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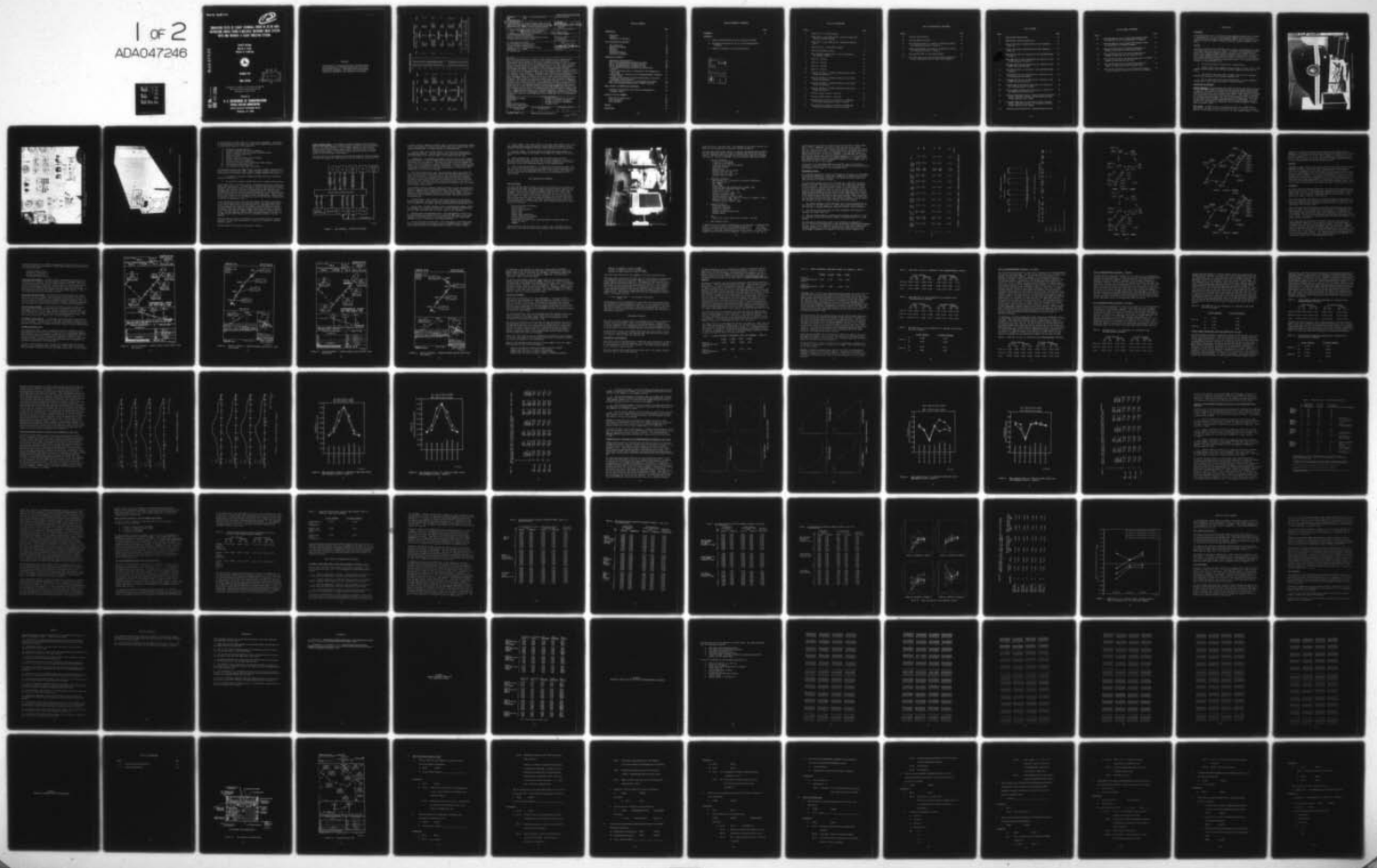

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SIMULATION TESTS OF FLIGHT TECHNICAL ERROR IN 2D/3D AREA NAVIGATION (RNAV) USING A MULTIPLE WAYPOINT RNAV SYSTEM WITH AND WITHOUT A FLIGHT DIRECTOR SYSTEM

Donald Eldredge
Warren G. Crook
William R. Crimbring

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OCTOBER 1977

FINAL REPORT

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METRIC CONVERSION FACTORS

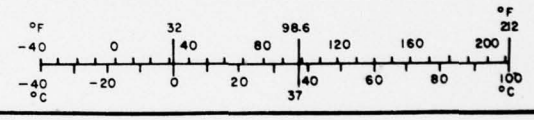
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in. = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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16. Abstract

Six pilots participated in a series of flight simulation tests employing solo pilot techniques which were conducted at the National Aviation Facilities Experimental Center (NAFEC) in the cockpit Simulation Facility in order to measure Total System Crosstrack (TSCT) and Flight Technical Error (FTE) using a multiple waypoint storage 2D/3D area navigation (RNAV) system. The tests were designed to assess pilot performance as a function of the interexperimental variables: (1) 2D RNAV mode versus 3D RNAV mode, (2) flight director versus no flight director, (3) insertion of an impromptu waypoint into a previously entered flight plan, and (4) different route structures. Performance was measured on the variables: horizontal tracking, vertical tracking, airspeed control, and procedural performance. Major findings include less TSCT error in the 2D mode, improved tracking accuracy using the flight director, and FTE consistently less than the amount budgeted in AC-90-45A. No statistically significant differences were found for the impromptu waypoint entry; however, one-third of the impromptus resulted in either blunders or procedural errors (including wrong information entered or large overshoots at the waypoint prior to the impromptu segments). Nonprecision approaches were handled quite well with little horizontal error using the RNAV ENROUTE mode; however, navigation signal failures close to the VORTAC caused larger horizontal errors in some runs. Significant differences in altitude performance were found for 2D RNAV mode versus 3D RNAV mode for climb/descent segments. Significant differences in airspeed control were found for the 2D RNAV mode versus 3D RNAV mode for the climb/descent segments.

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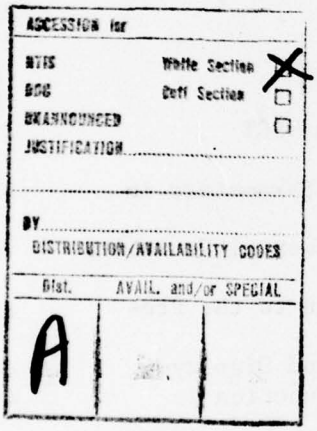

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INTRODUCTION

BACKGROUND.

The present study is one of a series of flight simulation experiments designed to investigate 2D, 3D, and 4D area navigation (RNAV) concepts in order to establish minimum operational characteristics (MOC's) and to determine certain operational aspects of RNAV interaction within the National Airspace System (NAS).

PURPOSE.

The primary purpose of this experiment was to acquire an operational data base concerning flight technical error (FTE) in a terminal area environment (including Standard Instrument Departure (SID), transition, and Standard Terminal Arrival Route (STAR) procedures using the National Aviation Facilities Experimental Center (NAFEC) Cockpit Simulation Facility configured with a Collins Radio Company FD-109(V) integrated flight director system and an EDO Commercial Corporation TCE-71A (20-waypoint storage) RNAV system. The interexperimental variables in this experiment were:

1. 2D versus 3D mode of navigation for climbs/descents,

2. Flight director (FD) command functions versus no flight director (NFD) command functions (basic pitch and bank attitude command bars biased out of view),

3. "As filed" flight plan versus in-flight insertion of an impromptu waypoint and navigation to the impromptu waypoint, and

4. Use of common route structures used previously in other simulation studies and in actual flight test studies - routes B1 and B2.

DESCRIPTION OF EQUIPMENT.

COCKPIT SIMULATOR. All testing was done using the Singer-Link General Aviation Trainer (GAT)-2B/XDS-530B twin-engine general aviation trainer facility shown in figure 1. The cockpit is mounted on a two-degree-of-freedom hydraulically operated motion system, and the aileron and elevator flight controls are hydraulically activated to provide realistic control feel. The trainer is equipped for complete instrument flight rule (IFR) flight capability, having dual navigation communication (NAV/COM) instrumentation and a transponder. It is also equipped with a Collins Radio Company FD-109 (V) integrated flight director system and an EDO Commercial Corporation TCE-71A 3D area navigation system as shown in figures 2 and 3.

RNAV SYSTEM. The RNAV system is an Aeronautical Radio Inc. (ARINC) Mark 13 level system, designed for high reliability and ease of operation to provide guidance in the terminal area, the enroute, and final approach phases of flight.

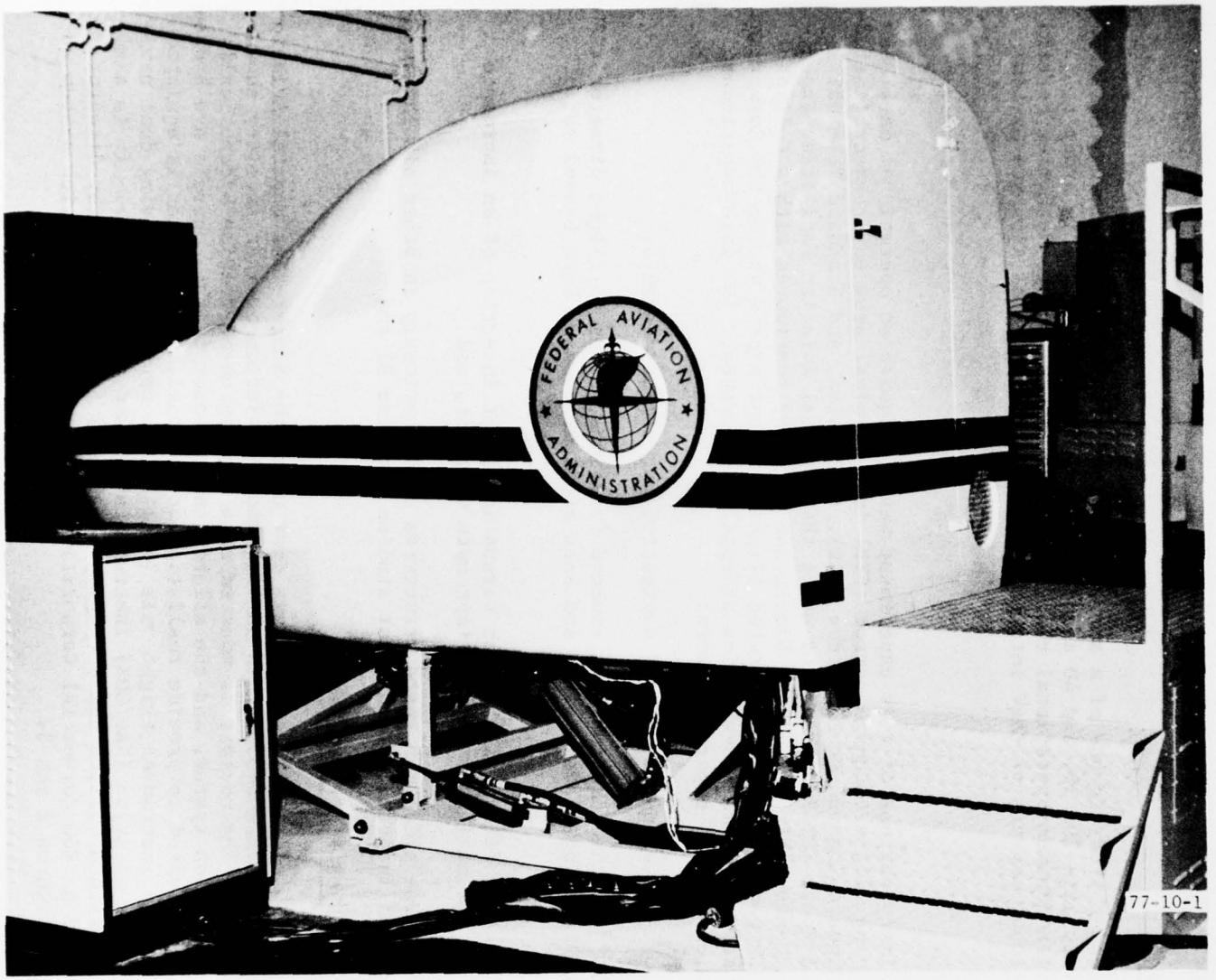

FIGURE 1. EXTERIOR VIEW-GAT-2B SIMULATOR

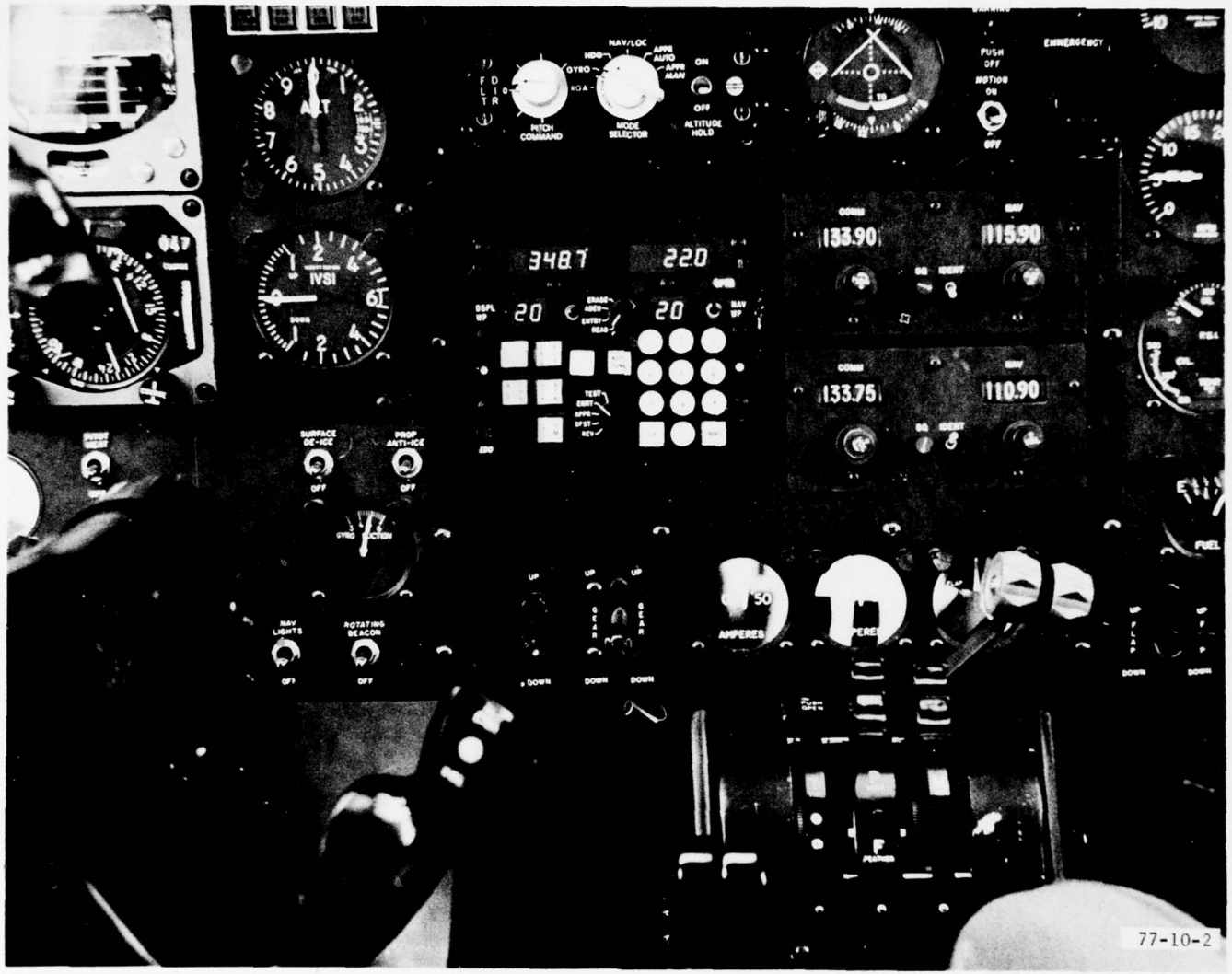

FIGURE 2. ARINC MARK 13 LEVEL RNAV SYSTEM - CONTROL DISPLAY UNIT MOUNTED IN GAT-2B COCKPIT

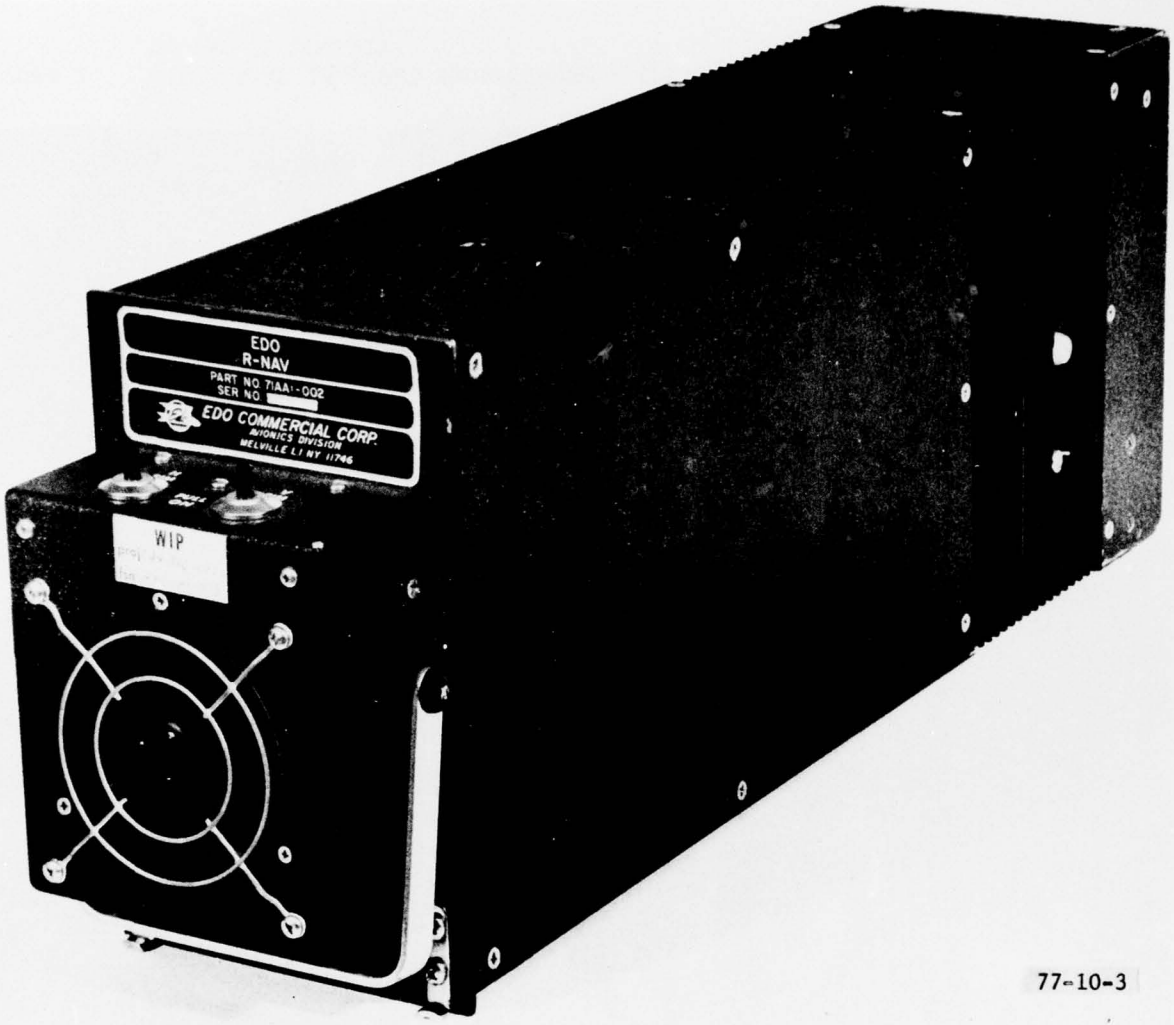

FIGURE 3. ARINC MARK 13 LEVEL RNAV SYSTEM - NAVIGATION COMPUTER UNIT

It has capability for SID, STAR, and cruise flight programming. In addition, it allows navigation with respect to a selected or computed vertical profile. The operational features of this system are:

1. 20-waypoint storage capacity,
2. Automatic horizontal and vertical guidance,
3. Manual flightpath angle and computed flightpath angle,
4. Automatic frequency selection,
5. Manual data entry,
6. Automatic time to waypoint and groundspeed,
7. Automatic distance to waypoint,
8. Parallel offset track capability,
9. Conventional flight director/autopilot (FD/AP) guidance,
10. Self-check data monitoring, and
11. Incorporation of slant range correction.

The navigation computer unit (NCU) accepts very high frequency omnirange (VOR) distance measuring equipment (DME), compass heading, altimeter, and true airspeed signals and processes these signals to compute guidance with respect to:

1. A preplanned, prestored 3-dimensional RNAV route leg or approach/departure procedure, or

2. An impromptu, manually inserted route leg or terminal area procedure.

Sensor input data to the computer unit is constantly monitored for integrating, status, and reasonability. Any VOR, DME, or altimeter data which the computer determines to be faulty causes the system to reject it and fall back to a dead reckoning (DR) mode until the fault is removed and the data becomes valid. The RNAV system computes deviation signals proportional to crosstrack error in the horizontal plane and vertical error in the vertical plane. These deviation signals are delivered to the standard aircraft instrumentation. Beside deviation signals, system status information is sent to the aircraft instrumentation to operate the appropriate flags.

In the horizontal situation, the deviation signals are computed with respect to the desired RNAV track or its parallel offsets. The displacement indications, unlike standard VOR deviation displays, are independent of distance from the waypoint, and therefore the amount of course bar deviation always represents a definite crosstrack distance regardless of distance to waypoint. In the RNAV mode, when the number 2 RNAV unit is tuned to a proper VOR frequency, the radio magnetic indicator (RMI) indicates bearing to the VOR, and the DME indicator will display the direct horizontal distance to wayline (DWYLIN).

Vertical deviation signals are delivered to the standard vertical situation displays. The deviation displacement is relative to a desired or computed vertical profile.

The RNAV system block design is presented in figure 4.

FLIGHT DIRECTOR SYSTEM. The FD-109(V) integrated flight director system consists of an attitude director indicator (ADI), a horizontal situation indicator (HSI) an instrument amplifier, a roll steering computer, a pitch steering computer, and a flight director control panel. The ADI and HSI are mounted on the instrument panel. The system is controlled by the selector switches mounted on the system mode control panel.

The ADI features a 3D color display of aircraft attitude with steering commands to rotate for takeoff and climb, maintain a desired attitude, capture and hold

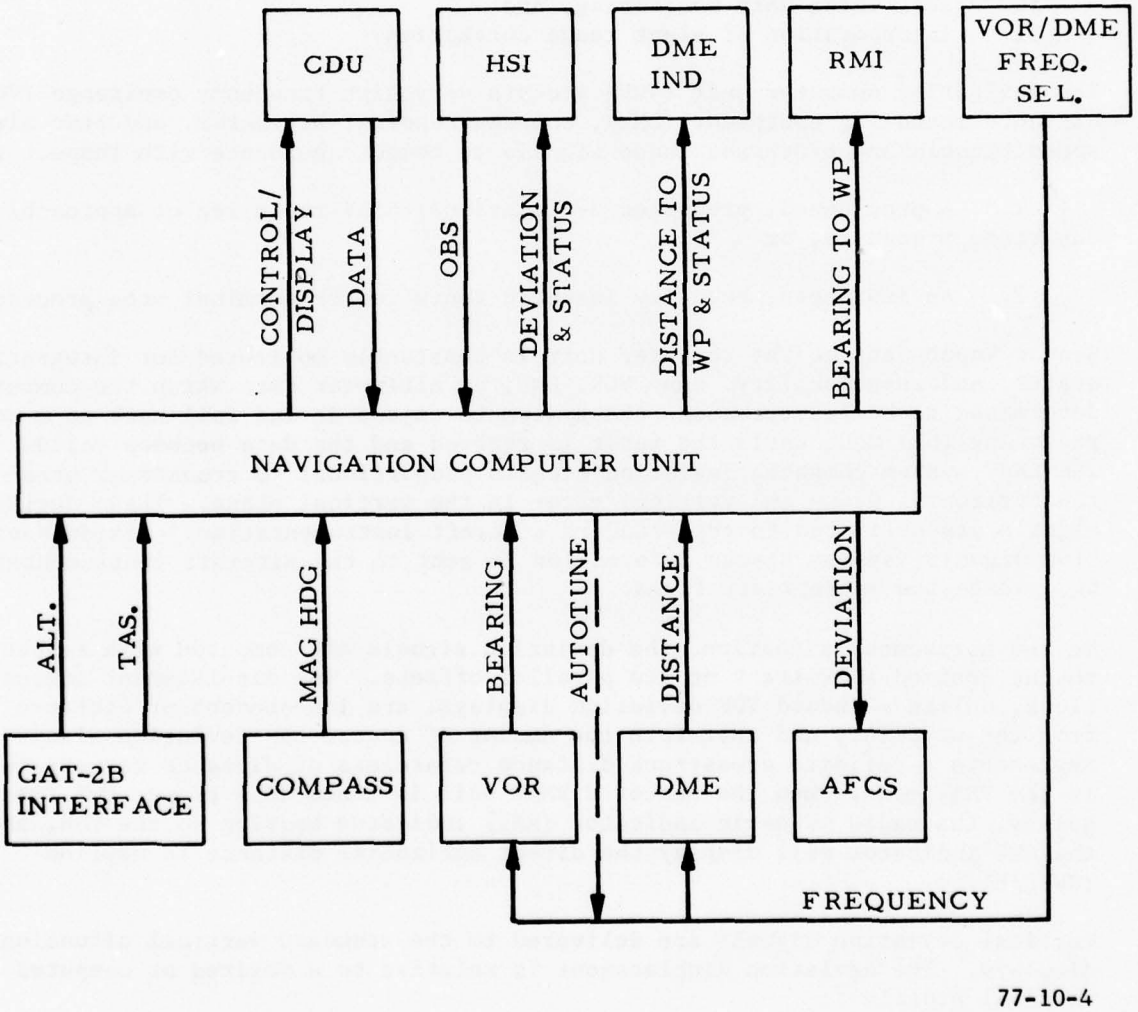

FIGURE 4. RNAV INTERFACE - SYSTEM BLOCK DIAGRAM

a desired altitude, heading, localizer, VOR, or tactical air navigation (TACAN) course, and automatically capture and descend along the glideslope beam to the runway touchdown zone. The main features of this display are:

1. Aircraft symbol and attitude display. The fixed, delta-shaped symbol represents the aircraft. Aircraft pitch and roll attitudes are displayed by the relationship of the aircraft symbol to the movable attitude tape.

2. Command Bars. The command bars display computed bank and pitch commands. These bars move up or down to command the pitch attitude required to maintain the desired vertical situation. The bars roll right or left to command the right or left turn required to capture and maintain a selected heading or radio course, such as capturing and tracking a VOR radial. To satisfy the commands, the aircraft is maneuvered so that the aircraft symbol is "flown into" the command bars until the two are aligned.

3. Glide slope pointer and scale. The glide slope pointer represents the center of the glide slope beam and displays vertical displacement of the aircraft from beam center. This pointer is in view only when the navigation receiver is tuned to an instrument landing system (ILS) localizer frequency. The position of the glide slope pointer in relation to the centerline on the glide slope scale represents aircraft position with respect to the center of the glidepath. This is raw glide slope deviation information only, as received from the glide slope receiver.

The horizontal situation indicator displays aircraft position and heading with respect to magnetic north and selected heading, slant range in nautical miles (nmi) to a selected DME or TACAN station, digital course readout, lateral deviation, relative bearing, direction to a selected VOR, TACAN, or localizer course, and vertical deviation from the glide slope. The main features of this display are:

1. Aircraft symbol. When related to the movable parts of the horizontal situation indicator, the fixed, miniature aircraft symbol shows aircraft position in relation to the azimuth card and ground-based radio navigation aids.

2. Azimuth card. Heading information from a gyrostabilized magnetic compass is displayed by the rotating azimuth card. Aircraft heading is indicated on the card under the lubber line at the top center of the instrument.

3. Heading marker and heading-set knob. The heading marker is set to the desired heading on the azimuth card by rotating the "HDG" knob. In the heading mode, the command bars in the attitude director indicator display bank commands to turn to and maintain the selected heading.

