Report No. FAA-RD-77-43

A FLIGHT INVESTIGATION OF SYSTEM ACCURACIES AND OPERATIONAL CAPABILITIES OF A GENERAL AVIATION AREA NAVIGATION SYSTEM

Jack D. Edmonds
Robert H. Pursel
John Gallagher

JUNE 1977

FINAL REPORT

Document is available to the public through the
National Technical Information Service
Springfield, Virginia 22151

Prepared for

U. S. DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
Systems Research & Development Service
Washington, D.C. 20590

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FAA-RD-77-43		

4. Title and Subtitle	5. Report Date
A FLIGHT INVESTIGATION OF SYSTEM ACCURACIES AND OPERATIONAL CAPABILITIES OF A GENERAL AVIATION AREA NAVIGATION SYSTEM	June 1977
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Jack D. Edmonds, Robert H. Pursel, and John Gallagher	FAA-NA-77-1
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Federal Aviation Administration National Aviation Facilities Experimental Center Atlantic City, New Jersey 08405	11. Contract or Grant No. 044-326-500
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U.S. Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, D.C. 20590	Final July 1975 - September 1975
	14. Sponsoring Agency Code ARD-333

15. Supplementary Notes

16. Abstract

Flight tests were conducted at the National Aviation Facilities Experimental Center (NAFEC) using a general aviation area navigation (RNAV) system to investigate system accuracies and resultant airspace requirements in the terminal area. Issues investigated were total system error and error budget, flight technical error, turn anticipation, waypoint storage capacity, and results of typical operational maneuvers. Subject pilots for the test represented two distinct levels of experience. Subjects were also restricted to a one-, two-, or three-waypoint storage capacity for various flights. Statistical data are presented for the various error components making up the RNAV total system error. Various operational capabilities were also investigated and graphical data are presented for parallel offsets and turn anticipation. A two standard deviation of $\pm$1.5 nmi was measured for total system crosstrack error in the terminal area.

17. Key Words	18. Distribution Statement
RNAV Area Navigation Flight Technical Error (FTE) Error Budget VOR/DME	Document is available to the public through the National Technical Information Service, Springfield, Virginia 22151

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	99	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

LIST OF ILLUSTRATIONS (continued)

LIST OF TABLES

LIST OF TABLES (continued)

INTRODUCTION

PURPOSE.

The flight test data presented in this report are the result of one part of a series of flight tests to investigate two-, three-, and four-dimensional (2D, 3D, and 4D) area navigation (RNAV) concepts. The purpose of these flights is to collect data to be used for the establishment of minimum operational characteristics (MOC) and to determine the impact of RNAV on the air traffic control (ATC) system.

BACKGROUND.

The Federal Aviation Administration (FAA) interest in RNAV is directed toward the implementation of RNAV routes and operational procedures that will permit navigation in any area within the radiation volume of ground-based very high frequency omnidirectional radio range (VOR) navigation facilities rather than only VOR inbound and outbound radial flight procedures as are now used in the present navigation system.

In January 1972, the FAA sponsored an RNAV symposium which highlighted the major operational and technical problem areas that were affecting the immediate implementation and acceptance of RNAV. Based on the intense interest evidenced during the symposium, an FAA/Industry Task Force was established to define how to implement RNAV in the National Airspace System (NAS) in an orderly manner, while at the same time, identifying the payoffs to the ATC system and users. A report entitled, "Application of Area Navigation in the National Airspace System," was published in February 1973 and defined the way RNAV would be implemented in the NAS. It also detailed an action plan which included substantial research and development efforts. This report covers a portion of the action plan, and deals with the 2D RNAV flight test data only. Further reports will cover other aspects of the overall action plan.

DESCRIPTION OF EQUIPMENT.

RNAV SYSTEM. The RNAV system selected for these tests is commercially available and considered representative of the RNAV systems available to general aviation. The system is manufactured by Air Data, Incorporated, Columbus, Ohio, and is designated the AD611 system. The system may be installed with either an "Alpha" or "Delta" type steering indication. The Alpha steering is identical to VOR steering, such that full deflection of the radio deviation indicator (RDI) needle is $\pm 10°$ enroute. With Alpha steering, the steering becomes more sensitive to offcourse positions as the aircraft is flown nearer the waypoint.

Delta steering provides a constant linear course width regardless of the distance to a waypoint. With this steering mode, full RDI deflection represents ± 5 nautical miles (nmi). An approach sensitivity setting provides for ± 1.25-nmi full-scale sensitivity. Delta steering was selected for these tests.

The AD611/D RNAV system consists of the following components:

1. RNAV Computer, 61RNC/D, contains the computing and signal conditioning elements of the system.

2. System Interface Unit, 61SIU/D, provides the interfacing of the RNAV computer to the navigation indicator and aircraft power.

3. Digital Range and Mode Control, 61DRM, displays the distance to waypoint (DTW) and bearing to waypoint (BTW) and contains system monitoring diagnostic annunciators. The "RNAV" pushbutton is an ON/OFF lighted button which engages computer operation and transfers the navigation mode from VOR/localizer or RNAV.

4. Waypoint Setter, 61WPS, provides eight digital thumbwheels for selecting a waypoint address defined in degrees and miles to the nearest tenths. It also contains a "WAYPOINT SELECT" pushbutton.

For flight tests in the National Aviation Facilities Experimental Center (NAFEC) Aero Commander 680, two additional waypoint selectors have been added to the basic AD611/D system. Figure 1 provides a brief description of the signal path of the basic RNAV system and associated sensors.

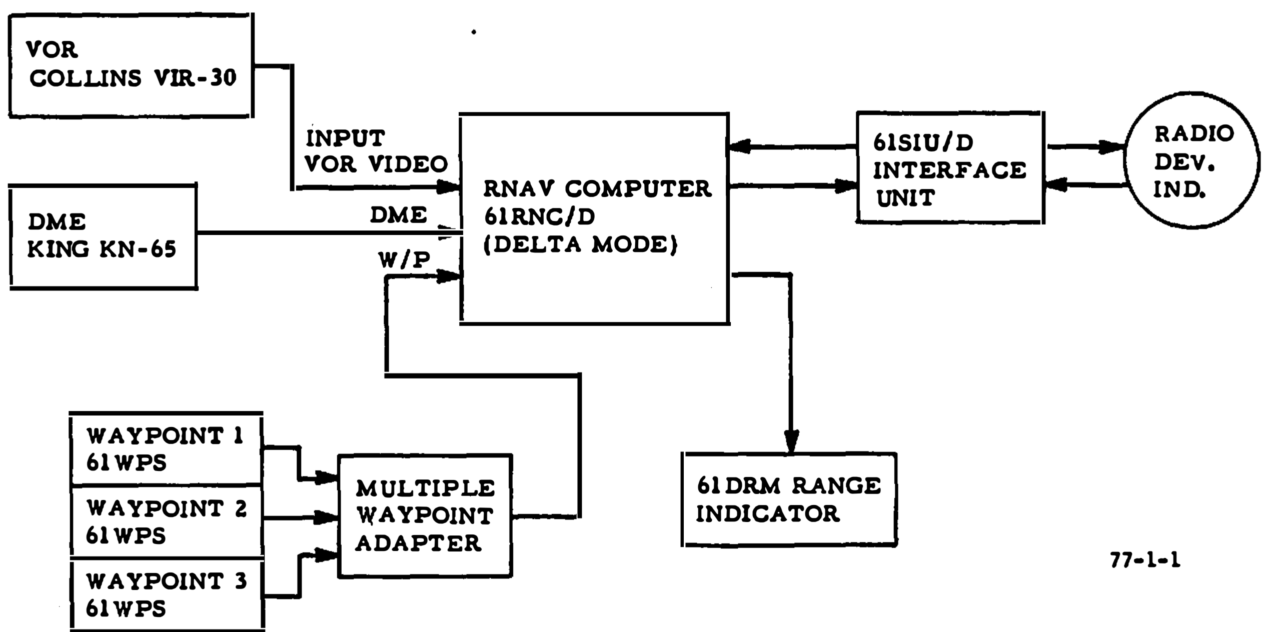


FIGURE 1. RNAV SYSTEM INTERCONNECT

ANCILLARY EQUIPMENTS. The following ancillary equipments were used with the basic AD611/D RNAV system:

Navigation Receiver--Collins VIR-30.

Distance Measuring Equipment (DME)--King KN-65 modified with range block interface adapter per Air Data Installation Bulletin IB-73006.

Flight Director System--Sperry HZ-444 Horizon Flight Director Indicator, RD-444 Radio Deviation Indicator (RDI), and ZC-200 Flight Director Computer/Controller.

Figure 2 shows the installation of the RNAV system and flight director in the test aircraft, an Aero Commander 680. This aircraft is a light twin-engine aircraft with a cruise speed of 160 knots indicated airspeed (IAS).

DISCUSSION

FLIGHT TEST OBJECTIVES.

The flight test objectives, using this RNAV system, were defined in the NAFEC product plan to be:

1. Quantify RNAV system errors using VOR/DME radio navigation.

2. Define the required protected airspace.

3. Quantify flight technical error (FTE).

4. Investigate the minimum waypoint storage capability for terminal operations.

5. Examine various RNAV operational maneuvers.

6. Examine the effects of turn anticipation.

ROUTE STRUCTURES.

All RNAV tests were flown within a 45-nmi radius of NAFEC in that airspace which falls within the jurisdiction of Atlantic City Tower, McGuire Radar Approach Control (RAPCON), and Dover RAPCON. All RNAV landings and takeoffs were made at the NAFEC Airport (ACY), Atlantic City, New Jersey.

Four different RNAV routes were designed for this series of 2D flight tests. One of these routes was used for pilot training and RNAV orientation. Three routes, A1, A2, and A6, were used for data flights and are shown in figures 3 through 5. Each route, including the orientation route, provided a standard instrument departure (SID), a route leg to transition to a standard terminal arrival route (STAR), and a STAR to an assigned runway. Figure 6 shows the approach plates used for routes A1 and A2.

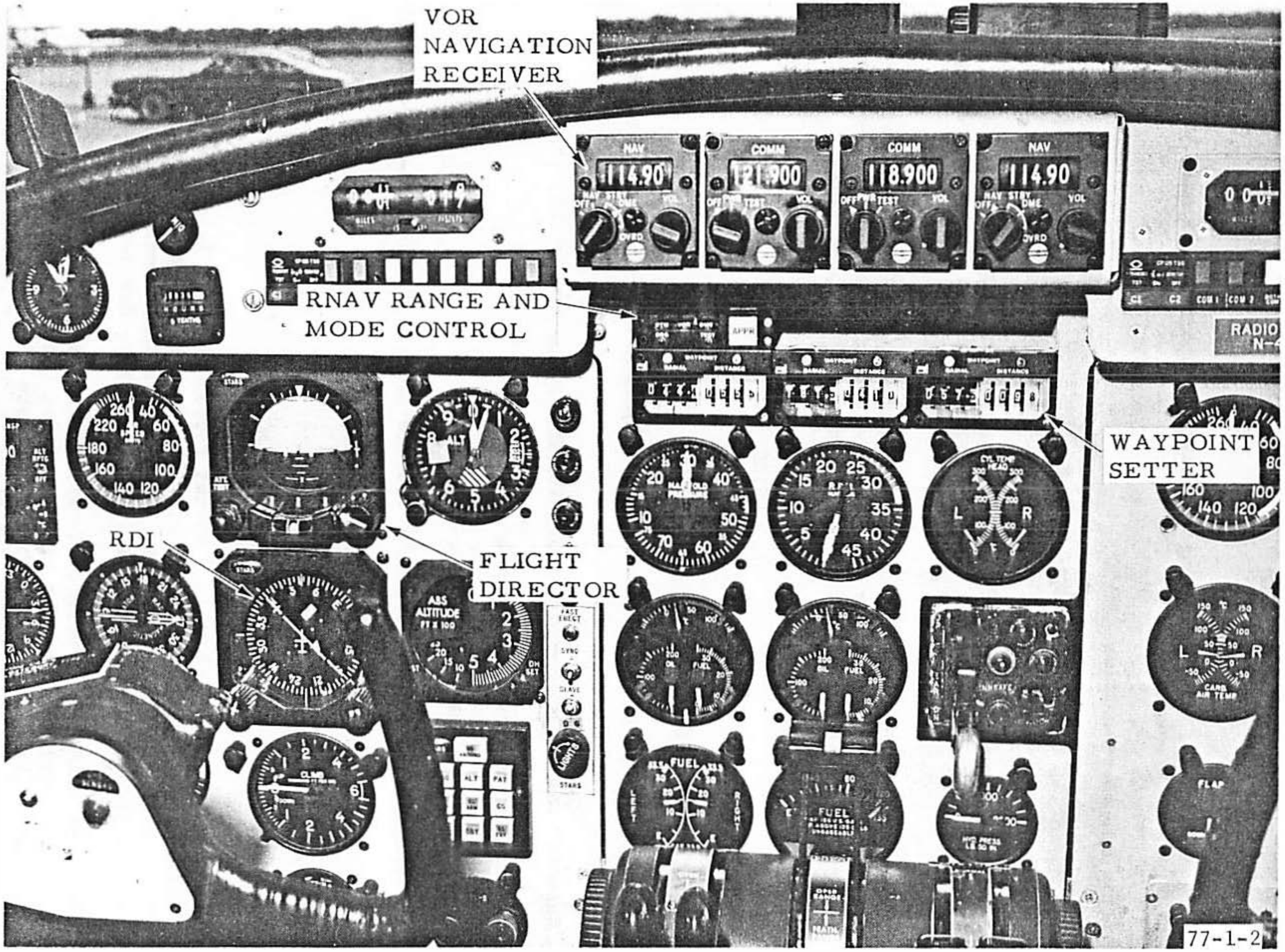
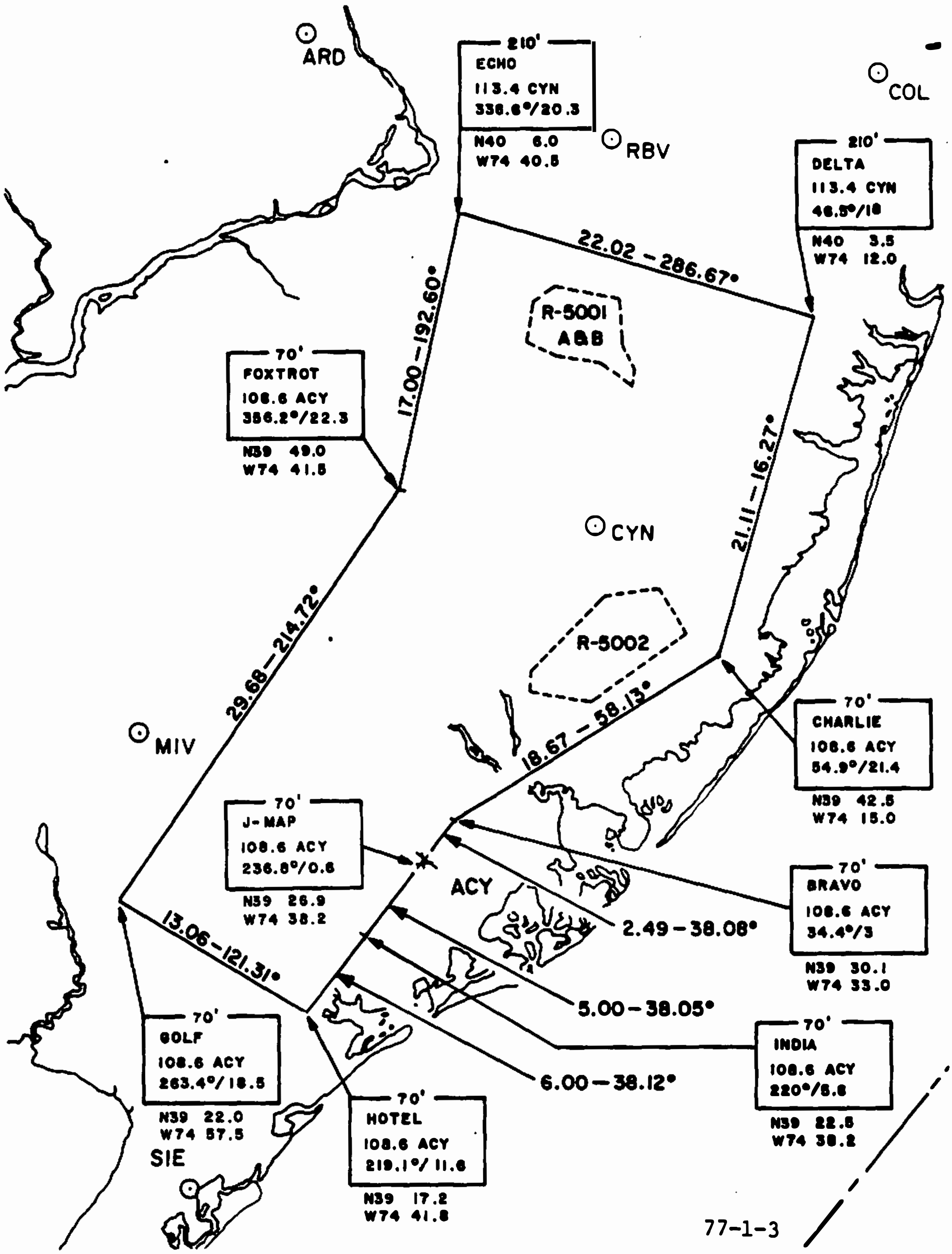


FIGURE 2. RNAV SYSTEM INSTALLATION



77-1-3

FIGURE 3. TEST ROUTE A1

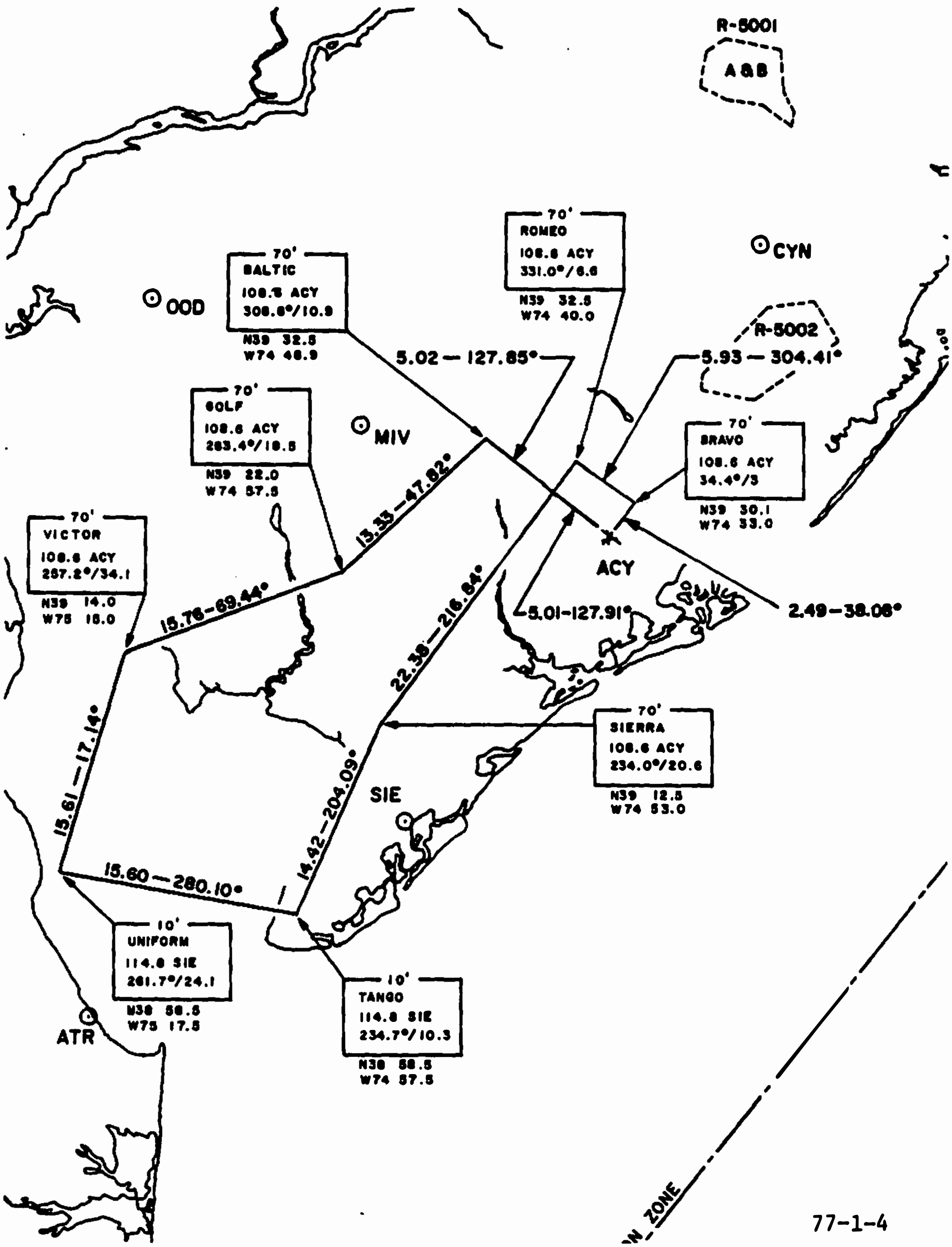
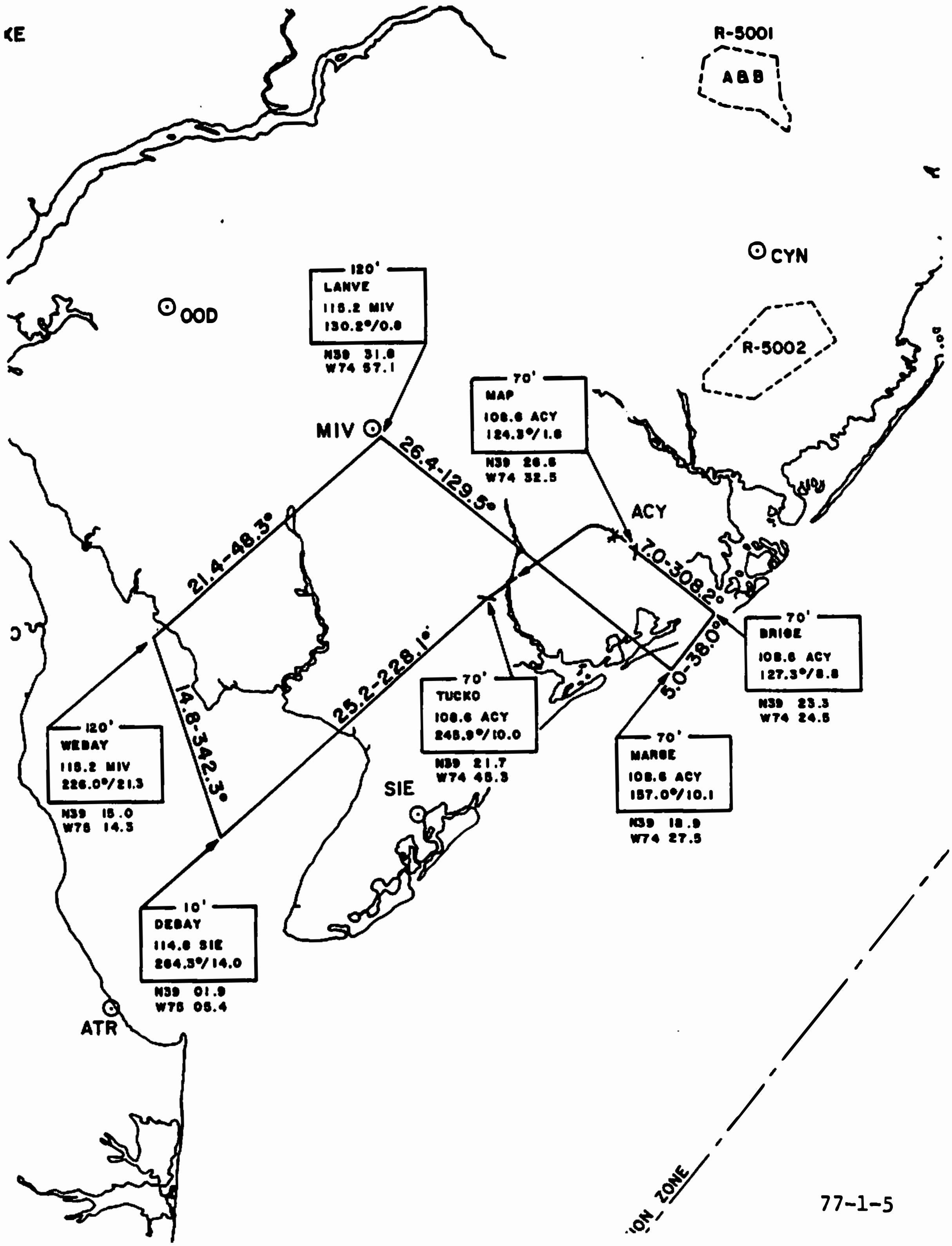
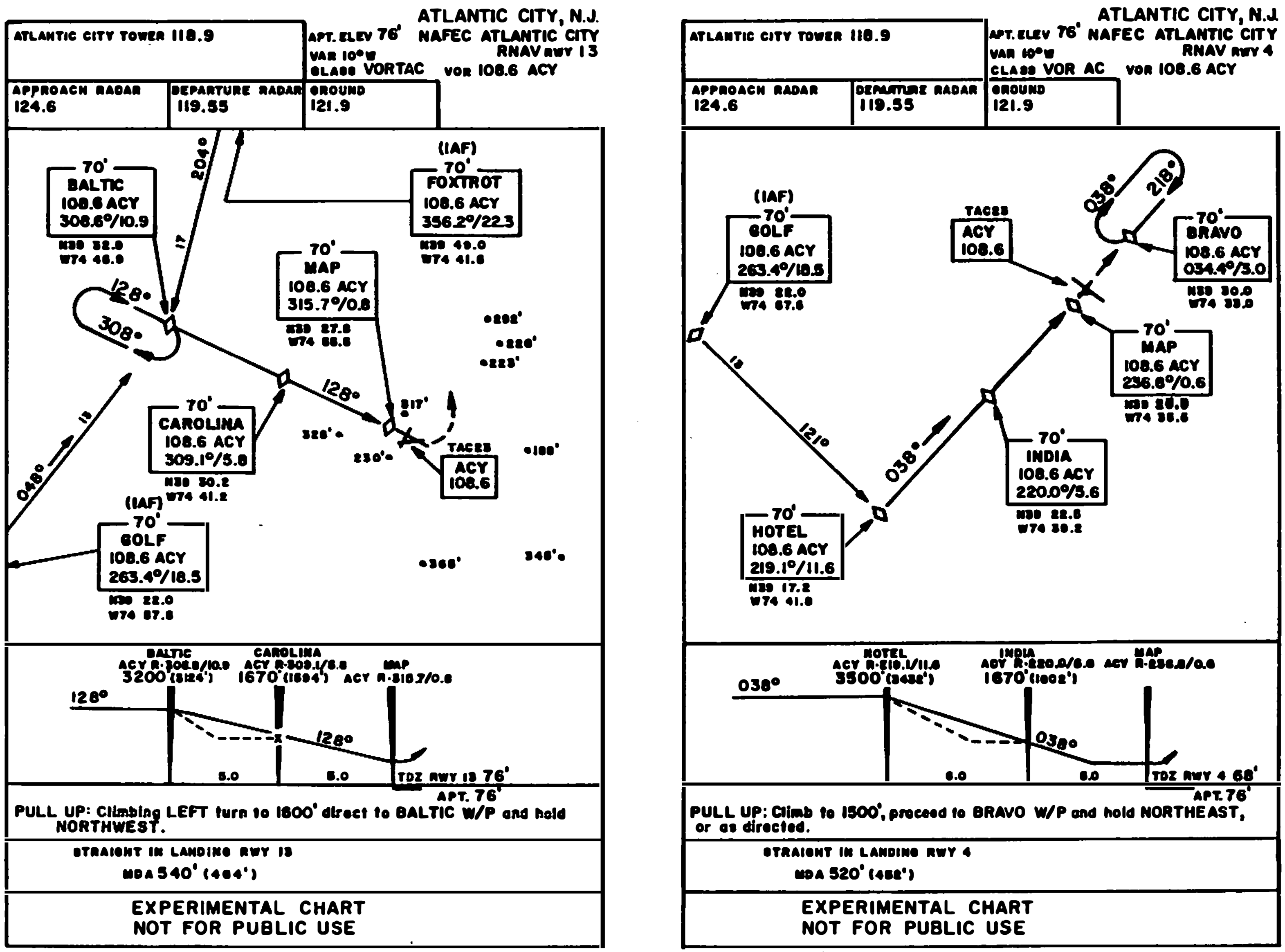


FIGURE 4. TEST ROUTE A2



77-1-5

FIGURE 5. TEST ROUTE A6



77-1-6

FIGURE 6. RNAV APPROACH PLATES FOR NAFEC RUNWAYS 4 AND 13

Routes A1 and A2 were used in previous flight tests conducted at NAFEC by Champlain Technology Incorporated (CTI) for RNAV baseline studies. These route geometries were developed by CTI and can be correlated data-wise to the routes used in a realtime 2D RNAV simulation done earlier at NAFEC (report No. FAA-RD-74-209, "Preliminary Two-Dimensional Area Navigation Terminal Simulation"). The A6 route geometry was designed at NAFEC to test those operational parameters not applicable in the other two routes.

SCENARIOS.

Route deviations were required to exercise RNAV system capabilities and experiment with various operational procedures. This was accomplished by use of scenarios which were designed for each route. The airborne observer was responsible for providing each pilot with the desired scenario event at the proper time. A scenario example is provided in figure 7. The operational maneuvers that were included in the scenarios are:

1. Parallel Offset is executed by the pilot making a turn of approximately 45° left or right of the route course set on the Omni Bearing Selector (OBS), flying this ±45° heading until reaching the desired offset distance, then flying parallel to the parent course. Since the RNAV system flown did not have a parallel offset function, the offset was established and maintained by decentering the course deviation needle on the RDI. Full RDI needle deflection with the RNAV system flown represents ±5 nmi in the enroute mode and ±1.25 nmi in the approach mode. With a two-dot full-scale RDI deflection, the crosstrack gradient would be ±2.5 nmi/dot in the enroute mode and ±0.63 nmi/dot in the approach mode. This limited the maximum practical offset to about ±4 nmi in the enroute mode.

Upon reaching the desired offset distance, the pilot turns back to the desired track heading of the parent course. The pilot is now flying parallel to the parent course and maintains the offset by keeping the RDI needle positioned at the proper lateral deflection for that distance. To cancel the offset, the pilot turns approximately 45° back to the parent course and holds that heading until the RDI needle returns to the center position. The pilot then turns to the course set in the OBS. It is good practice to lead each turn to prevent an overshoot. This maneuver can be used in lieu of a radar vector.

2. Direct to Waypoint is executed by using either of two methods. One method is to have the pilot select the waypoint coordinates toward which he is required to fly and then turn his OBS until the lateral deviation is zero (centered). This establishes a new OBS course that can be followed to the desired waypoint. The other method is to use the AD611/D Digital Range and Mode Control (61DRM) unit to obtain a reading of the present bearing-to-new-waypoint. The OBS is then set to this new bearing which can be followed direct to the desired waypoint. This maneuver is used for other than normal waypoint-to-waypoint RNAV.

