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Anil V. Phatak
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National Aeronautics and
Space Administration

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Moffett Field, California 94035

PREFACE

This effort was performed under NASA Contract No. NAS2-10850 from the NASA-Ames Research Center. Mr. H.N. Swenson of NASA-Ames was the technical monitor for this project.

The project manager at AMA, Inc. was Dr. Anil V. Phatak. Mr. Mahlon F. Lee was the project engineer.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

Name	Definition
ADI	Attitude Director Indicator
AHS	Airborne Hardware Simulator
ARC	Ames Research Center
BSPUTL	1819B Real Time EXUTIL
BITE	Built In Test Equipment
CIP	Computed Intercept Path
CLAZ	Center Line Azimuth
CLEL	Center Line Elevation
CSS	Control Stick Steering
DDAS	Digital Data Acquisition System
DH	Decision Height
DME	Distance Measuring Equipment
EXUTIL	Extended Utility Software Program
FD	Flight Director
FLR	Flare
GS	Glide Slope
GPIP	Glide Path Intercept Point
HSI	Horizontal Situation Indicator (RD-202 Radio Direction Indicator)
IAS	Indicated Airspeed
IFR	Instrument Flight Rules
IMC	Instrument Meterological Condition
IMU	Inertial Measurement Unit
INS	Litton LTN-51 Inertial Navigation System
IVSI	Instantaneous Vertical Speed Indicator
JTEC	J-TEC VA-210 True Airspeed Sensor
LVDT	Linear Variable Differential Transformer (linear position)
MAN	Manual
MFD	Multifunction Display
MLS	Microwave Landing System
MSD	Mode Status Display
MSP	Mode Select Panel

LIST OF ACRONYMS (Cont.)

Name	Definition
PERCON	Peripheral Controller
PIC	Pilot In Command
PID	Pilot Identification
PFT	Preflight
RMDU	Remote Multiplexer Demultiplexer Unit
S19	Fixed Base UH-1H Helicopter Simulator
SDF	Software Development Facility
SIU	Servo Interlock Unit
SP	Status Panel
TERPS	Terminal Instrument Procedures
TL	Turn Light
VFR	Visual Flight Rules
VG	Vertical Gyro
VOR	Very High Frequency Omni-Directional Range (provides bearing and range)
VOR/DME	Co-located VOR and DME

1. INTRODUCTION

This report describes the navigation and flight director guidance systems implemented in the NASA/FAA helicopter MLS curved approach flight test program. Flight tests were conducted at the U.S. Navy's Crows Landing facility, using the NASA Ames UH-1H helicopter equipped with the V/STOLAND avionics system. The purpose of these tests was to investigate the feasibility of flying complex, curved and descending approaches to a landing using MLS flight director guidance.

This report is organized as follows: Section 2 provides a description of the ground-based navigation aids available at Crows Landing. The UH-1H V/STOLAND avionics system is discussed in Section 3, wherein the details of the cockpit instrumentation and on-board navigation equipment are provided. Three generic reference flight paths were flown in the test program. They are the U-Turn, S-Turn and Straight-In flight profiles. These profiles and their geometries are described in detail in Section 4. Specifically, the (x,y) coordinates of the 12 waypoints in a runway reference frame, the lengths and curvature of each segment, and the path distances from the glide-path intercept point (GPIP) for each reference path and glide slope are given in tabular format. The operating procedures used by the pilots are described in Section 5. Section 6 describes the on-board navigation filters used in this program. A third-order complementary filter implementation was chosen for the horizontal (x and y) and vertical (h) channels.

A 3-cue flight director (pitch, roll and collective) was implemented on the UH-1H helicopter using the standard instruments - that is, the Attitude Director Indicator (ADI) for pitch and roll commands and the collective pitch command bar for the vertical axis. In addition, raw data in the form of lateral and vertical deviations from the reference flight path are displayed on the Attitude Director Indicator (ADI) and Horizontal Situation Indicator (HSI). These raw deviations were scaled as a function of the along-track distance to go from the azimuth and elevation antennas, respectively. Section 7 provides a description of the formulation and implementation of the raw data and flight director guidance laws.

Finally, Section 8 shows the actual performance data (for one pilot) in the form of response histories of seventeen key variables for the MLS flight director approaches. The data presented is representative of the response behavior exhibited by the overall population of pilots who participated in the flight test program.

Concluding remarks are given in Section 9.

2. GROUND - BASED NAVIGATION AIDS

The NASA/FAA helicopter MLS curved approach flight tests were conducted at the U.S. Navy's Crows Landing Auxiliary Landing Field near Patterson, CA. Figure 1 shows a plan view of the field and locations of the TACAN station, the MLS range/azimuth antenna, and the MLS elevation antenna. One navaid not shown but occasionally used is the Modesto VOR/DME, which is 28 km NNE.

All landing approaches are made to Runway 35. The runway coordinate system is defined such that the x-axis is on the runway centerline and positive northward, the z-axis is vertical and positive down, and the y-axis completes a right-handed Cartesian system. The origin is on the runway centerline and such that the MLS azimuth antenna is at a distance of 1353 m north on the x axes. The target touchdown point is defined to be the glide path intercept point (GPIP).

In order to evaluate pilot performance during the MLS curved approaches with and without flight director guidance, key variables are telemetered from the aircraft and recorded on the ground. Also, twin radars and a laser tracking system are used to compute and record the aircraft position and velocity.

The laser tracking system is mounted on the TTR radar and is only turned on during the final approach. At present, the radar uses only a type zero servo system for tracking. Future plans are to upgrade to a type one system.

The geometry of navigation with respect to either the TACAN station or VOR/DME station is shown in Figure 2. Slant range and magnetic bearing from the station are the measured quantities. Figure 3 depicts the geometry of MLS navigation, where the measured quantities are slant range, azimuth referenced to the runway centerline, and elevation angle. When available, MLS is used rather than TACAN, and TACAN is used rather than VOR/DME.

