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FLIGHT TESTS OF PILOTAGE ERROR IN AREA NAVIGATION WITH VERTICAL GUIDANCE: EFFECTS OF NAVIGATION PROCEDURAL COMPLEXITY

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15. Supplementary Notes Flight test results reported herein apply to area navigation procedures identified as "Simplified" in comparison with "Standard" Procedures in current use and tested in an earlier flight test program. Area navigation procedures are now being revised, with most of the simplifying changes being incorporated in the future Standard.

16. Abstract

Pilotage error resulting from a simplified three-dimensional area navigation procedure was measured during 32 hooded instrument flights in a Beechcraft Twin Bonanza. These empirical observations were compared statistically both with corresponding values of pilotage error previously reported in a study using Standard Procedures (Report FAA-RD-72-126) and with corresponding values previously assumed in FAA AC 90-45 and RTCA DO-152. Other experimental variables were pilot experience level and vertical display type. The major task variable was angle of climb or descent. Pilot performance measures were vertical and horizontal steering, airspeed control, and procedural errors. Statistical tests comparing overall pilotage error results for Simplified Procedures show reliable performance improvements compared with corresponding results for Standard Procedures for all four performance measures. Steady-state values of vertical and horizontal steering errors using Simplified Procedures were reliably smaller than previously assumed in DO-152 and AC 90-45, respectively, for all task variables except three-degree approach descents on which they were not reliably different. Reliable performance differences between airline transport pilots and commercial pilots with instrument ratings were found for horizontal steering error only. Differences between pilot groups were not reliable for all other measures. No reliable performance differences were found between a command leveloff display and an altimeter on the level MDA segment for any of the three flight control performance measures.

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PREFACE

This report presents the results of one of an ongoing series of simulation and flight experiments assessing pilotage error in area navigation operations. The Contracting Officer's Representative for the research reported herein was D. Michael Brandewie of the Systems Research and Development Service, Federal Aviation Administration. J. Earl Davis of the Logistics Service, Federal Aviation Administration, was the Contracting Officer. Edgar A. Post of the Office of Systems Engineering Management and Gregory W. Tomsic of the Systems Research and Development Service contributed substantially to the planning of the flight course used in this study and in the preparation of this report.

Assistance in business matters has been rendered by William M. Griffith, Bursar, and John J. Kamerer, Assistant Bursar, Research Grants and Contracts Division, University of Illinois at Urbana-Champaign and by John M. Johnson, Business Manager of the Institute of Aviation, University of Illinois at Urbana-Champaign. Technical assistance has been given by Donald J. Rose, Robert S. Lehocky, and John H. Mize of the Engineering Operations staff of the Aviation Research Laboratory.

CONTENTS

INTRODUCTION

The safety of instrument flight operations requires the protection of sufficient airspace around each aircraft in the system. The magnitude of the required airspace protection, which is proportional to the navigation system error, has wide implications for all users of the airspace system, because it determines allowable course proximity and vertical separation. Recently, efforts have been made to quantify airspace protection requirements for aircraft using area navigation equipment. The first of these, Radio Technical Commission for Aeronautics (RTCA) Document DO-140 (1969), followed shortly by FAA Advisory Circular AC 90-45 (1969), established an empirically quantitative basis for assigning protected airspace for horizontal area navigation. The third, RTCA Document DO-152 (1972), extended the guidelines to three dimensions, including vertical area navigation (VNAV). The fourth, Application of Area Navigation in the National Airspace System (1973), was the report of an FAA/Industry Task Force established to study the orderly implementation of RNAV service. These documents provide the basis for future RNAV planning both procedurally and quantitatively.

At the heart of the quantitative presentations in these documents is an error budget which includes inputs from all sources of error in the system. Most of the budget items are equipment errors. However, because the system is based on manual flying, errors contributed by the pilot are also included in the error budget. Specific magnitudes of vertical and horizontal pilotage error are assigned arbitrarily for three navigation operations: enroute, terminal, and approach. For each of these operations pilotage error is combined geometrically with other sources of error in the system. The result is a maximum acceptable total system error for these flight operations. These values are then used as guidelines for the assignment of protected airspace for aircraft operating under the given conditions.

Although some area navigation operations, including high altitude routes, terminal arrivals and departures, and approaches, have been approved on the basis of these assumed pilotage error values, it is essential that magnitudes of pilotage error be determined experimentally for all instrument flight tasks being anticipated in the new RNAV system to determine the validity of the assumed values.

In an earlier study in this series (Report FAA-RD-72-126), multiengine, instrument-rated professional pilots flew a Twin Bonanza over a course designed on the basis of typical RNAV approach procedures being approved in 1972. This course included three VNAV instrument approach procedures, two of which required the setting of four waypoints. These four waypoints were the initial approach waypoint (IAF), the final approach waypoint (FAF), the missed approach waypoint (MAP), and the pullup waypoint (PUP). In addition, the course included a standard instrument departure (SID) and a standard terminal arrival route (STAR) both of which were based on projected future RNAV terminal area tasks.

To the pilot, the setting and/or selecting of four waypoints during an approach procedure represents a considerable increase in workload compared with conventional approach procedures. However, the occurrence of this number of waypoints in approach procedures is not uncommon even today. In fact, an examination of the approved approach procedures in Part 97.33 of the Federal Aviation Regulations reveals that as late as February 1974, 55 percent of the RNAV procedures required four waypoints and 98 percent required at least three waypoints in close proximity to one another. Average distances between these waypoints were as follows:

IAF to FAF	6.2 nautical miles
FAF to MAP	5.3 nautical miles
MAP to PUP	10.1 nautical miles

For the purposes of this report approach procedures of this type, i.e., requiring three or four closely spaced waypoints, will be called Standard Procedures.

An examination of the results of the earlier flight study (Report FAA-RD-72-126) reveals that pilot performance on Standard Procedures is not as good as previously assumed in three areas. First, the report concludes that the overall procedural error rate is large. Second, horizontal steering error during final approach is greater than previously assumed in AC 90-45. Third, although steady-state vertical steering variability is not reliably different from that previously assumed in DO-152, the steady-state central error tendency for vertical pilotage error is reliably different from zero in the positive direction during three-degree approach descents. However, steady-state vertical steering error was particularly difficult to define in many cases because flight workload items, such as chart reading, waypoint selection, and communications, often caused excessive pilot response latencies to necessary pitch adjustments even after the apparent capture of the vertical gradient. These workload items might also have been responsible for the large vertical steering variability between pilots contributing to the absence of a reliable difference between the empirical results ($\pm 3\sigma = 196$ feet) and the DO-152 assumed value ($\pm 3\sigma = 150$ feet) for final approaches below 5000 feet.

One means of improving this steering variability and general pilot performance in RNAV involves the simplification of procedures to reduce the amount of navigation data that must be handled during the approach and missed approach phases of the flight. Most of the presently published RNAV approaches could be made using no more than the two essential waypoints. The initial approach waypoint is required in many cases as a transition from enroute or terminal operations, and the missed approach waypoint is required on all approaches because it is the point at the end of the runway to which the approach is made. However, on most approaches, the final approach waypoint could be eliminated and replaced with an indication of distance to the MAP. In addition, the waypoint to which the pullup procedure is made in most cases could be replaced with an indication of distance from the missed approach waypoint. Using this type of approach procedure with a "dual waypoint" RNAV system, the pilot could set up the complete approach and missed approach sequence while he is inbound to the initial approach waypoint, as he would for a conventional ILS approach. For the purpose of this report, RNAV approach procedures that require no more than two waypoints will be called Simplified Procedures.

The primary purpose of this experiment was to compare pilot performance using Simplified Procedures with previously obtained pilot performance using Standard Procedures. Secondarily, additional data concerning the comparative performances of Airline Transport Pilots (ATPs) and Commercial Pilots with

Instrument ratings (CIPs) for VNAV operations were collected. Additional evidence also was obtained to determine whether a leveloff command is needed at the Minimum Descent Altitude during VNAV approaches. Finally, the experiment was designed to investigate whether a scale factor more sensitive than that used in the immediately preceding flight experiment (Report FAA-RD-72-126) would reduce crosstrack errors during final approach to the value assumed in AC 90-45.

METHOD

Subjects

To provide data that are precisely comparable to those of the preceding flight experiment (FAA-RD-72-126), two groups of four subjects each were chosen randomly from the same two pools of pilots at the Institute of Aviation, University of Illinois at Urbana-Champaign. The flight experience levels of these two groups were widely different. One group, made up of currently experienced ATPs, was chosen from pilots of the University's staff air transport service. The second group, made up of CIPs, was chosen from the flight instructors of the Pilot Training Department. All of the pilots were on current flying status for the Institute of Aviation. In addition, all of the pilots had a prior working knowledge of area navigation gained while serving as subjects in previous experiments. The flight experience levels of the subjects used in the two experiments are shown in Table 1.

Equipment

The flight research facility was a Beechcraft Twin Bonanza (N1000V) equipped with a Butler Vector Analog Computer (VAC) and an Ascent/Descent Director (ADD). This equipment is shown in Figures 1 through 4. The horizontal situation display was a Butler Symbolic Pictorial Indicator (SPI) located in the center of the flight instrument panel. The SPI had five dots on either side of center comprising a distance of ± 1.1 inches. Four scale factors were available for selection including 0.25, 1.0, 2.0, and 10.0 nautical miles per dot. The scale factor used primarily was 1.0 nautical mile per dot (± 5.0 nautical miles full scale). The scale factor was changed to 0.25 nautical miles per dot (±1.25 nautical miles full scale) for the Champaign approach only. Vertical deviation information was presented on the glideslope needle of a crosspointer type course deviation indicator located to the right of the vertical speed indicator. This display, referred to in this report as a vertical deviation indicator (VDI), was used for vertical deviation information both during guided climbs and descents and during some level flight segments. The vertical scale factor was 100 feet per dot, with two dots above and two below comprising

Figure 1. Beechcraft Twin Bonanza, N1000V, at University of Illinois-Willard Airport.

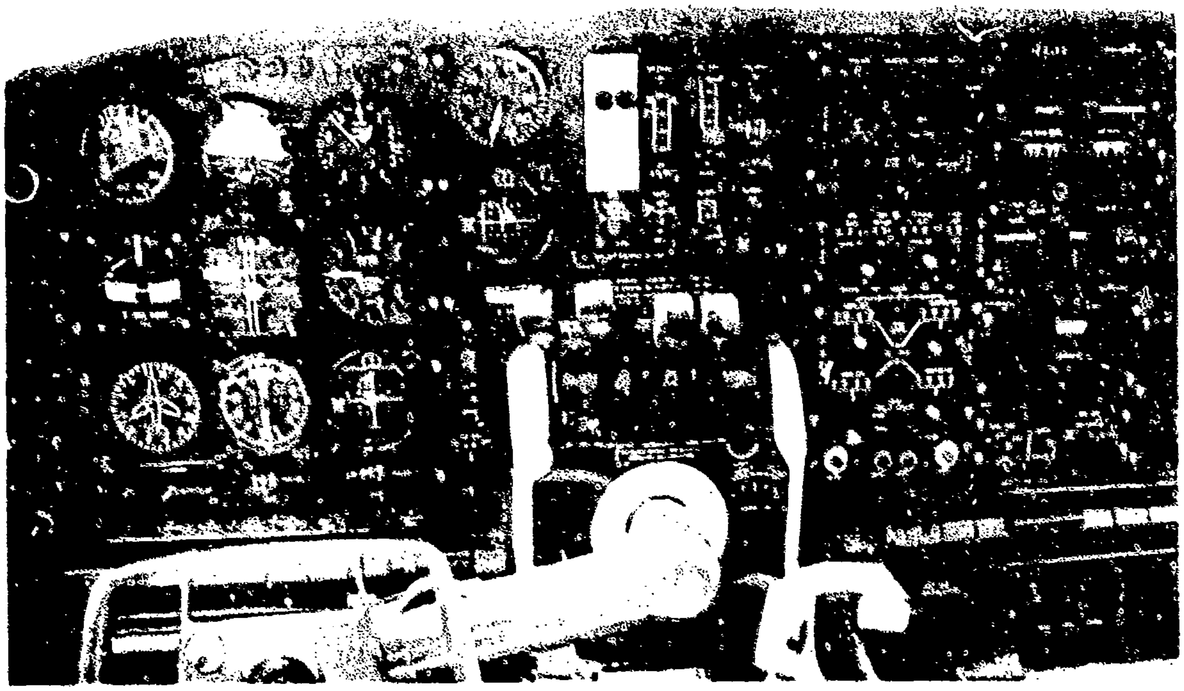

Figure 2. Instrument panel of Twin Bonanza showing the Butler Vector Analog Computer (VAC) control unit and the Ascent-Descent Director (ADD) control unit to the right of the engine controls and the Symbolic Pictorial Indicator (SPI) in the center of the flight instruments on the left side. The vertical deviation indicator (glideslope needle of the crosspointer CDI) is located on the right of the IVSI. Distance-to-waypoint is presented on the left side under the direction indicator

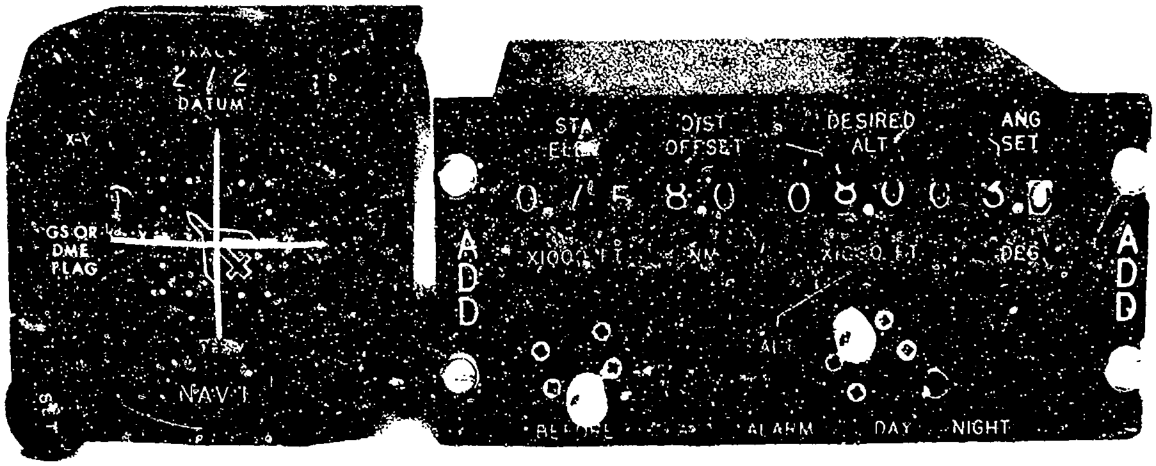

Figure 3. Close-up view of the VDI (left) and the ADD control unit (right).

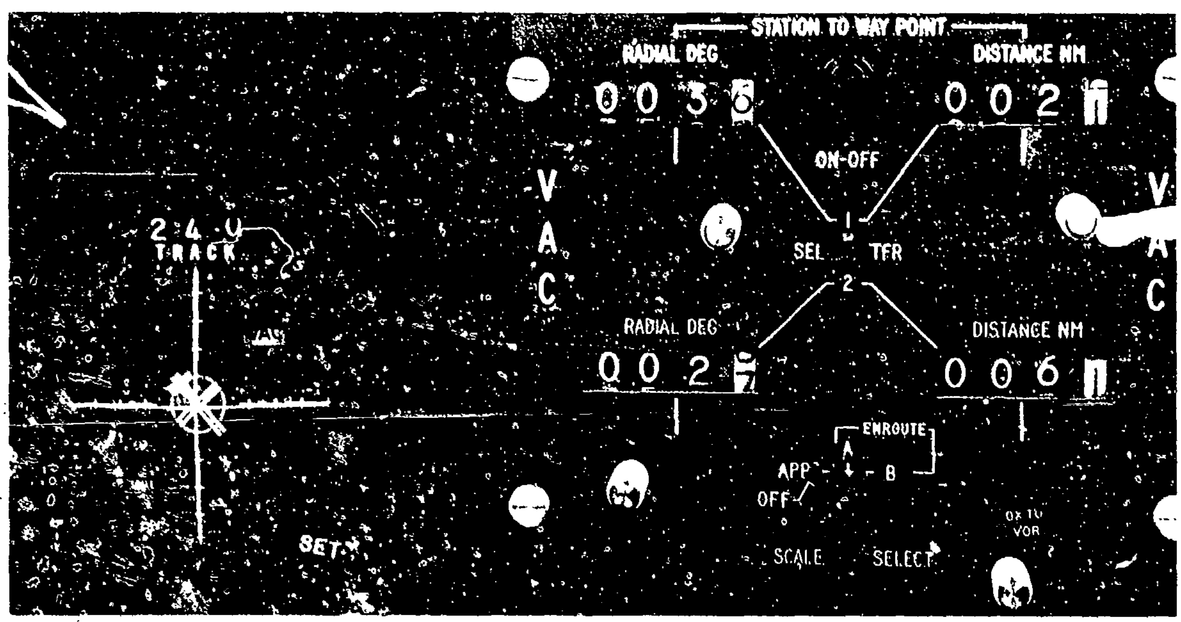

Figure 4. Close-up view of the SPI (left) and the VAC control unit (right).

Table 1. Flight Experience in Hours of Pilot Subjects.

Subject	Pilot Group	Total	Multi-Engine	Instrument	RNAV	Twin Bonanza
			STANDARD PROCEDURES			
1	ATP	7300	2950	530	6	0
2	ATP	6900	2050	375	6	0
3	ATP	5820	1140	440	6	0
4	ATP	3100	320	170	6	6
5	CIP	1460	38	105	6	6
6	CIP	1370	58	128	6	0
7	CIP	[illegible]270	16	71	6	0
8	CIP	350	25	75	6	0
			SIMPLIFIED PROCEDURES			
1	ATP	7000	2300	355	6	0
2	ATP	7700	5500	770	6	3
3	ATP	3000	220	220	6	6
4	ATP	3500	400	160	6	0
5	CIP	907	26	81	6	0
6	CIP	1900	50	110	6	0
7	CIP	1800	25	92	6	0
8	CIP	1450	40	70	6	0

a full scale of ± 200 feet (± 0.44 inches). An eight-channel strip-chart recorder was used to record altitude error, crosstrack error, airspeed error, and distance to waypoint.

Experimental Plan

The primary purpose of this study was to compare pilot performance on Simplified Procedures with pilot performance on Standard Procedures. Combining the data from this study with the data from the preceding flight experiment (FAA-RD-72-126) also provides a better indication of the performance differences for two other variables, pilot experience level and the need for leveloff commands at the minimum descent altitude, than was possible in the original study using Standard Procedures. In addition, this study provides final approach crosstrack error data using a far more sensitive horizontal scale factor to determine whether pilots flying under these conditions can meet the previously assumed crosstrack error criteria.

The flight course for Simplified Procedures used in this study (Figure 5) is basically the same as that used for Standard Procedures (Figure 6). A vertical profile of the Simplified Procedures course is shown in Figure 7 and the profile used for Standard Procedures course is shown in Figure 8. One can easily see from these figures that the flight task complexity for the Simplified Procedures was considerably reduced relative to Standard Procedures primarily through a reduction in the number of waypoints defining the approaches. On the Clinton approach, the Cayuga and Mecca waypoints were dropped and replaced with a distance-to-waypoint and an intersection, respectively. On the Paris approach, the Oliver and Morris waypoints were redefined in the same way. On the Champaign approach, the Garden waypoint is redefined as a distance-to-MAP.

In addition to these changes on the approaches, two other changes were made to lengthen the transition segments and further reduce the number of waypoints. First, the Mecca waypoint, which became the Mecca intersection, was moved out from the Clinton MAP to permit the elimination of the Hulman waypoint. A straight course was then drawn between the Mecca intersection and Wabash waypoint. Second, the Royal waypoint was moved back to the end point of the three-degree climb, and the turn at the beginning of the six-degree descent was eliminated. The course was then drawn directly across to intercept the extended Champaign final approach course at a 90-degree angle eliminating the Thomas waypoint.

The effect of these changes was to increase the overall number of segments from 18 to 20, to decrease the overall number of waypoints from 15 to 9, and to increase the overall course length from 153.5 nautical miles to 169.2 nautical miles. However, all of the vertical maneuvers remain intact as in the Standard Procedures

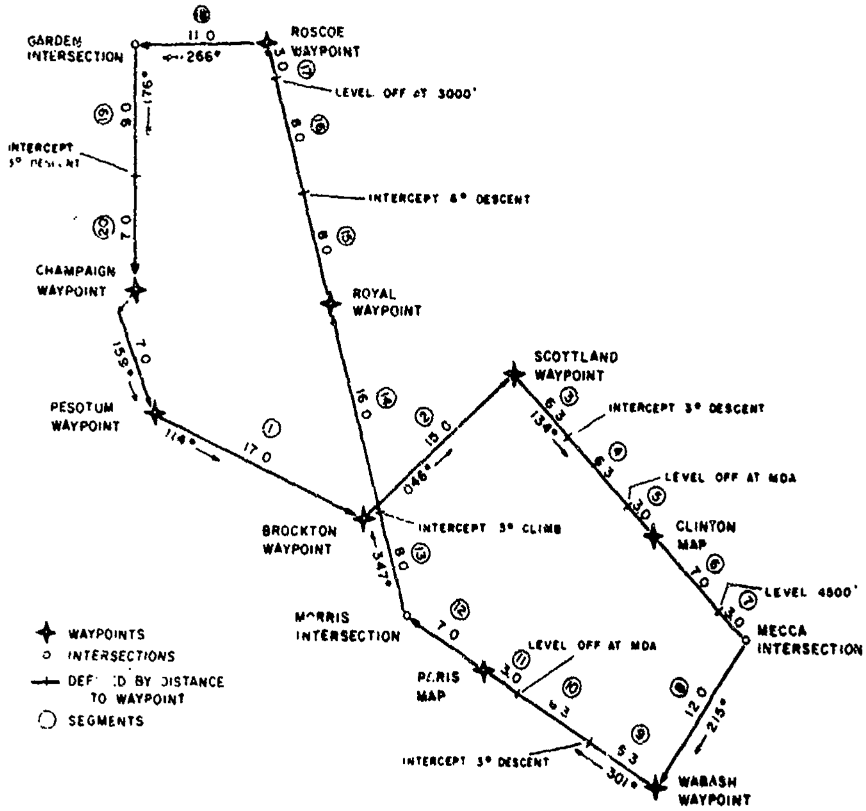

Figure 5. Horizontal view of the Simplified Procedures flight course.

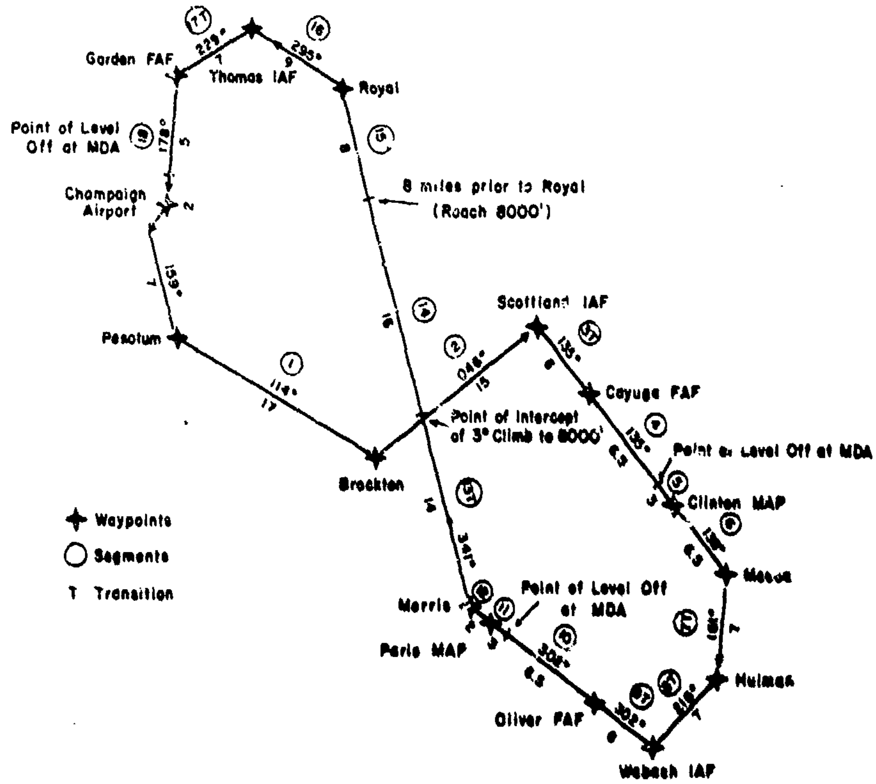

Figure 6. Horizontal view of the Standard Procedures flight course.

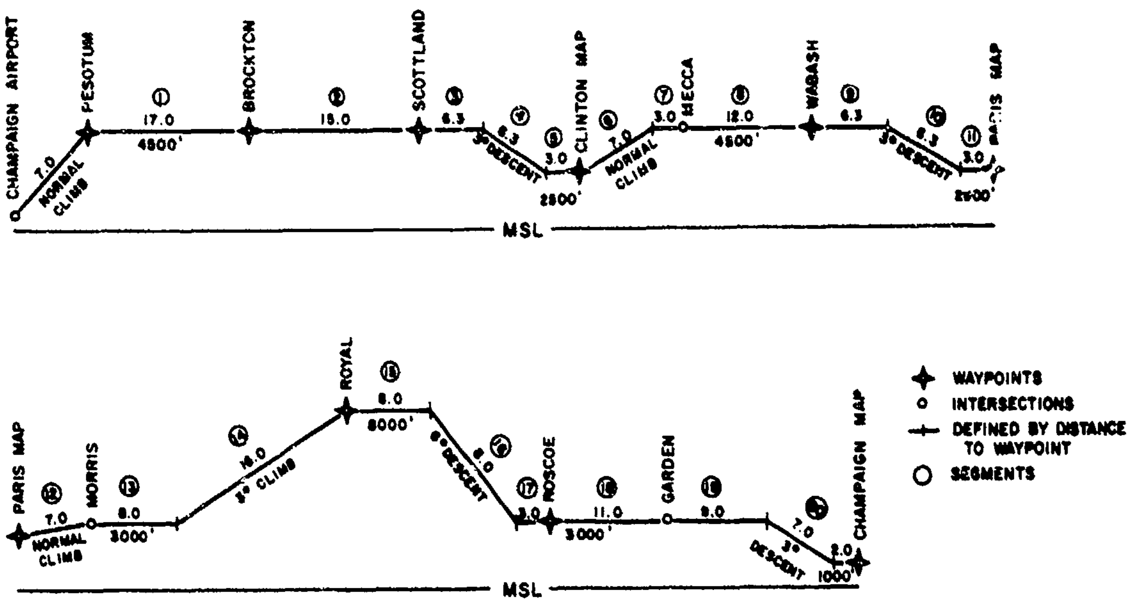

Figure 7. Vertical profile of the Simplified procedures flight course.