ROUTE A6 FOR RUNWAY 31 - SCENARIO 3

PREFLIGHT:

1. Mode: Use the Radio Deviation Indicator (RDI) or the full Flight Director System as specified for subject pilot in table 2.

2. RNAV SID: ATLANTIC CITY TWO RNAV DEPARTURE TO DEBAY; maintain 5,000 feet. Cross TUCKO at, or below 4,000 feet. Maintain runway heading until reaching 1,000 feet (or as directed by ATC) before proceeding direct to TUCKO.

IN-FLIGHT:

3. RNAV STAR: At no later than the 5 nmi Distance-To-Waypoint (DTW) DEBAY, clear N-50 for a NAFEC TWO RNAV ARRIVAL to Runway 31, via DEBAY direct WEBAY. Maintain 5,000 feet to the 8 nmi DTW MARGE.

4. Offset: At the 21-nmi DTW MARGE offset left 3 nmi; at the 13-nmi DTW MARGE cancel offset.

5. Extended Downwind Leg: Prior to MARGE, instruct N-50 to extend his downwind leg 5 nmi for spacing.

6. Approach: When 3 nmi past MARGE, instruct N-50 to proceed direct to BRIGE; cleared for an RNAV approach to Runway 31 after passing BRIGE.

FIGURE 7. TYPICAL TEST ROUTE SCENARIO

3. Delay Fan is executed for these tests by making a left or right offset to a requested distance (up to 4 nmi) and, upon reaching that distance, executing a direct-to-waypoint maneuver. ATC can instruct the pilot to proceed to the next waypoint at any time prior to reaching the offset distance. ATC can cancel the offset in the same manner and instruct the pilot to return to the parent course. ATC can also instruct the pilot to increase the offset distance at any time prior to reaching the initial offset distance or prior to the pilot starting the direct-to-waypoint maneuver.

4. Extended Downwind Leg is executed in these tests by continuing on the same OBS course downwind past the base-leg turn waypoint until reaching the required distance, then executing a direct-to-waypoint maneuver to the final approach fix waypoint. When the pilot proceeds past the base-leg turn waypoint, the RDI will display a "FROM" indication. The distance-to-waypoint (DTW) display on the AD611/D range mode unit will continually display an increase in distance from the waypoint instead of a decrease. ATC can instruct the pilot to proceed direct to the final approach fix at any time prior to reaching the initial distance. ATC can instruct the pilot to increase the downwind distance at any time prior to the direct-to-waypoint maneuver.

5. Turn Anticipation is executed by starting a turn to the next course prior to reaching the upcoming waypoint by using a speed/distance scale recommended in Advisory Circular (AC) 90-45A. It is recommended that the pilot lead a turn by 1 nmi per 100 knots true airspeed (TAS). This procedure was recommended to the subject pilots, but was not a mandatory requirement.

6. Distance-to-Waypoint Climb/Descent is executed by using the DTW RNAV display readout in lieu of a waypoint to begin a climb or a descent. Those subject pilots using one- or two-waypoint capability were given the option of using DTW information for a final approach descent to a missed approach point (MAP) fix in place of the final approach waypoint (INDIA and CAROLINA on the approach plates). DTW information was used as called for in the scenarios.

SUBJECT PILOT SELECTION AND TRAINING.

Twelve multiengine-rated subject pilots were selected on the basis of their instrument flying experience. All were instrument flight rule (IFR) rated. These pilots were divided into two groups of six. Those six pilots who had 300 hours or less total instrument experience (including cockpit simulator) were designated as group A. The remaining six pilots had over 300 hours total instrument experience (including cockpit simulator) and were designated as group B. Table 1 provides a brief pilot experience level summary on each subject at the time of their selection for these tests.

In preparation for the data flights, each pilot was given a 2-hour briefing on the flight test objectives, the AD611/D system, the pilot assignments, and training requirements. Each pilot was given an AD611/D operations manual and copies of the four routes that they would fly for orientation and for data flights.

TABLE 1. SUBJECT PILOT EXPERIENCE

Total Times in Hours (Including Simulator)

Pilots	Flight	Instrument (Sim)	Multiengine	RNAV
Group A				
1	2,117.3	47.4(148.5)	788.4	3
2	1,620	180(5)	16.0	0
3	401.6	27.2(50)	20.9	0
4	500	81(0)	11	0
5	1,560	150(30)	260	3
6	1,500+	200(2)	250	0
Group B				
7	6,000+	2,000(300)	5,000	0
8	5,000+	200(200)	500	0
9	4,400+	175(150)	240	20
10	3,500+	200(107)	1,950	0
11	18,000+	800(400)	17,000	0
12	11,040	797(260)	4,666	0

Five of the subjects in group A had no piloting experience in the Aero Commander (AC680). These five were given from 1 to 2 hours of flight training in the AC680 to familiarize them with its flight handling characteristics. Additional aircraft familiarization was gained during the RNAV orientation flights.

According to the flight test requirements, three pilots from each group were assigned to fly their tests using the aircraft's full flight director system capability, while the remaining three pilots used only the RDI. Instruction on the Sperry flight director system was required for the three group A pilots. A Sperry flight director system operation manual was provided for each of these pilots for study before hands-on training began. Prior to data flight tests, the three pilots received approximately 3 hours of hands-on flight director instruction including that time during the orientation flights.

The NAFEC project safety pilot provided the flight director instruction as well as the AC680 flight instruction for those pilots in group A. This type instruction was not needed for the group B pilots.

Each pilot in both groups was required to fly a minimum of two RNAV orientation (two SID and two STAR patterns) flights in preparation for the three data flights. By the end of the orientation flights, each pilot had performed, at least once, all of the route deviation events that would be encountered during the data flights. Before each orientation flight, the pilots were given a briefing regarding these flights, and hands-on instruction was provided on their use of the AD611/D system. The orientation flights were started after each subject pilot acknowledged that he was ready.

Each orientation flight required approximately 1 hour flight time. During the first flight, each pilot was led through the required events for each RNAV leg, step by step. Each pilot was promptly corrected when a mistake was made, including an explanation of what occurred, as time permitted. There was a pilot debriefing after the flight and an informal discussion on events of the flight. The same training procedures were used for the second orientation flight, except the subject pilot was allowed more freedom and time to discover and correct his mistakes on his own. Based on previous flight tests and simulator experiments, it was felt that this was the minimum amount of training required. Additional orientation flights were made if the subject pilot felt he was not prepared for the data flights or if the project safety pilot indicated it was necessary. One subject pilot, at his request, was given an additional orientation flight. Table 2 provides a list of the subject flight test assignments.

TEST CONDITIONS.

The following test conditions were established to assure as much operational test validity as possible without causing undue flight test delays and endangering the completion of these tests:

1. All flights were made using IFR regulations.

2. IFR flight plans were filed for each flight.

3. All flights adhered to the FAA rules and regulations established by ATC.

4. All flights were restricted to that terminal enroute airspace controlled by the Atlantic City Tower/Terminal Radar Approach Control Facility (TRACON), McGuire RAPCON, and Dover RAPCON.

5. Approval to fly the RNAV orientation routes and the three RNAV data routes in IFR conditions was received after local procedures were established with Atlantic City Tower TRACON, McGuire RAPCON, and Dover RAPCON.

6. Because none of group A pilots' flights were check rated in the AC680, the safety pilot was permitted, at his discretion, to control the throttle settings, prop pitch, flaps, and landing gear, but not the aircraft navigation or radio communications.

7. The safety pilot was permitted to take over full control of the aircraft only for safety reasons.

8. Due to the difficulty of providing a satisfactory cockpit IFR hood while flying in visual flight rules (VFR) weather conditions, only the final approach course was fully blocked from each subject pilot, thus providing an extra pair of eyes to look out for other aircraft.

9. All pilots were required to make their final approach to the runway in RNAV approach mode. (Approach RDI lateral sensitivity is 0.6 nmi/dot.)

TABLE 2. FLIGHT TEST ASSIGNMENTS

Subject Pilots	Pilot Navigation Indicators		Orientation Flights	Waypoint Capability		
Group A	Flight Director System	RDI Only	Number of	1WP	2WP	3WP
1	X		3	A1 A2 A6		
2		X	2		A2 A1 A6	
3	X		2			A6 A2 A1
4		X	2	A6 A1 A2		
5	X		2		A1 A6 A2	
6		X	2			A1 A6 A2
Group B						
7	X		2	A1 A2 A6		
8		X	2		A2 A1 A6	
9	X		2			A6 A2 A1
10		X	2	A6 A1 A2		
11	X		2		A1 A6 A2	
12		X	2			A1 A6 A2

DATA COLLECTION.

Initially, each flight produced two digital data tapes. The first tape was the airborne tape which contained all pertinent flight data recorded at a 2-hertz (Hz) rate on a digital incremental recorder on the aircraft. The flight data consisted of a mixture of analog, digital, and discrete signals which were conditioned and multiplexed by a data acquisition system designed and fabricated at NAFEC. (A complete list of the signals recorded in this manner is presented in appendix A.) The second tape contained the raw radar tracking data which were derived from NAFEC's Extended Area Instrumentation Radar (EAIR) facility. EAIR is a precision C-band tracking radar which has a maximum tracking distance of 190 nmi when operated in the beacon tracking mode (all flights were tracked in beacon tracking mode). Digital output data consisting of slant range, azimuth angle, elevation angle, and realtime, which were recorded on magnetic tape at a 10-Hz rate.

Analog track data in Z-Y, X-Y coordinates were recorded in realtime on 30-inch plot paper. Accuracy of the system is 0.2 milliradian in azimuth and elevation and a root-mean-square (rms) range error not exceeding 20 yards at 3,000 yard/second range rate.

DATA PROCESSING.

The raw radar data tapes from the EAIR facility were first processed on the International Business Machine (IBM) 7090 to generate a seven-track, 556 bits per inch (bpi) IBM format tape of actual aircraft position in latitude, longitude, and altitude referenced to time. The airborne tapes were dumped on a line printer and visually verified to be usable for the data analysis. The seven-track 200-bpi tape containing the airborne parameters referenced to time was then time merged every 0.5 seconds with the processed EAIR tape. The end product was a nine-track, 800-bpi, binary time-merged data tape containing both airborne and ground-based measurements, time correlated. A quick-look printout routine was then used to further screen the data for validity. A list of the signals on the merged tape is presented in appendix A, table A-1.

The merged tapes were then examined by a program (SEARCH) which checked pertinent aircraft parameters and flags and recorded any detected changes on a printout. Using SEARCH output listings, EAIR plots, merged tape dumps, and observer logs, times were determined for waypoint changes.

Using the merged data tape and the selected times as input, all error values were calculated nominally at 0.1-nmi increments along the route. These calculated error values, error validity flags, and the data for that sample were outputted to a seven-track 800-bpi parameter tape. In addition, each parameter tape had a header on it which identified the pattern flown, pilot, copilot, date, and flight number. Each record on the parameter tape was further identified by a segment code and a distance to waypoint. This made it possible to identify and retrieve information from any point on the run. Table A-2 in appendix A provides a list of the values calculated. The parameters listed in tables A-1 and A-2 of appendix A are therefore placed on the parameter tape in 0.1-nmi increments.

Finally, the parameter tapes were dumped on a line printer. This output together with EAIR plots, SEARCH output, and observer logs, was examined to determine start and stop times which bracketed the discrete segments which made up the test pattern. These start and stop times were then used to extract segmental data from the parameter tapes for statistical analysis.

TYPICAL TEST FLIGHT PATTERNS.

Figures 8 through 13 are photoreductions of the tracking radar realtime plots for some of the test flights which would be considered typical. These figures include samples of the three different patterns flown as well as the various test configurations used.

DATA ANALYSIS METHODOLOGY

In analyzing the flight test data collected during these tests, the sources of possible errors were first identified. This is the same procedure as indicated in appendix C of Advisory Circular 90-45A, dated February 21, 1975. For the horizontal case, there are three errors considered to be components of total system error. However, prior experience has shown that errors associated with the selection of the desired course using the OBS contribute significantly to the total system error. Therefore, the following errors were considered:

1. Sensor Error (VDCT). This is the error contributed by the ground and airborne sensor elements of VOR and DME.

2. Computer Error (CPCT). This error includes the error contributed by the RNAV input/output signal conversion equipment and by the computational elements of the RNAV equipment.

3. Flight Technical Error (FTE). This error term is a measure of the accuracy with which the pilot controls the aircraft with respect to the commanded position on the displays.

4. OBS Errors (OBSN). This is the error due to any deviation of the actual OBS setting from the desired setting. It encompasses errors which are human, mechanical, and electrical in nature.

5. Total System Crosstrack Error (TSCT). This is the measure of the difference between the desired position and actual position of the aircraft.

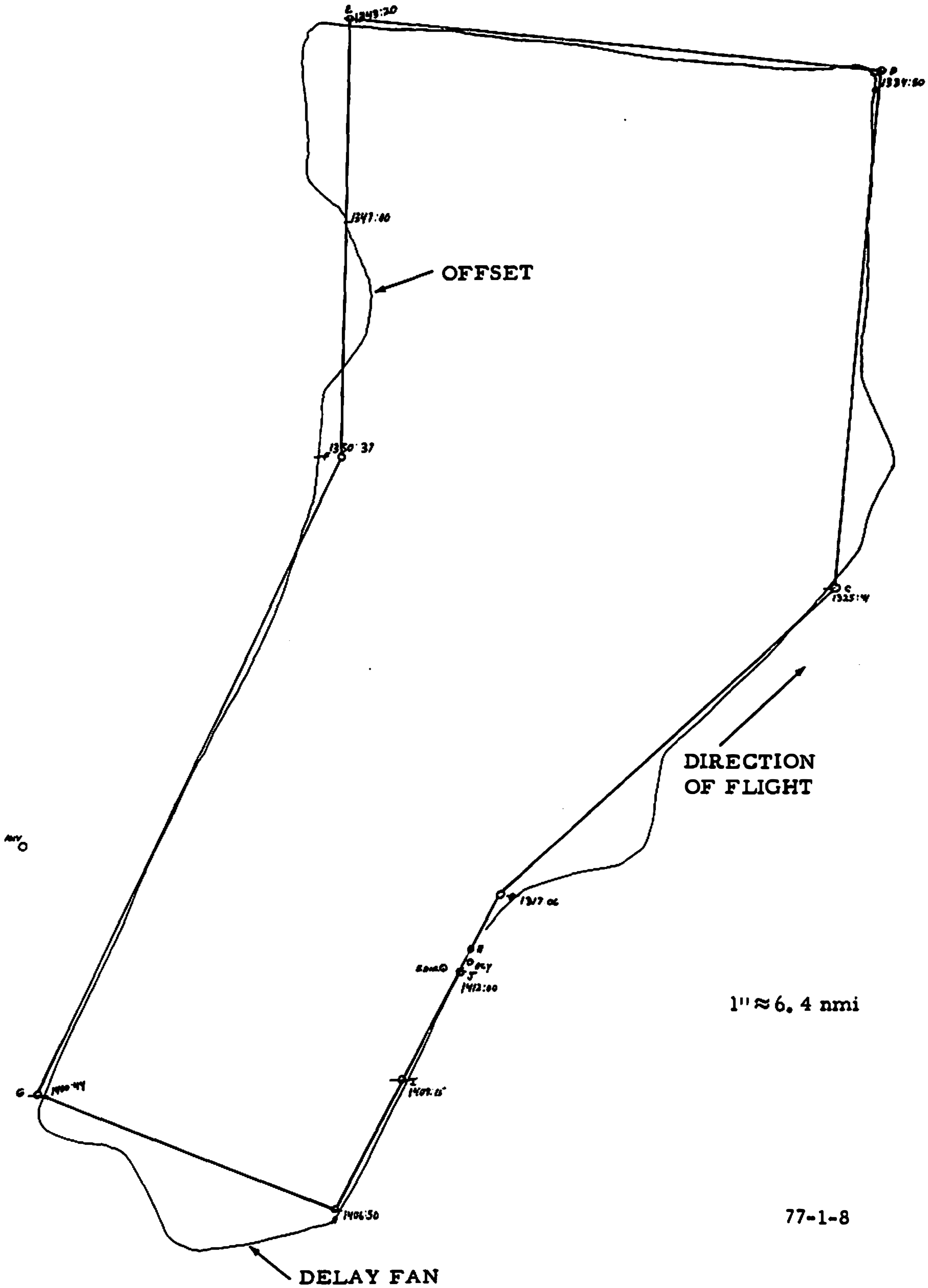


FIGURE 8. TYPICAL FLIGHT TEST PATTERN FOR TEST ROUTE A1 USING RDI GUIDANCE WITH THREE WAYPOINTS

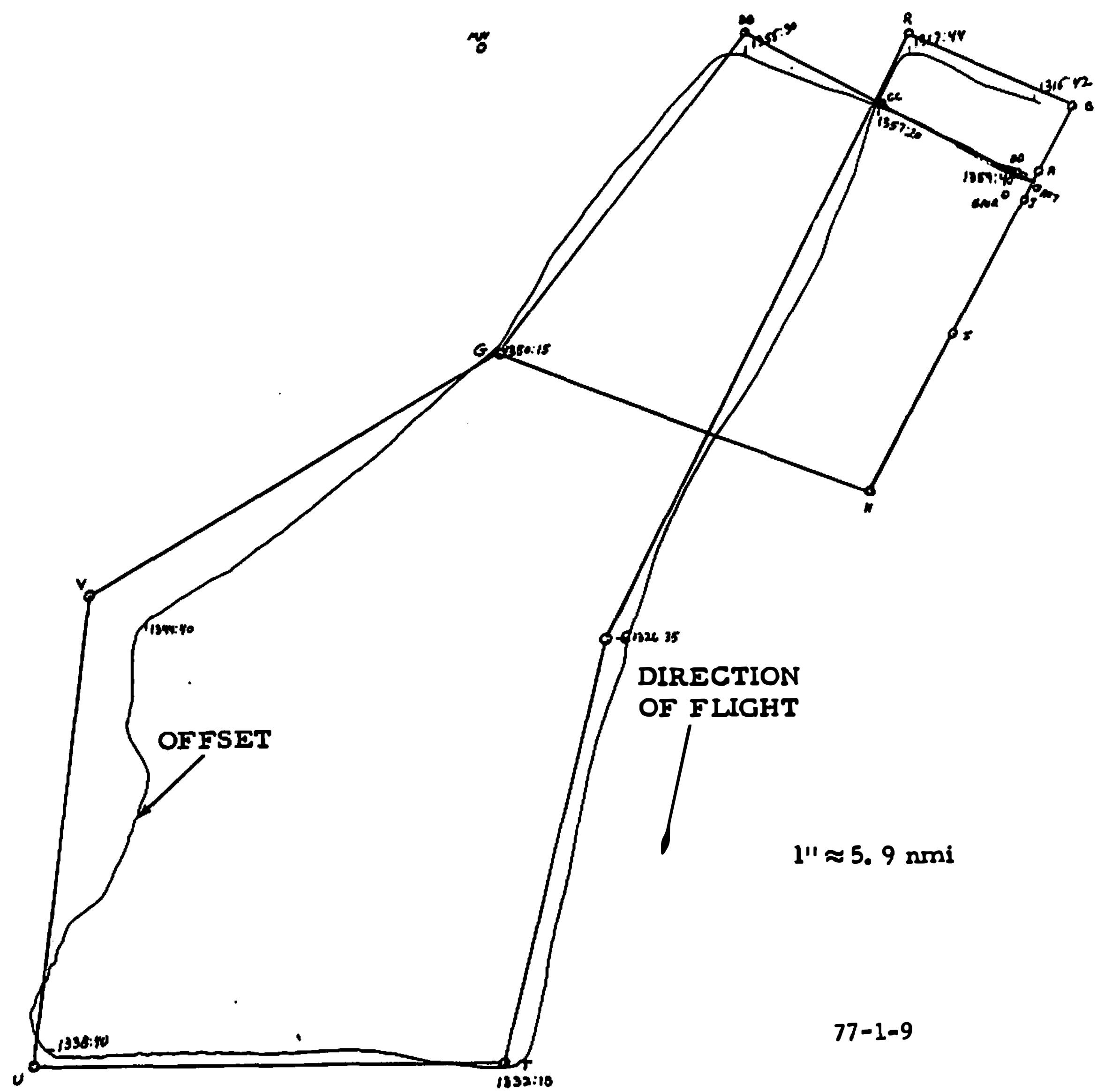
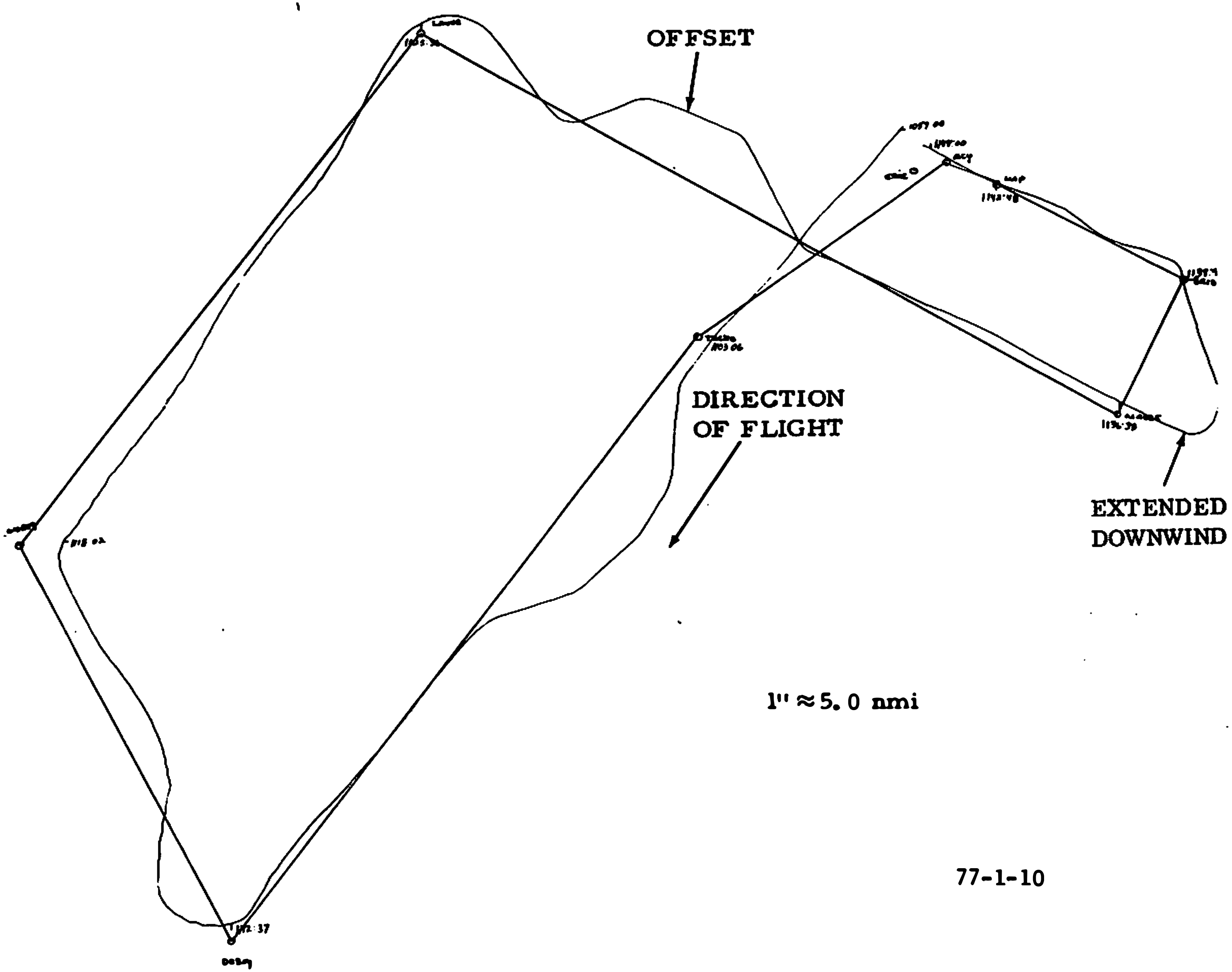


