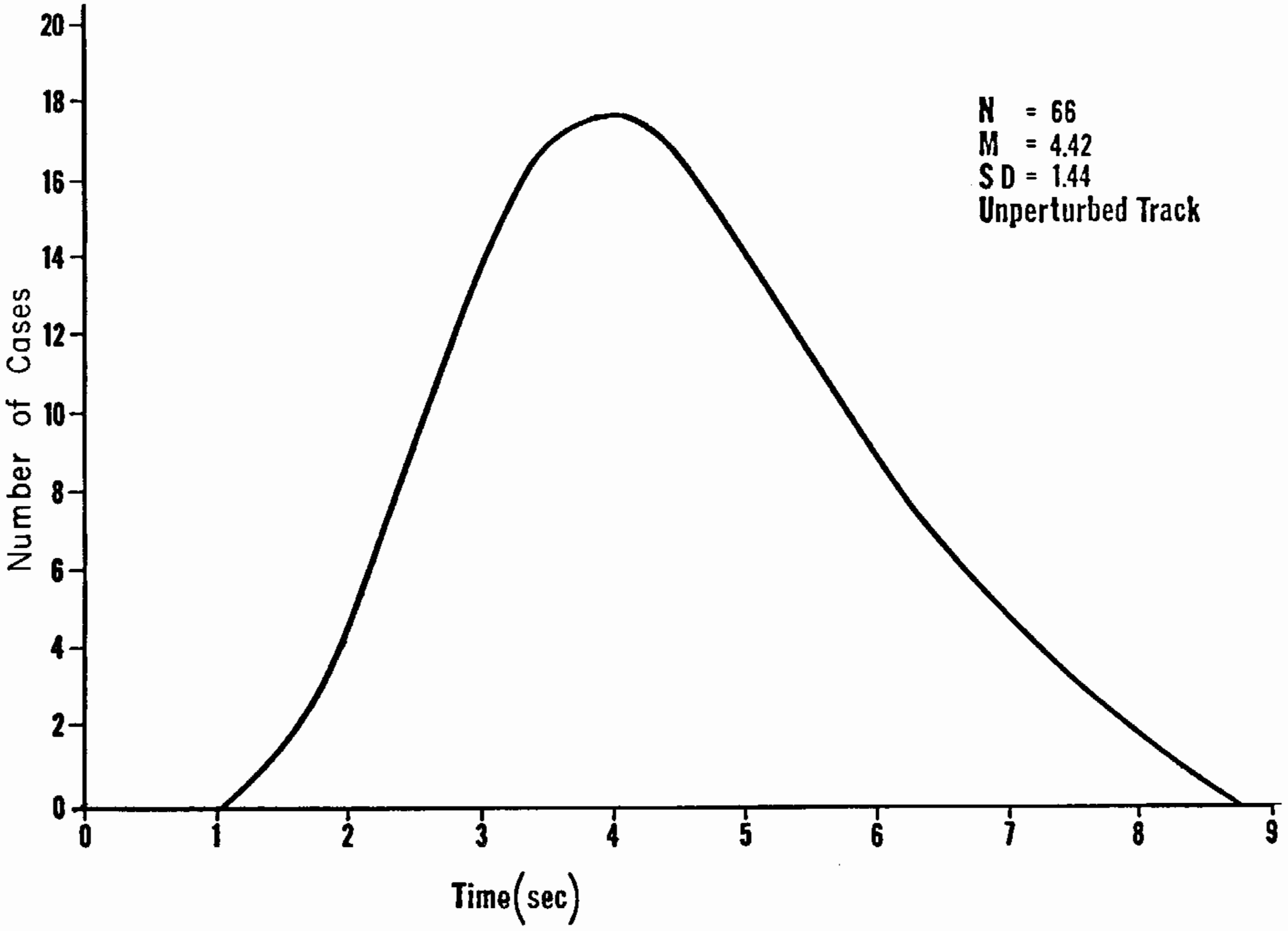

Figure 20. Time (Sec) Between Course Reversals

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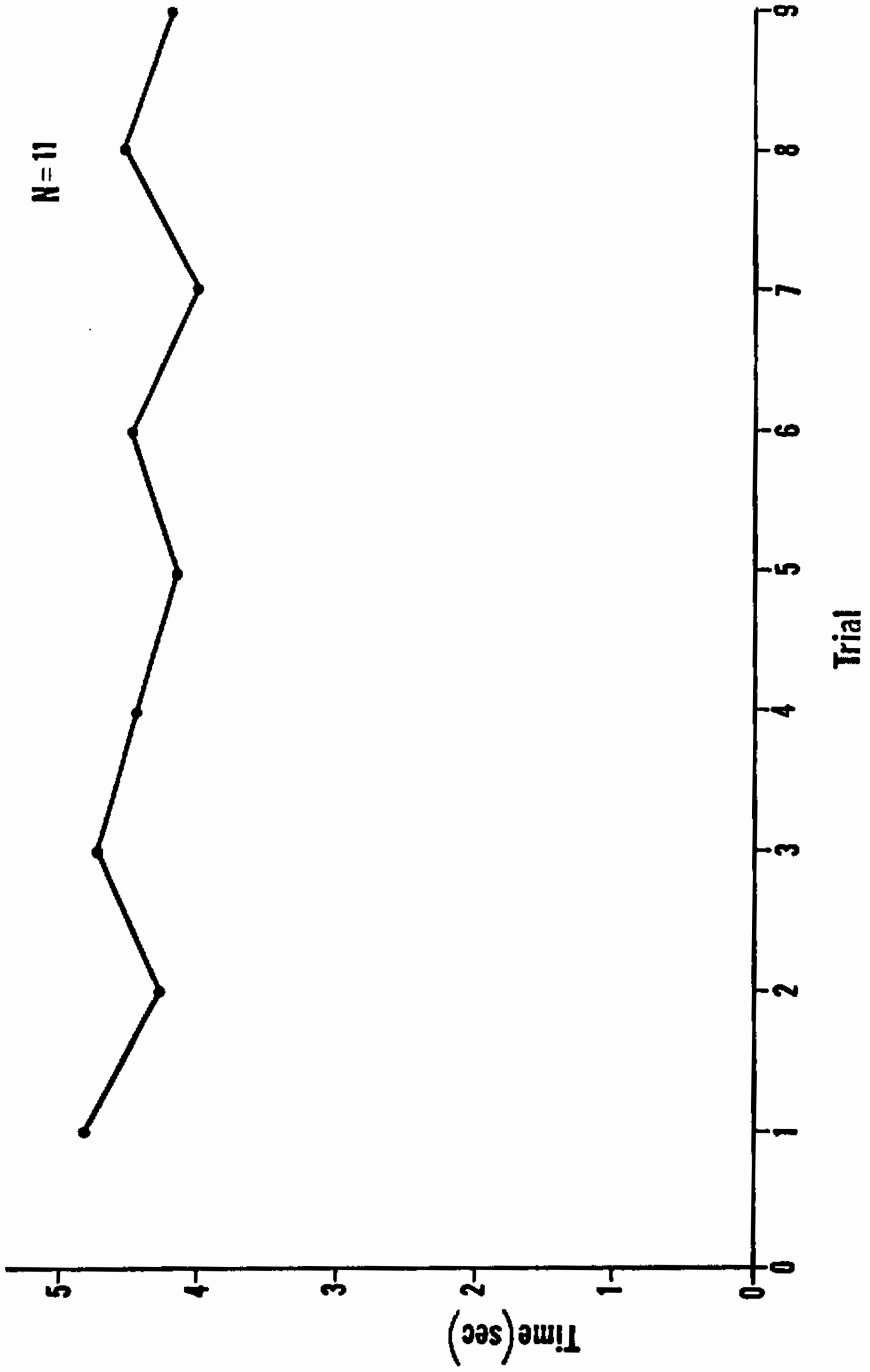

Figure 21. Time (Sec) Between Course Reversals Across Trials

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TABLE IV

CORRELATION COEFFICIENTS EXPRESSING RELATIONSHIPS BETWEEN PERFORMANCE MEASURES AND MILLIRADIAN ERROR, AAE

PERFORMANCE MEASURES	CORRELATION	
Steering Command Error vs Milliradian Error, AAE	.91	N = 180
Lateral Error vs Milliradian Error, AAE	.92	N = 180
Milliradian Error Times Steering Command vs Milliradian Error, AAE	.62	N = 180

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While the data in Table IV is expressed in terms of AAE, an alternate measure of tracking performance frequently used is RMS. This is another way of assessing variability around the desired tracking path (see Performance Measures Section II). A comparison between RMS and AAE is presented in Figure 22. The RMS score shows a parallel and slightly higher value than the AAE score, which leads one to conclude that either measure could be used to describe tracking performance. In general, this is true, especially when one is dealing with mean values. However, comparison of Figure 23 and Figure 11 shows that there is more variability and some skewness in the distribution of RMS scores, which makes extrapolation to a general population value based on a normal curve somewhat less rigorous. In view of this skewness, and the resulting restrictions on extrapolating from such data for purposes of establishing baseline norms for tracking ability of pilots, the authors prefer AAE as a primary performance measure.

6. STICK POSITION

Pilot performance was also evaluated according to the amount of stick movement or work required to track the target. The mean scores for the curves depicted in Figures 24 and 25 are approximately the same, indicating a minimum amount of effort to recover from the perturbed segment of the mission. Figure 26 indicates that the pilot is still working hard to track the target a half mile after the perturbation. However, when you compare this frequency distribution with that depicted in Figure 25, it is shown that after about one mile the stick movements are almost the same as for an unperturbed mission (Figure 24).