4. Course arrow and course-set knob. The course arrow is the yellow arrow that is rotated against the azimuth ring by the "COURSE" knob to a magnetic course that coincides with the desired VOR or TACAN or localizer course.

5. Course readout. The course counter in the upper right corner of the instrument improves the accuracy and speed of course selection by giving a digital readout on the VOR or TACAN or localizer course indicated by the course arrow.

6. Distance readout. A digital readout of TACAN slant range distance in nautical miles is given by the readout in the upper left corner of the instrument.

7. Course deviation bar. The HSI course deviation bar has two dots (at 5/16 inch and 5/8 inch) on either side of center comprising a distance of $\pm$5/8 inch, which represents $\pm$4 nmi in the crosstrack dimension for the enroute mode and $\pm$1 nmi in the crosstrack dimension for the approach mode.

8. Glide slope deviation pointer. The HSI glide slope deviation pointer has two dots (at 5/16 inch and 5/8 inch) on either side of center comprising a distance of $\pm$5/8 inch which represents $\pm$600 feet in the vertical track dimension for the enroute mode and $\pm$300 feet in the vertical track dimension for the approach mode.

DATA COLLECTION AND ANALYSIS

DATA COLLECTION.

The Xerox XDS-530 computer (figure 5) software interfaces with the GAT-2B cockpit simulator and reads into computer memory analog and digital signals using analog-to-digital (A/D) conversion equipment and direct input/output (DIO) equipment. The data are collected on magnetic tape, with a 1 second clock interrupt used to control system timing. The format on the data collection tape consists of a header record at the beginning of the tape and sequential data records, one record for each second of simulation run time. Both record types are 180 words in length. The header record is created from card input at the beginning of each GAT-2B data run. The information input via the header record is as follows:

Type of test identifying label
Date (Mo:Da:Yr)
Problem start (Hr:Mn:Sc)
Subject number
Subject name
Flight number (sequential)
Aircraft identification (ACID)
Subject replication number
Experimentation design matrix interexperimental variable number and number of levels
Comments

These cards have a specific format that is easy to use, reasonably flexible, and serves to identify the data at data reduction time, since these data are

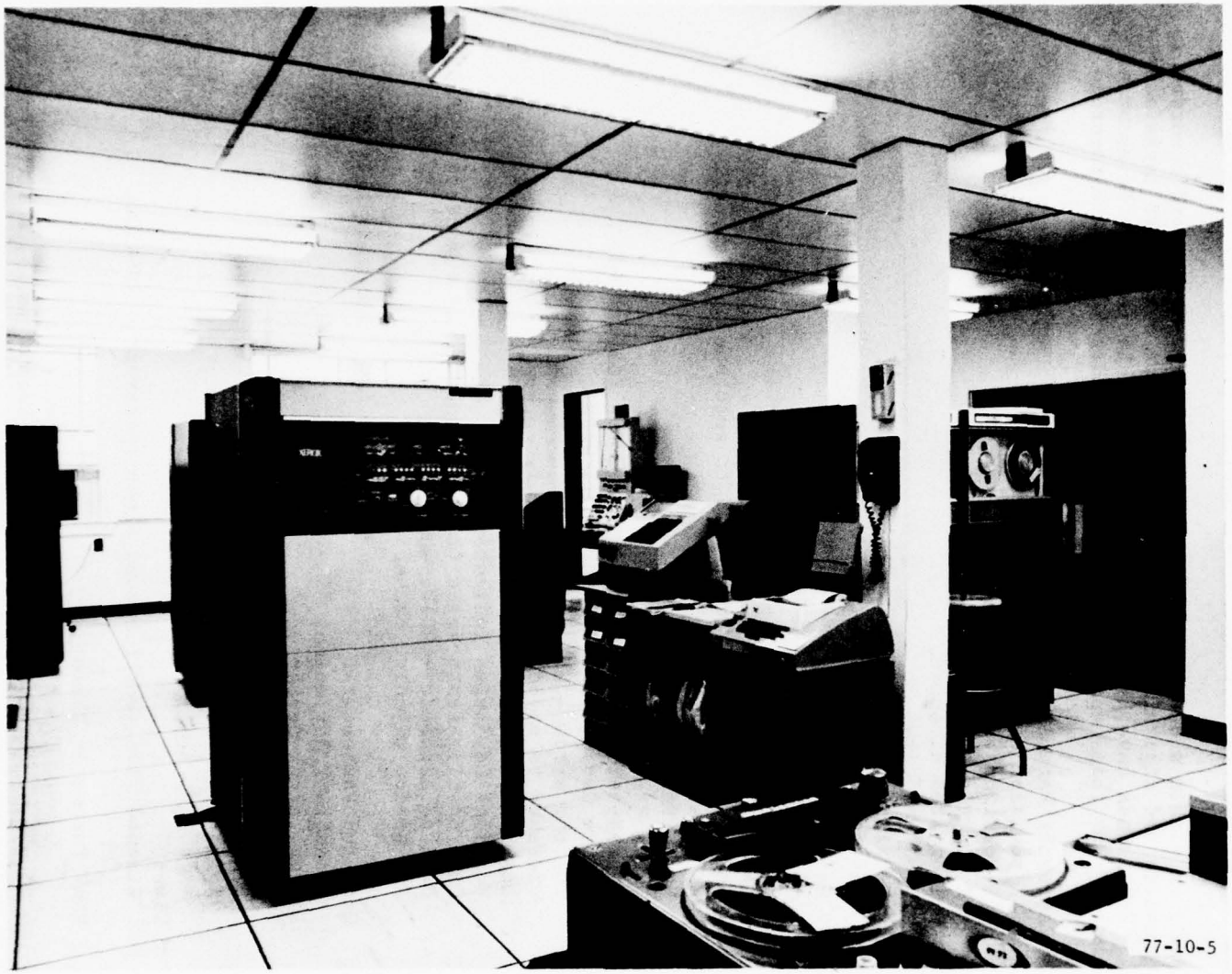

FIGURE 5. XDS-530 MINICOMPUTER SYSTEM

output directly to the data tapes. The remainder of the record contains zero data, but can be modified for additional desired information.

Each data item within a data record is a 16-bit, fixed-point word recorded in raw-form analog and digital voltages as measured from the GAT-2B interface devices. Provisions have been made for up to 180 data items to be recorded every second. For this experiment, the following data items were recorded:

1. Aircraft Parameters:
   X position of the GAT-2B,
   Y position of the GAT-2B,
   Z position (altitude) of the GAT-2B,
   Indicated airspeed,
   Wind velocity,
   Heading (earth axis yaw angle),
   Aircraft axis roll rate,
   Aircraft axis pitch rate, and
   Indicated rate of climb.

2. Navigation Parameters:
   NAV frequency No. 1 (connected to autotune on RNAV unit),
   NAV frequency No. 2,
   Rho - RNAV,
   Theta - RNAV,
   Course-set knob omni bearing selector (OBS) - HSI,
   Course Deviation Indicator (CDI) - HSI,
   To/from arrow - HSI,
   Distance to waypoint (DTW) - HSI,
   Bearing to waypoint - RMI,
   Vertical Deviation Indicator - HSI,
   Desired flightpath angle (manually entered or computed) - RNAV,
   Desired altitude - RNAV, and
   Navigation waypoint number - RNAV.

3. Computed Parameters:
   Crosstrack deviation,
   Along-track deviation,
   Distance to wayline,
   Distance to angle bisector, and
   Segment number.

4. Time:
   Elapsed time from 1 second clock interrupt - XDS-530.

5. RNAV Parameter Table:

In addition to all of the data collected on a 1-second basis, a different type of data is collected directly from the RNAV NCU and CDU u[illegible] These data relate to the input and output operations that result fro[illegible] pilot seeking information or entering information via the control display unit (CDU), and the automatic status monitoring of the RNAV NCU. The data in this table are in

the form of time tags which are created every time an item is either turned "ON" or "OFF." Initially, all values in the table are set to a minus one (-1). This value is replaced with a time tag that represents the initial time of occurrence of an item. A second time tag in a succeeding block represents the time at which the item is terminated. The time tag is based on elapsed time from the 1 second clock interrupt in the XDS-530B and is consistent with the regular data record time base; therefore, it can be correlated with ongoing aircraft navigation and computed parameters. An example of this RNAV parameter summary table is presented in figure 6. This summary table is computed at the end of every segment.

In addition to the GAT-2B/XDS-530B data collection system, an Electronic Associates Incorporated (EAI-1131) X-Y plotter was used to continuously monitor the progress of the flight over the prescribed route.

EXPERIMENTAL DESIGN.

The following experimental design was developed for the purpose of determining if operational differences existed when a ARINC Mark 13 RNAV system was used under various experimental conditions. Six subject pilots were each given eight data runs as outlined in table 1.

The experimental design used in this experiment was a split-plot factorial design of type SPF 2.222 (reference 1). There were three within variables, each at two levels. The within variables were: (1) flight director versus no flight director functions (table 2), (2) 2D (X and Y) navigation versus 3D (X, Y, and Z) navigation (table 2), and (3) as-filed route plan (with all waypoints preprogrammed versus as-filed route plan (modified by an impromptu waypoint during the flight per air traffic control (ATC) direction). These three within variables were administered in all possible (2x2x2) combinations to the subjects within each level of the between variable. The between variable was route structure (B1 route versus B2 route) (figures 7, 8, 9, and 10). This variable was used as a between variable for several reasons:

1. The primary emphasis of this experiment was to collect baseline data on the usability of the RNAV system in a flight director/no flight director context, and not to examine differences among the available route structures,

2. The two route structures used have been extensively evaluated both in simulator and flight tests, and

3. With the limited number of trained pilots available as subjects, it was not desirable to obtain an excessive number of repeated measures on a single subject.

The experimental design matrix used in this evaluation is presented in table 1. The order of presentation of the three within variables was randomized for each subject, and in addition, one-half of the eight test conditions were randomly assigned to be flown in a forward manner, departing and arriving using runway 4 (waypoint A to waypoint J for the B1 route; waypoint A to

1	TEST OFSET APPR	ERASE ENTRY READ	HALRT DR RMS	VOR DME HDG	WPNAV WPDIS WPU/D	XTK XTKL XTKR	ATK ATK+ ATK-	CLEAR FREQ ELEV	INSERT BRG DIST	VNAV ALT FPA	AUTO GS/TM TEST	SEG	
Q	-1	-1	575	-1	-1	-1	-1	604	605	345	345	3	
	-1	345	-1	-1	-1	-1	-1	-1	-1	405	-1	3	ON
Q	-1	404	-1	-1	345	-1	-1	-1	-1	345	345	3	
Q	-1	-1	634	-1	-1	-1	-1	605	606	-1	-1	3	
	-1	404	-1	-1	-1	-1	-1	-1	-1	603	-1	3	OFF
Q	-1	603	-1	-1	-1	-1	-1	-1	-1	404	-1	3	
Q	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	3	
	-1	603	-1	-1	-1	-1	-1	-1	-1	604	-1	3	ON
Q	-1	-1	-1	-1	-1	-1	-1	-1	-1	405	-1	3	
Q	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	3	
	-1	-1	-1	-1	-1	-1	-1	-1	-1	605	-1	3	OFF
Q	-1	-1	-1	-1	-1	-1	-1	-1	-1	603	-1	3	
Q	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	3	
	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	3	ON
Q	-1	-1	-1	-1	-1	-1	-1	-1	-1	605	-1	3	

77-10-6

FIGURE 6. RNAV PARAMETER SUMMARY TABLE - FROM DATA REDUCTION AND ANALYSIS PRINTOUT

TABLE 1. EXPERIMENTAL DESIGN MATRIX

	FLIGHT DIRECTOR				NO FLIGHT DIRECTOR			
	AS FILED		IMPROMPTU		AS FILED		IMPROMPTU	
Subject	2D	3D	2D	3D	2D	3D	2D	3D
1	4	6	3	7	1	2	5	8
2	7	3	2	1	5	6	8	4
3	6	5	4	8	2	1	7	3
4	5	8	6	4	3	7	1	2
5	1	7	5	3	8	4	2	6
6	3	4	1	2	7	3	6	5

Note: The numbers in the table refer to the order of presentation of the experimental conditions to the subjects.

TABLE 2. RNAV/AVIONICS SYSTEM CONFIGURATION

	FLIGHT DIRECTOR CONTROL SWITCH POSITION						FLIGHT DIRECTOR CAPABILITIES							
	GYRO	HDG	NAV/LOC	APP. AUTO	APP. MANUAL	VNAV	BASIC PITCH AND ROLL	AUTO INTCPT AND TRKG	ALT. HOLD	AUTO LOC	CAP. G.S.	G.S. GUIDE ONLY	FLT. DIR ANNUN.	PITCH COMM.
FLT. DIR. 2D*			X or	X				X	X**	X			X	X**
FLT. DIR. 3D				X		X		X	X**	X	X		X	X**
NO FLT. DIR. 2D*	X						X							
NO FLT. DIR. 3D	X						X					X		

*VNAV function switch in "OFF" position

**Prior to glide slope capture

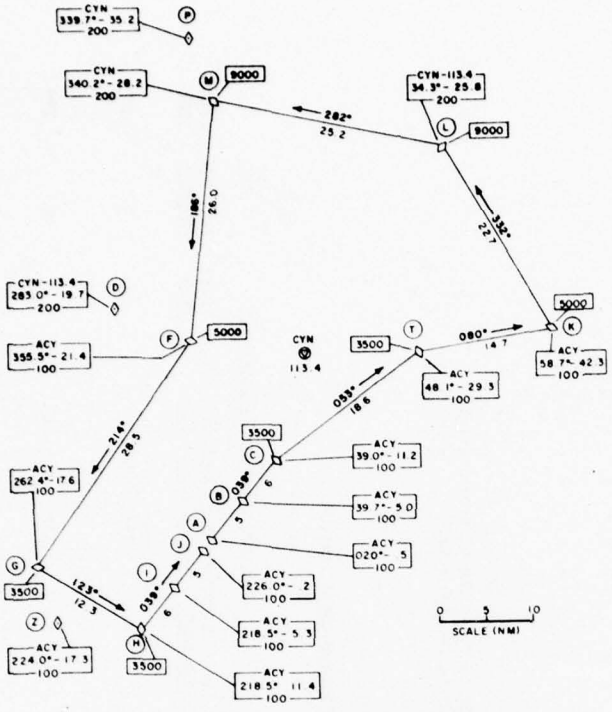

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FIGURE 7. ROUTE B1 - FORWARD

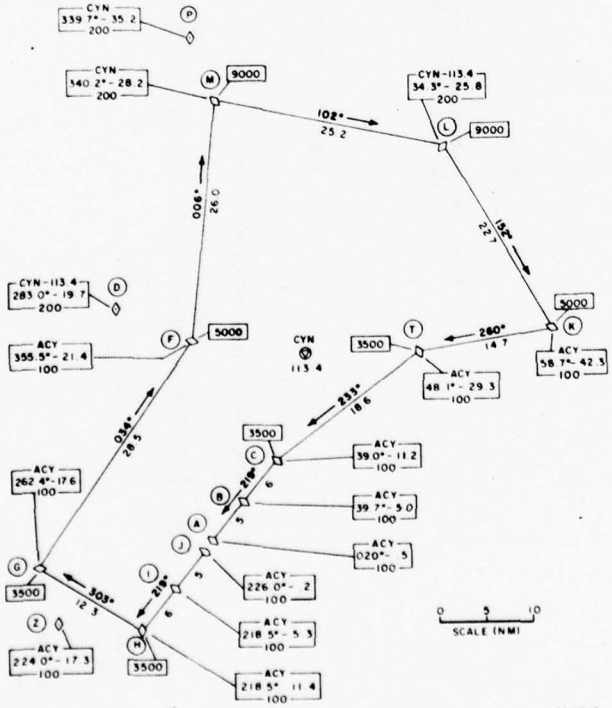

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FIGURE 8. ROUTE B1 - REVERSE

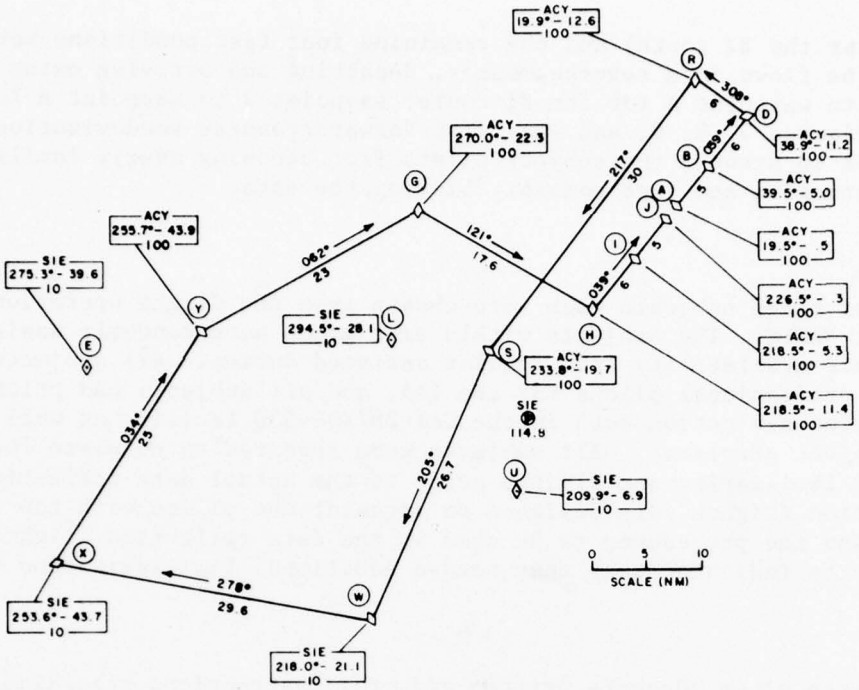


FIGURE 9. ROUTE B2 - FORWARD

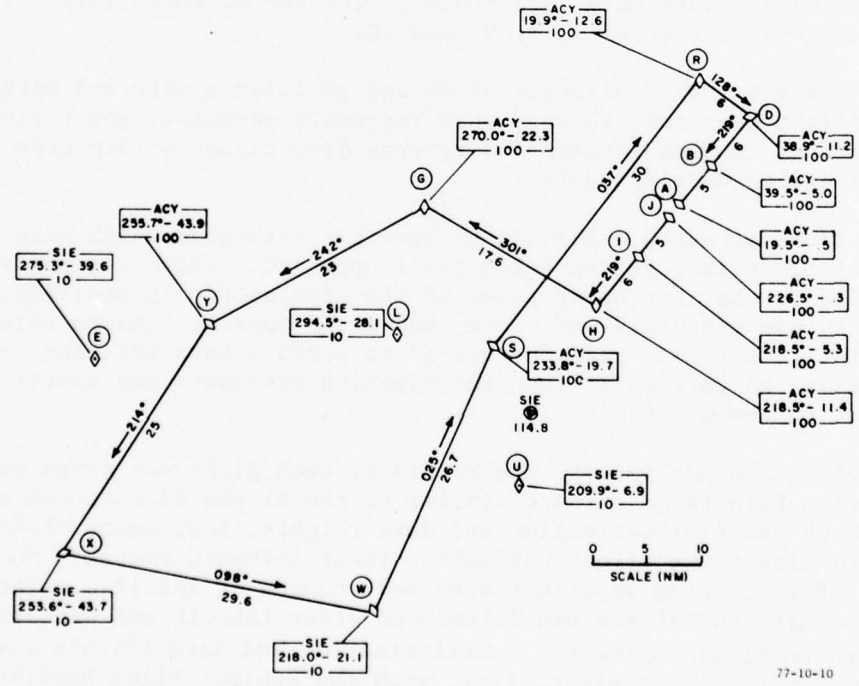


FIGURE 10. ROUTE B2 - REVERSE

waypoint J for the B2 route) and the remaining four test conditions were assigned to be flown in a reverse manner, departing and arriving using runway 22 (waypoint J to waypoint A for the B1 route; waypoint J to waypoint A for the B2 route) (figures 7, 8, 9, and 10). The forward/reverse randomization was done in order to prevent the subject pilots from becoming overly familiar with the route structure and thus possibly biasing the data.

SUBJECTS.

Two groups of three subjects each were chosen from the Flight Operations Branch (ANA-640) at NAFEC. The subjects within each group were randomly assigned based on their availability from regular assigned duties. All subjects were active professional pilots for the FAA, and all subjects had prior experience with area navigation both in the GAT-2B/XDS-530 facility as well as the FAA RNAV project airplanes. All subjects were required to complete four pre-experimental familiarization flights prior to the actual data collection. The familiarization flights were designed to acquaint the pilots with the route structures and the procedures to be used in the data collection flights. None of the subjects indicated that they needed additional familiarization flights.

PROCEDURES.

All pilots were given adequate written and oral instructions regarding experimental objectives, use of the navigational equipment, and specific flight task requirements. The six subject pilots were divided into two groups of three. Group 1 flew the B1 route only, and group 2 flew the B2 route only. These routings are shown in figures 7, 8, 9, and 10.

Both groups had equal randomization of 2D and 3D flights with and without the use of the flight director, flying to an impromptu waypoint, and flying their respective routes in both forward and reverse directions, as depicted in the experimental design matrix, table 1.

Oral instructions stressed adherence to specific airspeeds which were designated for climb, cruise, descent, and final approach. These airspeeds were also placarded on the instrument panel of the simulator. In addition, the route geometry was discussed and route charts and approach charts were given to the pilots. The pilots were instructed to perform turn anticipation in the turns. However, no particular turn anticipation procedure was specified. This item was left to the pilot.

After completing the preliminary instructions, each pilot was given four familiarization flights on a route similar to the B1 and B2 data routes. To complement both the familiarization and data flights, instrument clearances were given to direct the pilots throughout their intended course. Moderate values of wind velocities were initiated and changed at specific points in the routings, and mild turbulence was introduced after takeoff and withdrawn just prior to turn on final approach. Familiarization and data flights were flown in a solo mode without a copilot, i.e., with the subject pilot handling all navigation, flight control, and communications tasks.

The approach plates for the STAR's are presented in figures 11, 12, 13, and 14. The data flights with and without the flight director and in the 2D and 3D modes were flown as follows:

3D--With flight director
3D--Without flight director
2D--With flight director
2D--Without flight director

3D--WITH FLIGHT DIRECTOR. This mode allowed, and required, the insertion of established route waypoint crossing altitudes and the flightpath angle (FPA) to attain these altitudes. The FPA could be derived in two ways. First, it could be automatically computed by the RNAV system, or a specifically desired FPA could be inserted by the pilot. In both cases, the pilot derived his primary vertical flight profile commands from the command bars of the ADI, and also referenced glide slope deviations on the glide slope pointers. Glide slope deviations were also displayed on the HSI.

3D--WITHOUT FLIGHT DIRECTOR. In this mode, the flight director mode switch was put in the "gyro" position, and the flight director system only provided basic pitch and roll guidance. The command bars were biased out of view. The vertical navigation (VNAV) button of the RNAV system was activated, and insertion of desired altitude and FPA was possible. However, glide slope deviations were referenced on the glide slope pointers of the ADI and HSI instruments.

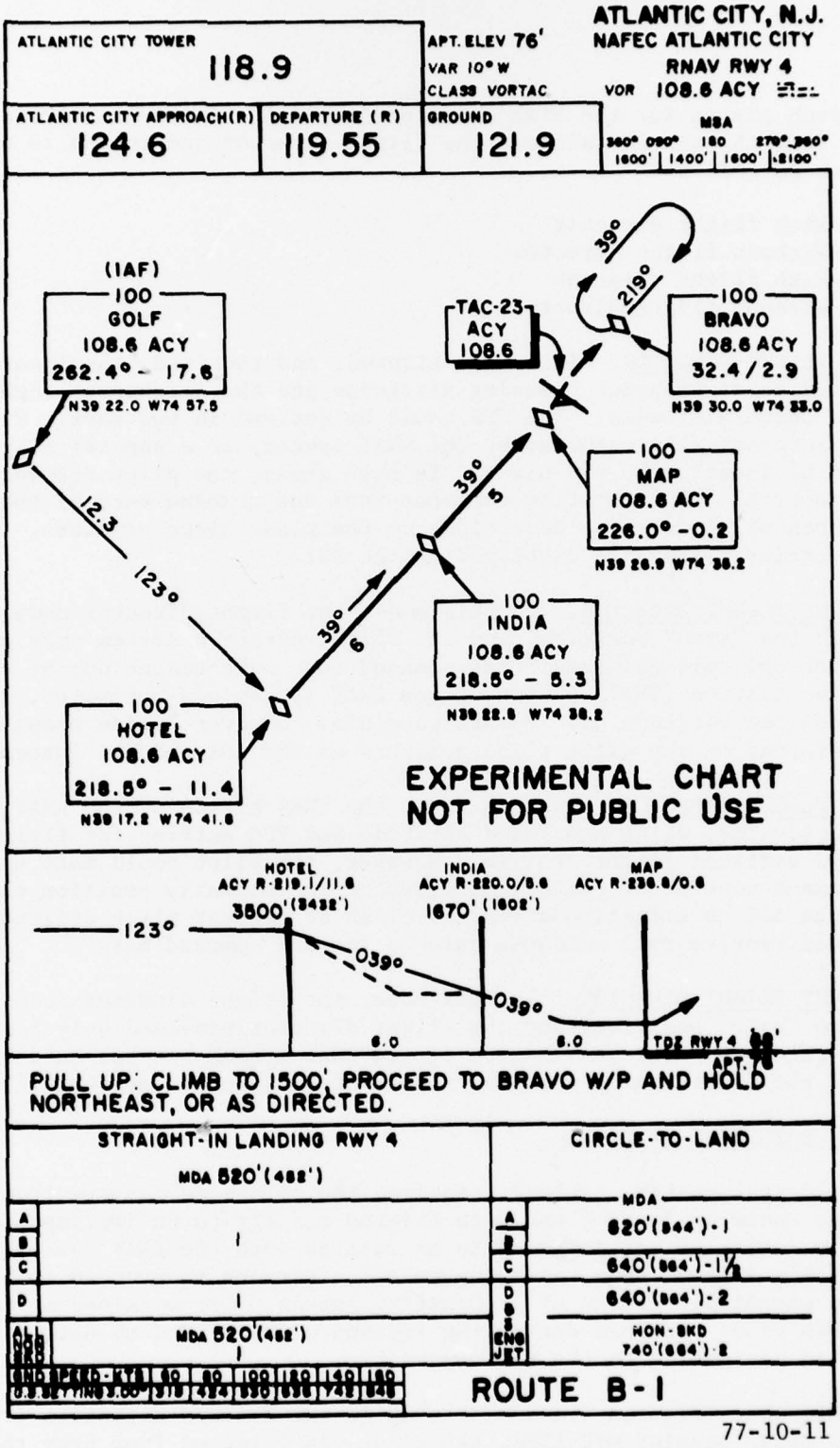
2D--WITH FLIGHT DIRECTOR. In this mode, the VNAV button of the RNAV system was not activated, which precluded altitude and FPA entries for flying a programmed vertical flight profile. However, the pilot could make use of the pitch command control of the flight director and manually position the command bars of the ADI to establish a desired climb or descent pitch attitude. The pilot would receive roll commands only on the ADI command bars.

2D--WITHOUT FLIGHT DIRECTOR. In this mode, the flight director mode switch was put in the "gyro" position, and the flight director provided only basic pitch and roll guidance. The VNAV button of the RNAV system was not activated, which precluded the insertion of altitude and FPA for flying a vertical flight profile.

IMPROMPTU WAYPOINTS (W/P).

The experimental matrix, table 2, required the pilots to deviate from their prescribed route on four of the data flights and fly to an impromptu waypoint. These waypoints were not intended to be entered into the RNAV system initially, but were only entered upon receiving an ATC clearance to proceed to that impromptu waypoint. It was of interest to assess pilot workload at that point and observe pilot workload during the impromptu entry, and to determine any problems in navigating to the new waypoint.