FIGURE 9. TYPICAL FLIGHT TEST PATTERN FOR TEST ROUTE A2 USING RDI GUIDANCE WITH TWO WAYPOINTS



77-1-10

FIGURE 10. TYPICAL FLIGHT TEST PATTERN FOR TEST ROUTE A6 USING RDI GUIDANCE WITH ONE WAYPOINT

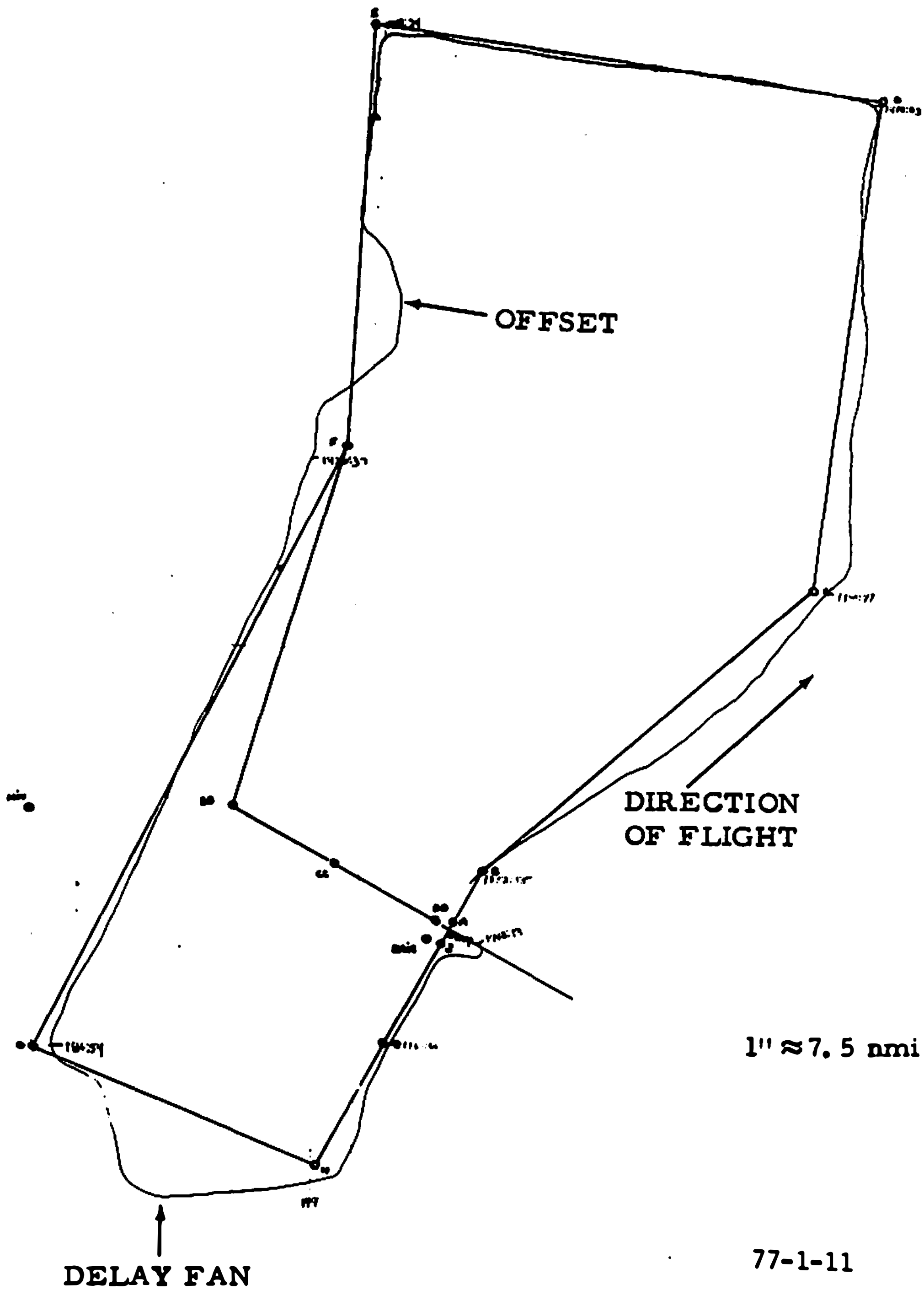


FIGURE 11. TYPICAL FLIGHT TEST PATTERN FOR TEST ROUTE A1 USING FLIGHT DIRECTOR GUIDANCE WITH TWO WAYPOINTS

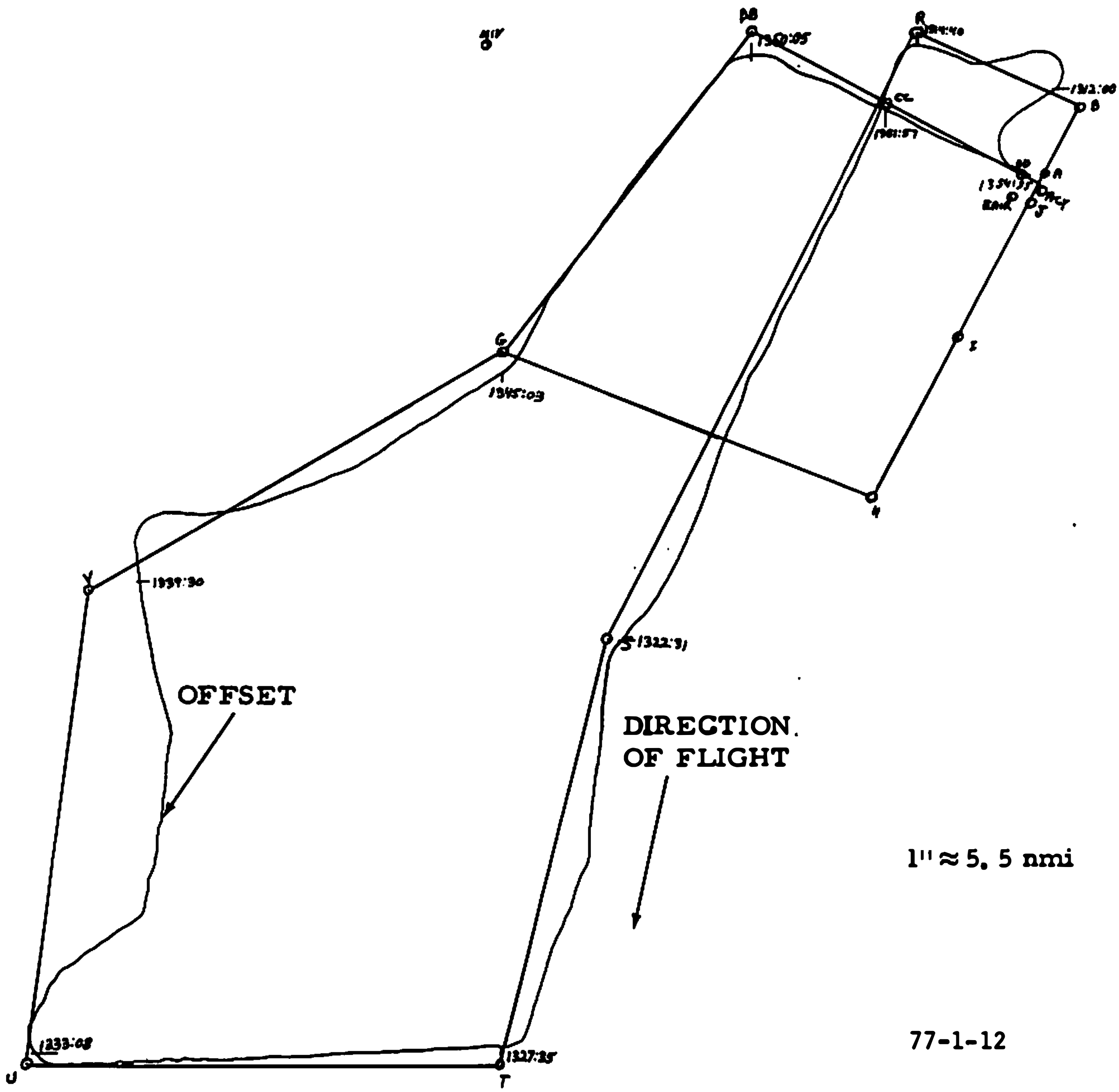


FIGURE 12. TYPICAL FLIGHT TEST PATTERN FOR TEST ROUTE A2 USING FLIGHT DIRECTOR GUIDANCE WITH THREE WAYPOINTS

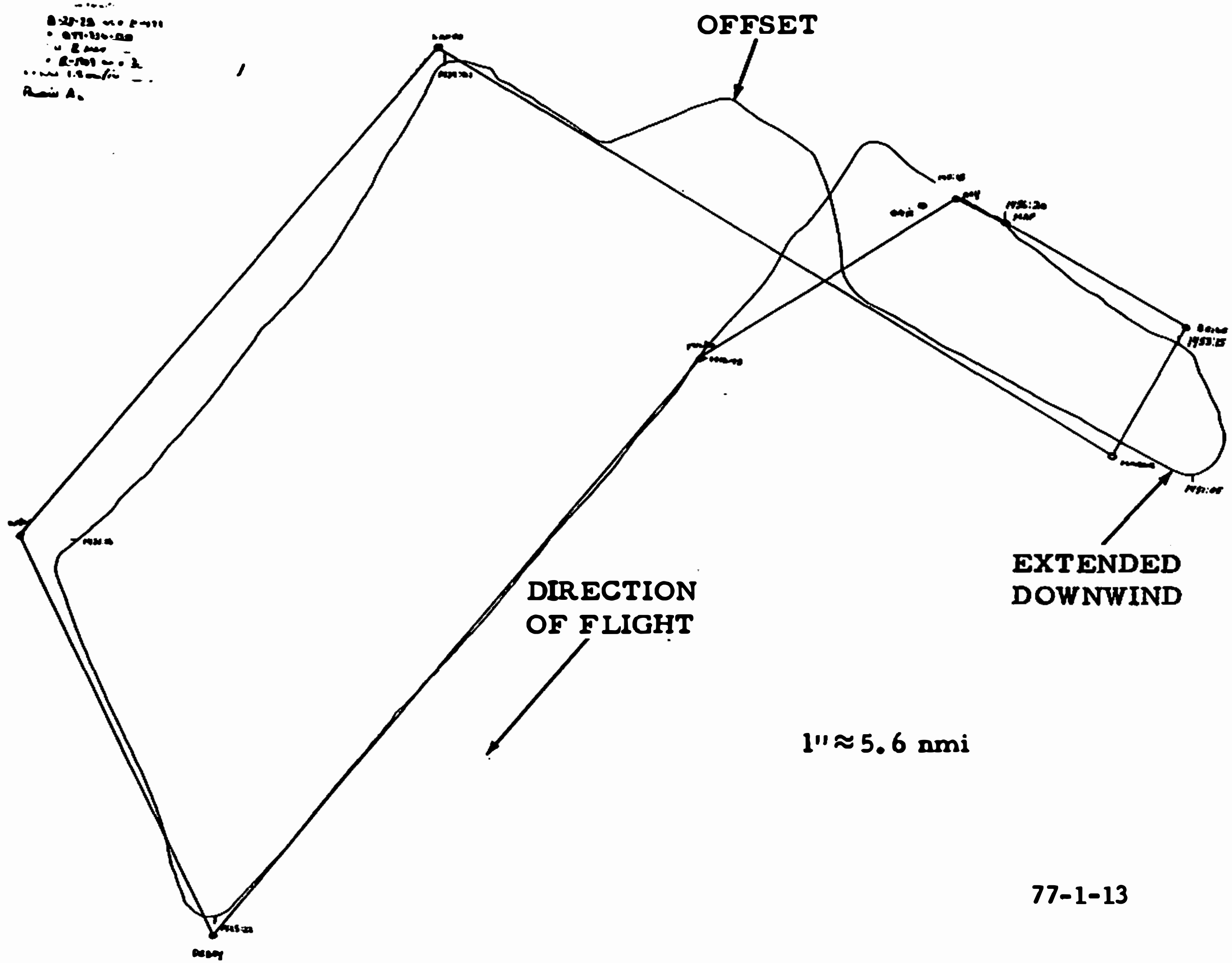


FIGURE 13. TYPICAL FLIGHT TEST PATTERNS FOR TEST ROUTE A6 USING FLIGHT DIRECTOR GUIDANCE WITH ONE WAYPOINT

These error elements in determining aircraft position in space combine as shown in the error paradigm of figure 14 to form total system crosstrack error. Details of error calculations are contained in appendix A.

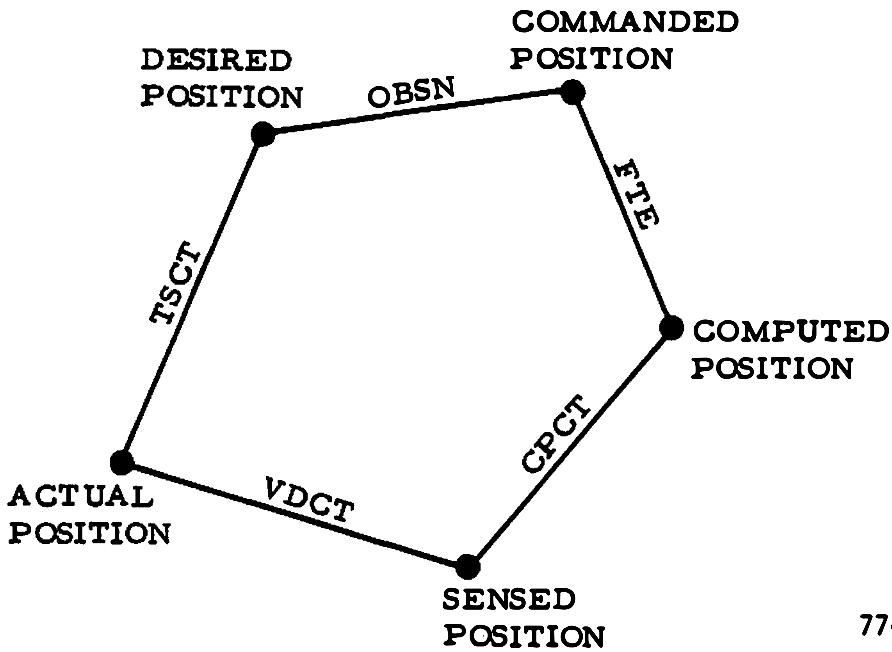


FIGURE 14. TOTAL SYSTEM ERROR PARADIGM

One very important error term that is not included in this error budget is the blunder. Blunders are gross human errors that can be caused by poor judgment, inattentiveness, or improper system operation caused by erroneous pilot inputs.

The blunder tendency is an extremely important consideration with respect to airspace and system design, but it should be considered separately from the error budget concept, since it cannot be treated statistically. The following discussions are intended to provide a greater insight into the guidelines which were established for the treatment of the five error components.

VOR AND DME SENSOR ERRORS.

The recorded VOR bearing and DME distance were used to compute sensor errors. This was done by first correcting the VOR bearing for the magnetic variation of the tuned station to give true bearing. The DME distance was converted to ground range by using the aircraft barometric altitude and station elevation. Then, utilizing the true bearing and ground range together with the latitude and longitude of the tuned station, a "sensed" aircraft position was computed. This VOR/DME position was compared to the actual radar tracking position as determined by the EAIR. These differences, oriented on a latitude-longitude coordinate system, were transformed to a coordinate system oriented to the desired track. The new values were the sensor crosstrack (VDCT) and the sensor along-track error (VDAT). These errors were considered valid for analysis whenever valid flags were asserted.

RNAV COMPUTER ERRORS.

The AD611 presents aircraft position information as a magnetic bearing to waypoint (BTW), and a distance to waypoint (DTW). By correcting the BTW for magnetic variation and converting BTW to a true bearing, the BTW and DTW may be converted to a latitude and longitude which represents the aircraft position as calculated by the RNAV computer. The RNAV computer position was compared to the sensed position (VOR/DME) and then rotated from the latitude-longitude coordinate system to a coordinate system oriented along the desired track. After rotation, these differences in position were the computer along-track error (CPAT) and computer crosstrack error (CPCT).

Computer errors were considered valid for the analysis whenever the correct waypoint coordinates were selected and valid sensor flags and a valid RNAV computer status were asserted.

FLIGHT TECHNICAL ERRORS.

Flight technical error (FTE) is a measure of the pilot's ability to fly the commanded track. Therefore, the crosstrack information which was presented to the pilot on the RDI was recorded directly as a voltage and scaled appropriately (FTE=RDI deflection times scale factor). This was the value used for all subsequent analyses involving crosstrack distances. As will be mentioned in the OBS error discussion, this would not be a true crosstrack distance, due to any rotation of the commanded track with respect to the desired track. However, this choice provides an adequate measure of the human factor.

To insure that pilot ability was fairly represented, flight technical error was only considered once the pilot had established himself in a steady-state condition on the new track. Each segment was considered on an individual basis. Aircraft parameters were carefully examined along with radar tracking plots and observer logs to determine the portions considered to be valid for the flight technical error analysis. No turn data were included.

OMNI BEARING SELECTOR ERRORS.

The desired track is described by a vector originating at the "FROM" waypoint and terminating at the "TO" waypoint. The bearing defined by this vector is the desired OBS setting or desired track. Any deviation of the OBS setting will rotate the commanded track away from the desired track. This will introduce a crosstrack error, the magnitude of which depends on the angle between the commanded track and the desired track, as well as the distance to the waypoint along the commanded track.

In "Preliminary RNAV Avionics Standards" (Report No. FAA-RD-75-178), for this geometry the OBS crosstrack error is calculated as the product of the distance to waypoint times the angular error.

$$\text{OBS Error} = \text{DTW} \times \alpha \qquad (1)$$

This is an approximation for small angles where sine $\alpha \approx \alpha$, and also, it does not take into account the effect of the added rotation due to flight technical error, which will be negligible except for very large flight technical errors due to blunders.

In figure 15, $|\overline{CD}|$ is the crosstrack error which results when the actual track is rotated from the desired track due to missetting the OBS. The equation to compute true value of this error is

$$|\overline{CD}| = |\overline{DB}| \times \sin \alpha \qquad (2)$$

One must note, however, that F in figure 15 is the aircraft position as presented by the RNAV computer, (and also for purposes of simplification, the aircraft position). Therefore, the DTW presented by the computer is $|\overline{FB}|$. If DTW $|\overline{FB}|$ is substituted into equation 1, it is obvious that the value obtained for OBS error will be different from the true value given by equation 2. The difference between the two results will be proportional to the difference between $|\overline{DB}|$ and $|\overline{FB}|$, and the difference between these two quantities will only be zero when $|\overline{FE}|$ (flight technical error by definition) is zero.

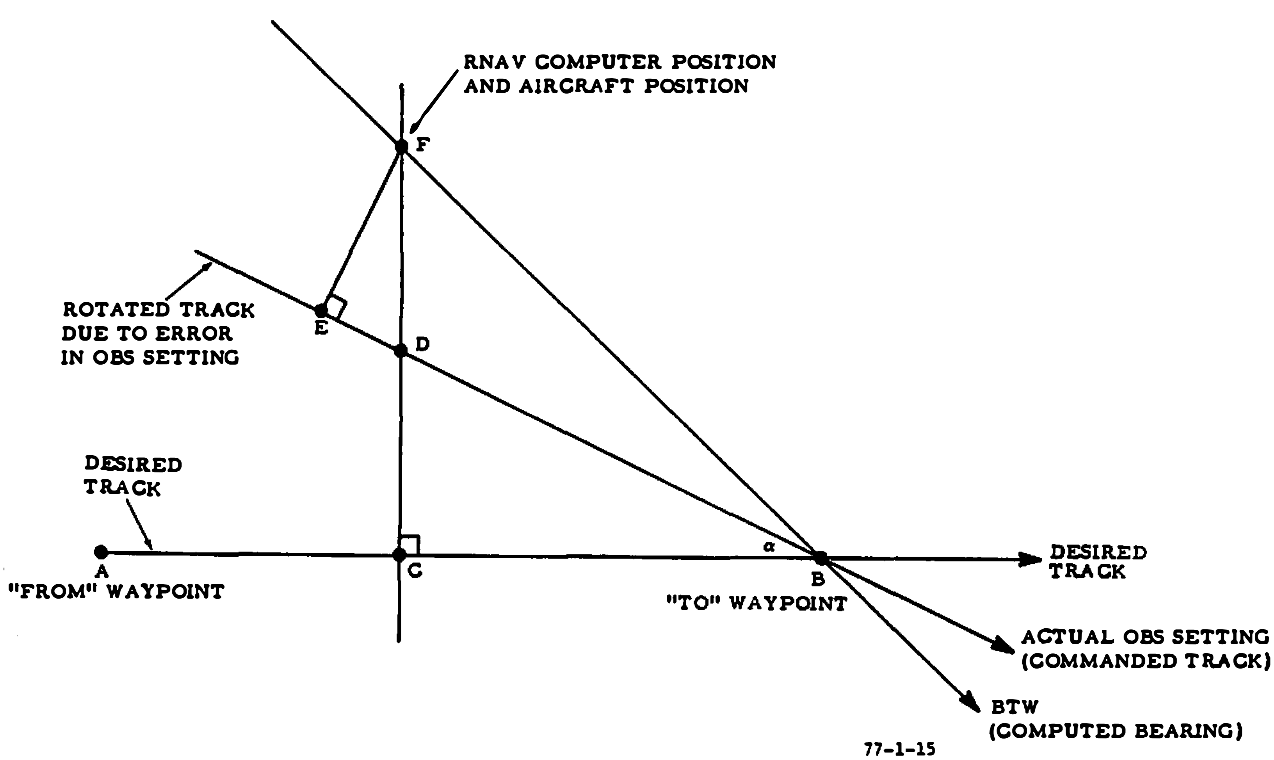


FIGURE 15. ERROR ANALYSIS GEOMETRY

Likewise, there is a difference between the flight technical error FE displayed to the pilot and referenced to the rotated track DB and the flight technical error $|\overline{FD}|$ when referenced to the desired track $|AB|$. It is evident, therefore, that when using a simplified analysis, there will be some interplay and contamination between flight technical error and OBS error.

To give some idea of the magnitude of these errors, typical values were substituted for the orthogonal projection of distance to waypoint (10 nmi), OBS angular error (2.1°), and flight technical error (0.5 nmi). The difference between using equation (1) versus equation (2) to calculate OBS error is about 7 feet. Likewise the difference between flight technical error (referenced to the rotated track) and the flight technical error referenced to the desired track is about 2 feet. For differences of such small magnitude, the interplay between flight technical and OBS error was disregarded.

The original formula utilizing the distance to go, henceforth called DTW, was slightly modified by using the sine of the angular error, rather than the small angle approximation. The modified equation used in this analysis was:

$$OBSN = DTW \times SIN(\alpha) \qquad (3)$$
$$\alpha = \text{ACTUAL OBS ANGLE} - \text{DESIRED TRACK ANGLE}$$

OBS errors were analyzed over all of the route, except when the pilot was in the act of resetting the OBS. Any deviation greater than 15° was rejected as a pilot blunder.

TOTAL SYSTEM CROSSTRACK ERROR.

Total System Crosstrack (TSCT) was defined as the difference between the desired position of the aircraft on a track and the actual position of the aircraft. The actual position of the aircraft was defined as the position recorded by the EAIR. The desired position was defined as the orthogonal projection of the actual position onto the desired track. Choosing this methodology fixes the total system along-track error (TSAT) as zero. Total system crosstrack error will be a composite of all the other errors; i.e., flight technical, sensor, OBS, and computer error.

$$TSCT=FTE+VDCT+OBSN+CPCT$$

$$TSCT=(\text{DESIRED POSITION}-\text{ACTUAL POSITION})$$

$$TSAT=0$$

Total system crosstrack error was considered only in the steady state. The same criteria applied to flight technical error were applied to total system crosstrack error.

TEST RESULTS

VOR/DME SENSOR AND RNAV COMPUTER ERRORS.

In analyzing system accuracies, one must first identify those parameters where differences may occur because of different test conditions, subjects, etc. For these tests, those parameters where differences might be expected are flight technical, total system crosstrack, and OBS errors. Accordingly, these errors are treated on an individual basis in subsequent sections. Data are presented in this section which are independent of different test conditions, subjects, etc. Those parameters that are independent are crosstrack sensor error (SNCT), along-track sensor error (SNAT), crosstrack computer error (CPCT), and along-track computer error (CPAT). Table 3 enumerates the statistics in the terminal area, while table 4 enumerates the statistics for the approach area. These data include not only straight-line segments, but also data taken in turns, offsets, and various operational maneuvers.

TABLE 3. SENSOR AND COMPUTER ERROR STATISTICS FOR THE TERMINAL AREA

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
SNCT	31,956	-0.007	0.336
SNAT	31,956	-0.007	0.195
CPCT	31,956	0.145	0.673
CPAT	31,956	-0.279	0.506

TABLE 4. SENSOR AND COMPUTER ERROR STATISTICS FOR THE APPROACH AREA

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
SNCT	2,304	-0.005	0.147
SNAT	2,304	-0.032	0.111
CPCT	2,304	0.274	0.188
CPAT	2,304	-0.177	0.231

The data base for the VOR/DME sensor error data was derived from utilizing the following four VOR/DME facilities in the vicinity of NAFEC, Atlantic City, New Jersey:

1. Atlantic City, New Jersey (ACY), 108.6 megahertz (MHz);
2. Coyle, New Jersey (CYN), 113.4 MHz;
3. Sea Isle, New Jersey (SIE), 114.8 MHz; and
4. Millville, New Jersey (MIV), 115.2 MHz.

OBS ERRORS.

** An error source previously identified as significant in its contribution to total system error is OBS setting error. This error will vary according to the type of equipment (i.e., pointer versus digital readout) and the care with which the pilot makes the setting. The effect of OBS setting error on the total system crosstrack error will vary with the distance to or from the waypoint. A more detailed explanation of this is contained in the DATA ANALYSIS section of this report.

For these flight tests, the OBS function was controlled by a COURSE SET knob on the RDI. The knob positioned a course arrow against a compass card. The resolution of the markings on the compass card was 5°. There was no digital readout of the course setting.

It should be pointed out that the RNAV system used for these tests offered a procedural method of setting the OBS to within 0.1°. This was accomplished by temporarily entering the desired track angle into the "radial" portion of the waypoint setter. The test button on the digital range and mode control was then pushed, and the OBS knob was rotated to center the RDI needle. The OBS was now set to the desired track within 0.1°. The procedure was not used in these tests because during the familiarization flights, it became obvious that the workload was already sufficiently high.

OBS errors were calculated both in nautical miles (as a function of the distance to or from a waypoint and the degrees of error) and in degrees (angularity). OBS errors calculated in nautical miles were calculated at each 0.1-nmi increment along the test routes. Those calculated in degrees represent the measured error between the desired course and the set course at the beginning of each leg of the test route. The sample size for these two measurements was, therefore, quite different.

The errors were then examined for effects as a function of test conditions, subjects, etc. Table 5 enumerates the statistics for the low-experience group (group A) versus the high-experience group (group B). Table 6 enumerates statistics for OBS error in the low-experience group (group A) as a function of waypoint storage capacity.

TABLE 5. OBS ERROR STATISTICS AS A FUNCTION OF EXPERIENCE LEVEL

	OBS Error (degrees)		OBS Error (nmi)	
	Mean	One Standard Deviation	Mean	One Standard Deviation
Group A (Low Experience	0.432	1.917	-0.142	0.584
Group B (High Experience	0.223	1.292	-0.020	0.274

TABLE 6. OBS ERROR STATISTICS AS A FUNCTION OF WAYPOINT STORAGE CAPACITY

	OBS Error (degrees)		OBS Error (nmi)	
	Mean	One Standard Deviation	Mean	One Standard Deviation
1 Waypoint	0.898	2.709	-0.252	0.726
2 Waypoint	-0.009	1.475	-0.135	0.654
3 Waypoint	0.431	1.282	-0.047	0.227

As can be seen, the difference between two- and three-waypoint storage capacity was minimal, but with a one-waypoint storage capacity, the OBS error was significantly higher. There was no difference between the standard deviations for OBS error as a function of waypoint storage capacity for group B (high experience).

When OBS errors were combined, the statistics shown in table 7 resulted.

TABLE 7. OMNI BEARING SELECTOR ERROR STATISTICS

	Samples	Mean	One Standard Deviation
OBS	243	0.325°	1.626°
OBSN	21,110	-0.072 nmi	0.358 nmi

Histograms for OBS error in both degrees and nautical miles are presented in figures 16 and 17.

FLIGHT TECHNICAL ERROR.

Flight technical error is a measure of the accuracy with which the pilot controls the aircraft with respect to the commanded signal or the displayed position as presented on the cockpit instrumentation. It could be expected that many factors would influence flight technical error. These factors would include display type, waypoint storage capacity and resultant workload, experience level, and individual pilot skill and technique.

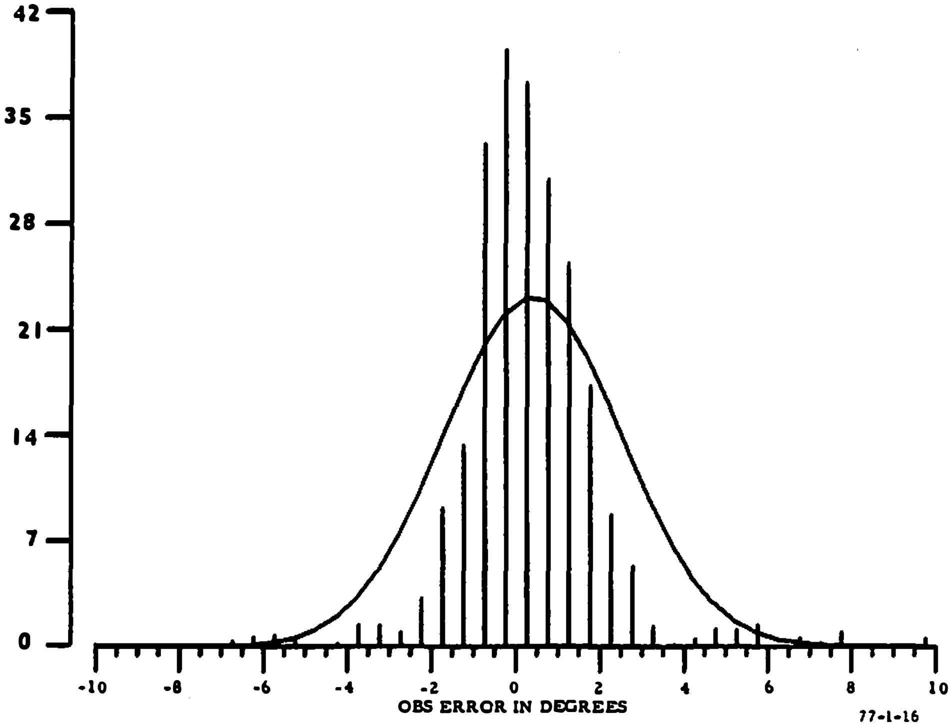


FIGURE 16. HISTOGRAM OF OBS ERROR IN DEGREES

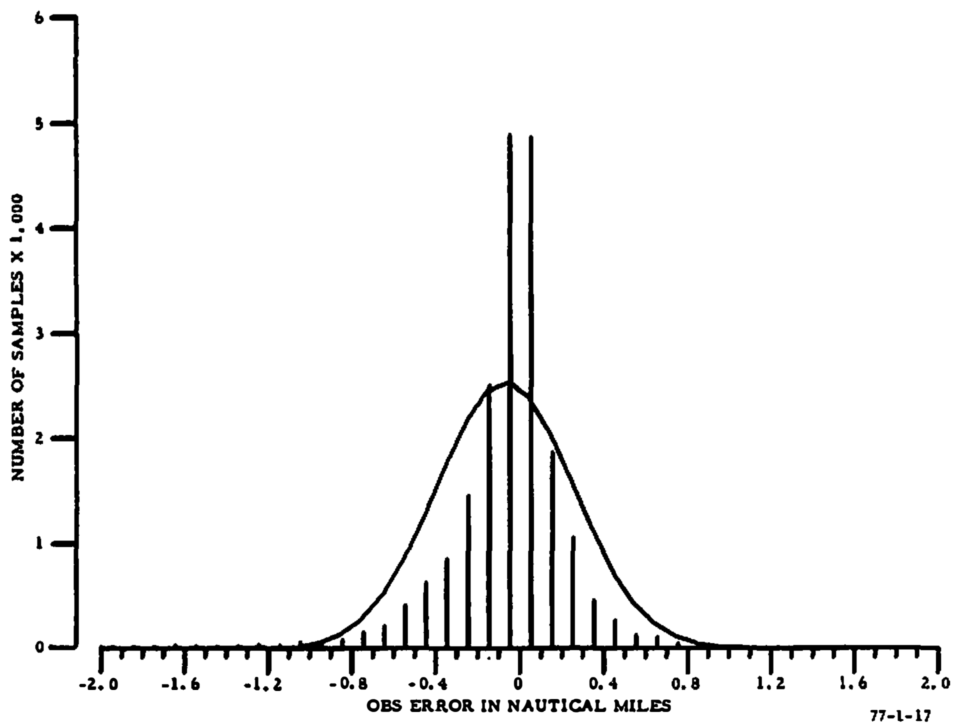


FIGURE 17. HISTOGRAM OF OBS ERROR IN NAUTICAL MILES

After examination of the data, summaries were made in those categories where differences were noted. No differences were noted as a function of flight pattern flown, although two of the three highest values for flight technical error (on a per run basis) occurred on pattern A2, which was considered a high-workload pattern.

Figures 18 and 19 consider flight technical error as a function of three test variables; guidance type, experience level, and waypoint storage. It can be seen that for the low-experience group, flight technical error, with a three-waypoint storage capability, was lower for both RDI and flight director guidance than it was for a one- or two-waypoint storage capacity. This trend did not follow through for the experienced group, however. Here, for both RDI and flight director guidance, the lowest flight technical error occurred when only one waypoint was available. For RDI guidance, flight technical error increased to its highest value when a two-waypoint storage capacity was available, then it decreased for a three-waypoint storage capacity. For flight director guidance, there was an increasing trend in flight technical error as the waypoint storage capacity was increased. Flight technical error was also examined as a function of experience level only and as a function of the type of guidance only. Tables 8 and 9 enumerate statistics for these two groupings.

TABLE 8. FLIGHT TECHNICAL ERROR AS FUNCTION OF EXPERIENCE LEVEL

	No. of Samples	Mean (nmi)	One Standard Deviation (nmi)
Group A (Low Experience)	10,673	0.062	0.538
Group B (High Experience)	11,056	0.170	0.523

TABLE 9. FLIGHT TECHNICAL ERROR AS FUNCTION OF TYPE OF GUIDANCE

	No. of Samples	Mean (nmi)	One Standard Deviation (nmi)
RDI	10,615	0.098	0.454
Flight Director	11,114	0.135	0.598

There is no difference in the standard deviations of flight technical error as a function of experience level. There was some difference as a function of the guidance used, but the difference is not statistically significant. Some explanation for this may be offered by understanding how a flight director works and how the RNAV system was interfaced to the flight director in this test.

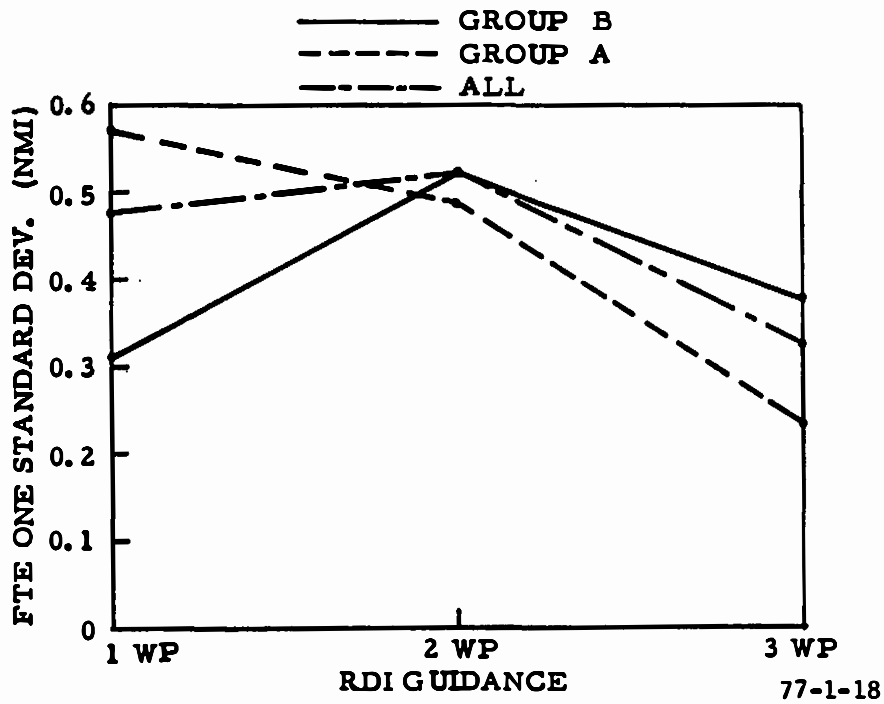


FIGURE 18. FLIGHT TECHNICAL ERROR AS A FUNCTION OF WAYPOINT STORAGE CAPACITY, TEST ROUTE, AND EXPERIENCE LEVEL WHEN USING RDI GUIDANCE

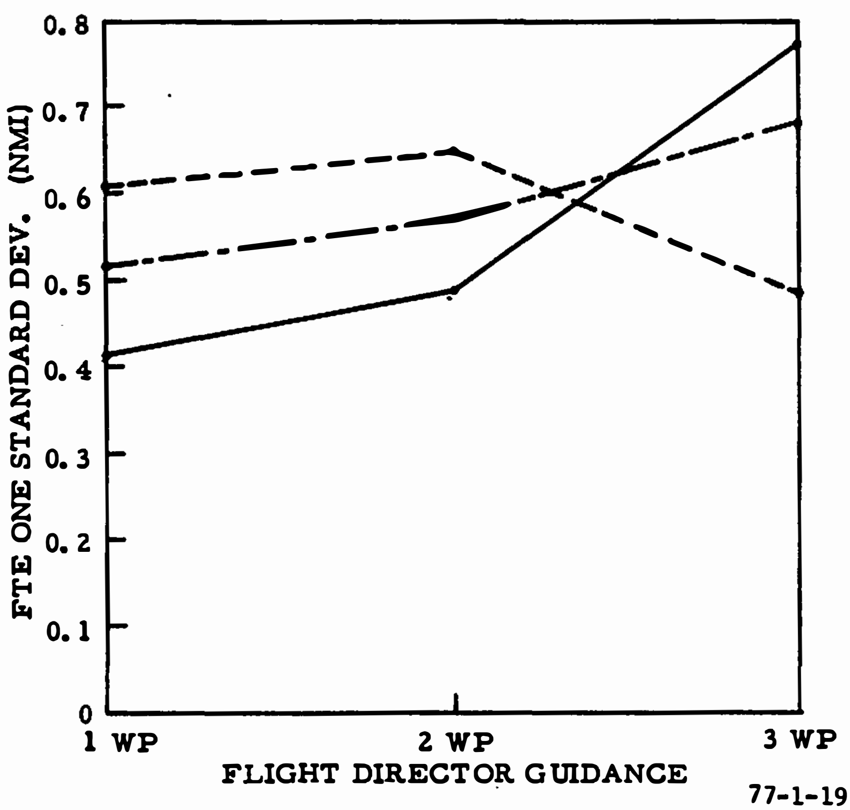


FIGURE 19. FLIGHT TECHNICAL ERROR AS A FUNCTION OF WAYPOINT STORAGE CAPACITY, TEST ROUTE, AND EXPERIENCE LEVEL WHEN USING FLIGHT DIRECTOR GUIDANCE

The flight director utilizes course error, radio deviation, and roll attitude to compute a steering signal which is presented on the lateral steering bar of the flight director. When the bank angle of the aircraft reaches that which is commanded to reach the desired track, the lateral steering bar is centered. The fact that the lateral steering bar is centered does not mean the aircraft is on the desired track, but rather it is on the proper path to intercept the desired track. A pilot flying this computed track may not be able to bring his aircraft onto the desired track as rapidly as the pilot flying raw deviation, but following the computed course has the advantage of being, generally, a much smoother course, with bank angles more shallow. On long VOR radials, this gradual convergence to the desired track would not be as noticeable as it was on the RNAV SID and STAR patterns, where the legs were short, demanding numerous turns and subsequent track reacquisition.