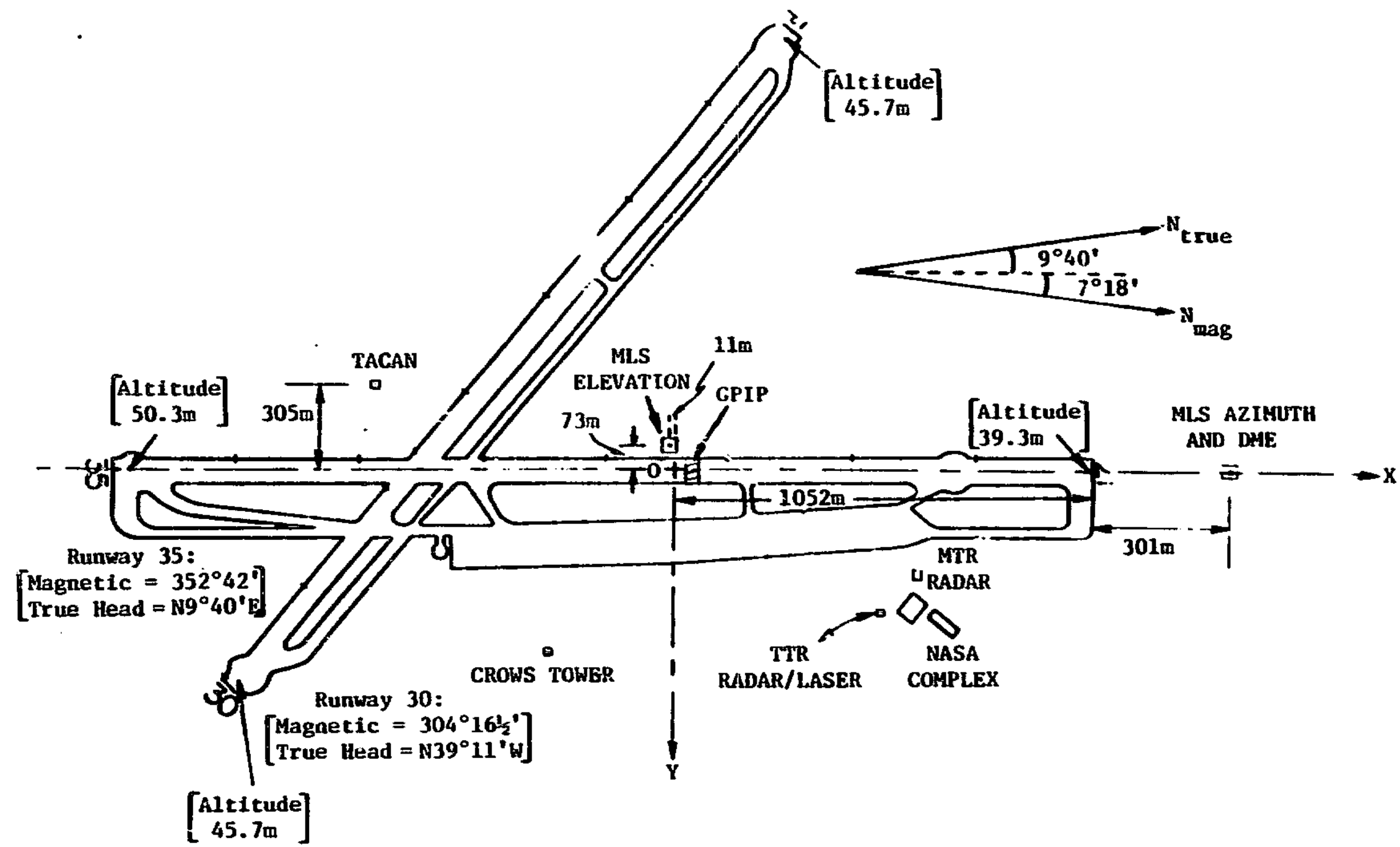


Figure 1. Plan View of Crows Landing Field

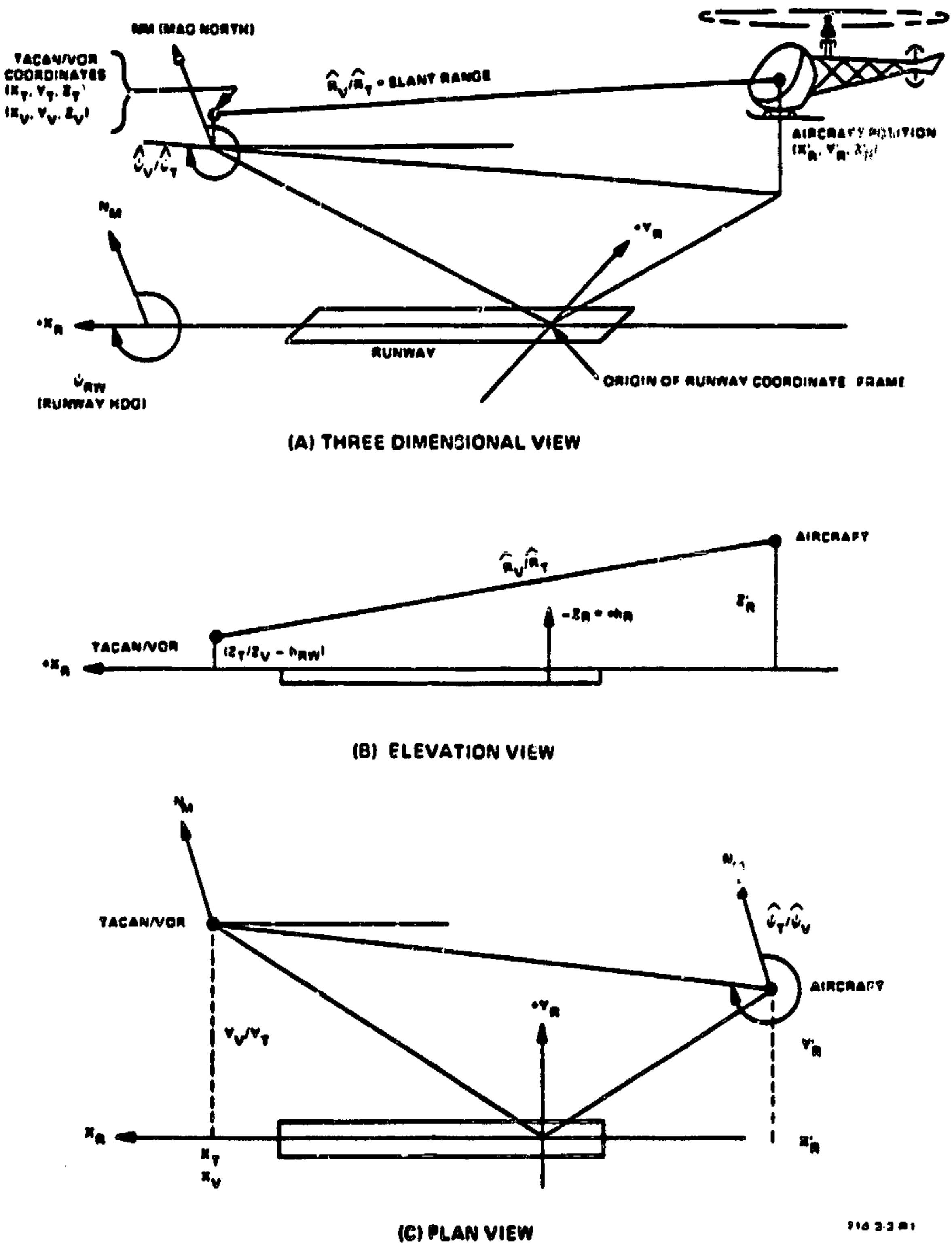
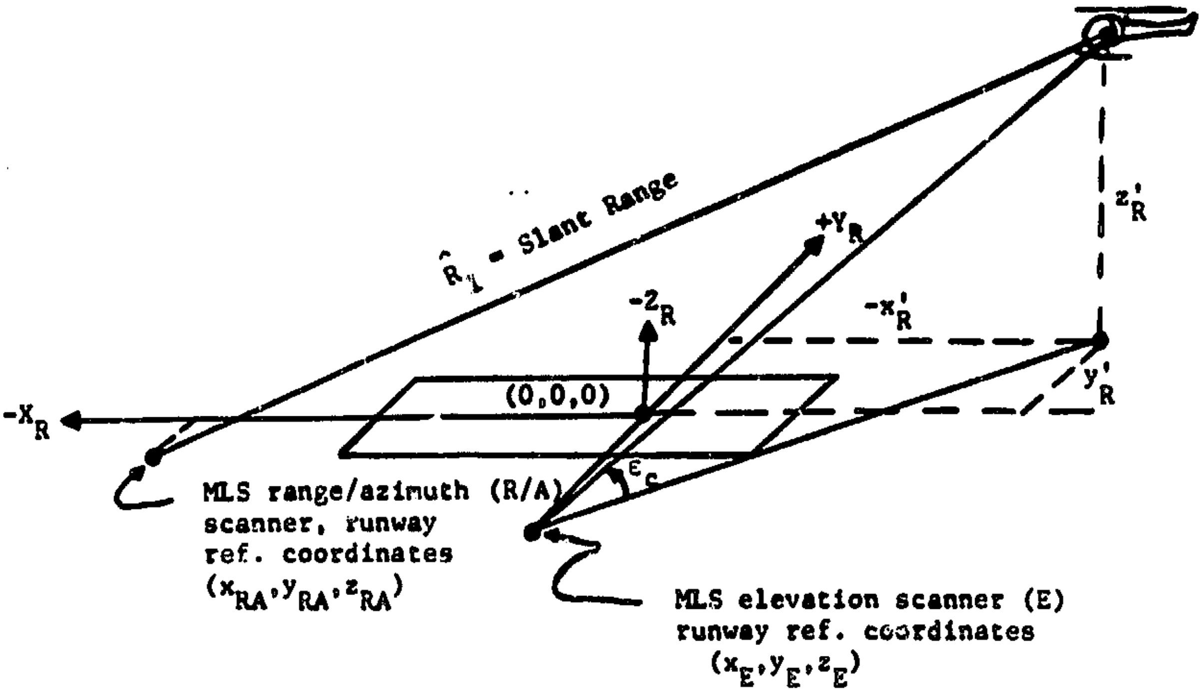
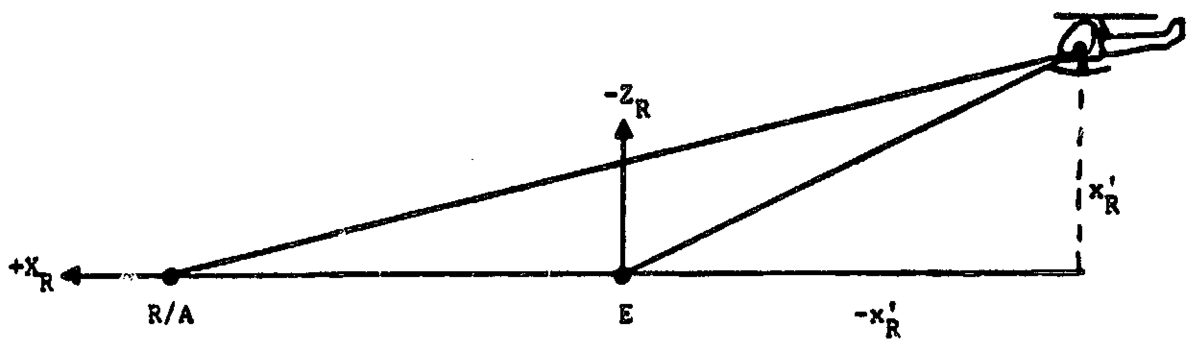


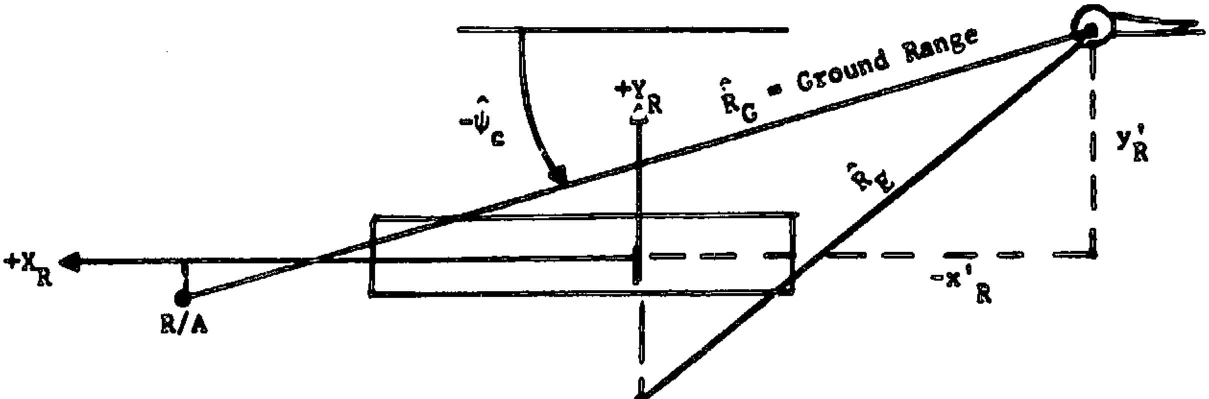
Figure 2. Geometry of TACAN and VOR/DME Navigation



(A) Three-dimensional view



(B) Elevation view



(C) Plan view

Figure 3. Geometry of MLS Navigation

3. UH-1H V/STOLAND AVIONICS SYSTEM DESCRIPTION

The UH-1H V/STOLAND avionics system provides the navigation, guidance, control and displays necessary for aircraft operation under instrument meterological conditions (IMC). The summary of the avionics system given here is extracted from Ref. 1, which provides a comprehensive description of the overall system. The avionics system is flexible, allowing evaluation of the aircraft's performance in various configurations of automatic control, display and navigation. The system is self-monitoring, with provisions for automatic disengagement when failures are detected by the system monitors.

The V/STOLAND system provides the capability to fly conventional modes such as airspeed select and hold, altitude select and hold, flight path angle select and hold, heading select and hold, and TACAN or VOR radial guidance modes. The Waypoint (WPT) guidance mode also provides radial guidance to an arbitrary waypoint selected by the pilot. Conventional approaches are possible using selectable MLS glideslopes. With MLS navigation data, the system may be used to fly complex curved, descending instrument approaches using guidance provided by a 3 - cue (longitudinal, lateral and vertical) flight director. The pilot uses the inclinometer and the pedals to control the yaw axis. In the basic navigation system, the TACAN, VOR/DME or MLS navigation sources may be selected manually or automatically by priority logic which selects the most accurate and valid navaid.

V/STOLAND may be operated in three basic control configurations, with or without the Flight Director:

1. Manual
2. CSS (Control-Stick Steering)
3. AUTO (Autopilot)

In the manual configuration, the pilot controls the helicopter manually by the cyclic stick, the collective lever and the pedals. No servos are engaged. If CSS is engaged, the Research Stick (left side) operates in a fly-by-wire mode, providing control of the helicopter through the 1819B computers and the servos. If AUTO is engaged, the guidance and control of the system is fully automatic. During the NASA/FAA MLS Flight-Tests, the manual mode alone was used.

The avionics system contains two 1819B Digital Computers; the Basic Computer and the Research Computer. The Basic Computer contains all the needed software to perform guidance, control, navigation, monitoring of sensors, displays, and keyboard entries.

The flexibility of the V/STOLAND system is significantly increased by providing for research modes which function through the Research Computer. Navigation, guidance, control and display modes may be programmed by the researcher in the Research Computer. The research modes can be exercised in any of the basic control configurations of the system.

A block diagram of the V/STOLAND system is shown in Figure 4. The 1819B is a general-purpose digital computer with 16K memory of 18-bit words and capable of real-time operations in an airborne environment. The I/O is fully buffered and parallel and uses a party-line transmission system. The data adapter provides the required interface between the basic computer and research computer. It performs all the analog-to-digital and digital-to-analog conversions and all digital-to-digital data transfers.

The displays such as the ADI, HSI, and the MFD (multifunction display) provide the inertial, navigation and guidance information. The ADI includes the flight director command bars in addition to basic attitude data. The HSI provides navigation and flight path data. The MFD displays the horizontal situation of the aircraft and pertinent background data such as geographical features, navaid descriptors and the reference flight path.