For the B1 route (figures 7 and 8) flying in the forward direction (runway 4 takeoff), after passing W/P LIMA, the pilot was "cleared from over the 8-nmi DTW of W/P MIKE to W/P GOLF via direct W/P DELTA, direct GOLF. Cross W/P DELTA



77-10-11

FIGURE 11. ROUTE B1 (FORWARD) - STANDARD TERMINAL ARRIVAL ROUTE (STAR) AND APPROACH

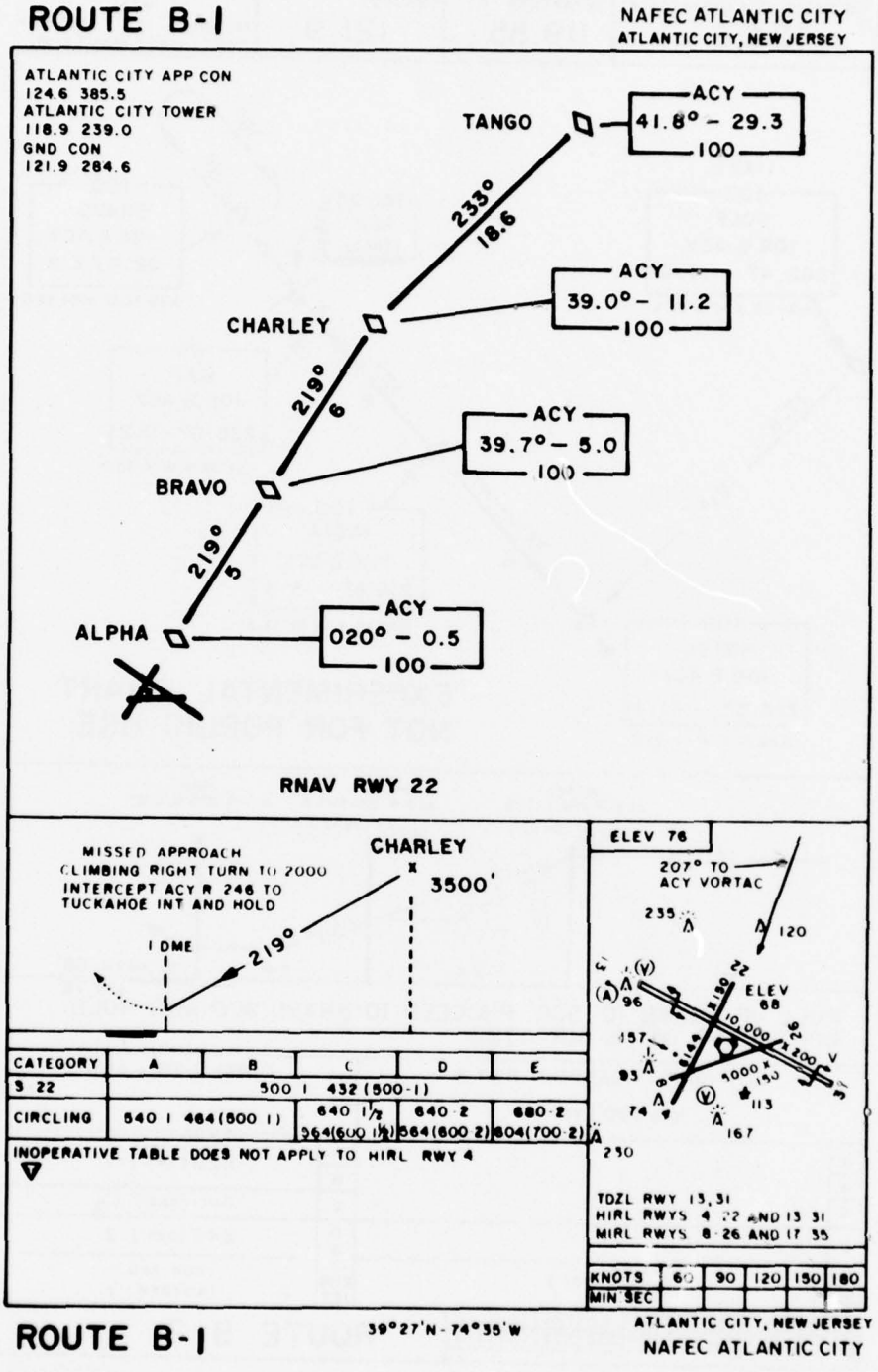
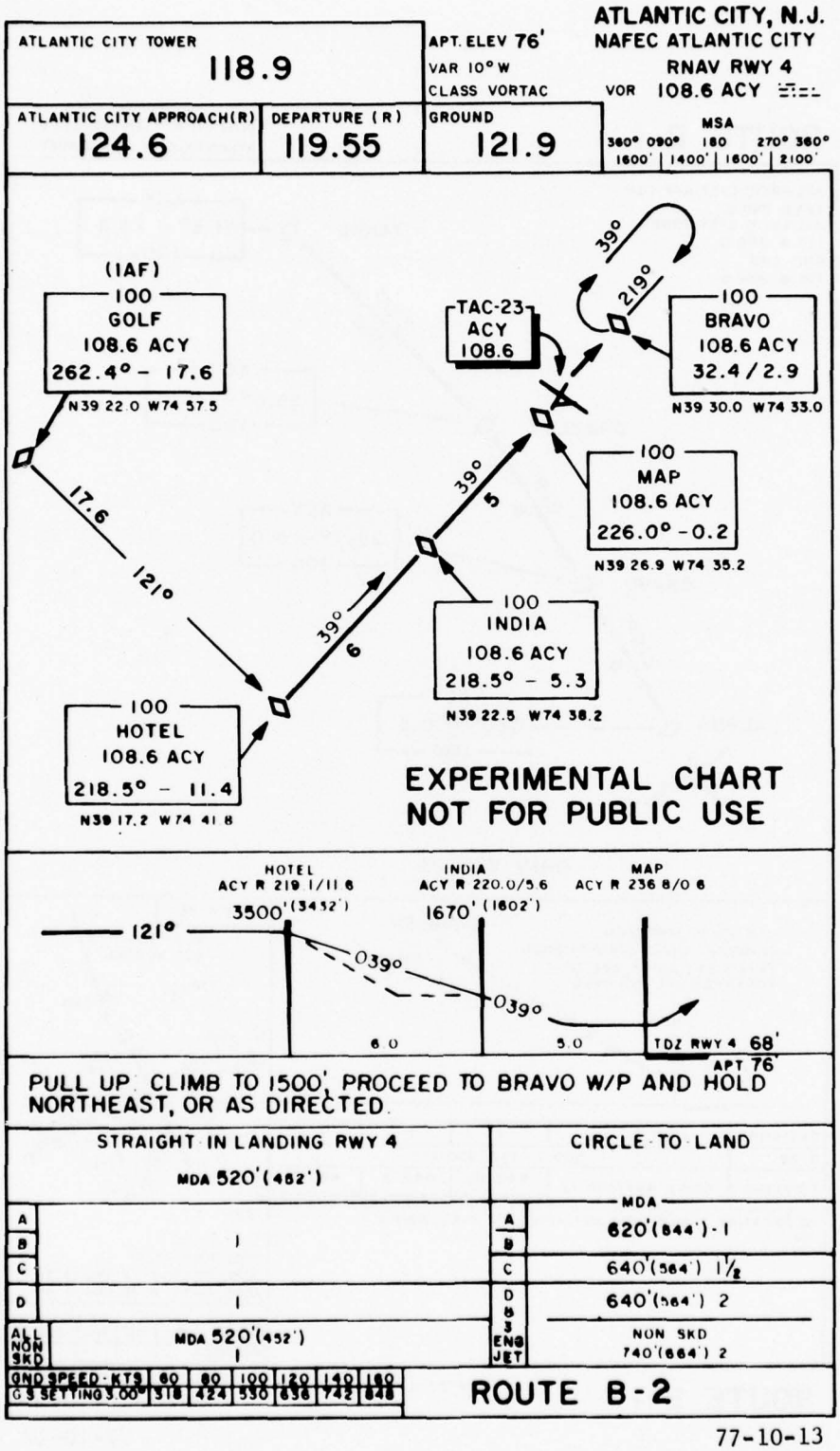


FIGURE 12. ROUTE B1 (REVERSE) - STANDARD TERMINAL ARRIVAL ROUTE (STAR) AND APPROACH



77-10-13

FIGURE 13. ROUTE B2 (FORWARD) - STANDARD TERMINAL ARRIVAL ROUTE (STAR) AND APPROACH

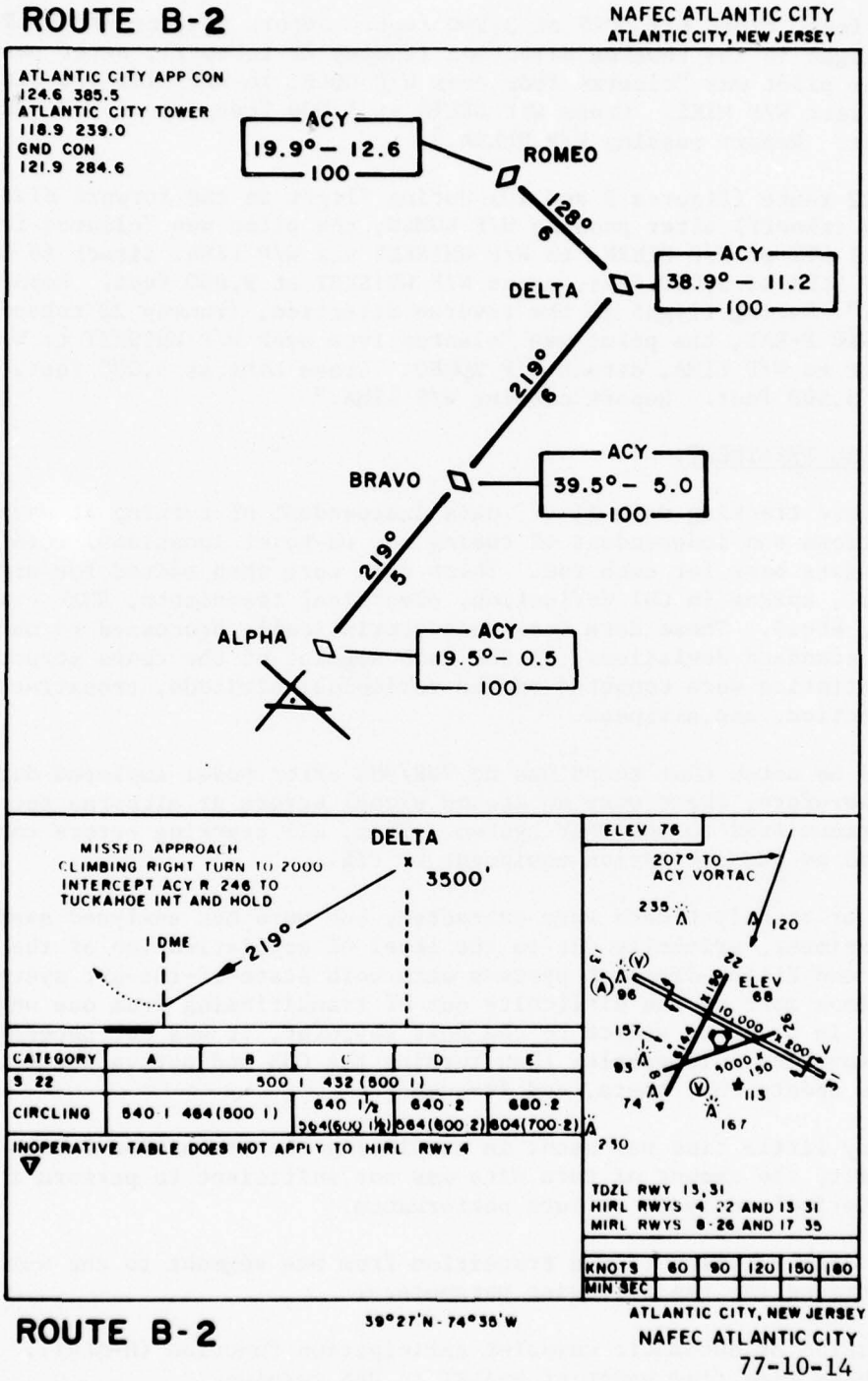


FIGURE 14. ROUTE B2 (REVERSE) - STANDARD TERMINAL ARRIVAL ROUTE (STAR) AND APPROACH

at 5,000 feet, cross W/P GOLF at 3,500 feet. Report passing W/P DELTA." During flight in the reverse direction (runway 22 takeoff), after passing W/P HOTEL, the pilot was "cleared from over W/P GOLF, to W/P MIKE via direct W/P DELTA, direct W/P MIKE. Cross W/P DELTA at 5,000 feet, cross W/P MIKE at 9,000 feet. Report passing W/P DELTA."

For the B2 route (figures 9 and 10) during flight in the forward direction, (runway 4 takeoff) after passing W/P ROMEO, the pilot was "cleared from over the 10-nmi DTW of W/P SIERRA to W/P WHISKEY via W/P LIMA, direct to W/P WHISKEY. Cross W/P LIMA at 5,000 feet, cross W/P WHISKEY at 9,000 feet. Report passing W/P LIMA." During flight in the reverse direction, (runway 22 takeoff), after passing W/P X-RAY, the pilot was "cleared from over W/P WHISKEY to W/P ROMEO via direct to W/P LIMA, direct W/P ROMEO. Cross LIMA at 5,000 feet, cross W/P ROMEO at 3,500 feet. Report passing W/P LIMA."

STATISTICAL TREATMENT.

Steady state tracking data (i.e., data independent of turning at waypoint intersections and independent of tuning new waypoint locations) were extracted from the data base for each run. These data were then edited for erroneous data (i.e., spikes in CDI deflection, electrical transients, RNAV computer failures, etc.). These data were then statistically processed to obtain means ($\bar{X}$), and standard deviations (σ) for each segment of the route structure flown. These statistics were computed on the variables: altitude, crosstrack deviation, CDI deflection, and airspeed.

It should be noted that there was no VOR/DME error model employed during these tests; therefore, there were no ground signal errors or airborne receiver errors transmitted to the RNAV system. Thus, all tracking errors can be attributed to the navigation equipment or FTE.

The turn or transient data were extracted, but were not analyzed separately in this experiment, primarily due to the level of sophistication of the avionics. The RNAV and flight director systems were both state-of-the-art systems and as such took most of the difficulty out of transitioning from one segment to another. In order to update to the next waypoint, it was not necessary to perform anything more complex than turning the OBS and activating a toggle switch to update rho, theta, and frequency.

Since very little time was spent in completing the transition from one segment to the next, the amount of turn data was not sufficient to perform a meaningful and statistical analysis of turn performance.

However, data relating to the transition from one segment to the next segment were extracted for the following parameters:

Duration of automatic waypoint anticipation function (H-ALRT),
Elapsed time from onset of H-ALRT to OBS turning,
Elapsed time from onset of H-ALRT to heading change,
Elapsed time from onset of H-ALRT to update of navigation waypoint,

Distance to waypoint at onset of H-ALRT
Distance to wayline at onset of H-ALRT, and
Distance to angle bisector at onset of H-ALRT.

These data were extracted for each segment of the route structure flown.

The steady state (time series) tracking data for the variables crosstrack deviation (computed) and CDI were extracted separately and processed to obtain a product moment correlation coefficient. The purpose of this statistic was to compare the measured track deviation of the GAT-2B from the course centerline with respect to course centerline displacement of the CDI. It was assumed that if the NCU was working properly, the computation of the actual position of the GAT-2B with respect to the course centerline based on input sensor signals and OBS input would be highly negative when correlated with the measured position. The obtained correlation scores were transformed to Fisher Z scores. The formula for Z is:

$$Z = 1/2 \ln \frac{(1+r)}{(1-r)}$$ (where r = the obtained correlation)

The advantage of the Z transformation is that while correlation coefficients are distributed in skewed fashion for values $\rho = -1, 0, 1$, the values of Z are approximately normally distributed for any value of its parameter. These data were then subjected to an analysis of variance to determine the statistical reliability of any differences that had been obtained due to the levels of the experimental variables.

DISCUSSION OF RESULTS

The results of these simulator tests are presented for horizontal (crosstrack) control, vertical (altitude) control, and airspeed control. In addition, results of procedural tasks involved in entering an impromptu waypoint (based on an ATC clearance) into a preprogrammed route structure are analyzed as well as the procedural use of the automated waypoint anticipation (H-ALRT) function.

The horizontal, vertical, and airspeed time series data were edited to obtain "steady-state" tracking data, and these data were then analyzed statistically. The results of these analyses are presented here.

EXPERIMENTAL CONSIDERATIONS.

Even though routes B1 and B2 were each constructed using 12 waypoints (to define the SID, transition, and STAR segments), the pilots preferred to use only 10 of the waypoints to define the route structure. The pilots deleted waypoints B and I from both routes B1 and B2.

The pilots deleted these waypoints because there were no turn angles involved and it cut down on the overall workload.

The RNAV system used in this experiment was a digital multiwaypoint storage system (up to 20 waypoints may be stored sequentially). Since the SID's and STAR's tested in this experiment contained less than 20 waypoints, it was decided to look at the two components of horizontal (crosstrack) error (total system crosstrack error and flight technical error) for each overall run (including all SID, transition, and STAR segments) as well as across individual segments.

Horizontal (crosstrack) error is defined primarily by Total System Crosstrack Error (TSCT). FTE is a contributing factor to TSCT. TSCT represents the actual deviations left or right of course while flying to a waypoint. For purposes of analysis, deviations to the right of course are indicated as positive, whereas deviations to the left of course are indicated as negative, and as such represent the actual aircraft position as it would have been tracked in flight. FTE represents the actual displacement of the CDI needle left or right of course while flying to a waypoint, and is affected by the accuracy with which the pilot sets his OBS (as well as the VOR, DME, true airspeed (TAS), and altitude reference signals). Displacements of the CDI needle to the right are (i.e., actual position left of course) indicated in this data as positive, whereas displacements to the left (actual position right of course) are indicated in this data as negative (for analysis purposes only), and as such represent the amount by which the pilot must correct his actual position in the direction of the needle displacement in order to be on course. Therefore, if the pilot is off course, there should exist a high negative correlation between TSCT and FTE.

The time series data for horizontal error (TSCT and FTE) were edited (using rate of heading change as the key parameter). This operation resulted in the deletion of approximately 1 to 1.5 nmi prior to and after the waypoint. All turn data were deleted as well as all erroneous data due to electrical spikes and transients. The remaining "steady-state" data were then used to calculate summary statistics for each segment as well as the entire run.

The summary statistics (including mean ($\bar{X}$) TSCT, two sigma (2σ) TSCT, mean FTE, and 2σ FTE) are presented in tables 3 and 4 for all data runs as a function of route structure (B1 and B2) and direction of flight (i.e., departures/arrivals via runway 4 or runway 22). These data are presented in this manner instead of the usual presentation in terms of the interexperimental variables in order to point out a problem which occurred in the data.

TABLE 3. OVERALL HORIZONTAL (CROSSTRACK) ERROR (ALL SEGMENTS) - ROUTE B1

	$\bar{X}$ TSCT	2σ TSCT	$\bar{X}$ FTE	2σ FTE
Route B1 Departure/Arrivals Runway 4	-0.188	0.800	-0.039	0.324
Route B1 Departure/Arrivals Runway 22	0.308	0.929	-0.013	0.361

TABLE 4. OVERALL HORIZONTAL (CROSSTRACK) ERROR (ALL SEGMENTS) - ROUTE B2

	$\bar{X}$ TSCT	2 σ TSCT	$\bar{X}$ FTE	2 σ FTE
Route B2 Departures/Arrivals Runway 4	0.049	0.782	-0.222	0.382
Route B2 Departures/Arrivals Runway 22	0.008	1.008	-0.034	0.349

From these data, it can be seen that there exists a marked bias in the route B1 mean TSCT data in that all data flights which departed and arrived using the runway 4 route structure were biased to the left of course, and all data flights which departed and arrived using the runway 22 route structure were biased to the right of course. The bias, however, is physically in the same location and direction and was influenced by a bias in the incoming VOR/DME signals from the GAT-2B navigation equations during the data collection flights on this particular route structure. Fortunately, the bias is in the $\bar{X}$ TSCT only, and is not reflected in the other three measures (2 σ TSCT, $\bar{X}$ FTE, and 2σ FTE) which indicates that the pilots were doing the best job that they could with the information available to them.

The apparent bias that occurred during the route B1 ($\bar{X}$ TSCT) data flights does not carry over to the route B2 data flights in that there was no observable bias in the $\bar{X}$ TSCT data either to the left or right of course. The two route structures were significantly different from each other in terms of waypoint locations and distances from the relevant VORTAC's (figures 7, 8, 9, and 10), and data were collected in a sequential manner, (i.e., all data from flights on the route B1 were collected prior to collecting data from the route B2 data flights). At the end of the route B1 data collection flights, the GAT-2B system was completely recalibrated with the introduction of the B2 route structure, thus eliminating the bias problem.

These same data ($\bar{X}$ TSCT only) are presented in table 5 in terms of the inter-experimental variables. It can be seen from table 5 that the biased values (±) cancel each other and do not reflect the relatively large mean TSCT values present in the data due to the biased data.

The raw data for the overall horizontal error are presented in appendix A as a function of route structure and direction of flight. These data were based on the entire flight.

Appendix B presents horizontal error data for all of the interexperimental variables as well as the individual segments. These data were subjected to analysis of variance tests and the results for 2 σ TSCT, $\bar{X}$ FTE, 2 σ FTE, and the correlation coefficient between TSCT and FTE are discussed in the following sections.

TABLE 5. MEAN TSCT (in nmi) AS A FUNCTION OF THE INTEREXPERIMENTAL VARIABLES

	FLIGHT DIRECTOR				NO FLIGHT DIRECTOR			
	AS FILED		IMPROMPTU		AS FILED		IMPROMPTU	
	2D	3D	2D	3D	2D	3D	2D	3D
Route B1	0.042	0.100	-0.009	0.186	0.194	0.192	0.017	-0.211
Route B2	0.104	0.092	0.039	-0.024	0.066	0.057	-0.015	0.112
Total	0.073	0.096	0.015	0.081	0.130	0.125	0.001	-0.050

TABLE 6. TWO-SIGMA TSCT (in nmi) VARIABILITY AS A FUNCTION OF THE INTEREXPERIMENTAL VARIABLES

	FLIGHT DIRECTOR				NO FLIGHT DIRECTOR			
	AS FILED		IMPROMPTU		AS FILED		IMPROMPTU	
	2D	3D	2D	3D	2D	3D	2D	3D
Route B1	0.192	0.200	0.225	0.366	0.229	0.358	0.233	0.239
Route B2	0.140	0.148	0.167	0.309	0.167	0.193	0.177	0.217
Total	0.166	0.174	0.196	0.337	0.198	0.276	0.205	0.228

TABLE 7. TWO-SIGMA TSCT (in nmi) VARIABILITY AS A FUNCTION OF THE FD/NFD AND 2D/3D VARIABLES

		FLIGHT DIRECTOR	NO FLIGHT DIRECTOR
Route B1	2D	0.208	0.231
	3D	0.283	0.299
Route B2	2D	0.154	0.172
	3D	0.228	0.205

TSCT BY INTEREXPERIMENTAL VARIABLES - (2 σ DATA).

The 2 σ TSCT data are presented in table 6 as a function of the interexperimental variables in this experiment. The data in this table have been collapsed across subjects and individual segments. The TSCT 2 σ data were subjected to an analysis of variance in order to determine if any systematic differences occurred in the data. The results of the analysis of variance indicated that the only main effect of significance was the 2D/3D RNAV mode variable ($F = 9.133$, $df = 1/4$, $P < 0.039$). The data from the analysis of variance summary tables were extracted for the FD/NFD and 2D/3D variables as a function of route structure (B1 and B2) and are presented in table 7. From table 7, it will be noticed that there appears to be a slight statistical effect for the FD/NFD variable; however, it is not significant statistically, but may have some operational significance in this study as related to the other variables being analyzed. This effect is in the form of lower variability in TSCT for the FD condition than for the NFD condition. The effect due to the 2D/3D variable is clearly visible. From table 7, it will be seen that the 2D RNAV mode yielded significantly less varability in TSCT than did the 3D RNAV mode condition. This effect was the same for both route structures. The increased variability in TSCT for the 3D RNAV mode is probably due to the increased concentration that the pilot finds necessary in order to track the vertical tape. In the 2D RNAV mode, under both the FD and NFD conditions, the level segments as well as the climb/descent segments produce nearly equal workload. In the 3D RNAV mode, the additional task of monitoring the calculated flightpath angle RNAV CDU as well as the flightpath angle displayed by the vertical tape on the HSI imposes a higher workload and therefore resulted in less precision in horizontal tracking.

In addition to the 2D/3D variable main effect, there was a significant effect for the FD/NFD by As Filed/Impromptu by 2D/3D Interaction ($F = 9.597$, $df = 1/4$, $P < 0.037$). The significant effect was due to a combination of things, but primarily the (1) large value for the FD/Impromptu/3D condition caused by the two blunders under this condition, and (2) the fact that the NFD values were consistently higher than those under the FD condition except for the one case mentioned above. This finding may have significance both in this study and the real world environment since it seems to indicate that when a flight director is coupled in a compatible manner to an ARINC Mark 13 RNAV System, the net result is an increase in tracking precision due to the fact that the flight director is provided with the appropriate commands for on-course tracking.

TABLE 8. MEAN FTE (in nmi) AS A FUNCTION OF THE INTEREXPERIMENTAL VARIABLES

	FLIGHT DIRECTOR				NO FLIGHT DIRECTOR			
	AS FILED		IMPROMPTU		AS FILED		IMPROMPTU	
	2D	3D	2D	3D	2D	3D	2D	3D
Route B1	-0.003	-0.003	-0.039	-0.007	-0.028	-0.017	-0.035	-0.008
Route B2	-0.028	-0.036	-0.045	-0.013	-0.005	-0.014	-0.031	-0.064
Total	-0.016	-0.020	-0.042	-0.010	-0.016	-0.015	-0.033	-0.036

FTE BY INTEREXPERIMENTAL VARIABLES - ($\bar{X}$ DATA)

The $\bar{X}$ FTE data are presented in table 8 as a function of the interexperimental variables in this experiment. The data in this table have been collapsed across subjects and individual segments. The mean FTE data were subjected to an analysis of variance in order to determine if any systematic differences occurred in the data. The results of the analysis of variance indicated that there were no main effects of significance in these data. The fact that there were no statistically significant main effects or interactions in these data cannot be interpreted to mean that these data have no operational significance. All of the $\bar{X}$ FTE values were well within the $\pm$1 nmi criteria and probably reflect the accuracy of the RNAV system used in this experiment. In addition, the pilot entered the desired OBS setting using a digital OBS display and did not have to interpolate between scaling marks as must be done using an analog system; therefore, the OBS input signal was highly accurate and had no effect on CDI displacement unless an inappropriate value was entered.

FTE BY INTEREXPERIMENTAL VARIABLES - (2 σ DATA).

The 2 σ FTE data are presented in table 9 as a function of the interexperimental variables in this experiment. The data in this table have been collapsed across subjects and individual segments. The 2 σ FTE data were subjected to an analysis of variance in order to determine if any systematic differences occurred in the data. The results of the analysis of variance indicated that there was a statistically significant effect due to the 2D/3D RNAV mode variable ($F = 33.418$, $df = 1/4$, $P < 0.006$), and that there appears to be a statistically significant effect for the FD/NFD variable in that the F Ratio approaches statistical significance ($F = 6.681$, $df = 1/4$, $P < 0.061$). Even though this effect is not significant statistically at the $P < 0.05$ level, the effect may indeed be considered to have operational significance in that the performance under the FD condition was better than under the NFD condition.

TABLE 9. TWO-SIGMA FTE (in nmi) VARIABILITY AS A FUNCTION OF THE INTEREXPERIMENTAL VARIABLES

	FLIGHT DIRECTOR				NO FLIGHT DIRECTOR			
	AS FILED		IMPROMPTU		AS FILED		IMPROMPTU	
	2D	3D	2D	3D	2D	3D	2D	3D
Route B1	0.195	0.213	0.195	0.215	0.226	0.356	0.247	0.245
Route B2	0.139	0.137	0.152	0.158	0.155	0.197	0.177	0.203
Total	0.167	0.175	0.173	0.186	0.190	0.276	0.212	0.224

The data from the analysis of variance summary tables were extracted for the FD/NFD and 2D/3D variables as a function of route structures (B1 and B2) and are presented in table 10. From table 10 it will be observed that there is a noticeable difference in performance between the FD and NFD conditions. This difference favors the FD condition in that there exists a smaller amount of FTE variability under this condition, which would tend to indicate that horizontal tracking performance was enhanced due to the bank steering commands complementing the CDE displacement and giving more precise guidance to the pilot. The effect due to the 2D/3D RNAV mode variable is also clearly visible. From table 10 it will be seen that for most part, the 2D RNAV mode yielded significantly less FTE variability than did the 3D RNAV mode condition. These effects for both the FD/NFD and the 2D/3D RNAV mode variables were consistent for both route structures. Once again, the lesser FTE variability under the 2D RNAV mode condition is perhaps due to the lower workload experienced under this condition than that experienced under the 3D RNAV mode which required the pilot to perform the additional task of monitoring the FPA on the RNAV CDU or the FPA vertical tape on the HSI in order to maintain the correct vertical profile.