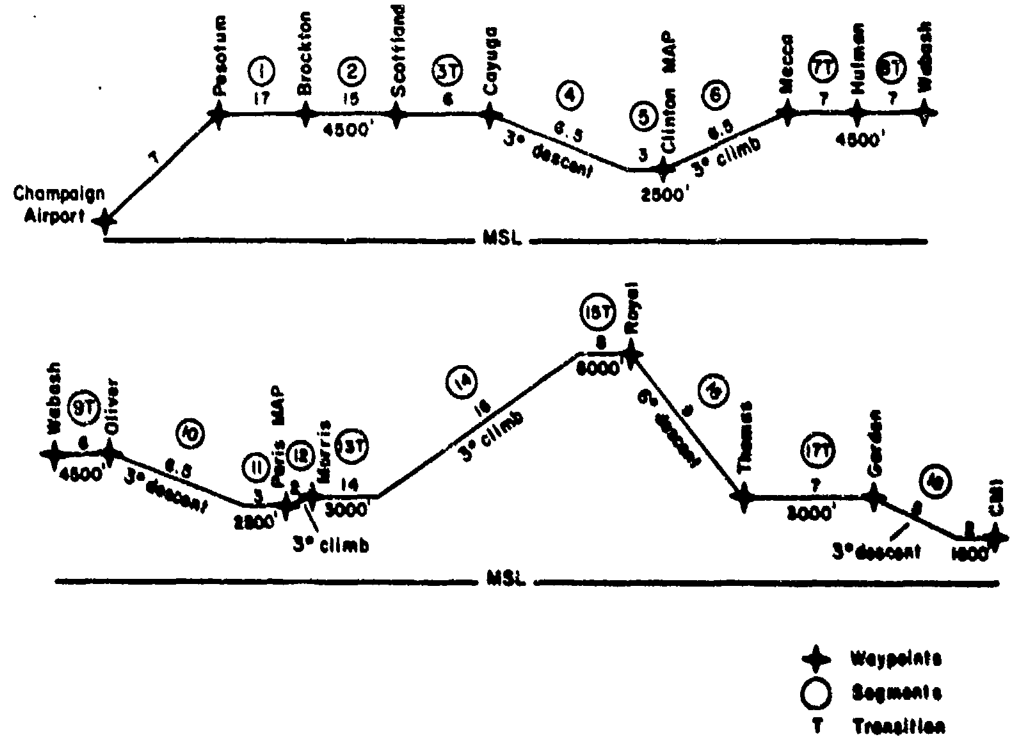

Figure 8. Vertical profile of the Standard Procedures flight course.

course allowing a direct comparison of the data. The intent of these changes was to reduce the pilot workload to the approximate level of conventional VOR navigation. It was the purpose of this study to determine whether these changes are sufficient to demonstrate acceptable pilot performance levels in all aspects of the VNAV flying task.

As in the experiment using Standard Procedures, four vertical gradients were included in the flight course for Simplified Procedures as shown in the following list:

Task	Segments
Level flight	1, 2, 3, 5, 7, 8, 9, 11, 13, 15, 17, 18, 19
Three-degree climb	14
Three-degree descent	4, 10, 20
Six-degree descent	16

The flight sequence consisted of a standard instrument departure (SID) from Champaign, a VNAV approach to Clinton, a missed approach from Clinton, a VNAV approach to Paris, a missed approach from Paris, a three-degree climb to 8000 feet, a six-degree descent to 3000 feet, and a VNAV approach to Champaign. All segments of the experimental course were designed to allow comparisons between variables such as vertical tasks, pilot groups, and vertical displays in terms of crosstrack, altitude, and airspeed error. These comparisons were to demonstrate the possible differences in pilot performance among the various types of navigation problems including three-degree climbs, three-degree descents, six-degree descents, and level flight. In addition, the course was designed to provide steady-state crosstrack and altitude error data for comparison with previously assumed values in AC 90-45 and DO-152 in a variety of instrument flight situations.

Two other experimental questions were investigated using the three VNAV approaches of the Simplified Procedures course. First, on the Clinton and Paris approaches the Minimum Descent Altitude (MDA), leveloff information was displayed in two ways. On one of these approaches, upon reaching MDA the pilot received command leveloff information on the VDI. On the other approach, upon reaching

MDA the pilot was forced to use the altimeter for leveloff because the VDI commanded a descent to field elevation. Therefore, on each flight, command leveloff was provided on one approach and not provided on the other. This factor was varied systematically over all subjects and flights as shown in Table 2.

Table 2. Design for varying information presented for leveloff at MDA on Clinton and Paris approaches.

Subject	Pilot Group	Flight			
		1	2	3	4
1	ATP	a	b	b	a
2	ATP	b	a	a	b
3	ATP	a	b	b	a
4	ATP	b	a	a	b
5	CIP	a	b	b	a
6	CIP	b	a	a	b
7	CIP	a	b	b	a
8	CIP	b	a	a	b

Legend:

a = Clinton MDA with command leveloff
Paris MDA without command leveloff

b = Clinton MDA without command leveloff
Paris MDA with command leveloff

The final experimental question concerned crosstrack error during final approach. To determine whether a more sensitive scale would reduce crosstrack error to the value assumed in AC 90-45, the horizontal scale factor was changed to 0.25 nautical mile per dot or ± 1.25 miles full scale (±1.1 inches) for the Champaign VNAV approach only. On the Clinton and Paris approaches, the scale factor was kept at 1.0 nautical mile per dot or ± 5.0 miles full scale (± 1.1 inches).

Procedure

Each pilot was given adequate written and oral instructions to understand the use of the navigation and flight equipment before flying. The written instructions included a copy of the Butler National Corporation's "Three-Dimensional Area Navigation" (December 1969), an operations manual for the aircraft, and other material concerning the specific flight task. The oral instructions included a cockpit familiarization using the navigation equipment in all operations required by the flight task. The final step in the instruction process was a familiarization flight that included examples of all types of problems to be encountered during experimental flights.

Instructions regarding the four types of error (altitude, crosstrack, airspeed, and procedural) were designed to give equal emphasis to all. The pilot was told that all four types of errors were to be kept to a minimum. However, to prevent the loss of crosstrack data near each turn, the pilot was told to wait until he was within one mile of the waypoint or intersection before changing the course selector to the new course. No special instructions were given regarding procedures for the anticipation of vertical path changes except that the clearances for guided climbs and descents always included the maintenance of airspeed at 120 miles per hour.

After completing the instruction and familiarization process, each subject made four experimental flights under simulated instrument conditions. During each flight, the subject pilot was responsible for all aspects of the flying task including aircraft control, flight planning, navigation data input, and communications. However, outside communication was not a high workload item because all flights were made in VFR conditions. The routing and vertical profile of each flight were as shown in Figures 5 and 7 for this Simplified Procedures Course. Subject pilots were given a series of simulated VNAV instrument charts to use for navigation during the experimental flights. This series of charts directed the subject pilot to fly a course very similar to that flown earlier in the previous study. The primary difference in this study, compared with the charts used in the previous study, is a reduction in the number of waypoints required on a VNAV approach. This can be seen by comparing the approach charts used for the Clinton approach in the two studies (Figures 9 and 10). To reduce the number of waypoints in this approach, the Cayuga waypoint was replaced with a distance-to-MAP, and the Mecca waypoint was replaced with a distance-from-MAP. Thus, the necessity to enter navigation data during the approach was eliminated for the Simplified Procedures. A complete set of charts used in both studies is presented in Appendix D.

To complement these charts a series of instrument clearances, shown in Figure 11, directed the subject pilots to fly the intended course. The safety pilot, acting as the air traffic controller, read these clearances to the subject at the appropriate time as the flight progressed.

As in the previous study, pilot performance data on the Clinton and Paris MDA segments were used to determine whether there is a need for a commanded level-off at MDA. Procedurally, this was accomplished through the use of two different waypoint (MAP) entry procedures. Indicated at the bottom of each approach chart was the proper setting for "desired altitude" and "waypoint offset" to be set on the Butler ADD before beginning the approach. In the command leveloff condition, "desired altitude" was set at MDA, and the waypoint offset was set at 0. In the altimeter leveloff condition, "desired altitude" was set to field elevation, and the waypoint offset was set at 3.0 miles "before." The effect of these two setting procedures was to provide in the first case, a glideslope to field elevation with no leveloff command at MDA, and in the second case, a glideslope to MDA with a programmed command to level off. The two conditions were varied between the Clinton and Paris approaches in a counterbalanced design as shown in Table 2.

There are two possible procedures for executing the guided climb maneuver. The first involves establishing an optimum airspeed prior to intercepting the climb gradient and maintaining that airspeed throughout the maneuver. The power setting is adjusted as the maneuver progresses to maintain the given airspeed. The climb gradient is maintained with the pitch control. The second procedure involves applying maximum allowable climb power at the intercept point of the climb gradient and maintaining that power setting throughout the climb. The climb

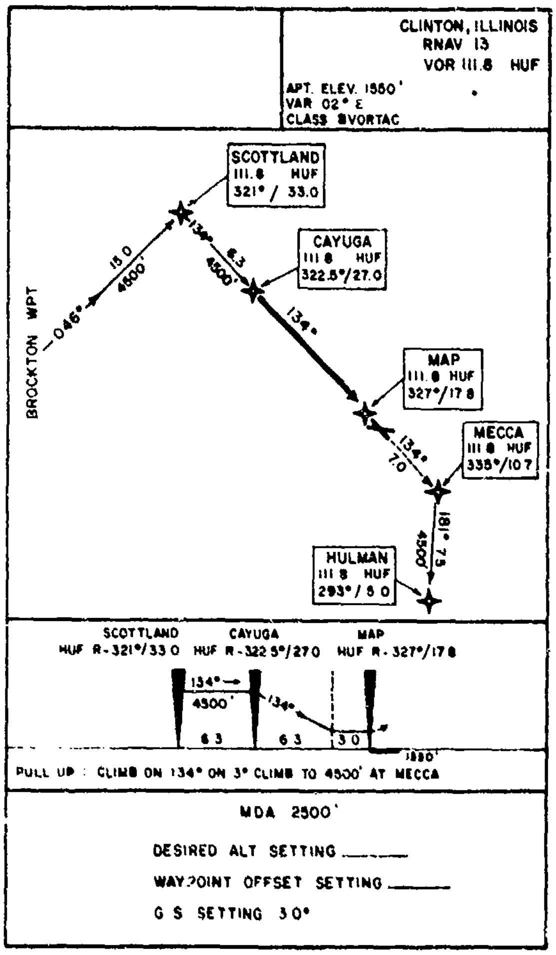

Figure 9. Clinton approach, Standard Procedures.

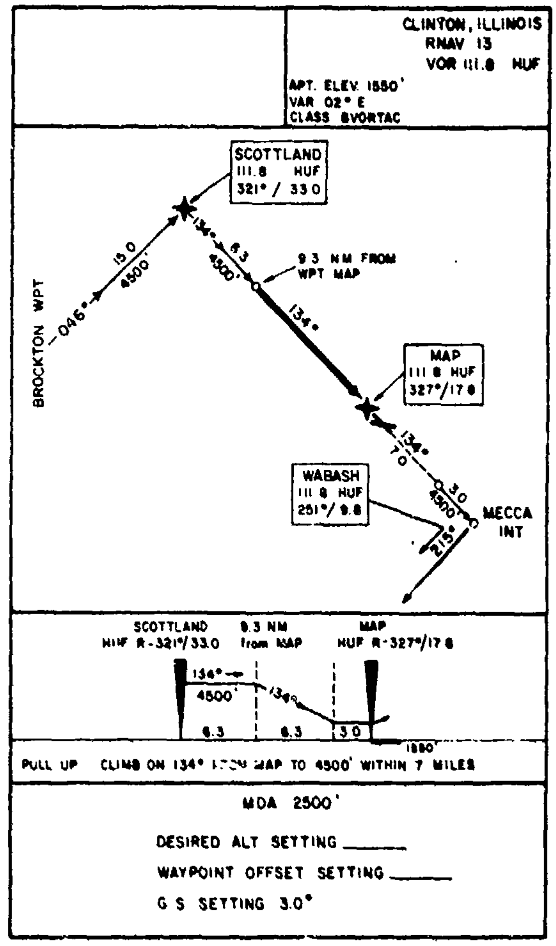

Figure 10. Clinton approach, Simplified Procedures.

CLEARANCE	LOCATION	NAVIGATION OPERATIONS									
		Freq		W/P		OBS	W/P	ADD			
		DME	VOR	RAD	DIS		Sel	Offset	G-P	ALT	ANG
1000V is cleared to the Clinton airport via the Possum ONE departure. Maintain 4500'.	Prior to take-off										
	After Possum										
1000V is cleared for the Clinton RNAV 13 approach. Maintain 120 indicated air speed after Scotland.	After Brockton										
In the event of missed approach 1000V is cleared to the Wabash waypoint via the Mecca intersection and the 215° course. Maintain 4500'.	After Scotland										
1000V is cleared for the Paris RNAV 30 approach. Maintain 120 indicated after Wabash.	After Mecca										
In the event of missed approach 1000V is cleared to the Royal waypoint via Morris intersection and the 347° course to Royal. Maintain 3000'.	After Wabash										
1000V is cleared to the Garden intersection via the Royal One STAR. Maintain 120 indicated air speed until Roscoe.	After Morris										
	After intercepting 3° slope										
1000V is cleared for the Champaign RNAV 18 approach. Maintain 120 indicated air speed after Garden. (AT 13 MILES FROM MAP SET SCALE AT .25 MILES)	After Roscoe										
	After Garden										

Figure 11. Experimenter's checklist.

gradient is maintained with pitch, and the airspeed is allowed to seek its own level. Pretesting of the experimental flight course indicated that the first procedure is preferable because it is similar to the technique that is required on guided descents in conventional ILS approaches. Airspeed control at 120 miles per hour was required during guided climb and descent maneuvers. To provide a better transition from level flight to guided descents on VNAV approaches, pilots were required to maintain an airspeed of 120 miles per hour on the level segment immediately prior to each of the three approache descents. These three level segments were 3, 9, and 19.

Performance Assessment

During the experimental flights, continuous recordings of altitude and crosstrack flight technical errors and distance to waypoint were made on a strip-chart recorder. Airspeed error was also recorded on the strip chart when airspeed control was required of the pilot. Navigation procedural errors were recorded manually on the observer checklist by the safety pilot when they occurred (Figure 11). Such errors were then pointed out and/or corrected by the safety pilot when it became evident to him that the subject pilot would not make the correction. To prevent discontinuities in the recorded data, no long delays in correcting procedural errors were allowed.

At this point two definitions may help clarify the classification of procedural errors. First, a procedural error is defined as any navigation control setting or aircraft control error which, if allowed to continue uncorrected, would result in a significant deviation from the assigned route of flight. Second, a blunder is defined as a procedural error which has resulted in a deviation from ATC assigned and protected airspace. It was the practice in this experiment to prevent blunders from occurring by pointing out procedural errors before they became blunders.

Incorrect settings of the following controls were classified as procedural errors: DME frequency, VOR frequency, waypoint radial, waypoint distance, course, offset distance, desired altitude, ascent-descent angle, and waypoint number (1 or 2). Errors in flight procedures such as failing to respond to a commanded change in vertical profile, which could be classed as procedural, were recorded as "other" procedural errors. Six of the categories involved continuous (analog) as opposed to discrete (digital) selection errors. For these the following accuracy criteria were established for error recording:

1. Waypoint radial ±0.1 degree
2. Waypoint distance ±0.1 mile
3. Offset distance ±0.1 mile
4. Desired altitude ±10.0 feet
5. Ascent/descent angle ±0.1 degree
6. Course ±1.0 degree

In each case, whenever an error exceeded the specified criterion, it was recorded and corrected.

The central tendency (M) and standard deviation (σ) of the tracking errors by the eight pilots were calculated at one-mile intervals along each flight course and its associated vertical gradient using the following formula:

$$\sigma = \sqrt{\frac{\Sigma(X_i - M)^2}{N - 1}} \qquad (1)$$

where

X_i = error measured at one of the sampling points

N = the number of measurements at that sampling point, and

M = the sample mean, $\frac{\Sigma X_i}{N}$.

The root mean square (RMS) error scores were calculated using the following formula:

$$RMS = \sqrt{\frac{\Sigma X_i^2}{n - 1}} \qquad (2)$$

where

X_i = error measured at one of the sampling points

n = number of sampling points for that variable by that subject on that flight.

Both statistics (RMS and σ) are measures of performance variability; RMS expresses the variability about the route centerline or assigned vertical gradient for an entire route segment or portion thereof, and σ expresses the variability relative to the central tendency (M) of a number of flight paths (N) at any particular point along the same route segment.

Statistical Treatment

Two types of statistical reliability tests were applied to the various performances as appropriate to the particular question of interest. First, analyses of variance were performed on the log-RMS error scores for altitude, course, and airspeed tracking and on the log-transformed procedural error scores to assess the statistical reliability of the observed differences in performances under the various experimental conditions. These tests were applied to the tracking scores taken at one-mile intervals along each route segment of the experimental flight profile. Second, the *t*-statistic was used to compare experimental standard deviation (σ) values to the corresponding values set forth in DO-152 and AC 90-45.

Use of the analysis of variance technique and the *t*-test requires the assumption of normal distributions of scores. Although departures from normality of sample distributions do not necessarily invalidate either test, when scores are known to be samples from a non-normal parent distribution, they should be transformed into a normal form if possible before applying the test. Because both RMS error scores and σ scores are bounded by zero on the lower side, their distributions are skewed positively by an amount that is readily correctable by a logarithmic transformation of the scores. This transformation has the effect of redistributing scores with a potential range from zero to infinity over a new potential range from minus to plus infinity and consistently yields a good approximation to a normal distribution of scores suitable for analysis by any normal probability statistical technique.

Because the objective of this study was to obtain values of vertical-gradient and straight-course tracking errors, as a function of procedural complexity, for comparison with corresponding steady-state error values assumed in DO-140, AC 90-45, and DO-152, steady-state portions of the altitude data were treated separately from the transient portions. The above documents also implicitly assume a value of zero for central tendency or bias error, and therefore, to correct for the non-zero central tendencies observed in the experimental data, standard deviations (σ scores) were computed for altitude errors ($\pm 3\sigma$ values presented) and for crosstrack and airspeed errors ($\pm 2\sigma$ values presented).

It should be remembered, however, that RMS error scores, which reflect the central tendency as well as the variability of flight paths, were used in the analyses of variance to evaluate the reliability of differences among performances in the various experimental conditions. Furthermore, standard deviations (σ scores) should always be interpreted in conjunction with their corresponding central tendencies because either systematic anticipation or delay in initiating changes in course or vertical gradient causes changes in the central tendency of flight paths that must be taken into account in the allocation of protected airspace.

The reliability of a statistical difference between two experimental conditions (*t*-test), or differences among more than two conditions (analysis of variance), is expressed as the probability, *p*, that a difference, or differences, as large or larger than observed in the particular experimental samples would be expected to occur by chance if the samples had been drawn at random from the same population. If the probability of a chance occurrence of the observed difference, or differences, is less than five times in 100 ($p < 0.05$), it is conventional to conclude that the observed difference, or differences, is statistically reliable and that the samples in fact represent different populations. However, the converse is not a valid conclusion; the fact that a sample difference, or differences, would be expected to occur by chance five times or more in 100 repetitions of the experiment does *not* indicate that the samples necessarily represent the *same* population.

RESULTS

Results of flight tests using simplified procedures are presented for four error measures: vertical, horizontal, airspeed, and procedural errors. Summary vertical, horizontal, and airspeed data for each mile are presented graphically in Appendix A. Regions of transient and steady-state performance are denoted along the distance scale of each figure; a solid line indicates transient data, and a dotted line indicates steady-state data. Appendix B presents corresponding data in tabular form. Using the steady-state variability (σ) scores for each vertical task, statistical comparisons were made between these data and corresponding assumed values in AC 90-45 and DO-152. These data were then pooled with corresponding Standard Procedures data from the previous study (FAA-RD-72-126) to allow a combined statistical comparison of all independent variables including pilot groups, procedures, tasks, and flights. In addition, the overall RMS scores from both Standard and Simplified Procedures for each vertical task were used to make statistical comparisons among the same independent variables.

Vertical Error

Figures A-1 through A-12 in Appendix A present mile by mile central tendency and 3σ variability of vertical error over 32 flights by ATPs and CIPs. Separate analyses were made for steady-state data only and for all data including both steady-state and transient performance. Following these, a third analysis was made using data from the MDA segments of the Clinton and Paris approaches.

Steady-State. DO-152 and the Task Force Report list the following criteria for stable 3σ vertical flight technical error:

Final approach 5000 feet MSL and below	150 feet
Terminal area 10,000 feet and below	250 feet
Enroute ascent or descent	250 feet
Enroute level flight	250 feet

In addition, a mean or central tendency value of zero is assumed in all conditions.

As described earlier, there were four basic vertical tasks performed on each flight. Empirical steady-state values of vertical tracking error were found for each of these vertical tasks. Steady-state vertical tracking data were found in level flight on Segments 1, 2, 3, 5, 7, 8, 9, 11, 13, 15, 18, and 19; in the three-degree climb on Segment 14; in three-degree descents on Segments 4, 10, and 20; and in the six-degree descent on Segment 16. Figures A-1 through A-12 of Appendix A should be examined to determine the exact points in these segments at which steady-state data are defined. Table 3 presents summaries of these data as functions of pilot group and vertical task.

Table 3. Central tendency and 3σ variability of vertical error in feet for steady-state performances by ATPs and CIPs on four VNAV instrument flight tasks for Simplified Procedures and the corresponding assumed values from DO-152.

Task	Pilot Group						DO-152
	ATP		CIP		Combined		Mean = 0
	Mean	± 3σ	Mean	± 3σ	Mean	± 3σ	± 3σ
Level flight	+ 1	99	+ 5	158	+ 3	129	250
Three-degree climb	+ 9	131	- 6	148	+ 2	140	250
Three-degree descent	+17	129	+22	165	+20	147	150
Six-degree descent	+36	164	+38	173	+37	169	250

Examination of the steady-state data in Table 3 shows that in two of the tasks, three-degree descents and six-degree descents, the combined central tendency values are consistently above the commanded vertical gradient, and these bias errors are reliably different from zero ($p < 0.05$). Furthermore, empirical vertical steering variability for the combined ATP and CIP groups is reliably smaller ($p < 0.05$)

than previously assumed in DO-152 for level flight, three-degree climbs, and six-degree descents in terminal areas. Although vertical steering variability in three-degree descents is not reliably different from the ±150-foot value assumed in DO-152, it is reliably smaller than the ±250-foot value assumed for all other operations.

To test for steady-state vertical error differences among vertical tasks and between pilot groups, the log-RMS values of steady-state vertical error were used in an analysis of variance. This test revealed reliable differences in vertical steering among the four vertical tasks ($p < .01$). The difference between pilot groups was not reliable ($p > .05$). These results suggest that level flight, three-degree climbs, three-degree descents, and six-degree descents be treated differently in the assignment of protected vertical airspace but do not support a requirement for differential treatment of CIP and ATP pilots.

To permit a comparison between steady-state vertical steering performances for Simplified and Standard Procedures, two additional data sets were constructed. The first set consists of vertical steering data for all portions of the Simplified Procedures course on which steady-state performance occurred and data for corresponding points on the Standard Procedures course, whether steady-state or not. The second set was the converse of the first, including comparative data for all points at which steady-state performance occurred with Standard Procedures. Correspondence of data in the level-flight task is approximated because level-flight segments on which there was steady-state performance differed from one course to the other.

Figure 12 presents three-RMS vertical error as a function of vertical task and flights for Standard and Simplified Procedures for data points at which steady-state performance occurred with Simplified Procedures. Examining Figure 12, one can see a dramatic improvement in steady-state vertical steering performance for Simplified Procedures compared with corresponding data for Standard Procedures for all vertical tasks. As one might expect, vertical steering performance deteriorates as the vertical task becomes more difficult both for Standard and Simplified Procedures.

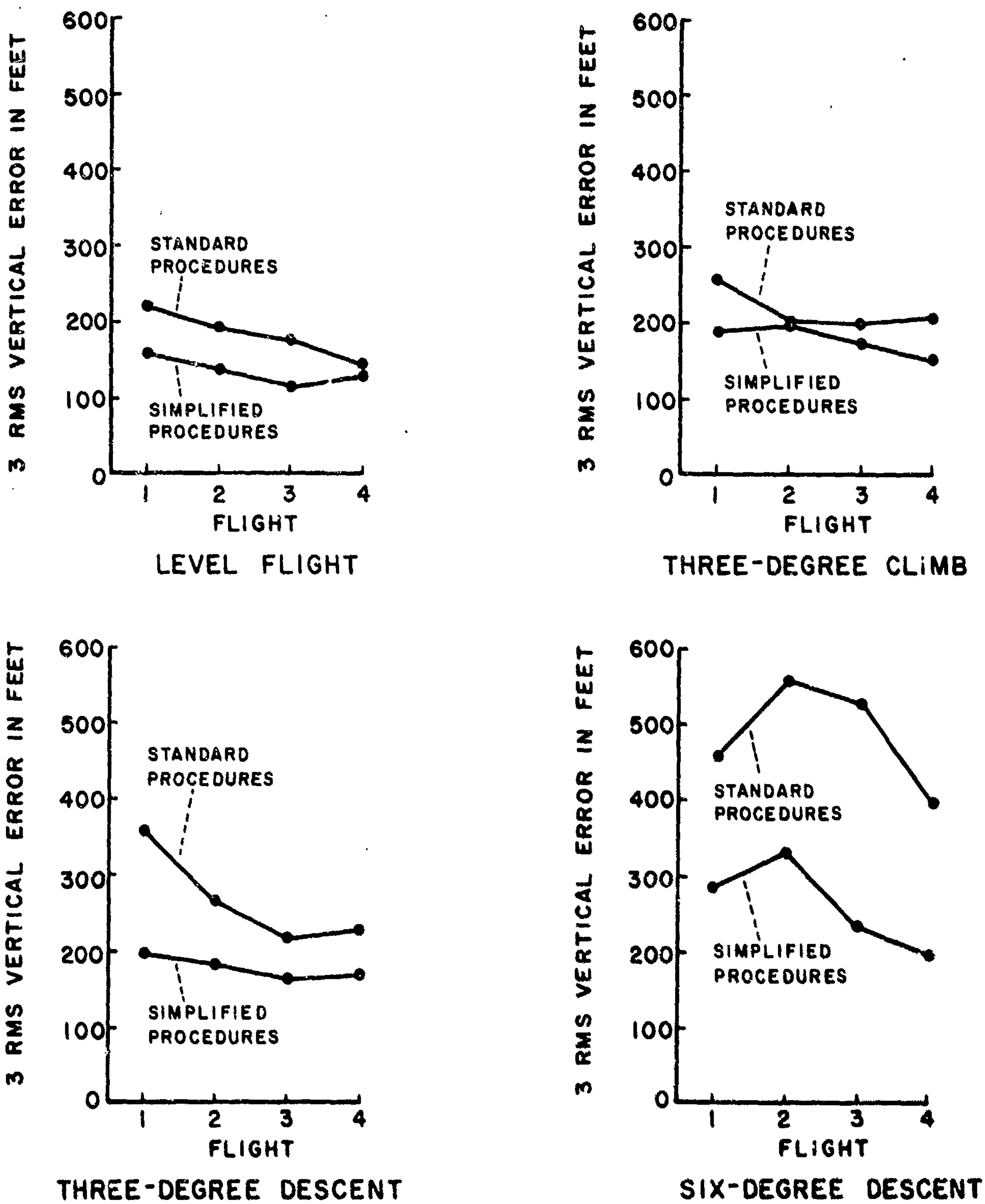

Figure 12. Three-RMS vertical flight technical error in feet as a function of procedural complexity and flights for four vertical tasks. Data for Simplified Procedures are steady-state and data for Standard Procedures represent directly corresponding portions of the course, whether steady-state or not.

The level-flight task results in the best performance, whereas the six-degree descent results in the poorest performance. Very small performance differences are indicated between three-degree climbs and three-degree descents. An analysis of variance of these data revealed a statistically reliable difference among vertical tasks ($p < .01$), between procedure types ($p < .01$), and over four flights ($p < .05$). The difference between pilot groups (ATP vs. CIP) was not statistically reliable ($p > .05$).