The V/STOLAND system also interfaces with the Digital Data Acquisition System (DDAS) which consists of a Multiplexer and Demultiplexer Unit (RMDU), a tape recorder and a telemetry transmitter. The sensor input data as well as the computed data are transmitted to the DDAS for recording on tape. The taped data can be converted on the ground into strip-chart recordings for flight analysis. The present data rate is 80 digital words per 50 ms. To increase the amount of data, five of the 80 digital words were combined at a lower data rate to generate 72 digital words in one second.

The ground station facility has provision for real time strip chart outputs, printer outputs, X-Y plots, and X-H plots. In addition a TV

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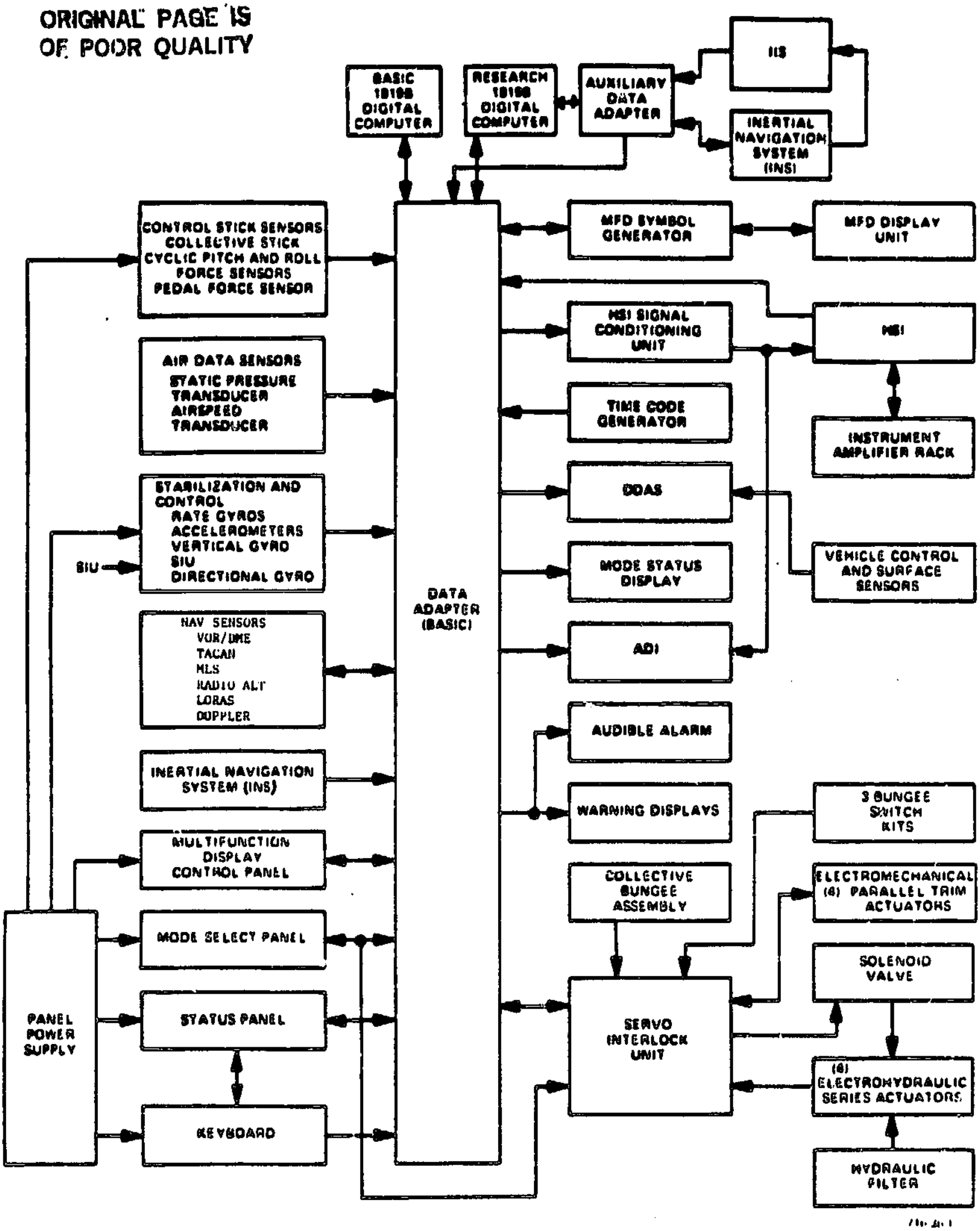

Figure 4. UH-1H V/STOLAND System Block Diagram

monitor display of navigation status modes and selected flight variables is also presented. With this setup, mode selection and pilot performance can be monitored in real time.

The remainder of this section describes the various elements of the UH-1H avionics system that are relevant to the operations used in the NASA/FAA MLS Flight Test Program.

3.1 Cockpit Instrumentation

Figure 5 shows a picture of the instrument panel as viewed by the research pilot. Standard instruments are used as identified in Figure 5. In addition the instrumentation includes the following five nonstandard display/control panels for monitoring and operating the UH-1H avionics system:

1. Multi-Function Display (MFD) Control Panel
2. Mode Status Display
3. Status Panel
4. Mode Select Panel
5. Keyboard

A functional description of each of these instruments is given in the following paragraphs.

3.1.1. MFD Control Panel

The MFD Control Panel has 13 push buttons and a slew switch. A front of the panel is shown in Figure 6. A description of the function performed by each button is provided in Table 1.

3.1.2. Mode Status Display (MSD)

The Mode Status Display consists of a 6-character, 16-segment alphanumeric display. The messages that are displayed on the mode status display are either warning messages, system mode status messages or research-mode related messages. Each message has a priority assigned and is displayed

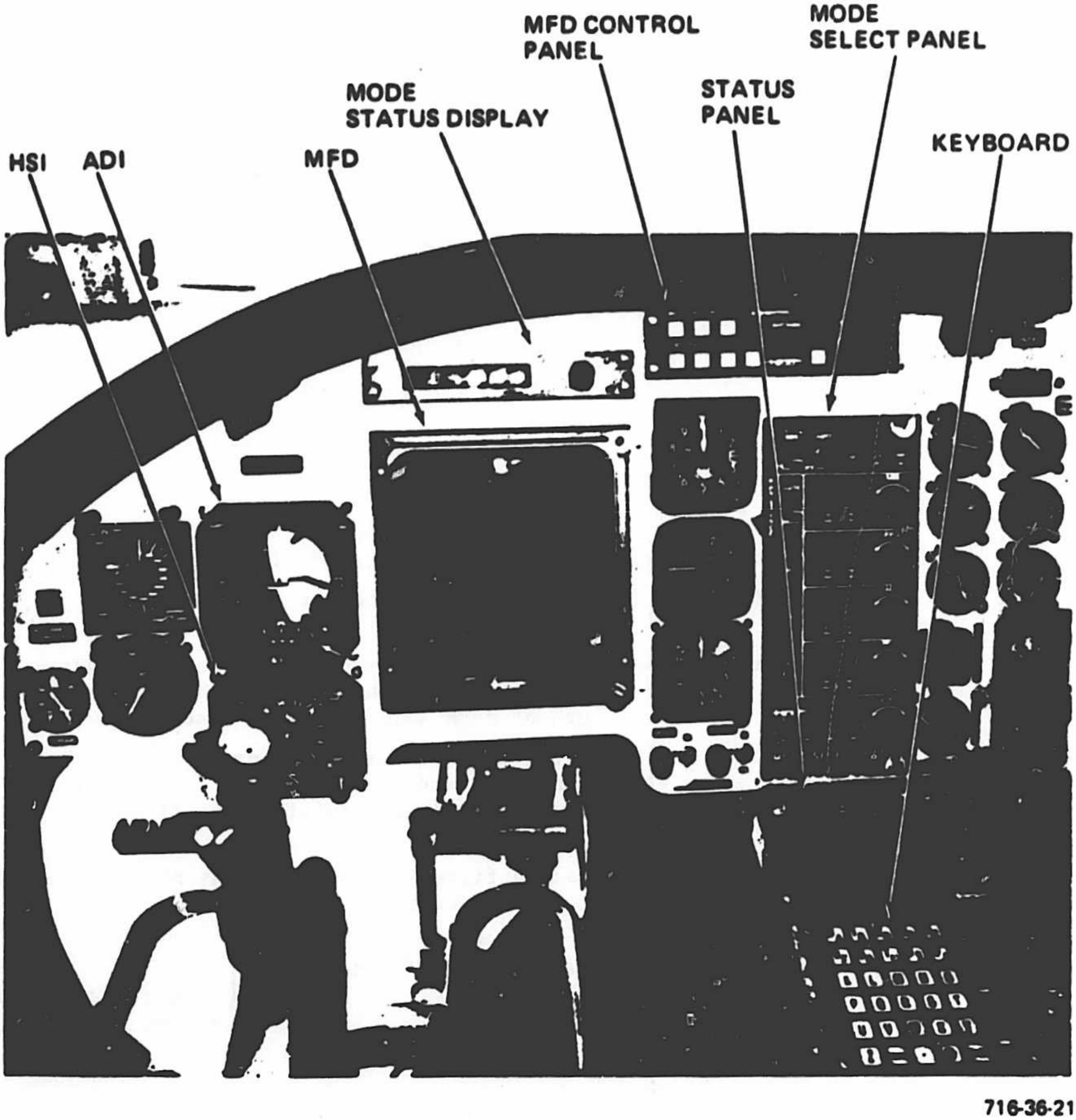

Figure 5. Research Pilot's Instrumentation

Table 1: Status Lights on MFD Control Panel

Button	Status Light	System Status
MAP SLEW	-	Moves the MFD map up, down, left or right, at a rate of 4 inches per second, when held in one of the four positions
SMALL SCALE	Green	1 nm/in on the MFD
	Off	5 nm/in on the MFD
HEADING UP	Green	A/C heading up display on MFD
	Off	Runway heading up display on MFD
MFD	Green	MFD on
	Off	MFD off
RESEARCH	Green	Research computer mode is on
	Off	Basic computer mode is on
PIC	Green	Indicates "PIC" mode is active. Automatically arms land mode when MLS becomes valid. The ground data acquisition is also started.
	Off	Indicates "PIC" mode is inactive. Deselects land mode and go around mode (if active). The ground data acquisition is stopped.
R3	Green	Kalman filter on but presently not connected to flight control.
R6	Amber	Barometric Altitude } Used for indicating Kalman filter source
	Green	MLS elevation
	Yellow	Radio altimeter
R7	Amber	Tacan bearing } Used for indicating Kalman filter source
	Green	Tacan range
	Yellow	Tacan bearing and range

Table 1: (Continued)

Button	Status Light	System Status
R8	Amber	MLS azimuth } Used for indicating Kalman filter source
	Green	MLS range } Used for indicating Kalman filter source
	Yellow	MLS azimuth and range } Used for indicating Kalman filter source
CIP	Green	Indicates roll F/D commands generated on reference line and not yet on runway center line.
	Off	Indicates either no guidance or roll F/D command generated on centerline approach.
TL	Green	Indicates roll F/D guidance on curved segment.
	Off	Indicates roll F/D guidance on straight segment.
CLAZ	Green	Indicates MLS azimuth and MLS DME are valid and roll F/D generated for centerline approach.
	Amber	Indicates MLS azimuth and MLS DME are valid.
	Off	Indicates either no MLS azimuth and/or MLS DME.
CLEL	Green	Indicates MLS elevation is valid and collective flight director guidance generated for glide-slope tracking.
	Amber	Indicates MLS elevation is valid and used in vertical complementary filter.
	Off	Indicates MLS elevation is invalid.

automatically when the conditions for display are satisfied. The front view of the MSD is shown in Figure 7. The mode status messages are listed in Table 2 in the order of priority.