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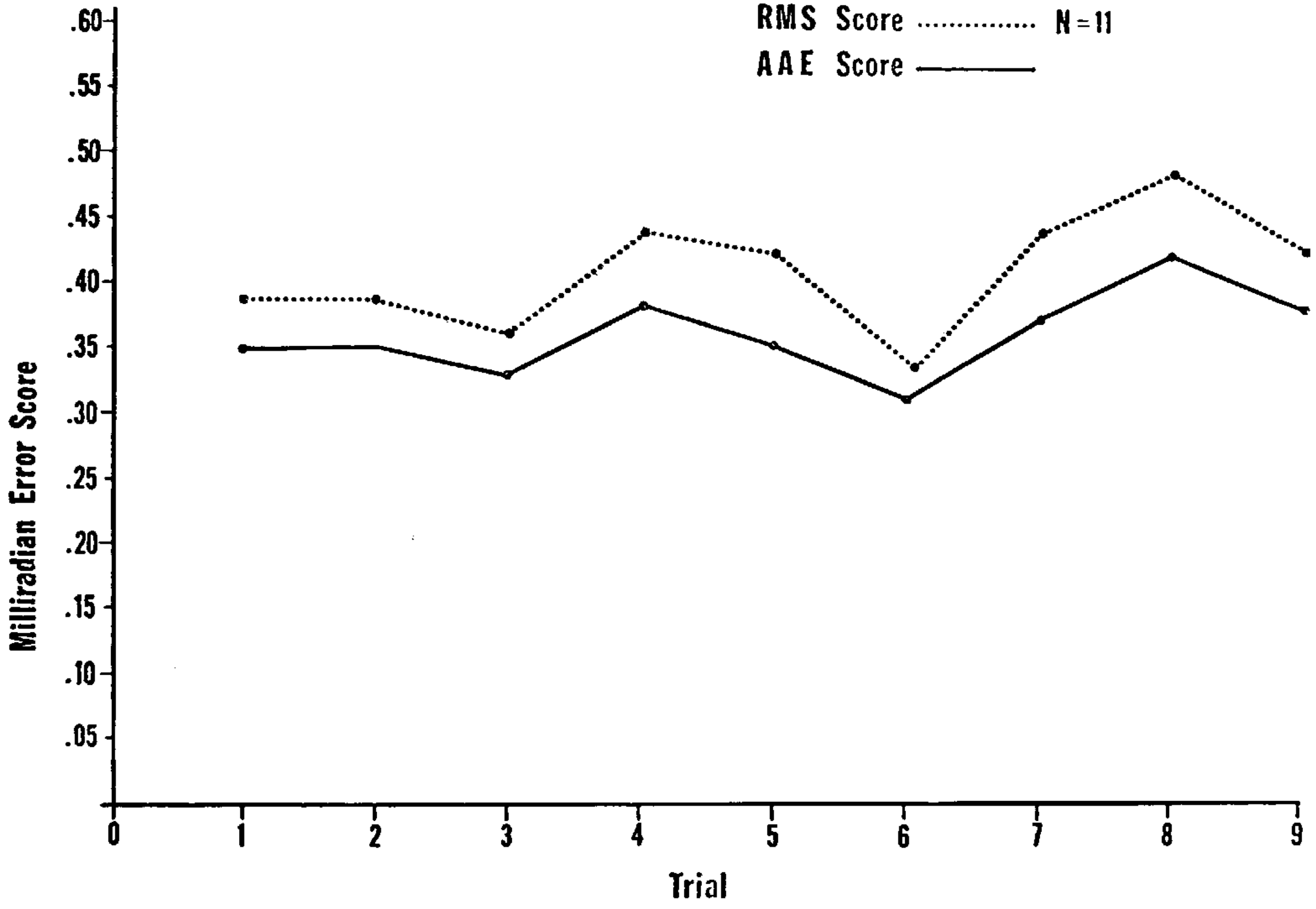