For the data set of points at which steady-state performance occurred with Standard Procedures, an exact correspondence of data sampling points between the two courses was achieved in all vertical tasks. Steady-state performances using Standard Procedures occurred in level flight on Segments 1 and 2 (all miles), in a three-degree climb on Segment 14 (the last 8 miles), and in three-degree descents on Segments 4, 10, and 18 (miles 5 and 4 in each case). Figure 13 presents corresponding three-RMS vertical error as a function of vertical tasks and flights for Standard versus Simplified Procedures. The analysis of variance showed reliable differences between types of procedures, among vertical tasks, and over four flights ($p < .05$). Again, the difference between pilot groups was not reliable ($p > .05$). The consistently reliable learning effect in steady-state data indicates that pilots continue to improve their steering performance in repeated flights over the same course even if they have received a relatively extensive RNAV training program prior to the experimental flights.

In a final demonstration of the performance differences resulting from Standard and Simplified Procedures, Table 4 presents the percentage of the data points at which steady-state vertical steering error was achieved for each task. This table shows that Simplified Procedures resulted in a greater proportion of steady-state error in all tasks except the three-degree climb indicating that asymptotic vertical steering performance is reached earlier on each task.

Overall error. Perhaps a better predictor of the relationships among the various factors under consideration is a data set consisting of both transient and steady-state performances. Figure 14 presents overall three-RMS vertical error as a function of vertical tasks and flights for Standard and Simplified Procedures.

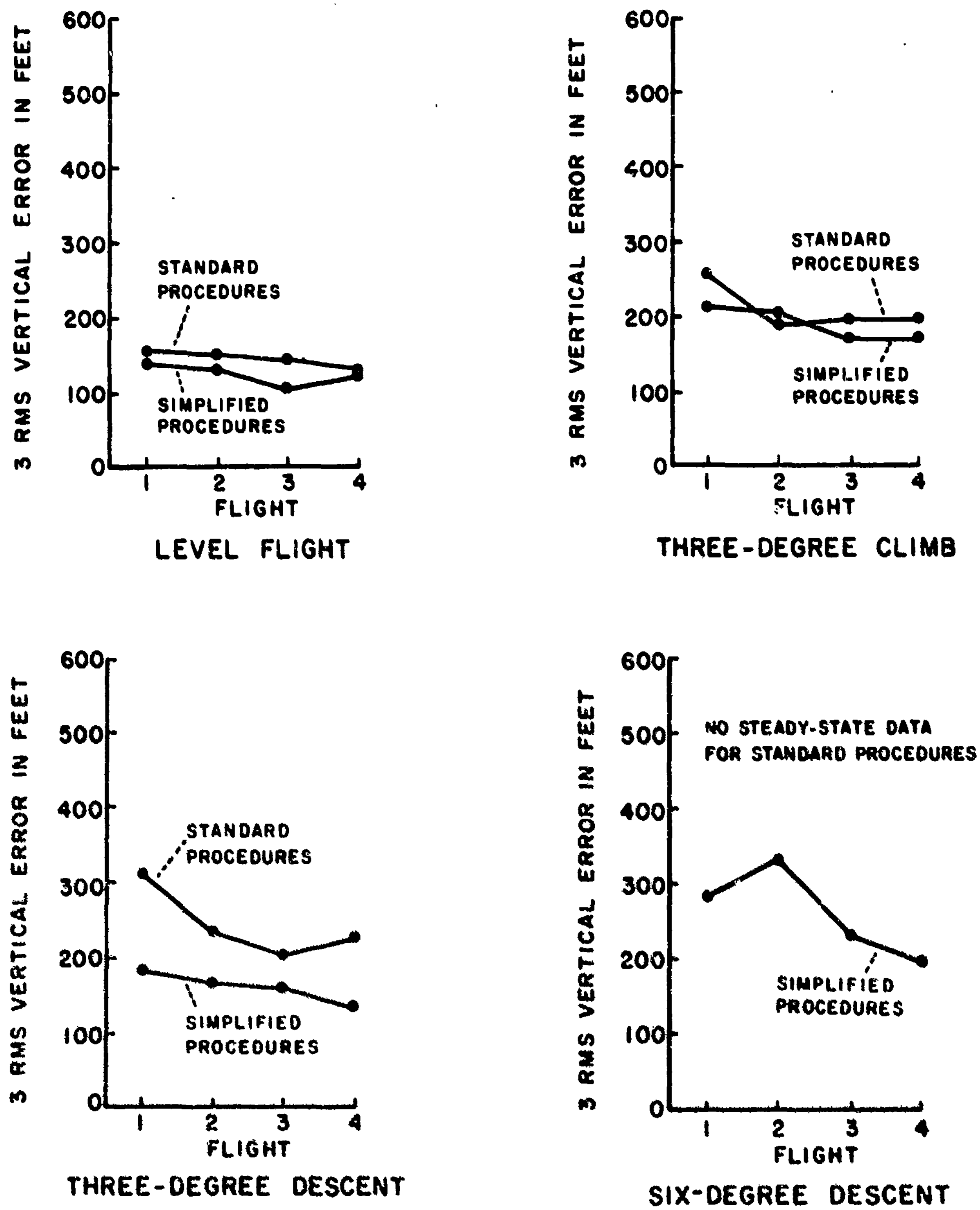

Figure 13. Three-RMS vertical flight technical error in feet as a function of procedural complexity and flights for four vertical tasks. Data for Standard Procedures are steady-state and data for Simplified Procedures represent directly corresponding portions of the course.

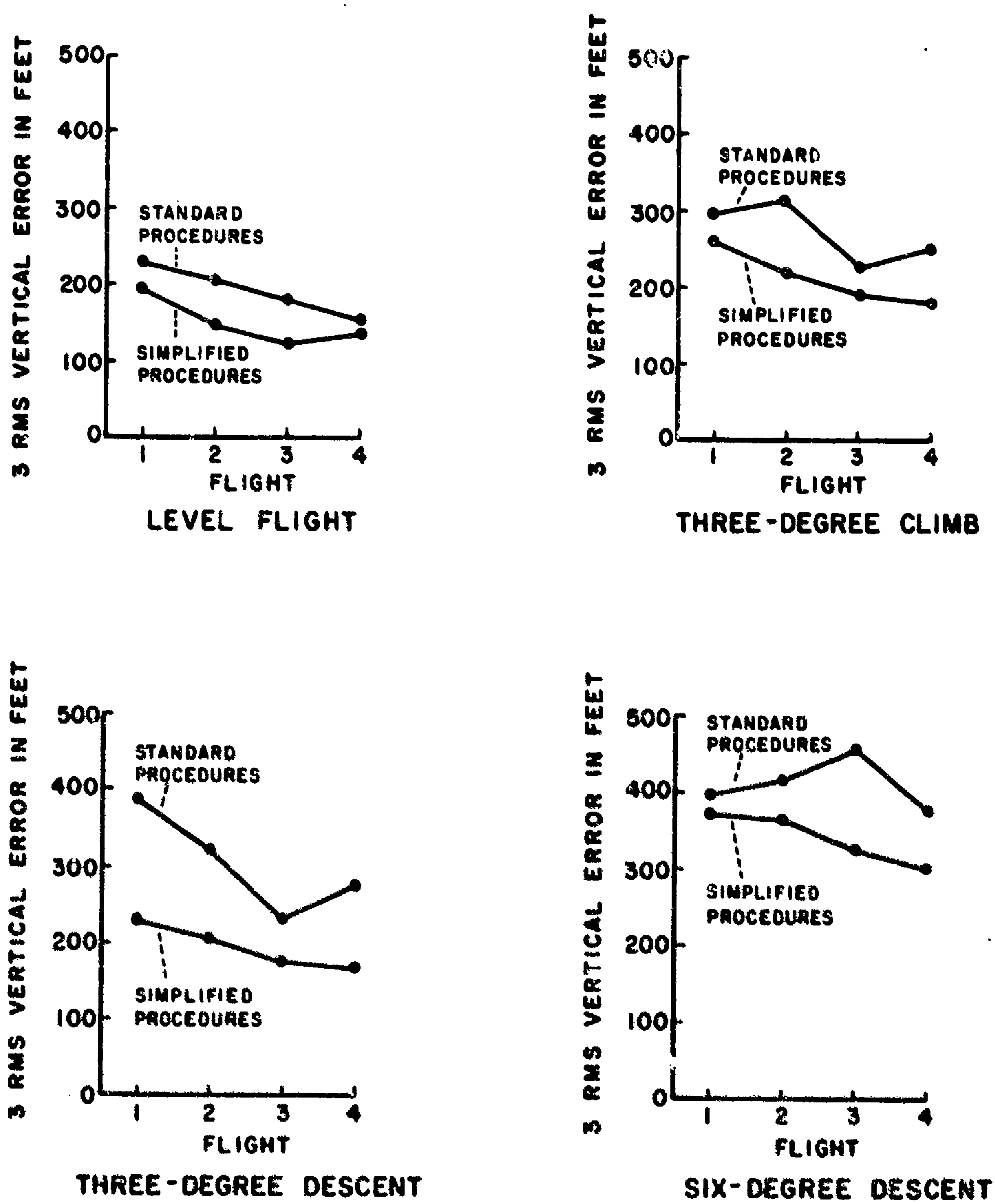

Figure 14. Overall three-RMS vertical error in feet as a function of procedural complexity and flights for four vertical tasks.

Table 4. Percentage of data points at which steady-state vertical steering performance occurred for each task.

Task	Standard Procedures	Simplified Procedures
Level flight	.39	.93
Three-degree climb	.50	.50
Three-degree descent	.30	.55
Six-degree descent	.00	.38

As in the case of steady-state data, the overall data demonstrate a noticeable improvement in vertical steering performance for Simplified Procedures compared with Standard Procedures. Also, the consistently wide margin of performance differences among vertical tasks for overall data remains evident. Finally, there appears to be a clear learning effect over four flights on the same course for both types of procedures.

The analysis of variance of these overall data generally confirmed these observations. The differences between procedure types, among vertical tasks, and among flights were all statistically reliable ($p < .05$), and the difference between pilot groups was not reliable ($p > .05$). As before, the scores used in the analysis of variance tests were log-RMS error scores.

Minimum Descent Altitude Error. The final data set, vertical steering error at MDA, is analyzed separately because it addresses the specific question of whether or not there is a need for a command leveloff display at MDA. Although one would expect an increase in vertical steering error during the transition from a three-degree descent to level flight at MDA, the vertical steering data for Segments 5 and 11 (Figures A-3 and A-6) reveal that, except for a transient increase in error at Mile 3 of the Paris approach, the primary performance change during this maneuver is an improvement in steering variability. For this reason, the data used in this analysis were restricted to vertical steering errors at Miles 2, 1, and 0 of both the Clinton and Paris approaches for both Standard and Simplified Procedures.

Three-RMS vertical error in feet for these sampling points are presented in Figure 15 as a function of type of procedure, type of leveloff, and flight number. Simplified Procedures resulted in reliably better vertical steering perfomance than Standard Procedures ($p < 0.05$). However, the differences between displays, between pilot groups, and among flights were not statistically reliable. These results do not indicate that vertical steering performance is affected by a command leveloff display at MDA.

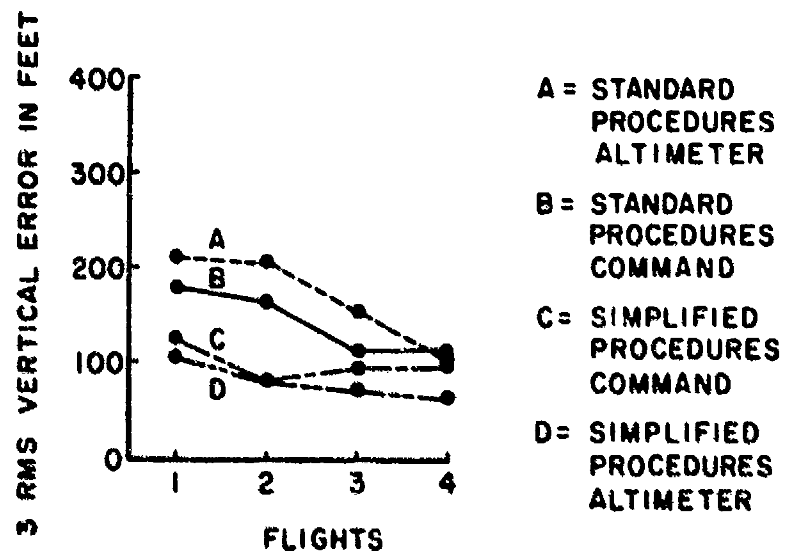

Figure 15. Three-RMS vertical error in feet as functions of procedure types, display types, and flights.

Horizontal Error

Figures A-13 through A-24 in Appendix A present mile-by-mile central tendency and 2σ variability of horizontal error over 32 flights by ATPs and CIPs. In the following analyses, three methods of evaluating the horizontal steering error are used. The first directly compares isolated steady-state data from this experiment with those values assumed in FAA AC 90-45. The second involves the overall error values obtained from the combination of transient and steady-state data. Finally, transient horizontal data immediately following the eight turns made in the Simplified

Procedures course are examined to evaluate overshoot and undershoot as functions of turn angle and type of turn.

Steady-State. Advisory Circular AC 90-45 and the FAA/Industry Task Force Report have specified criteria for stable 2σ horizontal flight technical error. The Task Force Report, however, specified time periods in which new criteria will apply. The following represents that time period denoted as 1973-77.

Final approach	0.5 Nautical mile
Terminal area	1.0 Nautical mile
Enroute	2.0 Nautical mile

In addition, a mean or central tendency value of zero is assumed in all conditions. Because flight tests were made in terminal and final approach areas only, the criteria that apply to these areas will be used for comparison with the empirical results.

Although the distinction is not as clear as in the case of vertical errors, empirical steady-state values of horizontal tracking error are separated for the four vertical tasks performed during each experimental flight. On three-degree descents, these data are further separated into approaches using a horizontal scale factor of ±5.0 nautical mile full-scale deflection (Clinton and Paris) and approaches using a horizontal scale factor of ±1.25 nautical mile full-scale deflection (Champaign). Figures A-13 through A-24 of Appendix A present data for level flight on Segments 1, 2, 3, 5, 7, 8, 9, 11, 12, 13, 15, 17, 18, and 19; three-degree climb on Segment 14; three-degree descent on Segments 4, 10, and 20; and six-degree descent on Segment 16. Table 5 presents summaries of steady-state data as functions of pilot group and vertical task for comparison with corresponding assumed values in AC 90-45.

Caution is urged in the interpretation of horizontal steering results for two reasons. First, all horizontal course changes were made in level flight, and for this reason the horizontal central error tendencies for level flight may have been affected adversely relative to those for the climbing and descending flight segments. Second, and more important, bends in the horizontal course due to signal anomalies

Table 5. Central tendency and 2σ variability of horizontal steering error in nautical miles for steady-state performances by ATPs and CIPs on four VNAV instrument flight tasks using Simplified Procedures and corresponding assumed values from AC 90-45.

Task	Pilot Group						AC 90-45
	ATP		CIP		Combined		Mean = 0
	Mean	± 2σ	Mean	± 2σ	Mean	± 2σ	± 2σ
Level flight	0.07 R	0.72	0.07 R	0.77	0.07 R	0.74	1.00
Three-degree climb	0.23 R	0.45	0.22 R	0.57	0.22 R	0.51	1.00
Three-degree descent (scale = ± 5.00 nmi)	0.08 L	0.60	0.05 L	0.52	0.06 L	0.56	0.50
Three-degree descent (scale = ± 1.25 nmi)	0.00 L	0.16	0.07 L	0.24	0.04 L	0.20	0.50
Six-degree descent	0.10 R	0.31	0.00 R	0.57	0.05 R	0.44	1.00

were observed at various points. The most severe of these bends was observed on the Paris approach segment for which a horizontal scale factor of ± 5.0 nautical miles was used. Only a very slight bend was observed on the Champaign approach segment where the scale factor of ± 1.25 nautical miles was used. Therefore, because the signal anomalies were more severe on the Clinton and Paris approaches, on which the ± 5.0 nautical mile scale factor was used, than they were on the Champaign approach, on which the ± 1.25 nautical mile scale factor was used, a direct comparison of the effects of scale factor cannot be made on the basis of these data. However, the horizontal steering error results from the Champaign approach are valid and are presented because they represent ATP and CIP performances under nearly ideal signal conditions using a scale factor of ± 1.25 nautical miles full scale.

An examination of the steady-state data in Table 5 reveals that the combined 2σ horizontal steering variability is smaller than previously assumed for all vertical maneuvers performed except three-degree approach descents using the less sensitive horizontal scale factor. It should be noted that the assumed value of horizontal steering error for approach descents is ± 0.5 nautical mile compared with ± 1.0 nautical mile for other terminal area operations. Empirical 2σ horizontal steering variability is reliably better than assumed in AC 90-45 for level flight, three-degree climbs, and six-degree descents. In three-degree descents, horizontal steering variability was not reliably different from the assumed value for the ± 5.0 nautical mile scale factor. However, it was reliably smaller than the value assumed in AC 90-45 for the ideal conditions of the Champaign approach using a ± 1.25 nautical mile scale factor.

The $\underline{p} < 0.05$ confidence interval for central tendency shows a reliable bias to the right side of course for the three-degree climb only. Other studies in this series have shown a reliable tendency to fly to the right of course in all maneuvers. This discrepancy does not necessarily invalidate the previous finding because, for those segments of the Simplified Procedures course on which a considerable amount of time is spent on the same heading (Segments 13 through 17), the same right-side phenomenon is observed (Figures A-20 through A-22).

Figure 16 presents two-RMS steady-state horizontal error as a function of pilot groups and flights for Simplified Procedures. Analysis of the variance of these data revealed reliable differences between pilot groups ($\underline{p} < .01$) and over four flights ($\underline{p} < .01$). The average 2 RMS steady-state horizontal error for the CIP group was 0.820 nautical miles for all vertical tasks. For the ATP group, this value was 0.702 nautical miles.

These results support the conclusion that, with Simplified Procedures, steady-state horizontal tracking performance can be significantly better than previously assumed in AC 90-45 for all terminal area vertical tasks tested. The results from the Champaign approach demonstrate that, given a good signal, a sensitive display scale factor, and Simplified Procedures, a 2σ steering variability significantly smaller than 0.5 nautical miles is achievable. Also, the tendency of pilots to fly on the right side

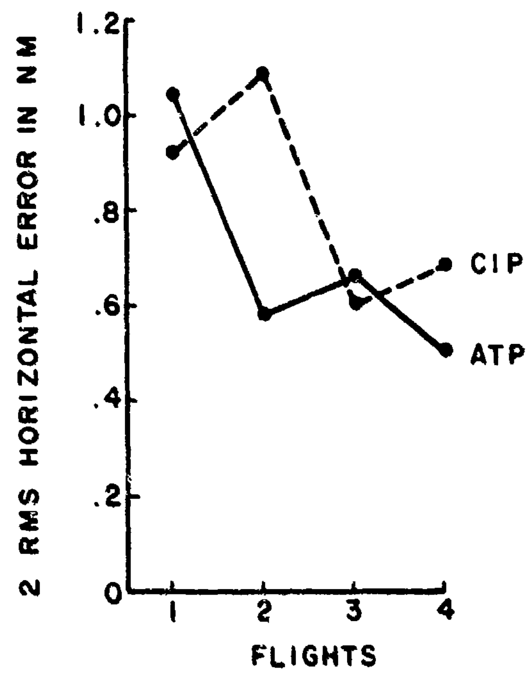

Figure 16. Two-RMS steady-state horizontal error as a function of pilot group and flight for Simplified Procedures. The combined central tendency curve shows the overall learning effect during four flights.

of the course was not as pronounced as previously found, although a right-side tendency persisted on long segments of the Simplified Procedures course. For steady-state horizontal steering only, there was a reliable difference between ATP performance and CIP performance. Finally, combining pilot groups, reliable learning effects over four flights on the same course suggests that steady-state performance may be better than that observed to date for pilots who repeatedly fly the same course.

Overall error. An overall data set consisting of transient and steady-state performances from both Standard and Simplified Procedures was constructed to permit a pooled data comparison of the independent variables. This data set includes all of the recorded horizontal steering data except that from Segment 20 of the Simplified Procedures course on which the scale factor was different. Figure 17 presents overall two-RMS horizontal steering data as a function of vertical task and flight for Standard and Simplified Procedures. The most striking effect among these factors is between

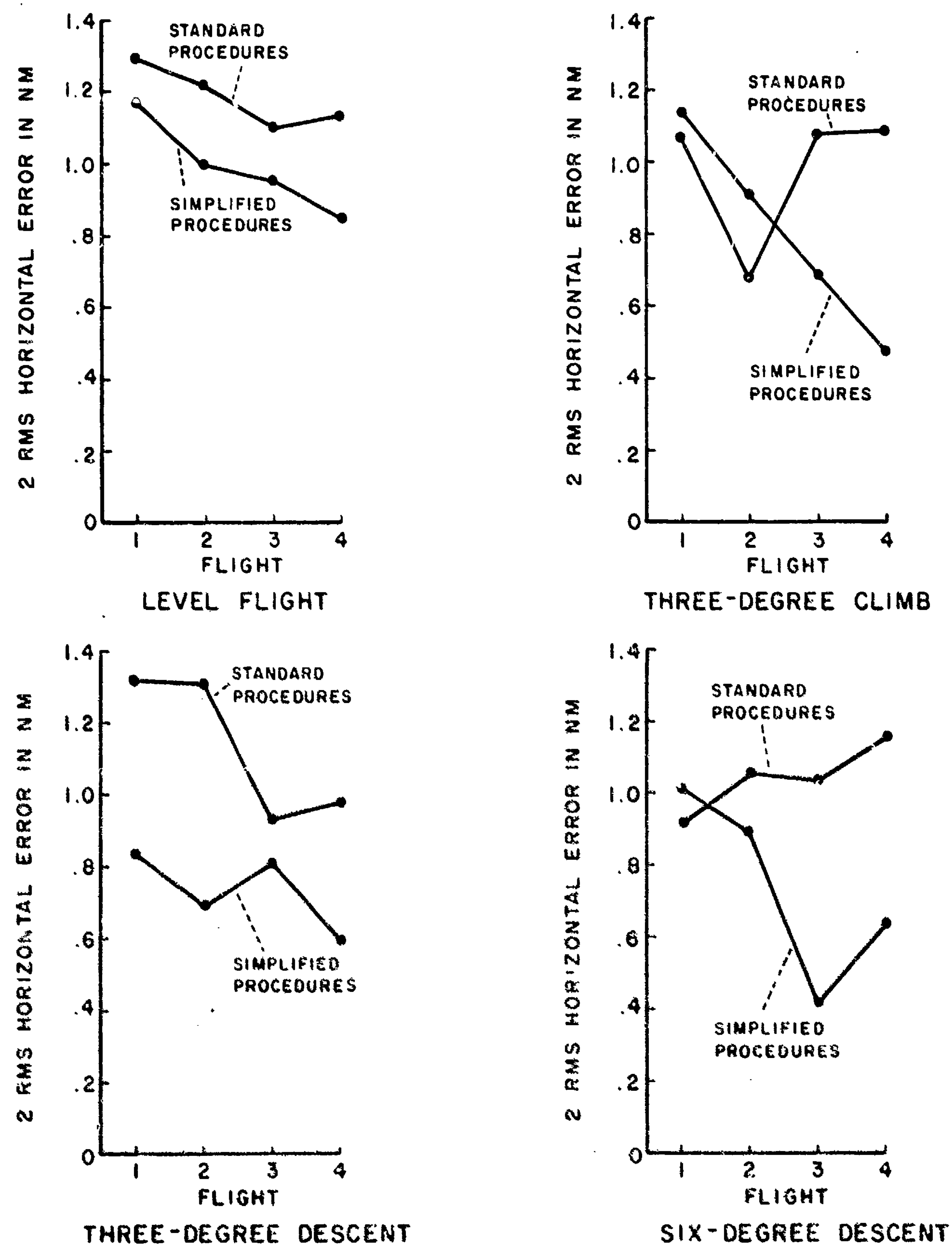

Figure 17. Two-RMS overall horizontal steering error as a function of procedural complexity and flights for four vertical tasks.

the two levels of procedural complexity. Noticeable improvements occurred as the flights progressed in all four vertical tasks when procedures were simplified.

It is interesting to note that horizontal tracking performance in level flight was not as good as in climbs or descents, especially with Simplified Procedures. This effect was probably due to the fact that most turns are made in level flight under Standard Procedures, and all turns were made in level flight with the Simplified Procedures used. Analysis of the variance of overall horizontal steering error using climb and descent data only revealed reliable differences between procedure types and over flights ($p < .01$). Differences between pilot groups and among tasks were not reliable ($p > .05$).

In conclusion, overall horizontal steering results indicate significantly smaller steering errors for Simplified Procedures than for Standard Procedures on climb and descent maneuvers and improved performance over four flights.

Transient error. Because horizontal steering data immediately following a course change provide an indication of airspace requirements in 2-D RNAV operations, a more detailed examination of transient error in course following would be informative at this point. Of the eight course changes in the Simplified Procedures flight task, five were defined by waypoints and three were defined by the intersection of waypoint radials. The procedure for performing waypoint turns was identical to that for intersection turns except that during the approach to waypoint turns, the distance indication decreases to zero, whereas during the approach to intersection turns the distance indication increases to the indicated distance of the intersection from the waypoint. Except for this difference, horizontal turn anticipation procedures should not have been affected.

However, as Figure 18 indicates, pilots apparently treated these two turn designators differently. That is, although pilots were told to anticipate both waypoint and intersection turns by no more than one mile, it is evident that in approaching intersections they often began turns prematurely, whereas they tended increasingly to overshoot waypoint turns as angles between courses increased.

Figure 18 presents average horizontal central error tendencies between the waypoint or intersection and five miles beyond for eight course changes of 45 degrees to 90 degrees in magnitude. The far right point of the waypoint turn curve includes data from three course changes having magnitudes of between 80 degrees and 90 degrees. The average of these three is 85 degrees. Analysis of the variance of these data revealed a reliable difference ($p<0.01$) between waypoint turns and intersection turns in terms of the amount of undershoot or overshoot and a reliable interaction ($p<0.01$) between type of turn and magnitude of course change. Performance differences associated with other factors, including pilot groups and flights, were not reliable ($p>.05$).

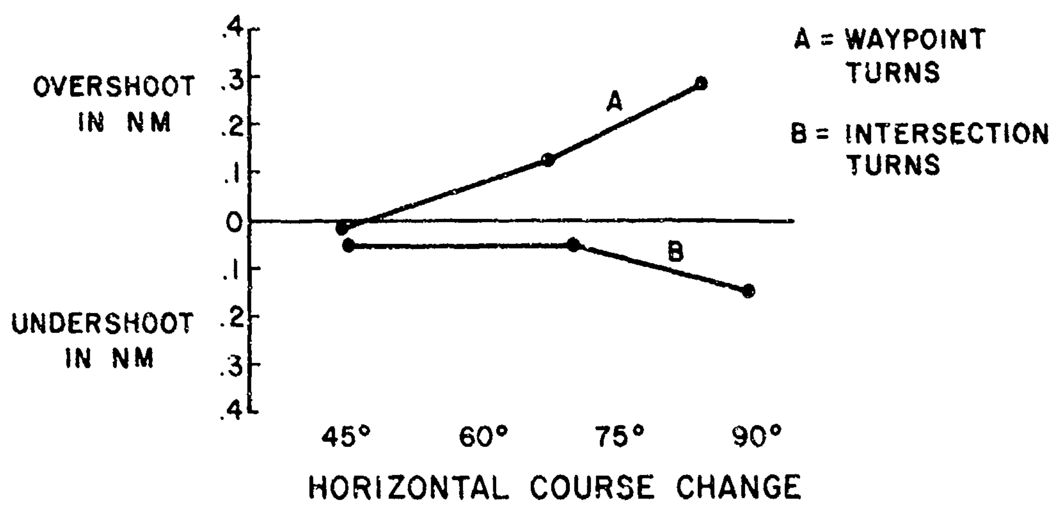

Figure 18. Transient tendency to overshoot and undershoot, respectively, as a function of horizontal course change for waypoint and intersection turns using Simplified Procedures.