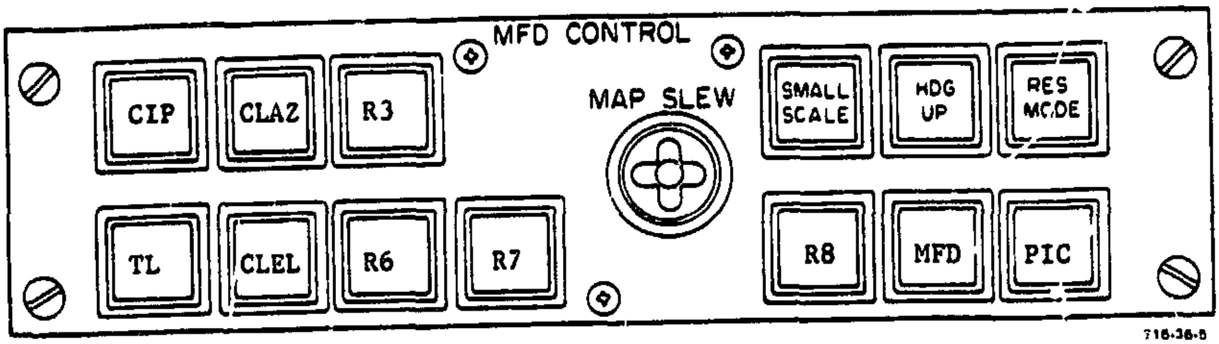

Figure 6. Multifunction Display (MFD) Control Panel

3.1.3 Status Panel

The status panel contains 8 push buttons and a twelve-character alphanumeric display as shown in Figure 8. The push button functions and the alphanumeric messages are described in Table 3.

Table 2: MSD Messages

Message	Mode Status
TDOWN	Indicates the helicopter has touched down on ground.
LNDARM	Indicates that MLS navigation is on and the land mode is armed.
GSARM	Indicates that MLS navigation is on, lateral reference line is captured, and glideslope is armed.
LAND	Indicates that MLS navigation is on, and tracking both the lateral reference line and vertical reference line.
STNDBY	Indicates V/STOLAND system is in the standby mode.
MANUAL	Indicates the V/STOLAND system is on and no flight director or autopilot or control stick steering is selected.

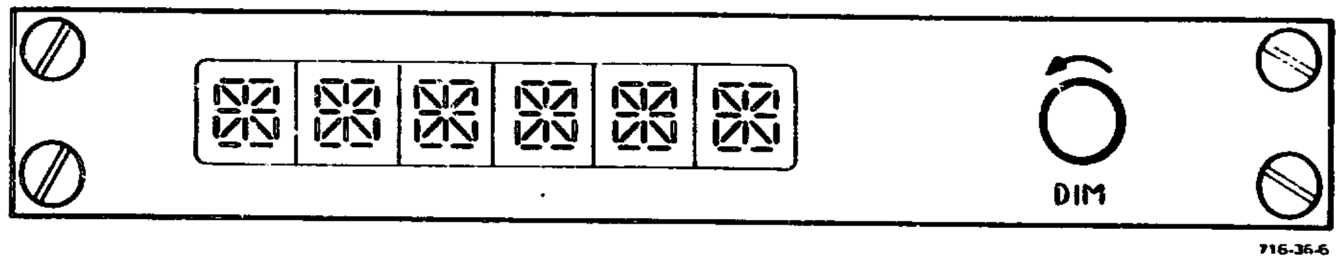

Figure 7. Mode Status Display

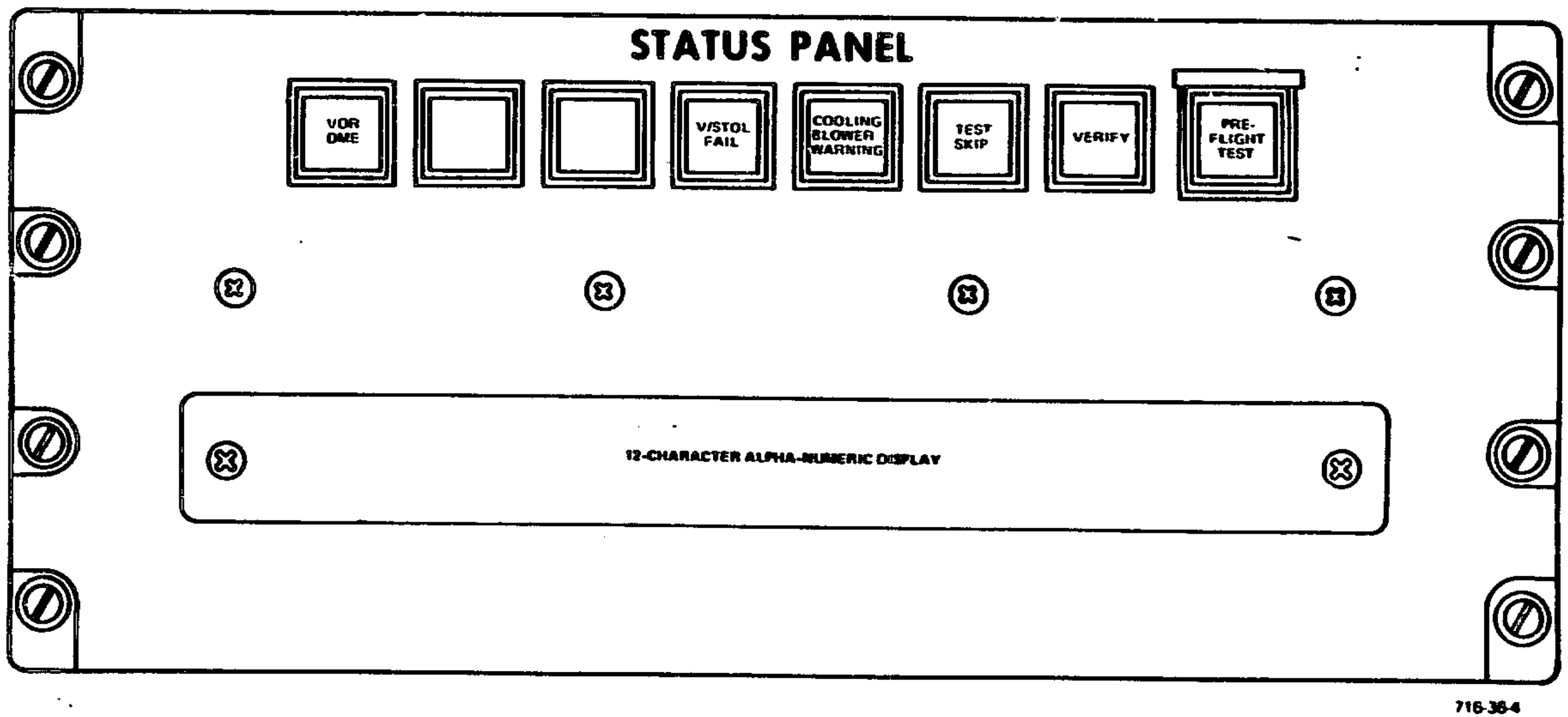

Figure 8. Status Panel, Front View

Table 3: Status Panel Button Functions and Display Messages

Status Panel Button	Description
PREFLIGHT TEST	Used on the ground to activate the simulation mode. The avionics system software can be exercised to check out all the desired modes. Since this only checks out the software, the attitude display on the ADI and the heading display on the HSI are inoperative. The only external requirements are having hydraulic power and electrical power.
VERIFY	Not operative
TEST SKIP	Not operative
VSTOL FAIL	Lights amber when a failure is detected. Pressing the button will cause the failure message to be displayed on the status panel.
COOLING BLOWER AMBER	Flickers amber or off indicates cooling blower is normal.
VOR DME	Selects VOR DME when the button is pressed.
Alpha Numeric Display	**Failure Message**
LARGE LATERR	Indicates that the helicopter is off track laterally by more than 4500 ft. The system disconnects along with failure message.
MLS FAIL	Indicates that MLS has failed while in land mode. The system disconnects along with failure message.
BAS/RES IO	Indicates failure in checkword from basic to research computer. The system disconnects along with failure message.
RES/BAS IO	Indicates failure in checkword from research to basic computer. The system disconnects along with failure message.
RES COMP	Indicates failure in research computer. The system disconnects along with failure message.

3.1.4. Mode Select Panel (MSP)

The Mode Select Panel (MSP), illustrated in Figure 9, has 18 push buttons and three toggle switches that provide the means for (1) servo mode engagement, (2) flight director engagement, (3) selection of navigation mode, and (4) selection of the guidance mode. The MSP also displays five reference variables, with slew switches for selecting reference values for associated guidance modes.

The V/STOLAND system comes up in the STANDBY mode when it is initially powered, which is indicated by amber illumination of the STBY segment of the STBY/ON push button. In the STANDBY mode, all other push buttons and toggle switches are disabled except for the ones related to navigation. The valid navaids are indicated by amber illumination of the corresponding push buttons. If the NAV SOURCE SWITCH is in the AUTO position, the best valid navaid is automatically selected for navigation.

The V/STOLAND system is placed in the ON mode by pressing STBY/ON. The ON segment of the STBY/ON push button then lights green.

3.1.4.1. Flight Director Engagement

The flight director mode is engaged by pressing FLT DIR; when engaged, the button lights green. Selecting any of the guidance modes with FLT DIR engaged causes the guidance information to be displayed by the ADI flight director command bars. When failures occur involving pitch and roll attitude and rate sensors, the FLT DIR mode is disengaged and the flight director command bars are biased out of view. In addition, FD flag in the ADI is dropped into view. The flight director mode can be disengaged at any time by pressing FLT DIR.

3.1.4.2. Guidance Mode Selection

The V/STOLAND guidance modes are selected by the associated push buttons on the MSP. The altitude, airspeed, flight path angle and heading modes have 2 submodes: select and hold. The select mode enables the system to guide the aircraft to a new reference value for each of the 4 parameters. The hold mode becomes engaged when the aircraft acquires the new reference. The hold and select modes are annuciated green when engaged.