Figure 22. Comparison Between RMS and AAE Error Score

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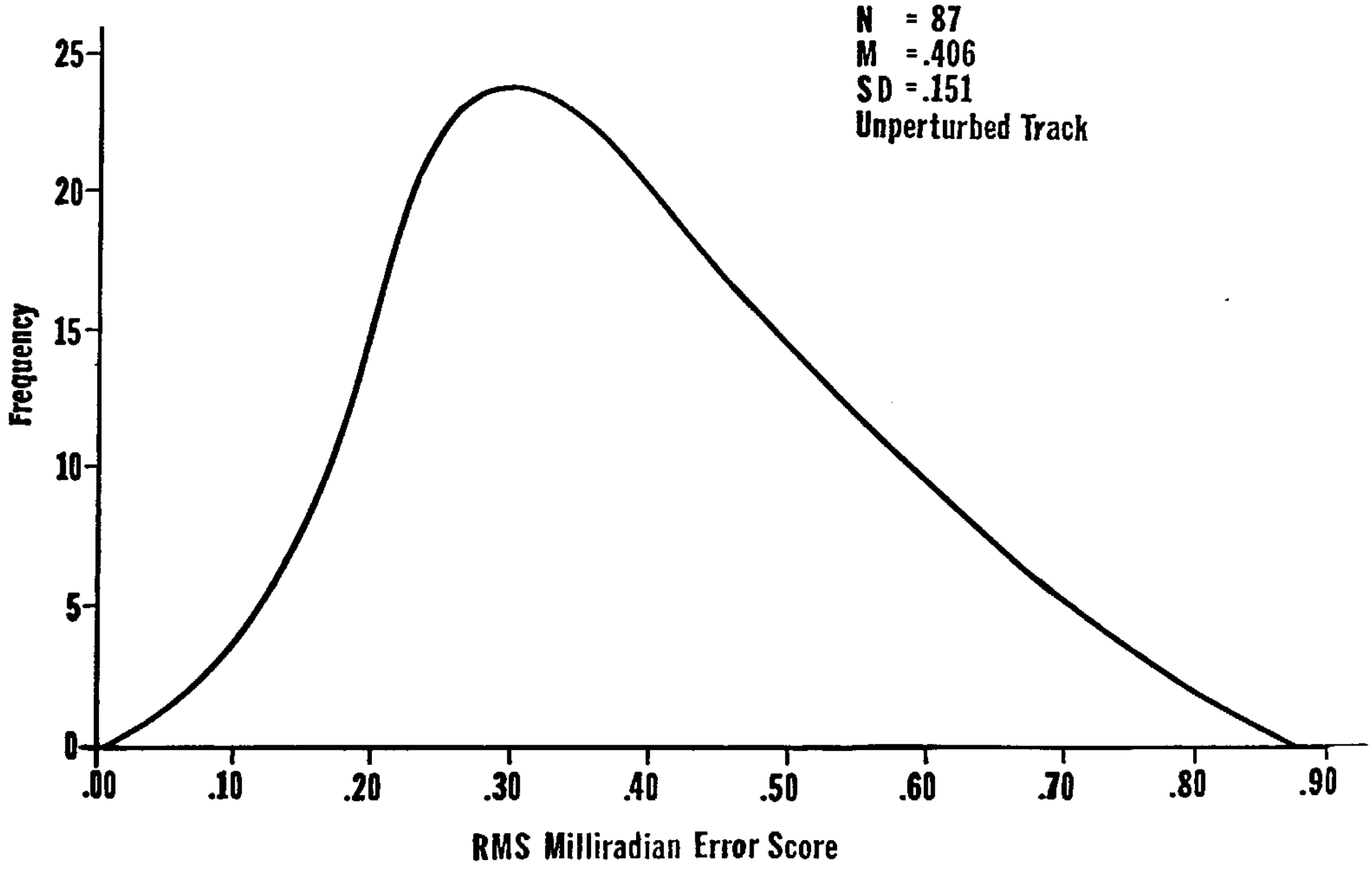