To show the relative amounts of airspace being used for these two turn designators, Figure 19 presents two-RMS horizontal error as a function of magnitude of course change for waypoint and intersection turns. From an examination of this figure one can see a reliable interaction between type of turn designator and magnitude of horizontal course change ($p<0.01$). Two-RMS waypoint turn error is

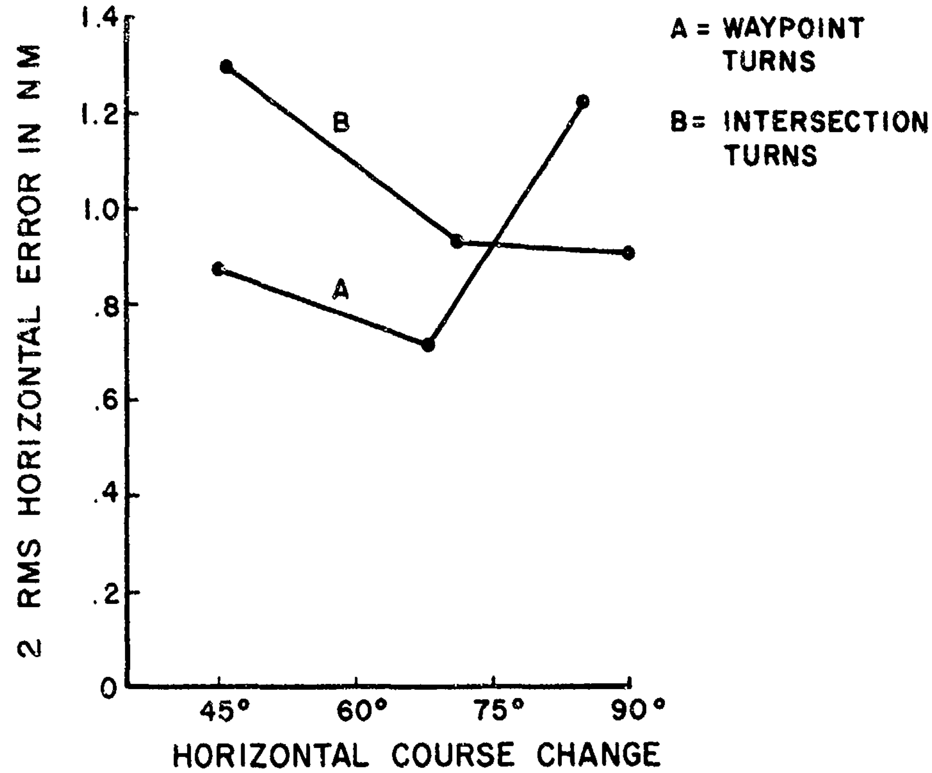

Figure 19. Two-RMS transient horizontal error as a function of magnitude of horizontal course change for waypoint and intersection turns using Simplified Procedures.

smaller than intersection turn error for course changes having magnitudes between 45 degrees and 75 degrees and larger for course changes approximating 90 degrees. Performance differences associated with magnitudes of course change and flights were reliable ($p < .05$). Differences between pilot groups were not reliable ($p > .05$).

In conclusion, these results clearly show that pilots treated waypoint turns and intersection turns differently although they were instructed to perform them in a similar manner. In waypoint turns there is a definite tendency to overshoot the new course. This tendency becomes more pronounced as the angle of turn increases. In intersection turns there is a definite tendency to undershoot the new course. This tendency also becomes more pronounced as the angle of turn increases. On the other hand, although the amount of airspace required for these two types of turn designators is not different over the range of turns tested, there is a definite interaction between angle of turn and type of turn designator, namely, for small turn magnitudes, less airspace is used for waypoint turns than for intersection turns, whereas for large turn magnitudes less airspace is required for intersection turns.

Airspeed Error

An analysis of airspeed error is included in this report because it provides a measure of pilot performance on the third flight variable being controlled by the pilot on most vertical tasks. The comparison of airspeed control performance on Standard and Simplified Procedures provides a further indication of workload and residual attention differences between these two levels of procedural complexity. Figures A-25 through A-31 in Appendix A present mile-by-mile central tendency and 2σ variability of airspeed error from 120 miles per hour over 32 flights by ATPs and CIPs. These data were evaluated both for steady-state values, as indicated by the dotted portions of the distance scales in these figures, and for overall values. Two of the figures (A-25 and A-27) present indicated airspeed rather than airspeed error and are presented to show the tendency of pilots to anticipate the required airspeed change on subsequent segments. These data were not used in either analysis.

Steady-state. Empirical steady-state values of airspeed error (from 120 miles per hour) were analyzed in terms of the four vertical tasks performed during each flight. Figures A-26 and A-28 through A-31 of Appendix A present data for level flight on Segments 3, 5, 9, 11, 15, 17, and 19; three-degree climb on Segment 14; three-degree descent on Segments 4, 10, and 20, and six-degree descent on Segment 16. Table 6 presents summaries of these data as functions of pilot group and vertical task.

Differences in steady-state airspeed performance among the four vertical tasks were quite small for Simplified Procedures. In addition, very small differences are indicated between pilot groups for all tasks. Finally, central tendency scores were not reliably different from 120 miles per hour, the desired airspeed ($p > 0.05$).

Table 6. Central tendency and 2σ variability of airspeed error in miles per hour for steady-state performances by ATPs and CIPs on four VNAV instrument flight tasks for Simplified Procedures.

Task	Pilot Group					
	ATP		CIP		Combined	
	Mean	± 2σ	Mean	± 2σ	Mean	± 2σ
Level flight	+1.38	7.06	+0.02	7.42	+0.68	7.24
Three-degree climb	+0.32	5.84	+1.13	8.14	+0.73	6.99
Three-degree descent	-1.09	6.32	+0.21	7.34	-0.44	6.83
Six-degree descent	-1.58	6.56	-1.40	8.06	-1.49	7.31

As in previous sections, steady-state airspeed errors with Simplified Procedures were pooled with corresponding Standard Procedures data to permit a comparison between airspeed performances for the two levels of procedural complexity. Figure 20 presents two-RMS steady-state airspeed error during three vertical tasks over four flights for Standard and Simplified Procedures. Level flight airspeed error was not used in this analysis because, in several cases, Standard Procedures subjects failed to slow the aircraft to approach airspeed even by the point at which steady-state airspeed was achieved in Simplified Procedures. These large errors would have disproportionately weighted the Standard Procedures scores. Nevertheless, even without the level-flight airspeed errors, one can see from Figure 20 that performance is better for Simplified Procedures than for Standard Procedures. This difference was shown to be reliable ($\underline{p} < 0.05$). In separate tests on each vertical task, airspeed performance was reliably better for Simplified Procedures than it was for Standard Procedures on three-degree climbs and three-degree descents ($\underline{p} < 0.05$). The difference on six-degree descents was not reliable ($\underline{p} > 0.05$).

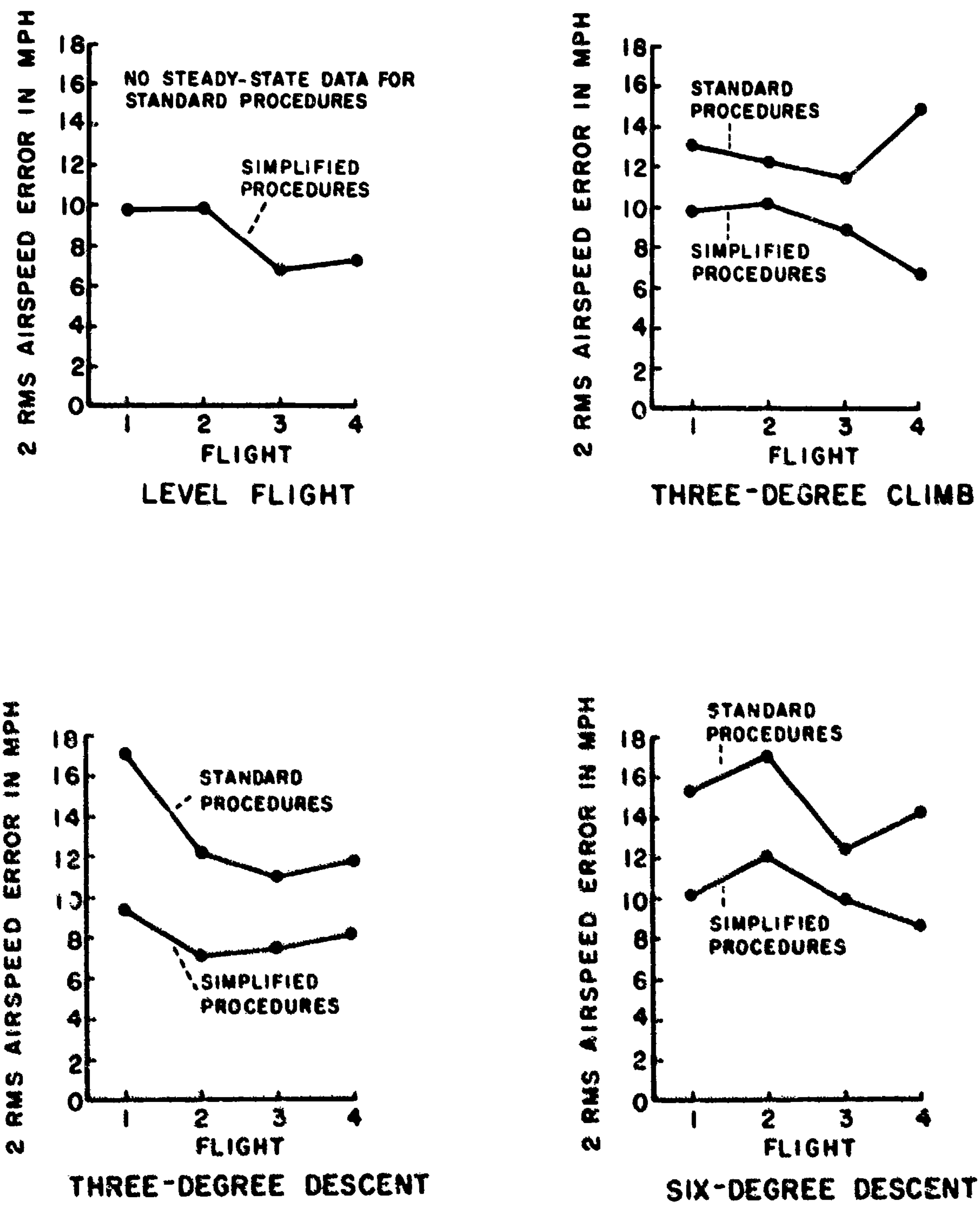

Figure 20. Two-RMS steady-state airspeed error in miles per hour as a function of procedural complexity and flights for four vertical tasks. No comparable data were available in level flight for Standard Procedures.

Overall error. Combined transient and steady-state airspeed data provide a better sample on which to test for differences between independent variables. Figure 21 presents these overall airspeed data as a function of vertical tasks, flights, and procedural complexity. Figure 21 reveals a large and systematic improvement in airspeed error for Simplified Procedures compared with airspeed error for Standard Procedures. There also appear to be consistent differences among the four vertical tasks especially for Standard Procedures. Differences between Standard and Simplified Procedures, among vertical tasks, and over four flights were all reliable ($p < 0.05$). The difference between pilot groups was not reliable ($p > 0.05$).

In conclusion, airspeed performance results showed significant improvement when VNAV procedures were simplified. Although airspeed is not a navigation control variable in 3-D navigation, these results indicate that Simplified Procedures allow the pilot more time for basic control of the aircraft than Standard Procedures. These results also indicate that similar performance differences can be expected in 4-D navigation for similar task complexities.

Procedural Errors

As pointed out earlier (p. 16), a procedural error was counted whenever an incorrect navigation control setting or inappropriate aircraft control operation would have resulted in a significant deviation from the intended route of flight if allowed to continue uncorrected. Table 7 presents, for each of the ten basic types of navigation procedural operations, the number of operations required, the number of errors which occurred, and the average number of errors per operation.

One can see from this table that total errors were much fewer for Simplified Procedures than they were for Standard Procedures. This can be partly explained by the reduction in the number of procedural operations. However, the average number of errors per operation was also smaller. In fact, it is smaller for every type of procedural operation. The overall average number of errors per operation was reduced by more than two-thirds by simplifying procedural complexity.

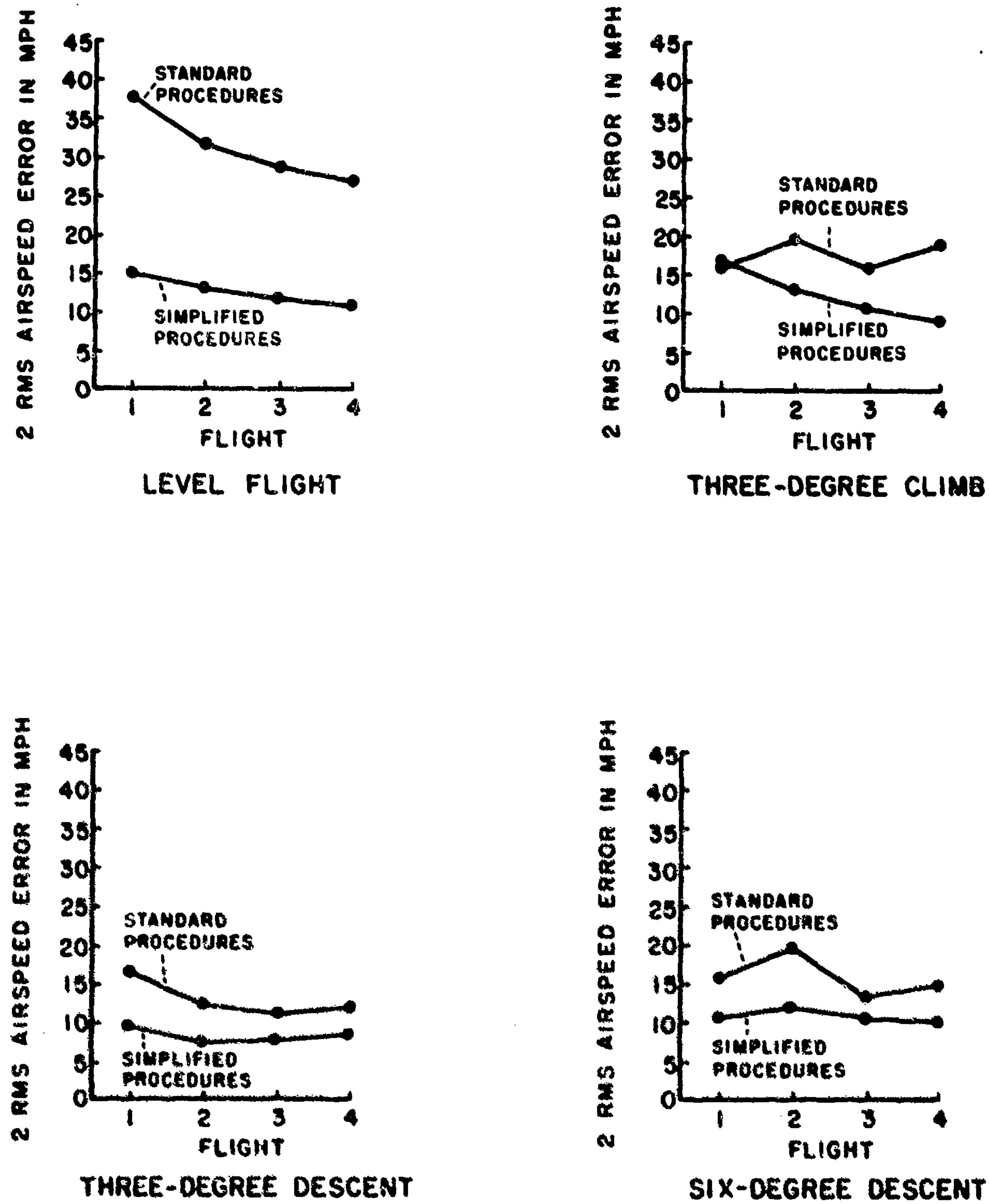

Figure 21. Two RMS overall airspeed error in miles per hour as a function of procedural complexity and flights for four vertical tasks.

Table 7. Procedural Errors by Type for Standard and Simplified Procedures.

Type	Standard Procedures			Simplified Procedures		
	Number of Operations	Number of Errors	Errors per Operation	Number of Operations	Number of Errors	Errors per Operation
Vortac Frequency	96	13	.135	96	4	.042
DME Frequency	96	10	.104	96	3	.031
Waypoint Radial	480	32	.067	288	3	.010
Waypoint Distance	480	28	.058	288	2	.007
Course	352	11	.031	288	2	.007
Desired Altitude	160	16	.100	160	6	.038
Vertical Angle	160	11	.069	160	3	.019
Alongtack Offset	160	21	.131	160	5	.031
Before/Past	32	2	.063	32	0	.000
Waypoint Select	480	27	.056	288	14	.049
	2496	171	.069	1856	42	.023

In addition to those shown in Table 7, there were 19 procedural errors classed as "other" for Standard Procedures and 12 classed as "other" for Simplified Procedures. A description of the 12 procedural errors classed as "other" for Simplified Procedures follows:

1. Subject 1 on his second flight overshot Roscoe waypoint while making settings for Champaign approach.
2. Subject 2 on his third flight began Clinton pullup procedure too early.
3. Subject 2 on his third flight confused "station elevation" with "desired altitude."
4. Subject 3 on his second flight failed to slow to 120 miles per hour in three-degree climb.

5. Subject 4 on his first flight climbed through 3000 feet in Paris pullup procedure. This was a blunder because the altitude error exceeded 500 feet.
6. Subject 4 on his first flight failed to slow to 120 miles per hour in six-degree descent.
7. Subject 4 on his second flight failed to slow to 120 miles per hour beyond the Scottland waypoint.
8. Subject 4 on his second flight failed to slow to 120 miles per hour until beyond the Wabash waypoint.
9. Subject 4 on his second flight overshot six-degree slope. This was a blunder because the VDI needle moved off scale. Subject recovered the centerline of the vertical gradient within three miles.
10. Subject 5 on his first flight switched frequencies too early in the Paris pullup procedure.
11. Subject 6 on his first flight climbed through 3000 feet in Paris pullup procedure. This was a blunder because the altitude error exceeded 800 feet.
12. Subject 8 on his first flight overshot three-degree climb slope. This was a blunder because the VDI needle moved off scale. Subject recovered centerline of the course within four miles.

Although the experimental procedure was designed to eliminate blunders, the above list shows that they did occur on four occasions. In each of these four cases, after the error was pointed out to the subject, there was not enough time remaining to make the correction necessary to avoid departure from protected airspace. The remainder of the procedural errors of all types were pointed out and corrected before airspace limits were exceeded. Therefore, it is not possible to determine the number of these errors which would have led to blunders. However, in each case the subject was not told of his error until a significant divergence from the intended course would have resulted if the correction had not been made immediately. Therefore, it is fair to conclude that each of the recorded procedural errors represents some divergence from the intended flight path and possibly many of them represent blunders.

Table 8 presents the total number of navigation procedural errors of all types made by each pilot on each flight. The number of days since previous VNAV flights are denoted in parentheses. One can see from an examination of Table 8 that despite the use of Simplified Procedures, navigation procedural errors continue to occur, especially during early exposure to a particular course.

Looking only at the last two Simplified Procedures flights, a total of 13 procedural errors occurred in 928 procedural operations. The average number of procedural errors per operation on these two flights was 0.014. The average number of errors per pilot per flight was 0.81. These data look even better for the fourth flight alone on which only three errors were made in eight flights, an average of 0.38 errors per pilot per flight.

Table 8. Navigation procedural errors made during each flight using Simplified Procedures. Numbers in parentheses indicate the number of days since the previous VNAV flight (including the practice flight preceding the first test flight). This table includes 12 "other" errors.

		Flight				
Subject	Pilot Group	1	2	3	4	Total
1	ATP	3(12)	1(10)	0(9)	0(0)	4(31)
2	ATP	1(1)	0(4)	3(8)	0(1)	4(14)
3	ATP	2(6)	2(7)	0(7)	0(0)	4(20)
4	ATP	3(9)	7(3)	2(1)	1(3)	13(16)
5	CIP	3(1)	0(5)	2(6)	0(3)	5(15)
6	CIP	2(11)	0(3)	0(0)	0(7)	2(21)
7	CIP	8(9)	5(3)	1(3)	1(1)	15(16)
8	CIP	3(7)	1(9)	2(3)	1(2)	7(21)
		25(56)	16(44)	10(37)	3(17)	54(154)

The average numbers of procedural errors per flight for each pilot group and for each level of procedural complexity over four flights are presented in Figure 22. Analysis of the variance of these combined data revealed reliable differences between Standard and Simplified Procedures and over four flights ($p < .05$). However, the difference between pilot groups was not reliable.

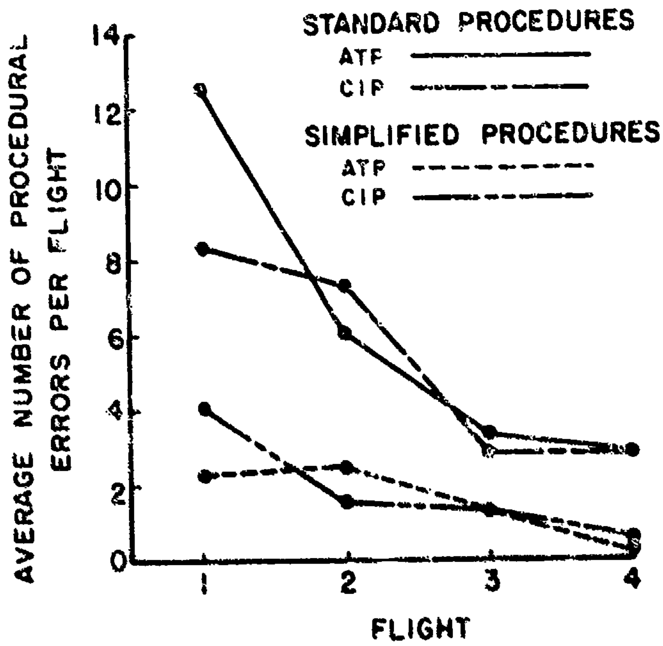

Figure 22. Average numbers of procedural errors made by ATPs and CIPs during four successive flights over the Simplified Procedures course requiring procedural operations and over the Simplified Procedures course requiring 58 procedural operations.

In conclusion, these procedural error results show that significant improvement in the performance of VNAV procedural operations are possible through a reduction in their complexity. The results of the fourth flights on each subject indicate that with Simplified Procedures the frequency of procedural errors can be reduced to a very small number. These results are especially important to the RNAV user operating with a minimum system.

DISCUSSION

The major underlying issue in all aspects of this study and the previous study is cockpit workload. One can see from Table 7 that there are ten basic types of navigation procedural operations required of the pilot using the Butler VAC/ADD system as installed in Twin Bonanza 1000V. Although most waypoints do not require all ten operations, any waypoint could, and safe operating procedures dictate that all settings should be checked at least once for every waypoint used. Comparing this system requiring ten operations with the conventional VOR navigation system which requires only two operations (VORTAC frequency and course), one can see that 3-D RNAV in this form may represent a higher level of cockpit workload than conventional VOR navigation. This higher workload involved in Area Navigation also represents a greater degree of cockpit responsibility because the pilot is responsible for the accurate location of the points of reference being used for navigation.

The results of this study clearly show that four aspects of pilot performance can be improved by a reduction in the number of procedural operations required in a given task. Another study has shown that increased waypoint storage can also improve pilot performance (Roscoe and Kraus, 1973). These studies demonstrate that the problems of increased workload associated with 3-D RNAV due to increased procedural operations and cockpit responsibility can be dealt with and that partial solutions have been found. The evidence presented here is an overwhelming argument for using simplified area navigation procedures as one means of improving overall pilot performance through reduced cockpit workload.

However, it should be observed that this reduced cockpit workload and resultant improvement in pilot performance during approaches was not simply the result of a random reduction in the number of procedural operations during the execution of the VNAV approach. Undoubtedly, it was the specific elimination of the final approach waypoint and the pullup waypoint that produced a more conventional approach task, both in chart appearance and in execution, than the four-waypoint Standard Procedures approach. Pilots could easily recognize from the charted procedure a task which they had performed many times and could execute stereotypically. Pilots also indicated that they felt comfortable doing Simplified approach procedures, whereas pilots who flew the Standard approach procedures indicated a high level of irritation with procedural tasks that were required at unusual points during the approach.

Although it is desirable to generalize, caution must be exercised in making generalizations from the results of a flight study such as this. Flight research in the airborne environment is subject to a number of limitations that can be overridden or controlled in the ground-based simulation environment. Among the environmental items that limit the capability of flight research to provide generalizable results are wind speed and direction, weather conditions, turbulence, navaid signal quality, and traffic. These limitations do not mean that flight research should not be done, but they do suggest very careful interpretation of the results of such research.

Of these items, the one that causes the most difficulty in the interpretation of the results of this study is variations in the quality of the ground-propagated VOR and DME signals. Although such variations were unmeasurable with the equipment used in this study, it became obvious through observation during the experiment that signal quality changed from one point in the course to another. These signal variations were evident in the form of oscillations of the CDI needle, both high frequency oscillations, commonly referred to as scallops, and low frequency oscillations, commonly referred to as bends. Low frequency needle oscillations were also evident on the vertical display in some instances. High frequency horizontal oscillations were apparent in two places. The first occurred shortly after takeoff until approximately two miles beyond the Pesotum waypoint. The second began during the three-degree approach descent to Clinton on Segment 4 and disappeared during the climb to 4500 feet on Segment 6. Bends or low frequency oscillations of the horizontal course needle were difficult to detect by observation in the dynamic environment of changing wind conditions. However, an observable bend in the horizontal course did occur during the Paris final approach, MDA, and missed approach segments. Regardless of wind speed and direction, pilots were forced to make relatively large and consistent heading changes to keep the needle centered during these three segments. A very small bend of approximately one runway width was observable on the Champaign approach. During the 3° climbs and 6° descents, low frequency oscillations were observed on the VDI. These oscillations were not as easily identifiable as they were in the horizontal dimension, and their persistence could not be explained by heading changes or changes in wind direction and speed. It is possible that these vertical signal perturbations contributed to the small quantity of steady-state data on these two segments.

In addition to environmental factors, a number of other factors must be accounted for in the interpretation of these results. These include workload, the instrument and control panel configuration, type of communication, and procedures for identifying and correcting blunder errors. All of these factors interrelate and may have differential effects on measured pilot performance over the variables being considered in the Standard Procedures and Simplified Procedures studies.

Workload on any instrument flight is variable from one point to another. The variations which occurred between some tasks of the Standard and Simplified Procedures course are particularly important in the interpretation of the results. For example, two differences between the six-degree descent in Standard Procedures and the six-degree descent in Simplified Procedures were (1) horizontal turns and (2) waypoints at the beginning and end of the descent in Standard Procedures, neither of which were present within three miles of the Simplified Procedures descent path. The apparent effect of these changes was a significant improvement in overall vertical steering and airspeed control in Simplified Procedures. It is interesting to note that the difference in overall horizontal steering performance between these two procedures was not reliable despite the beginning horizontal turn of 46 degrees in Standard Procedures. Therefore, the introduction of horizontal turns and waypoints at the beginning and end of a vertical gradient has a significant detrimental effect on vertical steering and airspeed performance, but not on horizontal steering performance.