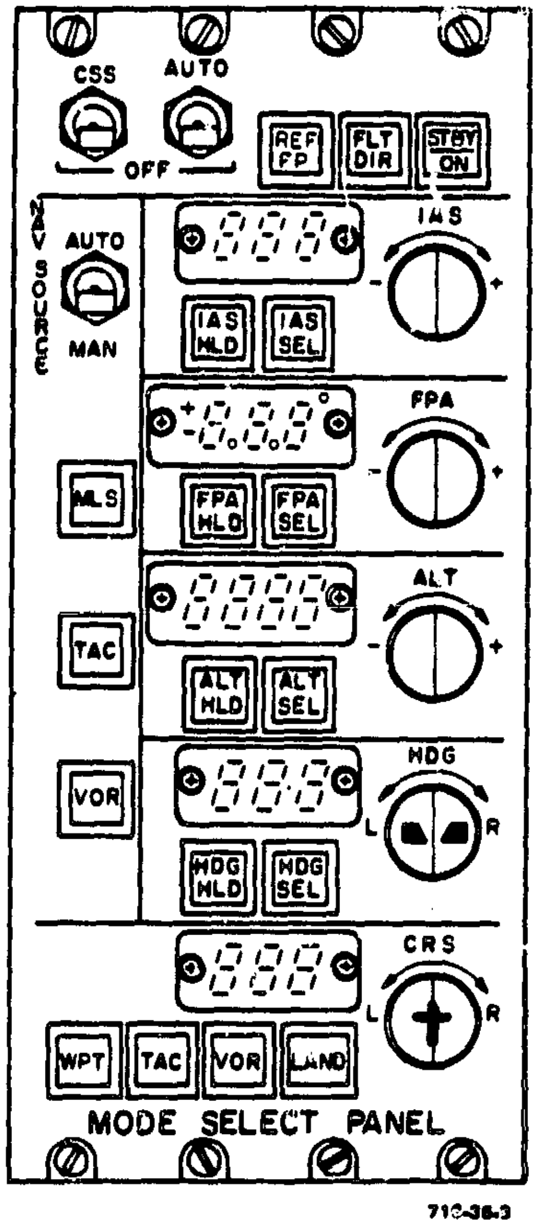

Figure 9. Mode Select Panel, Front View

The WPT/TACAN/VOR/LAND/REF FP modes have 2 submodes: armed and engaged. The desired mode is armed by pressing the associated button and is indicated by amber illumination When the capture conditions are satisfied, the armed mode transitions to engagement, which is indicated by the illumination changing to green. The armed or engaged mode can be disengaged by pressing the corresponding button.

3.1.4.3. Navigation Mode Selection

The NAV SOURCE toggle switch allows automatic or manual selection of the navaids for navigational computations. When in the AUTO position, the navaids are selected automatically on a priority basis, depending on validity. MLS has top prioity, followed by TACAN and then VOR. When the NAV SOURCE switch is in the Manual (MAN) position, the navigation source is manually selected by pressing a navigation push button which indicates validity.

The validity of a navaid is annunciated by amber illumination of the corresponding push button. The source that is selected, either automatically or manually, is indicated by green illumination of the corresponding push button.

Manual selection of a navaid is not possible when the NAV SOURCE switch is in the AUTO position.

If the selected navaid becomes invalid, the associated push-button illumination turns off. If in AUTO navigation, the valid navaid next in order of priority is automatically selected. If no navaid is valid, or if in MAN (manual) navigation when the selected navaid becomes invalid, navigation by dead reckoning is initiated for a period of 2 minutes. If a valid navaid is not selected within the 2 minutes, navigation is terminated, and this is indicated by a flashing aircraft symbol.

The position of the NAV SOURCE switch is independent of the AUTO, CSS or Flight Director guidance modes.

3.1.5 Keyboard

The keyboard provides, in conjunction with the status panel alphanumeric display, a general purpose interactive interface between the pilot and

V/STOLAND. The pilot may use the keyboard to insert and retrieve data which is in turn displayed on the status panel alphanumeric display shown in Figure 8. A front view of the keyboard is shown in Figure 10.

The keyboard contains 30 push buttons, arranged in a 5 x 6 matrix, plus NUMBER/LETTER, CLEAR and ENTER push buttons. The matrix of push buttons includes keys for the alphabet, numerics and four special characters - "*", "-", "←" and "SPACE".

The NUMBER/LETTER button only annunciates the type of data to be entered, i.e., letter or number. The ENTER button is used to enter into the computer the numeric data displayed on the Status Panel.

The CLEAR button is used to clear the alphanumeric display. The alphanumeric keys are used for inserting 3-letter mnemonics and numeric data. When the 3 letters of the mnemonic are entered, the software looks for a match of the mnemonic entered with those stored in the computer. If a match occurs, an equals sign (=) followed by the current value of the data referenced by the mnemonic is displayed on the status panel. Also the keyboard reverts to the NUMBER mode, indicated by the "NUMBER" annunciation on the NUMBER/LETTER button. The pilot can then change the value of the displayed mnemonic by inserting new data. When the first digit is entered, the old value is cleared, the equal sign is replaced by an asterisk (*) and the digit entered is displayed. The digit may be followed by other digits that constitute the desired data. After the new data has been entered, pressing ENTER enters the data into the computer and replaces the asterisk with an equals sign.

If a keyed-in mnemonic does not match one of the valid mnemonics, the message "ILLEG ENTRY" is displayed. Also if the numerical data entered falls beyond the assigned limits for that data, either the message "ILLEG ENTRY" is displayed on the status panel or the limit value of the data is entered into the computer and displayed on the status panel. When "ILLEG ENTRY" is displayed, pressing the back space "←" button causes the previous mnemonic and its last shown value to be displayed.

To assist the pilot in the keyboard operation, the "space " button is used for displaying the next entry in the keyboard table, and the

"NUMBER/LETTER" button is used for displaying the previous entry in the keyboard table.

The button marked * is used for inserting decimal points. The "-" button is used to enter negative numbers. The keyboard may be used for the following functions:

- Selection of MSP reference parameters
- Selection of essential navigation and guidance parameters
- Changing the aircraft flight control gains
- Selection of research modes and data
- Selection of MFD display content.

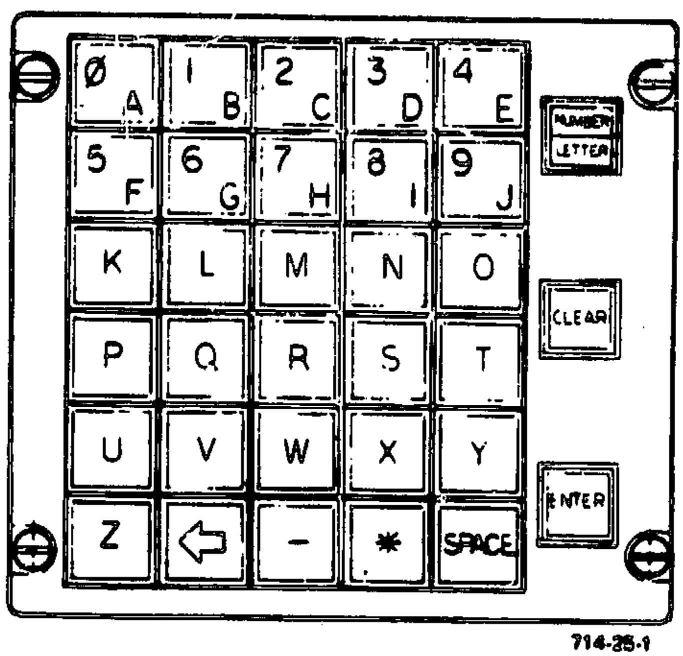

Figure 10. Keyboard Arrangement

3.2 On-Board Navigation Equipment

The UH-1H avionics system is currently implemented with the following navigation equipment.

1. Microwave landing system (MLS) receiver providing range, azimuth and elevation measurements.
2. TACAN receiver providing range and bearing measurements.
3. VOR/DME receiver providing range and bearing measurements.
4. Barometric altitude.
5. Indicated airspeed.
6. Radio altimeter.
7. Vertical gyro for aircraft pitch and roll measurements.
8. Directional gyro for aircraft heading measurement.
9. Triad of body mounted accelerometers.
10. A platform type inertial navigation system (LTN 51).
11. LORAS providing airspeed.
12. DOPPLER providing ground speed.

All measurements are available in the dual Sperry 1819B computers of the avionics system.

The navigation systems provide position and velocity in the runway coordinate system shown in Figure 1. TACAN data and barometric altitude provide position information in the terminal area prior to acquiring MLS. MLS range and azimuth are used through touchdown for the x-y position information. MLS elevation data are used for vertical information within the coverage area and $x > -10856$m (-35616 ft).

The on-board navigation systems use filtering techniques implemented in the airborne computer software to combine the raw position data with data from inertial reference information from either (a) the body mounted accelerometers and the vertical and directional gyros (strapped-down IMU) or (b) inertial navigation system (INS). The navigation system implemented for the NASA/FAA MLS flight tests uses a complementary filter with body mounted accelerometer data.

4. REFERENCE FLIGHT PATH GEOMETRIES

Three reference flight path geometries were flown in the NASA/FAA flight test program. They are the U-turn, S-turn and Straight-In flight paths and approaches with horizontal profiles as shown in Figure 11-13, respectively. Each of these paths are composed of concatenated straight and circular segments. The vertical flight profile for each of these three paths consists of a constant altitude segment followed by capture and descent on a 3°, 6°, 9° or 12° glideslope angle reference trajectory.

A total of 12 waypoints - WP(1) thru WP(12), are allowed in each of the reference flight paths. However, in each of the paths, WP(12) is chosen as the glide path intercept point (GPIP) on the x axis of the runway based coordinate system, and WP(11) represents the point of initiation for the final straight line segment. The final segment length from WP(11) to WP(12) was chosen to provide the pilot with a reasonable time for establishing glideslope and localizer tracking. The runway referenced (x,y) coordinates of these 12 waypoints for each of the 3 flight paths (3 glide slopes for each of the three flight paths resulting in 9 distinct approach profiles) are given in Tables 4-6, respectively.

The lengths of the individual straight line segments and the radius of the circular segments chosen to form the reference flight paths reflect the subjective preference of pilots based upon UH-1H helicopter handling quantities and other operational considerations.

In the S-turn approach, a straight line segment (762m for 3° and 6° approaches and 1524m for 9° approach) connecting waypoints 9-10 was inserted between two circular segments in order to prevent possible pilot disorientation or vertigo from occurring while switching from a bank right circular turn to a bank left situation. The straight segment is made longer for the 9° approach in order to assure that the descent phase follows the curved segment. This is because most pilots do not like to turn and descend at the same time.