Figure 23. Frequency Distribution of RMS Scores

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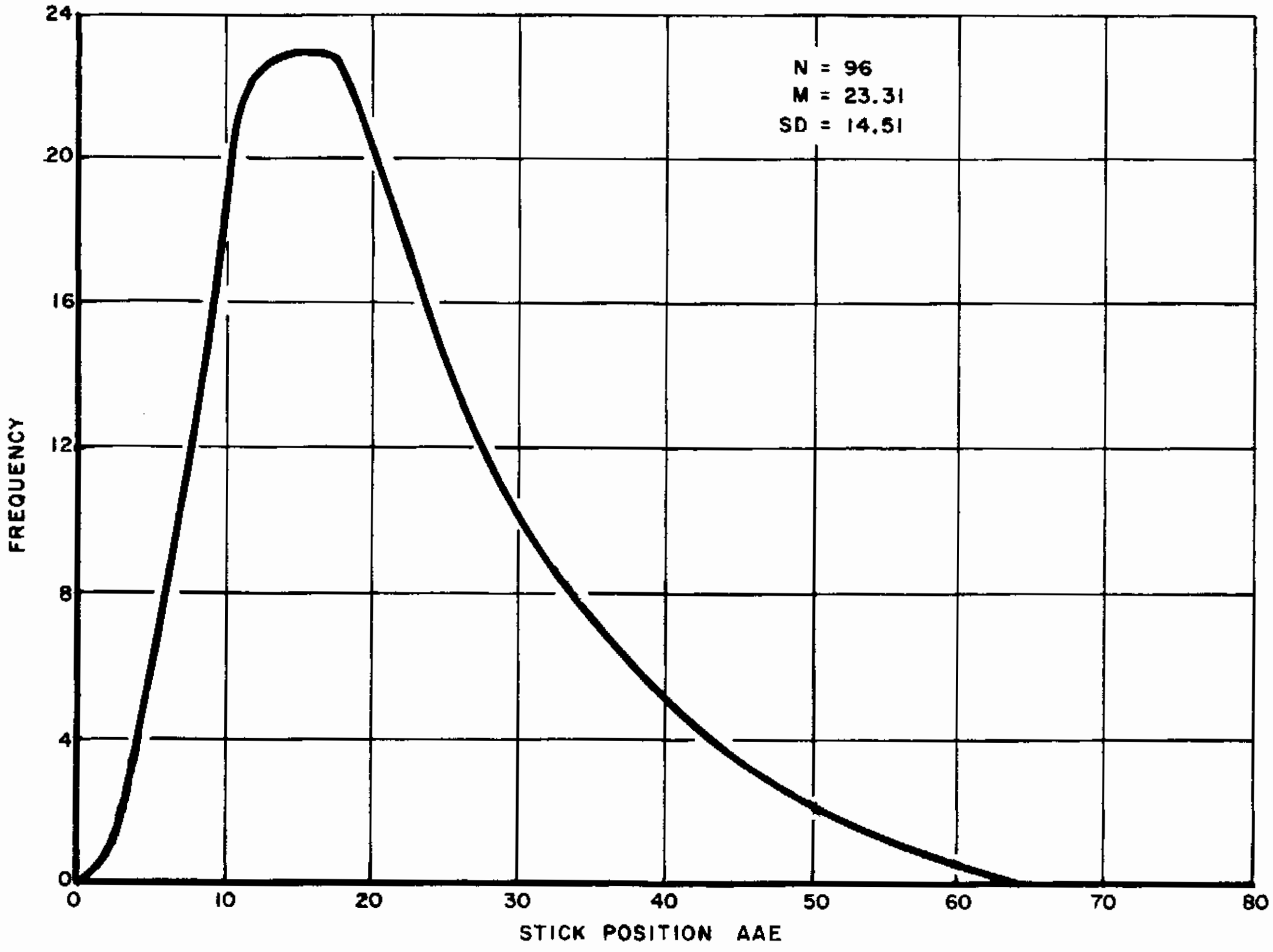

Figure 24. Lateral Movement in Stick Position, Three Mile Unperturbed

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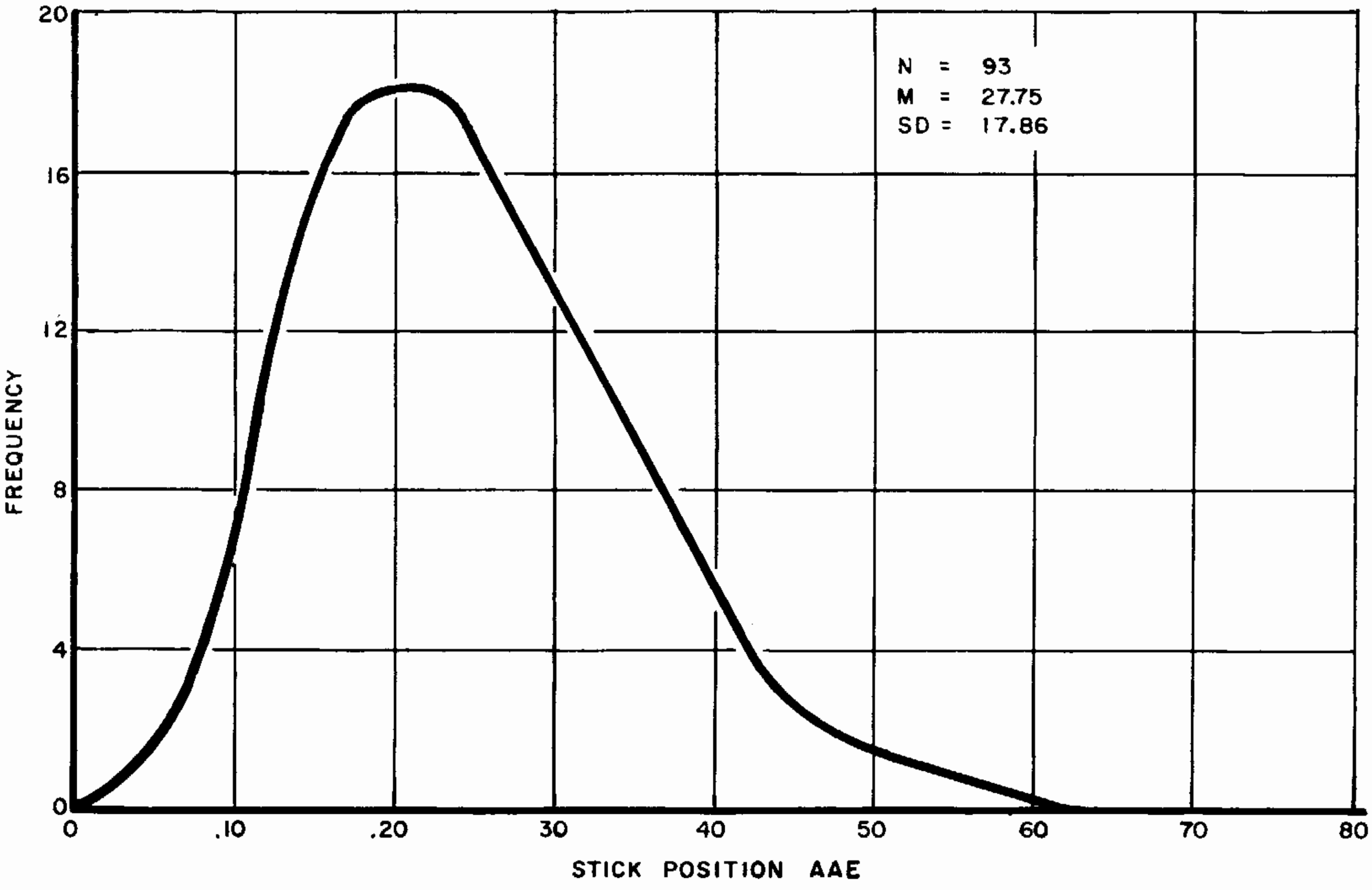