The effect of reducing the number of required waypoint entries on steering performance is also evident in the results for Clinton and Paris approaches. On these approaches, highly reliable differences between standard and simplified Procedures were found for all three steering performance measures: vertical and horizontal steering and airspeed. Because all other conditions including the steering task remained constant, it must be assumed that the improved steering performances were the result of a reduced procedural workload permitting a higher level of attention to be devoted to the three continuous control tasks.

It should be pointed out that, although workload levels were eased, the overall workload represented by the number of operations required in the Simplified experimental task was greater than one would expect on a normal RNAV instrument flight from one airport to another given no changes to the planned route of flight. The task was composed of a SID, a STAR, three VNAV approaches, and two missed approaches. Although they were made on transition segments during which workload was relatively light, two frequency changes were required during each flight. The relatively short transition segments between these procedures and the aircraft speed of 130 knots permitted the pilot little time to study the charts.

These problems are somewhat offset in the experiment by repeatedly flying the same sequence of procedures using a booklet of charts bound in the correct order. By their fourth experimental flights, pilots were becoming very familiar with the task sequence. This familiarity undoubtedly provided a better performance on final flights than one would expect if the order had been shifted, as may happen in the real world. This may be a primary reason for the significant decrease in procedural errors through the fourth flights.

Another possible explanation for the decrease in procedural errors is that pilots were inadequately trained in the use of the RNAV equipment prior to their first experimental flights. As explained earlier (page 13), subjects were given a thorough briefing and familiarization of the equipment prior to their first experimental flights. However, given the complexity of the VNAV equipment and procedures, it may be necessary to require pilots to have a certain amount of experience with the particular equipment before admitting them into the system on their own.

Finally, although these were highly experienced professional pilots, most of them had minimal flight time in the type of aircraft flown. Each pilot was given a one-hour checkout in the aircraft. Thus, he was legally qualified to fly the aircraft IFR with RNAV in a terminal area, even if better judgement would dictate otherwise. Some experimental data is available which provides an indication of performance improvement due to increased familiarity with the aircraft itself. The initial segments of each flight, the Champaign SID, did not require a sophisticated knowledge of the RNAV system. This task consisted of a normal climb to 4500 feet followed by two fairly long level segments. Because this part of the flight is relatively free of new RNAV concepts, horizontal and vertical performance on these segments over four flights provides an indication of change in aircraft steering performance as a function of increasing familiarity with the aircraft. An analysis of these data over both Standard and Simplified Procedures shows some improvement in horizontal and vertical steering error. However, the differences were not reliable ($p > 0.05$) indicating that the change in familiarity with the aircraft was not a major factor in the overall performance improvement over four flights.

Another factor that may have had a detrimental effect on pilot performance in both Standard and Simplified Procedures is the configuration of the instrument and navigation control panels in the aircraft. From an examination of Figure 2, one can see that this configuration is less than optimum for instrument flight. For example, the normal "T" arrangmenet is broken by the SPI which is located between the gyro horizon and the heading indicator. The distance-to-waypoint indicator and the VDI were both located outside of the normal instrument scan pattern. The VOR and DME frequency selectors, both of which had to be set, were the upper right and lower left controls, respectively, of the four frequency selectors shown on the right side of the panel. Finally, the location of the area navigation control panels at the right required the pilot to stretch to read the digital displays. Each of these locations was less than optimum and may have had detrimental effects on pilot performance.

Although pilots did not complain about it, there is some evidence indicating that the vertical scale factor may have been too sensitive. For example, two of the blunders were vertical course overshoots. One of these was a delayed entry to three-degree climb, the othe, was a delayed entry to a six-degree descent. In addition, the vertical tracking data on segments involving vertical grudients indicate a general overshoot tendency on the Clinton approach (Figure A-3), the three-degree climb (Figure A-9), and the six-degree descent (Figure A-10). Other vertical gradients (Figures A-6, and A-12) fail to show this tendency. All of these cases represent a tendency for pilots to be late in initiating changes in vertical gradients, possibly attributable to insufficient warning from the initial movement of the guidance needle coming out of saturation.

The 100-foot per dot scale factor (±200 feet full scale over ±0.45 inches) was chosen for this experiment because it was found to yield the best vertical steering performance in the study by VanderKolk and Roscoe (FAA-RD-73-202). However, an unpublished study by Roscoe at Hughes Aircraft Company in the late 1950s has shown that pilots may object to a sensitive scale factor that yields the most accurate attack steering performance because of the increased workload involved with keeping the needle centered. The study concluded that the ideal aircraft display scale factor is somewhat less sensitive than the level that produces best steering results. A definite relationship exists between overall pilot workload and the display sensitivity that can be tolerated. If the pilot is overloaded with other tasks, a less sensitive display scale factor will yield better overall results. Given the relatively, high workload of terminal area operations, a less sensitive vertical scale factor than ±200 feet full scale (±0.45 inches) may be required.

The frequency of outside communication also may affect pilot performance. In neither experiment were pilot-subjects required to monitor or make outside communications. The simulated ATC clearances required to fly the intended course were given to the pilot from inside the aircraft by an experimenter. This method of handling communications undoubtedly reduced the normal vigilance requirement of the pilot, thus freeing a greater amount of attention for his task of aircraft control and navigation. It can be assumed that these effects would, at least in part, offset the effects of a less than optimum instrument panel.

The final area of concern in the interpretation of the results is the effect of procedural errors, their identification, and their correction on measurements of error on all four variables. As shown in Figure 22, pilots continue to make procedural errors even with Simplified Procedures. However, the number and frequency of errors are probably inflated by the method used to identify such errors. As indicated earlier, this method was to note a procedural error when it occurred but to refrain from recording it and pointing it out to the pilot until it appeared to the experimenter that the error would not be corrected before it would disrupt one or more of the recorded steering performance measures. There were only a few cases involving course overshoot that were not caught in time to prevent their influencing steering error. It is likely that in most cases for which a procedural error was recorded in these studies, given more time, the pilot would have noticed strange indications on one or more of the displays, and he would have found and corrected the procedural error. However, each of these procedural errors, even if detected and corrected, would have resulted in larger steering errors. Therefore, in the interpretation of the results of both studies one must keep in mind that the procedural error rate is probably inflated and that measured steering errors for the most part represent steering performance given that no procedural errors are made.

There are two peculiarities in the procedural error data which deserve further examination. For example, one type of operation, waypoint selection, yielded a large proportion (one-fourth) of the total procedural errors for Simplified Procedures. This phenomenon may have been a purely random result. However, there is some evidence that two waypoint systems may present special procedural problems. A simulator study (Roscoe and Kraus, 1973) in which waypoint storage was varied from one to eight waypoints has shown that the two-waypoint system presented the highest workload as indicated by the pilots' measured residual attention. This may be a result of confusing the waypoint in use with the waypoint to be set which did not occur for other waypoint storage capacities.

However, it was observed in the present experiment that pilots occasionally completed all required operations except for switching to the new waypoint. The typical situation in which this error occurred was on the segment following the IAF and before the descent in the approach procedure. The pilot navigating outbound from IAF may forget that unless he selects MAP he will not receive descent guidance. In each case, when the distance indicator read six miles outbound from IAF, to prevent a severe overshoot of the glide path, the error was pointed out to the subject, and MAP was selected.

The frequency of this type of error could be reduced either by standardizing a waypoint selection procedure or by greater familiarity with the RNAV equipment through more extensive training. A closer examination of the data, however, reveals that the number of waypoint selection errors that occurred on each flight was: Flight 1, seven errors; Flight 2, two errors; Flight 3, five errors; and Flight 4, no errors. These data indicate that some improvement did occur over four flights, but the performance is variable. A procedure for keeping track of the waypoint in use by numbering the chart was suggested but infrequently used by the pilots with Simplified Procedures.

Training does indeed command a place in any man-machine system. As pointed out by Roscoe (1974) in discussing the complementary processes of behavioral engineering and the selection and training of personnel, "the former serves to reduce the need for the latter and the latter completes the job left undone by the former." Therefore, training could be used as a mechanism for reducing procedural errors. However, given the wide variety of possible procedural errors in area navigation, the wide variety of experience levels of the pilots using the system, and the catastrophic consequences of many procedural errors, one is well cautioned against relying upon training to eliminate these errors. It should also be pointed out that in some situations, such as emergencies, training is a particularly poor substitute for good human engineering.

A second peculiarity in the procedural error results, Table 8, is that more than half (28 of 54) of the errors were made by two pilots. To determine whether the relatively poor performance of these pilots on procedures also carried over to the other performance measures, Table 9 presents the overall rank of all 16 pilots in both experiments in terms of total flight experience; performance on vertical,

TABLE 9. Ranking for 16 pilots in terms of total flight experience, overall performance, and performance on vertical, horizontal, airspeed, and procedural error measures.

Subject	Total Flight Experience	Overall Rank	Vertical Errors	Horizontal Errors	Airspeed Errors	Procedural Errors
	STANDARD PROCEDURES					
1 ATP	2	12	9	8	13	16
2 ATP	4	9	8	7	14	7
3 ATP	5	16	16	13	16	13
4 ATP	7	11	7	14	10	12
5 CIP	12	10	10	10	9	10.5
6 CIP	14	14	14	15	12	14
7 CIP	9	15	15	16	11	15
8 CIP	16	13	13	11	15	8
	SIMPLIFIED PROCEDURES					
1 ATP	3	2.5	6	2	1	3
2 ATP	1	1	1	3	2	3
3 ATP	8	4	4	4	8	3
4 ATP	6	5	5	1	5	9
5 CIP	15	8	11	12	7	5
6 CIP	10	2.5	2	6	3	1
7 CIP	11	6	3	5	6	10.5
8 CIP	13	7	12	9	4	6

horizontal, airspeed, and procedural error measures; and overall performance rank. Subjects 4 and 7, who accounted for most of the procedural errors with Simplified Procedures, ranked below two of the pilots who flew using Standard Procedures. However, their performances were better on the other three measures, giving them overall ranks of 5 and 6 respectively.

The relative rankings of the other pilots reveal moderately high correlations between tracking and procedural performances. A paired comparisons test of each of the three tracking performances with procedural performance indicates the following reliable correlations: vertical, $r = .52$ ($p < .05$); horizontal, $r = .53$ ($p < .05$); airspeed, $r = .67$ ($p < .01$). Taken together the overall ranking in tracking performance correlates even more highly with procedural performance ($r = .72$, $p < .01$). However, comparing rankings of flight experience with overall performance fails to yield a reliable correlation ($r = .27$, $p > .05$).

These results tend to confirm the conclusion that has been supported repeatedly in this series of experiments. Namely, wide differences in overall pilot performances are evident even in a relatively homogeneous group of professional pilots, such as airline transport pilots or commercial instrument pilots, at the University of Illinois. The high correlation of procedural performance with the three other performance measures indicates that generally, pilots who perform procedural tasks well, also maintain vertical and horizontal course centerlines very accurately. The converse is also true.

Despite the general negative tone of this section dealing with procedural errors, the overall results of this study indicate that, with some adjustments to the system, flight technical errors in area navigation with vertical guidance can be much smaller than previously estimated. This experiment provides strong evidence that the primary adjustment needed is a simplification of area navigation procedures. Other adjustments not specifically addressed in this study but observed as possible improvements to the system include: the use of the same frequency throughout a STAR and approach procedure; a waypoint storage capacity sufficient to store a complete STAR approach and missed approach procedure; and automatic computation of the course from one waypoint to the next, thereby eliminating the requirement for manual course selection.

It is apparent that all RNAV systems will rely on training to a considerable extent in meeting the FTE budget requirements, but this is especially true for one- and two-waypoint systems. However, given Simplified Procedures, proper training and current experience, it seems probable that one-pilot/dual-waypoint RNAV systems can meet FTE budget requirements in most procedures currently planned for the ATC system.

Finally, it should be pointed out that the FAA is now incorporating in new RNAV approaches the Simplified Procedures suggested herein. It is the apparent intention of the FAA to give the pilot the option of using a distance to MAP indication in lieu of setting the FAF. It seems likely that the Simplified Procedures used in this study will be the future standard for RNAV approaches.

CONCLUSIONS

The following conclusions are based on the results of this flight experiment and are referenced to the particular VNAV test route and procedures tested. This experiment was performed for the purpose of comparing data obtained in an earlier flight test (Report FAA-RD-72-126) to data obtained using less complex operational procedures. The procedures in the earlier report have herein been designated Standard Procedures. The procedures employed in this report have been denoted Simplified Procedures.

The scale factors employed in this experiment are as follows unless otherwise noted: ± 200 feet full-scale (± 0.45 inch) on the vertical display (VDI) with two scale divisions above and below center spaced 0.22 inch between dots, and ± 5.0 nautical miles full-scale (± 1.10 inch) on the course deviation display (SPI) with five scale divisions left and right of center also spaced 0.22 inch between dots.

Unless otherwise indicated, the conclusions stated refer to performances of the combined ATP and CIP pilot groups with Simplified Procedures.

<u>In level flight:</u>

1. a. The steady-state central tendency in vertical pilotage error of +3 feet for combined pilot groups was not reliably different from zero, the value assumed in RTCA DO-152. The corresponding value for Standard Procedures was +9 feet, not reliably different from zero.

   b. The steady-state 3σ variability in vertical pilotage error of ± 129 feet was not reliably different from ± 150 feet, the value assumed in DO-152. The corresponding value for Standard Procedures was ± 144 feet, also not reliably different from ± 150 feet.

2. a. The steady-state central tendency in crosstrack pilotage error of 0.07 nmi right of route centerline was not reliably different from zero, the value assumed in FAA AC 90-45. No corresponding value was reported for Standard Procedures.

b. The steady-state 2σ variability in crosstrack pilotage error of ± 0.74 nmi was reliably smaller than ± 1.0 nmi, the value assumed in FAA AC 90-45. No corresponding value was reported for Standard Procedures.

<u>In 3° climbs from 3000 to 8000 feet MSL:</u>

3. a. The steady-state central tendency in vertical pilotage error of +2 feet was not reliably different from zero, the value assumed in DO-152. The corresponding value for Standard Procedures was -11 feet, not reliably different from zero.

b. The steady-state 3σ variability in vertical pilotage error of ± 140 feet was not reliably different from ± 150 feet, the value assumed in DO-152 for altitudes below 5000 feet, and was reliably smaller than ± 250 feet, the value assumed in DO-152 for altitudes above 5000 feet. The corresponding value for Standard Procedures of ± 171 feet was reliably larger than ± 150 feet and reliably smaller than ± 250 feet.

4. a. The steady-state central tendency in crosstrack pilotage error of 0.22 nmi to the right of route centerline was reliably different from zero, the value assumed in FAA AC 90-45. No corresponding value was reported for Standard Procedures.

b. The steady-state 2σ variability in crosstrack pilotage error of ± 0.51 nmi was reliably smaller than ± 1.0 nmi, the value assumed in FAA AC 90-45. No corresponding value was reported for Standard Procedures.

<u>In 3° descents:</u>

5. a. The steady-state central tendency in vertical pilotage error of +20 feet was reliably different from zero, the value assumed in DO-152, indicating a bias to fly above the descending vertical gradient. With Standard Procedures a similar tendency was exhibited, with a reliable bias of +38 feet.

b. The steady-state 3σ variability in vertical pilotage error of ± 147 feet was not reliably different from ± 150 feet, the value assumed in DO-152. The corresponding value for Standard Procedures was ± 196 feet, also not reliably different from ± 150 feet.

6. a. The steady-state central tendency in crosstrack pilotage error of 0.06 nmi to the left of route centerline was not reliably different from zero, the value assumed in FAA AC 90-45. No corresponding value was reported for Standard Procedures.

b. The steady-state 2σ variability in crosstrack pilotage error of ± 0.56 nmi was not reliably different from 0.5 nmi, the value assumed in FAA AC 90-45. No corresponding value was reported for Standard Procedures.

7. a. Using ± 1.25 nmi full-scale crosstrack scale factor on a different approach, the steady-state central tendency in crosstrack pilotage error of 0.04 nmi to the left of route centerline was not reliably different from zero, the value assumed in FAA AC 90-45.

b. Using ± 1.25 nmi full-scale crosstrack scale factor, the steady-state 2σ variability in crosstrack pilotage error of ± 0.20 nmi was reliably smaller than ± 0.5, the value assumed in FAA AC 90-45.

<u>In 6° descents from 8000 to 3000 feet MSL:</u>

8. a. The steady-state central tendency in vertical pilotage error of +37 feet was reliably different from zero, the value assumed in DO-152, indicating a bias above the descending vertical gradient. With Standard Procedures no comparable steady-state performance was achieved, but a similar tendency was exhibited with a reliable bias of +55 feet.

b. The steady-state 3σ variability in vertical pilotage error of ± 169 feet was reliably smaller than ± 250 feet, the value assumed in DO-152 for altitudes above 5000 MSL, and was not reliably different from ± 150 feet, the value assumed in DO-152 for altitudes below 5000 feet. With Standard Procedures no comparable steady-state performance was achieved, and the 3σ variability was ± 369 feet, reliably larger than ± 250 feet.

9. a. The steady-state central tendency in crosstrack pilotage error of 0.05 nmi to the right of route centerline was not reliably different from zero, the value assumed in FAA AC 90-45. No corresponding value was reported for Standard Procedures.

   b. The steady-state 2σ variability in crosstrack pilotage error of ± 0.44 nmi was reliably smaller than ± 1.0 nmi, the value assumed in FAA AC 90-45. No corresponding value was reported for Standard Procedures.

Overall performances with Simplified Procedures and Standard Procedures:

10. Overall transient and steady-state vertical and horizontal steering, airspeed control, and procedural performance are all reliably better with Simplified Procedures than with Standard Procedures; procedural errors per operation were reduced by more than two-thirds by simplifying procedural complexity.

11. Overall transient and steady-state performances by ATP and CIP pilot groups are not reliably different for any of the four performance measures on any of the four vertical flight tasks.

12. Performances using a vertically guided command leveloff and using the altimeter display for leveloff at MDA were not reliably different for any of the three continuous control performance measures.

13. Overall transient and steady-state performances differed reliably from task to task in some respect for each of the three continuous control performance measures.

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APPENDIX A

Graphical Presentation of Summary Vertical, Horizontal, and Airspeed Error Statistics

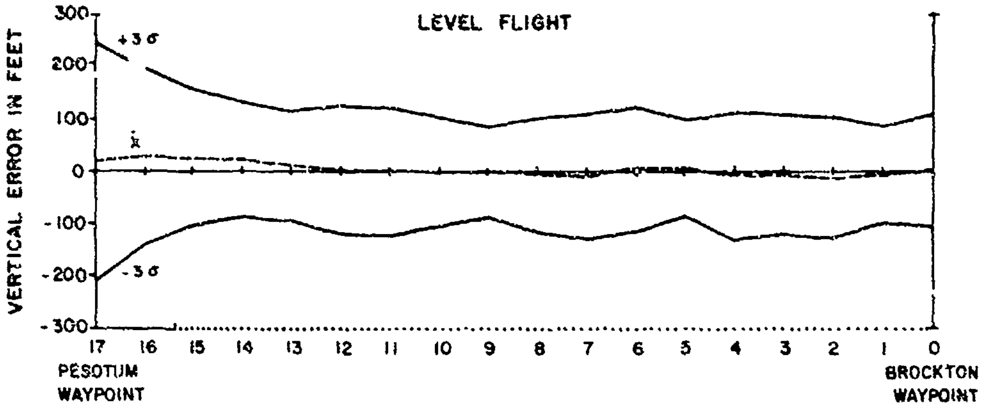

Figure A-1. Central tendency and 3σ variability of vertical error in level flight for Segment 1 between Pesotum and Brockton waypoints.

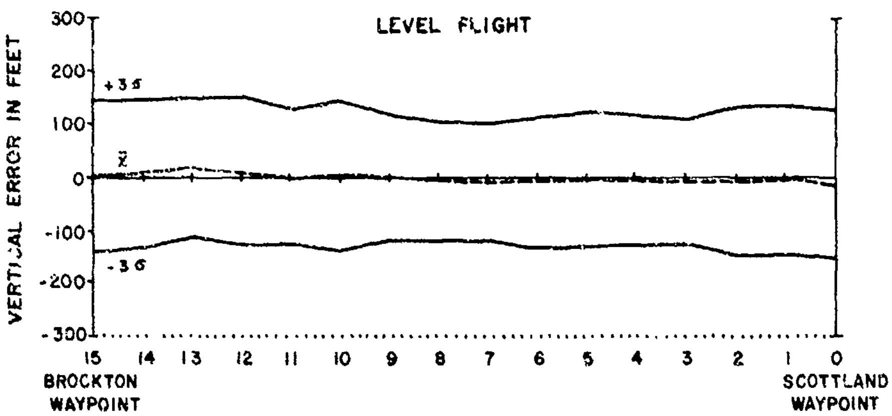

Figure A-2. Central tendency and 3σ variability of vertical error in level flight for Segment 2 between Brockton and Scottland waypoints.

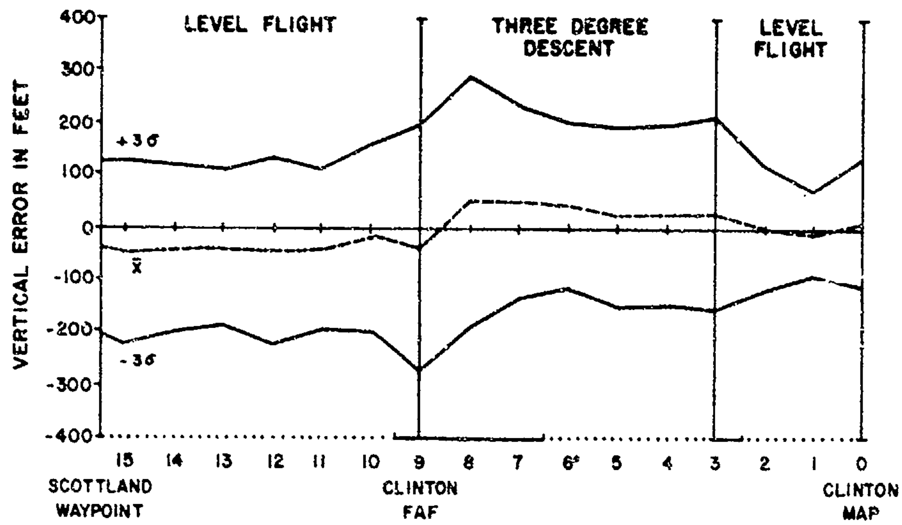

Figure A-3. Central tendency and 3σ variability of vertical error in level flight and three-degree descent for Segments 3, 4, and 5 between Scottland waypoint and Clinton MAP.

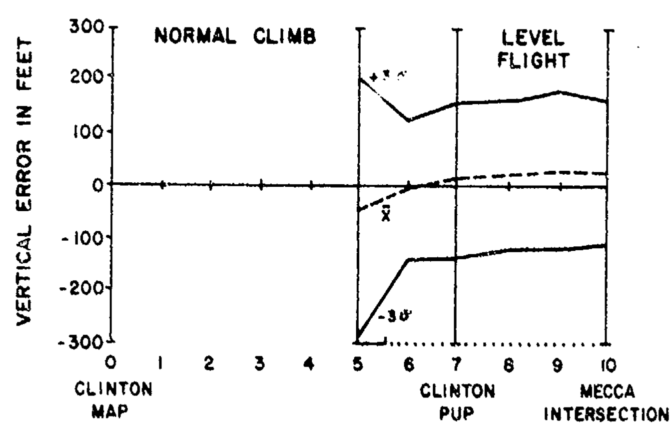

Figure A-4. Central tendency and 3σ variability of vertical error in level flight for Segments 6 and 7 between Clinton MAP and Mecca intersection. Data is not available in the normal climb until level flight is reached at Mile 5.

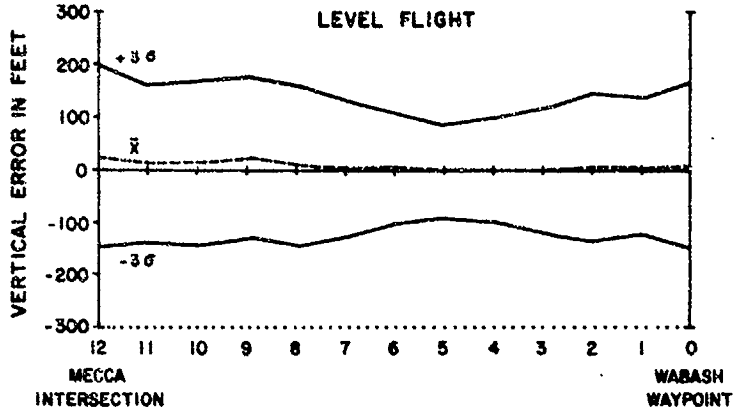

Figure A-5. Central tendency and 3σ variability of vertical error in level flight for Segment 8 between Mecca intersection and Wabash waypoint.

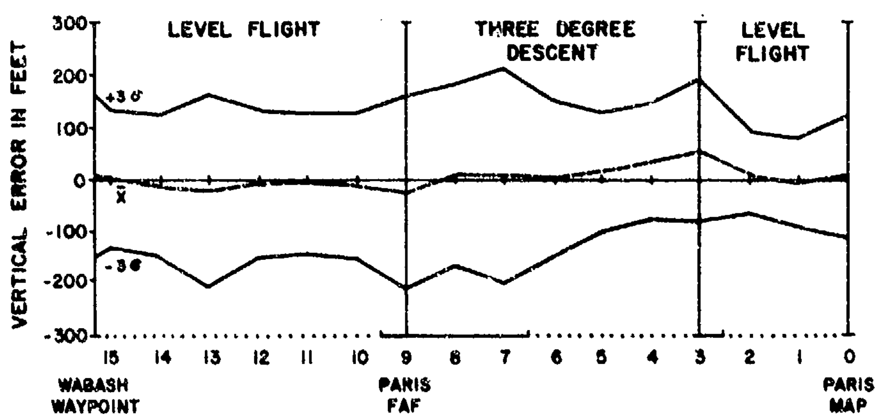

Figure A-6. Central tendency and 3σ variability of vertical error in level flight and three-degree descent for Segments 9, 10, and 11 between Wabash waypoint and Paris MAP.

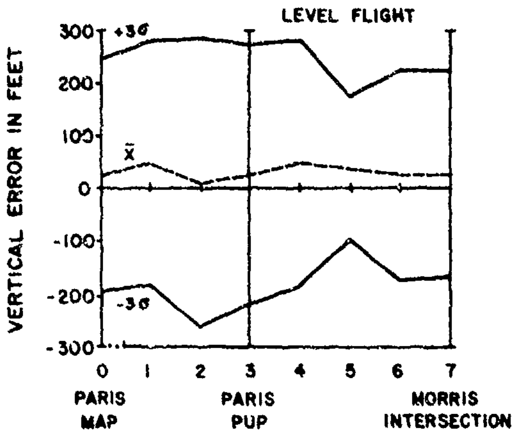

Figure A-7. Central tendency and 3σ variability of vertical error in level flight for Segment 12 between Paris MAP and Morris intersection.