TABLE 10. TWO-SIGMA FTE (in nmi) VARIABILITY AS A FUNCTION OF THE FD/NFD AND 2D/3D VARIABLES

		FLIGHT DIRECTOR	NO FLIGHT DIRECTOR
Route B1	2D	0.195	0.236
	3D	0.214	0.300
Route B2	2D	0.146	0.166
	3D	0.147	0.200

PRODUCT MOMENT CORRELATION COEFFICIENT BETWEEN TSCT AND FTE.

The product moment correlation coefficient between the TSCT and FTE time series data was calculated in order to determine if there was any consistent behavior between these two parameters. Prior to calculating the correlation coefficient, it was assumed that if the aircraft were exactly on course the correlation would be approximately zero (0), and that if the aircraft were not on course there would exist a high negative correlation between TSCT and FTE, assuming that the RNAV equipment system error was within the 0.5 nmi tolerance specified by AC-90-45A. The correlation coefficient was calculated for every segment on the "steady-state" data and was subjected to an analysis of variance in order to determine if there were any systematic differences in the data. The correlation coefficient data are presented in table 11 as a function of the interexperimental variables in this experiment. The overall experimental correlation coefficient between TSCT and FTE resulted in a high negative correlation ranging between

-0.4 and -0.7. The data in this table have been collapsed across subjects and individual segments. The results of the analysis of variance indicated that the main effect of significance for the correlation coefficient measure was the FD/NFD variable ($F = 7.832$, $df = 1/4$, $P < 0.049$). The results of the analysis of variance also indicated that the statistically significant effect due to the 2D/3D variable evident in both the 2σ TSCT and FTE data is not evident in the correlation coefficient data ($F = 4.402$, $df = 1/4$, $P < 0.013$). However, inspection of table 11 indicates that operational differences do exist; in that the 3D RNAV mode has a consistantly higher negative correlation than the 2D RNAV mode condition. The values in table 11 are all high negative correlation coefficients, which indicates that TSCT and FTE operate in the predicted manner. That is, as the aircraft gets further off course in one direction the CDI needle moves in the opposite direction, and, conversely, as the aircraft converges towards the course centerline, the CDI needle also converges to the center of the display.

TABLE 11. PRODUCT MOMENT CORRELATION COEFFICIENT AS A FUNCTION OF THE INTEREXPERIMENTAL VARIABLES

	FLIGHT DIRECTOR				NO FLIGHT DIRECTOR			
	AS FILED		IMPROMPTU		AS FILED		IMPROMPTU	
	2D	3D	2D	3D	2D	3D	2D	3D
Route B1	-0.528	-0.538	-0.446	-0.547	-0.587	-0.707	-0.644	-0.684
Route B2	-0.423	-0.578	-0.630	-0.536	-0.652	-0.681	-0.586	-0.684
Total	-0.476	-0.557	-0.538	-0.541	-0.619	-0.694	-0.615	-0.684

Therefore, it would be expected that if the variability of the data increased under a given set of conditions, the correlation coefficient would be larger than if there were very little variability in the data. Thus, the correlation coefficient should be a good indicator of the pilots' horizontal tracking performance and should indicate any difference due to the interexperimental variables. The lower the correlation coefficient, the better his performance.

TABLE 12. PRODUCT MOMENT CORRELATION COEFFICIENT AS A FUNCTION OF THE FD/NFD AND 2D/3D VARIABLES

		FLIGHT DIRECTOR	NO FLIGHT DIRECTOR
Route B1	2D	-0.488	-0.616
	3D	-0.541	-0.695
Route B2	2D	-0.526	-0.619
	3D	-0.557	-0.682

The data from the analysis of variance summary tables were extracted for the FD/NFD and 2D/3D variables as a function of route structures (B1 and B2) and are presented in table 12. From table 12, it will be noticed that there exists a pronounced difference between the FD and NFD conditions as well as the 2D RNAV mode and 3D RNAV mode conditions. These differences favor the FD and 2D RNAV mode conditions in that the correlation coefficients are lower for the FD condition than the NFD condition, and the correlation coefficients are lower for the 2D RNAV mode than for the 3D RNAV mode. The differences between the FD and NFD conditions are probably due to the fact that under the FD condition the pilots had additional information available to them in the form of the pitch and bank steering bars, especially the bank steering bars. The bank steering bars, even though they received the same signal at the same time from the RNAV system, were more sensitive than the raw CDI needle and moved prior to the CDI. Therefore, the pilots were able to "anticipate" any movement of the CDI needle and made corrective actions earlier, which resulted in less overall TSCT and FTE variability. The operational and statistical differences obtained for the FD/NFD variable, (demonstrated by the 2σ TSCT and FTE data and the correlation coefficient data) offer evidence that the results obtained with the FD system may indeed be significant and, with additional testing, may be proved to offer a serious advantage for RNAV. In other words, RNAV performance may be improved greatly by using it in conjunction with an FD; however, further testing for data is needed to quantify this condition. The operational and statistical differences obtained for the 2D/3D variable (using the same data as above) indicate that the 2D RNAV mode results in less variability in the data than the 3D RNAV mode and indicates that additional work needs to be done to define the 3D RNAV mode of operation.

VERTICAL (ALTITUDE) DATA AS A FUNCTION OF THE PARAMETERS IN THIS STUDY.

The vertical flight profiles used in this study are presented in figures 15 and 16. Figures 17 and 18 present $\overline{X}$ altitude data for routes B1 and B2 as a function of RNAV mode (2D/3D). The data in figures 17 and 18 are plotted as a function of the different types of performance activity which are defined by the various level, climb, or descending activities in a given segment. These data are considered "steady-state," in that they were edited using the same procedures which were used for the horizontal error data. It can be seen from figures 17 and 18 that the altitude data appear to have the same distribution and in fact can be compared statistically. An analysis of variance on the mean altitude data indicated that significant differences existed between the different performance activities ($F = 1991.614$, $df = 6/24$, $P < 0.001$) and that there was a significant interaction between the 2D/3D RNAV mode variable and the different performance activities ($F = 36.336$, $df = 6/24$, $P < 0.001$). No significant differences existed for any of the other variables of $\overline{X}$ altitude data. The 2D/3D RNAV mode by Performance Activity Interaction data are presented in table 13 as a function of the two route structures (B1 and B2) and RNAV mode (2D/3D). From table 13 it will be noticed that for the 2D/3D RNAV mode parameter there is a distinct difference for the climb or descent segments. There exists a significant difference between the two levels of this parameter as follows:

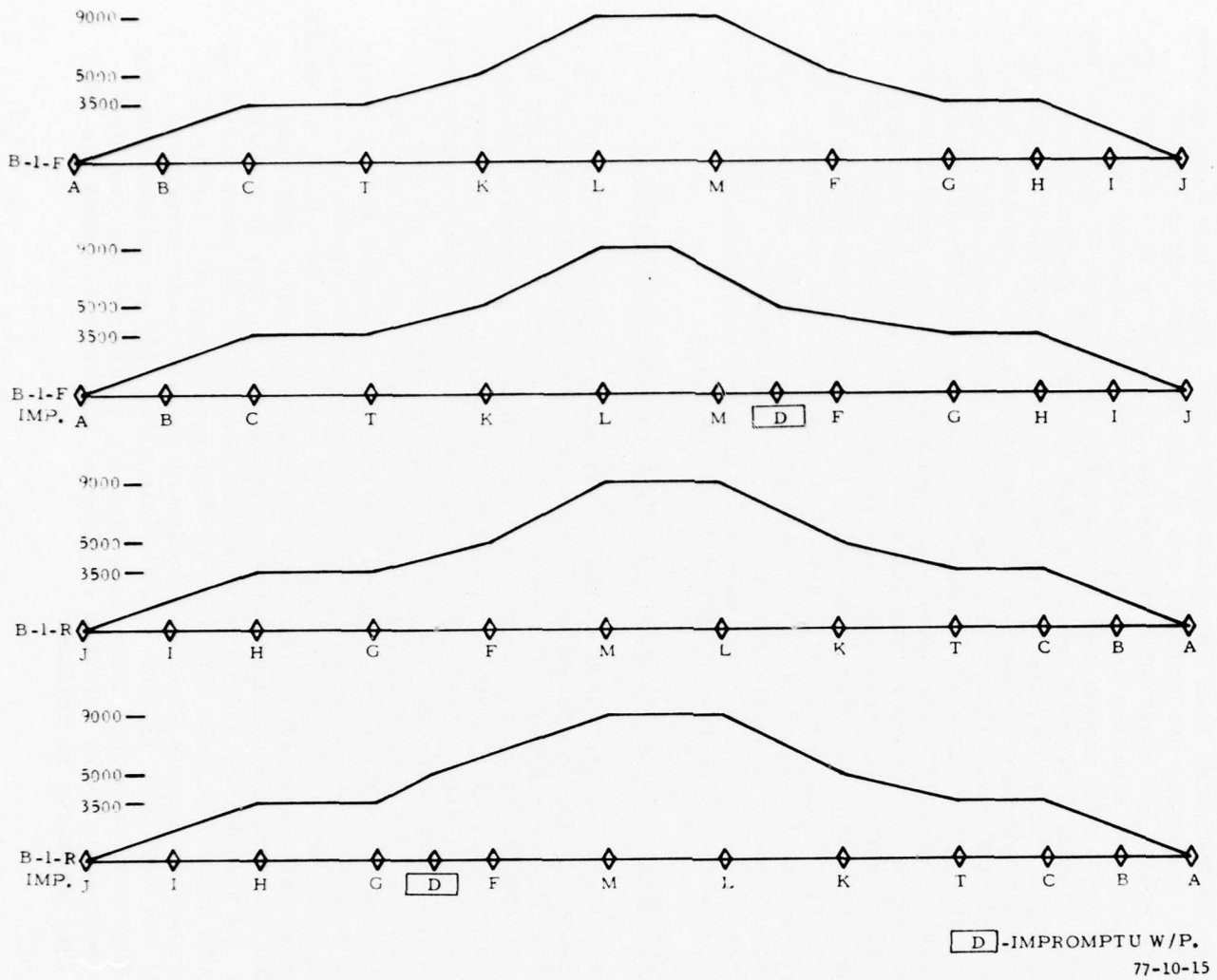


FIGURE 15. VERTICAL FLIGHT PROFILES - ROUTE B1

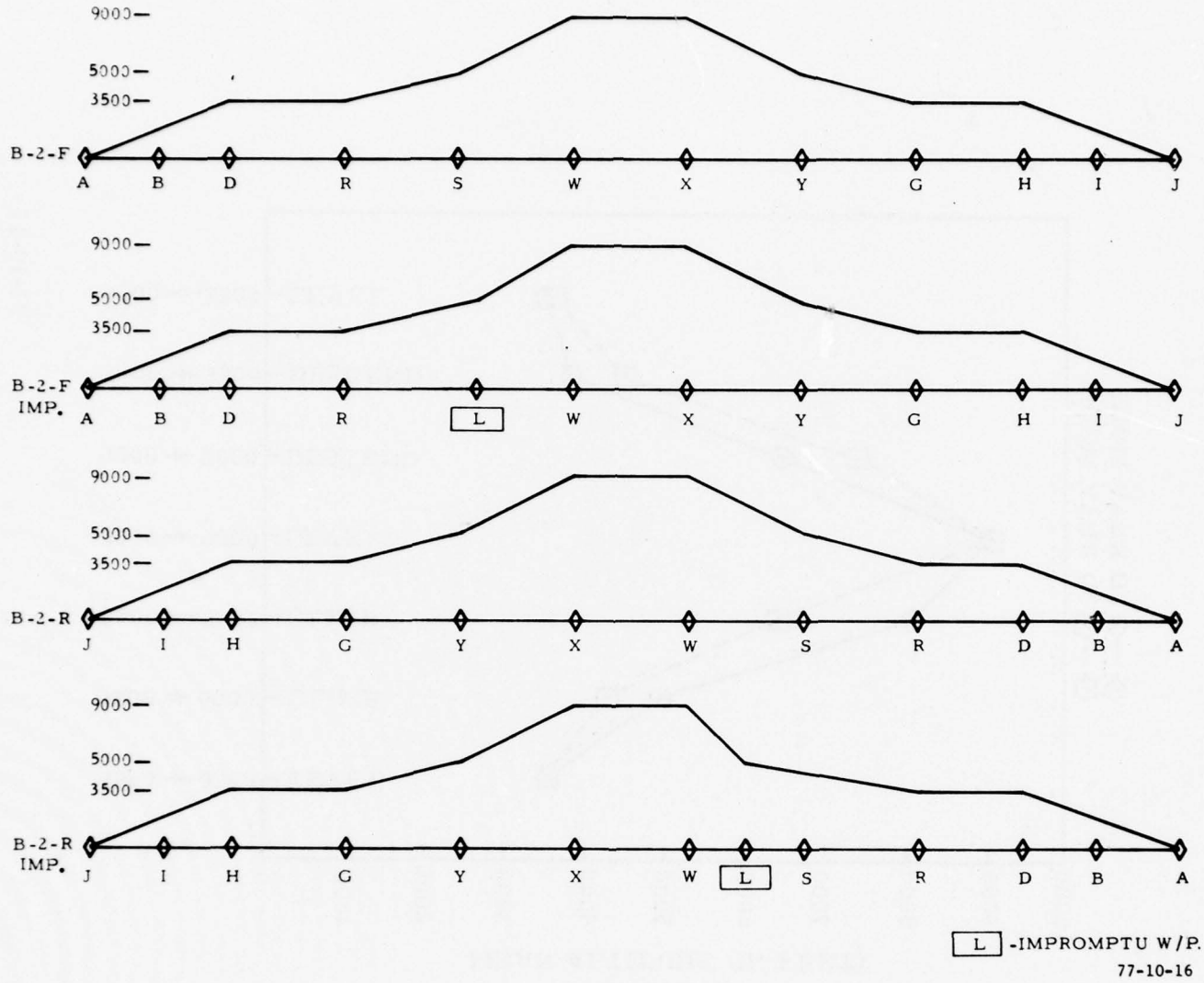


FIGURE 16. VERTICAL FLIGHT PROFILES - ROUTE B2

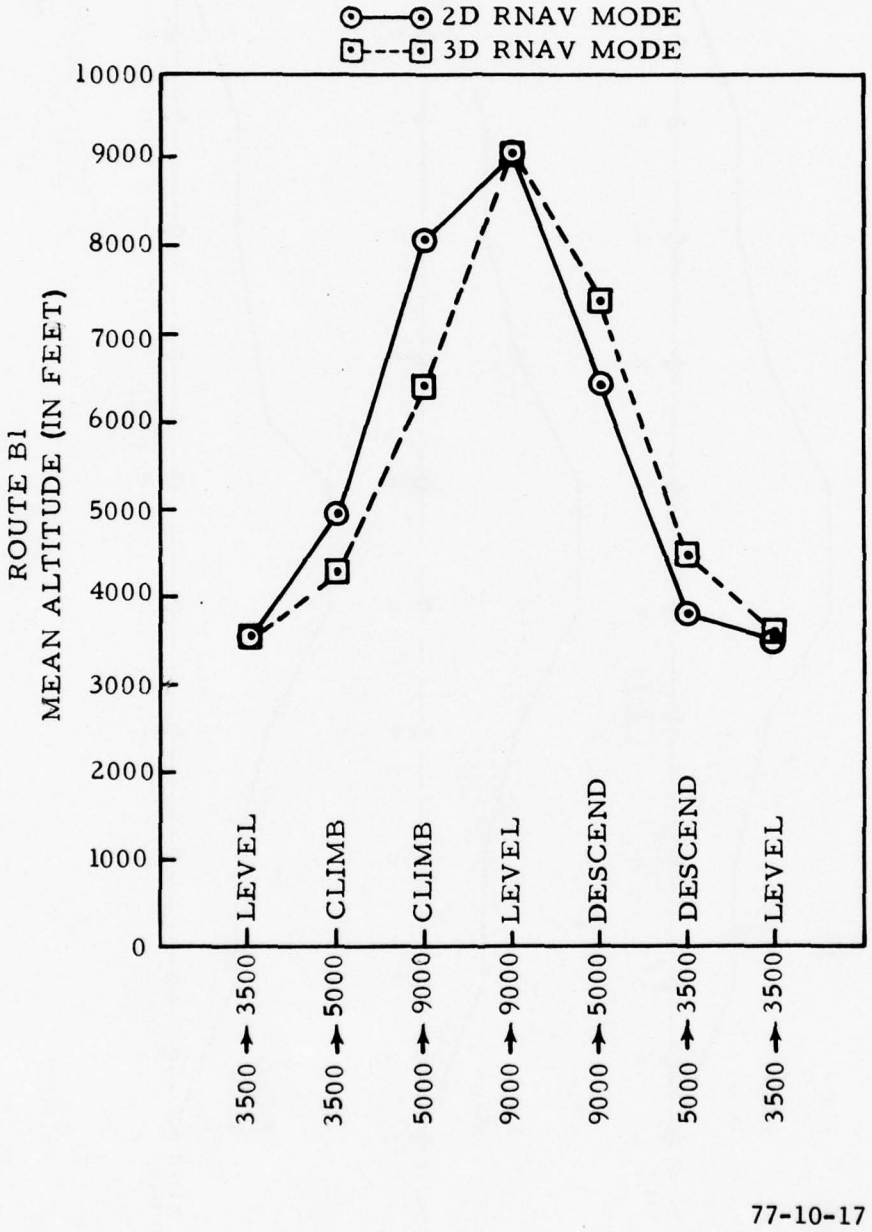


FIGURE 17. MEAN ALTITUDE (IN FEET) AS A FUNCTION OF RNAV MODE (2D/3D) AND PERFORMANCE ACTIVITY - ROUTE B1

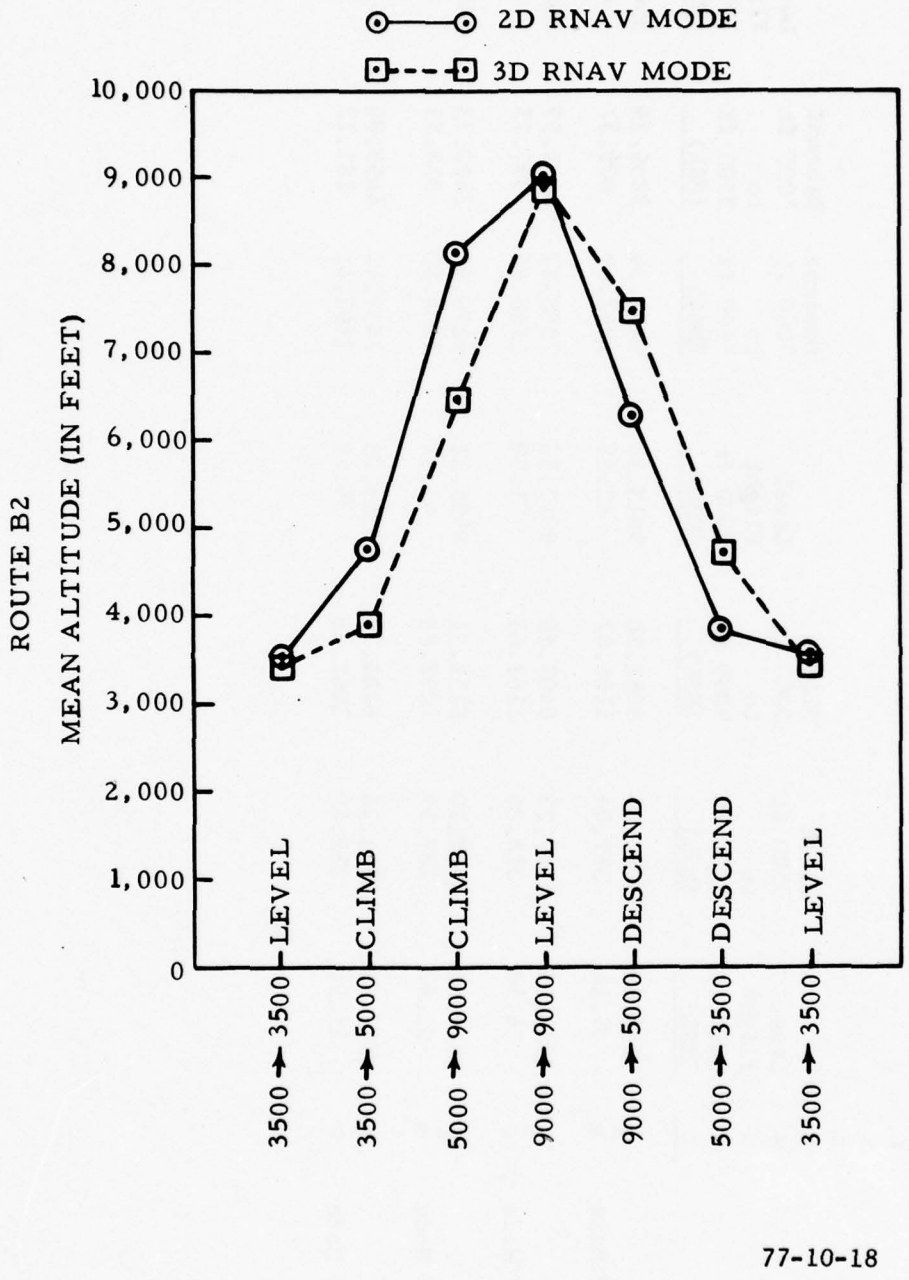


FIGURE 18. MEAN ALTITUDE (IN FEET) AS A FUNCTION OF RNAV (2D/3D) AND PERFORMANCE ACTIVITY - ROUTE B2

TABLE 13. VERTICAL (ALTITUDE) DATA AS A FUNCTION OF ROUTE STRUCTURE (B1/B2), RNAV MODE (2D/3D), AND PERFORMANCE ACTIVITY (CLIMB, DESCEND, LEVEL FLIGHT)

	Statistic	Level Flight 3500 ft (MSL)	Climb 3500 ft to 5000 ft (MSL)	Climb 5000 ft to 9000 ft (MSL)	Level Flight 9000 ft (MSL)	Descent 9000 ft to 5000 ft (MSL)	Descent 5000 ft to 3500 ft (MSL)	Level Flight 3500 ft (MSL)
2D RNAV Mode	$\bar{X}$	3556.83	4093.26	8062.30	9013.34	6401.39	3806.39	3546.0
	σ	39.16	387.84	1166.87	42.59	1262.09	409.37	41.9
3D RNAV Mode	$\bar{X}$	3538.25	4287.23	6407.69	9017.85	7358.81	4481.57	3563.7
	σ	54.58	318.86	1163.68	51.59	1166.46	397.75	45.5
2D RNAV Mode	$\bar{X}$	3517.62	4787.10	8159.31	8995.51	6279.92	2820.73	3526.2
	σ	32.97	287.59	1098.83	41.51	1104.60	338.55	34.94
3D RNAV Mode	$\bar{X}$	3472.63	3931.76	6484.70	8955.23	7439.44	4659.86	3477.1
	σ	28.90	285.80	1062.36	39.29	1195.41	281.12	39.5

1. For the climb segments, the pilots under the 2D RNAV mode condition tended to climb directly (or nearly so) to the assigned altitude and flew the majority of the segment at the assigned altitude.

2. For the climb segments, the pilots under the 3D RNAV mode condition tended to fly along at the initial altitude until they intercepted a desired climb gradient (usually 2.5° to 3.0°) and then climbed directly to the new assigned altitude just prior to the end of the segment.

3. For the descent segment, the pilots under the 2D RNAV mode condition descended almost immediately to the assigned altitude and flew the majority of the segment at the assigned altitude.

4. For the descent segment, the pilots under the 3D RNAV mode condition tended to fly at the initial altitude until they intercepted a desired glide path (usually 2.5° to 3.0°) and then descended to the new assigned altitude just prior to the end of the segment.

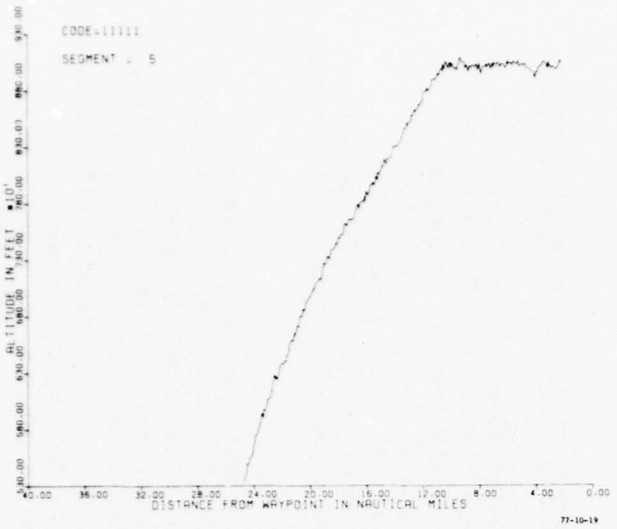
Examples of these activities are presented in figures 19 and 20. These activities are significant in that they could impact airspace utilization and fuel consumption since pilots do not like to fly shallow gradients and probably would not accept a minimal (approximately 1°) climb rate.

No attempt was made, in this data analysis, to compare altitude gradient errors, since the gradients flown in this experiment were fairly shallow and the pilots were not specifically told to maintain a gradient. The desired waypoint crossing altitudes were given on the pilots' charts, and the pilot was aware of them.

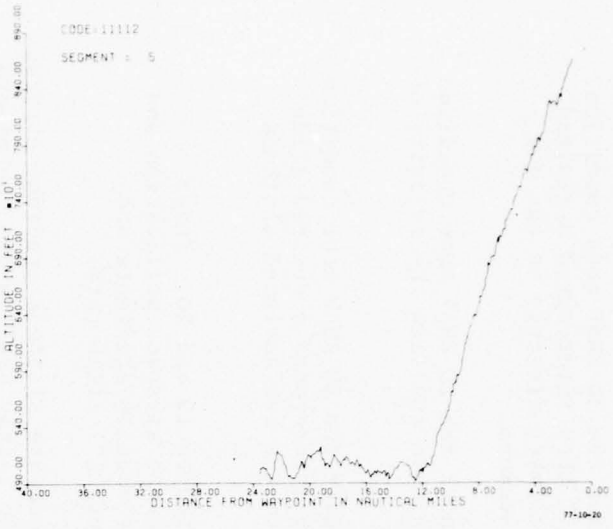
AIRSPEED DATA AS A FUNCTION OF THE INTEREXPERIMENTAL VARIABLES IN THIS STUDY.

Figures 21 and 22 present $\bar{X}$ airspeed data for routes B1 and B2 as a function of RNAV mode (2D/3D). The data in each figure are plotted as a function of the different types of performance activity as well as the level of avionics equipment in use. These data represent "steady-state" data in that they are edited using the same procedures used for the horizontal error data. The pilots had been instructed to maintain an airspeed of 160 knots indicated airspeed (IAS), except during climbs where they were expected to maintain 140 knots IAS.