A second factor was the signal gradient itself. Referring to figure 20, the full-scale deviation 150 microampere (A) lines for VOR and RNAV are plotted as a function of distance to waypoint or VOR and the perpendicular distance from desired track. It can be seen that the RNAV line is independent of the distance to waypoint or VOR, because the RNAV steering deviation is a constant course width. The RNAV and VOR course-width sensitivities were equal at about 30 nmi to the waypoint or VOR. At this point, however, the equivalent RNAV course-width sensitivity progressively decreased (relative to the VOR course sensitivity) as the distance to waypoint became less. This resulted in course "softening" as the distance to waypoint decreased. This did, however, allow for smooth waypoint passage. Switching to operation in the approach mode quadrupled the sensitivity. In the approach mode, the crossover point was 7 nmi (figure 20).

Despite the fact that there were some differences in flight technical error as a function of guidance type, waypoint storage capacity, etc., this mixture of experience and equipment levels was what would be found in the real world (general aviation case). One set of statistics was therefore developed which combined all groups in the terminal area. These statistics are enumerated in table 10.

TABLE 10. FLIGHT TECHNICAL ERROR STATISTICS FOR ENROUTE/TERMINAL AREA

No. of Samples	Mean (nmi)	Standard Deviation (nmi)
21,729	0.117	0.533

Flight technical error data for the final approach track were similarly processed. It should be remembered that for flying the final approach, all subjects were required to use the approach sensitivity of the RNAV system. This feature increased the course-width sensitivity by a factor of 4 from ±5-nmi to ±1.25-nmi full-scale sensitivity. Table 11 enumerates statistics for the final approach area.

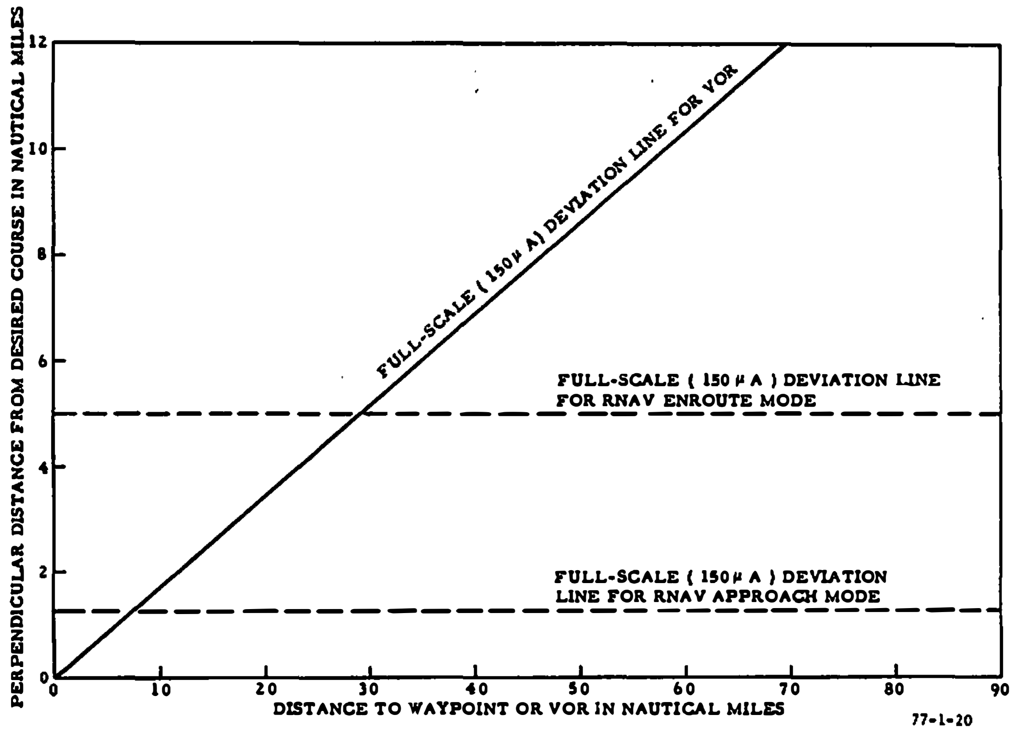


FIGURE 20. MICROAMPERE DEVIATIONS FOR RNAV AND VOR GUIDANCE AS A FUNCTION OF DISTANCE TO WAYPOINT OR VOR

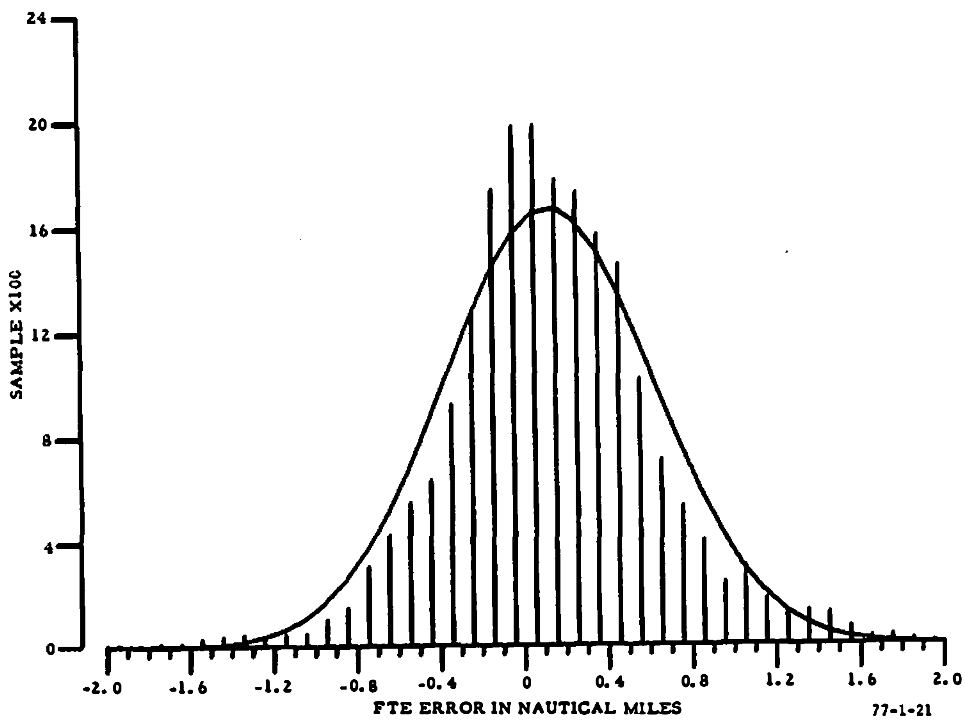


FIGURE 21. HISTOGRAM OF FLIGHT TECHNICAL ERROR IN NAUTICAL MILES

TABLE 11. FLIGHT TECHNICAL ERROR STATISTICS FOR APPROACH

No. of Samples	Mean (nmi)	Standard Deviation (nmi)
1,933	-0.003	0.176

As can be seen comparing tables 10 and 11, the increase in approach sensitivity over enroute/terminal sensitivity by a factor of 4, reduced the flight technical error standard deviation between the two conditions by a factor of 3. A histogram of the flight terminal error samples for the terminal area is presented in figure 21.

TOTAL SYSTEM CROSSTRACK ERROR AND ERROR BUDGET.

The single most important figure in the analysis of RNAV system is the total system crosstrack (TSCT) error. This figure determines the requirements for the amount of protected airspace. Two methods of determining this figure are to measure TSCT in actual flight test or to identify and measure the error components of TSCT and calculate it. Both methods were used in these tests. The method used to calculate TSCT was the root-sum-square method as described in FAA Advisory Circular AC-90-45A.

Initially, the statistics were accumulated on a segment-by-segment basis for the three patterns flown. Sample sizes for the different parameters were not necessarily equal for each segment. This was because samples for TSCT and flight technical error were taken on the stabilized, straight-line portion of the segment, while samples for sensor error (SNCT) and computer error (CPCT) were taken over the entire segment. Also, samples for OBS error were not taken when the desired track was being changed.

Statistics for pattern A1 segments are enumerated in table 12. As can be seen, there are mean errors in TSCT for some segments which are fairly large. In particular, segment ECHO-FOXTROT exhibits a TSCT mean of 0.764 nmi. The main cause of the mean TSCT error seems to be a very large mean RNAV computer error. The influence of the large mean computer error in the TSCT mean was further demonstrated in the stepwise multiple regression analysis which will be discussed in this section. The large mean computer error seems to have been caused, in turn, by poor quality VOR signals on this segment. This is evidenced by a sensor error standard deviation for this segment of 0.771 nmi. This is roughly five times larger than the sensor error standard deviation for any other segment on this pattern.

Statistics for the segments for pattern A2 are enumerated in table 13. Again, on pattern A2, segments UNIFORM-VICTOR and VICTOR-GOLF exhibited high mean TSCT errors due to corresponding high RNAV computer errors. The cause again appeared to be due to the high sensor error standard deviation indicative of VOR scalloping.

Pattern A6 statistics are enumerated in table 14. Segment DEBAY-WEBAY exhibited the highest computer error mean for this pattern. Data from all segments were then combined to present one set of statistics for all parameters.

TABLE 12. SEGMENTAL ERROR STATISTICS FOR TEST PATTERN A1

Segment BRAVO-CHARLIE

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	1,502	0.013	0.637
SNCT	1,830	-0.079	0.115
CPCT	1,830	-0.160	0.329
FTE	1,502	0.405	0.518
OBSN	1,763	0.066	0.257

Segment CHARLIE-DELTA

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	1,865	-0.515	0.535
SNCT	2,236	-0.073	0.110
CPCT	2,236	-0.366	0.182
FTE	1,865	0.032	0.407
OBSN	2,205	-0.208	0.279

Segment DELTA-ECHO

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	1,952	-0.215	0.302
SNCT	2,359	0.033	0.127
CPCT	2,359	-0.494	0.262
FTE	1,952	0.193	0.339
OBSN	2,233	-0.241	0.326

Segment ECHO-FOXTROT

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	361	0.764	0.659
SNCT	1,760	0.231	0.771
CPCT	1,760	1.486	0.469
FTE	361	-0.640	0.827
OBSN	1,750	-0.053	0.350

Segment FOXTROT-GOLF

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	2,881	-0.162	0.513
SNCT	3,253	-0.013	0.146
CPCT	3,253	-0.061	0.500
FTE	2,881	0.035	0.311
OBSN	3,232	-0.171	0.658

Segment GOLF-HOTEL

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	189	0.659	0.197
SNCT	1,416	-0.031	0.162
CPCT	1,416	0.488	0.373
FTE	189	0.330	0.775
OBSN	837	-0.288	0.140

TABLE 13. SEGMENTAL ERROR STATISTICS FOR TEST PATTERN A2

Segment BRAVO-ROMEO

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	280	0.130	0.433
SNCT	428	0.024	0.084
CPCT	428	-0.371	0.113
FTE	280	0.357	0.455
OBSN	402	-0.034	0.091

Segment ROMEO-SIERRA

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	2,138	-0.613	0.405
SNCT	2,476	-0.079	0.139
CPCT	2,476	-0.391	0.288
FTE	2,138	0.068	0.451
OBSN	2,461	-0.232	0.776

Segment SIERRA-TANGO

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	1,211	-0.735	0.488
SNCT	1,412	-0.010	0.097
CPCT	1,412	-0.306	0.172
FTE	1,211	-0.070	0.623
OBSN	1,388	-0.357	0.622

Segment TANGO-UNIFORM

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	1,384	-0.149	0.485
SNCT	1,623	0.063	0.161
CPCT	1,623	-0.278	0.398
FTE	1,384	0.232	0.359
OBSN	1,618	0.067	0.237

Segment UNIFORM-VICTOR

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	142	1.035	0.323
SNCT	1,451	0.208	0.563
CPCT	1,451	0.919	0.529
FTE	142	-0.369	1.156
OBSN	1,406	0.091	0.130

Segment VICTOR-GOLF

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	1,140	1.262	0.571
SNCT	1,582	-0.280	0.863
CPCT	1,582	1.156	0.609
FTE	1,140	0.433	0.796
OBSN	1,569	0.124	0.210

Segment GOLF-BB

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	881	0.343	0.446
SNCT	1,309	0.044	0.156
CPCT	1,309	0.284	0.220
FTE	881	0.002	0.385
OBSN	1,283	-0.156	0.274

TABLE 14. SEGMENTAL ERROR STATISTICS FOR TEST PATTERN A6

Segment TUCKO-DEBAY

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	2,155	-0.376	0.447
SNCT	2,377	0.000	0.143
CPCT	2,377	0.036	0.420
FTE	2,155	-0.048	0.449
OBSN	2,374	-0.237	0.466

Segment DEBAY-WEBAY

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	788	1.185	0.457
SNCT	1,310	-0.022	0.227
CPCT	1,310	0.643	0.195
FTE	788	0.362	0.422
OBSN	1,275	0.058	0.217

Segment WEBAY-LANVE

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	1,666	0.930	0.547
SNCT	2,149	0.045	0.119
CPCT	2,149	0.376	0.355
FTE	1,666	0.534	0.397
OBSN	2,129	0.179	0.313

Segment LANVE-MARGE

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	1,194	-0.269	0.379
SNCT	2,560	-0.072	0.178
CPCT	2,560	0.199	0.528
FTE	1,194	-0.363	0.491
OBSN	2,554	0.133	0.263

TABLE 15. TOTAL SYSTEM ERROR STATISTICS FOR TERMINAL AND APPROACH AREA

	Terminal			Approach		
Error	Samples	Mean (nmi)	One Standard Deviation (nmi)	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	21,110	-0.011	0.765	1,880	0.213	0.234
SNCT	21,110	-0.032	0.266	1,880	0.000	0.131
CPCT	21,110	-0.038	0.578	1,880	0.253	0.170
FTE	21,110	0.122	0.526	1,880	0.000	0.176
OBSN	21,110	-0.072	0.358	1,880	-0.018	0.073

Table 15 enumerates the statistics on TSCT and the components of TSCT for both terminal and approach cases. The data were taken in the steady-state case, and no data were taken in turns or in operational maneuvers. Also, the data were "paired" data; that is, the sample size of TSCT and all the error components were equal, and each sample represented a set of data where all components were valid and were measured at the same time. It will be noted, therefore, that the sample sizes of sensor, computer, flight technical, and OBS errors, as discussed in their individual preceding sections, are, in most cases, greater than the sample sizes in this section, because of the requirement to have paired data. The mean and standard deviations are therefore slightly different, because of the different sample sizes, but the differences are measured in hundredth's of a nautical mile.

Table 16 compares the measured value of TSCT against the value of TSCT calculated from the error components of table 15. The calculated value is computed using the root-sum-square method. Both terminal and approach conditions are considered. As can be seen, the root-sum-square-calculated value offers a slightly more conservative figure of crosstrack error in comparison to the actual measured TSCT.

To more thoroughly examine the relationship between TSCT and the components that make it up, a stepwise multiple regression was run on the paired data. Stepwise multiple regression is a statistical technique for analyzing a relationship between a dependent variable, total system crosstrack error (TSCT) and a set of assumed independent variables, sensor (SNCT), computer (CPCT), flight technical (FTE), and OBS errors and for selecting the independent variables in the order of their importance. The criterion of importance is based on the reduction of sums of squares, and the independent variable most important in this reduction in a given step is entered in the regression. The stepwise regression allows any variable in the original set to be used as the depen-dent variable. For the purposes of this analysis, TSCT was used as the dependent variable.

A correlation matrix was also an output of this program. Table 17 presents the correlation matrix for the terminal data. Good correlation was shown between TSCT and computer, flight technical, and OBS error. The results of the stepwise multiple regression for the terminal data are presented in table 18. The error components identified in their order of significance are computer, flight technical, OBS, and sensor error. This contrasts significantly with previous flight test results using a sophisticated air transport area navigation system where the VOR/DME sensor error was the most significant error term (report FAA-RD-76-32). The order of ranking was probably influenced by the fact that large computer mean errors were evident in areas where VOR scalloping was present.

Table 19 presents the correlation matrix for the approach data. High correlation between TSCT and flight technical error is shown, but only a slight correlation between TSCT and both computer and sensor error is evidenced. The results of the stepwise multiple regression for the approach data are presented in table 20. The error components identified in their order of significance are flight technical, sensor, computer, and OBS error.

TABLE 16. COMPARISON OF MEASURED AND RSS-CALCULATED TOTAL SYSTEM ERROR STATISTICS

Terminal		Approach	
Measured TSCT One Standard Deviation (nmi)	Calculated TSCT One Standard Deviation (nmi)	Measured TSCT One Standard Deviation (nmi)	Calculated TSCT One Standard Deviation (nmi)
0.765	0.899	0.234	0.287

TABLE 17. CORRELATION MATRIX FOR TERMINAL AREA DATA

Error	TSCT	SNCT	CPCT	FTE	OBSN
TSCT	1.0000	-0.0371	0.5803	0.5347	0.4497
SNCT	-0.0371	1.0000	-0.1441	-0.3361	-0.0264
CPCT	0.5803	-0.1441	1.0000	-0.0401	0.1691
FTE	0.5347	-0.3361	-0.0401	1.0000	-0.0939
OBSN	0.4497	-0.0264	0.1691	-0.0939	1.0000

TABLE 18. STEPWISE MULTIPLE REGRESSION ANALYSIS FOR TERMINAL AREA DATA

STEP 1

Variable Entered = CPCT

Sum of squares reduced in this step = 4163.782
Proportion reduced in this step = 0.337

Cumulative sum of squares reduced = 4163.782
Cumulative proportion reduced = 0.337 of 12365.561

For one variable entered
Multiple correlation coefficient = 0.580
(Adjusted for D.F.) = 0.580
Standard error of estimate = 0.623
(Adjusted for D.F.) = 0.623

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
CPCT	0.76813	0.00742	103.517
Intercept	0.01743		

STEP 2

Variable Entered = FTE

Sum of squares reduced in this step = 3856.595
Proportion reduced in this step = 0.312

Cumulative sum of squares reduced = 8020.377
Cumulative proportion reduced = 0.649 of 12365.561

For two variables entered
Multiple correlation coefficient = 0.805
(Adjusted for D.F.) = 0.805
Standard error of estimate = 0.454
(Adjusted for D.F.) = 0.454

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
CPCT	0.79779	0.00541	147.590
FTE	0.81297	0.00594	136.871
Intercept	-0.08066		

STEP 3

Variable Entered = OBSN

Sum of squares reduced in this step = 2055.911
Proportion reduced in this step = 0.166

Cumulative sum of squares reduced = 10076.288
Cumulative proportion reduced = 0.815 of 12365.561

For three variables entered
Multiple correlation coefficient = 0.903
(Adjusted for D.F.) = 0.903
Standard error of estimate = 0.329
(Adjusted for D.F.) = 0.329

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
CPCT	0.70672	0.00398	177.615
FTE	0.86571	0.00433	200.007
OBSN	0.88746	0.00645	137.675
Intercept	-0.02647		

STEP 4

Variable Entered = SNCT

Sum of squares reduced in this step = 903.548
Proportion reduced in this step = 0.073

Cumulative sum of squares reduced = 10979.836
Cumulative proportion reduced = 0.888 of 12365.561

For four variables entered
Multiple correlation coefficient = 0.942
(Adjusted for D.F.) = 0.942
Standard error of estimate = 0.256
(Adjusted for D.F.) = 0.256

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
CPCT	0.76547	0.00314	244.090
FTE	1.01200	0.00359	281.806
OBSN	0.90807	0.00502	180.951
SNCT	0.83703	0.00714	117.309
Intercept	-0.01388		

TABLE 19. CORRELATION MATRIX FOR APPROACH DATA

Error	TSCT	SNCT	CPCT	FTE	OBSN
TSCT	1.0000	0.3214	0.3778	0.7228	0.2881
SNCT	0.3214	1.0000	0.2163	-0.0859	-0.2146
CPCT	0.3778	0.2163	1.0000	-0.0036	-0.0893
FTE	0.7228	-0.0859	-0.0036	1.0000	0.0185
OBSN	0.2881	-0.2146	-0.0893	0.0185	1.0000

WAYPOINT STORAGE CAPACITY AND PILOT WORKLOAD.

Although each pilot flew the same routes and performed the same maneuvers, some of them were restricted from using the full three-waypoint capacity of the AD611/D system. Four pilots (two from each experience-level group) were restricted to one-waypoint capacity, four were restricted to two-waypoint capacity, and four were allowed to use the full three-waypoint capacity.

In the terminal airspace, high pilot workload levels are encountered on takeoffs, for a short period thereafter, and on the approach to a landing. A higher-than-normal pilot workload can be encountered during the handoff phase from enroute to terminal ATC. This high workload results from the pilot/ATC communications requirement to complete the handoff. These conditions were encountered during these tests, and it was found that the route designs did have an additional effect on pilot workload when interacting with limited waypoint storage capacity. Appendix B provides additional information from pilot response to questionnaires.

ROUTE A1. The highest pilot workload was encountered in three areas along this route: (1) the first 4 nmi after departure; (2) an approximate 3-nmi area around waypoint FOXTROT during the handoff from McGuire AFB to Atlantic City Approach as the pilot was returning to course from a parallel offset; and (3) during the 11-nmi final approach to runway 4 at NAFEC and at the outer approach waypoint (HOTEL) where the pilot was completing a delay fan maneuver.

One-Waypoint Capacity. The one-waypoint capacity subjects had little or no option but to dial the coordinates for the next waypoint regardless of the high workload situations. It normally takes 12 to 18 seconds to dial a set of waypoint coordinates into each 61WPS unit, provided there is little or no air turbulence to disturb the pilot's hand movements and there are no errors made on dialing in the bearing and distance. Each time this waypoint function is required, the pilot must perform this function collaterally with his other duties. This can be a demanding task for a pilot who is already involved in a high-workload situation. One-waypoint subjects were allowed the option of using the 5-nmi DTW MAP-4 in lieu of INDIA during the final approach. This did eliminate the 12 to 18 seconds of time usually needed to dial in new waypoint coordinates.

TABLE 20. STEPWISE MULTIPLE REGRESSION ANALYSIS FOR APPROACH DATA

STEP 1

Variable Entered = FTE

Sum of squares reduced in this step = 53.759
Proportion reduced in this step = 0.522

Cumulative sum of squares reduced = 53.759
Cumulative proportion reduced = 0.522 of 102.892

For one variable entered
Multiple correlation coefficient = 0.723
(Adjusted for D.F.) = 0.723
Standard error of estimate = 0.162
(Adjusted for D.F.) = 0.162

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
FTE	0.96070	0.02119	45.330
Intercept	0.21185		

STEP 2

Variable Entered = SNCT

Sum of squares reduced in this step = 15.246
Proportion reduced in this step = 0.148

Cumulative sum of squares reduced = 69.005
Cumulative proportion reduced = 0.671 of 102.892

For two variables entered
Multiple correlation coefficient = 0.819
(Adjusted for D.F.) = 0.819
Standard error of estimate = 0.134
(Adjusted for D.F.) = 0.134

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
FTE	1.00482	0.01767	56.863
SNCT	0.69217	0.02382	29.059
Intercept	0.21155		

STEP 3

Variable Entered = OBSN

Sum of squares reduced in this step = 13.746
Proportion reduced in this step = 0.134

Cumulative sum of squares reduced = 82.750
Cumulative proportion reduced = 0.804 of 102.892

For three variables entered
Multiple correlation coefficient = 0.897
(Adjusted for D.F.) = 0.897
Standard error of estimate = 0.104
(Adjusted for D.F.) = 0.104

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
FTE	1.00478	0.01363	73.734
SNCT	0.83603	0.01880	44.462
OBSN	1.19384	0.03337	35.781
Intercept	0.23269		

STEP 4

Variable Entered = CPCT

Sum of squares reduced in this step = 10.596
Proportion reduced in this step = 0.103

Cumulative sum of squares reduced = 93.346
Cumulative proportion reduced = 0.907 of 102.892

For four variables entered
Multiple correlation coefficient = 0.952
(Adjusted for D.F.) = 0.952
Standard error of estimate = 0.071
(Adjusted for D.F.) = 0.071

Variable	Regression Coefficient	Std Error of Reg. Coeff.	Computed T-Value
FTE	0.99816	0.00938	106.360
SNCT	0.71342	0.01322	53.948
OBSN	1.24108	0.02300	53.962
CPCT	0.45279	0.00992	45.622
Intercept	0.11899		

Two-Waypoint Capacity. The two-waypoint-capacity subjects could dial the next waypoint prior to or after the high-workload areas of departure and handoff. This was possible because there was ample distance between waypoints in these areas to select a more opportune time to formulate a new waypoint. However, since there were three waypoints in close proximity on the final approach course, these pilots still had to dial in the MAP-4 waypoint while on the final approach course.

Three-Waypoint Capacity. The subjects flying with three-waypoint storage capacity could dial the waypoint coordinates prior to entering the high-workload areas. There were adequate opportunities outside these areas for the pilots to keep two waypoints dialed in ahead of the one being used. This allowed them to avoid the problem of formulating a waypoint in any of the high-workload areas.

ROUTE A2. The highest pilot workloads on this route were encountered in three areas: (1) the first 9 nmi, where two waypoints (BRAVO and ROMEO) occurred within a 5-nmi space of each other; (2) a 3-nmi area around the VICTOR waypoint during a handoff from Dover Air Force Base (AFB) to Atlantic City Approach, where in approaching VICTOR, the pilot was returning to course from a parallel offset; and (3) the 11-nmi final approach to runway 13 at NAFEC. Additionally, an impromptu runway change from runway 4 to 13 created a high-workload starting approximately 5 nmi prior to GOLF waypoint.

One-Waypoint Capacity. Subjects with a one-waypoint storage capacity, encountered problems of formulating another waypoint within a 5-nmi distance (between BRAVO and ROMEO) shortly after takeoff. Otherwise, their waypoint workload was essentially the same as that encountered while flying along route A1.

Two-Waypoint Capacity. Subjects with a two-waypoint storage capacity had to formulate a waypoint within a 5-nmi distance (between BRAVO and ROMEO) shortly after takeoff in order to keep the second waypoint available for the next waypoint after ROMEO. Therefore, the two-waypoint storage capacity provided little workload alleviation during the departure phase.

When the subjects flying with a two-waypoint capacity were required to change runways, additional workload was required to reset new coordinates in the extra waypoint unit to accommodate the runway change. The waypoint workload in the handoff and final approach areas of this route were essentially the same as that encountered during route A1.

Three-Waypoint Capacity. Subjects with a three-waypoint storage capacity were able to avoid the additional workload of dialing in waypoint coordinates in the three highest workload areas. There was additional workload required to exchange the coordinates already set in two of the waypoint storage units when the subjects were rerouted to another runway.

ROUTE A6. Due to the design of this route, only the 8-nmi final approach area presented the highest pilot workload. Also, at the outer approach waypoint (BRIGE), the pilots were completing an extended downwind leg maneuver.

One-Waypoint Storage Capacity. The subjects flying with a one-waypoint capacity had to turn toward the first approach waypoint (BRIGE) from the extended downwind leg before dialing in the coordinates for BRIGE. Until this point, they were required to use the MARGE coordinates for their extended downwind leg maneuver. The pilot had approximately 3 nmi in which to change to the BRIGE coordinates and establish a direct course to BRIGE. After passing MARGE, the pilot then had to dial in the MAP-31 fix coordinates for the final descent to the runway.

Two-Waypoint Capacity. The two-waypoint-capacity subjects did have slightly more flexibility over the one-waypoint-capacity subjects in that only one additional waypoint had to be formulated during the final approach instead of two.

Three-Waypoint Capacity. The three-waypoint-capacity subjects had all of the needed waypoints dialed into waypoint units prior to starting the extended downwind leg. This allowed them to avoid the additional waypoint workload during the extended downwind leg as well as during the final approach.

BLUNDERS AND ERRORS.

For these results, a blunder was defined as a pilot error that developed or could develop into a situation causing a disruption to the ATC traffic flow or placing the pilot into a hazardous flight situation if the flight had not been conducted under controlled conditions. When flight conditions permitted (VFR weather), the pilot was given time to detect the blunders and take corrective action. When a blunder was not detected by the pilot, the observer intervened and alerted the pilot to prevent the flight from being aborted before completion.

Pilot errors were defined as mistakes which the pilot detected and took corrective action before they could evolve into blunders. There were other pilot errors that were undetectable, i.e., small OBS course setting errors, small numerical waypoint coordinate errors, etc., but they did not cause a detrimental effect on those flights. Resolving a blunder or a pilot error did create additional pilot workload.