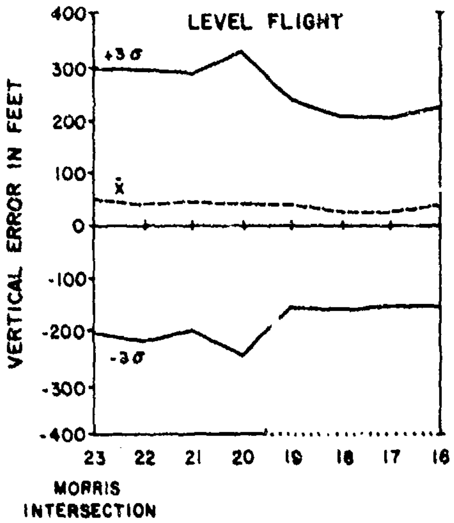

Figure A-8. Central tendency and 3σ variability of vertical error in level flight for Segment 13 between Morris intersection and the three-degree climb interception point (Mile 16).

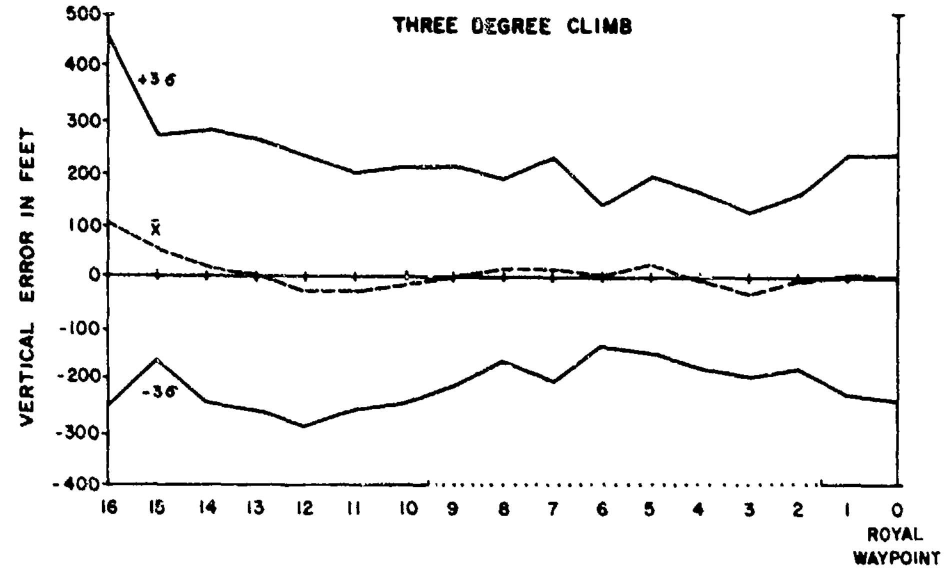

Figure A-9. Central tendency and 3σ variability of vertical error in a three-degree climb for Segment 14 between the three-degree climb interception point and Royal waypoint.

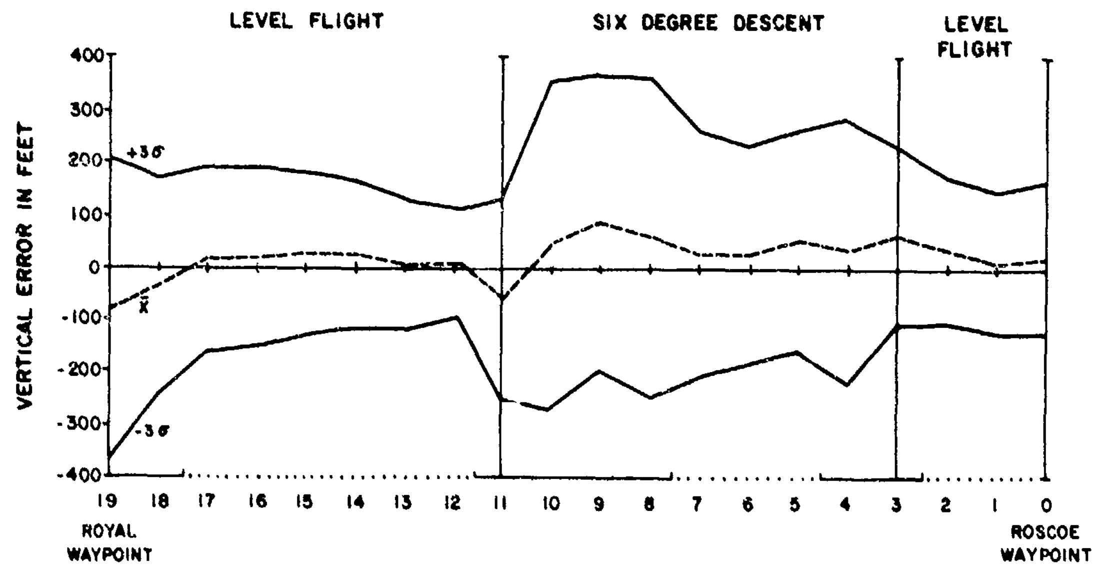

Figure A-10. Central tendency and 3σ variability of vertical error in level flight and a six-degree descent on Segments 15, 16, and 17 between Royal waypoint and Roscoe waypoint.

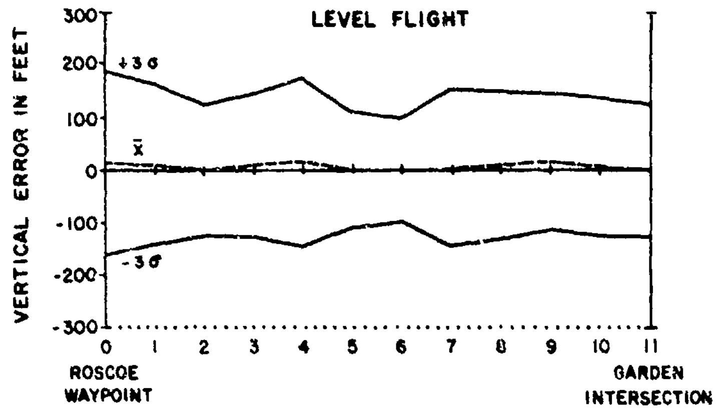

Figure A-11. Central tendency and 3σ variability of vertical error in level flight on Segment 18 between Roscoe waypoint and Garden intersection.

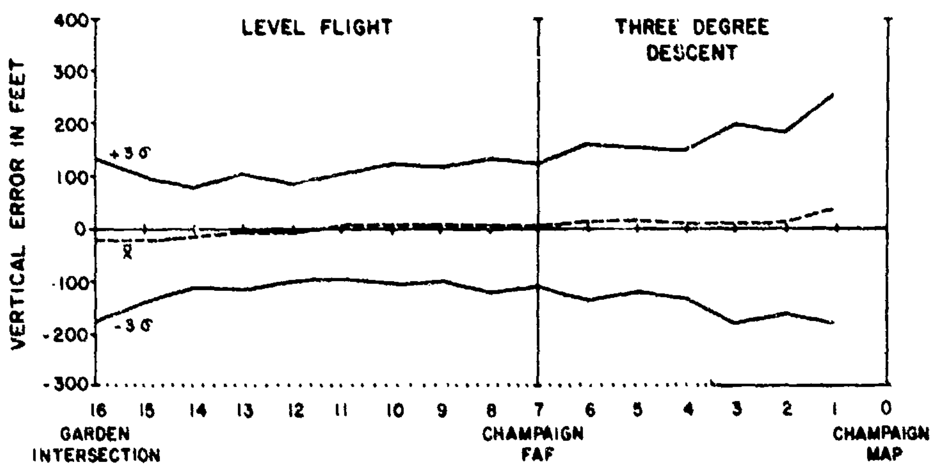

Figure A-12. Central tendency and 3σ variability of vertical error in level flight and three-degree descent on Segments 19 and 20 between Garden intersection and Champaign MAP.

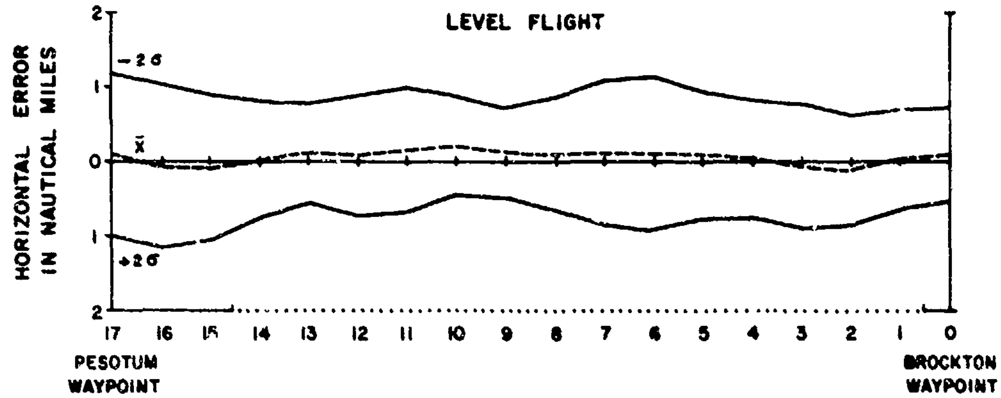

Figure A-13. Central tendency and 2σ variability of horizontal error on Segment 1 between Pesotum and Brockton waypoints.

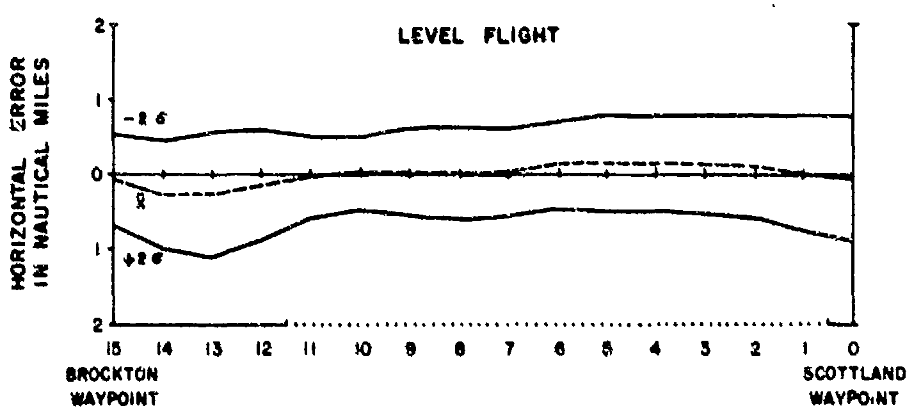

Figure A-14. Central tendency and 2σ variability of horizontal error on Segment 2 between Brockton and Scottland waypoints.

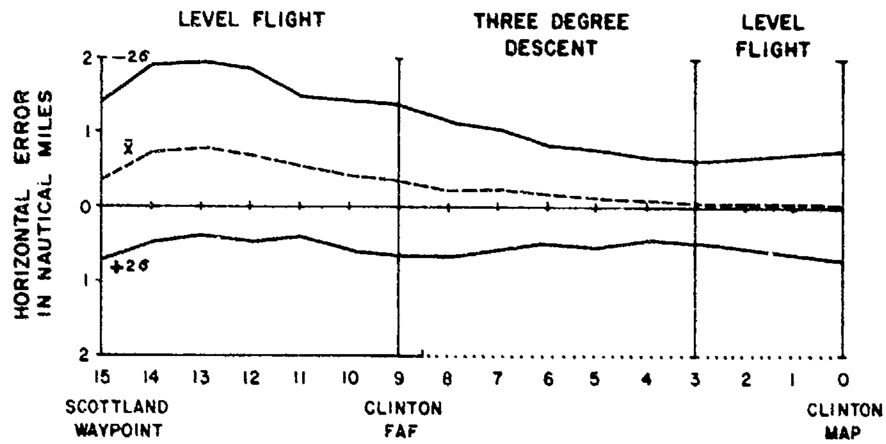

Figure A-15. Central tendency and 2σ variability of horizontal error on Segments 3, 4, and 5 between Scottland waypoint and Clinton MAP.

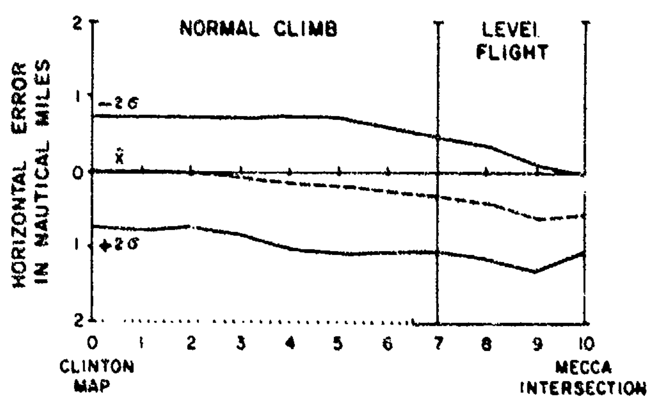

Figure A-16. Central tendency and 2σ variability of horizontal error on Segments 6 and 7 between Clinton MAP and Mecca intersection.

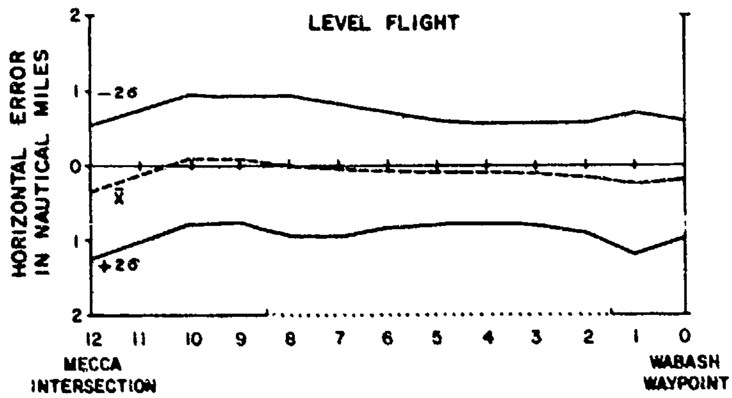

Figure A-17. Central tendency and 2σ variability of horizontal error on Segment 8 between Mecca intersection and Wabash waypoint.

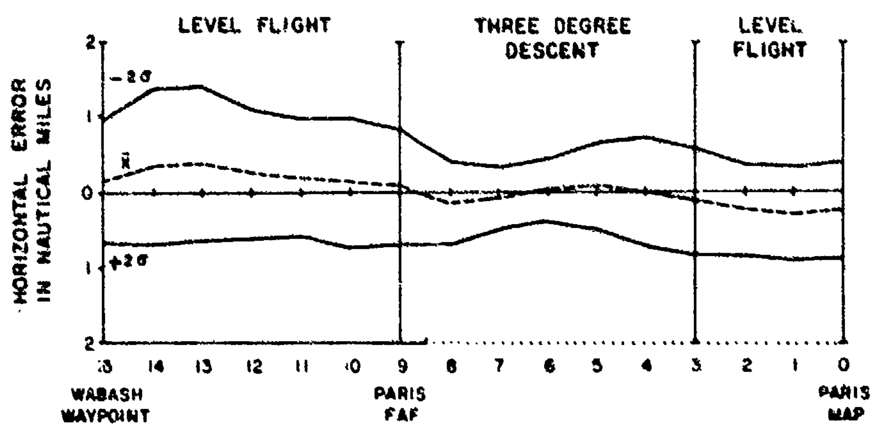

Figure A-18. Central tendency and 2σ variability of horizontal error on Segments 9, 10, and 11 between Wabash waypoint and Paris MAP.

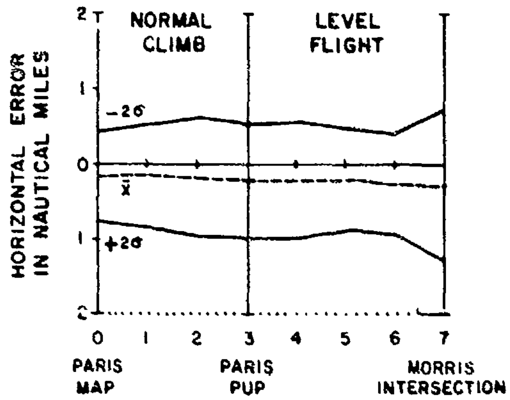

Figure A-19. Central tendency and 2σ variability of horizontal error on Segment 12 between Paris MAP and Morris intersection.

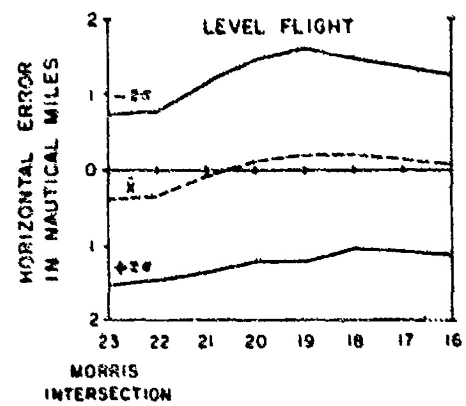

Figure A-20. Central tendency and 2σ variability of horizontal error on Segment 13 between Morris intersection and the three-degree climb interception point.

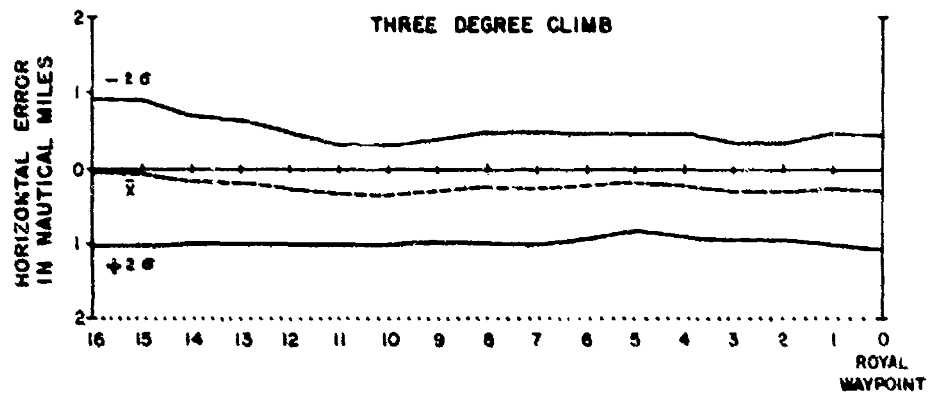

Figure A-21. Central tendency and 2σ variability of horizontal error on Segment 14 between the three-degree climb intercept and Royal waypoint.

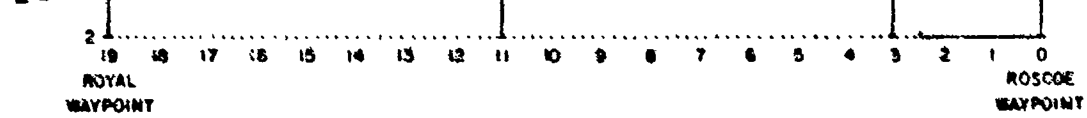

Figure A-22. Central tendency and 2σ variability of horizontal error on Segments 15, 16, and 17 between Royal waypoint and Roscoe waypoint.

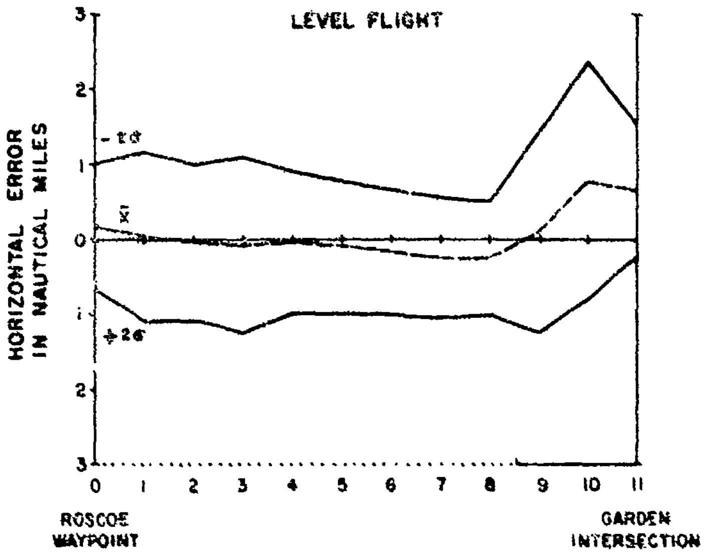

Figure A-23. Central tendency and 2σ variability of horizontal error on Segment 18 between Roscoe waypoint and Garden intersection.

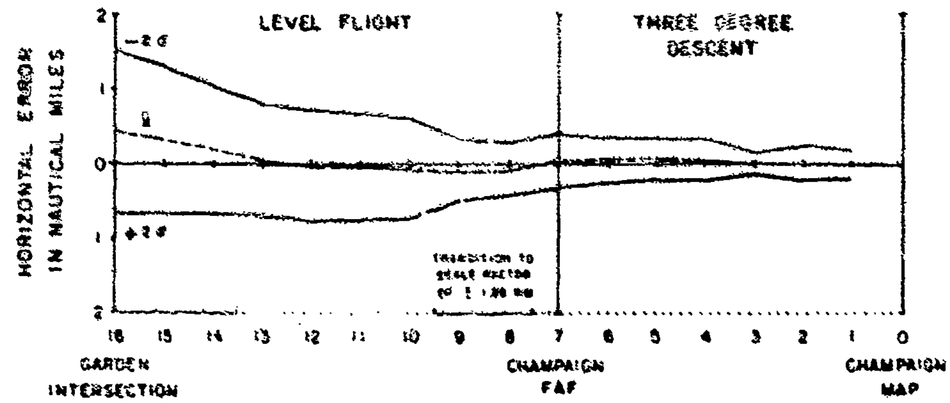

Figure A-24. Central tendency and 2σ variability of horizontal error on Segments 19 and 20 between Garden intersection and Champaign MAP.

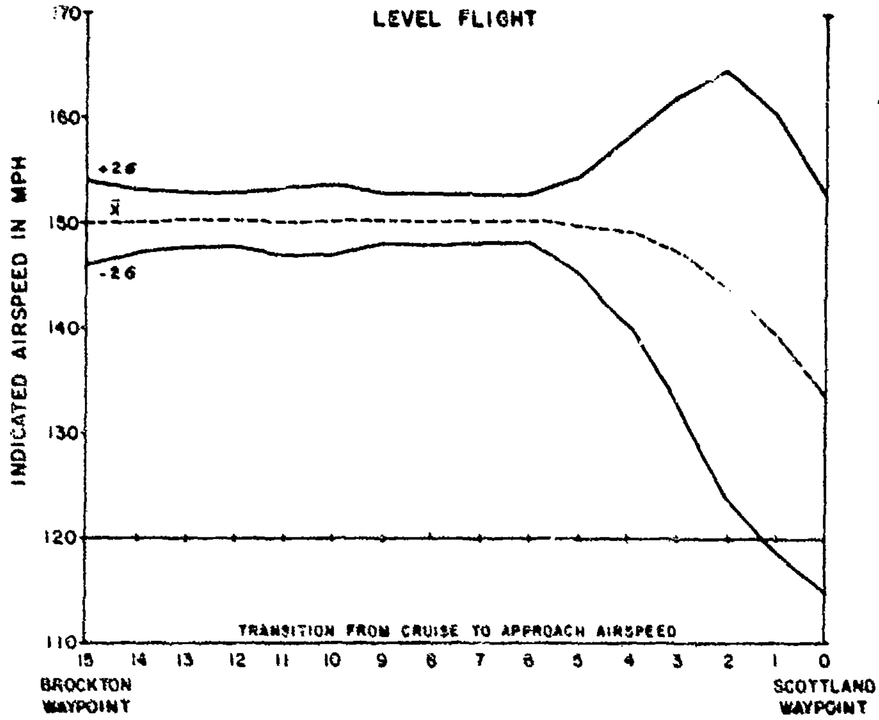

Figure A-25. Central tendency and 2σ variability of indicated airspeed on Segment 2 between Brockton waypoint and Scottland waypoint.

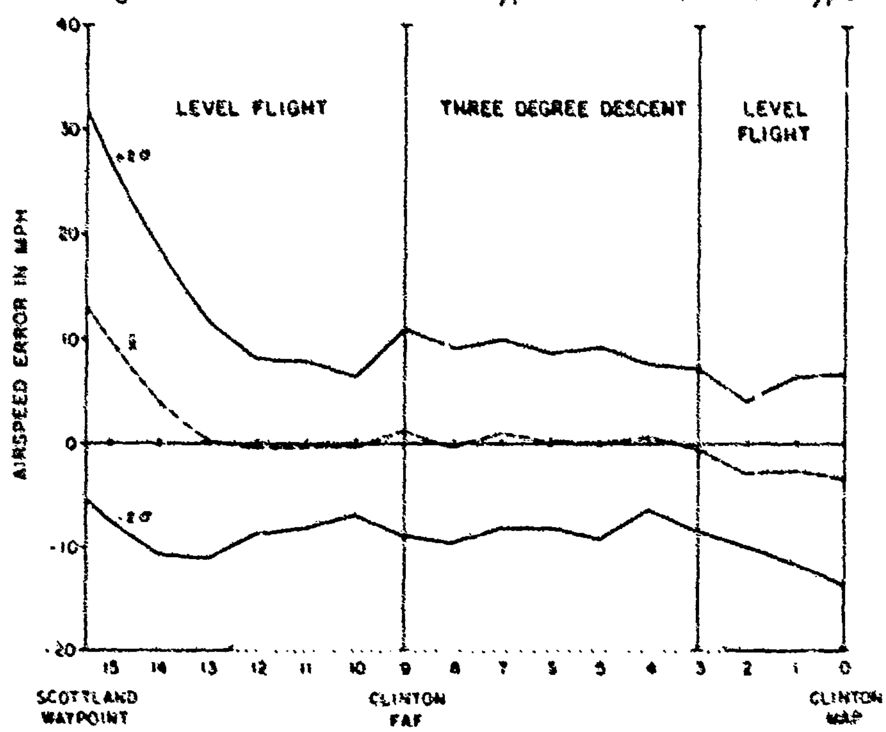

Figure A-26. Central tendency and 2σ variability of airspeed error on Segments 3, 4, and 5 between Scottland waypoint and Clinton waypoint.

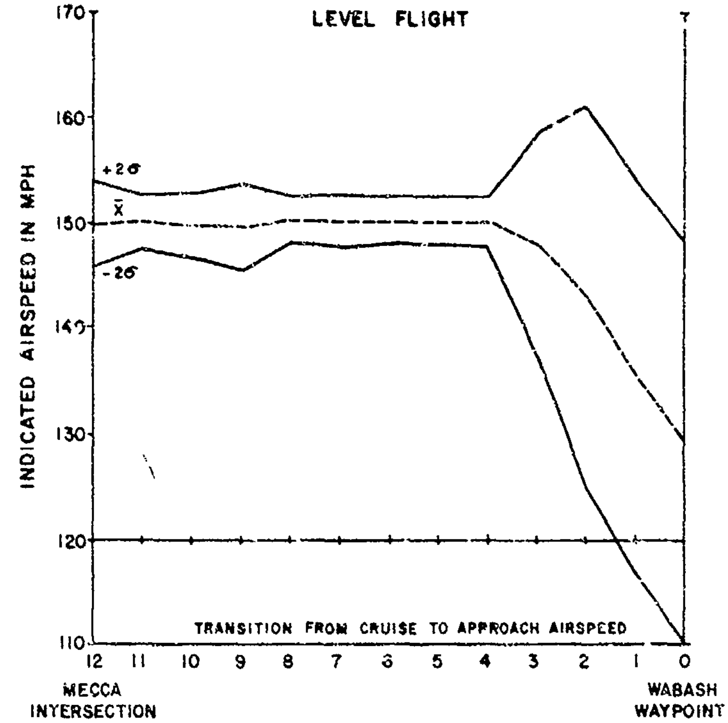

Figure A-27. Central te[illegible]y and 2σ variability of indicated airspeed on Segment 8 between Mecca intersection and Wabash waypoint.