Figure 25. Lateral Movement in Stick Position, One Mile Perturbed

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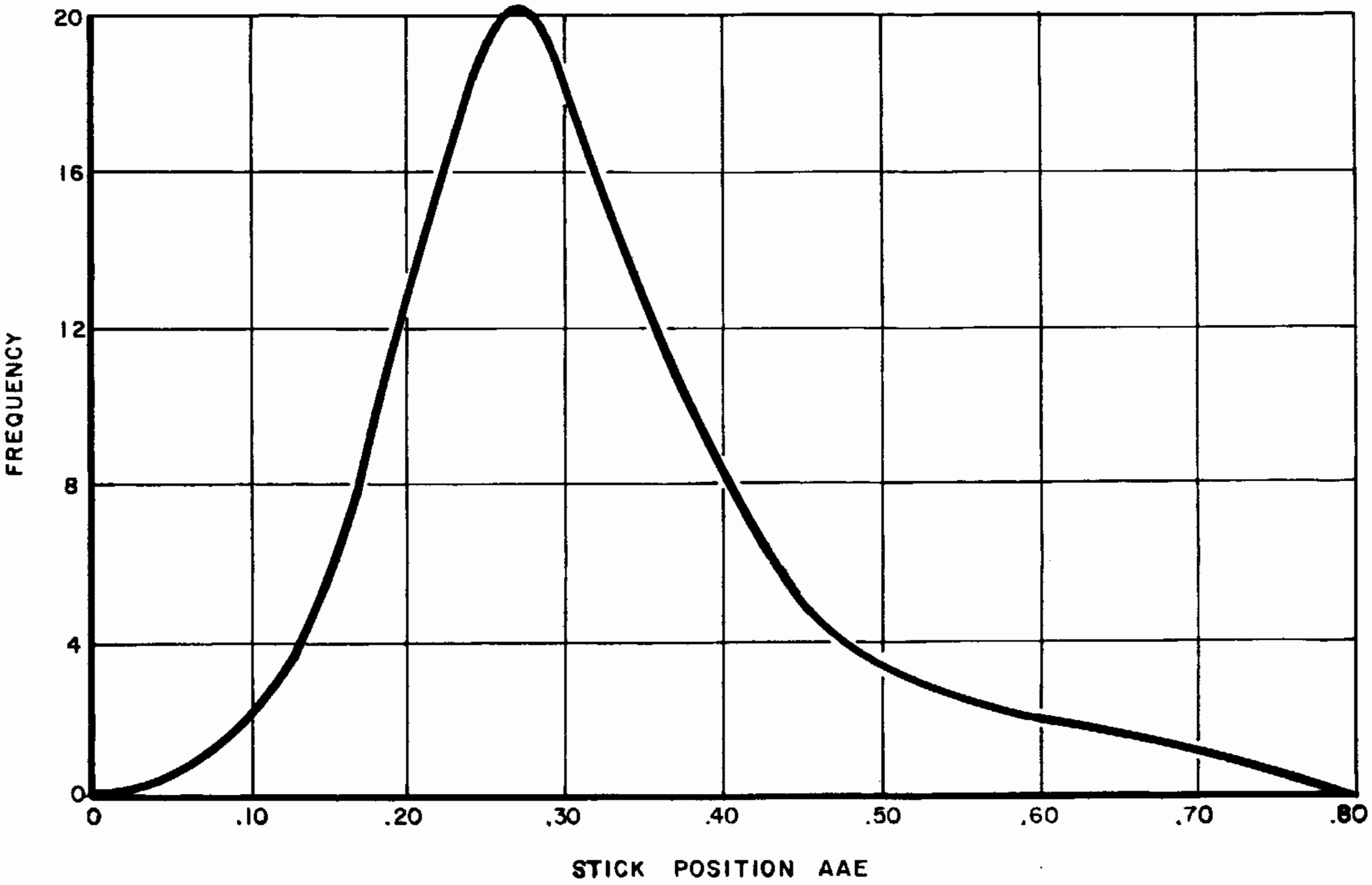