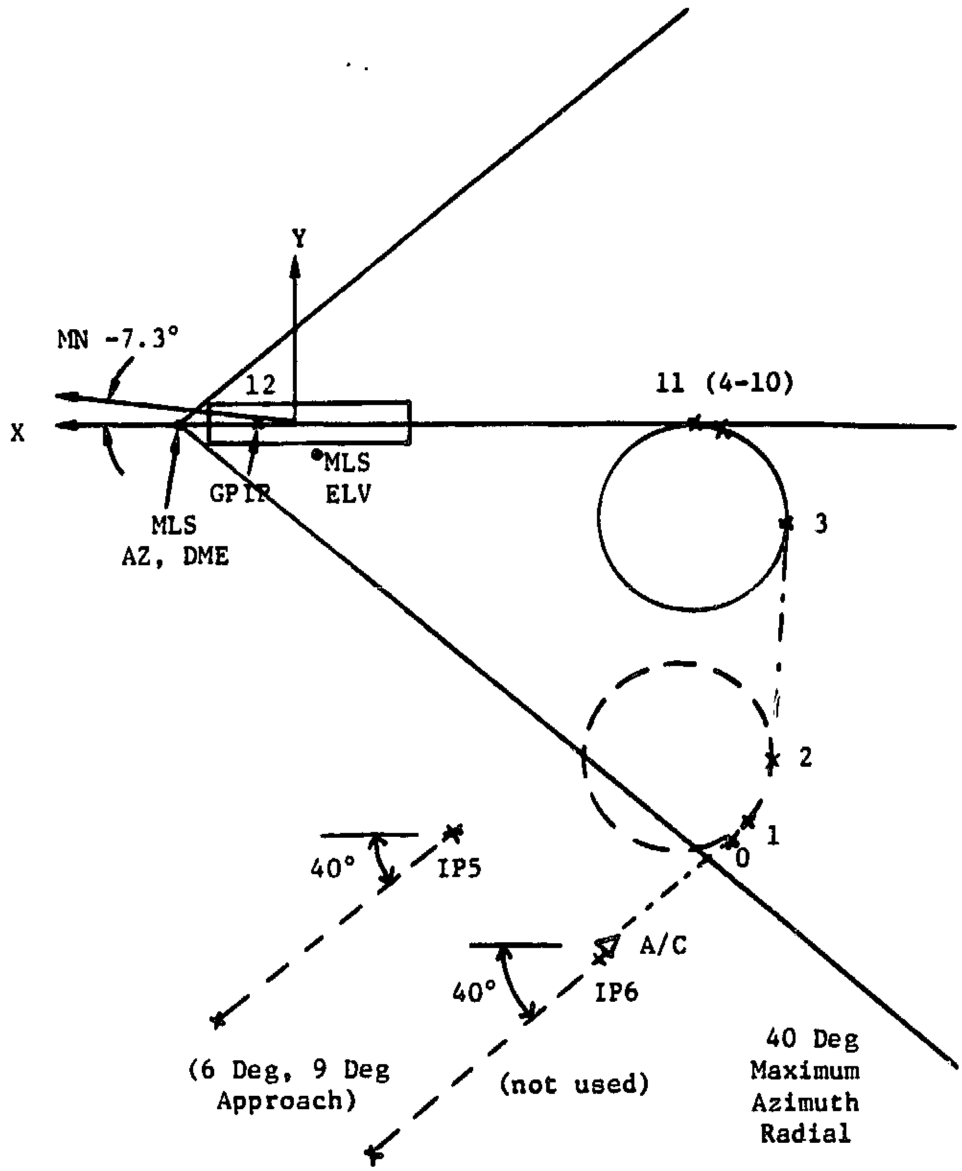

Figure 11. U-Turn Reference Flight Path

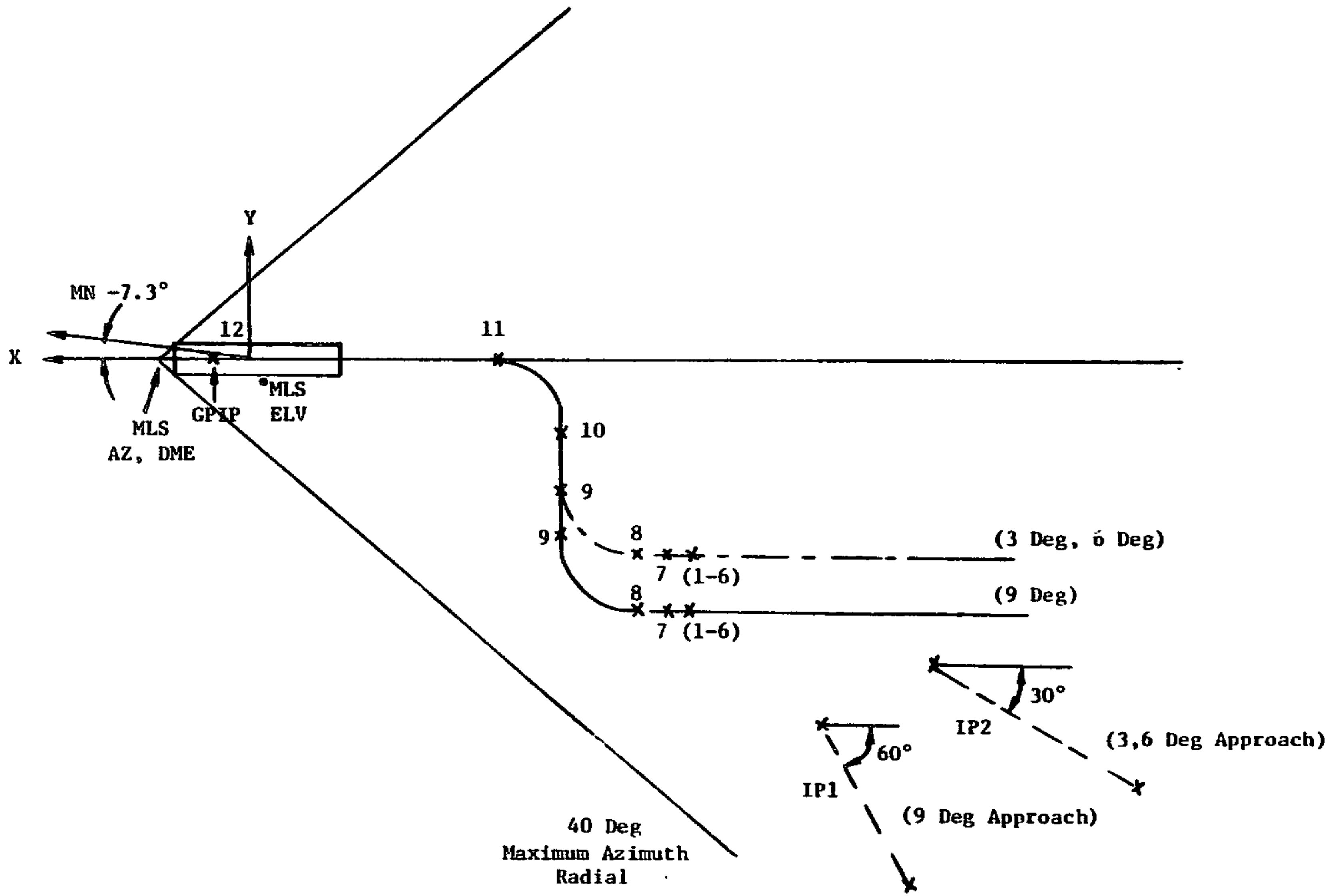

Figure 12. S-Turn Reference Flight Path

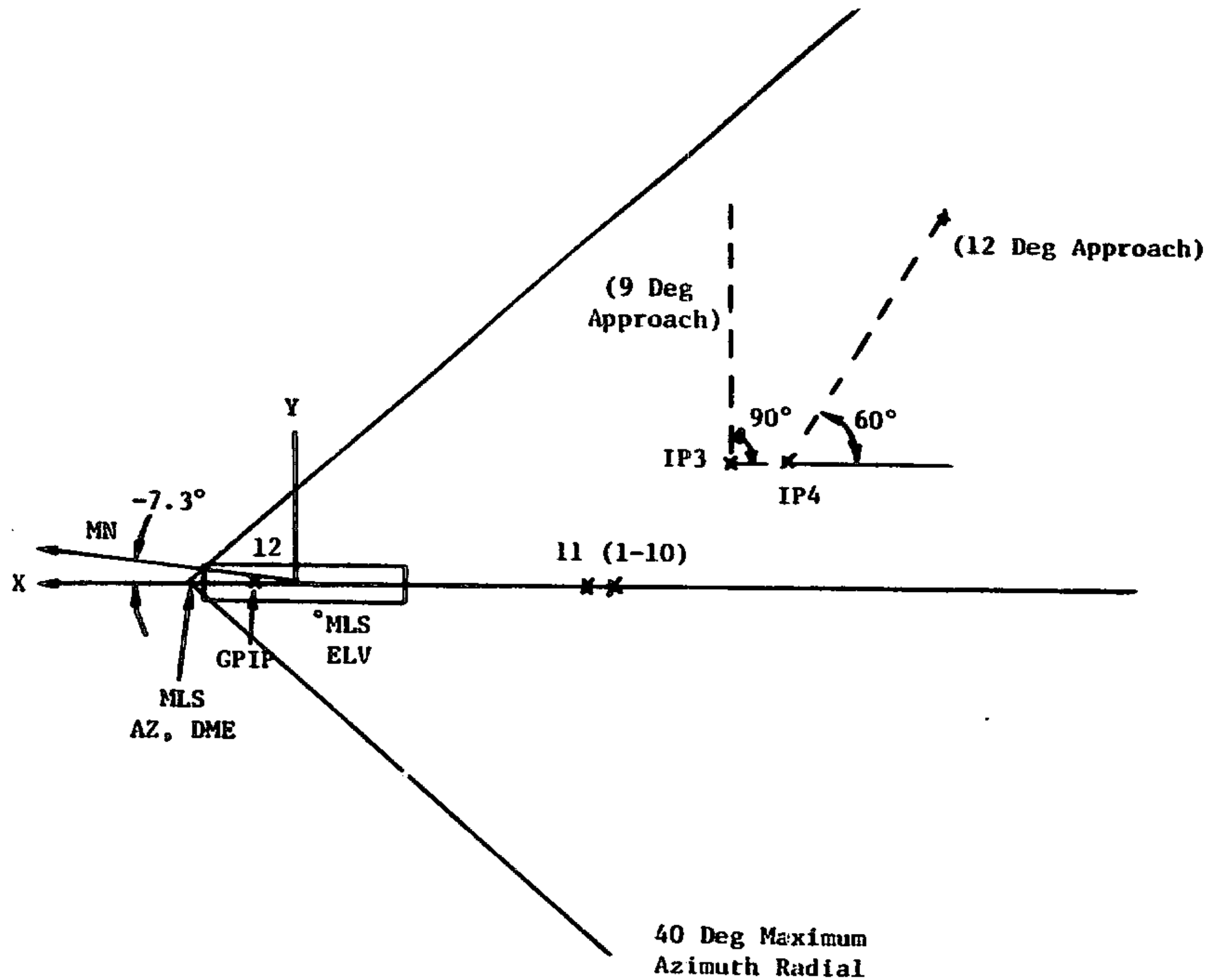

Figure 13. Straight-In Reference Flight Path

Table 4: Waypoint Data for U-Turn Approach: Coordinates in meters (ft)

Waypoint Coordinates	Flight Path Number			Path Distance to GPIP
	1: $\gamma_{ref} = 3°$	2: $\gamma_{ref} = 6°$	3: $\gamma_{ref} = 9°$	
x_{IP5}	-1,828 (-6,000)	-1,828 (-6,000)	-1,828 (-6,000)	Not Applicable
y_{IP5}	-5,029 (-16,500)	-5,029 (-16,500)	-5,029 (-16,500)	
x(1)	GENERATED BY LATERAL CAPTURE LAW			
y(1)	↓	↓	↓	↓
x(2)				
y(2)				
x(3)				
y(3)				
x(4)	-5,055 (-16,584)	-5,078 (-16,660)	-5,085 (-16,684)	5,090 (16,700)
y(4)	0	0	0	