BLUNDERS. There were a total of 18 blunders recorded during the 36 flights. The blunders fell within these five categories: (1) OBS setting errors; (2) wrong waypoint coordinates used; (3) incorrect VOR frequency; (4) RNAV system operational error; and (5) miscellaneous.

Within these categories, the blunders are quantified as follows:

1. There were 12 blunders (67 percent of total blunders) in which the pilot forgot to set the OBS to the new course or set the OBS to the incorrect course (5° or larger course error).

2. There were three blunders (17 percent of the total blunders) in which the wrong waypoint coordinates were set and used.

3. There was one blunder (6 percent of the total blunders) in which the pilot forgot to change to the frequency of the VOR upon which the active waypoint was based.

4. There was one blunder in which the pilot attempted to fly a 3-nmi right delay fan with the approach mode selected on the RNAV equipment. The higher RDI sensitivity resulted in the pilot flying much less than a required 3-nmi right delay fan.

5. There was one blunder in which the pilot was approximately 1,000 feet above the desired altitude at the final approach fix and was not able to complete the approach.

The two most significant causes of blunders were pilot experience level and cockpit workload. Test route A2 produced the highest number of blunders (table 21). This was attributed to the high workload associated with certain portions of the A2 route.

When examining the effects of pilot workload and experience level (table 21), it can be seen that all of the blunders on the high-workload A2 route were committed by pilots with a low experience level. The low-experience group accounted for 15 (83 percent) of the 18 total blunders. Also, of these 18 blunders, 11 (61 percent) occurred during the first 5 minutes after takeoff or during the last 5 minutes prior to landing.

Examining the blunders as a function of waypoint storage capacity, the lowest number of total blunders occurred with a two-waypoint storage capacity. The improvement with two-waypoints was most noticeable with the low experience level subjects.

The introduction of another level of system complexity (use of the flight director system) into the low experience level group also had an effect on the number of blunders committed by this group (figure 22). Ten (70 percent) of the 15 blunders committed by this group were committed when using the flight director system. The introduction of the use of the flight director system into the experienced group had no effect (figure 23).

In summarizing the blunder performance of the various groups under the various test conditions, the combination of high workload, system complexity, and low time in aircraft, coupled with a low experience level, saturated some of the subject pilots and resulted in a much higher level of blunders than were expected. It should also be pointed out that among the low experience level pilots, there were several who did very well and whose flights were relatively blunder free. The most noticeable difference between these subjects and those whose blunder tendency was higher was the degree of self-preflight preparation. RNAV flight in the high-workload terminal area is a demanding task which requires careful planning and high concentration. In this respect, RNAV is no different than any other terminal procedure. The results of careful preparation were most noticeable in these tests.

TABLE 21. BLUNDER QUANTIFICATION BY ROUTE, WAYPOINT STORAGE CAPACITY, AND PILOT EXPERIENCE LEVEL

WAYPOINT STORAGE CAPACITY	ROUTES: A1	A2	A6	Totals
1 Waypoint	2-L 0-E	4-L 0-E	1-L 0-E	7-L 0-E
2 Waypoints	0-L 0-E	2-L 0-E	0-L 2-E	2-L 2-E
3 Waypoints	1-L 1-E	3-L 0-E	2-L 0-E	6-L 1-E
Totals	3-L 1-E	9-L 0-E	3-L 2-E	15-L 3-E

Grand total (routes A1, A2, A6): 15-L, 3-E

L = Low-Experience Subject
E = Experienced Subject

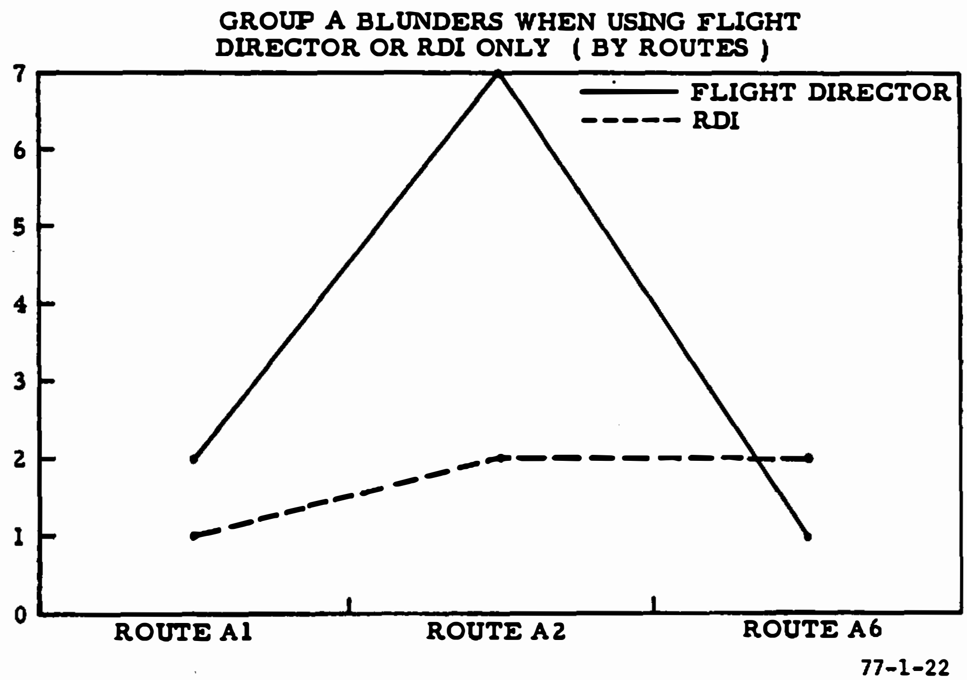


FIGURE 22. GROUP A BLUNDERS AS A FUNCTION OF GUIDANCE TYPE AND TEST ROUTE

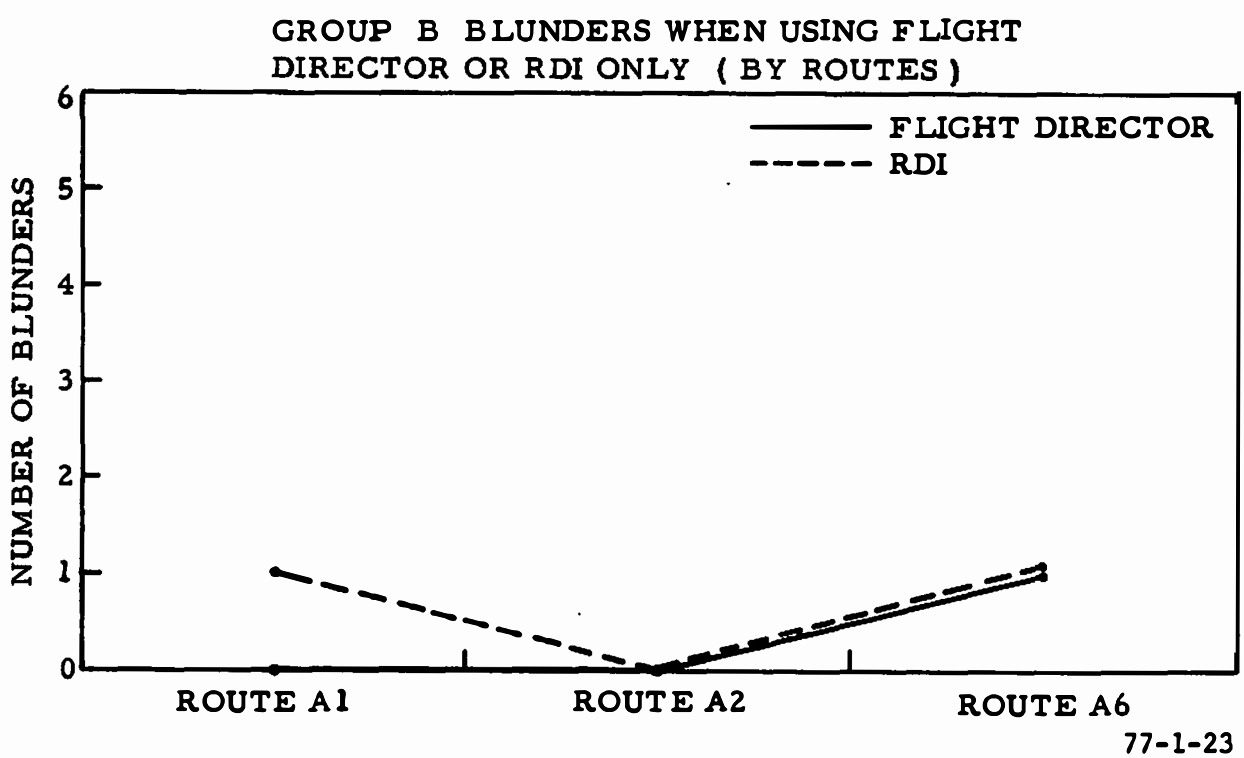


FIGURE 23. GROUP B BLUNDERS AS A FUNCTION OF GUIDANCE TYPE AND TEST ROUTE

The route structure (SID, STAR, and approach) design can have a significant effect on the blunder tendency. For example, waypoints should not be placed where radar handoffs normally occur and the resultant increased communication workload takes place. The increased cockpit workload definitely contributes to the blunder tendency.

ERRORS. There were 25 pilot errors recorded during the 36 data flights. These 25 errors fell within the same 5 categories as did the blunders: (1) OBS setting errors; (2) wrong waypoint coordinates used; (3) incorrect VOR frequency used; (4) RNAV system operational error; and (5) miscellaneous.

Within these categories, the errors were quantified as follows:

1. There were 10 (40 percent of the total) errors in which the pilots forgot to set the OBS to the new course, but quickly corrected the error; or they made small OBS setting errors which were not detected, but did not cause a blunder deviation.

2. There were six (24 percent of total) errors in which the pilots used the wrong waypoint unit to formulate waypoint coordinates, accidently dislodged correct waypoint coordinate settings with their hand while formulating coordinates in one of the other 61WPS units, or used waypoint coordinates that were in error by not more than 0.2° or not more than 0.2 nmi.

3. There were four (16 percent of total) errors in which the pilots forgot to change VOR stations along with the appropriate waypoint change, but were alerted by skewed flight director and RDI needle indications.

4. There were four (16 percent of total) errors in which the approach mode was selected at inappropriate times.

5. There was one (4 percent of total) error in which the pilot was approximately 370 feet below the assigned altitude at a final approach waypoint and had to adjust the descent rate.

Of the 25 recorded pilot errors, nine (36 percent) occurred within 5 minutes after takeoff or during the last 5 minutes before landing. Test route A1 produced the highest number of errors (table 22). Figures 24 and 25 depict the error tendency of groups A and B, respectively, as a function of guidance type and test route.

RESULTS OF TYPICAL OPERATIONAL MANEUVERS.

PARALLEL OFFSETS. Each pilot was required to execute one parallel offset on each route, as per scenario, while flying the STAR pattern.

On the route A1 STAR, a "2-nmi left offset" instruction was given at the 12-nmi DTW FOXTROT fix, and the "cancel offset" instructions was given at 5-nmi DTW FOXTROT fix.

TABLE 22. ERROR QUANTIFICATION BY ROUTE, WAYPOINT STORAGE CAPACITY, AND PILOT EXPERIENCE LEVEL

		ROUTES				
		A1	A2	A6	Totals	
WAYPOINT STORAGE CAPACITY	1 Waypoint	3-L 1-E	2-L 1-E	1-L 0-E	6-L 2-E	16-L 9-E
	2 Waypoints	0-L 4-E	3-L 0-E	2-L 1-E	5-1 5-E	
	3 Waypoints	2-L 1-E	1-L 0-E	2-L 1-E	5-L 2-E	
	Totals	5-L 6-E	6-L 1-E	5-L 2-E		
		16-L 9-E				

L = Low-Experience Subject
E = Experienced Subject

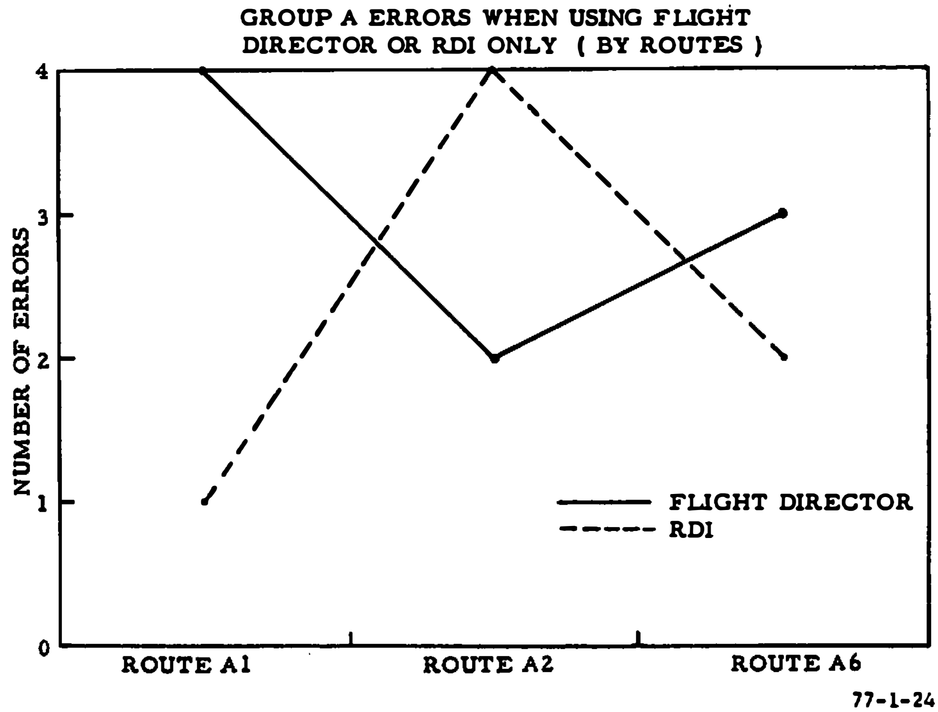


FIGURE 24. GROUP A ERRORS AS A FUNCTION OF GUIDANCE TYPE AND TEST ROUTE

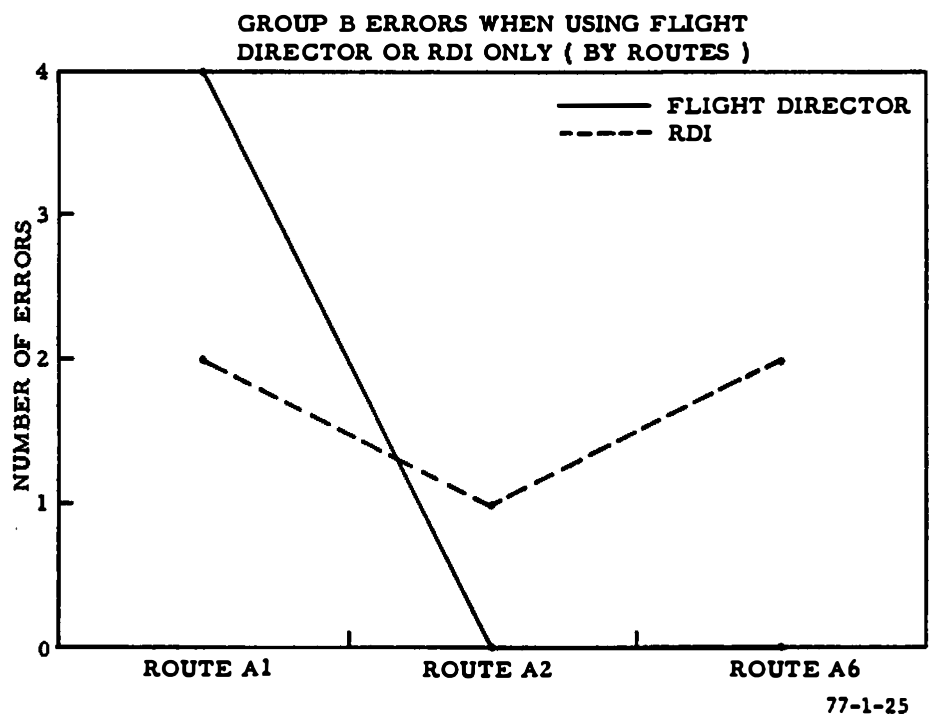


FIGURE 25. GROUP B ERRORS AS A FUNCTION OF GUIDANCE TYPE AND TEST ROUTE

On the route A2 STAR, a "2-nmi right offset" instruction was given at the 10-nmi DTW VICTOR fix, and the "cancel offset" instruction was given at the 5-nmi DTW VICTOR fix.

On the route A6 STAR, a "3-nmi left offset" instruction was given at the 21-nmi DTW MARGE fix, and the "cancel offset" instruction was given at the 15-nmi DTW MARGE fix.

The parallel offsets were flown by using a decentered RDI needle. The procedure that was used is described in the SCENARIO section of this report. The offsets were gauged by the pilot using the dots on the RDI. It was recommended to the pilots that when the lateral deviation needle of the RDI touched the inner edge of the first ($\pm$2.5 nmi) dot, the aircraft was considered to be on a $\pm$2-nmi offset. Similarly, when the lateral deviation needle of the RDI touched the outer edge of the first ($\pm$2.5 nmi) dot, the aircraft was considered to be on a $\pm$3-nmi offset.

Figures 26, 27, and 28 represent the radar tracks of all offset maneuvers conducted on pattern A1, A2, and A6, respectively. It becomes obvious in examining the tracks for these offsets that flights for patterns A1 and A2 exhibit considerably less precision than those for pattern A6. Statistics for these three patterns for the offset case were generated and are enumerated in tables 23, 24, and 25 for patterns A1, A2 and A6, respectively.

Examination of the statistics explains why the A1 and A2 patterns exhibit poor offset performance. In both cases, the TSCT means are high as a result of high RNAV mean computer errors (CPCT). As previously explained in the segmented statistics, the high RNAV computer error means were caused by VOR scalloping (evidenced by high VOR/DME sensor standard deviations). The values of flight technical error standard deviation were not significantly different from the flight technical error statistics for segments where offsets were not flown. It could be concluded that the reason for the poor offset performance on patterns A1 and A2 was the VOR/DME sensor (SNCT) variability (caused by VOR scalloping) and the resultant RNAV computer mean error. The subjects ability to fly a decentered needle for the offset was evidenced by the fact that the flight technical error standard deviations for the offsets were not significantly different from those segments where offsets were not flown.

The A6 pattern statistics support what can be confirmed visually by examining the radar tracks of the A6 offsets. The much smaller sensor standard deviation results in lower computer errors, and therefore, better offset tracking.

DELAY FAN. There were 12 delay fan patterns made during the route A1 STAR. Subject pilots were instructed to make a 3-nmi right offset near the 8-nmi DTW HOTEL fix (on base leg). Upon reaching the 3-nmi offset, they were then instructed to proceed direct to HOTEL for an RNAV approach to runway 4. All subjects executed the maneuver satisfactorily. A composite of the radar tracks for all of the delay fan maneuvers is presented in figure 29.

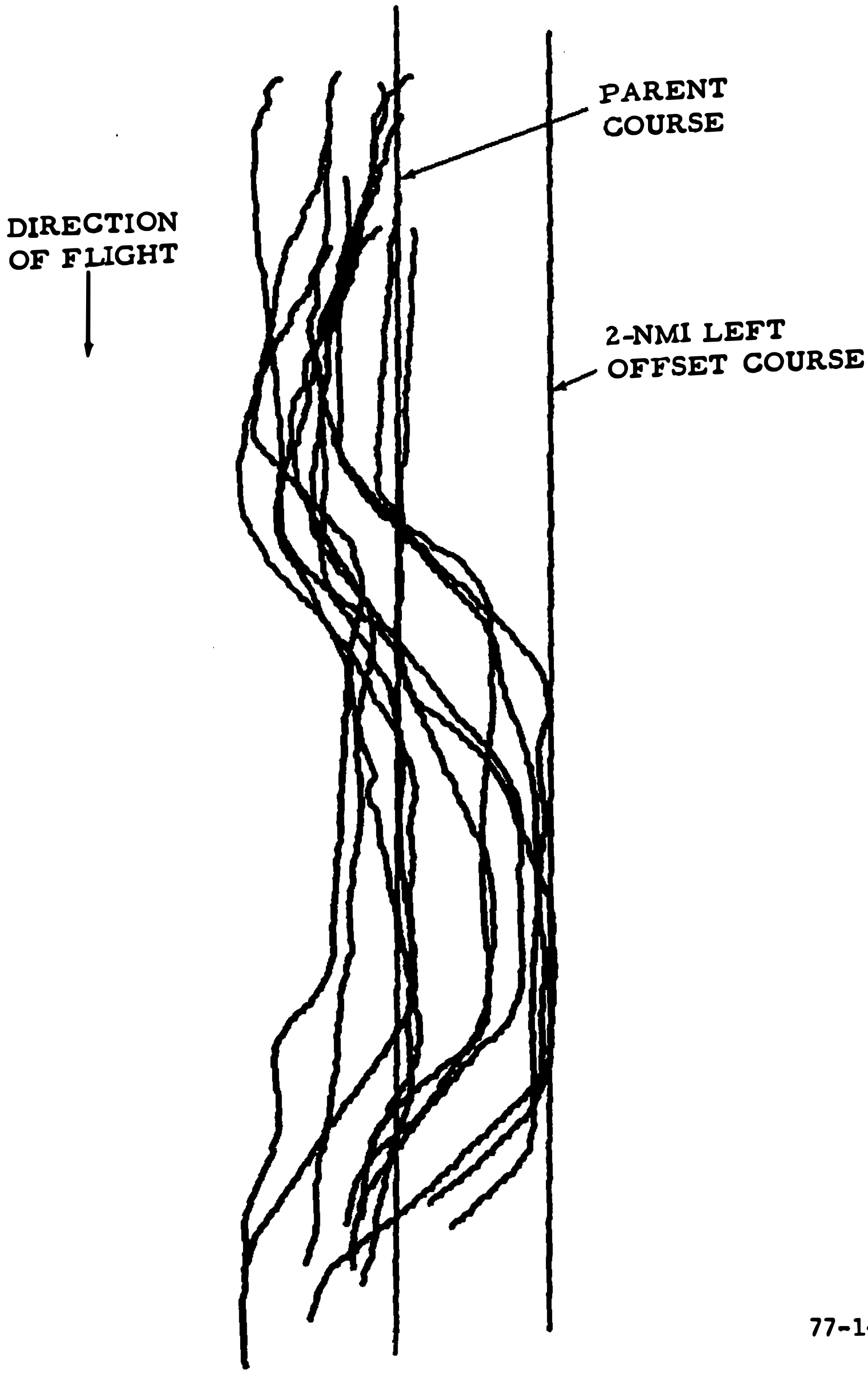


FIGURE 26. PARALLEL OFFSETS ON ROUTE A1

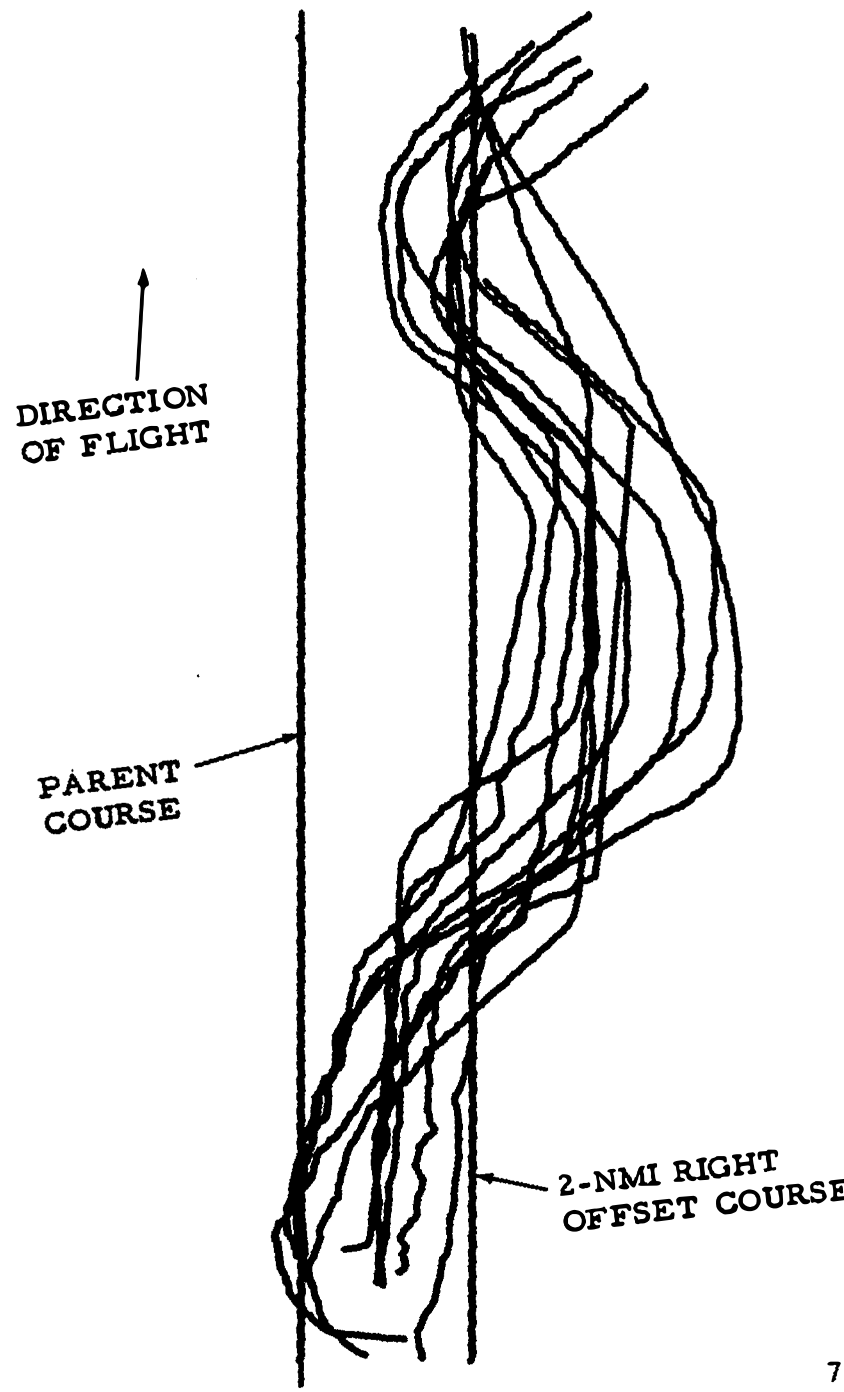


FIGURE 27. PARALLEL OFFSETS ON ROUTE A2

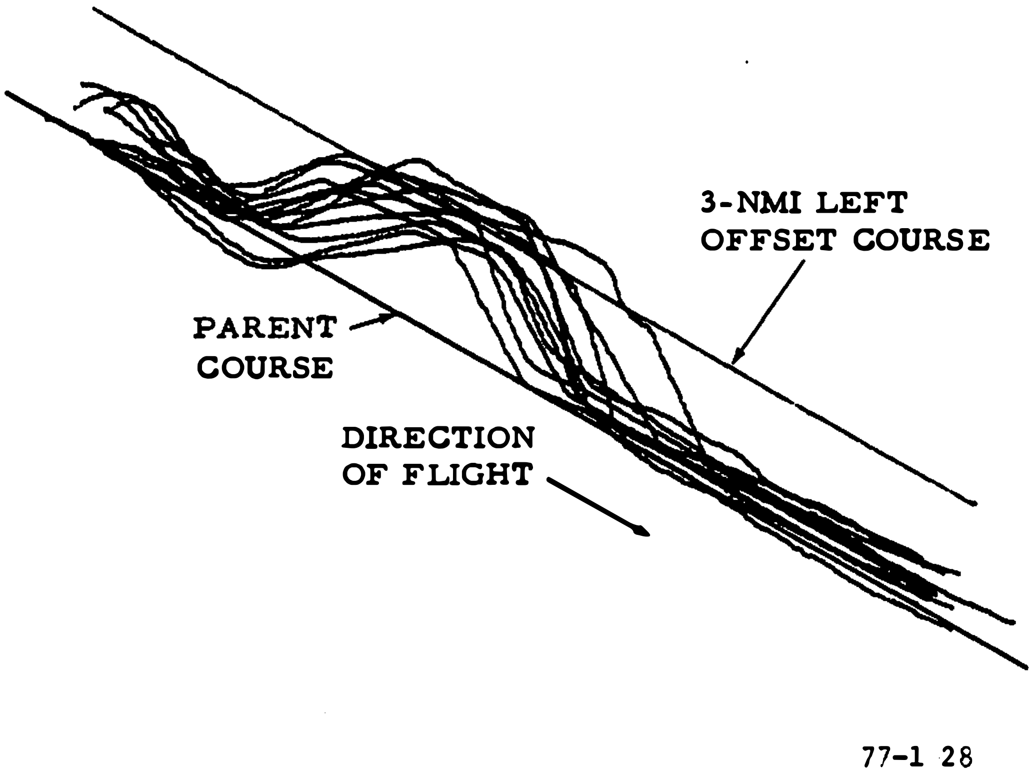


FIGURE 28. PARALLEL OFFSETS ON ROUTE A6

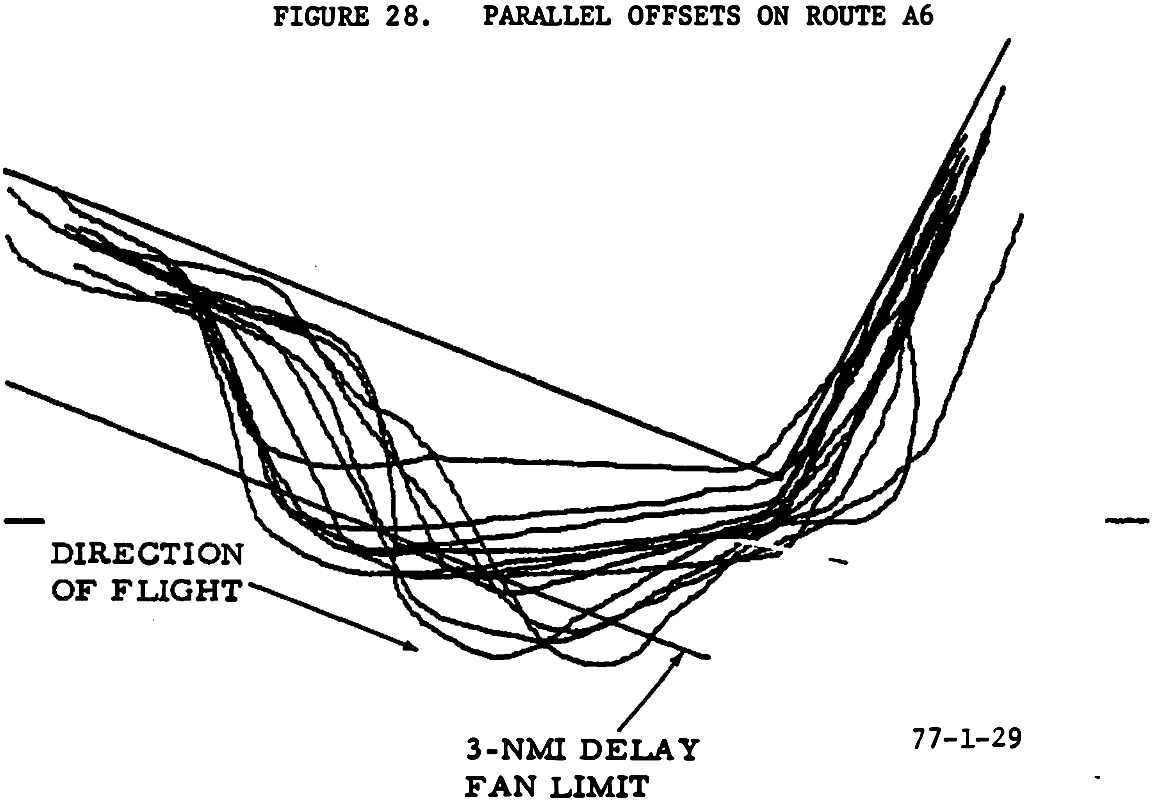


FIGURE 29. DELAY FANS ON ROUTE A1

TABLE 23. OFFSET STATISTICS FOR TEST PATTERN A1

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	472	1.515	1.118
SNCT	472	0.417	0.632
CPCT	472	1.363	0.323
FTE	472	0.032	0.744
OSBN	472	-0.038	0.269

TABLE 24. OFFSET STATISTICS FOR TEST PATTERN A2

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	247	1.472	0.762
SNCT	247	0.167	0.546
CPCT	247	0.830	0.480
FTE	247	0.076	0.587
OBSN	244	0.129	0.125

TABLE 25. OFFSET STATISTICS FOR TEST PATTERN A6

Error	Samples	Mean (nmi)	One Standard Deviation (nmi)
TSCT	316	0.455	0.771
SNCT	292	-0.064	0.074
CPCT	292	0.379	0.199
FTE	316	0.089	0.678
OBSN	292	0.164	0.192

EXTENDED DOWNWIND LEG. There were 12 extended downwind leg patterns flown on route A6. The observer started this event by instructing the pilot, prior to reaching MARGE, to extend his downwind leg 5 nmi beyond MARGE for traffic spacing. The pilot maintained the downwind course past MARGE, using MARGE as the navigation waypoint for the extended downwind leg. When the aircraft passed MARGE, the RDI displayed a FROM indication, and the DTW mileage on the Air Data 61DRM digital display unit started to increase. At the 3-nmi distance past MARGE, the observer, acting as controller, instructed the pilot to proceed direct to BRIGE, for an RNAV approach to runway 31. The pilot then selected the BRIGE coordinates on one of the Air Data 61WPS units, turned toward BRIGE, and turned the OBS knob until the RDI needle was centered for the new course, BRIGE.