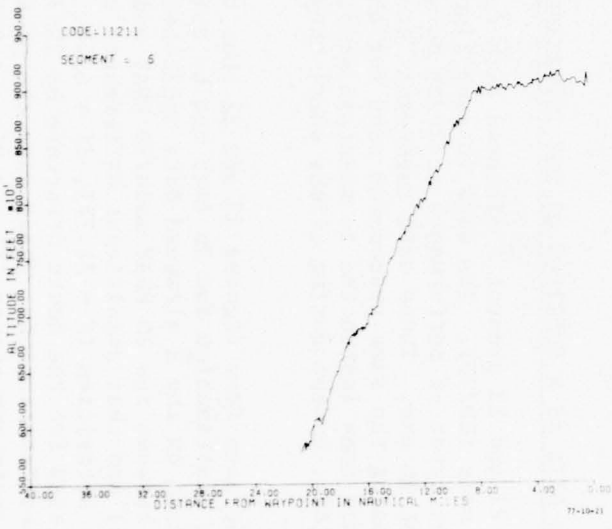
It can be seen from figures 21 and 22 that the airspeed data appear to have the same distribution and in fact can be compared statistically. An analysis of variance on the $\bar{X}$ airspeed data indicated that significant differences existed between the 2D RNAV mode/3D RNAV mode conditions ($F = 39.053$, $df = 1/4$, $P < 0.005$) and that significant differences existed between the different performance activities ($F = 31.775$, $df = 6/24$, $P < 0.001$). Significant differences also existed for the Route Structure by 2D/3D RNAV Mode by Performance Activities Interaction. These data are presented in table 14 as a function of the two route structures (B1 and B2) and RNAV Mode (2D/3D). From table 14, it will be noticed that for the route B1 data there are significant differences in the $\bar{X}$ airspeed for the two descent segments. The $\bar{X}$ airspeed data for the route B1/3D RNAV mode conditions are much closer to the 160 knots required



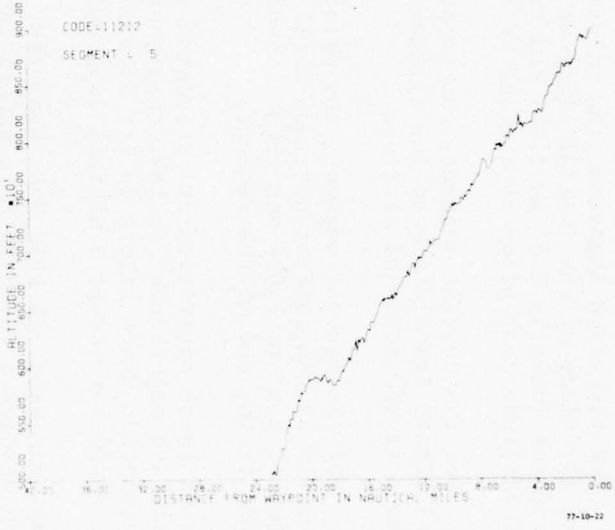
FD-2D CONDITION



FD-3D CONDITION

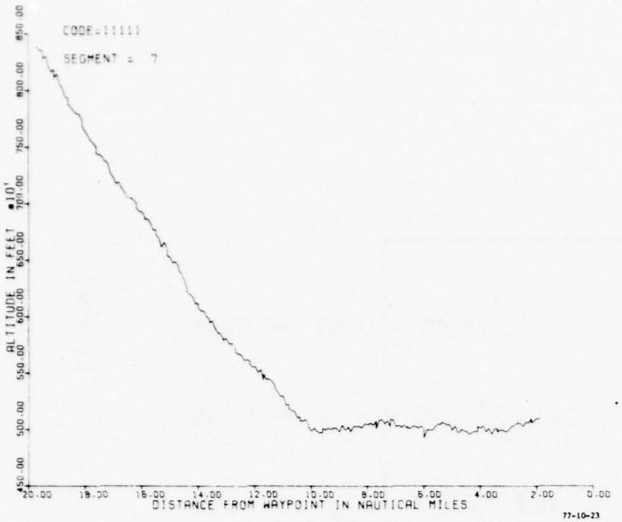


NFD-2D CONDITION

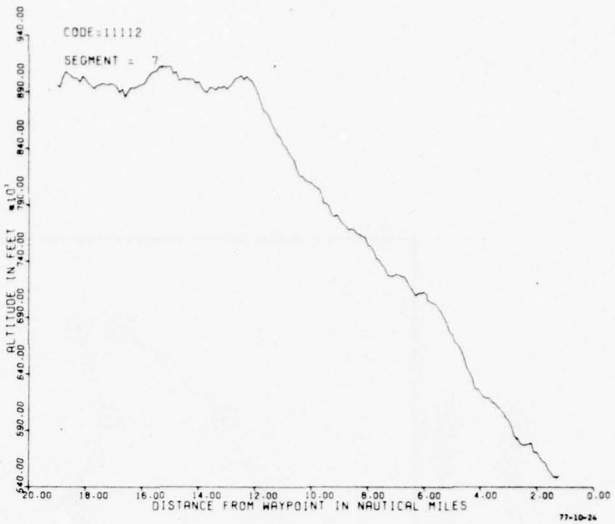


NFD-3D CONDITION

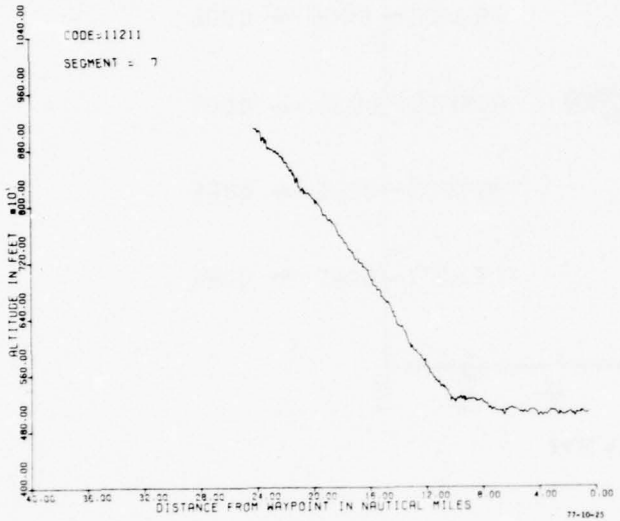
FIGURE 19. VERTICAL CLIMB PROFILES



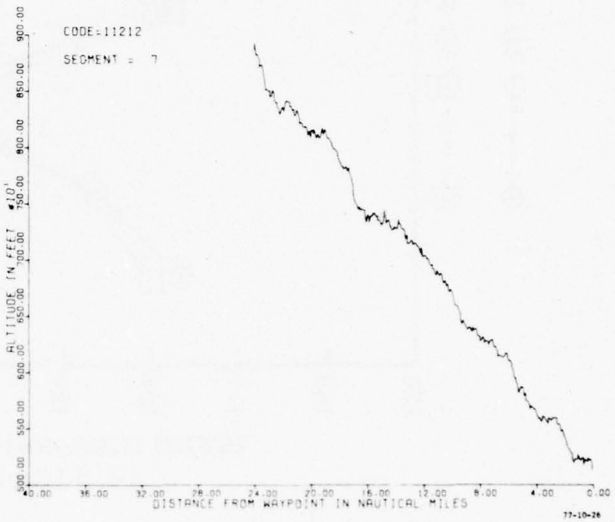
FD-2D CONDITION



FD-3D CONDITION



NFD-2D CONDITION



NFD-3D CONDITION

FIGURE 20. VERTICAL DESCENT PROFILES

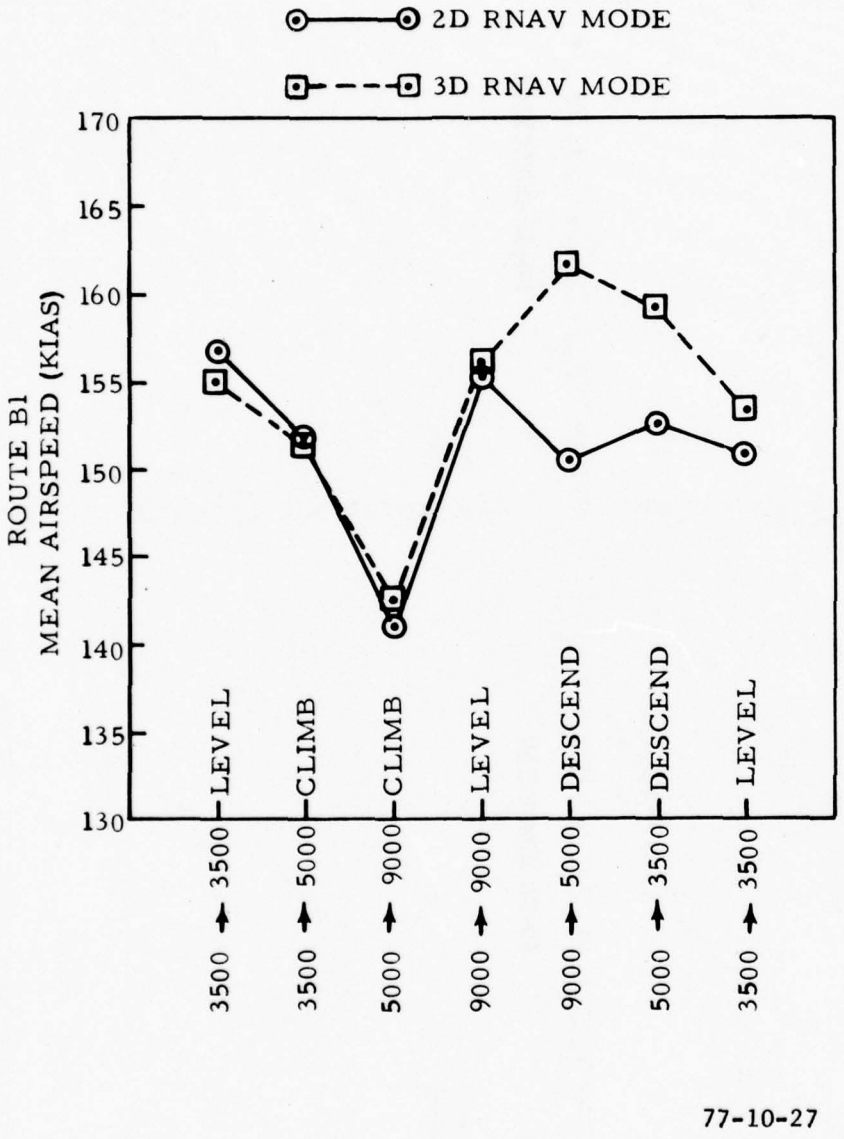


FIGURE 21. MEAN AIRSPEED (KIAS) AS A FUNCTION OF RNAV MODE (2D/3D) PERFORMANCE ACTIVITY - ROUTE B1

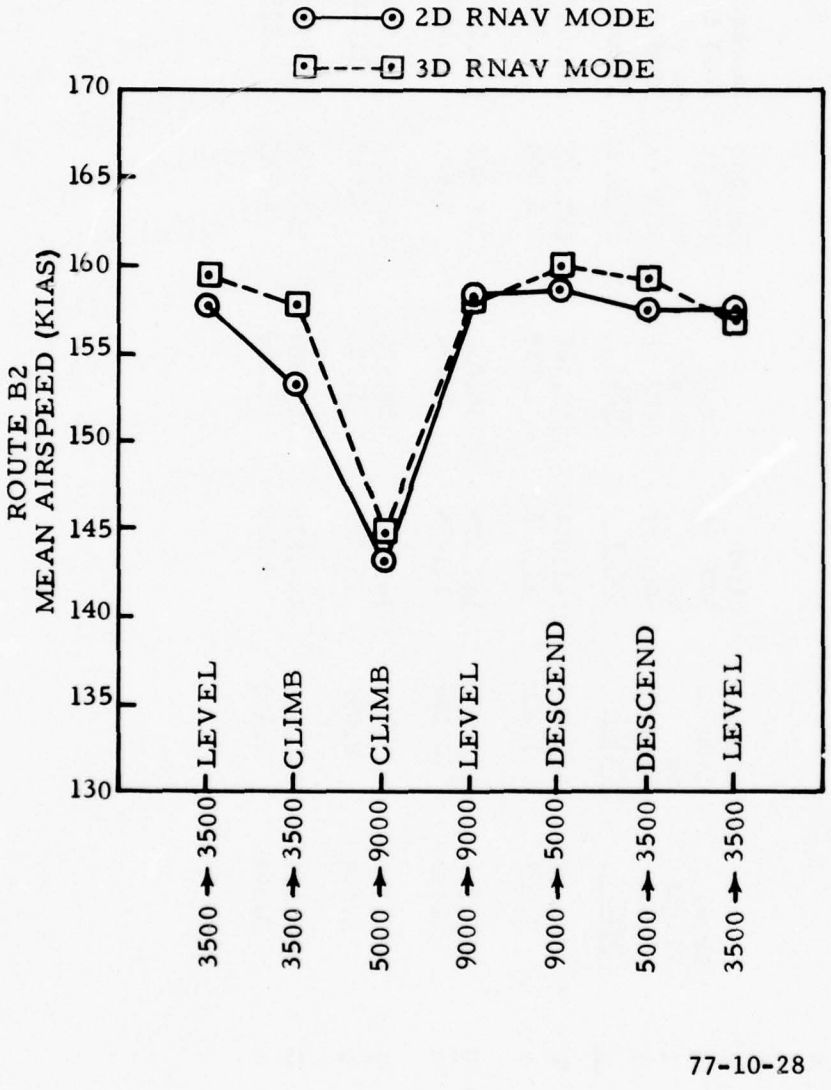


FIGURE 22. MEAN AIRSPEED (KIAS) AS A FUNCTION OF RNAV MODE (2D/3D) AND PERFORMANCE ACTIVITY - ROUTE B2

TABLE 14. AIRSPEED (KIAS) DATA AS A FUNCTION OF ROUTE STRUCTURE (B1/B2), RNAV MODE (2D/3D), AND PERFORMANCE ACTIVITY (CLIMB, DESCEND, LEVEL FLIGHT)

	Statistic	Level Flight 3500 ft (MSL)	Climb 3500 ft to 5000 ft (MSL)	Climb 5000 ft to 9000 ft (MSL)	Level Flight 9000 ft (MSL)	Descent 9000 ft to 5000 ft (MSL)	Descent 5000 ft to 3500 ft (MSL)	Level Flight 3500 ft (MSL)
2D RNAV Mode	$\bar{X}$	156.888	151.841	141.048	155.149	150.571	152.697	150.969
	σ	2.405	7.842	11.692	1.959	6.300	6.386	4.706
3D RNAV Mode	$\bar{X}$	154.954	151.672	142.579	156.052	161.666	159.240	153.335
	σ	5.695	10.106	11.739	5.294	5.87	4.406	7.205
2D RNAV Mode	$\bar{X}$	157.762	153.018	143.262	158.126	158.652	157.514	157.494
	σ	1.624	9.094	13.209	1.755	3.017	2.728	1.714
3D RNAV Mode	$\bar{X}$	159.419	157.645	144.876	157.988	157.988	159.292	156.913
	σ	3.346	7.153	9.520	3.119	4.615	3.825	2.198

airspeed than that for the route B1/2D RNAV mode condition. In fact, in 14 out of the 16 possible climb/descent segments, the 3D RNAV mode condition resulted in a higher mean airspeed (i.e., an airspeed closer to the desired 160 knots). This would tend to indicate that using the 3D RNAV mode results in an increase in precision with which the pilot controls his airspeed.

ANALYSIS OF THE IMPROMPTU WAYPOINT MODIFICATION TO THE PREPROGRAMMED ROUTE STRUCTURE.

Twenty-four of the 48 data runs in this experiment were modified by an impromptu waypoint change to the preprogrammed route structure. This change was directed via ATC communications and the pilot was not told in advance that he was going to have to make a change to the route structure while in flight. The impromptu changes were as follows:

1. Route B1 departures/arrivals via runway 4 received the following clearance change. The pilots, after passing W/P LIMA, were "cleared from over the 8-nmi DTW point for W/P MIKE to W/P GOLF via direct W/P DELTA direct to W/P GOLF. Cross W/P DELTA at 5,000 feet, cross W/P GOLF at 3,500 feet. Report passing W/P DELTA."

2. Route B1 departures/arrivals via runway 22 received the following clearance change. The pilots, after passing W/P HOTEL, were "cleared from over W/P GOLF to W/P MIKE via direct to W/P DELTA, direct to W/P MIKE. Cross W/P DELTA at 5,000 feet, cross W/P MIKE at 9,000 feet. Report passing W/P DELTA."

3. Route B2 departures/arrivals via runway 4 received the following clearance change. The pilots, after passing W/P ROMEO were "cleared from over the 10-nmi DTW of W/P SIERRA, to W/P WHISKEY via direct W/P LIMA, direct W/P WHISKEY. Cross W/P LIMA at 5,000 feet, cross W/P WHISKEY at 9,000 feet. Report passing W/P LIMA."

4. Route B2 departures/arrivals via runway 22 received the following clearance change. The pilots, after passing W/P X-RAY, were "cleared to W/P ROMEO via direct W/P LIMA, direct W/P ROMEO. Cross W/P LIMA at 5,000 feet, cross W/P ROMEO at 3,500 feet. Report passing over W/P LIMA."

The purpose of this section is to analyze the total workload involved in entering an impromptu waypoint into the RNAV system and to examine the effects of entering the waypoint on the navigational activities of the pilots. Table 15 presents the overall workload analysis in terms of total system workload times including all times involved in finding an open (or available) waypoint storage location, manipulating the various function buttons and switches, and manually entering the desired Rho, Theta, Frequency, and VORTAC elevation values into the CDU keyboard device. Several things can be learned from looking at table 15. First, it can be seen that on six of the 24 data runs the pilots anticipated the possibility of entering an impromptu waypoint and entered the impromptu waypoint as part of the preprogrammed route structure. This information was available to the pilots on their charts and they entered the impromptu waypoint (DELTA) in one of the remaining 10-waypoint slots,

TABLE 15. OVERALL WORKLOAD ANALYSIS FOR IMPROMPTU WAYPOINT ENTRY

	Run No.	Total Workload Time (Start to End) (Seconds)	Total Time Entry Mode (Seconds)	Total Input Time (First Entry to Last Entry) (Seconds)	Type of Error/Remarks
Route B1 Departures/ Arrivals Runway 4	1	98	61	38	
	2	81	42	27	
	3	50	39	25	
	4	51	63[3]	24	
	5	67	52	34	
	6	103	66	18	
	7	(11)[1]	(-)	(-)	
	8	59	48	29	Blunder-flew to w/p "F" - turned early
Route B1 Departures/ Arrivals Runway 22	1	45	62[3]	24	Procedural-9071'-right of course
	2	67	47	32	
	3	74	166[3]	32	Blunder- flew to w/p "F" wrong "FREQ"/OBS
	4	(-)[2]	(-)[2]	(-)[2]	
Route B2 Departures/ Arrivals Runway 4	1	34	29	18	
	2	67	61	46	
	3	39	40[3]	24	Procedural-forgot to press "FREQ" button
	4	(-)[2]	(-)[2] 43[5]	(-)[2] 16[5]	
	5	45	147[3]	28	Blunder-forgot to press "FREQ" button-high OBS workload
	6	(-)[2]	(-)[2]	(-)[2]	
Route B2 Departures/ Arrivals Runway 22	1	107	62 45*[4]	51 5*[4]	Blunder-wrong "BRG/DIST" twice
	2	80	78	52	Procedural-1.9 nmi-wrong OBS
	3	(-)[2]	(-)[2]	(-)[2]	Procedural-overshot w/p "W" by 6600 feet
	4	49	47	24	
	5	(12)[1]	(-)[2]	(-)[2]	Procedural-overshot w/p "W" by 8800 feet
	6	51	35	21	

[1] Pilot checked to see if waypoint was stored properly prior to actually using it. Waypoint was inserted prior to flight as part of pre-programmed route structure since it was on the pilot's chart.

[2] Pilot did not check to see if waypoint was stored properly. Waypoint was inserted prior to flight as part of pre-programmed route structure since it was on the pilot's chart.

[3] Pilot reversed procedure and changed to read mode after finishing entry.

[4] The numbers asterisked are the times for the second set of data entry.

[5] Pilot entered waypoint "J" in No. 20 after he realized that he forgot to enter it as part of flight plan initially.

usually 20. One pilot, anticipating the impromptu waypoint, inserted the W/P DELTA in the correct sequence in the route structure and modified the route structure at the end by putting the final approach fix (FAF) waypoint J into slot No. 20. The pilot had apparently forgotten to enter this waypoint initially and corrected this while reviewing the waypoints that he had stored. It will also be noticed that three of the six previously entered impromptu waypoints ended in either blunder or procedural errors. The blunder resulted from entering a wrong frequency and the wrong OBS. Thus, even though the pilot had all of the information entered, he flew towards waypoint "F," the one to which he ordinarily would have flown. The two other cases resulted in large overshoot errors at waypoint "W." While these were not blunders by definition, they do portray the type of distraction or confusion that can be introduced by the assignment of impromptu waypoints. The reasons for these overshoots are not clear. It can be assumed, however, that the pilot became distracted by other duties and, as a result, did not begin to turn until after passing the waypoint. Of the remaining 18 data runs, six, or one-third of the remainder, resulted in blunders or procedural errors. Almost all of the errors occurred on the route B1 and route B2 departures/arrivals via runway 22. The impromptu waypoints in these cases were given as a direct to after being cleared to the prior waypoint (for example: "cleared to W/P GOLF via direct to W/P DELTA direct W/P GOLF"). Basically, two types of errors were noted. In committing the first type of error, it would appear that the pilot had established a "set" for the next waypoint which would have been flown to, and in fact the predominant cause of the errors was a wrong OBS setting. Even though the correct information had been set into the RNAV CDU keyboard, the pilot almost always automatically tuned the OBS for the next waypoint and began navigating towards it. The second type of error was caused by indecision which resulted in passing the waypoint and inducing a large TSCT error. The "set" may have been induced by the pilot's use of his charts. Pilots comments after the flights indicated that if they had bothered to draw the impromptu segment on their charts they might not have become confused.

The two navigation errors, that resulted from the impromptu waypoint in the route B2 departure/arrivals via runway 4, were functional, in that in both cases when inputting the required information, the pilot forgot to press the function button for FREQ. In the case of the procedural error, the pilot realized his error and corrected it within a very short time period. In the case of the blunder, the pilot did not understand his error and spent considerable time setting and resetting the OBS in an attempt to center the CDI needle. He finally realized his error and corrected it.

A final observation that may be drawn from these data is that with a multiwaypoint system, if an impromptu clearance is given to the pilot that requires additional monitoring (i.e., DTW, etc.) or requires immediate action, it is more likely to be completed accurately than if it is stored and implemented at next previously defined waypoint. In this experiment, when the pilot approached the next waypoint, his tendency was to follow the route that had been laid out in advance and set in the OBS for the previously defined course and not the new, impromptu course. The reduction in workload (due to preprogrammed waypoints) afforded by the multiwaypoint system may indeed cause a problem of false security for the pilot since he becomes "set" to just updating via the

waypoint update switch and following the course outlined on his charts. Whereas, with the immediate impromptu or the additional monitoring task associated with a fixed DTW, the pilot would be more aware that he is going to do something different and, in fact, has a higher probability of successfully accomplishing the assigned task.

HUMAN FACTORS EVALUATION OF THE CDU KEYBOARD AND DISPLAY.

In order to define a waypoint, it was necessary to input four items of information into the RNAV CDU:

1. Bearing of waypoint from the VORTAC
2. Distance of waypoint from the VORTAC
3. Frequency of the VORTAC
4. Elevation of the VORTAC

The bearing angle was entered as xxx.x°, and the next two items distance and frequency were required to be entered as xxx.xx. The decimal point on the display was automatically entered at all times. It was quite small, and due to its size was difficult to locate immediately. This caused a considerable amount of confusion on the part of the pilots and, in fact, resulted in a number of erroneous entries and blunders in tracking. In several cases, the pilots forgot to put in the final zero (0) which resulted in a frequency of xx.xx. Thus, a pilot who entered 114.8 would have an erroneous frequency of 11.48. Similarly, the pilots when entering the distance would forget to enter the final zero. Thus, a distance of 14 nmi would end up as 1.4 nmi. In order to improve this condition, it would be desirable to reprogram the RNAV NCU such that all decimal points would be entered by the pilots as part of the entry sequence, and a standard format should be provided for all decimal input (bearing, distance, and frequency).

USE OF THE AUTOMATED WAYPOINT ALERT (H-ALRT) FUNCTION.

The onset of the H-ALRT function was set to be activated at a time of 0.9 minute (or 54 seconds) prior to the waypoint. The DTW of the onset, in this experiment, ranged between 2.1 nmi and 3.1 nmi to the waypoint, depending on the speed history of the aircraft. An examination of the data, related to the onset of the H-ALRT light and the transition to a new segment, indicated that for the most part, the pilot's sequence of activities after the H-ALRT was activated was: (1) Turn the OBS to the new course heading, (2) Initiate a turn to the new course, and (3) Update the RNAV update switch to enter the next waypoint. The H-ALRT light was terminated as soon as the new waypoint information was entered. It would appear that the primary benefit of the H-ALRT function was to alert the pilots to the fact that a turn to a new course (based on airspeed, turn angle, or other parameters) was imminent; however, the H-ALRT light did not give specific turn guidance as an automated turn anticipation light would do.

The data from the H-ALRT evaluation are presented in table 16. The data are presented in terms of the interexperimental variables for each of the three measures: (1) H-ALRT duration which is defined as the elapsed time between the onset of the H-ALRT light and its termination, (2) Elapsed time from the onset

of the H-ALRT light to the OBS update by the pilot, and (3) Elapsed time from the onset of the H-ALRT light to the initiation of the turn to the next segment by the pilot. It will be noticed from table 16 that in almost all cases, the H-ALRT duration was less than the allotted time of 54 seconds, and the pilots initiated their turns prior to overshooting the waypoint. In this experiment, the pilots were not given specific instructions regarding turn anticipation technique; however, almost all of the pilots used some technique which minimized overshoot at the turns.

TABLE 16. AUTOMATED WAYPOINT ALERT (H-ALRT) MEAN RESPONSE TIMES AS A FUNCTION OF THE INTEREXPERIMENTAL VARIABLES

	FLIGHT DIRECTOR				NO FLIGHT DIRECTOR			
	AS FILED		IMPROMPTU		AS FILED		IMPROMPTU	
	2D	3D	2D	3D	2D	3D	2D	3D
H-ALERT Duration (Onset to Termination)	47.36	49.46	49.65	48.54	47.75	55.73	49.83	48.90
Elapsed Time- H-ALERT to OBS Update	28.69	34,99	36.00	39.78	37.87	41.16	40.53	32.71
Elapsed Time - H-ALRT to Initiate Turn	46.22	46.08	43.76	44.07	48.25	53.75	49.95	46.57

The data in table 16 have been isolated as a function of the Flight Director/ No Flight Director condition and are presented in table 17. This table shows that there exists a slight difference between these two conditions. The times for the Flight Director condition are consistently less than those under the No Flight Director condition. This indicates that, in addition to monitoring the H-ALRT light, the pilots were monitoring the bank steering bars, updating to the next waypoint, and beginning their turns earlier in order to capture the next segment by following the commands on the bank steering bars. T-tests conducted on these data indicated that these differences were not statistically significant. They may have operational significance and should be considered as meaningful differences in favor of using the Flight Director in an RNAV environment, especially while transitioning across different segments.

TABLE 17. AUTOMATED WAYPOINT ALERT (H-ALERT) MEAN RESPONSE TIMES AS A FUNCTION OF THE FD/NFD VARIABLES

	FLIGHT DIRECTOR	NO FLIGHT DIRECTOR
H-ALRT Duration (Onset to Termination)	48.76	50.56
Elapsed Time H-ALRT to OBS Update	34.62	38.07
Elapsed Time H-ALRT to Initiate Turn	45.04	49.63

An interesting note concerning the H-ALRT function is that in the case of an impromptu waypoint based on a DTW fix, the H-ALRT function would not be activated and, therefore, would not provide a "warning" or cue that the transition to a new course is imminent. The same would be true of an offset procedure; the pilot would never get the H-ALRT light, since as he passed through the angle bisector, he would be at a distance greater than that allowed by the 0.9-minute criteria.

RNAV ACCURACY IN NONPRECISION APPROACHES

HORIZONTAL (CROSSTRACK) ERROR DURING THE APPROACHES TO RUNWAYS 4 AND 22.

In this study there were four approach configurations depending on which route structure the pilot flew. The four approach configurations were as follows:

1. Route B1 approaches to runway 4; these approaches consisted of a 12.3-nmi base leg coupled with a 90° left turn onto an 11-nmi final.

2. Route B1 approaches to runway 22; these consisted of an 18.6-nmi transition segment coupled with a 14° left turn onto an 11-nmi final.

3. Route B2 approaches to runway 4; these approaches consisted of a 17.6-nmi base leg coupled with a 90° left turn onto an 11-nmi final.

4. Route B2 approaches to runway 22; these approaches consisted of a 6-nmi base leg coupled with a 90° right turn onto an 11-nmi final.

Even though a final approach fix (FAF) waypoint was depicted on the pilot's charts at a point 5 nmi from the Missed Approach Fix (MAP), the pilots did not program this fix into the RNAV route structure and flew the 11-nmi final

as one segment. However, the data were treated as if this fix had been input and indicates the quality of horizontal tracking performance from the initial approach fix to the point at which the outer marker (OM) would have been located (i.e., a distance of 6 nmi); and from the OM to approximately where the middle marker (MM) would have been located (i.e., a distance of 5 nmi). The TSCT and FTE data for these three segments are presented in tables 18, 19, 20, and 21. Also included in these tables are the correlation coefficient between TSCT and FTE.