Figure 26. Lateral Movement in Stick Positon, Half Mile Perturbed

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SECTION IV

DISCUSSION

The results of this study show that pilots are able to follow steering commands with a high degree of accuracy if the proper error information is displayed to them on the ADI command bar. For unperturbed flight conditions, the pilots flew 87% of all target passes with an average error at any point along the track of less than .50 milliradians. There was no serious decrement in performance for subjects in this study who flew the tracking task under perturbed conditions as compared to an unperturbed flight condition. That is, subjects were able to compensate for fairly large target updates in steering the simulated aircraft. Learning the tracking task was not a factor in assessing pilot tracking performance. The majority of the pilots yielded fairly uniform tracking scores for each of the flight missions.

Each of the measures of tracking performance used in the study had a unique mathematical definition and each measure was selected to be sensitive to a different aspect of pilot tracking performance. Based, however, on the high correlations found between these measures they were all shown to be useful in predicting tracking performance. Consequently, no single measure can be recommended as the most basic to clearly defining pilot tracking performance.

The data collected in this study generally surpasses that assumed possible by many design engineers of bomb/navigation equipment. This is because the data was collected using an ideal system that provides more

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complex feedback information to the pilot relevant to tracking error than is provided in present operational aircraft. However, the system simulated is well within the state-of-the-art in avionics equipment. This suggests that, rather than increasing the design tolerances of present day avionics equipment, it might be more advantageous to use existing systems and improve upon the tracking information presented to the pilot. The study showed that the tolerances required for precision bombing are well within the capability of the pilot if he isn't limited by the system.

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SECTION V

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

Based on the data collected the following conclusions are drawn.

a. Tracking performance yielding an average error of less than .4 milliradian when steering an aircraft in the lateral direction is attainable by pilots if operational conditions are ideal and sufficient and proper error information is displayed on the ADI command bar.

b. Pilots are able to satisfactorily adjust to a fairly large target update in steering a simulated aircraft and nearly equal the performance of pilots who have an uninterrupted approach to a target.

c. Pilots are able to follow steering commands very well and are probably more limited by system parameters than individual ability to track.

d. All performance measures employed in the study are useful in describing tracking performance with absolute average error (AAE) being preferred for statistical inference.

e. Sufficiently reliable data on tracking was obtained to establish baseline norms for pilot tracking ability in the lateral direction, based on an ideal system.

2. RECOMMENDATIONS

Several areas are recommended for further study of this problem.

a. System degradation on angle rate tracking (remove inertial guidance system, etc).

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b. Introduction of systems operator using simulation of TV tracker to provide angle rate error information, with pilot having visual reference available.

c. Man-machine tradeoff analysis using complete multiloop simulation of two operators - a pilot and systems operator interacting.

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APPENDIX

METHOD USED IN DEVELOPING FREQUENCY DISTRIBUTIONS

The frequency distribution was derived in the following manner for all distributions depicted in the report.

Step 1 - Collect raw data.

Step 2 - Data is grouped into frequency intervals.

Interval		Frequency	Cumulative Frequency	% of Cases
0 - .09		0	0	0
.10 - .19		2	2	2.29
.20 - .29		24	26	27.58
.30 - .39		30	56	34.48
.40 - .49		20	76	22.98
.50 - .59		7	83	8.04
.60 - .69		4	87	4.59
	TOTAL	87	87	100

Step 3 - Histogram is drawn (Figure 27).

Step 4 - Frequency polygon (dotted line) is drawn (Figure 27).

Step 5 - Curve of best fit drawn, yielding smooth frequency distribution. (See Figure 11, Section III for an illustrative example.)