All subjects executed the extended downwind leg maneuver in a satisfactory manner. Figure 30 is a composite of the radar tracks of all of the extended downwind leg maneuvers. The large deviation on the figure occurred after the completion of the extended downwind, and was caused by a blunder.

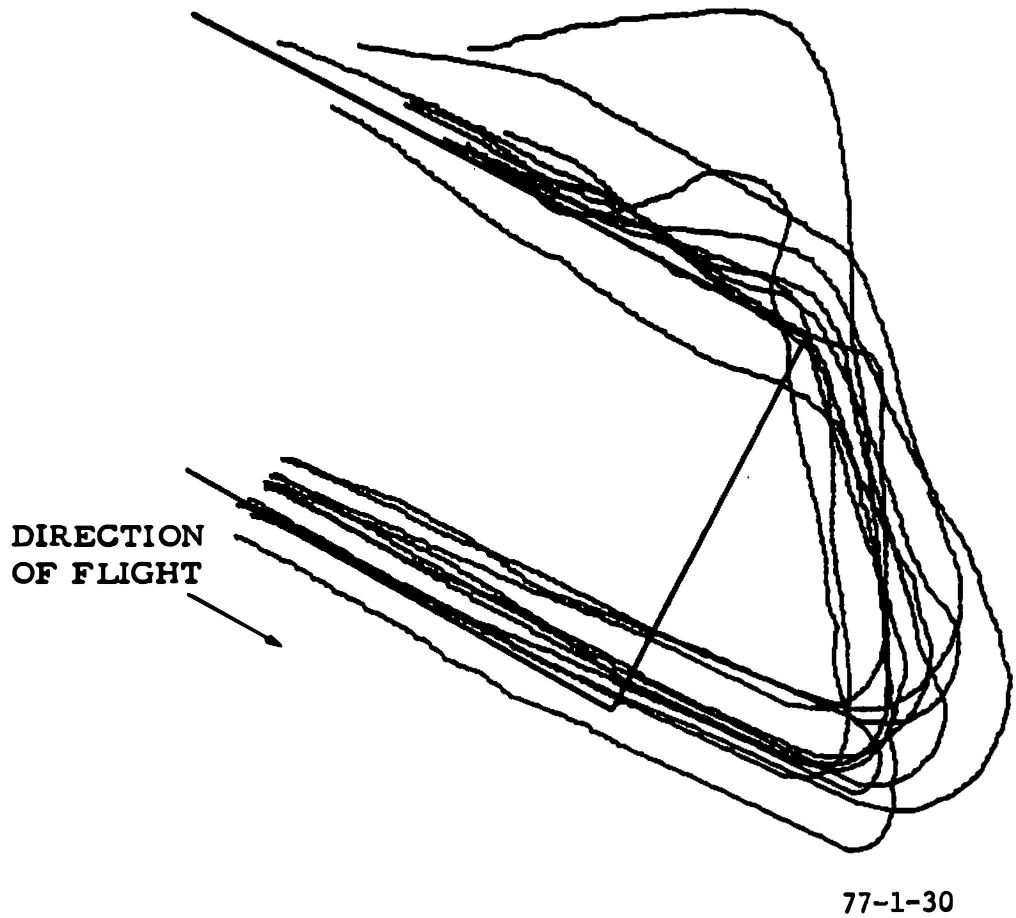


FIGURE 30. EXTENDED DOWNWIND LEG ON ROUTE A6

DIRECT TO WAYPOINT. The direct-to-waypoint function was used a total of 24 times. Twelve were made as part of a delay fan on route A1 and 12 were made as a part of an extended downwind leg on route A6. The preferred method of going direct to the required waypoint was to turn the aircraft toward the waypoint and turn the OBS until the RDI needle was centered. This method provided a direct course to fly to the waypoint from present position. The Air Data 61DRM unit was seldom used for obtaining a bearing to the waypoint for OBS course selections.

Of the 24 direct-to-waypoint patterns flown, there were 14 (58 percent) waypoint overshoots, 1 undershoot, and 9 satisfactory oncourse turns at the direct to waypoint. Although six of the nine satisfactory waypoint turns were made by group B pilots, the overshoots were approximately the same for both pilot groups. No contributing factors could be found between flight director system flights versus RDI-only flights or between waypoint capacities used.

All pilots were entering a heavy workload situation, i.e., landing preparations and radio communications, when "direct-to" maneuvers were required. Each direct-to-waypoint pattern led to the final approach course turn waypoint. This workload did cause some pilots to overlook or become distracted from using adequate turn anticipation procedures.

USE OF DTW FIX IN LIEU OF A WAYPOINT. Those pilots who were restricted to a one-waypoint capability were given the option of using the 5-nmi DTW MAP for runway 4 in lieu of INDIA and the 5-nmi DTW MAP for runway 13 in lieu of CAROLINA to start the final descent to the runways. All pilots were required to use the 8-nmi DTW MARGE fix, on the route A6 STAR, as a point to start a descent from last assigned altitude down to 2,000-feet mean sea level.

All pilots who were restricted to the one-waypoint capability chose using DTW in lieu of the waypoint to start their final descent to the runways. This eliminated the workload of dialing in the waypoint coordinates on the 61WPS unit during an already high-workload phase of the flight. Although all pilots had to be very alert in monitoring the DTW display, no difficulty was noted in using a DTW fix in lieu of a waypoint for starting descents.

IMPROMPTU RUNWAY CHANGE. Each of the 12 pilots were given an impromptu runway change to runway 13 while flying the route A2 STAR for planned approach to runway 4. At no later than the 5-nmi DTW GOLF fix (a waypoint common to starting a base leg for either runway), each pilot was told of the runway change and then recleared for an RNAV arrival to runway 13 via GOLF direct to BALTIC and to maintain assigned altitude to GOLF. This action caused each pilot to study the approach plate for runway 13; replan his flight to the reassigned runway; and for those with a two or three waypoint capacity, change the waypoint coordinate previously set. The more waypoint coordinates the pilot had to change, the greater the workload became. All pilots made the transition to the new runway without incident. From statements made by some of the pilots, a good deal of mental stress was created by having to abruptly reorient themselves to this kind of change. Considerable "heads down" was needed by each pilot to orient, prepare, and make the necessary route changes. This distracted them from other flight duties.

TURN ANTICIPATION.

The application of pilot turn anticipation by leading a turn at 1 nmi per 100 knots of true airspeed (TAS), as recommended in AC90-45A, had mixed results. Although applying this turn method was voluntary on the pilot's part, 10 of the 12 pilots attempted to use it during their flights. Only 2 of these 10 pilots used the recommended turn anticipation procedure consistently for all routes. The others would apply it for some turns, but not others. Most pilots who did not apply the turn procedure correctly were distracted by other duties at those times. When applied consciously and correctly, the AC90-45A turn anticipation method worked well.

To analyze the turn anticipation performance of the subjects, the tracking radar-data for each subject was plotted to make a composite plot of all subjects for each turn. The desired course, as well as a ±1.5-nmi route width, are also plotted on the composite. The analysis of turn performance follows.

ROUTE A1.

CHARLIE (Figure 31) 42° Turn Angle. Subjects generally undershot this turn, but most stayed within the ±1.5-nmi airspace. Four subjects deviated from the general trend and either violated the airspace boundary or came very close to it. Of these four, three were from group B (high experience). Configurations for these four were one-waypoint/flight director, one-waypoint/RDI, two-waypoint/flight director, and three-waypoint/RDI.

DELTA (Figure 32) 90° Turn Angle. Subjects generally performed well on the turn at DELTA. Tracking for the group B pilots was much better entering the turn than that of the group A pilots. The two deviations from the general trend are labeled in figure 32. In the one case, a group B subject was flying in the one-waypoint/flight director configuration. In the other case, a group A subject undershot the turn and then set the wrong OBS course (blunder), which resulted in his track crossing the desired track and diverging. His configuration was one-waypoint/RDI. All turns were within the confines of the ±1.5-nmi airspace.

ECHO (Figure 33) 94° Turn Angle. The general trend of both subject groups was to overshoot the turn at ECHO. The problem here seems to be the poor quality sensor signals for the ECHO-FOXTROT segment. All subjects exhibit good tracking going into the turn at ECHO, but tracking outbound from ECHO is very poor. With three exceptions, the subjects started the turn at the proper time, but drifted to the right of the desired course coming out of the turn. Segmental statistics showed a high standard deviation for VOR/DME sensor errors for the ECHO-FOXTROT segment.

Three subjects continued past ECHO waypoint. Although the poor quality sensor signals may have had some effect, it appears as though they did not follow the correct turn anticipation procedure. The largest overshoot was by a group B subject with a three-waypoint/RDI configuration. Two smaller overshoots were by two group A subjects with a three-waypoint/RDI and a two-waypoint/flight director configuration.

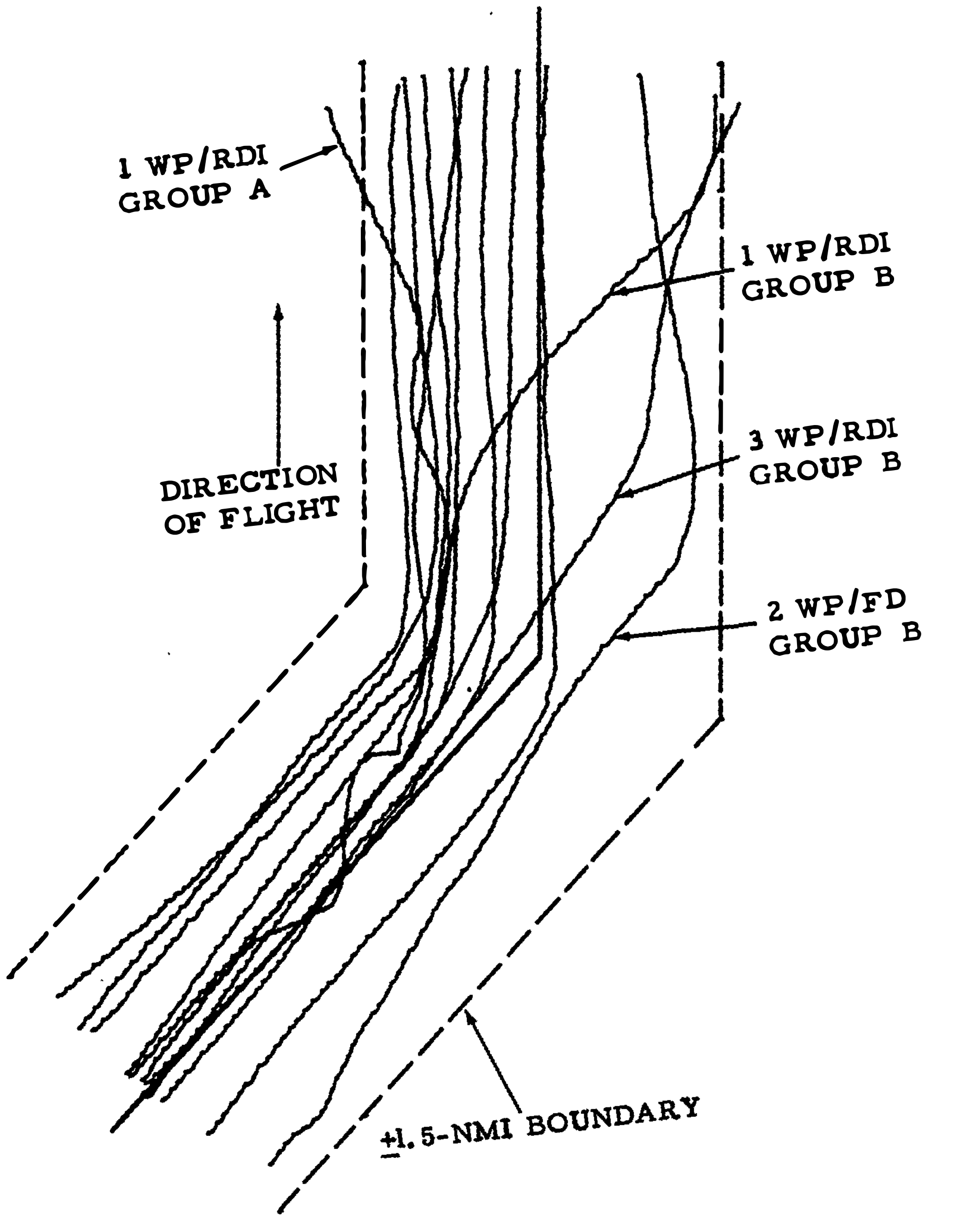
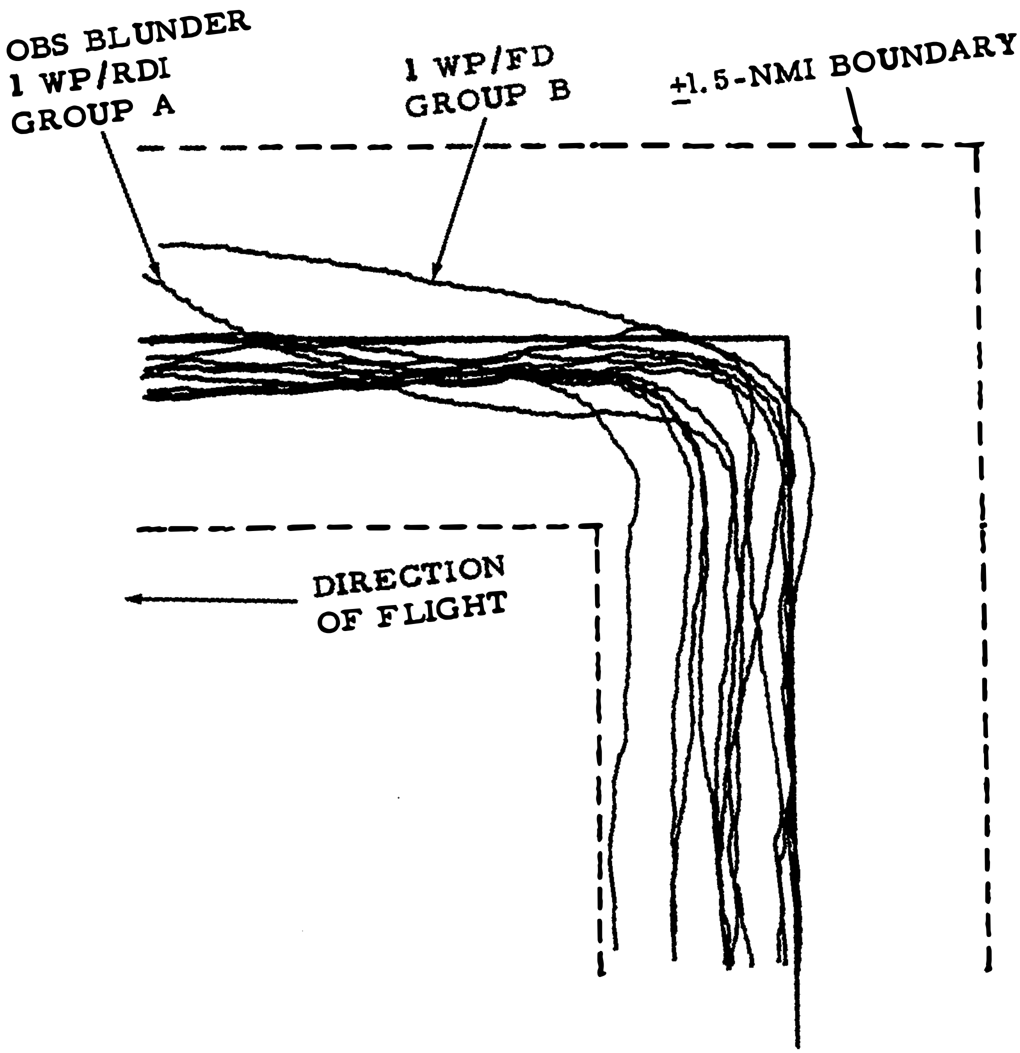
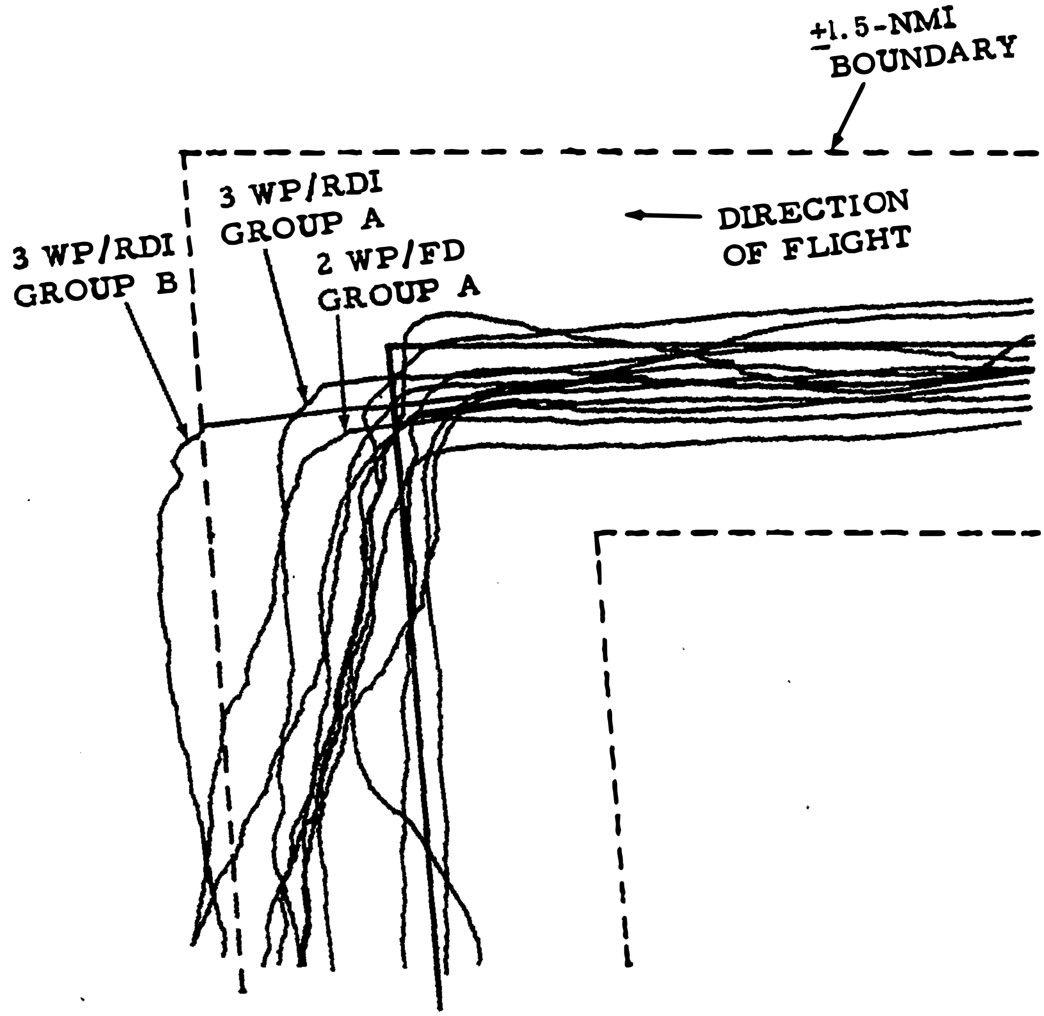


FIGURE 31. TURN ANTICIPATION FOR TURN CHARLIE ON ROUTE A1



77-1-32

FIGURE 32. TURN ANTICIPATION FOR TURN DELTA ON ROUTE A1



77-1-33

FIGURE 33. TURN ANTICIPATION FOR TURN ECHO ON ROUTE A1

FOXTROT (Figure 34) 22° Turn Angle. No comments can be made regarding turn anticipation at FOXTROT because of the poor quality of guidance signals in this area.

GOLF (Figure 35) 93° Turn Angle. Overshoots were predominant on this turn, with no undershoots at all. Of the three largest overshoots, two were executed by group A pilots, and one was executed by a group B pilot. The configurations were as follows: for the group A pilots, one-waypoint/RDI and three-waypoint/RDI; and for the one group B pilots, three-waypoint/RDI. The deviations after the turn were intentional (a delay fan maneuver was started after the turn).

HOTEL (Figure 36) 83° Turn Angle. Subjects were returning from a delay fan maneuver at turn HOTEL. There was only one slight undershoot, and the general trend was toward an overshoot situation. Of the two overshoots, one was committed by a group B subject, while one was committed by a group A subject. The configuration for the group B subject was three-waypoint/flight director. The group A subject's configuration was one-waypoint/flight director.

ROUTE A2.

ROMEO (Figure 37) 88° Turn Angle. Turn anticipation performance at ROMEO was generally good. The group B subjects performed much more consistently than did the group A subjects. The largest overshoot was committed by a group A subject with a two-waypoint/RDI configuration. The large deviation outside the confines of the ±1.5-nmi airspace was the result of a blunder error.

SIERRA. No turn anticipation performance was considered at waypoint SIERRA because of the shallow turn angle (13°).

TANGO (Figure 38) 76° Turn Angle. Turn anticipation at TANGO was quite good. There were more undershoots than overshoots, but in both cases, the degree of undershoot or overshoot was small.

UNIFORM (Figure 39) 97° Turn Angle. Turn performance at UNIFORM was difficult to analyze because of the high mean errors evidenced by the statistics for segment UNIFORM-VICTOR in table 13. The straight-line tracks followed by the subjects after apparent undershoots made it rather obvious that these turns were not procedural undershoots, but were due to a combination of sensor and computer errors. Likewise, those turns which appeared to be procedurally correct were most likely overshoots in relation to the guidance signals presented to the subject.

VICTOR (Figure 40) 52° Turn Angle. Turn anticpation at VICTOR was difficult to analyze because of the poor quality guidance signals in this area. The one run that deviated from the general trend was flown by a group A subject with a three-waypoint/flight director configuration.