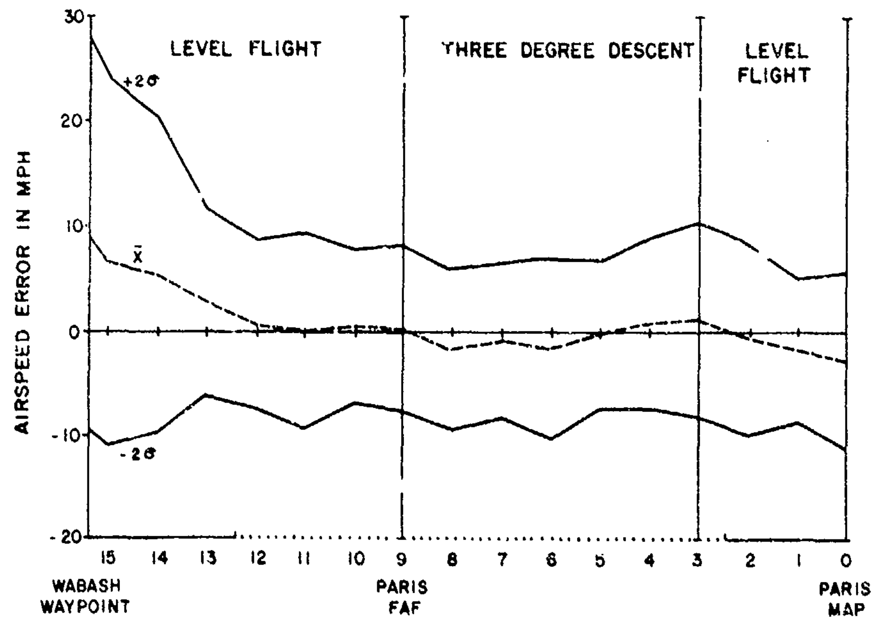

Figure A-28. Central tendency and 2σ variability of airspeed error on Segments 9, 10, and 11 between Wabash waypoint and Paris MAP.

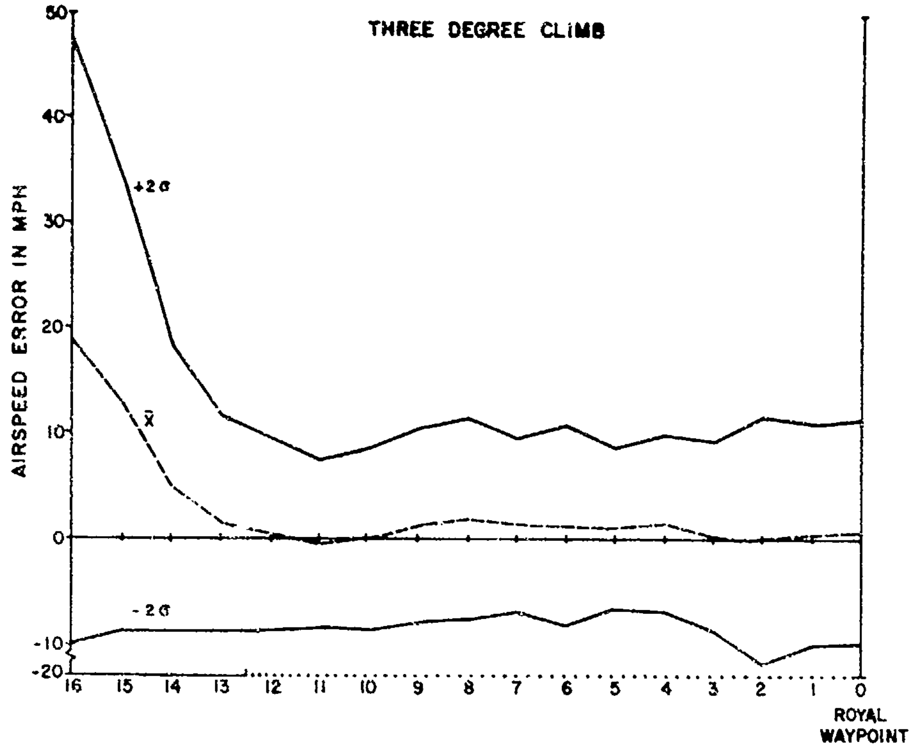

Figure A-29. Central tendency and 2σ variability of airspeed error on Segment 14 between the three-degree climb intercept and the Royal waypoint.

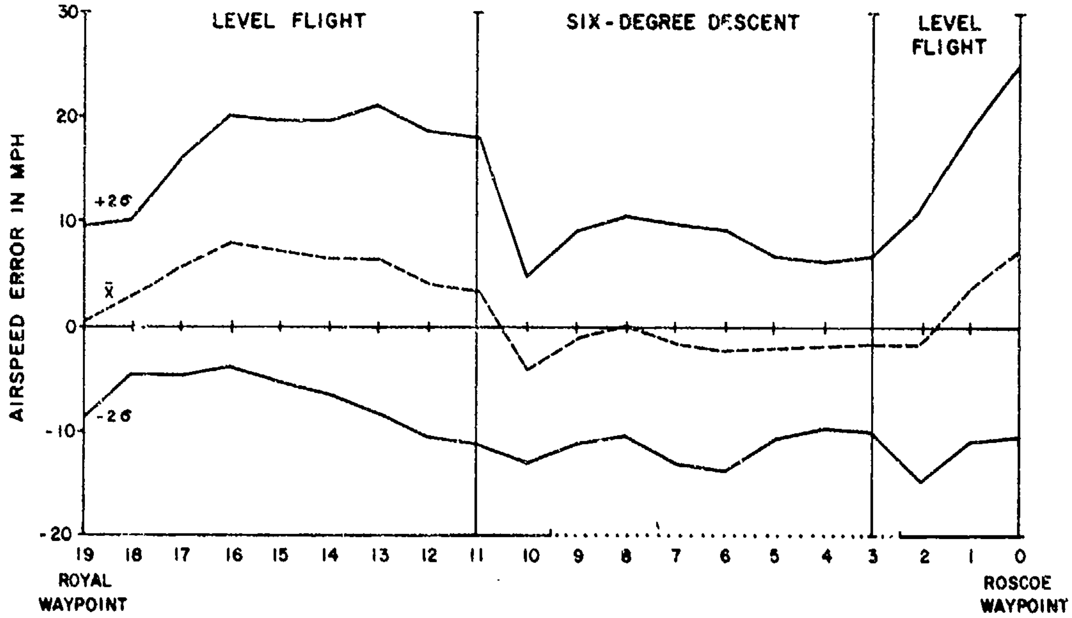

Figure A-30. Central tendency and 2σ variability of airspeed error on Segments 15, 16, and 17 between Royal waypoint and Roscoe waypoint.

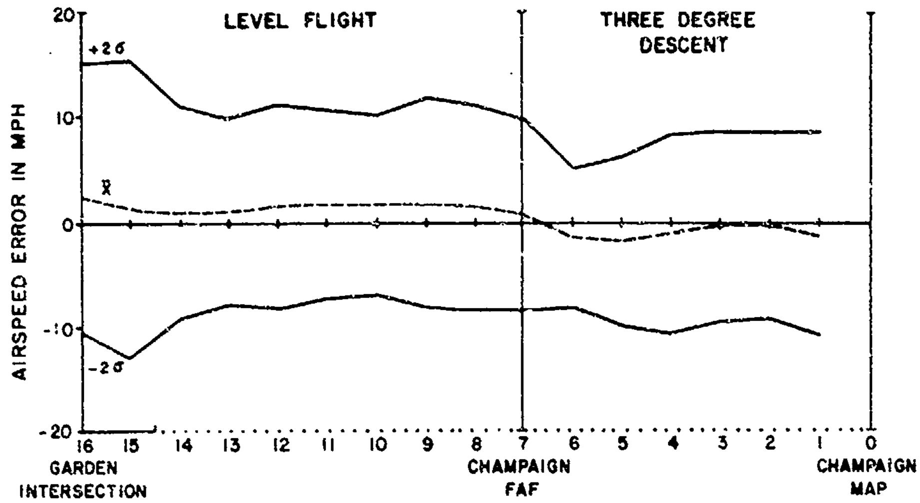

Figure A-31. Central tendency and 2σ variability of airspeed error on Segments 19 and 20 between Garden intersection and Champaign MAP.

Tabulation of Summary Vertical, Horizontal, and Airspeed Error Statistics

Table B-1. Vertical deviations in feet for level flight on Segment 1. These statistics are presented graphically in Figure A-1.

Dist.	N	Mean	σ	Mean +3σ	Mean -3σ
17	32	19.12	76.15	247.60	-209.34
16	32	27.35	56.84	197.88	-143.17
15	32	26.01	43.47	156.43	-104.40
14	32	22.14	36.90	132.86	- 88.58
13	32	9.60	34.90	114.33	- 95.12
12	32	2.44	41.06	125.63	-120.74
11	32	- .51	40.99	122.47	-123.49
10	32	.63	34.04	102.76	-101.50
9	32	- 1.39	28.50	84.10	- 86.89
8	32	- 5.93	36.45	103.43	-115.29
7	32	-11.09	39.21	106.53	-128.72
6	32	4.37	39.01	121.43	-112.67
5	32	5.94	30.16	96.42	- 84.53
4	32	- 8.41	40.12	111.97	-128.79
3	32	- 7.66	37.47	104.76	-120.10
2	32	-11.40	38.30	103.51	-126.32
1	32	- 6.83	30.54	84.79	- 98.46
0	32	1.53	34.92	106.31	-103.23

Table B-2. Vertical deviations in feet for level flight on Segment 2. These statistics are presented graphically in Figure A-2.

Dist.	N	Mean	σ	Mean +3σ	Mean -3σ
15	28	3.67	47.51	146.23	-138.87
14	32	7.81	46.62	147.70	-132.06
13	32	18.82	43.55	149.49	-111.84
12	32	12.17	46.43	151.48	-127.13
11	32	2.79	42.17	129.32	-123.72
10	32	4.33	47.29	146.23	-137.56
9	32	1.39	39.56	120.08	-117.30
8	32	- 5.99	37.92	107.78	-119.76
7	32	- 6.38	36.79	104.01	-116.77
6	32	- 7.90	41.37	116.23	-132.03
5	32	- 2.48	42.59	125.30	-130.26
4	32	- 4.63	41.12	118.74	-128.01
3	32	- 6.97	39.25	110.78	-124.73
2	32	- 7.26	46.61	132.57	-147.11
1	32	- 4.96	46.56	134.71	-144.64
0	32	-13.14	46.56	126.55	-152.85

Table B-3. Vertical deviations in feet for level flight (miles 15-10, and 2-0) and three-degree descent (miles 9-3) on Segments 3, 4, and 5. These statistics are presented graphically in Figure A-3.

Dist.	N	Mean	σ	Mean +3σ	Mean -3σ
15	31	-46.05	57.58	126.71	-218.81
14	32	-40.30	52.51	117.24	-197.85
13	32	-37.38	49.58	111.37	-186.15
12	32	-43.24	59.12	134.13	-220.61
11	32	-39.34	50.61	112.49	-191.17
10	32	-18.17	59.27	159.64	-195.98
9	32	-37.45	77.85	196.11	-271.02
8	32	51.62	79.66	290.61	-187.36
7	32	51.85	61.16	235.34	-131.63
6	32	44.33	52.53	201.93	-113.26
5	32	24.11	57.02	195.19	-146.97
4	32	27.59	56.30	196.50	-141.30
3	32	31.05	61.36	215.14	-153.02
2	32	2.11	38.98	119.07	-114.85
1	32	- 7.49	26.85	73.08	- 88.07
0	32	13.63	40.12	134.00	-106.74

Table B-4. Vertical deviations in feet for level flight on Segments 6 and 7. These statistics are presented graphically in Figure A-4.

Dist.	N	Mean	σ	Mean +3σ	Mean -3σ
5	32	-44.32	81.95	201.54	-290.18
6	32	- 6.10	43.93	125.69	-137.89
7	30	4.07	61.87	189.70	-181.56
8	31	23.62	47.53	166.21	-118.96
9	30	30.24	50.41	181.49	-120.99
10	20	27.06	45.87	164.68	-110.55

Table B-5. Vertical deviations in feet for level flight on Segment 8. These statistics are presented graphically in Figure A-5.

Dist	N	Mean	σ	Mean +3σ	Mean -3σ
12	22	27.33	57.83	200.84	-146.18
11	31	13.99	49.63	162.89	-134.90
10	32	16.00	51.59	170.78	-138.77
9	32	24.69	50.67	176.70	-127.31
8	32	9.58	50.60	161.41	-142.24
7	32	4.08	43.18	133.62	-125.45
6	32	5.16	34.62	109.03	- 98.69
5	32	- .66	29.63	88.23	- 89.55
4	32	.52	32.88	99.17	- 98.12
3	32	- .21	39.55	118.45	-118.87
2	32	7.63	46.29	146.52	-131.26
1	32	8.72	43.07	137.96	-120.51
0	32	10.22	52.65	168.19	-147.74

Table B-6. Vertical deviations in feet for level flight (miles 15-10, 2-0) and three-degree descent (miles 9-3) on Segments 9, 10, and 11. These statistics are presented graphically in Figure A-6.

Dist.	N	Mean	σ	Mean +3σ	Mean -3σ
15	26	1.31	44.06	133.52	-130.89
14	32	-11.56	45.44	124.76	-147.88
13	32	-20.46	61.91	165.28	-206.20
12	32	- 7.78	47.33	134.22	-149.79
11	32	- 6.02	45.41	130.22	-142.27
10	32	- 9.80	46.56	129.88	-149.49
9	32	-32.07	57.42	140.18	-204.33
8	32	12.44	57.93	186.23	-161.35
7	32	8.80	68.77	215.13	-197.53
6	32	4.28	49.38	152.45	-143.87
5	32	16.49	37.61	129.34	- 96.34
4	32	36.75	36.96	147.64	- 74.14
3	32	57.59	45.43	193.91	- 78.72
2	32	13.49	25.62	90.36	- 63.38
1	32	- 4.84	28.44	80.48	- 90.16
0	32	6.65	38.75	122.93	-109.61

Table B-7. Vertical deviations in feet for level flight on Segment 12. These statistics are presented graphically in Figure A-7.

Dist.	N	Mean	σ	Mean +3σ	Mean -3σ
1	32	48.35	76.94	279.17	-182.46
2	32	18.99	91.01	284.04	-262.07
3	32	27.20	81.93	273.01	-218.61
4	32	49.30	77.82	282.77	-184.15
5	32	40.06	45.05	175.24	- 95.11
6	32	27.30	66.53	226.90	-172.30
7	26	30.68	65.57	227.40	-166.03

Table B-8. Vertical deviations in feet for level flight on Segment 13. The statistics are presented graphically in Figure A-8.

Dist.	N	Mean	σ	Mean +3σ	Mean -3σ
23	22	48.94	83.94	300.78	-202.90
22	31	38.87	85.94	296.70	-218.95
21	31	44.79	81.47	289.23	-199.64
20	32	42.16	96.14	330.59	-246.26
19	32	40.78	65.65	237.74	-156.16
18	32	24.50	61.21	208.14	-159.14
17	32	25.32	59.56	204.01	-153.37
16	32	36.64	62.90	225.35	-152.06

Table B-9. Vertical deviations in feet for three-degree climb on Segment 14. These statistics are presented graphically in Figure A-9.

Dist.	N	Mean	σ	Mean +3σ	Mean -3σ
16	23	103.63	118.04	457.76	-250.49
15	32	52.60	71.26	266.41	-161.19
14	32	18.80	86.55	278.47	-240.86
13	32	3.95	86.21	262.61	-254.69
12	32	- 27.88	85.69	229.20	-284.97
11	32	- 28.27	75.79	199.09	-255.64
10	32	- [illegible]	75.44	210.51	-242.15
9	32	1.88	70.47	213.31	-209.55
8	32	14.11	57.86	187.71	-159.48
7	32	14.28	70.81	226.73	-198.16
6	32	4.36	44.47	137.79	-129.05
5	32	23.95	56.43	193.26	-145.34
4	32	- 5.45	56.02	162.61	-173.53
3	32	- 31.22	51.88	124.41	-186.86
2	32	- 7.71	55.32	158.25	-173.68
1	32	4.81	76.15	233.26	-223.63
0	32	1.87	77.74	235.11	-231.36

Table B-10. Vertical deviations in feet for level flight (miles 19-12 and 2-0) and six-degree descent (miles 11-3) on Segments 15, 16, and 17. These statistics are presented graphically in Figure A-10.

Dist.	N	Mean	σ	Mean +3σ	Mean -3σ
19	20	-79.82	96.33	209.17	-368.82
18	32	-35.76	69.34	172.27	-243.80
17	32	16.96	58.88	193.63	-159.70
16	32	20.72	57.04	191.85	-150.40
15	32	28.16	51.81	183.60	-127.28
14	32	27.07	47.06	168.27	-114.12
13	32	8.59	41.66	133.57	-116.39
12	32	10.04	35.08	115.31	- 95.22
11	31	-166.73	76.39	62.43	-395.90
10	32	48.14	104.22	360.82	-264.54
9	32	90.62	94.28	373.49	-192.24
8	32	61.74	102.25	368.50	-245.01
7	32	28.10	77.80	261.50	-205.29
6	32	27.95	69.31	235.90	-179.98
5	32	54.64	69.85	264.20	-154.91
4	32	34.95	84.17	287.47	-217.55
3	32	65.01	56.87	235.64	-105.61
2	32	34.77	45.71	171.92	-102.37
1	32	12.32	45.35	148.39	-123.74
0	32	21.97	48.05	166.14	-122.18

Table B-11. Vertical deviations in feet for level flight on Segment 18. These statistics are presented graphically in Figure A-11.

Dist.	N	Mean	σ	Mean +3σ	Mean -3σ
0	31	14.55	57.99	188.53	-159.41
1	32	11.10	50.96	164.01	-141.80
2	32	.20	41.95	126.08	-125.66
3	32	9.38	45.37	145.51	-126.73
4	32	15.41	53.49	175.89	-145.07
5	32	- .13	36.52	109.43	-109.70
6	32	- 1.48	33.06	97.70	-100.66
7	32	3.71	49.42	151.99	-144.56
8	32	9.04	47.28	150.89	-132.80
9	32	15.26	43.45	145.62	-115.09
10	32	4.00	43.77	135.33	-127.33
11	28	- 2.62	41.49	121.85	-127.09

Table B-12. Vertical deviations in feet for level flight (miles 16-8) and three-degree descent (miles 7-1) on Segments 19 and 20. These statistics are presented graphically in Figure A-12.

Dist.	N	Mean	σ	Mean +3σ	Mean -3σ
16	29	-20.22	51.38	133.92	-174.36
15	32	-20.14	39.98	99.80	-140.09
14	32	-15.30	32.17	81.23	-111.83
13	32	- 4.86	36.78	105.50	-115.23
12	32	- 3.84	30.83	88.66	- 96.35
11	32	5.07	33.30	105.00	- 94.84
10	32	10.29	37.92	124.06	-103.46
9	32	11.17	36.53	120.79	- 98.44
8	32	7.21	42.66	135.21	-120.77
7	30	4.73	56.58	174.47	-165.02
6	32	13.94	49.59	162.72	-134.83
5	32	18.37	46.53	157.97	-121.22
4	32	9.91	47.08	151.16	-131.32
3	32	9.34	63.46	199.73	-181.05
2	32	11.82	57.94	185.65	-162.01
1	32	36.92	73.22	256.61	-182.75

Table B-13. Horizontal deviations in nautical miles for level flight on Segment 1. These statistics are presented graphically in Figure A-13.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
17	32	-.0926	.5424	.9921	-1.1773
16	32	.0669	.5485	1.1639	-1.0301
15	32	.0859	.4903	1.0665	- .8948
14	32	-.0243	.4004	.7765	- .8251
13	32	-.1048	.3413	.5777	- .7874
12	32	-.0809	.4078	.7347	- .8965
11	32	-.1615	.4207	.6800	-1.0029
10	32	-.2121	.3270	.4420	- .8661
9	32	-.1210	.2987	.4764	- .7183
8	32	-.0946	.3798	.6651	- .8543
7	32	-.1210	.4856	.8502	-1.0922
6	32	-.1074	.5177	.9280	-1.1428
5	32	-.0815	.4318	.7821	- .9451
4	32	-.0398	.4003	.7608	- .8405
3	32	.0663	.4260	.9184	- .7857
2	32	.1252	.3723	.8697	- .6193
1	32	-.0154	.3361	.6568	- .6875
0	32	-.0804	.3159	.5515	- .7122

Table B-14. Horizontal deviations in nautical miles for level flight on Segment 2. These statistics are presented graphically in Figure A-14.

Dist.	N	Mean	σ	Mean + 2σ	Mean -2σ
15	28	.0699	.3145	.6989	-.5591
14	32	.2655	.3655	.9964	-.4654
13	32	.2736	.4233	1.1202	-.5731
12	32	.1454	.3751	.8956	-.6047
11	32	.0342	.2738	.5818	-.5134
10	32	-.0205	.2520	.4835	-.5245
9	32	-.0210	.2980	.5749	-.6169
8	32	-.0170	.3092	.6015	-.6355
7	32	-.0377	.2959	.5542	-.6295
6	32	-.1388	.3001	.4615	-.7391
5	32	-.1601	.3299	.4997	-.8199
4	32	-.1622	.3248	.4874	-.8117
3	32	-.1432	.3306	.5180	-.8045
2	32	-.1209	.3493	.5777	-.8195
1	32	-.0023	.3873	.7722	-.7769
0	32	.0472	.4211	.8894	-.7949

Table B-15. Horizontal deviations in nautical miles for level flight (miles 15-10, 2-0) and three-degree descent (miles 9-3) on Segments 3, 4, and 5. These statistics are presented graphically in Figure A-15.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
15	31	-.3609	.5412	.7215	-1.4432
14	32	-.7233	.6032	.4831	-1.9297
13	32	-.7884	.5900	.3916	-1.9684
12	32	-.7012	.5860	.4708	-1.8732
11	32	-.5599	.4726	.3854	-1.5051
10	32	-.4318	.5096	.5874	-1.4510
9	32	-.3282	.5175	.7069	-1.3632
8	32	-.2372	.4599	.6827	-1.1571
7	32	-.2442	.4162	.5882	-1.0766
6	32	-.1776	.3272	.4769	- .8320
5	32	-.1297	.3317	.5337	- .7932
4	32	-.1141	.2781	.4420	- .6702
3	32	-.0704	.2894	.5083	- .6492
2	32	-.0462	.2964	.5466	- .6391
1	32	-.0451	.3344	.6237	- .7139
0	32	-.0318	.3717	.7115	- .7752

Table B-16. Horizontal deviations in nautical miles for level flight on Segments 6 and 7. These statistics are presented graphically in Figure B-16.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
0	32	-.0096	.3826	.7557	-.7748
1	32	.0161	.3890	.7941	-.7619
2	32	.0068	.3698	.7464	-.7328
3	32	.0645	.3959	.8563	-.7273
4	32	.1367	.4551	1.0469	-.7734
5	32	.1792	.4610	1.1013	-.7428
6	32	.2362	.4220	1.0751	-.6128
7	30	.2949	.3968	1.0885	-.4987
8	31	.4120	.3943	1.2006	-.3766
9	30	.6268	.3664	1.3596	-.1061
10	20	.5635	.2657	1.0949	.0322

Table B-17. Horizontal deviations in nautical miles for level flight on Segment 8. These statistics are presented graphically in Figure B-17.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
12	22	.3581	.4527	1.2635	-.5474
11	31	.1359	.4464	1.0287	-.7569
10	32	.0882	.4345	.7809	-.9573
9	32	-.0847	.4301	.7755	-.9449
8	32	-.0017	.4755	.9493	-.9526
7	32	.0622	.4384	.9391	-.8146
6	32	.0705	.3886	.8477	-.7068
5	32	.0970	.3522	.8013	-.6073
4	32	.0934	.3345	.7625	-.5756
3	32	.1036	.3474	.7984	-.5913
2	32	.1582	.3724	.9030	-.5867
1	32	.2492	.4849	1.2191	-.7206
0	32	.1943	.4009	.9961	-.6075

Table B-18. Horizontal deviations in nautical miles for level flight (miles 15-10, 2-0) and three-degree descent (miles 9-3) on Segments 9, 10, and 11. These statistics are presented graphically in Figure A-18.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
15	26	-.1644	.4181	.6719	-1.0007
14	32	-.3607	.5279	.6951	-1.4165
13	32	-.3993	.5213	.6432	-1.4418
12	32	-.2602	.4437	.6273	-1.1476
11	32	-.2194	.4028	.5863	-1.0251
10	32	-.1341	.4410	.7478	-1.0161
9	32	-.0509	.4018	.7527	- .8545
8	32	.1446	.2852	.7150	- .4259
7	32	.0719	.2110	.4939	- .3501
6	32	-.0328	.2137	.3946	- .4603
5	32	-.0901	.2953	.5006	- .6807
4	32	-.0044	.3697	.7351	- .7439
3	32	.1156	.3625	.8406	- .6095
2	32	.2375	.3095	.8565	- .3815
1	32	.2918	.3227	.9371	- .3535
0	32	.2512	.3342	.9195	- .4172

Table B-19. Horizontal deviations in nautical miles for level flight on Segment 12. These statistics are presented graphically in Figure A-19.