Table 4: (Continued)

Waypoint Coordinates	Flight Path Number			Path Distance to GPIP
	1: $\gamma_{ref} = 3°$	2: $\gamma_{ref} = 6°$	3: $\gamma_{ref} = 9°$	
x(5)	-5024 (-16,484)	-5047 (-16,560)	-5035 (-16,584)	5060 (16,600)
y(5)	0	0	0	
x(6)	-4994 (16,384)	-5017 (-16,460)	-5024 (-16,484)	5029 (16,500)
y(6)	0	0	0	
x(7)	-4963 (-16,284)	-4987 (-16,360)	-4994 (-16,384	4999 (16,400)
y(7)	0	0	0	
x(8)	-4933 (-16,184)	-4956 (16,260)	-4963 (-16,284)	4968 (16,300)
y(8)	0	0	0	
x(9)	-4902 (-16,084)	-4926 (-16,160)	-4933 (-16,184)	4938 (16,200)
y(9)	0	0	0	
x(10)	-4872 (-15,984)	-4895 (-16,060)	-4902 (-16,084)	4907 (16,100)
y(10)	0	0	0	
x(11)	-4841 (-15,884)	-4865 (-15,960)	-4872 (-15,984)	4877 (16,000)
y(11)	0	0	0	
x(12)	35 (116)	12 (40)	5 (16)	0
y(12)	0	0	0	

Table 5: Waypoint Data for S-Turn Approach: Coordinates in meters (ft)

Waypoint Coordinates	Flight Path Number		Path Distance to GPIP
	4: $\gamma_{ref} = 3°$	5: $\gamma_{ref} = 6°$	
x_{IP2}	-10,461 (-34,324)	-10,461 (-34,324)	Not Applicable
y_{IP2}	-4,630 (-15,192)	-4,630 (-15,192)	
x(1)	-6,222 (-20,416)	-6,246 (-20,492)	8,383 (27,504)
y(1)	-3,149 (-10,332)	-3,149 (-10,332)	
x(2)	-6,192 (-20,316)	-6,215 (-20,392)	8,352 (27,404)
y(2)	-3,149 (-10,332)	-3,149 (-10,332)	
x(3)	-6,161 (-20,216)	-6,185 (-20,292)	8,322 (27,304)
y(3)	-3,149 (-10,332)	-3,149 (-10,332)	
x(4)	-6,131 (-20,116)	-6,185 (-20,192)	8,291 (27,204)
y(4)	-3,149 (-10,332)	-3,149 (-10,332)	

Table 5: (Continued)

Waypoint Coordinates	Flight Path Number		Path Distance to GPIP
	4: $\gamma_{ref} = 3°$	5: $\gamma_{ref} = 6°$	
x(5)	-6101 (-20,016)	-6124 (-20,092)	8261 (27,104)
y(5)	-3149 (-10,332)	-3149 (-10,332)	
x(6)	-6070 (-19,916)	-6094 (-19,992)	8231 (27,004)
y(6)	-3149 (-10,332)	-3149 (-10,332)	
x(7)	-6040 (-19,816)	-6063 (-19,892)	8200 (26,904)
y(7)	-3149 (-10,332)	-3149 (-10,332)	
x(8)	-6009 (-19,716)	-6033 (-19,792)	8170 (26,804)
y(8)	-3149 (-10,332)	-3149 (-10,332)	
x(9)	-4816 (-15,800)	-4839 (-15,876)	6295 (20,652)
y(9)	-1956 (- 6,416)	-1956 (- 6,416)	
x(10)	-4816 (-15,800)	-4839 (-15,876)	5533 (18,152)
y(10)	-1194 (- 3,916)	-1194 (- 3,916)	
x(11)	-3622 (-11,884)	-3645 (-11,960)	3658 (12,000)
y(11)	0	0	
x(12)	35 (116)	12 (40)	0
y(12)	0	0	

Table 5: (Continued)

Waypoint Coordinates	Flight Path Number 6: $\gamma_{ref} = 9°$	Path Distance to GPIP
x_{IP1} y_{IP1}	-8,751 (-28,712) -5,392 (-17,692)	Not Applicable
x(1) y(1)	-6,253 (-20,516) -3,911 (-12,832)	9,144 (30,004)
x(2) y(2)	-6,222 (-20,416) -3,911 (-12,832)	9,114 (29,904)
x(3) y(3)	-6,192 (-20,316) -3,911 (-12,832)	9,083 (29,804)
x(4) y(4)	-6,161 (-20,216) -3,911 (-12,832)	9,053 (29,704)

Table 5: (Continued)

Waypoint Coordinates	Flight Path Number 6: $\gamma_{ref} = 9°$	Path Distance to GPIP
x(5) y(5)	-6131 (-20,116) -3911 (-12,832)	9042 (29,604)
x(6) y(6)	-6101 (-20,016) -3911 (-12,832)	8993 (29,504)
x(7) y(7)	-6070 (-19,916) -3911 (-12,832)	8962 (29,404)
x(8) y(8)	-6040 (-19,816) -3911 (-12,832)	8932 (29,304)
x(9) y(9)	-4846 (-15,900) -2718 (- 8,916)	7058 (23,152)
x(10) y(10)	-4846 (-15,900) -1194 (- 3,916)	5533 (18,152)
x(11) y(11)	-3653 (-11,984) 0	3658 (12,000)
x(12) y(12)	5 (16) 0	0

Tabl 6: Waypoint Data for Straight-In Approach: Coordinates in meters (ft)

Waypoint Coordinates	Flight Path Number: 7: $\gamma_{ref} = 6°$	8: $\gamma_{ref} = 9°$	9: $\gamma_{ref} = 12°$	Path Distance to GPIP
$x_{IP_{3,4}}$	-5,555 (-18,228)	-5,555 (-18,228)	-6,411 (-21,036)	Not Applicable
$y_{IP_{3,4}}$	1,481 (4,860)	1,481 (4,860)	1,481 (4,860)	
x(1)	-3,950 (-12,960)	-3,958 (-12,984)	-3,963 (-13,000)	3,963 (13,000)
y(1)	0	0	0	
x(2)	-3,920 (-12,860)	-3,927 (-12,884)	-3,932 (-12,900)	3,932 (12,900)
y(2)	0	0	0	
x(3)	-3,889 (-12,760)	-3,897 (-12,784)	-3,902 (-12,800)	3,902 (12,800)
y(3)	0	0	0	
x(4)	-3,859 (-12,660)	-3,866 (-12,684)	-3,871 (-12,700)	3,871 (12,700)
y(4)	0	0	0	

Table 6: (Continued)

Waypoint Coordinates	Flight Path Number			Path Distance to GPIP
	7: $\gamma_{ref} = 6°$	8: $\gamma_{ref} = 9°$	9: $\gamma_{ref} = 12°$	
x(5)	-3828 (-12,560)	-3835 (-12,584)	(-12,600)	3840 (12,600)
y(5)	0	0	0	
x(6)	-3798 (-12,460)	-3805 (-12,484)	(-12,500)	3810 (12,500)
y(6)	0	0	0	
x(7)	-3767 (-12,360)	-3775 (-12,384)	(-12,400)	3780 (12,400)
y(7)	0	0	0	
x(8)	-3737 (-12,260)	-3744 (-12,284)	(-12,300)	3749 (12,300)
y(8)	0	0	0	
x(9)	-3706 (-12,160)	-3714 (-12,184)	(-12,200)	3719 (12,200)
y(9)	0	0	0	
x(10)	-3676 (-12,060)	-3683 (-12,084)	(-12,100)	3688 (12,100)
y(10)	0	0	0	
x(11)	-3645 (-11,960)	-3653 (-11,984)	(-12,000)	3658 (12,000)
y(11)	0	0	0	
x(12)	12 (40)	5 (16)	0	0
y(12)	0	0	0	

To simulate ATC vectors, two IP (intermediate path) segments are created for each of the reference flight paths in order to provide data on 30°, 60° and 90° lateral captures. The IP segments terminate approximately 1500m (1 nmi) from the reference flight path because this is a reasonable distance that ATC can vector traffic to. During the IP segment, flight director commands are generated using heading hold, altitude hold, and airspeed hold guidance. As a result, the helicopter may drift due to winds or small navigation errors.

The U-turn approach of Figure 11 is the only flight path that starts with the IP segment outside of MLS coverage (uses Tacan navigation and heading hold guidance). The reference flight path guidance starts when the complementary filter is on MLS azimuth and DME data (10 sec initialization time). When the U-turn guidance is initiated, a lateral capture path (waypoint 0-10) is created to capture the circle at waypoint 3. The flight path connecting waypoints 0 to 10 is as follows:

Waypoint 0 to 1: Waypoint 0 is defined as the initial position of the helicopter and the straight segment is defined by its present course and ground speed. The length of the segment is defined to be the distance flown over 10 seconds at its current ground speed.

Waypoint 1 to 2: This is a circular segment (radius = 1194m (3916 ft)) for capturing the straight segment tangent to the final circular segment at waypoint 3.

Waypoint 2 to 3: This is a straight tangent segment for connecting the circular segment from waypoint 2 to the circular segment at waypoint 3.

Waypoint 3 to 4: Waypoint 3 is the start of the final turn segment and waypoint 4 is the termination of the circular segment.

Waypoint 4 to 10: These are short 100 feet straight segments. These segments can be modified to generate more complex flight paths.

Two sets of parameters are used in the V/STOLAND system: (1) System parameters shown in Table 7A, and (2) Reference flight path parameters shown in Table 7B. These two parameter sets must be entered into the system computer using the keyboard shown in Figure 10. The parameters and the corresponding mnemonics that must be keyed in are defined in Tables 7A and 7B. Note that the keyboard mnemonic AAA must be set to one to select/modify system parameters in Table 7A, and to two for reference flight path parameters in Table 7B. The values of these parameters in Table 7B selected for the U-turn, S-turn and Straight-in approach profiles are given in Tables 8 thru 10, respectively. Note that each table has 3 columns corresponding to 3°, 6° and 9° glide slope angles for the U and S-turn approaches or 6°, 9° and 12° for the Straight-in approach.

Table 7A: System Parameters (AAA = 1)

Keyboard Mnemonic	Parameter	Definition	Value
AAA	1	Selects keyboard gain table below	1
BBB	CFDSGN	†1 Collective flight director sense	$\neq 0$
CCC	KHHIGH	FD altitude error gain (end value)	.1875 1/s
DDD	KHLOW	FD altitude error gain (start value)	.025 1/s
EEE	KCFD	Collective FD display gain	$.21 \frac{cm}{m/s}$ $(0.025 \frac{in}{ft/s})$: Full Scale = $\pm$ 1.27 cm ($\pm$ .5 in)
FFF	KTHTC1	Pitch proportional gain	$-.82 \frac{deg}{m/s}$ $(-.25 \frac{deg}{ft/s})$
GGG	KTHTFD	Pitch FD display gain	$1 \frac{deg}{deg}$
HHH	KDYI	Lateral error gain	$0.16 \frac{deg}{m}$ $(.05 \frac{deg}{ft})$
III	KPHIFD	Roll FD display gain	$0.04 \frac{cm}{deg}$ $(.015 \frac{in}{deg})$
JJJ	LOGAIN	Roll FD display gain multiplier (start value) (100%)	1.0
KKK	HIGAIN	Roll FD display gain multiplier (end value) (125%)	1.25
LLL	FDKD	†2 Flight director display enable	$\neq 0$
MMM thru XXX	(not used)	-------	------
YYY	NAVDIS	†3 Navigation mode	33000
ZZZ	GUIDIS	†4 Guidance mode	10103

†1	Non Zero Value	Indicates "fly to" collective FD
	Zero Value	Indicates "fly from" collective FD
†2	Non Zero Value	Indicates enable FD
	Zero Value	Bias FD out of view and used for raw data approaches
†3	33000 Value	Means use Tacan or MLS bearing/range in complementary filter.
†4	10103 Value	Means use basic complementary filter with research guidance mode. Use ground speed in roll feed-forward. Use research guidance in research mode.