Because of problems in the RNAV/Flight Director/GAT-2B interface, neither the localizer signal nor the glideslope signal was available for use in this experiment. Therefore, all approaches were made using the RNAV system only. The pilots were instructed to use whatever means they preferred for the approach segments. Since none of the pilots elected to use the RNAV APPROACH mode, all approaches were made using the RNAV system in the RNAV ENROUTE mode with the CDI sensitivity remaining at 1 dot equal to 2 nmi. The pilots felt that the extra accuracy provided by the approach mode was offset by its ultrasensitivity which produced excessive needle motion.

The mean crosstrack error data in tables 18, 19, 20, and 21 are plotted in figure 23. The values in these figures are mean crosstrack error for the "steady-state" portion of the segment. All turn data have been deleted for the transition to the base and final legs. There are no turn data for the two final approach segments since the 11-nmi final is a straight-in approach. The TSCT and FTE $\bar{X}$ and 2σ data calculated from tables 18 through 21 are presented in table 22 and figure 24 as a function of route structure/approach runway and the three final segments (including base leg and final).

An examination of figure 24 reveals that, for the approaches to runway 4 (for both the route B1 and B2), the pilots tended to decrease the amount of crosstrack error as they progressed from the base leg to the outer marker to the MAP. As would be expected, the larger base leg (17.6 nmi base leg for route B2 versus 12.3 nmi base leg for route B1) resulted in less overall crosstrack error due to the fact that the pilots had more time to stabilize the aircraft and to prepare for the final approach segments. Furthermore, the approach data for runway 22 (for both route B1 and B2) are not as consistent as the approach data for runway 4. In fact, the pilots experienced considerable difficulty, especially on the FAF to MAP segment. This difficulty stemmed from the fact that, at a point approximately 1 to 3 nmi from the runway threshold, the RNAV computer went into a failure mode and the pilot simply had to hold a heading, since at that point he lost all horizontal CDI guidance. This RNAV computer failure, which did not occur on the approaches to runway 4, was related to the exact placement of the ACY VORTAC and differences in the signal at waypoint "A" (reference approaches to runway 22) and at waypoint "J" (reference approaches to runway 4). If this type of error occurred under IFR conditions the RNAV computer would have gone into the Dead Reckoning (DR) mode and would have provided the necessary guidance to complete the approach. The data, however, would not be as reliable as the full RNAV guidance.

TABLE 18. TSCT AND FTE STATISTICS FOR ROUTE B1 APPROACHES TO RUNWAY 4 (BASE LEG AND FINAL APPROACH DATA)

	Run No.	Total System Crosstrack Error (TSCT) Mean ($\bar{X}$)	TSCT 2 Sigma (2σ)	Course Deviation Indicator Displacement (FTE) Mean ($\bar{X}$)	FTE 2 Sigma (2σ)	Correlation Coefficient (TSCT vs. FTE)
Base Leg Segment 90°	1	-0.583	0.220	-0.012	0.318	-0.748
	2	-0.544	0.226	0.013	0.146	-0.750
	3	-0.273	0.370	-0.130	0.452	-0.960
	4	-0.044	0.614	-0.206	0.490	-0.846
	5	-0.507	0.106	-0.002	0.178	-0.384
	6	-0.483	0.298	-0.117	0.320	-0.635
	7	-0.248	0.498	-0.174	0.350	-0.719
	8	0.090	0.576	-0.504	0.606	-0.848
	9	-0.605	0.112	-0.065	0.488	-0.717
	10	-0.178	0.370	-0.099	0.362	-0.535
	11	-0.539	0.202	0.016	0.292	-0.445
	12	-0.394	0.330	-0.072	0.436	-0.627
Initial Approach Fix To Outer Marker (Distance=6.0 nmi)	1	-0.108	0.178	-0.068	0.244	-0.972
	2	-0.094	0.228	0.012	0.262	-0.976
	3	-0.233	0.160	0.101	0.190	-0.916
	4	0.303	0.836	-0.450	0.910	-0.997
	5	0.004	0.066	-0.116	0.078	-0.767
	6	-0.129	0.186	-0.005	0.146	-0.800
	7	-0.034	0.104	-0.108	0.158	-0.894
	8	-0.131	0.144	0.080	0.186	-0.916
	9	-0.052	0.084	-0.094	0.100	-0.867
	10	-0.231	0.278	-0.044	0.312	-0.979
	11	-0.270	0.070	0.190	0.060	-0.635
	12	-0.107	0.230	-0.070	0.274	-0.959
Outer Marker To Inner Marker (Distance=5.0 nmi)	1	-0.102	0.120	0.035	0.096	-0.283
	2	-0.077	0.166	0.044	0.142	-0.936
	3	-0.047	0.142	-0.014	0.204	-0.730
	4	-0.124	0.138	0.111	0.100	-0.646
	5	-0.026	0.056	-0.019	0.104	-0.078
	6	-0.090	0.114	-0.038	0.098	-0.211
	7	-0.081	0.032	0.045	0.100	0.186
	8	-0.055	0.038	0.028	0.090	0.222
	9	-0.024	0.108	-0.011	0.064	-0.348
	10	-0.170	0.062	-0.026	0.134	-0.736
	11	-0.314	0.133	0.194	0.073	-0.610
	12	-0.057	0.088	-0.021	0.082	0.093

TABLE 19. TSCT AND FTE STATISTICS FOR ROUTE B1 APPROACHES TO RUNWAY 22 (BASE LEG AND FINAL APPROACH DATA)

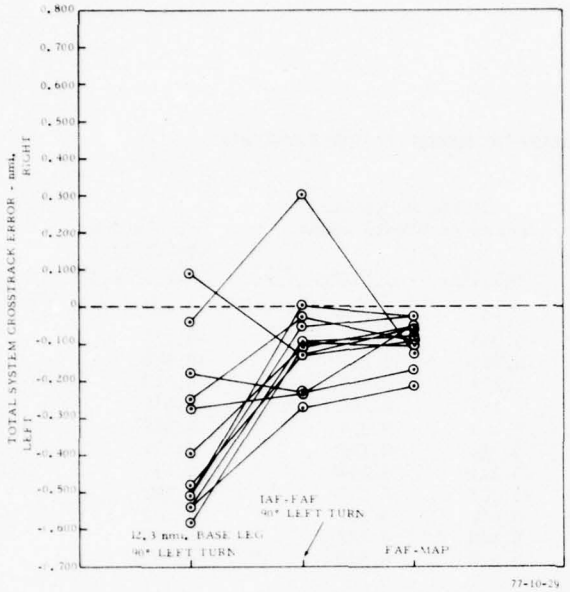
	Run No.	Total System Crosstrack Error (TSCT) Mean ($\bar{X}$)	TSCT 2 Sigma (2σ)	Course Deviation Indicator Displacement (FTE) Mean ($\bar{X}$)	FTE 2 Sigma (2σ)	Correlation Coefficient (TSCT vs. FTE)
	1	-0.046	0.118	-0.378	0.130	-0.646
Base Leg	2	-0.078	0.124	0.045	0.142	-0.607
Segment	3	-0.030	0.266	-0.112	0.234	-0.891
14° Left Trans-	4	-0.163	0.104	0.105	0.144	-0.517
ition to Final	5	-0.086	0.122	-0.035	0.124	-0.732
(Distance=	6	-0.193	0.148	0.021	0.186	-0.757
18.6 nmi)	7	0.045	0.124	-0.198	0.108	-0.612
	8	-0.183	0.146	0.026	0.202	-0.784
	9	0.034	0.188	-0.098	0.154	-0.781
	10	-0.109	0.114	0.007	0.156	-0.739
	11	-0.282	0.144	0.090	0.162	-0.674
	12	-0.170	0.290	0.017	0.294	-0.929
	1	0.151	0.088	-0.002	0.074	-0.539
	2	-0.067	0.318	0.245	0.260	-0.978
	3	0.360	0.290	-0.211	0.368	-0.987
Initial	4	0.040	0.136	0.093	0.084	-0.580
Approach Fix	5	0.147	0.048	0.010	0.064	-0.173
to Outer	6	0.080	0.136	0.022	0.084	-0.757
Marker	7	-0.160	0.060	0.314	0.068	-0.315
(Distance=	8	0.212	0.026	-0.023	0.084	-0.472
6.0 nmi)	9	0.182	0.028	-0.069	0.092	-0.580
	10	0.100	0.160	0.084	0.154	-0.916
	11	0.050	0.168	0.139	0.138	-0.916
	12	-0.131	0.282	0.240	0.200	-0.957
	1	0.271	0.030	0.004	0.056	-0.260
Outer	2	0.229	0.096	0.046	0.100	-0.698
Marker to	3	0.206	0.056	0.057	0.104	-0.543
Inner	4	0.174	0.044	0.049	0.100	-0.600
Marker	5	0.093	0.076	0.171	0.092	-0.782
(Distance=	6	0.209	0.062	0.003	0.066	-0.058
5.0 nmi)	7	0.092	0.176	0.164	0.102	-0.901
	8	0.171	0.082	0.095	0.096	-0.600
	9	0.210	0.036	0.023	0.092	0.009
	10	0.312	0.074	-0.025	0.044	-0.347
	11	0.215	0.064	0.052	0.108	-0.529
	12	0.123	0.120	0.108	0.062	-0.299

TABLE 20. TSCT AND FTE STATISTICS FOR ROUTE B2 APPROACHES TO RUNWAY 4 (BASE LEG AND FINAL APPROACH DATA)

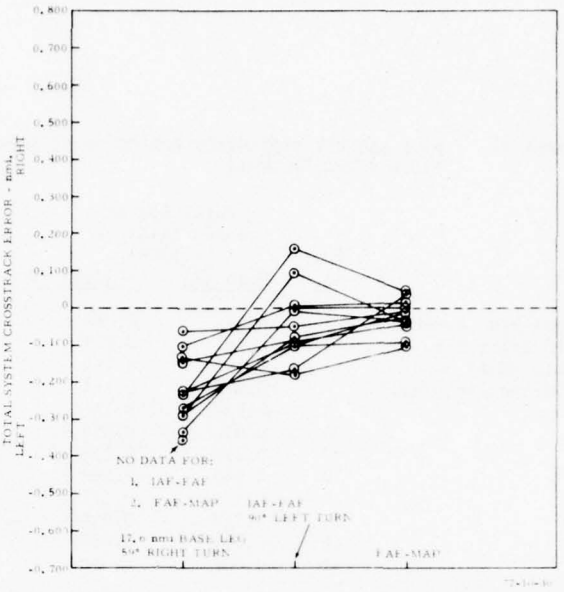
	Run No.	Total System Crosstrack Error (TSCT) Mean ($\bar{X}$)	TSCT 2 Sigma (2σ)	Course Deviation Indicator Displacement (FTE) Mean ($\bar{X}$)	FTE 2 Sigma (2σ)	Correlation Coefficient (TSCT vs FTE)
Base Leg Segment 90° Left Turn onto Final (Distance - 17.6 nmi)	1	-0.355	0.216	-0.032	0.282	-0.024
	2	-0.106	0.308	-0.125	0.282	-0.109
	3	-0.137	0.370	-0.065	0.250	-0.223
	4	-0.294	0.336	-0.060	0.130	0.507
	5	-0.270	0.416	-0.131	0.316	-0.563
	6	-0.142	0.114	-0.035	0.194	0.164
	7	-0.226	0.360	0.005	0.204	-0.857
	8	-0.230	0.454	-0.074	0.296	-0.520
	9	-0.064	0.304	-0.142	0.316	-0.349
	10	-0.291	0.474	-0.079	0.370	-0.642
	11	-0.236	0.176	-0.085	0.236	0.091
	12	-0.336	0.392	-0.165	0.492	-0.786
Initial Approach Fix to Outer Marker (Distance = 6.0 nmi)	1	-	-	-	-	-
	2	0.009	0.054	-0.054	0.100	-0.727
	3	-0.181	0.060	-0.020	0.106	-0.881
	4	0.090	0.206	-0.141	0.190	-0.953
	5	-0.106	0.078	-0.063	0.100	-0.843
	6	-0.090	0.052	0.067	0.098	-0.753
	7	-0.169	0.144	0.098	0.172	-0.946
	8	-0.098	0.056	0.016	0.074	-0.870
	9	-0.052	0.094	-0.068	0.130	-0.870
	10	-0.081	0.210	-0.030	0.240	-0.967
	11	0.158	0.230	-0.204	0.220	-0.972
	12	0.010	0.082	-0.164	0.104	-0.876
Outer Marker to Inner Marker (Distance = 5.0 nmi)	1	-	-	-	-	-
	2	-0.015	0.068	-0.006	0.046	-0.394
	3	-0.105	0.108	0.026	0.088	-0.018
	4	-0.037	0.134	0.030	0.092	0.130
	5	-0.097	0.104	0.002	0.030	0.086
	6	-0.046	0.114	0.079	0.084	0.294
	7	0.037	0.080	-0.127	0.132	-0.820
	8	-0.019	0.048	-0.026	0.088	-0.026
	9	-0.016	0.086	-0.027	0.090	-0.250
	10	-0.027	0.148	-0.002	0.148	-0.704
	11	0.040	0.028	-0.075	0.102	-0.001
	12	-0.042	0.090	-0.024	0.124	0.146

TABLE 21. TSCT AND FTE STATISTICS FOR ROUTE B2 APPROACHES TO RUNWAY 22 (BASE LEG AND FINAL APPROACH DATA)

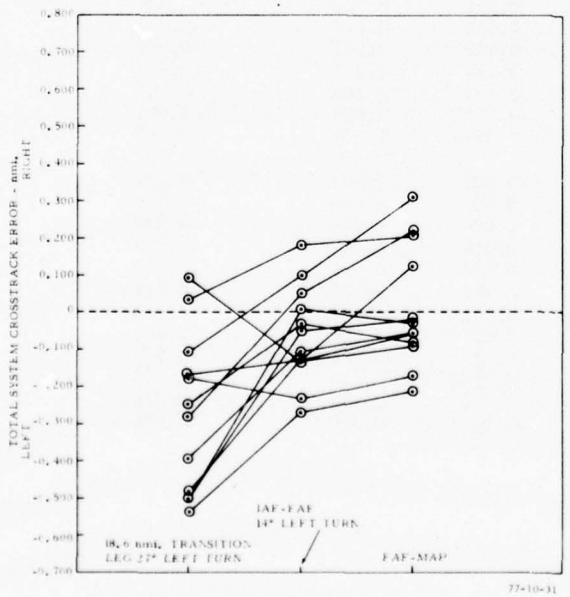
	Run No.	Total System Crosstrack Error (TSCT) Mean ($\bar{X}$)	2 Sigma (2σ)	Course Deviation Indicator Displacement FTE Mean ($\bar{X}$)	2 Sigma (2σ)	Correlation Coefficient (TSCT vs. FTE)
Base Leg Segment	1	0.294	0.058	-0.193	0.128	-0.002
90° Right Turn	2	0.561	0.014	-0.055	0.102	-0.220
onto Final	3	0.702	0.192	-0.384	0.214	-0.890
(Distance=6.0 nmi)	4	0.086	0.144	0.173	0.170	-0.810
	5	-0.284	0.186	0.136	0.224	-0.936
	6	0.050	0.254	0.442	0.324	-0.949
	7	0.216	0.058	0.011	0.152	-0.777
	8	0.618	0.108	-0.271	0.140	-0.612
	9	0.599	0.112	-0.267	0.114	-0.607
	10	0.313	0.014	0.051	0.102	-0.313
	11	-0.299	0.098	0.130	0.122	-0.686
	12	-0.001	0.050	-0.078	0.120	-0.675
Initial Approach	1	0.249	0.086	-0.103	0.148	-0.726
Fix to Outer Marker	2	0.082	0.158	0.018	0.086	-0.795
(Distance=6.0 nmi)	3	0.129	0.130	0.037	0.100	-0.818
	4	-0.004	0.262	0.126	0.188	-0.941
	5	0.073	0.148	0.040	0.098	-0.892
	6	-0.091	0.746	0.151	0.522	-0.924
	7	0.094	0.234	0.021	0.178	-0.871
	8	0.104	0.070	0.040	0.102	-0.653
	9	-0.031	0.260	0.140	0.202	-0.937
	10	-0.202	0.202	0.335	0.166	-0.945
	11	0.455	0.374	-0.272	0.428	-0.981
	12	0.143	0.258	0.063	0.226	-0.969
Outer Marker	1	0.315	0.056	-0.038	0.104	0.006
to Inner Marker	2	0.225	0.044	0.000	0.000	0.000
(Distance=5.0 nmi)	3	0.265	0.042	0.000	0.000	0.000
	4	0.181	0.056	0.060	0.098	-0.249
	5	0.277	0.126	-0.037	0.098	-0.840
	6	0.334	0.144	-0.089	0.192	-0.908
	7	0.240	0.074	0.007	0.130	-0.673
	8	0.218	0.066	0.025	0.086	-0.402
	9	0.158	0.098	0.075	0.086	-0.753
	10	0.158	0.154	0.105	0.118	-0.815
	11	0.340	0.092	-0.055	0.156	-0.846
	12	0.297	0.060	-0.014	0.070	-0.296



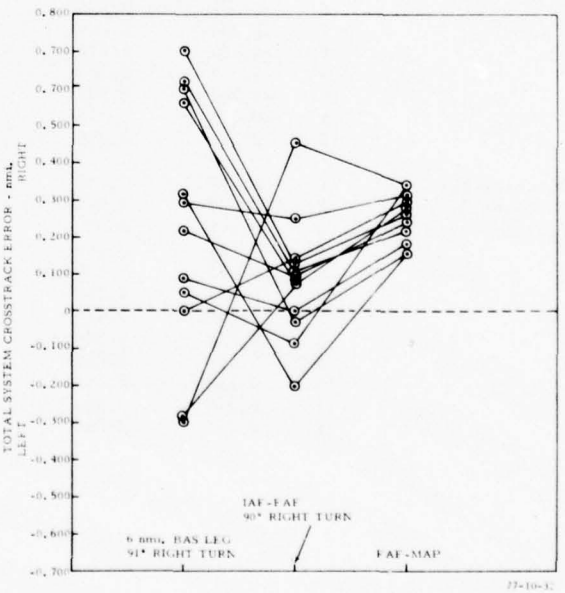
ROUTE B1, APPROACH TO RUNWAY 4



ROUTE B2, APPROACH TO RUNWAY 4



ROUTE B1, APPROACH TO RUNWAY 22



ROUTE B2, APPROACH TO RUNWAY 22

FIGURE 23. MEAN APPROACH TSCT FOR INDIVIDUAL FLIGHTS

TABLE 22. TSCT AND FTE ($\bar{X}$ AND 2σ)(nmi) AS A FUNCTION OF ROUTE STRUCTURE/ APPROACH RUNWAY AND THE THREE FINAL SEGMENTS

	Statistic	Base Leg TSCT	Base Leg FTE	Initial Approach Fix to Final Approach Fix TSCT	Initial Approach Fix to Final Approach Fix FTE	Final Approach Fix to Missed Approach Point TSCT	Final Approach Fix to Missed Approach Point FTE
Route B1 Approaches to Runway 4	$\bar{X}$	-0.351	-0.112	-0.090	-0.048	-0.089	0.034
	2σ	0.327	0.370	0.214	0.243	0.100	0.107
Route B2 Approaches to Runway 4	$\bar{X}$	-0.224	-0.082	-0.046	-0.051	-0.030	-0.014
	2σ	0.327	0.281	0.115	0.139	0.092	0.093
Route B1 Approaches to Runway 22	$\bar{X}$	-0.105	-0.018	0.080	0.070	0.192	0.062
	2σ	0.157	0.170	0.145	0.139	0.076	0.085
Route B2 Approaches to Runway 22	$\bar{X}$	0.238	-0.025	0.083	0.050	0.250	0.003
	2σ	0.107	0.159	0.244	0.204	0.084	0.114

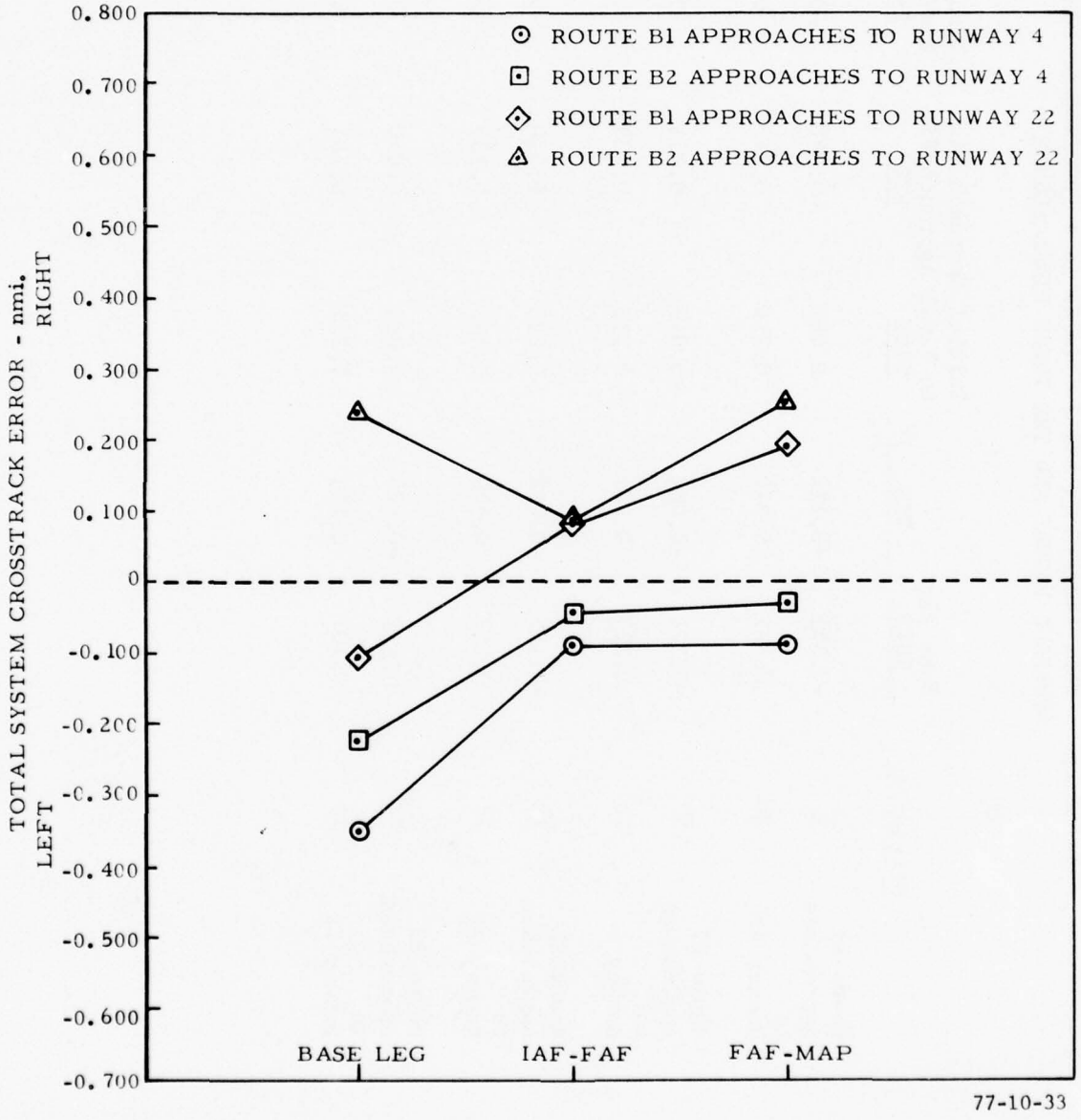


FIGURE 24. MEAN TSCT (nmi) AS A FACTOR OF ROUTE STRUCTURE/APPROACH RUNWAY CONFIGURATION AND THE THREE FINAL SEGMENTS

ANALYSIS OF PILOT COMMENTS

At the completion of the eight data flights, each pilot was given a questionnaire (appendix C) which covered three major areas: RNAV Control Display Unit, Pilot Procedures, and Pilot Workload. A summary of the pilots' responses to the questionnaire can also be found in appendix C. Pilot identifications are shown as (P-1), (P-2), etc.

RNAV CONTROL DISPLAY UNIT.

As a whole, the pilots quickly became familiar with the CDU (figure C-1) controls and annunciators and found no significant undesirable physical layout or functional features of the EDO RNAV unit. The pilots had no real difficulty in entering waypoint/impromptu information. However, as reflected in the data, all pilots made some entry errors simply by pushing the wrong value button and/or forgetting to position the mode switches properly.

One cause for not initially observing an erroneous entry was the difficulty in seeing the decimal point in the data display windows. This item should be made larger for more positive identification of decimal values, i.e., 108.6 megahertz (MHz), 32.6°, 11.4 nmi, etc.

The majority of the pilots commented on a rather restricted capability of the ARINC Mark 13 level RNAV in its ability to enter only one altitude and flight path angle at a time when flying VNAV profiles. Preprogramming the system so as to fly a continuing series of VNAV profiles such as a SID or STAR could be beneficial especially if there were no impromptu altitude changes by ATC.

PILOT PROCEDURES.

Initially, the pilots had minor difficulty in keeping track of their position/waypoints on their route charts. It was suggested that they number the waypoints on the chart to correspond to the numerical sequence of the waypoints as entered in the RNAV unit. This practice proved satisfactory and was used extensively throughout the experiment. The pilots also remarked that this chart numbering technique would even be practical for 20 waypoints and over. The alternative, of course, was to switch to the "Read" mode and display waypoint bearing and distance and visually verify it with those listed on the chart, which they did the majority of the time.

For those flights employing VNAV, after the desired altitude was entered, two methods of reaching altitude were available; first, allowing the RNAV system to compute FPA; or second, the pilot could enter his own desired flight path angle. In both of these cases, the aircraft reached its altitude and waypoint at about the same time. The pilots were unanimous in their preference to arrive at altitude some distance prior to reaching the waypoint, because it reduced their overall workload at the waypoint.

The pilots were overwhelmingly against using an RNAV computed flight path angle, and yet were divided in their opinions when asked if they preferred to enter their own FPA. Four of the six pilots stated that they preferred not to enter any FPA, but to climb/descend at a rate commensurate with aircraft performance. This last technique is in keeping with usual pilot desires to reach altitudes as soon as possible, especially in jets.

Until full and final development of RNAV route structures and complete familiarization with RNAV capability is realized by ATC, it is probable that the extensive use of VNAV, especially in the terminal area, might not fully be utilized (see reference 2).

Referencing the approved RNAV approach plate, figure C-2, which utilizes a series of waypoints for approaches into Bakersfield, California, it was of interest to determine if the pilots felt it necessary to enter every waypoint, for a full RNAV approach or whether, in their judgment, some waypoints might be omitted or perhaps used as DTW fixes in order to ease pilot workoad.

Unfortunately, no detailed reasons were given for the answers in these two questions, and although the questions were not directly related to the experiment as flown, an analysis of the answers indicate that some pilots would not enter all of the waypoints, but rather use some of the waypoints as DTW fixes. These pilots would have no particular problem flying the approaches in 2D where NILES waypoint was used as a DTW fix on final approach. However, to fly that entire approach to MDA using VNAV (3D), would appear to create an unacceptable pilot workload from NILES W/P inbound due to data entering time for MDA altitude/FPA, pilot workload in putting the aircraft in landing configuration, checklist, etc. The alternative of flying directly from ARVIN to MDA would violate the 2000 foot crossing altitude at NILES by 250 to 515 feet. This situation again points out the disadvantage of not being able to program more than one altitude/FPA at a time.

PILOT WORKLOAD.

Recall that the pilots flew their routings under four different conditions; with and without the flight director, and in a 2D or 3D mode. The pilots very definitely preferred using the flight director to flying without it. Using the flight director, they were equally divided in preference for 2D or 3D. Without the flight director, they found the 3D operation somewhat more difficult than the 2D.

Although the 3D-NFD was the least preferred means of navigation, the pilots were evenly divided as to whether or not they would use it for an instrument approach under full IFR conditions.

In general, they felt that an RNAV system similar to the EDO unit could be used by a single pilot under IFR conditions.

Communications workload was stated as "Normal to Light" with overall cockpit workload listed as "Moderate."

RESULTS

Simulated flight tests using the ARINC Mark 13 level RNAV system produced a number of meaningful results. These are listed below.

1. The mean and two standard deviation data for total system crosstrack (TSCT) error in the terminal area were both within the ±2 nmi error range permitted by AC-90-45A.

2. Tracking proficiency, in terms of TSCT, was better in the 2D mode of operation than in the 3D mode.

3. Tracking precision, in terms of TSCT, was significantly increased when the RNAV system was coupled with the flight director.