Dist.	N	Mean	σ	Mean +2σ	Mean −2σ
0	31	.1579	.3136	.7850	-.4693
1	32	.1500	.3536	.8572	-.5572
2	32	.1771	.4065	.9901	-.6359
3	32	.2156	.3890	.9936	-.5624
4	32	.2117	.3945	1.0007	-.5774
5	32	.2009	.3482	.8973	-.4955
6	32	.2699	.3391	.9482	-.4083
7	26	.2820	.5065	1.2950	-.7310

Table B-20. Horizontal deviations in nautical miles for level flight on Segment 13. These statistics are presented graphically in Figure A-20.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
23	22	.3992	.5842	1.5677	- .7693
22	31	.3516	.5781	1.5078	- .8046
21	31	.0968	.6492	1.3953	-1.2017
20	32	-.1231	.6876	1.2521	-1.4983
19	32	-.1992	.7282	1.2571	-1.6556
18	32	-.2216	.6461	1.0706	-1.5137
17	32	-.1471	.6287	1.1102	-1.4044
16	32	-.0657	.6152	1.1647	-1.2961

Table B-21. Horizontal deviations in nautical miles for three-degree climb on Segment 14. These statistics are presented graphically in Figure A-21.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
16	23	.0356	.5004	1.0365	-.9650
15	32	.0504	.4958	1.0420	-.9413
14	32	.1408	.4341	1.0089	-.7274
13	32	.1629	.4205	1.0039	-.6781
12	32	.2413	.3707	.9826	-.5001
11	32	.3179	.3318	.9815	-.3457
10	32	.3401	.3361	1.0123	-.3322
9	32	.2739	.3484	.9707	-.4229
8	32	.2372	.3747	.9866	-.5122
7	32	.2420	.3874	1.0167	-.5327
6	32	.2214	.3626	.9466	-.5037
5	32	.1655	.3323	.8301	-.4991
4	32	.1969	.3561	.9091	-.5153
3	32	.2880	.3326	.9531	-.3772
2	32	.2852	.3279	.9411	-.3706
1	32	.2551	.3796	1.0143	-.5042
0	32	.2946	.3913	1.0773	-.4880

Table B-22. Horizontal deviations in nautical miles for level flight (mile 19-12 and 2-0) and six-degree descent (miles 11-3) on Segments 15, 16 and 17. These statistics are presented graphically in Figure A-22.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
19	20	.2159	.3570	.9300	- .4981
18	32	.3277	.4286	1.1849	- .5296
17	32	.2848	.4646	1.2140	- .6444
16	32	.2122	.4951	1.2025	- .7780
15	32	.1748	.5365	1.2477	- .8982
14	32	.1367	.5508	1.2382	- .9649
13	32	.0813	.5682	1.2176	-1.0550
12	32	.0782	.5518	1.1819	-1.0254
11	31	.1044	.5738	1.2520	-1.0433
10	32	.1083	.5200	1.1484	- .9318
9	32	.0456	.4465	.9386	- .8474
8	32	.0196	.4116	.8429	- .8036
7	32	.0091	.4112	.8314	- .8133
6	32	.0188	.3976	.8141	- .7765
5	32	.0506	.3671	.7847	- .6835
4	32	.0692	.3156	.7005	- .5620
3	32	.0542	.2615	.5773	- .4688
2	32	.0165	.2714	.5593	- .5264
1	32	-.1557	.3266	.4975	- .8089
0	32	-.3235	.4403	.5571	-1.2041

Table B-23. Horizontal deviations in nautical miles for level flight on Segment 18. These statistics are presented graphically in Figure A-23.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
0	31	-.1926	.4269	.6613	-1.0464
1	32	-.0467	.5779	1.1092	-1.2026
2	32	.0189	.5315	1.0820	-1.0441
3	32	.0677	.5960	1.2596	-1.1243
4	32	.0379	.4810	.9999	- .9241
5	32	.0883	.4500	.9882	- .8117
6	32	.1663	.4231	1.0125	- .6800
7	32	.2468	.4117	1.0703	- .5766
8	32	.2532	.3899	1.0329	- .5266
9	32	-.0970	.6843	1.2715	-1.4655
10	32	-.7891	.8071	.8252	-2.4033
11	28	-.6560	.4437	.2314	-1.5435

Table B-24. Horizontal deviations in nautical miles for level flight (miles 16-8) and three-degree descent (miles 7-1) on Segments 19 and 20. These statistics are presented graphically in Figure A-24.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
16	29	-.4415	.5579	.6742	-1.5573
15	32	-.3252	.5022	.6792	-1.3295
14	32	-.1899	.4333	.6767	-1.0564
13	32	-.0490	.3856	.7222	- .8201
12	32	.0271	.3761	.7794	- .7252
11	32	.0445	.3633	.7711	- .6820
10	32	.0666	.3417	.7501	- .6169
9	32	.1160	.2174	.5508	- .4348
8	32	.0842	.2143	.5128	- .3444
7	30	-.0409	.1840	.3271	- .4089
6	32	-.0465	.1594	.2723	- .3653
5	32	-.0793	.1508	.2222	- .3808
4	32	-.0624	.1374	.2125	- .3372
3	32	-.0155	.0724	.1293	- .1603
2	32	-.0093	.1162	.2231	- .2418
1	32	.0128	.0926	.1979	- .1723

Table B-25. Airspeed indications in miles per hour for level flight on Segment 2. These statistics are presented graphically in Figure A-25.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
15	28	150.08	1.93	153.95	146.21
14	32	150.11	1.52	153.17	147.06
13	32	150.27	1.32	152.92	147.62
12	32	150.31	1.29	152.89	147.72
11	32	150.17	1.66	153.51	146.83
10	32	150.24	1.70	153.64	146.83
9	32	150.33	1.20	152.73	147.93
8	32	150.27	1.24	152.76	147.78
7	32	150.39	1.10	152.60	148.18
6	32	150.36	1.10	152.57	148.14
5	32	149.84	2.22	154.29	145.39
4	32	149.21	4.47	158.16	140.26
3	32	147.32	7.30	161.92	132.71
2	32	144.10	10.17	164.46	123.75
1	32	139.47	10.43	160.34	118.60
0	32	133.66	9.34	152.34	114.99

Table B-26. Airspeed deviations in miles per hour for level flight (miles 15-10, 2-0) and three-degree descent (miles 9-3) on Segments 3, 4, and 5. These statistics are presented graphically in Figure A-26.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
15	31	9.71	8.56	26.84	- 7.42
14	32	3.84	7.27	18.40	-10.71
13	32	.22	5.68	11.60	-11.15
12	32	- .38	4.18	7.97	- 8.74
11	32	- .25	3.97	7.70	- 8.20
10	32	- .35	3.31	6.27	- 6.98
9	32	.94	4.98	10.98	- 9.01
8	32	- .36	4.63	8.90	- 9.64
7	32	.82	4.54	9.91	- 8.26
6	32	.09	4.19	8.47	- 8.29
5	32	- .06	4.56	9.07	- 9.19
4	32	.46	3.51	7.48	- 6.55
3	32	- .62	3.92	7.23	- 8.48
2	32	-3.04	3.45	3.86	- 9.95
1	32	-2.73	4.47	6.21	-11.68
0	32	-3.55	5.04	6.52	-13.63

Table B-27. Airspeed indications in miles per hour for level flight on Segment 8. These statistics are presented graphically in Figure A-27.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
12	22	150.15	1.99	154.15	146.15
11	31	150.23	1.29	152.82	147.64
10	32	149.91	1.52	152.97	146.86
9	32	149.77	2.07	153.91	145.63
8	32	150.39	1.09	152.59	148.19
7	32	150.32	1.25	152.82	147.82
6	32	150.40	1.08	152.56	148.23
5	32	150.36	1.18	152.73	148.00
4	32	150.30	1.13	152.58	148.03
3	32	148.11	5.24	158.60	137.61
2	32	143.14	9.87	161.30	124.98
1	32	135.62	9.28	154.19	117.06
0	32	129.28	9.53	148.36	110.21

Table B-28. Airspeed deviations in miles per hour for level flight (miles 15-10, 2-0) and three-degree descent (miles 9-3) on Segments 9, 10, and 11. These statistics are presented graphically in Figure A-28.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
15	26	6.71	8.82	24.35	-10.92
14	32	5.51	7.56	20.63	- 9.60
13	32	2.88	4.42	11.73	- 5.96
12	32	.80	4.05	8.91	- 7.29
11	32	.21	4.69	9.60	- 9.18
10	32	.61	3.68	7.98	- 6.76
9	32	.55	3.97	8.49	- 7.39
8	32	-1.53	3.85	6.16	- 9.23
7	32	- .69	3.73	6.78	- 8.17
6	32	-1.49	4.30	7.11	-10.10
5	32	- .14	3.55	6.97	- 7.25
4	32	.99	4.08	9.16	- 7.17
3	32	1.27	4.63	10.55	- 8.00
2	32	- .65	4.51	8.38	- 9.69
1	32	-1.75	3.44	5.14	- 8.65
0	32	-2.74	4.23	5.73	-11.21

Table B-29. Airspeed deviations in miles per hour for three-degree climb on Segment 14. These statistics are presented graphically in Figure A-29.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
16	23	18.71	14.29	47.31	- 9.80
15	32	12.84	10.82	34.50	- 8.80
14	32	4.87	6.74	18.37	- 8.62
13	32	1.43	5.11	11.67	- 8.79
12	32	.49	4.59	9.68	- 8.68
11	32	- .49	3.94	7.38	- 8.38
10	32	- .04	4.27	8.49	- 8.58
9	32	1.22	4.55	10.33	- 7.89
8	32	1.86	4.77	11.41	- 7.67
7	32	1.35	4.08	9.53	- 6.81
6	32	1.23	4.74	10.73	- 8.25
5	32	1.03	3.81	8.67	- 6.59
4	32	1.49	4.16	9.82	- 6.84
3	32	.26	4.49	9.24	- 8.71
2	32	- .11	5.85	11.59	-11.82
1	32	.44	5.24	10.93	-10.05
0	32	.67	5.34	11.35	-10.01

Table B-30. Airspeed deviations in miles per hour for level flight (miles 19-12 and 2-0) and six-degree descent (miles 11-3) on Segments 15, 16, and 17. These statistics are presented graphically in Figure A-30.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
19	20	.43	4.56	9.57	- 8.69
18	32	2.85	3.68	10.21	- 4.50
17	32	5.76	5.16	16.10	- 4.57
16	32	8.16	6.02	20.22	- 3.89
15	32	7.26	6.23	19.72	- 5.19
14	32	6.65	6.53	19.72	- 6.41
13	32	6.57	7.32	21.22	- 8.07
12	32	4.19	7.27	18.73	-10.34
11	31	3.61	7.29	18.28	-10.97
10	32	-4.13	4.46	4.79	-13.06
9	32	-1.07	5.12	9.16	-11.31
8	32	.07	5.26	10.61	-10.45
7	32	-1.54	5.72	9.89	-12.98
6	32	-2.13	5.74	9.34	-13.62
5	32	-2.02	4.35	6.69	-10.73
4	32	-1.72	4.00	6.28	- 9.73
3	32	-1.52	4.23	6.93	- 9.99
2	32	-1.54	6.54	11.54	-14.63
1	32	3.92	7.39	18.70	-10.85
0	32	7.32	8.90	25.13	-10.47

Table B-31. Airspeed deviations in miles per hour for level flight (miles 16-8) and three-degree descent (miles 7-1) on Segments 19 and 20. These statistics are presented graphically in Figure B-31.

Dist.	N	Mean	σ	Mean +2σ	Mean -2σ
16	29	2.49	6.34	15.18	-10.19
15	32	1.38	7.05	15.49	-12.72
14	32	1.01	5.06	11.14	- 9.11
13	32	1.09	4.42	9.94	- 7.75
12	32	1.57	4.81	11.21	- 8.06
11	32	1.77	4.46	10.70	- 7.16
10	32	1.69	4.29	10.29	- 6.90
9	32	1.92	4.94	11.81	- 7.97
8	32	1.50	4.80	11.10	- 8.10
7	30	.75	4.49	9.74	- 8.24
6	32	-1.36	3.24	5.12	- 7.85
5	32	-1.76	4.02	6.28	- 9.80
4	32	-1.04	4.72	8.40	-10.49
3	32	- .36	4.48	8.59	- 9.33
2	32	- .25	4.46	8.67	- 9.17
1	32	-1.09	4.83	8.58	-10.76

APPENDIX C

Tabulation of Statistics Presented Graphically in the Text

Table C-1. Three-RMS vertical flight technical error in feet comparing steady-state performance for Simplified Procedures with corresponding data for Standard Procedures. These data are presented graphically in Figure 12.

Task	Procedural Complexity	Flight			
		1	2	3	4
Level	Standard	216	194	177	144
Flight	Simplified	158	138	113	126
Three-degree	Standard	254	199	196	208
Climb	Simplified	186	192	170	150
Three-degree	Standard	357	266	214	227
Descent	Simplified	191	177	164	167
Six-degree	Standard	455	554	524	397
Descent	Simplified	283	329	231	195

Table C-2. Three-RMS vertical flight technical error in feet comparing steady-state performance for Standard Procedures with corresponding data for Simplified Procedures. These data are presented graphically in Figure 13.

Task	Procedural Complexity	Flight			
		1	2	3	4
Level	Standard	155	147	140	128
Flight	Simplified	136	128	99	119
Three-degree	Standard	250	192	193	194
Climb	Simplified	206	199	163	165
Three-degree	Standard	309	231	197	221
Descent	Simplified	181	168	155	131

Table C-3. Three-RMS overall vertical flight technical error in feet. These statistics are presented graphically in Figure 14.

Task	Procedural Complexity	Flight			
		1	2	3	4
Level Flight	Standard	225	204	180	153
	Simplified	189	144	120	135
Three-degree Climb	Standard	297	312	222	249
	Simplified	258	213	186	171
Three-degree Descent	Standard	387	321	222	276
	Simplified	228	204	177	165
Six-degree Descent	Standard	390	414	459	375
	Simplified	369	363	324	300

Table C-4. Three-RMS vertical flight technical error in feet for level flight at MDA. These statistics are presented graphically in Figure 15.

Display	Procedural Complexity	Flight			
		1	2	3	4
VCH	Standard	180	165	111	111
	Simplified	123	81	96	96
Altimeter	Standard	210	204	153	105
	Simplified	117	81	69	63

Table C-5. Two-RMS steady-state horizontal flight technical error in nautical miles for Simplified Procedures. These statistics are presented graphically in Figure 16.

Pilot Group	Flight			
	1	2	3	4
ATP	1.04	.58	.66	.50
CIP	.92	1.08	.60	.68

Table C-6. Two-RMS overall horizontal flight technical error in nautical miles. These statistics are presented graphically in Figure 17.

Task	Procedural Complexity	Flight			
		1	2	3	4
Level	Standard	1.30	1.22	1.08	1.12
Flight	Simplified	1.16	0.98	0.94	0.84
Three-degree	Standard	1.06	0.68	1.08	1.08
Climb	Simplified	1.14	0.90	0.68	0.48
Three-degree	Standard	1.32	1.30	0.92	0.98
Descent	Simplified	0.84	0.68	0.80	0.60
Six-degree	Standard	0.90	1.06	1.04	1.14
Descent	Simplified	1.02	0.88	0.40	0.62

Table C-7. Transient tendency to undershoot or overshoot in nautical miles course changes for Simplified Procedures. Negative sign indicates undershoot. These statistics are presented graphically in Figure 18.

Course Change	Waypoint Turns	Course Change	Intersection Turns
45	-.025	46	-.055
68	.128	71	-.044
85	.282	90	-.150

Table C-8. Two-RMS transient horizontal flight technical error in nautical miles for Simplified Procedures. These statistics are presented graphically in Figure 19.

Course Change	Waypoint Turns	Course Change	Intersection Turns
45	0.88	46	1.95
68	0.72	71	1.40
85	1.22	90	1.36

Table C-9. Two-RMS steady-state airspeed error in miles per hour. These statistics are presented graphically in Figure 20.

Task	Procedural Complexity	Flight			
		1	2	3	4
Level	Standard	None	None	None	None
Flight	Simplified	9.7	9.8	6.8	7.1
Three-degree	Standard	13.0	12.2	11.3	14.8
Climb	Simplified	9.7	10.2	8.9	6.7
Three-degree	Standard	17.0	12.3	11.0	11.8
Descent	Simplified	9.4	7.1	7.4	8.2
Six-degree	Standard	15.3	17.0	12.3	14.2
Descent	Simplified	10.1	12.3	9.8	8.7

Table C-10. Two-RMS overall airspeed flight technical error in miles per hour. These statistics are presented graphically in Figure 21.

Task	Procedural Complexity	Flight			
		1	2	3	4
Level Flight	Standard	37.8	31.4	28.8	27.0
	Simplified	14.9	13.1	11.8	10.3
Three-degree Climb	Standard	16.0	19.6	15.7	19.0
	Simplified	16.9	13.0	10.6	8.9
Three-degree Descent	Standard	16.8	12.3	10.7	11.8
	Simplified	9.7	7.2	8.0	8.1
Six-Degree Descent	Standard	13.8	19.7	13.1	14.7
	Simplified	10.4	12.0	10.4	9.1

Table C-11. Average numbers of procedural errors per flight. These statistics are presented graphically in Figure 22.

Pilot Group	Procedural Complexity	Flight			
		1	2	3	4
ATP	Standard	12.5	6.0	3.3	2.8
	Simplified	2.3	2.5	1.3	0.0
CIP	Standard	8.3	7.3	2.8	2.8
	Simplified	4.3	1.5	1.3	0.5

APPENDIX D

Navigation Charts Used in Experimental Flights

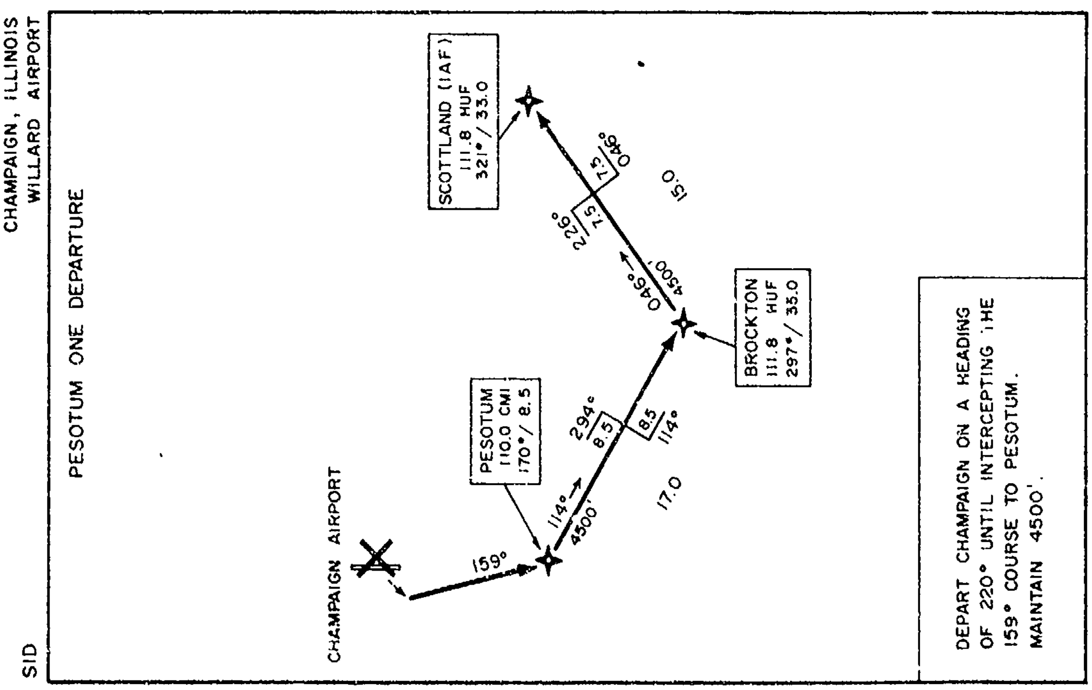

Figure D-1. Champaign Standard Instrument Departure.

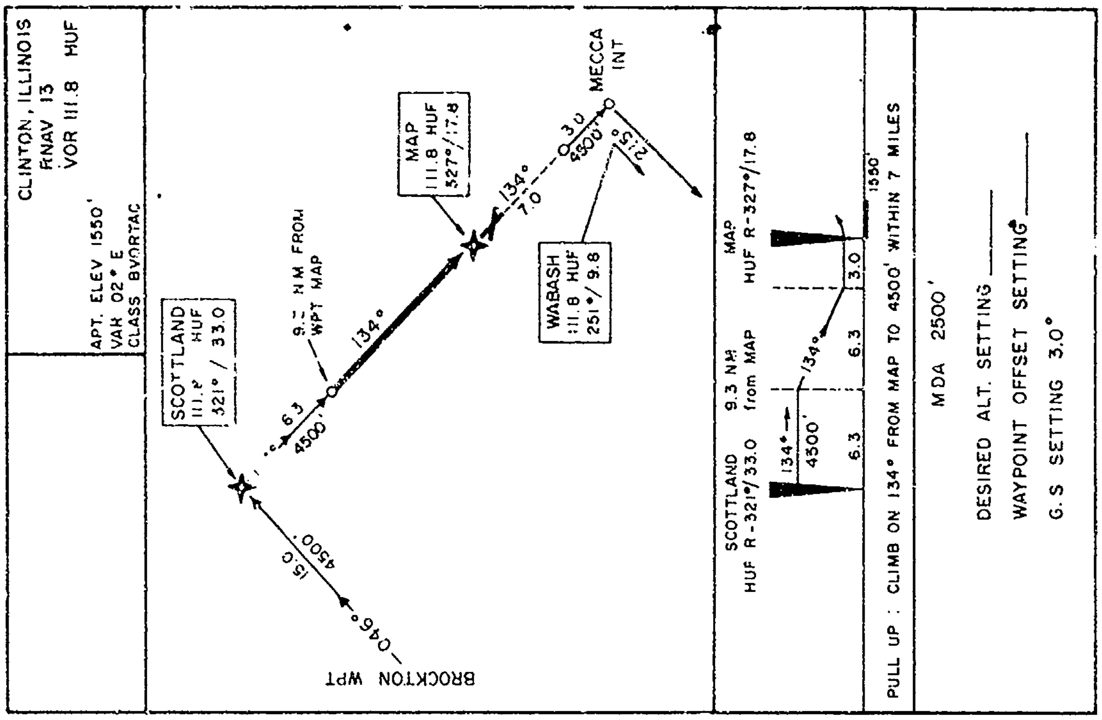

Figure D-2. Clinton Approach.

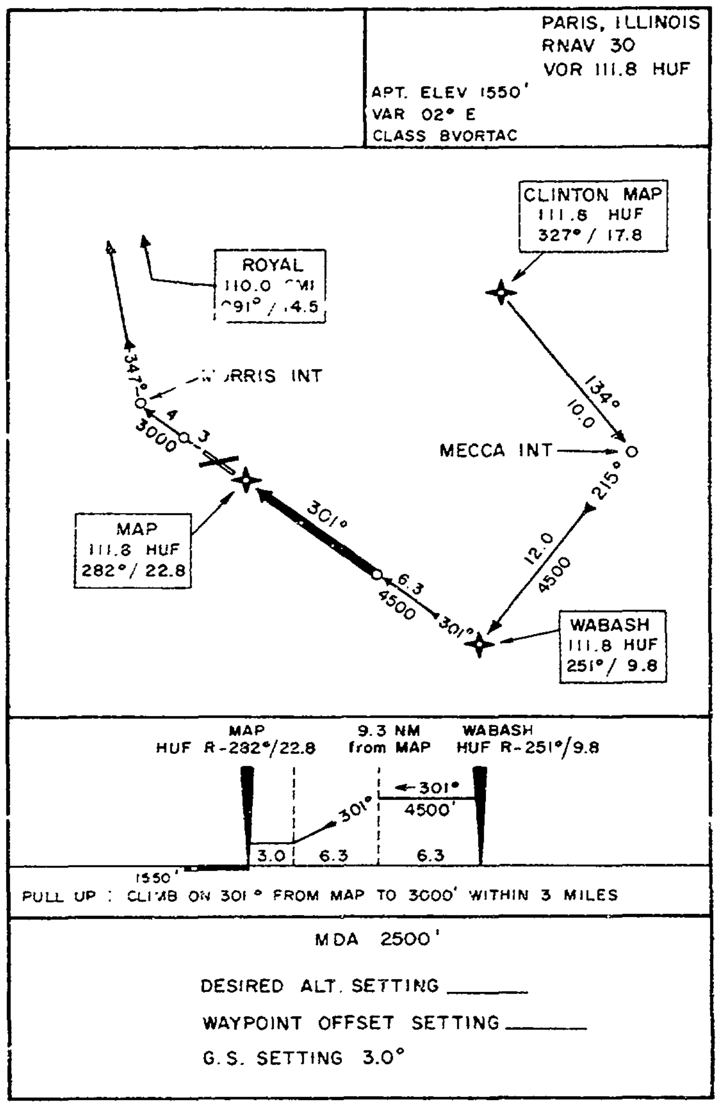

Figure D-3. Paris Approach.

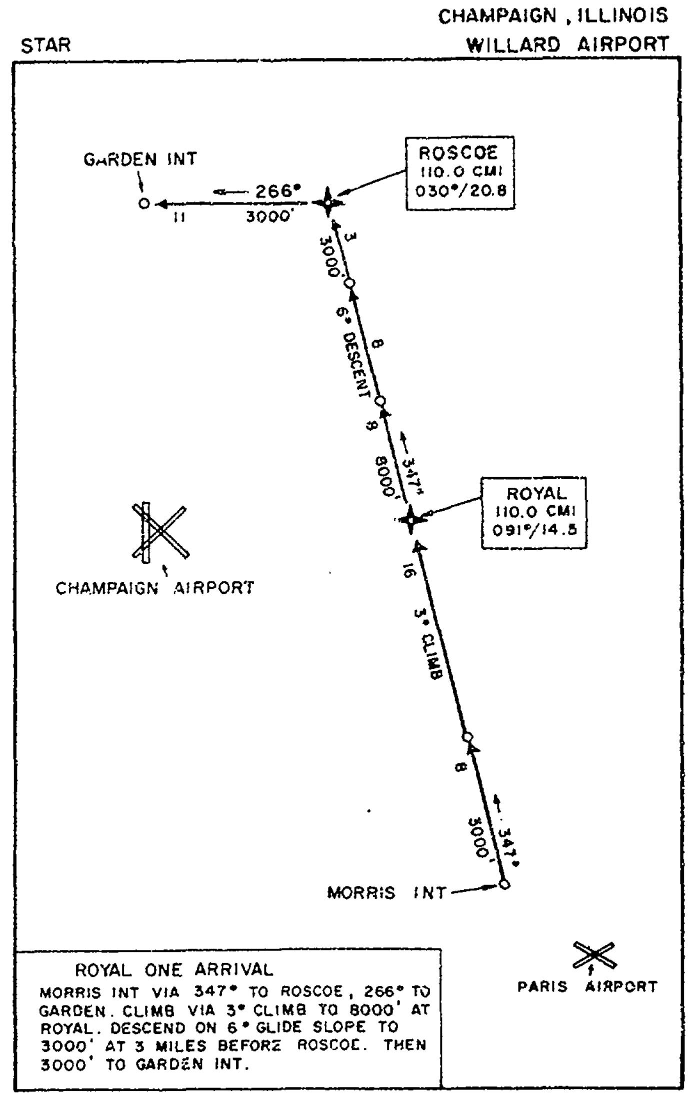

Figure D-4. Champaign Standard Arrival Route.

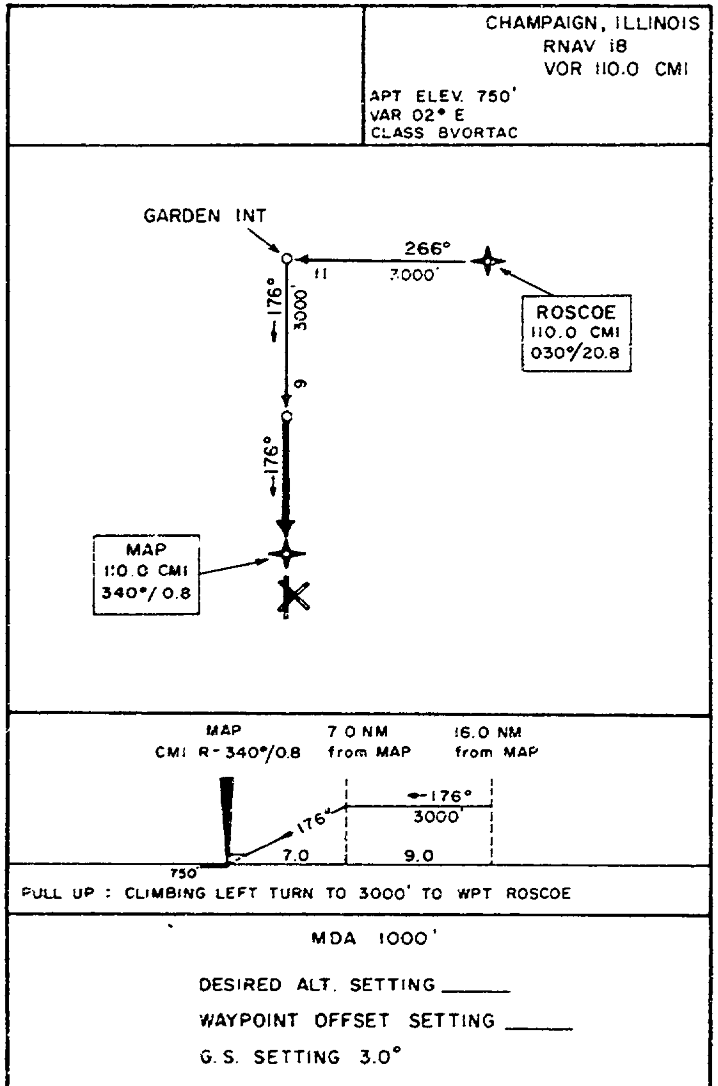

Figure D-5. Champaign Approach.