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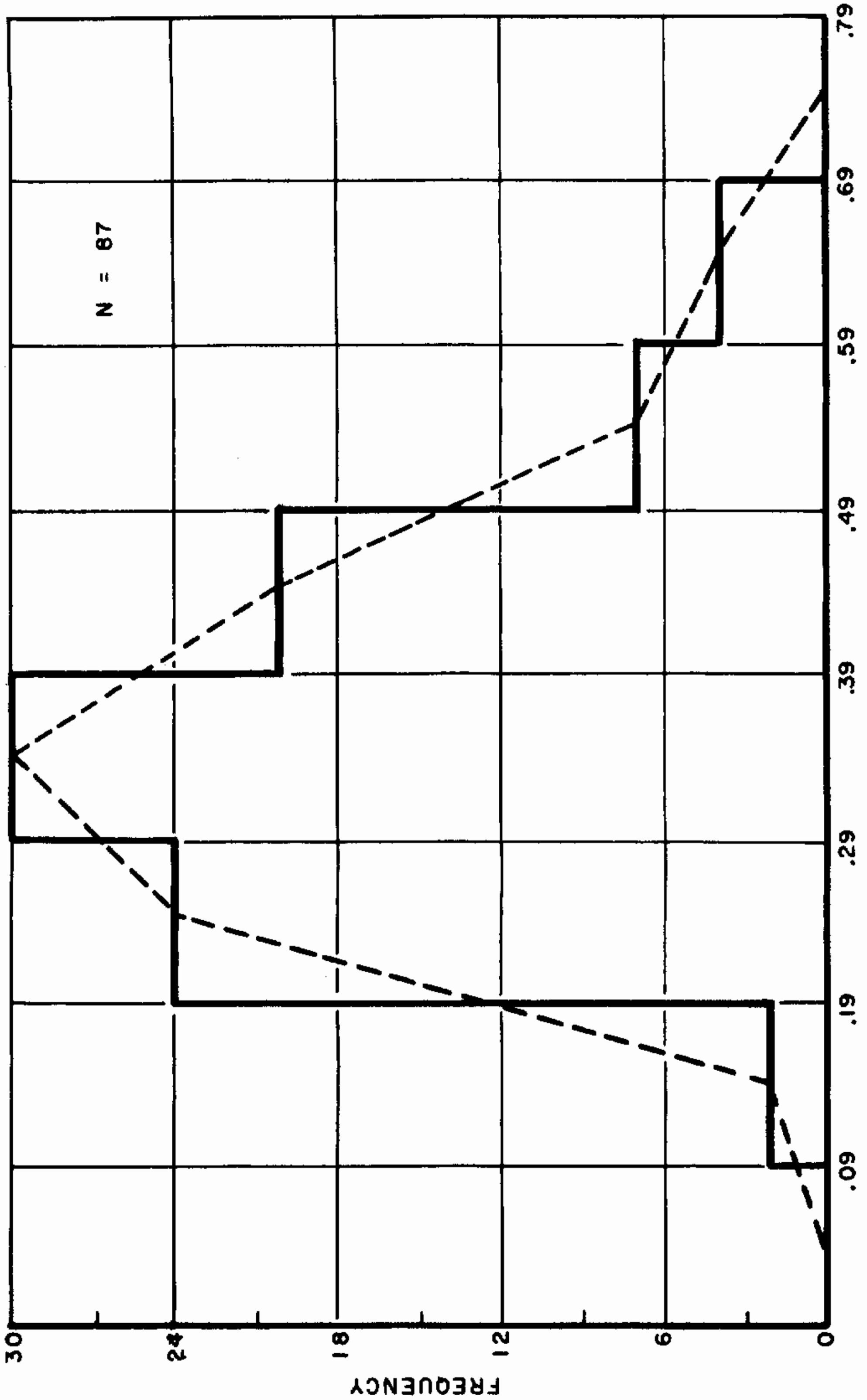

Figure 27. Histogram

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REFERENCES

1. Chapanis, A., Garner, W.R., and Morgan, C.T., Applied Experimental Psychology. New York: John Wiley & Sons, Inc., 1949.

2. Fitts, P.M., Bahrick, H.P., Briggs, G.E., and Noble, M.E., Skilled Performance - Part I. The Ohio State University Research Foundation, 1959.

3. Lindquist, E.F., Design and Analysis of Experiments in Psychology and Education. Boston: Houghton Mifflin Co., 1953.

4. Muckler, F.A., Studies in Human Operator Response Measurements. Martin Co. (In-house proposal).

5. Obermayer, R.W., Swartz, W.F., and Muckler, F.A., Human Operator Control Systems: I. The Interaction Between Modes of Information Display and Control System Dynamics with a Sine Wave Course. The Martin Co. Engineering Report No. 11,494, 1960.

6. Obermayer, R.W., Swartz, W.F., and Mucker, F.A., Human Operator Controls Systems: II. The Interaction of Display Mode, Control System Dynamics and Course Frequency. The Martin Co. Engineering Report No. 11,494-2, 1960.

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13. ABSTRACT

Ten Air Force pilots having current flying status flew a series of missions to establish baseline normative data for pilot tracking performance. An F-111A flight simulator was used as the test-bed for the experiment. The mission consisted of flying the aircraft simulator at 450 knots and 6000 feet to a designated target while tracking or keeping the bank steering needle centered. Various segments of the mission were designed to measure pilot racking ability under perturbed and unperturbed conditions. Twenty-seven different evaluation scores were obtained to determine pilot tracking performance. From evaluation of the performance data, it was concluded that by employing a state-of-the-art avionics system an average tracking error of less than .4 milliradian is attainable by pilots when steering an aircraft about the vertical axis. Recommendations are made for further studies on tracking performance as a function of system and pilot constraints.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Pilot Tracking Performance						
Pilot Tracking Capability						
Roll Command Display						
Precision Bombing System						
Angle Rate Tracking						

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