4. Use of the 3D mode improved airspeed control with a subsequent reduction in variability around the specified airspeeds.

5. Comparison of 2D and 3D vertical performance data yielded significant differences in the manner in which climbs and descents were accomplished.

6. Analysis of the mean flight technical error (FTE) data indicated that no significant differences were obtained as a result of the interexperimental variables.

7. Analysis of the two standard deviation data for FTE showed that the least amount of error existed during the 2D/flight director mode of operation.

8. The mean and two standard deviation data for FTE in the terminal area were less than the ±1 nmi error range permitted by AC-90-45A.

9. The use of impromptu waypoints produced a relatively high rate of pilot error which resulted in numerous blunders and procedural errors, which in turn resulted in excursions outside the airspace limits (±2.0 nmi).

10. Most CDU errors were the result of nonstandardized formats for data entry and the use of fixed point decimal logic.

11. During this experiment, pilots preferred enroute mode tracking data (1 dot=2 nmi) to approach mode tracking data (1 dot=1/2 nmi), even on final approach.

12. The "H-ALRT" light, which activates at 0.9 minutes to the waypoint, was of significant value and was used extensively by the pilots in cuing them to update the next course OBS and waypoint, and aiding in turn anticipation.

13. The product moment correlation coefficient between TSCT and FTE resulted in high negative correlations running between -0.4 and -0.7.

14. No significant differences were recorded for FTE or TSCT as a function of route direction or complexity (B1 versus B2).

15. Tracking accuracy during nonprecision approaches (in RNAV enroute mode) improved as the aircraft neared the missed approach point, even under conditions of navigation signal failures.

16. Even though these tests were conducted with only one pilot in the cockpit, pilot workload using an ARINC Mark 13 type RNAV unit was judged acceptable.

CONCLUSIONS

The following conclusions are based upon the results of the GAT-2 Simulator tests described in this report.

1. ARINC Mark 13 level RNAV systems can be operated within the TSCT and FTE tolerances specified by AC-90-45A.

2. The use of a flight director enhances the tracking accuracy (in terms of TSCT) of an ARINC Mark 13 level RNAV system.

3. The increase in workload required in using a 3D system causes an increase in the amount of FTE over that mode using a 2D system.

4. Nonuniform message input formats and fixed decimal logic are responsible for the major portion of the CDU input entry errors.

5. The smoother tracking provided by the RNAV enroute mode is preferred by the subject pilots to the more accurate, but highly sensitive tracking provided by the RNAV approach mode.

6. The incorporation of an automated waypoint alert function into the RNAV computer for turn anticipation makes the turning function associated with transition to a new waypoint easier for the pilot.

7. The use of impromptu waypoints should be limited because of the relatively high rate of pilot error induced by the added workload which they create.

8. Use of an ARINC Mark 13 type RNAV unit in a single pilot operation does not produce excessive pilot workload.

REFERENCES

1. Kirk, R. E., Experimental Design: Procedures for the Behavorial Sciences, Belmont, California, Brooks/Cole Publishing Company, 1968.

2. Crimbring, W. R. and Maurer, J. J., Area Navigation/Vertical Area Navigation Terminal Simulation, FAA-RD-76-211, National Technical Information Service, Springfield, Virginia, 1977.

APPENDIX A
OVERALL HORIZONTAL ERROR DATA AS A FUNCTION OF ROUTE

		$\bar{X}$ Crosstrack Error	2 σ Crosstrack Error	$\bar{X}$ CDI Displacement	2 σ CDE Displacement	Test Condition
Route B2	1	-0.026	0.622	0.039	0.300	FD/2D
Departures/Arrivals	2	-0.037	0.680	-0.045	0.474	FD/3D
Runway 2	3	0.067	0.606	-0.021	0.272	FD/3D
Pre-programmed	4	0.044	0.962	-0.071	0.346	NFD/3D
Route B2	1	0.055	0.500	-0.010	0.316	FD/2D
Departures/Arrivals	2	0.120	0.788	-0.118	0.340	FD/3D
Runway 22	3	0.001	0.686	0.079	0.348	FD/3D
Modified	4	-0.007	0.948	-0.006	0.330	NFD/2D
	5	0.084	0.458	-0.070	0.310	NFD/2D
	6	0.140	1.756	-0.044	0.454	NFD/3D
Route B2	1	0.115	0.382	-0.021	0.192	FD/2D
Departures/Arrivals	2	0.063	1.080	-0.067	0.196	FD/2D
Runway 22	3	0.144	0.530	-0.023	0.230	FD/3D
Pre-programmed	4	0.027	0.626	-0.020	0.340	NFD/2D
	5	0.005	0.726	-0.061	0.132	NFD/2D
	6	0.001	0.988	-0.060	0.458	NFD/3D
Route B2	1	0.079	0.888	-0.088	0.278	FD/2D
Departures/Arrivals	2	-0.227	0.648	0.016	0.372	FD/2D
Runway 22	3	-0.172	3.770	0.032	0.562	FD/3D
Modified	4	0.004	1.008	-0.032	0.398	NFD/2D
	5	0.184	0.820	-0.116	0.542	NFD/3D
	6	-0.127	0.636	0.024	0.496	NFD/3D

		$\bar{X}$ Crosstrack Error	2 σ Crosstrack Error	$\bar{X}$ CDI Displacement	2 σ CDE Displacement	Test Condition
Route B1	1	-0.306	0.870	-0.005	0.228	FD/2D
Departures/Arrivals	2	-0.280	0.850	-0.023	0.208	FD/3D
Runway 4	3	-0.114	0.732	-0.057	0.348	NFD/2D
Pre-programmed	4	-0.008	0.718	-0.073	0.598	NFD/3D
Route B1	1	-0.278	0.962	-0.057	0.216	FD/2D
Departures/Arrivals	2	-0.220	0.806	-0.011	0.204	FD/2D
Runway 4	3	-0.060	0.560	-0.096	0.306	FD/3D
Modified	4	-0.025	0.750	-0.182	0.448	NFD/2D
	5	-0.343	0.964	0.024	0.340	NFD/2D
	6	-0.050	0.430	-0.025	0.316	NFD/3D
	7	-0.339	1.154	-0.009	0.430	NFD/3D
	8	-0.332	0.806	0.038	0.254	NFD/3D
Route B1	1	0.200	0.538	-0.029	0.284	FD/2D
Departures/Arrivals	2	0.008	0.374	-0.014	0.318	FD/2D
Runway 22	3	0.326	0.694	-0.071	0.268	FD/3D
Pre-programmed	4	0.257	0.754	0.082	0.400	FD-3D
	5	0.392	0.824	-0.091	0.324	NFD/2D
	6	0.403	0.990	0.006	0.274	NFD/2D
	7	0.415	1.084	-0.056	0.580	NFD/3D
	8	0.268	0.760	0.023	0.314	NFD/3D
Route B1	1	0.420	1.140	-0.050	0.376	FD/2D
Departures/Arrivals	2	0.316	0.934	0.011	0.336	FD/3D
Runway 22	3	0.305	2.082	0.027	0.488	FD/3D
Modified	4	0.396	0.976	0.007	0.376	NFD/2D

Note: Errors expressed in nautical miles.

APPENDIX B
HORIZONTAL ERROR DATA FOR ALL OF THE INTEREXPERIMENTAL VARIABLES

Raw data were used in the analysis of variance tests. This data correlated with the following parameters:

1. Mean Total System Crosstrack Error
2. Two-Sigma Total System Crosstrack Error
3. Mean Flight Technical Error
4. Two-Sigma Flight Technical Error
5. Product Movement Correlation Coefficient between TSCT and FTE. Compute on time series data.

The data is organized by the following characteristics:

1. Route structure (B1 = 1; B2 = 2)
2. Subject (1 through 6)
3. Flight Director/No Flight Director Variable. (FD=1, NFD = 2)
4. As Filed/Impromptu Variable (AF =1, IMP = 2)
5. 2D RNAV Mode/3D RNAV Mode Variable (2D =1, 3D =2)
6. Segment Number (3 through 11)

1 1 111 3	0.169	0.142	0.109	0.126	-0.230	1 1 211 3	0.240	0.402	-0.010	0.360	-0.926
1 1 111 4	0.614	0.458	0.029	0.448	-0.311	1 1 211 4	0.359	0.274	-0.072	0.296	-0.945
1 1 111 5	0.044	0.386	0.022	0.272	-0.451	1 1 211 5	0.317	0.266	0.056	0.272	-0.856
1 1 111 6	0.387	0.144	-0.070	0.164	-0.591	1 1 211 6	-0.303	0.294	-0.021	0.294	-0.894
1 1 111 7	0.243	0.138	-0.096	0.210	-0.602	1 1 211 7	0.205	0.364	-0.165	0.364	-0.965
1 1 111 8	-0.050	0.120	-0.080	0.150	-0.733	1 1 211 8	-0.636	0.402	-0.108	0.390	-0.521
1 1 111 9	-0.046	0.118	-0.078	0.130	-0.646	1 1 211 9	-0.273	0.370	-0.130	0.452	-0.960
1 1 111 10	0.151	0.088	-0.002	0.074	-0.539	1 1 211 10	-0.233	0.160	0.101	0.190	-0.916
1 1 111 11	0.271	0.030	0.004	0.056	-0.260	1 1 211 11	-0.047	0.142	-0.014	0.204	-0.730
1 1 112 3	0.413	0.132	0.019	0.114	-0.573	1 1 212 3	0.125	0.434	0.052	0.354	-0.923
1 1 112 4	0.758	0.508	-0.066	0.354	-0.322	1 1 212 4	-0.060	0.436	0.072	0.440	-0.979
1 1 112 5	0.257	0.374	-0.074	0.248	-0.440	1 1 212 5	0.061	0.642	-0.047	0.692	-0.974
1 1 112 6	0.585	0.118	-0.027	0.188	-0.510	1 1 212 6	-0.018	0.308	-0.010	0.304	-0.894
1 1 112 7	0.553	0.066	-0.112	0.188	-0.309	1 1 212 7	0.281	0.810	-0.232	0.876	-0.994
1 1 112 8	-0.258	0.148	-0.098	0.178	-0.818	1 1 212 8	-0.408	0.584	-0.060	0.306	-0.674
1 1 112 9	-0.030	0.266	-0.112	0.234	-0.891	1 1 212 9	-0.044	0.614	-0.206	0.490	-0.846
1 1 112 10	0.360	0.290	-0.211	0.368	-0.987	1 1 212 10	0.303	0.836	-0.450	0.910	-0.997
1 1 112 11	0.206	0.056	0.057	0.104	-0.543	1 1 212 11	-0.124	0.138	0.111	0.100	-0.646
1 1 121 3	0.480	0.446	-0.133	0.346	-0.956	1 1 221 3	0.470	0.390	-0.029	0.240	-0.912
1 1 121 4	1.445	1.390	0.001	0.822	-0.002	1 1 221 4	1.094	0.564	-0.079	0.224	-0.014
1 1 121 5	0.382	0.104	0.007	0.164	0.029	1 1 221 5	0.599	0.254	-0.064	0.194	-0.639
1 1 121 6	0.551	0.080	-0.035	0.086	-0.049	1 1 221 6	0.519	0.432	0.148	0.482	-0.946
1 1 121 7	0.377	0.080	-0.104	0.200	-0.281	1 1 221 7	0.575	0.132	0.035	0.364	-0.487
1 1 121 8	-0.270	0.044	-0.033	0.122	-0.434	1 1 221 8	-0.325	0.136	-0.043	0.146	-0.730
1 1 121 9	0.034	0.188	-0.098	0.154	-0.781	1 1 221 9	-0.170	0.290	0.017	0.294	-0.929
1 1 121 10	0.132	0.028	-0.069	0.092	-0.580	1 1 221 10	-0.131	0.282	0.240	0.200	-0.957
1 1 121 11	0.210	0.036	0.023	0.092	0.009	1 1 221 11	0.213	0.120	0.108	0.062	-0.299
1 1 122 3	0.300	0.164	-0.048	0.158	-0.559	1 1 222 3	0.311	0.414	-0.059	0.324	-0.877
1 1 122 4	0.319	0.076	0.020	0.112	-0.344	1 1 222 4	0.091	0.138	-0.069	0.164	-0.796
1 1 122 5	-0.324	0.162	-0.091	0.170	-0.636	1 1 222 5	-0.154	0.344	0.128	0.412	-0.945
1 1 122 6	-0.288	0.106	-0.319	0.160	-0.646	1 1 222 6	-0.149	0.178	0.005	0.194	-0.572
1 1 122 7	0.156	0.662	-0.194	0.282	-0.860	1 1 222 7	-0.026	0.304	-0.057	0.214	-0.776
1 1 122 8	-0.118	0.190	-0.104	0.192	-0.597	1 1 222 8	-0.089	0.388	-0.050	0.312	-0.791
1 1 122 9	-0.248	0.498	-0.174	0.350	-0.719	1 1 222 9	-0.178	0.370	-0.099	0.362	-0.535
1 1 122 10	-0.034	0.104	-0.108	0.158	-0.894	1 1 222 10	-0.231	0.278	-0.044	0.312	-0.979
1 1 122 11	-0.081	0.072	0.045	0.100	0.186	1 1 222 11	-0.170	0.062	-0.026	0.134	-0.736

1 2 111	3	-0.149	0.202	-0.007	0.104	-0.142	1 2 211	3	0.614	0.102	-0.073	0.132	-0.719
1 2 111	4	0.215	0.464	-0.055	0.444	-0.247	1 2 211	4	0.976	0.392	-0.235	0.226	0.177
1 2 111	5	0.000	0.280	-0.174	0.250	-0.251	1 2 211	5	0.473	0.344	-0.207	0.214	-0.254
1 2 111	6	0.117	0.174	0.029	0.190	-0.785	1 2 211	6	0.614	0.098	0.041	0.216	-0.746
1 2 111	7	-0.039	0.168	0.017	0.196	-0.439	1 2 211	7	0.596	0.418	-0.039	0.414	-0.905
1 2 111	8	-0.206	0.052	-0.009	0.120	-0.552	1 2 211	8	-0.215	0.098	-0.220	0.098	-0.544
1 2 111	9	-0.078	0.124	0.045	0.142	-0.607	1 2 211	9	-0.086	0.122	-0.035	0.124	-0.732
1 2 111	10	-0.067	0.318	0.245	0.260	-0.978	1 2 211	10	0.147	0.048	0.010	0.064	-0.173
1 2 111	11	0.229	0.096	0.046	0.100	-0.698	1 2 211	11	0.093	0.076	0.171	0.092	-0.782
1 2 112	3	0.262	0.122	-0.035	0.204	-0.794	1 2 212	3	0.607	0.200	-0.114	0.152	-0.439
1 2 112	4	0.404	0.122	0.016	0.158	-0.783	1 2 212	4	1.056	0.770	-0.184	0.974	-0.841
1 2 112	5	-0.464	0.144	-0.085	0.152	-0.191	1 2 212	5	0.380	0.[illegible]08	-0.067	0.540	-0.757
1 2 112	6	-0.573	0.122	-0.030	0.160	-0.546	1 2 212	6	0.690	0.[illegible]	0.140	0.196	-0.593
1 2 112	7	-0.067	0.102	-0.013	0.124	-0.627	1 2 212	7	0.443	0.[illegible]38	0.027	0.340	-0.378
1 2 112	8	-0.900	0.354	-0.028	0.322	-0.340	1 2 212	8	-0.612	0.452	0.057	0.450	-0.978
1 2 112	9	-0.544	0.226	0.013	0.146	-0.750	1 2 212	9	0.045	0.124	-0.198	0.108	-0.612
1 2 112	10	-0.094	0.228	0.012	0.262	-0.976	1 2 212	10	0.212	0.026	-0.023	0.084	-0.472
1 2 112	11	-0.077	0.166	0.044	0.142	-0.936	1 2 212	11	0.092	0.176	0.164	0.102	-0.901
1 2 121	3	0.294	0.070	-0.116	0.092	-0.350	1 2 221	3	0.357	0.146	-0.190	0.154	-0.780
1 2 121	4	0.459	0.046	-0.071	0.114	-0.466	1 2 221	4	0.506	0.092	0.054	0.136	-0.576
1 2 121	5	-0.403	0.134	-0.055	0.158	-0.494	1 2 221	5	-0.517	0.154	0.037	0.262	-0.749
1 2 121	6	-0.502	0.072	-0.048	0.138	-0.541	1 2 221	6	-0.502	0.246	-0.049	0.248	-0.864
1 2 121	7	-0.160	0.504	-0.029	0.234	-0.876	1 2 221	7	-0.006	0.256	-0.237	0.266	-0.521
1 2 121	8	-1.053	0.330	-0.052	0.344	-0.230	1 2 221	8	0.296	0.370	-0.347	0.336	-0.869
1 2 121	9	-0.507	0.106	-0.002	0.178	-0.384	1 2 221	9	0.090	0.576	-0.504	0.606	-0.848
1 2 121	10	0.004	0.066	-0.116	0.078	-0.767	1 2 221	10	-0.131	0.144	0.080	0.186	-0.916
1 2 121	11	-0.026	0.056	-0.019	0.104	-0.078	1 2 221	11	-0.055	0.038	0.028	0.090	0.222
1 2 122	3	0.071	0.202	0.262	0.224	-0.676	1 2 222	3	0.488	0.124	-0.273	0.118	-0.668
1 2 122	4	0.324	0.344	-0.057	0.286	-0.899	1 2 222	4	0.772	0.314	-0.254	0.320	-0.952
1 2 122	5	0.479	0.222	-0.090	0.152	-0.436	1 2 222	5	-0.633	0.594	0.039	0.570	-0.966
1 2 122	6	0.527	0.440	0.057	0.526	-0.929	1 2 222	6	-0.928	0.218	0.085	0.260	-0.874
1 2 122	7	1.526	1.026	0.022	0.322	0.211	1 2 222	7	-0.418	0.436	0.087	0.294	-0.716
1 2 122	8	-0.323	0.048	0.001	0.122	-0.567	1 2 222	8	-0.936	0.262	0.013	0.330	-0.150
1 2 122	9	0.109	0.114	0.007	0.156	-0.739	1 2 222	9	-0.539	0.202	0.016	0.292	-0.445
1 2 122	10	0.100	0.160	0.084	0.154	-0.916	1 2 222	10	-0.270	0.070	0.190	0.060	-0.635
1 2 122	11	0.312	0.074	-0.026	0.044	-0.347	1 2 222	11	-0.213	0.122	0.193	0.072	-0.610

1	3	111	3	0.230	0.138	0.011	0.174	-0.298	1	3	211	3	0.524	0.118	0.066	0.102	0.279
1	3	111	4	0.449	0.148	0.015	0.216	-0.846	1	3	211	4	0.913	0.392	-0.057	0.370	0.009
1	3	111	5	-0.546	0.112	0.000	0.144	-0.120	1	3	211	5	0.431	0.424	-0.027	0.324	-0.453
1	3	111	6	-0.725	0.180	0.109	0.168	-0.700	1	3	211	6	0.788	0.208	0.072	0.188	-0.527
1	3	111	7	-0.114	0.136	-0.103	0.132	-0.770	1	3	211	7	0.833	0.250	0.053	0.258	-0.691
1	3	111	8	0.841	0.442	-0.042	0.280	-0.496	1	3	211	8	-0.567	0.080	0.053	0.122	-0.504
1	3	111	9	-0.583	0.220	-0.012	0.318	-0.748	1	3	211	9	-0.193	0.148	0.021	0.186	-0.757
1	3	111	10	-0.108	0.178	-0.068	0.244	-0.972	1	3	211	10	0.080	0.136	0.022	0.084	-0.757
1	3	111	11	-0.102	0.120	0.035	0.096	-0.283	1	3	211	11	0.209	0.062	0.003	0.066	-0.058
1	3	112	3	0.376	0.128	0.043	0.134	0.345	1	3	212	3	0.415	0.200	0.000	0.204	-0.375
1	3	112	4	0.614	0.464	0.147	0.406	-0.328	1	3	212	4	0.700	0.478	-0.008	0.430	-0.213
1	3	112	5	0.121	0.356	0.063	0.296	-0.492	1	3	212	5	0.300	0.398	-0.015	0.392	-0.512
1	3	112	6	0.610	0.184	0.024	0.432	0.276	1	3	212	6	0.481	0.168	0.089	0.192	-0.717
1	3	112	7	0.547	0.344	0.076	0.368	-0.614	1	3	212	7	0.916	0.506	-0.069	0.426	-0.881
1	3	112	8	-0.409	0.086	0.057	0.146	-0.611	1	3	212	8	-0.481	0.170	0.086	0.182	-0.786
1	3	112	9	-0.163	0.104	0.105	0.144	-0.517	1	3	212	9	-0.183	0.146	0.026	0.202	-0.784
1	3	112	10	0.040	0.136	0.093	0.084	-0.580	1	3	212	10	-0.160	0.060	0.314	0.068	-0.315
1	3	112	11	0.174	0.044	0.049	0.100	-0.600	1	3	212	11	0.171	0.082	0.095	0.096	-0.600
1	3	121	3	0.647	0.188	0.003	0.128	-0.683	1	3	221	3	0.217	0.108	-0.017	0.158	-0.616
1	3	121	4	0.550	0.168	0.022	0.209	-0.809	1	3	221	4	0.611	0.080	-0.211	0.144	-0.801
1	3	121	5	-0.637	0.206	-0.022	0.154	-0.516	1	3	221	5	-0.666	0.292	0.055	0.244	-0.820
1	3	121	6	-0.734	0.194	0.004	0.210	-0.780	1	3	221	6	-0.824	0.230	0.134	0.182	-0.791
1	3	121	7	-0.068	0.730	-0.004	0.280	-0.141	1	3	221	7	-0.221	0.348	0.120	0.504	-0.161
1	3	121	8	-0.402	0.202	-0.029	0.142	-0.231	1	3	221	8	-0.967	0.314	-0.084	0.384	-0.455
1	3	121	9	-0.483	0.298	-0.117	0.320	-0.635	1	3	221	9	-0.504	0.112	-0.054	0.388	-0.717
1	3	121	10	-0.123	0.186	-0.005	0.146	-0.800	1	3	221	10	-0.052	0.084	-0.094	0.100	-0.867
1	3	121	11	-0.090	0.114	0.038	0.098	-0.211	1	3	221	11	-0.024	0.108	-0.011	0.064	-0.348
1	3	122	3	0.354	0.164	0.084	0.116	0.368	1	3	222	3	0.249	0.080	-0.058	0.106	-0.566
1	3	122	4	0.521	4.016	-0.096	0.892	-0.262	1	3	222	4	0.437	0.038	0.109	0.114	-0.500
1	3	122	5	0.579	0.242	-0.019	0.156	-0.489	1	3	222	5	-0.623	0.288	0.023	0.262	-0.821
1	3	122	6	0.568	0.160	0.100	0.194	-0.618	1	3	222	6	-0.862	0.118	0.016	0.194	-0.746
1	3	122	7	0.665	0.144	0.039	0.234	-0.644	1	3	222	7	-0.627	0.254	0.112	0.208	-0.788
1	3	122	8	-0.454	0.106	0.082	0.130	-0.632	1	3	222	8	-0.451	0.220	-0.088	0.184	-0.525.
1	3	122	9	-0.262	0.144	0.090	0.162	-0.674	1	3	222	9	-0.394	0.330	-0.072	0.436	-0.627
1	3	122	10	0.050	0.168	0.139	0.138	-0.916	1	3	222	10	-0.107	0.230	-0.070	0.274	-0.959
1	3	122	11	0.215	0.064	0.052	0.108	-0.529	1	3	222	11	-0.057	0.088	-0.021	0.082	0.093

2	4	111	3	-0.178	0.213	-0.009	0.169	-0.569	2	4	211	3	0.181	0.027	0.029	0.046	-0.180
2	4	111	4	0.013	0.035	-0.012	0.066	-0.553	2	4	211	4	0.058	0.230	0.021	0.205	-0.249
2	4	111	5	0.261	0.046	0.023	0.077	-0.355	2	4	211	5	0.414	0.320	-0.164	0.238	-0.738
2	4	111	6	0.136	0.234	0.084	0.348	-0.124	2	4	211	6	-0.144	0.146	0.111	0.276	-0.856
2	4	111	7	0.006	0.031	-0.047	0.061	-0.662	2	4	211	7	-0.205	0.288	0.234	0.339	-0.984
2	4	111	8	0.237	0.172	-0.032	0.084	-0.211	2	4	211	8	0.323	0.160	-0.080	0.119	-0.947
2	4	111	9	0.294	0.058	-0.193	0.128	0.002	2	4	211	9	-0.234	0.336	-0.060	0.130	0.507
2	4	111	10	0.249	0.086	-0.103	0.148	-0.726	2	4	211	10	0.090	0.206	-0.141	0.190	-0.953
2	4	111	11	0.315	0.056	-0.038	0.104	0.006	2	4	211	11	-0.037	0.134	0.030	0.092	0.130
2	4	112	3	-0.281	0.046	0.137	0.073	-0.703	2	4	212	3	0.502	0.150	-0.124	0.231	-0.726
2	4	112	4	-0.057	0.156	0.029	0.117	-0.605	2	4	212	4	-0.165	0.156	-0.177	0.094	-0.778
2	4	112	5	-0.165	0.102	-0.014	0.093	-0.240	2	4	212	5	-0.720	0.307	0.125	0.293	-0.979
2	4	112	6	0.198	0.156	-0.025	0.154	-0.645	2	4	212	6	0.094	0.160	0.132	0.172	-0.833
2	4	112	7	0.322	0.040	-0.035	0.107	-0.700	2	4	212	7	0.469	0.098	-0.141	0.117	-0.797
2	4	112	8	0.196	0.036	-0.054	0.056	-0.584	2	4	212	8	0.391	0.144	-0.052	0.132	-0.270
2	4	112	9	-0.106	0.308	-0.125	0.282	-0.109	2	4	212	9	0.050	0.254	0.442	0.324	-0.949
2	4	112	10	0.009	0.054	-0.054	0.100	-0.727	2	4	212	10	-0.091	0.746	0.151	0.522	-0.924
2	4	112	11	-0.015	0.068	-0.006	0.046	-0.394	2	4	212	11	0.334	0.144	-0.089	0.192	-0.908
2	4	121	3	0.192	0.132	-0.340	0.117	-0.905	2	4	221	3	-0.253	0.019	-0.087	0.056	-0.492
2	4	121	4	-0.200	0.142	-0.010	0.151	-0.501	2	4	221	4	-0.423	0.200	0.136	0.256	-0.814
2	4	121	5	-0.019	0.276	-0.051	0.139	-0.744	2	4	221	5	-0.737	0.064	0.004	0.166	-0.274
2	4	121	6	0.175	0.306	0.018	0.136	-0.922	2	4	221	6	-0.153	0.484	0.114	0.284	-0.768
2	4	121	7	0.502	0.079	-0.053	0.122	-0.812	2	4	221	7	0.809	0.065	-0.135	0.088	-0.619
2	4	121	8	0.136	0.043	-0.033	0.061	-0.159	2	4	221	8	0.220	0.066	-0.117	0.095	-0.577
2	4	121	9	-0.226	0.360	0.005	0.204	-0.857	2	4	221	9	-0.291	0.474	-0.079	0.370	-0.642
2	4	121	10	-0.169	0.144	0.098	0.172	-0.946	2	4	221	10	-0.031	0.210	-0.030	0.240	-0.967
2	4	121	11	0.037	0.080	-0.127	0.132	-0.820	2	4	221	11	-0.027	0.148	-0.002	0.148	-0.704
2	4	122	3	0.467	0.151	0.005	0.151	-0.524	2	4	222	3	-0.106	0.294	0.043	0.241	-0.938
2	4	122	4	-0.632	0.166	0.110	0.109	-0.912	2	4	222	4	0.233	0.055	-0.110	0.096	-0.790
2	4	122	5	-1.164	0.059	0.023	0.078	0.307	2	4	222	5	0.150	0.369	-0.042	0.411	-0.985
2	4	122	6	-0.923	0.296	0.143	0.364	-0.858	2	4	222	6	0.222	0.458	-0.126	0.368	-0.962
2	4	122	7	-1.789	2.971	0.109	0.420	-0.524	2	4	222	7	0.840	0.559	-0.228	0.110	-0.135
2	4	122	8	2.128	0.990	0.008	0.074	0.008	2	4	222	8	-0.066	0.267	-0.031	0.121	-0.685
2	4	122	9	0.599	0.112	-0.267	0.114	-0.607	2	4	222	9	-0.299	0.098	0.130	0.122	-0.686
2	4	122	10	-0.031	0.260	0.140	0.202	-0.937	2	4	222	10	0.455	0.374	-0.273	0.428	-0.981
2	4	122	11	0.158	0.098	0.075	0.086	-0.753	2	4	222	11	0.340	0.092	-0.055	0.156	-0.846