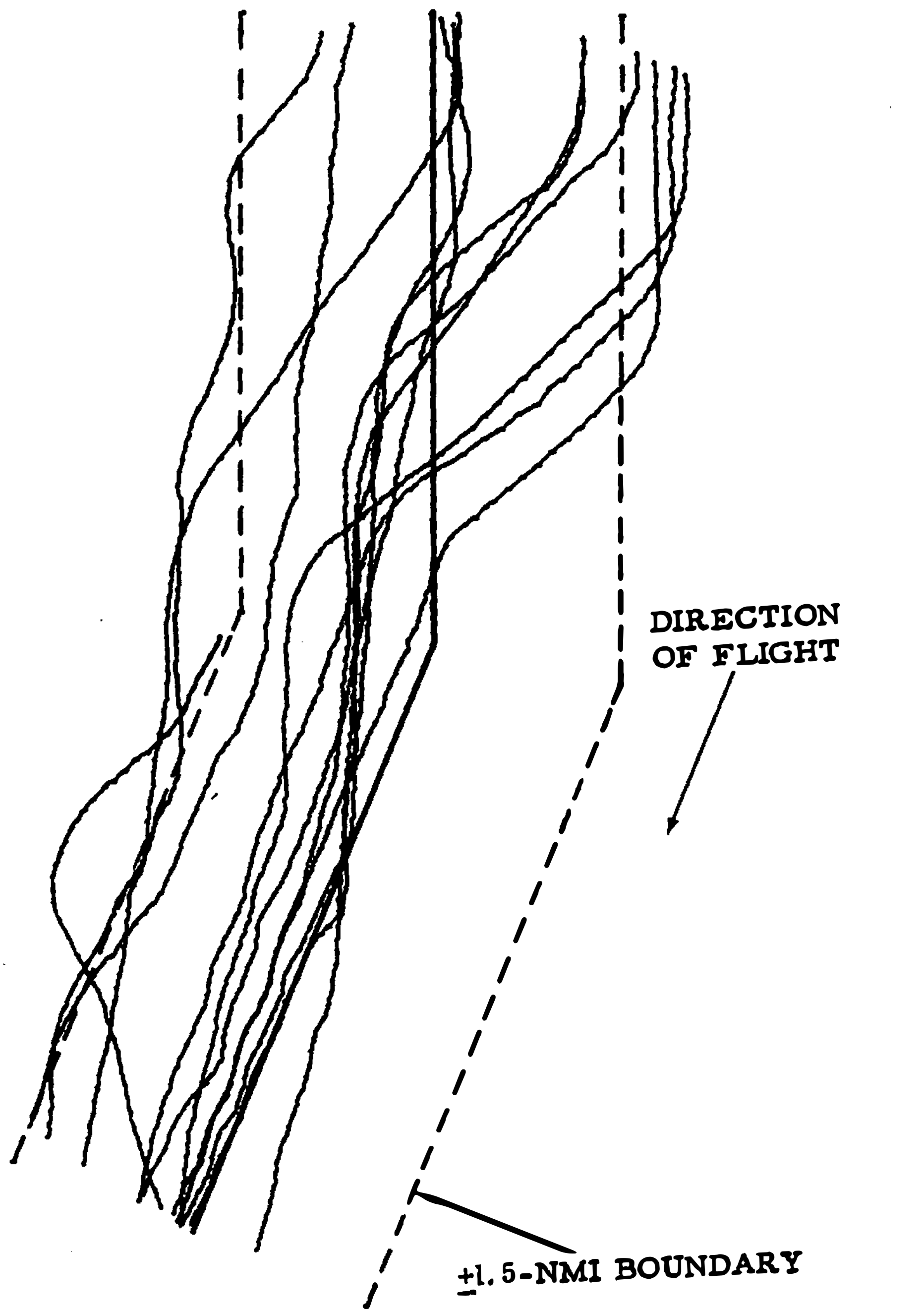


FIGURE 34. TURN ANTICIPATION FOR TURN FOXTROT ON ROUTE A1

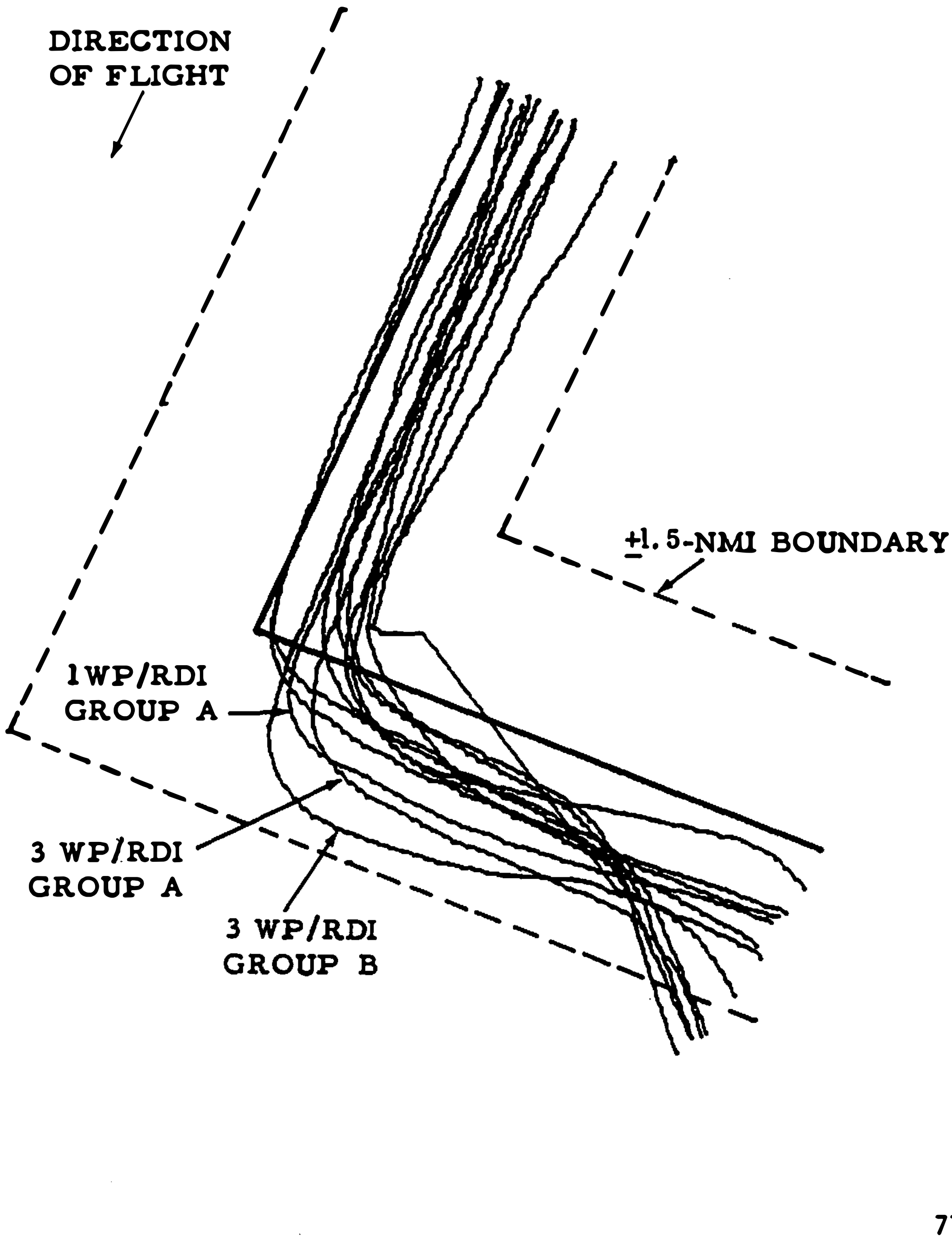


FIGURE 35. TURN ANTICIPATION FOR TURN GOLF ON ROUTE A1

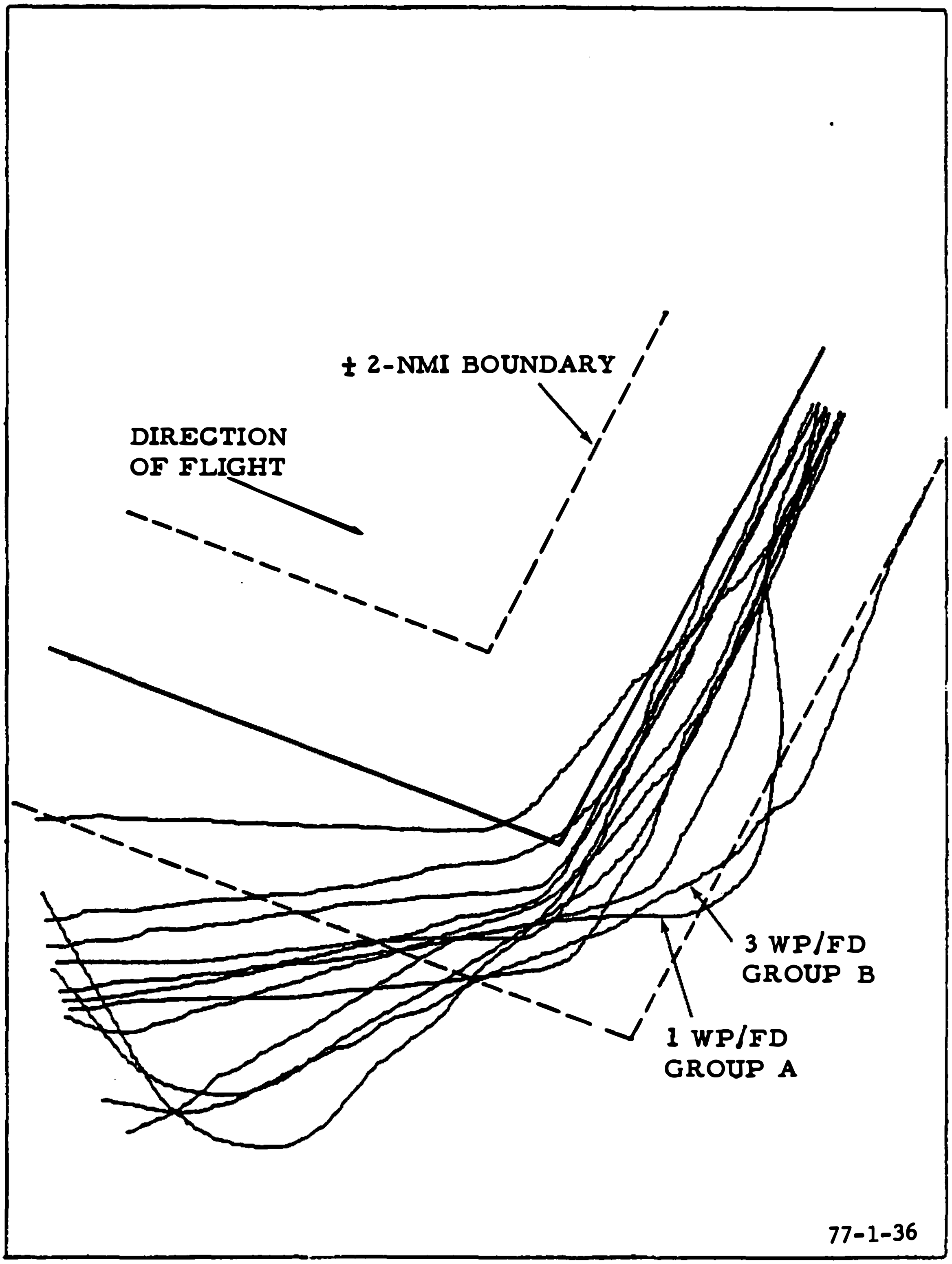


FIGURE 36. TURN ANTICIPATION FOR TURN HOTEL ON ROUTE A1

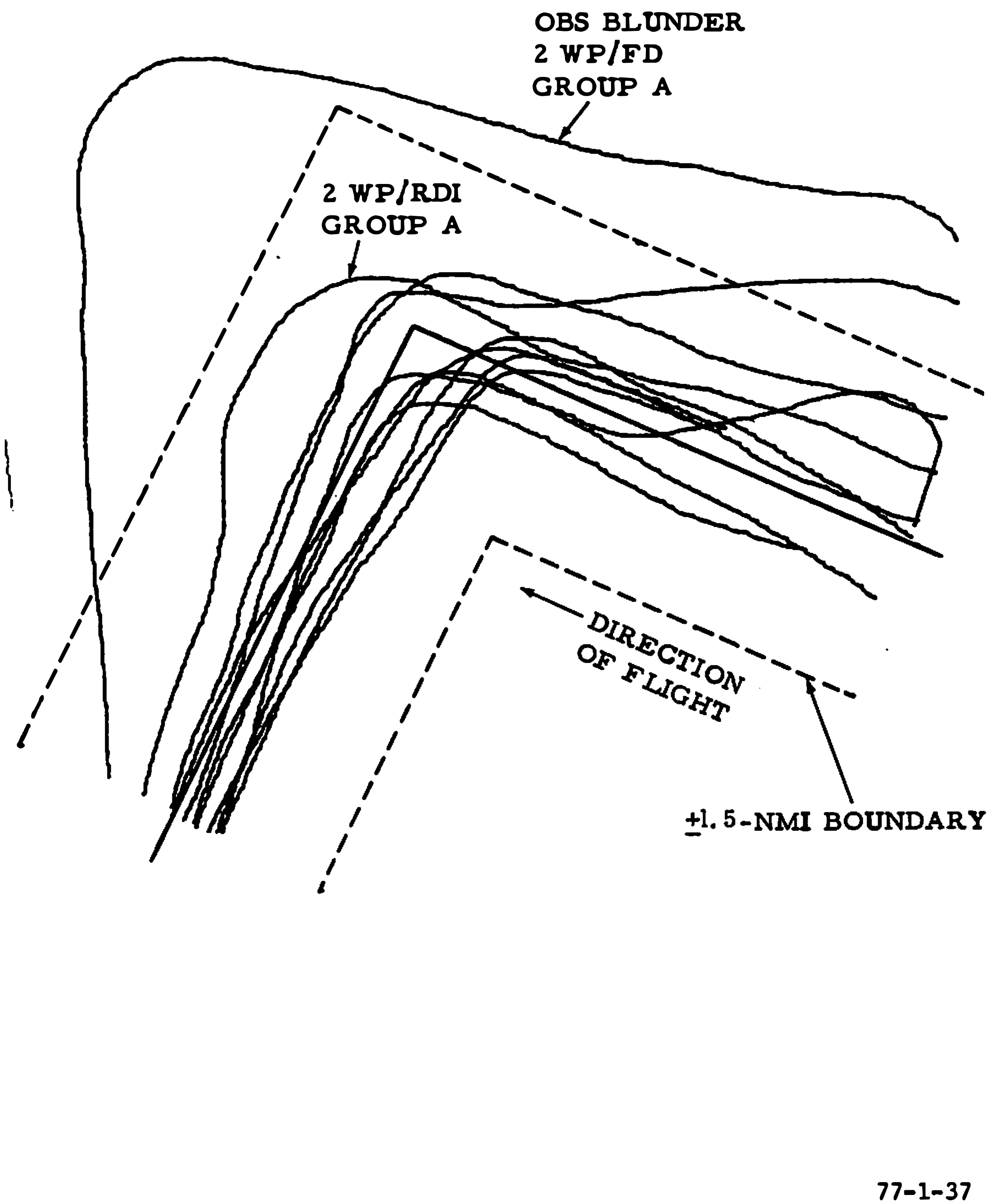


FIGURE 37. TURN ANTICIPATION FOR TURN ROMEO ON ROUTE A2

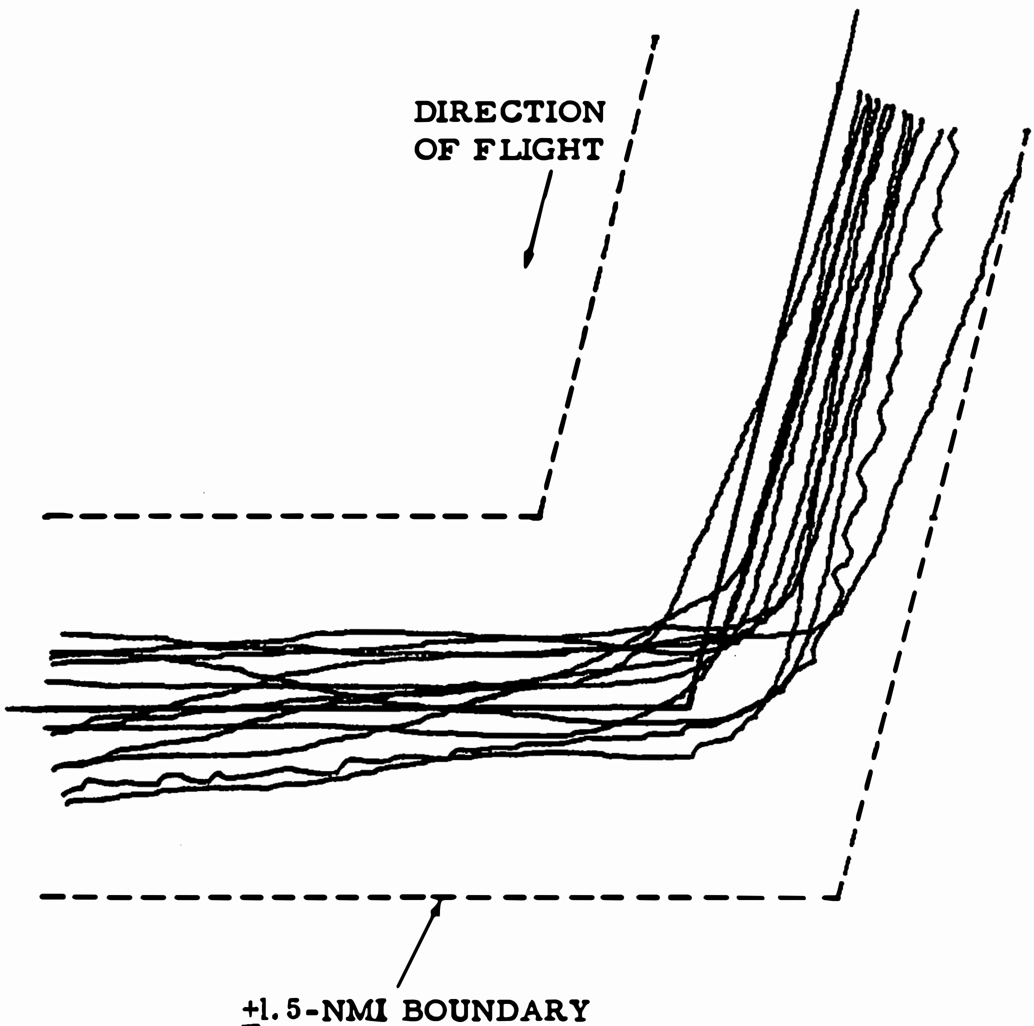
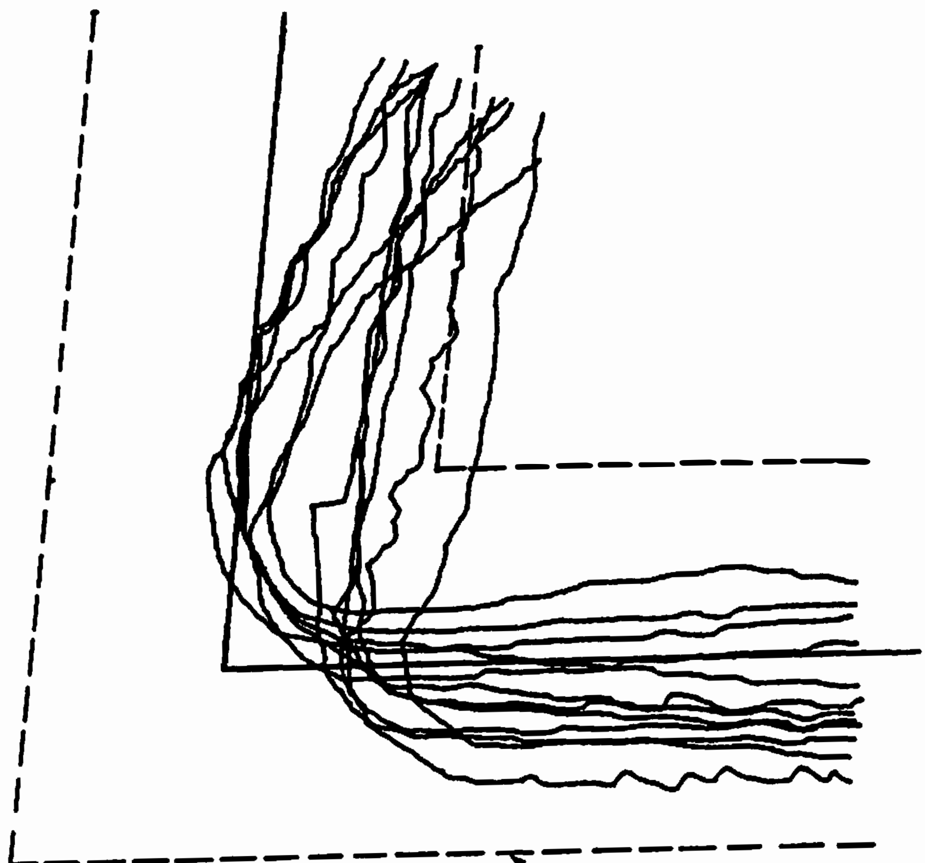


FIGURE 38. TURN ANTICIPATION FOR TURN TANGO ON ROUTE A2



77-1-39

FIGURE 39. TURN ANTICIPATION FOR TURN UNIFORM ON ROUTE A2

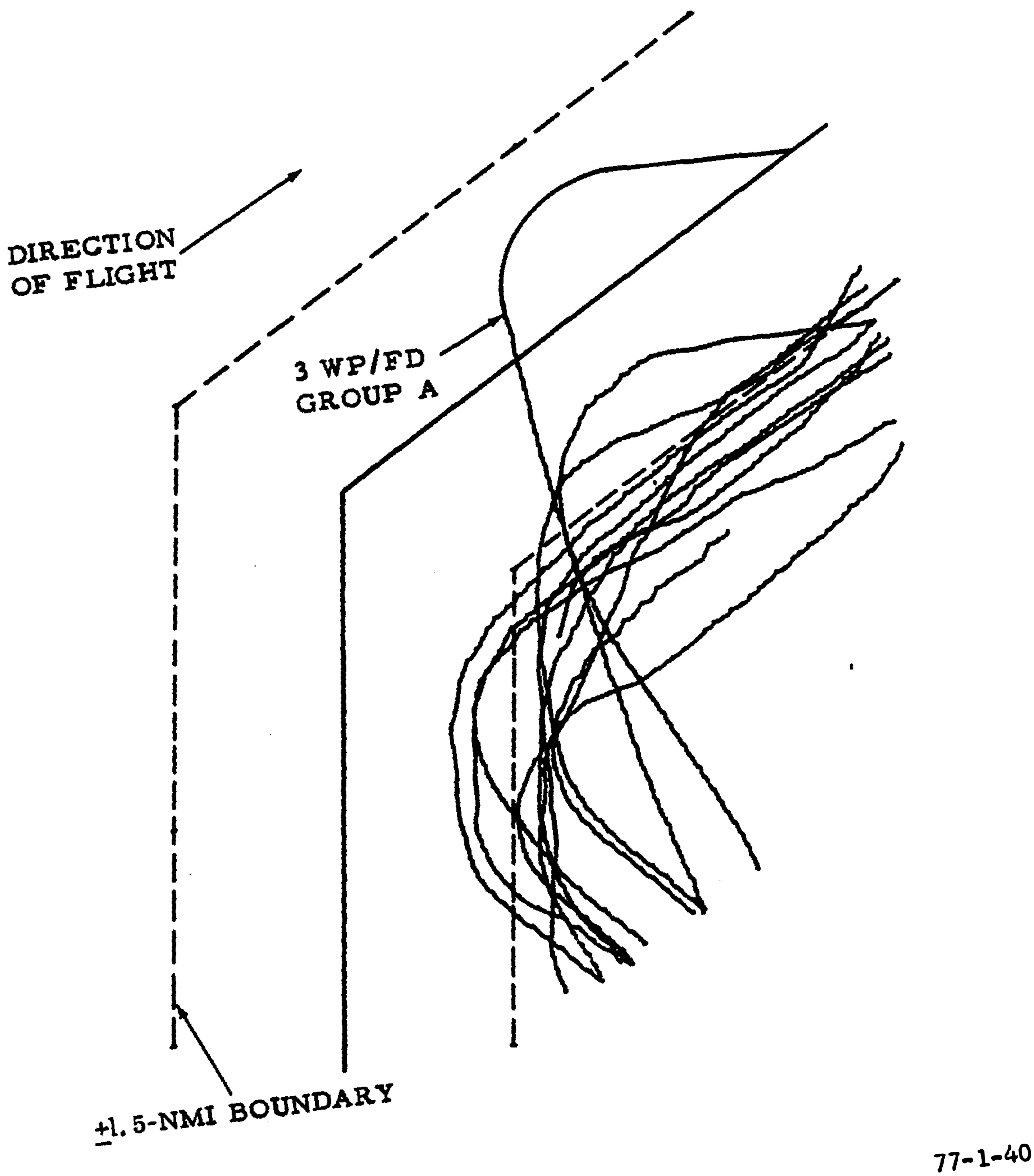


FIGURE 40. TURN ANTICIPATION FOR TURN VICTOR ON ROUTE A2

GOLF (Figure 41) 21° Turn Angle. Turn performance at GOLF was uniform with respect to executing the turn at the proper time. The subject's flightpaths showed a bias to the right upon entering and leaving the turn, but there were no overshoots or undershoots evident.

BB (Figure 42) 80° Turn Angle. Turn performance at BB was consistent, with all subjects turning inside of the intended waypoint. This effect was due more to sensor and computer errors than procedural errors. Three subjects did essentially "cut the corner" and intercept the next leg at a 45° angle, but none violated the ±1.5-nmi airspace.

ROUTE A6.

TUCKO. No turn performance was measured at TUCKO because of the small turn angle involved.

DEBAY (Figure 43) 114° Turn Angle. Turn performance at DEBAY was consistent with two exceptions from group A. The configurations were two-waypoint/flight director and one-waypoint/RDI. The subject with the one-waypoint configuration was attempting to set in the coordinates of the next waypoint just after he started the turn. This distracted him to the extent that he did not realize he was overshooting the turn until he completed the task of setting up the next waypoint.

WEBAY (Figure 44) 66° Turn Angle. Turn performance at WEBAY was consistent with all subjects turning inside of the waypoint. Again, this was due to a combination of sensor and computer errors, rather than procedural errors. One subject did start his turn earlier than the other subjects. The subject was from group A and was flying with a one-waypoint/flight director configuration.

LANVE (Figure 45) 81° Turn Angle. There was a definite overshoot tendency at LANVE, particularly with the group A pilots. There were five overshoots on turn LANVE, three of which came close to encroaching on the ±1.5-nmi route boundary. Four of the five overshoots were committed by group A subjects, and four of the five subjects had a multiple-waypoint storage capacity.