2	5	111	3	0.583	0.177	-0.182	0.144	-0.502	2 5 211 3	0.277	0.141	-0.135	0.221	-0.652
2	5	111	4	-0.398	0.147	-0.044	0.077	-0.768	2 5 211 4	-0.356	0.107	-0.002	0.167	-0.809
2	5	111	5	-0.551	0.075	-0.070	0.090	-0.555	2 5 211 5	-0.245	0.148	0.010	0.151	-0.842
2	5	111	6	0.408	0.086	-0.056	0.156	-0.356	2 5 211 6	0.336	0.218	0.061	0.196	-0.754
2	5	111	7	0.956	0.214	-0.057	0.060	-0.359	2 5 211 7	0.280	0.110	-0.081	0.118	-0.875
2	5	111	8	0.370	0.126	-0.050	0.088	-0.561	2 5 211 8	0.330	0.252	-0.071	0.168	-0.698
2	5	111	9	0.561	0.014	-0.055	0.102	-0.220	2 5 211 9	0.086	0.144	0.173	0.170	-0.810
2	5	111	10	0.082	0.158	0.018	0.086	-0.795	2 5 211 10	-0.004	0.262	0.126	0.188	-0.941
2	5	111	11	0.225	0.044	999.999	999.999	999.999	2 5 211 11	0.181	0.056	0.060	0.098	-0.249
2	5	112	3	-0.096	0.156	0.008	0.099	-0.177	2 5 212 3	-0.392	0.041	-0.123	0.067	-0.639
2	5	112	4	0.292	0.101	-0.053	0.093	-0.918	2 5 212 4	-0.235	0.191	-0.144	0.213	-0.833
2	5	112	5	0.105	0.071	0.026	0.066	-0.715	2 5 212 5	-0.394	0.206	0.007	0.170	-0.816
2	5	112	6	-0.162	0.206	0.139	0.366	0.021	2 5 212 6	0.401	0.228	0.040	0.244	-0.711
2	5	112	7	0.572	0.240	-0.090	0.112	-0.872	2 5 212 7	0.951	0.162	-0.141	0.179	-0.929
2	5	112	8	0.030	0.254	0.004	0.098	-0.299	2 5 212 8	0.397	0.068	-0.134	0.087	-0.704
2	5	112	9	0.702	0.192	-0.384	0.214	-0.890	2 5 212 9	-0.270	0.416	-0.131	0.316	-0.563
2	5	112	10	0.129	0.130	0.037	0.100	-0.818	2 5 212 10	-0.106	0.078	-0.063	0.100	-0.843
2	5	112	11	0.265	0.042	999.999	999.999	999.999	2 5 212 11	-0.097	0.104	0.002	0.030	0.086
2	5	121	3	0.364	0.172	-0.038	0.163	-0.467	2 5 221 3	-0.129	0.061	-0.091	0.062	-0.581
2	5	121	4	-0.248	0.051	-0.151	0.080	-0.492	2 5 221 4	-0.087	0.116	0.011	0.089	-0.541
2	5	121	5	-0.457	0.092	-0.058	0.110	-0.665	2 5 221 5	0.017	0.203	-0.044	0.121	-0.291
2	5	121	6	-0.390	0.348	-0.050	0.314	-0.703	2 5 221 6	-0.413	0.294	-0.022	0.244	-0.542
2	5	121	7	0.757	0.329	-0.178	0.141	-0.529	2 5 221 7	0.369	0.230	-0.129	0.257	-0.962
2	5	121	8	0.377	0.106	-0.060	0.104	-0.480	2 5 221 8	0.403	0.065	-0.241	0.089	-0.455
2	5	121	9	0.216	0.058	0.011	0.152	-0.777	2 5 221 9	-0.236	0.176	-0.085	0.236	0.091
2	5	121	10	0.Y 4	0.234	0.021	0.178	-0.871	2 5 221 10	0.158	0.230	-0.204	0.220	-0.972
2	5	121	11	0.240	0.074	0.007	0.130	-0.673	2 5 221 11	0.040	0.028	-0.075	0.102	-0.001
2	5	122	3	-0.127	0.082	-0.165	0.071	-0.741	2 5 222 3	-0.011	0.133	-0.307	0.133	-0.972
2	5	122	4	-0.102	0.142	-0.134	0.106	-0.675	2 5 222 4	-0.167	0.206	-0.064	0.149	-0.322
2	5	122	5	-0.249	0.251	-0.076	0.218	-0.819	2 5 222 5	1.095	0.217	-0.089	0.282	-0.104
2	5	122	6	-0.394	0.420	-0.073	0.190	-0.212	2 5 222 6	-0.538	0.340	-0.016	0.374	-0.803
2	5	122	7	0.769	0.036	-0.119	0.083	-0.442	2 5 222 7	1.000	0.172	0.101	0.146	-0.879
2	5	122	8	0.526	0.264	-0.288	0.229	-0.965	2 5 222 8	0.512	0.081	-0.219	0.083	-0.488
2	5	122	9	-0.230	0.454	-0.074	0.296	-0.520	2 5 222 9	-0.336	0.392	-0.165	0.492	-0.786
2	5	122	10	-0.098	0.056	0.016	0.074	-0.870	2 5 222 10	0.010	0.082	-0.164	0.104	-0.876
2	5	122	11	-0.019	0.048	-0.026	0.038	-0.026	2 5 222 11	-0.042	0.090	-0.024	0.124	0.146

2 6 111 3	0.210	0.049	-0.030	0.067	-0.699	2 6 211 3	0.339	0.108	-0.095	0.208	-0.739
2 6 111 4	0.219	0.246	-0.008	0.117	-0.368	2 6 211 4	-0.216	0.104	-0.137	0.069	-0.696
2 6 111 5	0.312	0.294	-0.022	0.153	-0.738	2 6 211 5	-0.468	0.053	-0.091	0.090	-0.557
2 6 111 6	-0.030	0.130	0.063	0.168	-0.603	2 6 211 6	0.111	0.240	0.006	0.028	-0.729
2 6 111 7	-0.107	0.161	0.174	0.217	-0.344	2 6 211 7	0.337	0.109	-0.073	0.107	-0.921
2 6 111 8	-0.253	0.290	0.051	0.102	-0.273	2 6 211 8	0.336	0.160	-0.011	0.140	-0.389
2 6 111 9	-0.355	0.216	-0.033	0.288	-0.024	2 6 211 9	-0.284	0.186	0.136	0.224	-0.936
2 6 111 10	999.999	999.999	999.999	999.999	999.999	2 6 211 10	0.073	0.148	0.040	0.098	-0.892
2 6 111 11	999.999	999.999	999.999	999.999	999.999	2 6 211 11	0.277	0.126	-0.037	0.098	-0.840
2 6 112 3	0.400	0.164	-0.239	0.156	-0.964	2 6 212 3	0.368	0.065	-0.141	0.062	-0.858
2 6 112 4	0.255	0.249	-0.043	0.119	-0.204	2 6 212 4	0.216	0.194	-0.032	0.276	-0.441
2 6 112 5	0.399	0.252	-0.117	0.157	-0.449	2 6 212 5	0.541	0.380	-0.419	0.367	-0.784
2 6 112 6	-0.142	0.192	0.052	0.252	-0.845	2 6 212 6	-0.175	0.204	0.121	0.302	-0.967
2 6 112 7	-0.204	0.093	0.057	0.102	-0.865	2 6 212 7	-0.445	0.261	0.303	0.278	-0.963
2 6 112 8	0.272	0.141	-0.009	0.131	-0.941	2 6 212 8	0.190	0.187	0.094	0.167	-0.966
2 6 112 9	-0.137	0.370	-0.065	0.250	-0.223	2 6 212 9	-0.142	0.114	-0.035	0.194	0.164
2 6 112 10	-0.181	0.060	-0.020	0.106	-0.881	2 6 212 10	-0.090	0.052	0.067	0.098	-0.753
2 6 112 11	-0.105	0.102	0.026	0.088	-0.018	2 6 212 11	-0.046	0.114	0.079	0.084	0.294
2 6 121 3	-0.049	0.124	-0.019	0.218	-0.622	2 6 221 3	0.253	0.089	-0.028	0.149	-0.224
2 6 121 4	-0.167	0.119	-0.034	0.117	-0.699	2 6 221 4	-0.369	0.146	-0.104	0.213	-0.852
2 6 121 5	-0.036	0.075	0.010	0.114	-0.674	2 6 221 5	-0.565	0.171	-0.078	0.237	-0.896
2 6 121 6	-0.145	0.240	0.029	0.168	-0.525	2 6 221 6	-0.414	0.320	0.065	0.292	-0.683
2 6 121 7	-0.260	0.303	-0.064	0.336	-0.168	2 6 221 7	0.905	0.360	-0.078	0.167	-0.120
2 6 121 8	-0.620	0.378	0.057	0.166	-0.323	2 6 221 8	0.326	0.180	-0.033	0.223	-0.872
2 6 121 9	0.618	0.108	-0.271	0.140	-0.612	2 6 221 9	0.313	0.014	0.051	0.102	-0.313
2 6 121 10	0.104	0.070	0.040	0.102	-0.653	2 6 221 10	-0.202	0.202	0.335	0.166	-0.945
2 6 121 11	0.218	0.066	0.025	0.086	-0.402	2 6 221 11	0.158	0.154	0.105	0.118	-0.815
2 6 122 3	0.079	0.012	0.156	0.050	-0.022	2 6 222 3	0.053	0.196	-0.076	0.133	-0.373
2 6 122 4	-0.017	0.287	0.084	0.170	-0.183	2 6 222 4	0.076	0.123	-0.047	0.118	-0.914
2 6 122 5	0.626	0.242	-0.035	0.074	-0.186	2 6 222 5	-0.511	0.182	0.154	0.261	-0.905
2 6 122 6	0.035	0.134	0.015	0.130	-0.801	2 6 222 6	-0.286	0.320	0.093	0.338	-0.934
2 6 122 7	-0.360	0.226	0.246	0.272	-0.954	2 6 222 7	0.064	0.241	-0.207	0.166	-0.876
2 6 122 8	0.237	0.083	0.015	0.069	-0.784	2 6 222 8	-0.111	0.156	0.012	0.114	-0.418
2 6 122 9	-0.064	0.304	-0.142	0.316	-0.349	2 6 222 9	-0.001	0.050	-0.078	0.120	-0.675
2 6 122 10	-0.052	0.094	-0.068	0.130	-0.370	2 6 222 10	0.143	0.258	0.063	0.226	-0.969
2 6 122 11	-0.016	0.086	-0.027	0.090	-0.250	2 6 222 11	0.297	0.060	-0.014	0.070	-0.296

APPENDIX C
SUMMARY OF RESPONSES TO PILOT QUESTIONNAIRE

LIST OF ILLUSTRATIONS

Figure		Page
C-1	CDU Controls and Annunciators	C-1
C-2	Bakersfield RNAV Star	C-2

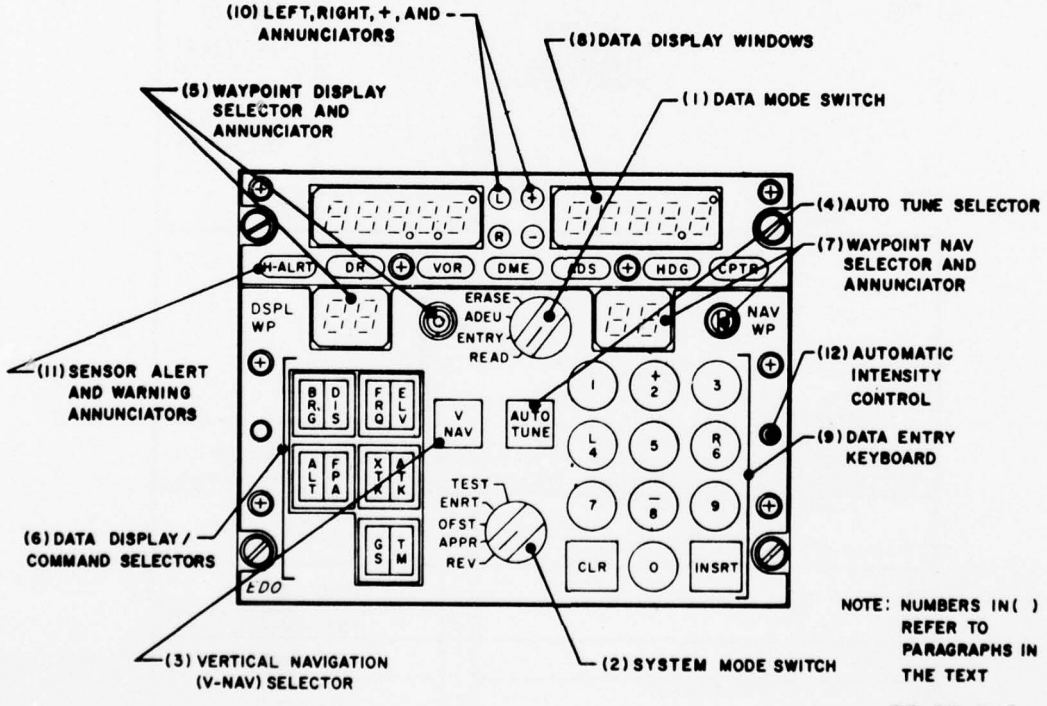
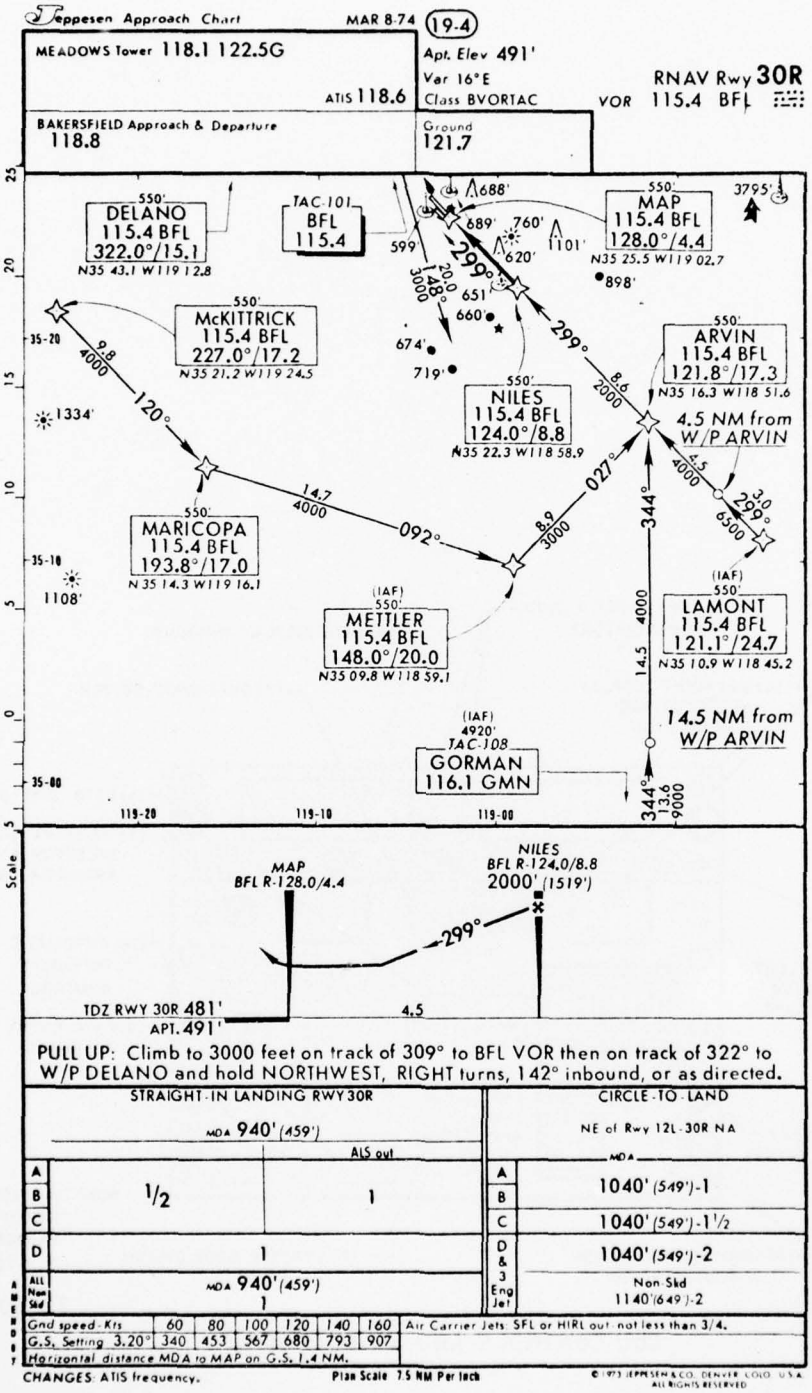


FIGURE C-1. CDU CONTROLS AND ANNUNCIATORS



77-10-C-2

FIGURE C-2. BAKERSFIELD RNAV STAR

A. RNAV CONTROL DISPLAY UNIT

1. Did you experience any difficulty or confusion when entering waypoint information?

   a. NO ☐ YES ☐

   b. If yes, please explain._____

COMMENT:

   a. NO-4 YES-2

   b. (P-2) Failure to punch distance and entering data on top. Some instances of punching wrong keyboard number.

   (P-4) Checklist necessary to be sure "AUTO TUNE" is selected prior to takeoff, system mode switch in "ENROUTE," etc.

2. Did you experience any difficulty or confusion when entering an "impromptu" W/P?

   a. NO ☐ YES ☐

   b. If yes, please explain._____

COMMENT:

   a. NO-5 YES-1

   b. (P-1) No comment

(P-4) (Although he answered "No" pilot (P-4) gave this comment.)

"However, without co-pilot and/or auto pilot, in turbulence especially, can drift off course, altitude and possibly get in unusual attitude while entering "impromptu" W/P. Necessary to recheck entry after inserting, i. e., more than "on-ground" programming.

3. The "H" alert feature of the EDO RNAV flashed when 0.9 min to/from the W/P. Is this feature of significant importance?

a. NO ☐ YES ☐

b. If yes, please explain. _____

COMMENT:

a. NO-0 YES-6

b. (P-1) It would alert me to double check next W/P, routing and time I would want to make my turn.

(P-2) Position awareness - check to see if next W/P still inserted and correct.

(P-3) Allows planning for turns and switchover to next W/P in the EDO. Also serves as a reminder of changeover.

(P-4) Alerts when approaching W/P, but I believe it could be reduced to something like 0.5 minutes.

(P-5) Could be dreaming along and not fully aware of DTW - blinking light will sure wake you up.

(P-6) Major assist to preclude your overshooting turn requirements at W/P.

c. Should the "H" alert light also emit an aural signal?

a. NO ☐ YES ☐

Comment:

a. No-5 Yes-1

d. Did you use the "H" alert for turn anticipation?

a. NO ☐ OCCASIONALLY ☐ ALWAYS ☐

Comment:

a. No-2 Occasionally-0 Always-4

4. Are there any undesirable physical layout features of the EDO RNAV with respect to:

1a. Entering W/P information? NO ☐ YES ☐

2a. Output/Storage display? NO ☐ YES ☐

b. If yes, please explain. _____

COMMENT:

1a. NO-5 YES-1

2a. NO-5 YES-1

b. (P-2) 1a. Would prefer having one display selector - similar to I. N. S.

(P-6) 2a. Would like some kind of alert system to let me know stored information has dropped out.

5. Was it easy to recognize when a piece of W/P data "dropped out" of the EDO RNAV?

a. NO ☐ YES ☐

COMMENT:

a. NO-3 YES-3

b. Was it difficult to re-enter that data?

NO ☐ YES ☐ SOMEWHAT ☐

Comment:

b. No-2 Yes-0 Somewhat-4

(P-2) Depends at what point in flight it occurs.

(P-4) Especially at critical maneuver times.

(P-6) Yes, when very close to turn or reaching an altitude

6. Did you find the EDO RNAV capability of only being able to enter one altitude/FPA (VNAV) at a time:

a. Too restrictive

b. Satisfactory because it did not cause confusion

COMMENT:

a. Too restrictive - 4

b. Satisfactory - 2

(P-2) Comment: Too restrictive because it did not allow optimum climb or descent.

B. PILOT PROCEDURES

1. Did you have any trouble keeping track of yourself on the pilot chart?

a. NO ☐ YES ☐

b. If no, explain _____

COMMENT:

a. NO-6 YES-0

b. (P-1) Because I numbered chart to match W/P selection

(P-2) Used OBS to monitor bearing to station

(P-3) I numbered W/P's on chart in same sequence they were entered in RNAV.

(P-4) Constant advance checking of W/P's necessary to pre-empt getting confused.

(P-5) No comment

(P-6) No comment

2. Given an approved RNAV aeronautical chart, would you physically number each waypoint on the chart that you had stored in your RNAV?

a. NO ☐ YES ☐

COMMENT:

a. NO-1 YES-5

(P-1) Or list them on scratch pad.

This must be checked against settings each time you change W/P to verify proper insert of data points.

b. Would this be practical for up to:

1. 5 W/P's
2. 10 W/P's
3. 20 W/P's
4. Over 20 W/P's

(b) 1 - 1

2 - 1

3 - 2

4 - 3

(P-2) Any number, i. e., on I. N. S. with only 9 W/P's, how would you identify high number W/P if you chose to skip some?

(P-4) Not necessary if proficiency maintained in using RNAV EDO system.

3. Can you think of any practical method (other than physically numbering the route segments) of correlating the EDO navigation waypoint information with your routing on the RNAV aeronautical chart?

a. Comment: _____

COMMENT:

a. NO-5

(P-2) Have co-pilot do it.

4. Did you enter the Missed Approach W/P (approach plate) at any time during your approaches?

a. NO ☐ YES ☐

COMMENT:

a1. NO-6 YES-0

a2. If no, would you enter it under actual flight conditions?

a2. NO-0 YES-6

b. (P-2) With I. N. S. we enter the runway threshold for emergency return

(P-4) Under marginal approach minima and turbulent weather only.

(P-5) Probably, not sure

5. With regard to reaching assigned altitudes at the same time you arrived at the W/P (VNAV), would you prefer to reach altitude:

a. Prior to W/P

b. At the W/P (VNAV)

COMMENT:

a. Prior to W/P - 5 No preference - 1

b. At the W/P - 0

If a, how far prior to W/P? _____nmi Why_____

a. (P-1) 8 nmi - Less workload arriving at W/P level for next change over W/P.

(P-2) No comment - Climb as quickly as possible to altitude and remain there until optimum time to descend.

(P-3) No comment - No comment

(P-4) No comment - Varies with type aircraft, best climb performance and TAS.

(P-5) 5 nmi - Level turn easier when changing to next W/P.

(P-6) ASAP - Work load reduction.

6. Did flying the RNAV profiles without full flight director cause any particular difficulty.

a. NO ☐ YES ☐

b. If yes, explain.

COMMENT:

a. NO-6 YES-0

7. While flying an approved RNAV SID or STAR under IFR, would you probably:

a. 1. Let the RNAV compute a flight path angle (FPA) to your next required altitude and fly that FPA?

NO ☐ YES ☐

2. Enter your own best estimated FPA and fly it to your required altitude?

NO ☐ YES ☐

3. Not use an FPA and climb/descend to your altitude at a rate commensurate with your aircraft performance?

NO ☐ YES ☐

COMMENT:

a. 1. NO-5 YES-1

(P-6) Comment: If tied into auto-pilot.

2. NO-3 YES-3

3. NO-2 YES-4

8. How often did you fly in the "Read" mode?

a. RARELY ☐ OCCASIONALLY ☐ OFTEN ☐ ALWAYS ☐

COMMENT:

a. RARELY-0 OCCASIONALLY-1 OFTEN-3 ALWAYS-2

b. Is this a useful feature? NO ☐ YES ☐

(b) NO-0 YES-6

c. What information did you monitor most?

1. BRG/DIST

2. FREQ/ELEV.

3. ALT/FPA

(c) 1 - 6

2 - 1

3 -2

AD-A047 246 NATIONAL AVIATION FACILITIES EXPERIMENTAL CENTER ATL--ETC F/G 17/7
SIMULATION TESTS OF FLIGHT TECHNICAL ERROR IN 2D/3D AREA NAVIGA--ETC(U)
OCT 77 D ELDREDGE, W G CROOK, W R CRIMBRING

UNCLASSIFIED FAA-NA-77-10 FAA-RD-77-112 NL

2 OF 2
ADA047248

END
DATE FILMED
1-78
DDC

9. Using attached approach plate for Bakersfield Airport, list the waypoints you probably would NOT enter into your RNAV in making a full IFR RNAV approach. (Starting at McKittrick W/P)

a1. _____, _____, _____, _____, _____, _____, NONE

COMMENT:

a1. (P-1) NILES

(P-2) NILES

(P-3) NONE

(P-4) NONE- NILES is apparently F. A. F. for slow down to approach configuration.

(P-5) NONE

(P-6) LAMONT

a2. Would you designate any of the waypoints as a useable DTW Fix rather than a Fixed W/P.

a. NO YES

b. If yes, list them.

_____, _____, _____, _____, _____

Comment:

a. NO-2 YES-3

b. (P-1) MAP

(P-2) (Didn't understand the question)

(P-3) MARICOPA, NILES

(P-4) NILES

(P-5) (NO)

(P-6) (NO)

10. If making your approach straight-in from Lamont W/P, would you NOT enter any W/P's?

a. NO ☐ YES ☐

b. If yes, list them. _____, _____, _____, _____

COMMENT:

a. NO-2 YES-4

b. (P-1) NILES

(P-2) NILES

(P-3) ARVIN

(P-4) ARVIN (DTW to NILES would suffice)

(P-5) (NO)

(P-6) (NO)

c. Would you designate any of the waypoints as DTW Fixes rather than Fixed W/P's?

a. NO ☐ YES ☐

b. If yes, please list. _____, _____, _____, _____

Comment:

a. NO-2 YES-3

b. (P-1) NILES

(P-2) (Don't understand the question)

(P-3) ARVIN

(P-4) ARVIN

(P-5) (NO)

(P-6) (NO)

C. PILOT WORKLOAD

1. Of the various conditions you were asked to fly during the data runs, rate them on a score of 1 through 4 as to their degree of difficulty. (Most difficult = 4)

a. A. No flight director - 2D (No VNAV)

B. With flight director - 3D (With VNAV)

C. With flight director - 2D (No VNAV)

D. No flight director - 3D (With VNAV)

COMMENT:

a.	P-1	P-2	P-3	P-4	P-5	P-6
A	4	3	3	3	4	3
B	1	2	1	2	1	2
C	2	1	2	1	2	1
D	3	4	4	4	3	4

2. Would you feel confident in using Choice #4 (most diff.) in Question #6, for an RNAV approach under IFR into a major airport?

   a. NO ☐ YES ☐

COMMENT:

   a. NO-3 YES-3

   b. (P-2) If with auto-pilot and co-pilot

      (P-4) Category 1 conditions only is understood, of course!

3. Do you think RNAV systems similar to EDO in design and function can be flown by a single pilot under IFR:

   a1. With Flt. Dir./Auto-Pilot

   2. No Flt. Dir./Auto-Pilot

   3. In an RNAV environment

   4. In a mixed RNAV/Non-RNAV environment

COMMENT:

	YES	NO
a1.	6	0
2.	4	2
3.	3	3
4.	4	2

4. Was the ATC communication workload:

a. EXCESSIVE ☐ NORMAL ☐ LIGHT ☐

COMMENT:

a. EXCESSIVE - 0 NORMAL - 3 LIGHT-3

5. How would you rate your overall cockpit workload during your RNAV simulation flights?

a. MINIMAL ☐ MODERATE ☐ HEAVY ☐

COMMENT:

a. MINIMAL-1 MODERATE-4 HEAVY-1

Comments:

(P-1) - (Moderate) with VNAV and Flight Director

(P-2) - (Heavy) Because without auto-pilot or co-pilot, too much attention devoted to monitoring/verifying RNAV equipment to conduct a smooth flight. Too much head inside to allow normal outside traffic scan.

(P-6) - (Minimal) The EDO RNAV unit would be more effective and reduce workload if it were functioning at design capability. By this I mean the ADEU operation and not so much stored information dropout.