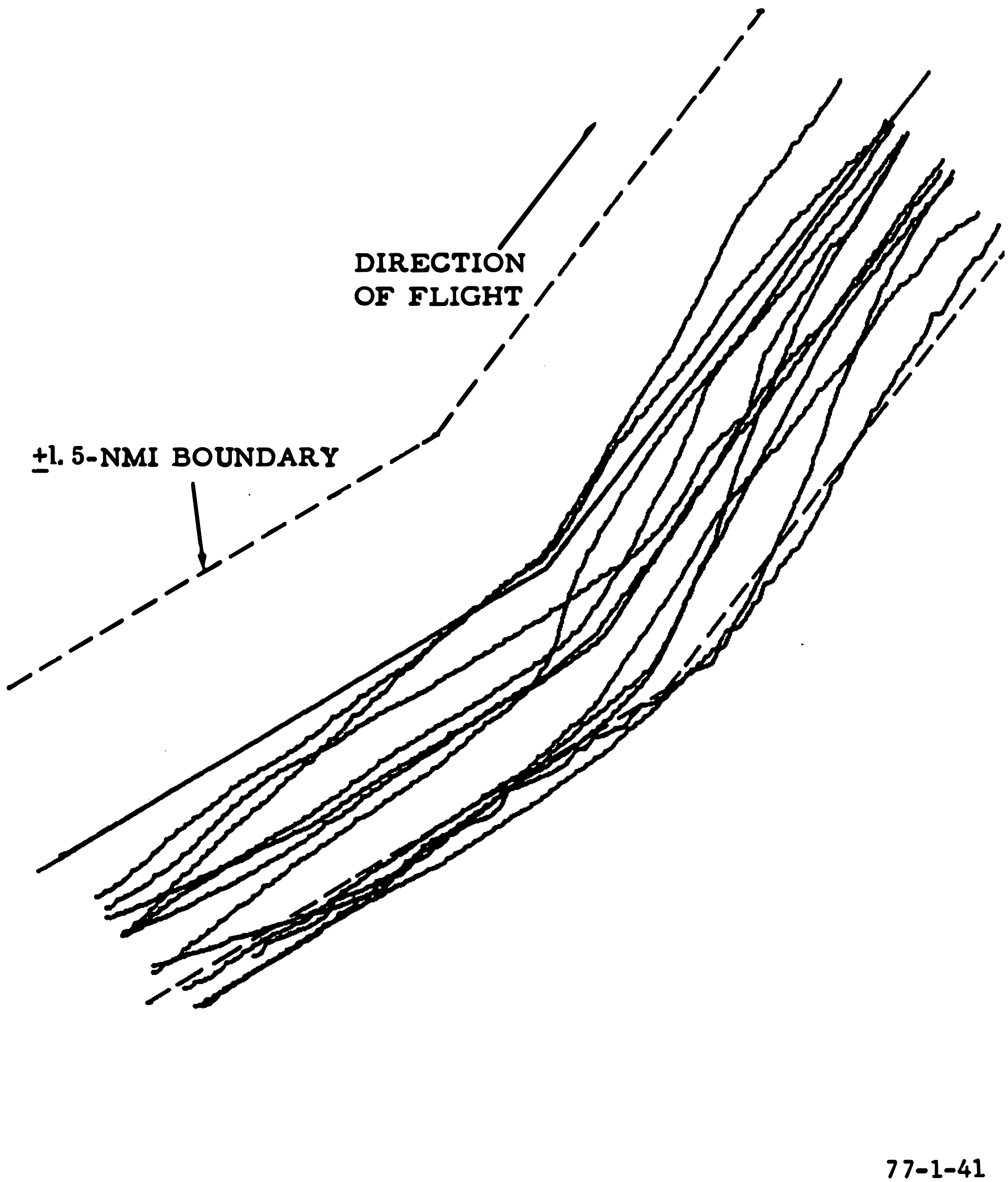


FIGURE 41. TURN ANTICIPATION FOR TURN GOLF ON ROUTE A2

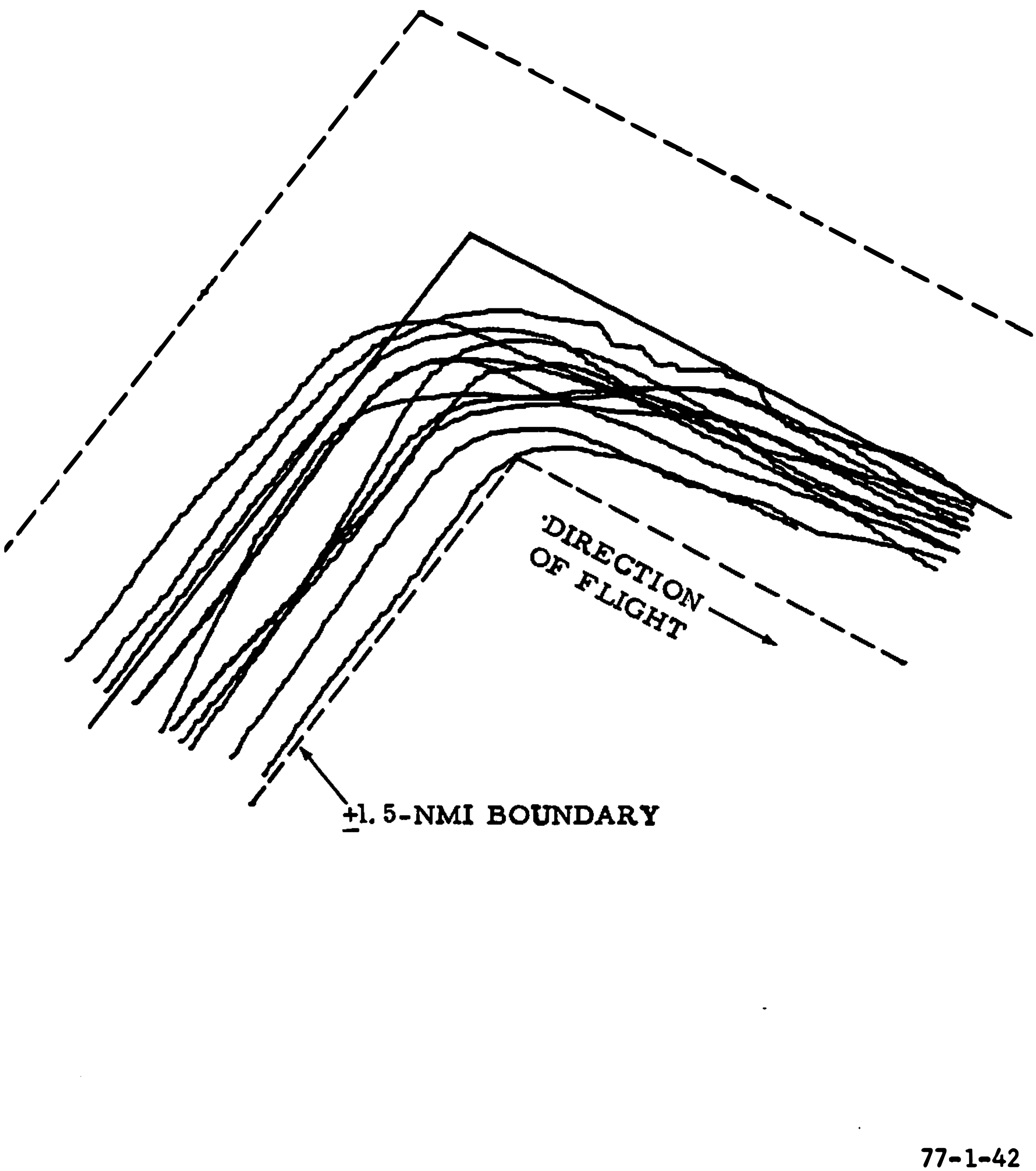


FIGURE 42. TURN ANTICIPATION FOR TURN BB ON ROUTE A2

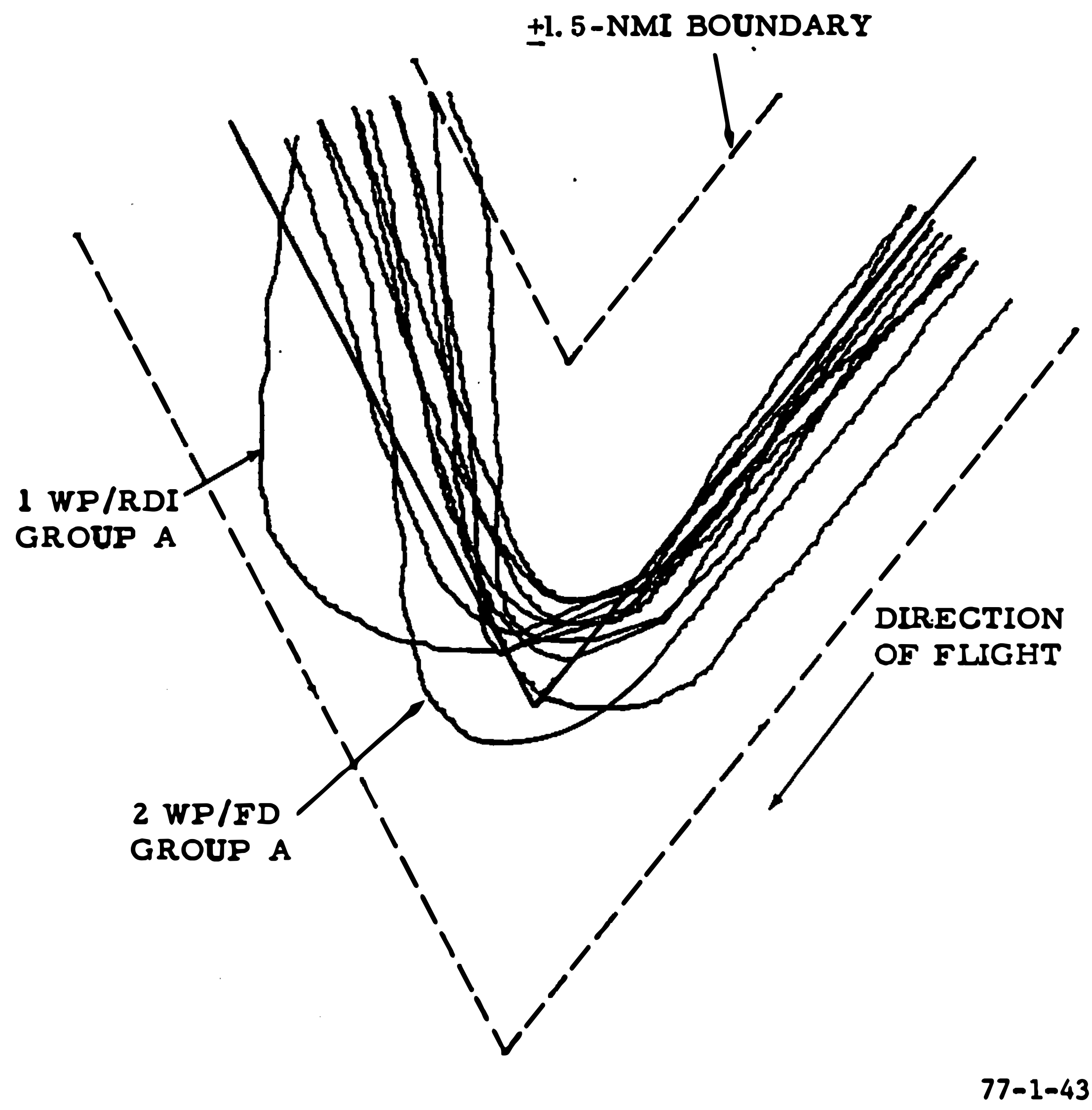


FIGURE 43. TURN ANTICIPATION FOR TURN DEBAY ON ROUTE A6

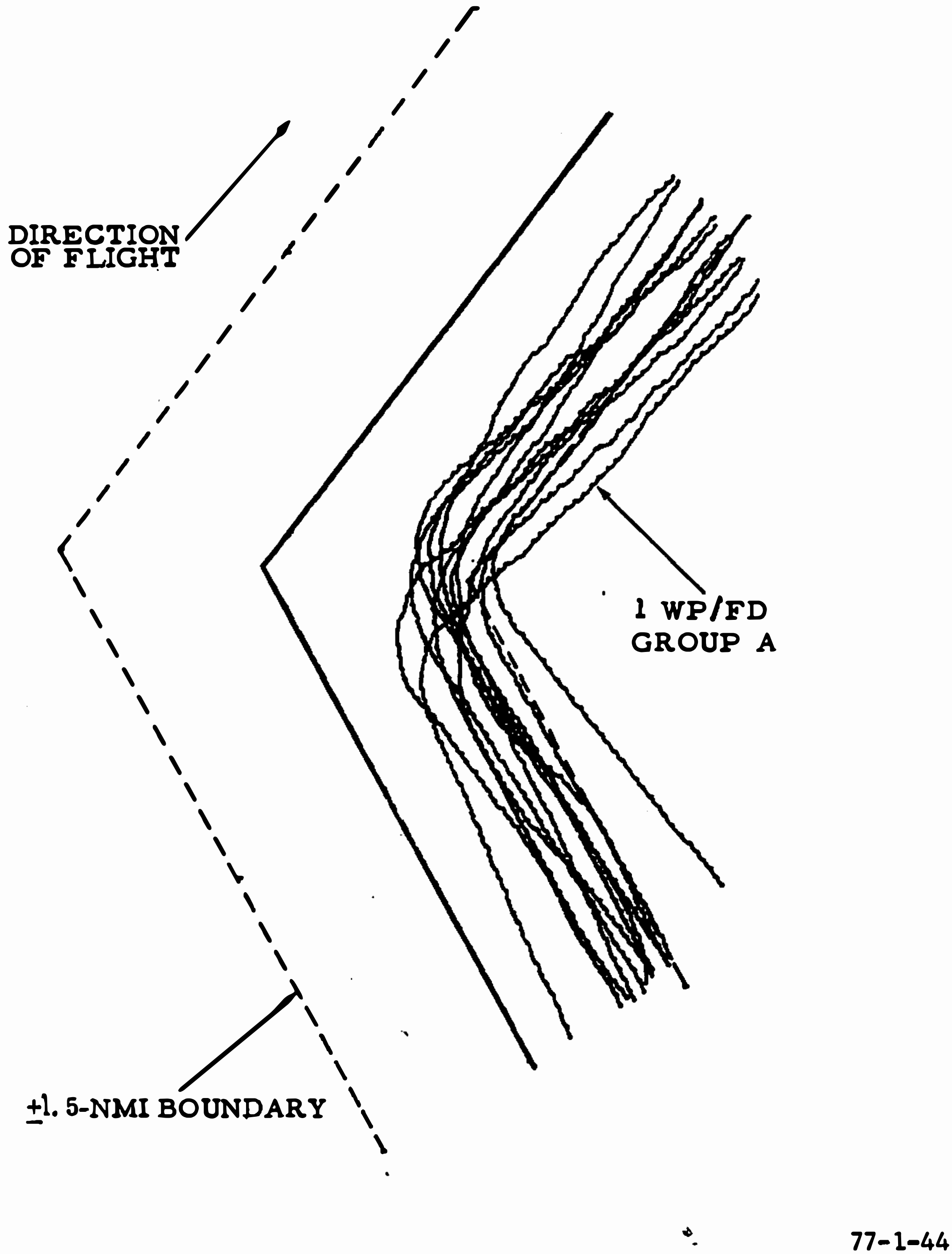
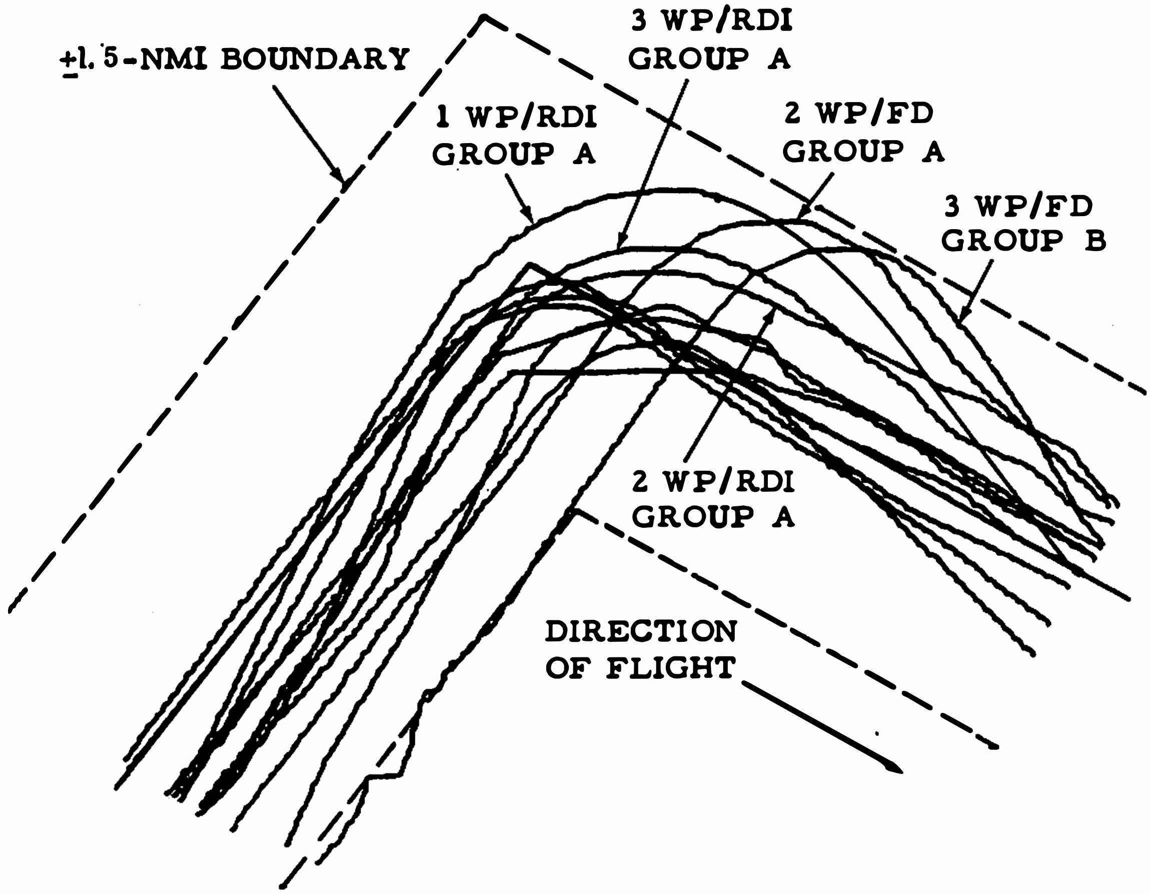


FIGURE 44. TURN ANTICIPATION FOR TURN WEBAY ON ROUTE A6



77-1-45

FIGURE 45. TURN ANTICIPATION FOR TURN LANVE ON ROUTE A6

SUMMARY OF RESULTS

1. The one standard deviation for sensor crosstrack error (airborne and ground combined) was 0.336 nmi, while the one standard deviation for sensor along-track error (airborne and ground combined) was 0.195 nmi. These values are for VOR/DME navigation in the terminal area.

2. The one standard deviation for RNAV computer crosstrack error was 0.673 nmi, while the one standard deviation for RNAV computer along-track error was 0.506 nmi. These values are for VOR/DME navigation in the terminal area. This is higher than the presently assumed AC90-45A computer error budget figure of 0.5 nmi.

3. On some route segments with VOR scalloping present, the mean value for RNAV computer error was as much as two to three times as large as the RNAV computer error one standard deviation.

4. The one standard deviation for OBS setting errors was 2.1°. This corresponds to a one standard deviation of 0.358 nmi when calculated along the RNAV route.

5. The one standard deviation for flight technical error in the terminal area was 0.533 nmi. This value was a composite for pilots of two distinct experience levels using either flight director or RDI for guidance. The one standard deviation of 0.176 nmi for flight technical error on approach was also obtained.

6. The one standard deviation for total system crosstrack error in the terminal area was 0.765 nmi. This value was for VOR/DME navigation on manually flown flights. The one standard deviation of 0.234 nmi was obtained for total system crosstrack error on approach.

7. A comparison between measured total system crosstrack error and total system crosstrack error calculated using the root-sum-square method yielded the following results:

	Measured Crosstrack Error One Standard Deviation (nmi)	Root-Sum-Square Crosstrack Error One Standard Deviation (nmi)
Terminal	0.765	0.899
Approach	0.234	0.287

8. On some route segments with VOR scalloping present, the mean value for total system crosstrack error was as much as two to three times as large as the total system crosstrack one standard deviation for that segment. This was primarily caused by the high mean RNAV computer error in the presence of VOR scalloping.

9. For the terminal area statistics, total system crosstrack error had good correlation with both RNAV computer crosstrack error and flight technical error, fair correlation with OBS error, and no correlation with sensor crosstrack error.

10. The error components of total system error crosstrack identified in the order of their contribution to total system error in the terminal area are RNAV computer crosstrack error, flight technical error, OBS error, and VOR/DME sensor crosstrack error.

11. For approach statistics, total system crosstrack errors show very good correlation with flight technical error and fair to little correlation with RNAV computer error, VOR/DME sensor crosstrack error, and OBS error.

12. The error components of total system crosstrack error identified in the order of their contribution to total system error on approach are flight technical error, sensor crosstrack error, OBS error, and RNAV computer error.

13. A large amount of blunders (18) and errors (25) were committed during the 36 test flights. The blunders and errors fall into five categories which are listed in the order of their frequency of occurrence; (1) OBS setting, (2) wrong waypoint coordinates used, (3) incorrect VOR frequency used, (4) RNAV system operational error, and (5) miscellaneous.

14. Eighty-three percent of the blunders were committed by the low-experienced group of subjects.

15. Sixty-one percent of the blunders occurred during the first 5 minutes after takeoff or during the last 5 minutes prior to landing.

16. The least amount of total blunders occurred with subjects using a two-waypoint storage capacity.

17. The one standard deviation of flight technical error for subjects flying parallel offsets using a decentered RDI needle was slightly higher than the one standard deviation of flight technical error achieved when flying the parent course.

18. When using procedural turn anticipation, there was more of a tendency to overshoot rather than undershoot the turns.

CONCLUSIONS

From the results, it was concluded that:

1. The two-standard-deviation value of ±1.53 nmi measured for total system crosstrack error in the terminal area is well within the ±2-nmi route width requirement.

2. The two-standard-deviation value of ±1.05 nmi measured for flight technical error in the terminal area is not reliably different from the ±1.0-nmi flight technical error cited in the task force report.

3. The two-standard-deviation value of ±0.35 nmi measured for flight technical error on approach supports the RNAV Task Force report flight technical error budget of ±0.5 nmi for approach.

4. The error contribution introduced by inaccuracies in setting the OBS to the desired course is significant and should be considered in the total system error budget for RNAV systems not using automatic or digital OBS setting devices.

5. The root-sum-square method of calculating total system crosstrack error provided figures which are close to, but slightly higher than the measured total system crosstrack error.

6. Subject pilots utilizing a two-waypoint storage capacity committed fewer blunders than those subjects with a one- or three-waypoint storage capacity. From the cockpit workload standpoint, subjects with one-waypoint storage capacity were observed to have unacceptably high workload periods, while those with two- or three-waypoint storage capacity could select reduced workload periods for setting up new waypoint coordinates. With multiple-waypoint storage capacity, however, bookkeeping chores increased, and more heads-down time was required for map studying and bookkeeping chores. It is therefore concluded that for terminal area RNAV operations, a one-waypoint storage capacity is unacceptable, and that between the two- and three-waypoint configuration, the two-waypoint storage capacity is optimum.

7. The most significant factors in pilot blunders are pilot experience level, the amount of preflight planning, and cockpit workload.

8. Subject pilots demonstrate the ability to fly parallel offsets using a decentered RDI needle with flight technical error only slightly larger than the centered RDI needle technique. The decentered needle limits the amount of allowable offset to a maximum of about 4 nmi, with the RDI scale factor of the type of equipment used in these tests.

9. The use of procedural turn anticipation results in a mix of satisfactory turns, overshoots, and undershoots. Turn overshoots are much more likely to violate protected airspace than are undershoots. It is concluded that if procedural turn anticipation is used, additional protected airspace, as presently defined in Air Traffic Procedures Handbook 7110.65, Section 7, is a definite requirement.

10. There was no statistically significant difference in the flight technical error when subjects used either a flight director or a radio deviation indicator for RNAV guidance.

11. The subjects experienced no difficulty in using a distance-to-waypoint fix in lieu of a waypoint for starting descents. It was not used for climbouts.

12. The preflight pilot training (2 to 4 hours) and flight training (3 to 5 hours) was considered the minimum needed to accomplish these RNAV tests. More training may have reduced the blunder tendency, but the key to lower blunder tendencies was found in those pilots who demonstrated a high degree of self-preflight preparation and good cockpit management.

13. The subjects encountered no difficulty in executing the delay fan, even though one subject did blunder at the start of this maneuver because he was in the RNAV APPROACH mode. However, using the decentered RDI needle for the offset portion of this maneuver did not provide enough accuracy for subjects to consistently determine when they had reached the desired 3-nmi offset distance.

14. The subjects executed the modified extended downwind leg maneuver in a satisfactory manner. One blunder and one error were made after this maneuver was completed, because the OBS was incorrectly reset to the final approach course.

15. The subjects executed the direct-to-waypoint function, as part of the delay fan and extended downwind leg maneuver, in a satisfactory manner.

16. The subjects made the transistion to the new assigned runway, as the result of an impromptu runway change, in a satisfactory manner. However, the considerable "heads down" time and additional workload required by each pilot to orient, prepare, and make the necessary route changes caused distractions from other flight duties.

17. When it is required to formulate waypoint coordinates (one waypoint capability) while flying between closely located waypoints, or it is elective, most pilots can expect to encounter serious workload problems. This is especially true near the final approach or departure areas where heavy workloads already exist.

APPENDIX A

ERROR CALCULATIONS

By using latitude and longitude as the basis for all error computations, the number of computer subroutines were held to a minimum and a uniformity of error calculations resulted. Spherical earth computations were used throughout.

Initially, all errors were calculated referenced to a desired position, P_d, located on the desired track. The coordinate system was defined with the origin at P_d and with axes aligned with lines of latitude and longitude. After the computation of the error values in X and Y coordinates referenced to this coordinate system, a coordinate transformation was performed to align the error values into along-track and crosstrack components.

SUBROUTINES.

Most of the error calculations could be accomplished through the use of subroutines. These subroutines included (1) bearing and distance computed from a pair of latitudes and longitudes, (2) a latitude and longitude computed from a bearing and distance from a given latitude and longitude, and (3) coordinate rotation to align errors with desired track.

HORIZONTAL ERROR CALCULATIONS--ORTHOGONAL DISTANCE-TO-WAYPOINT PROJECTION.

All error calculations were based on a projected position of the aircraft on the desired track. Since the actual position of the aircraft was not always on the desired track, an orthogonal projection of the actual aircraft position on the desired track was needed. The first step in this process was to use subroutine number 1 to compute bearing and distance between the two waypoints which define the segment. Then the same subroutine was used to compute bearing and distance from present position (actual position derived from EAIR) to the "TO" waypoint. The difference in the bearings from the TO waypoint was all that was needed to calculate the orthogonal projection of the actual track on the desired track. The projection was equal to the distance from the actual position to the TO waypoint times the cosine of the bearing difference (figure A-1). This distance was then used as an index on the parameter tape. Error values were calculated at 0.1-nmi increments of this distance.

SENSOR ERRORS.

After obtaining the distance-to-waypoint increment, sensor errors were calculated. Latitudes and longitudes of the VOR/DME stations were determined by using a look-up table and matching the frequencies tuned on the VOR/DME's to those in the look-up table. When this was done, the actual bearing and ground range of the aircraft, relative to the station, was calculated by using subroutine number 1. This results in P_a and θ_a (terms are explained in attached glossary).

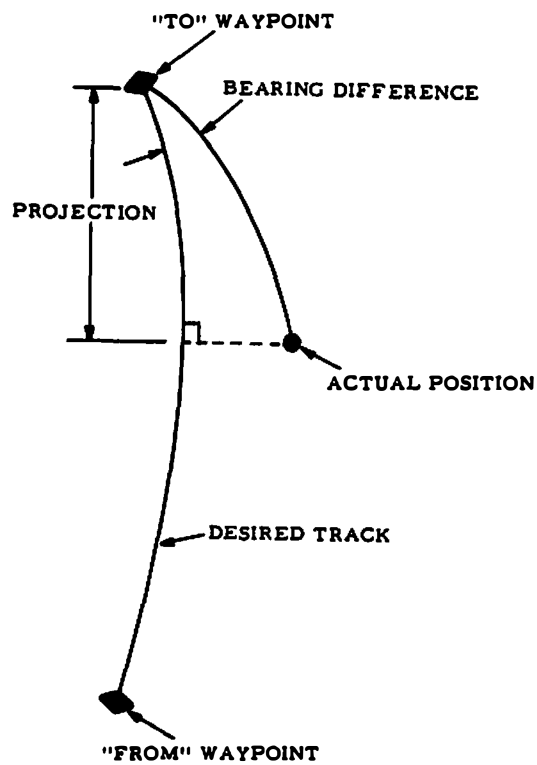


FIGURE A-1. ORTHOGONAL PROJECTION OF ACTUAL POSITION ON DESIRED TRACK

To find the total DME error, the measured slant range was first corrected to ground range.

$$\rho_s = [D_s^2 - (H_a - H_\theta)^2]^{1/2}$$

The total DME error was then

$$\Delta\rho = \rho_s - \rho_a$$

VOR error was calculated in a similar way. Total bearing error was then

$$\Delta\theta = \theta_s - \theta_a$$

For the purpose of establishing system errors, a sensed position was calculated based on the VOR/DME information. The sensed position was calculated (by subroutine number 2) from sensed bearing and corrected ground range.

$$\begin{matrix} P_s(X) \\ P_s(Y) \end{matrix} = f(\theta_s, \rho_s, \text{ and VOR/DME station position})$$

The next value computed was the RNAV computer position. RNAV computer position (P_c) was computed (using subroutine number 2) from the bearing-to-waypoint (BTW) and distance-to-waypoint (DTW) output from the RNAV computer, as well as the latitude and longitude of the waypoint.

$P_c(X)$
$P_c(Y)$ =f(BTW, DTW, and waypoint latitude and longitude)

Flight technical error was defined as the amount of deflection of the RDI.

FTE=RDI (nmi)

Error values were then computed from these previously computed positions as follows: Sensed position error was computed from

Sensor $(X)=P_s(X)-P_a(X)$
Sensor $(Y)=P_s(Y)-P_a(Y)$

RNAV computer error was computed from

COMP $(X)=P_s(X)-P_c(X)$
COMP $(Y)=P_s(Y)-P_c(Y)$

Crosstrack total system error was computed from

TS $(X)=P_d(X)-P_a(X)$
TS $(Y)=P_d(Y)-P_a(Y)$

where P_d was previously computed (using subroutine 2) from the bearing from the TO waypoint and the orthogonally projected distance on the desired track. By definition, P_d was on the desired track.

P_a is the actual aircraft position determined by the EAIR. The constants to convert from differences in latitudes and longitudes to nautical miles are deleted from the above equations.

COORDINATE ROTATION.

With all errors computed from latitudes and longitudes and expressed in nautical miles on a coordinate system with axes aligned with lines of latitude and longitude, a coordinate rotation was done to resolve the error measurements into crosstrack and along-track components. This was done by computing the desired track (θ_d) at the desired position (P_d) and performing a coordinate rotation. The desired track at P_d to the TO waypoint was computed using subroutine number 1. The new values (representing crosstrack and along-track values) were then $X_1=X \cos \theta_d+Y \sin \theta_d$ and $Y_1=Y \cos \theta_d-X \sin \theta_d$.

Table A-1 lists the signals recorded on the airborne digital recorder, while table A-2 lists the values calculated for the error analysis.

TABLE A-1. EAIR-INCRE-DATA TIME MERGED TAPE

IEDATA

2	EAIR MONTH
3	EAIR DAY
4	EAIR YEAR
5	EAIR RUN NUMBER

ITIME

I	INCRE-DATA DAYS
IHR	
IMIN	FROM TIME VALID SIGNAL SOURCE
ISEC	
IMS	

E(N)

1	EAIR LATITUDE (DEGREES)
2	EAIR LONGITUDE (DEGREES)
3	EAIR ALTITUDE (FEET)

PARAM

1	CAL SIGNAL	A/D 1
2	DME 1	A/D 2
3	DME 2	A/D 3
4	PITCH ATTITUDE	A/D 4
5	ROLL ATTITUDE	A/D 5
6	XTRK DEV	A/D 6
7	IAS	A/D 7
8	BARO ALT	A/D 8
9	LATERAL STEERING	A/D 9
10	VERTICAL STEERING	A/D 10
11	SPARE	A/D 11
12	SPARE	A/D 12
13	MANUAL DATA	A/D 13
14	WAYPOINT RADIAL	A/D 14
15	WAYPOINT DISTANCE	A/D 15
16	BEARING TO WAYPOINT	A/D 16
17	DISTANCE TO GO	MUX 0
18	VOR #1	MUX 1
19	VOR #2	MUX 2
20	COURSE ERROR	MUX 3
21	MAGNETIC HEADING	MUX 4
22	FINE ALTITUDE	MUX 5
23	COARSE ALTITUDE	MUX 6
24	OBS	MUX 7
25	SPARE	MUX 8
26	SPARE	MUX 9
27	SPARE	MUX 10
28	SPARE	MUX 11

DES

1	D	0.1-MHZ VOR/DME 1 TUNING
2	C	
3	B	
4	A	
5	D	0.1-MHZ VOR/DME 1 TUNING
6	C	
7	B	
8	A	
9	D	0.1-MHZ VOR/DME 2 TUNING
10	C	
11	B	
12	A	
13	D	1-MHZ VOR/DME 2 TUNING
14	C	
15	B	
16	A	
17	SPARE	
18	SPARE	
19	VOR #2 FLAG	
20	SPARE	
21	FROM	
22	TO	
23	DME DIAGNOSTIC	
24	VOR DIAGNOSTIC	
25	APPROACH ACTIVATE	
26	AUTO BEARING	
27	DTW DIAGNOSTIC	
28	TEST	
29	W.P. CHANGE (INOP)	
30	VOR #1 FLAG	
31	DME #1 FLAG	
32	DME #2 FLAG	
33	EVENT MARKER	
34	SPARE	
to		
48	SPARE	

SD

1	SPARE
2	SPARE
3	EAIR DATA VALID
4	INCRE-DATA VALID
5	END OF MERGE TAPE
6	SPARE
to	
16	SPARE

TABLE A-2. CALCULATED VALUES ON THE PARAMATER TAPE

1	DTW	Orthogonal DTW Projection on Desired Track
2	ρ 1	Total DME 1 Error (Ground Range)
3	ρ 2	Total DME 2 Error (Ground Range)
4	$\theta 1$	Total VOR 1 Angular Measurement Error
5	$\theta 2$	Total VOR 2 Angular Measurement Error
6	$P_s(X)1$	VOR/DME 1 Sensed Position Latitude
7	$P_s(Y)1$	VOR/DME 1 Sensed Position Longitude
8	$P_s(X)2$	VOR/DME 2 Sensed Position Latitude
9	$P_s(Y)2$	VOR/DME 2 Sensed Position Longitude
10	VD1CT	Crosstrack (VOR/DME 1 - Actual)
11	VD1AT	Along Track (VOR/DME 1 - Actual)
12	VD2CT	Crosstrack (VOR/DME 2 - Actual)
13	VD2AT	Along Track (VOR/DME 2 - Actual)
14	COMPCT	(Computed - Sensed) Crosstrack
15	COMPAT	(Computed - Sensed) Along Track
16	FTCT	RDI (NMI)
17	FTE DEG	ADI (DEG)
18	TSCT	(Desired - Actual) Crosstrack
19	TSAT	(Desired - Actual) Along Track
20	OBSERR	(Actual - Desired)

AFLG (20) False=Invalid
True=Valid

GLOSSARY OF SYMBOLS

P_d	=	Desired position
P_a	=	Actual position (derived from EAIR)
P_c	=	RNAV computer position
P_s	=	Position derived from sensor information
ρ	=	Ground range
ρ_a	=	Actual ground range (derived from EAIR)
ρ_s	=	Sensor derived ground range
$\Delta\rho$	=	DME ground range error
D_s	=	Slant range distance, sensor derived
H_a	=	Aircraft altitude
H_θ	=	Elevation of VOR/DME station
θ_s	=	Sensed VOR bearing
θ_a	=	Actual VOR bearing (derived from EAIR)
θ	=	VOR bearing error
DTW	=	Distance-to-waypoint
BTW	=	Bearing to waypoint
θ_d	=	Desired track

APPENDIX B

SUBJECT PILOT RESPONSES TO QUESTIONNAIRES

Responses were solicited from the subject pilots by means of questionnaires that were given to these pilots after completion of their third data flight. The questions as well as a comment summary to each question are presented below. The responses are divided to indicate those from group A (low experience) or group B (high experience).

Question 1 - Did RNAV ground training and orientation flights provide adequate preparation for your data flights?

	Yes	No
Group A	5	1*
Group B	6	—
Totals	11	1

*NOTE: This pilot flew two additional data flights after completing his questionnaire due to a data tape recorder malfunction.

Comment Summary. Group A - Yes, but more time would have been preferred in learning flight director system operations. More pilot proficiency was desired in the AC680. No, because familiarity was needed in operating the RNAV system prior to data flights.

Question 2 - Did you encounter any problems with RNAV system data entry?

	Yes	No
Group A	4	2
Group B	4	2
Totals	8	4

Comment Summary. Group A - Yes, the waypoint coordinate setting wheels were too close to each other making it easy to disturb one setting while adjusting another.

Group B - Yes, the thumbwheel switches used to dial in waypoint coordinates are too close together and can be easily misset or changed inadvertently.

Question 3 - Rate the difficulty factor of the following RNAV maneuvers:

GROUP A

	None	Little	Average	Above Average
Impromptu Runway Change		2	1	3
Course Offset	2	1	3	
Delay Fan	2		2	2
Extended Downwind	3		3	

GROUP B

	None	Little	Average	Above Average
Impromptu Runway Change	3	1	1	1
Course Offset	4	2		
Delay Fan	5	1		
Extended Downwind	5		1	

Comment Summary. None.

Question 4 - Do you feel that using the distance to waypoint (DTW) as a fix for altitude control procedures is acceptable?

	Yes	No	Undecided
Group A	5		1
Group B	5	1	
Totals	10	1	1

Comment Summary. Group A - Yes, using a DTW fix is easier than dialing waypoint coordinates.

Group B - None.

Question 5 - Did you feel disoriented while flying the data routes?

	Yes	No	Sometimes
Group A		2	4
Group B		6	
Totals		8	4

Comment Summary. Group A - Sometimes I became disoriented on departures with waypoints close together; e.g., route A2. This happened when I was distracted during a heavy workload.

Group B - None.

Question 6 - Did you understand the ATC clearance and instructions?

	Yes	No
Group A	5	1
Group B	6	
Totals	11	1

Comment Summary. Group A - No, because on cancelling the offset, I preferred to turn left/right and intercept the RNAV course at the next waypoint.

Group B - Yes, but I had some difficulty in understanding "cancel offset" versus "direct to" a waypoint.

Question 7 - When direction changes of RNAV courses are required at waypoints would you prefer:

a. To work out your own methods of anticipating each turn;
b. To be provided with some kind of standard procedures for anticipating each turn.

	Answer A	Answer B
Group A	5	1
Group B	4	2
Totals	9	3

Comment Summary. Group A - None.

Group B - One mile per 100 knots seems adequate.

Question 8 - Do you feel that RNAV procedures could replace present navigation procedures?

	Yes	No	Undecided
Group A	5	1	
Group B	4		2
Totals	9	1	2

Comment Summary. Group A - Yes, a single waypoint seems a lot easier than single VOR navigation. Yes, but manipulation of RNAV system equipment has to be improved or simplified.

Group B - Yes, it is acceptable with reservation because clearances are more complicated and the chances for blunder errors are much greater. However, with proper training, RNAV is more flexible than present system. Undecided, but stored waypoints with an index would make terminal RNAV easier.

Question 9 - Do you feel that RNAV makes the pilot's task more difficult?

	Yes	No
Group A	2	4
Group B	5	1
Totals	7	5

Comment Summary. Group A - Yes, in the terminal area unless routes can be simplified. No, there is less difficulty due to reduced communications with ATC.

Group B - Flying the display is OK, but the extra operation in changing RNAV fix coordinates requires full attention which distracts from other essential efforts. Entering waypoint coordinates was my problem. No, but it makes the pilot check more for mistakes.

Question 10 - Do you feel RNAV can be flown safely in terminal areas?

	Yes	No	Undecided
Group A	6		
Group B	2	1	3
Totals	8	1	3

Comment Summary. Group A - Yes, provided the pilot is proficient in the aircraft, the RNAV system, and in instrument flying. It is no place for a "Sunday Pilot." Yes, but with at least two waypoints. Yes, but waypoints should be further apart than 5 miles during busy time, i.e., takeoffs.

Group B - Yes, but since the pilot workload in terminal areas is already high, mixing in extra waypoints, vectors, offsets, etc. coupled with bad weather may be too much for a low-experienced pilot to handle. No, because without autopilot and with a single-waypoint operation, you could be very busy. Yes, but it depends on capability of RNAV system. For instance, single-waypoint RNAV is unacceptable in high-density areas. Undecided, because the pilot must really know his aircraft, and a low-experienced pilot could have a real problem with so many things to do on takeoff and landing.