Table 7B. Definitions of Reference Flight Path Parameters (AAA = 2)

Keyboard Mnemonic	Parameter	Definition
AAA	2	Selects keyboard gain table below
BBB	RFPNO	Selects flight path (1 to 9)
CCC	DTOGO1	F/D gain schedule dist (gain schedule starts) m(ft)
DDD	DTOGO2	F/D gain schedule dist (gain schedule ends) m(ft)
EEE	LOGAIN	F/D gain (%) starting gain
FFF	LNDCR1	Final course (DEG)
GGG	WPRI(11)	Radius† of segment 11 m(ft)
HHH	HLNGTH(6)	Length of segment 11 m(ft)
III	WPRI(10)	Radius of segment 10 m(ft)
JJJ	HLNGTH(5)	Length of segment 10 m(ft)
KKK	WPRI(9)	Radius of segment 9 m(ft)
LLL	HLNGTH(4)	Length of segment 9 m(ft)
MMM	WPRI(8)	Radius of segment 8 m(ft)
NNN	HLNGTH(3)	Length of segment 8 m(ft)
OOO	WPRI(7)	Radius of segment 7 m(ft)
PPP	HLNGTH(2)	Length of segment 7 m(ft)
QQQ	WPRI(6)	Radius of segment 6 m(ft)
RRR	HLNGTH(1)	Length of segment 6 m(ft)
SSS	SCALEF(2)	MFD small scale 1 = .364 $\frac{km}{cm}$ (.5 $\frac{nmi}{in}$), 2 = .73 $\frac{km}{cm}$ (1.0 $\frac{nmi}{in}$)
TTT	HLNGTH	Length of segment 5 m(ft)
UUU	STWYPT	Starting waypoint
VVV	VSGS	Final glideslope (deg)
WWW	HLXRAD	Radius for U turn approach m(ft)
XXX	RHDECIS	Decision height m(ft)
YYY	GAIAS	Go around air speed command knots
ZZZ	STRTIN	Lateral capture mode ††

† Negative value indicates left turn segment.
Positive value indicates right turn segment.

††	1 Value	Straight-in capture
	0 Value	Helix mode capture
	-1 Value	Self generating capture
	-2 Value	Sperry capture

Table 8: U-Turn Flight Path Parameters
(units defined in Table 7B)

Keyboard Mnemonic	Parameter Value					
AAA	2		2		2	
BBB	1		2		2	
CCC	3,658	(12,000)	3,658	(12,000)	3,658	(12,000)
DDD	305	(1,000)	305	(1,000)	305	(1,000)
EEE	100		100		100	
FFF	-7.3		-7.3		-7.3	
GGG	0		0		0	
HHH	4,877	(16,000)	4,877	(16,000)	4,877	(16,000)
III	0		0		0	
JJJ	30	(100)	30	(100)	30	(100)
KKK	0		0		0	
LLL	30	(100)	30	(100)	30	(100)
MMM	0		0		0	
NNN	30	(100)	30	(100)	30	(100)
OOO	0		0		0	
PPP	30	(100)	30	(100)	30	(100)
QQQ	0		0		0	
RRR	30	(100)	30	(100)	30	(100)
SSS	2		2		2	
TTT	30	(100)	30	(100)	30	(100)
UUU	11		11		11	
VVV	3		6		9	
WWW	-1,194	(-3,916)	-1,194	(-3,916)	-1,194	(-3,916)
XXX	15	(50)	30	(100)	45	(150)
YYY	65		65		65	
ZZZ	1		1		1	

Table 9: S-Turn Flight Path Parameters
(units defined in Table 7B)

Keyboard Mnemonic	Parameter Value					
AAA	2		2		2	
BBB	4		5		6	
CCC	3,658	(12,000)	3,658	(12,000)	3,658	(12,000)
DDD	305	(1,000)	305	(1,000)	305	(1,000)
EEE	100		100		100	
FFF	-7.3		-7.3		-7.3	
GGG	0		0		0	
HHH	3,658	(12,000)	3,658	(12,000)	3,658	(12,000)
III	-1,194	(-3,916)	-1,194	(-3,916)	-1,194	(-3,916)
JJJ	1,875	(6,152)	1,875	(6,152)	1,875	(6,152)
KKK	0		0		0	
LLL	762	(2,500)	762	(2,500)	762	(5,000)
MMM	1,194	(3,916)	1,194	(3,916)	1,194	(3,916)
NNN	1,875	(6,152)	1,875	(6,152)	1,875	(6,152)
OOO	0		0		0	
PPP	30	(100)	30	(100)	30	(100)
QQQ	0		0		0	
RRR	30	(100)	30	(100)	30	(100)
SSS	2		2		2	
TTT	30	(100)	30	(100)	30	(100)
UUU	7		7		7	
VVV	3		6		9	
WWW	-1,194	(-3,916)	-1,194	(-3,916)	-1,194	(-3,916)
XXX	15	(50)	30	(100)	45	(150)
YYY	65		65		65	
ZZZ	-2		-2		-2	

Table 10: Straight-In Flight Path Parameters (units defined in Table 7B)

Keyboard Mnemonic	Parameter Value					
AAA	2		2		2	
BBB	7		8		9	
CCC	3,658	(12,000)	3,658	(12,000)	3,658	(12,000)
DDD	305	(1,000)	305	(1,000)	305	(1,000)
EEE	100		100		100	
FFF	-7.3		-7.3		-7.3	
GGG	0		0		0	
HHH	3,658	(12,000)	3,658	(12,000)	3,658	(12,000)
III	0		0		0	
JJJ	30	(100)	30	(100)	30	(100)
KKK	0		0		0	
LLL	30	(100)	30	(100)	30	(100)
MMM	0		0		0	
NNN	30	(100)	30	(100)	30	(100)
OOO	0		0		0	
PPP	30	(100)	30	(100)	30	(100)
QQQ	0		0		0	
RRR	30	(100)	30	(100)	30	(100)
SSS	2		2		2	
TTT	30	(100)	30	(100)	30	(100)
UUU	11		11		11	
VVV	6		9		12	
WWW	-1,194	(-3,916)	-1,194	(-3,916)	-1,194	(-3,916)
XXX	30	(100)	45	(150)	60	(200)
YYY	65		65		65	
ZZZ	-2		-2		-2	

5. OPERATING PROCEDURES

1) The Safety pilot (right side) turns on the V/STOLAND system by depressing the standby/on button on the mode select panel to on.

2) The research computer is engaged by depressing the research button on the MFD control panel.

3) The selection of Crows Landing Tacan is performed by selecting NRC = 1 on the keyboard.

4) The safety pilot performs all the keyboard entries needed to fly the flight path. There is a total of 9 different flight paths (3 straight in, 3 U turn, and 3 S turn approaches). Once a flight path is entered on the keyboard, via keyboard entry BBB of Table 7B (AAA = 2), the flight path geometry can still be modified. The safety pilot enters a PID code on the keyboard to identify the pilot and the type of approach.

5) The automatic navigation switch on the mode select panel should be in auto to select the best navigation source.

6) The safety pilot selects flight director by depressing the flight director button on the mode select panel. The safety pilot selects the appropriate airspeed, heading, and altitude needed to fly towards the IP segment on the MFD.

7) When the helicopter is established on the IP segment as indicated on the MFD, the safety pilot hands over control to the test and evaluation pilot (left side), and depresses the PIC button on the MFD control panel. The PIC button performs two functions

   1) starts data recording process on the ground,
   2) arms the land mode when MLS navigation is valid.

   Alternately, PIC can be activated, by selecting PIC = 1 on the keyboard.

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8) The MFD display can be turned on or off by the MFD button on the MFD control panel.

9) The research pilot follows the roll, pitch, and collective flight director commands on the ADI to decision height. The collective flight director can be displayed as either a command ("fly to") or as a situation ("fly from") director by selecting BBB on Table 7A (AAA = 1) on the keyboard as

BBB $\neq$ 0 , "fly to" collective flight director

= 0 , "fly from" collective flight director.

Raw data approaches (without flight director) can be flown by setting LLL = 0 on Table 7A (AAA = 1) on the keyboard. Otherwise, set LLL = 1 to enable flight director.

10) At decision height, the research pilot (left side) is given a verbal instruction by the safety pilot to either perform a go around or visually decelerate to a hover over any reasonable place on the runway.

11) The go around mode can only be activated, when on the final course and past waypoint 11, by depressing the cargo release button on the cyclic stick. The go around mode is annunciated by the flare light on the ADI. The commands generated in the go around mode are based upon an airspeed of 65 knots, altitude of 305m (1000 ft) (ASL), and heading of 353 degrees.

12) The approach terminates when the safety pilot (right side) depresses the "PIC" button on the MFD control panel or setting PIC = 0 on the keyboard. This also turns off the ground recording process.

6. NAVIGATION SYSTEMS DESCRIPTION

6.1 Overview

All the navigation systems described here provide the estimated position and velocity of the VTOL aircraft by combining inertial measurements with measurements from the navaids [2,3]. Figure 14 shows how the navigation systems are implemented for tests in the V/STOLAND avionics system. The estimated positions and velocities are computed from the pre-filters and complementary filters in the basic computer. A Kalman filter residing in the research computer was not used in this flight test program. Radio altitude was not used in the vertical complementary filter since the vertical tracking task was to evaluate MLS elevation.

As shown on Figure 14, all data for navigation experiments except the LTN-51 INS accelerometer outputs come into the basic computer. All data input to the basic computer are also sent to the research computer. The switches shown on Figure 14 are under the pilot's control. As can be seen, either the complementary filter or Kalman filter state estimates may be used for driving the basic computer's display, guidance and control logic. The research-mode button controls which state estimates are used. Also by use of keyboard inputs, the pilot may select either the strapped down IMU or the LTN-51 as the source of acceleration input to the complementary filter in the basic computer or the Kalman filter in the research computer.

Figure 15 is a block diagram illustrating the general structure and functions of all the navigation systems. The inertial measurement unit (IMU) provides sufficient data for calculating the aircraft acceleration in a runway referenced coordinate frame. The accelerations are integrated to keep the position and velocity estimates current. When hardware discretes indicate the navaid measurements are valid, their values are compared with estimated position data. If the difference satisfies the data rejection algorithm, then state corrections are calculated by a specified algorithm and added appropriately to the estimated state.

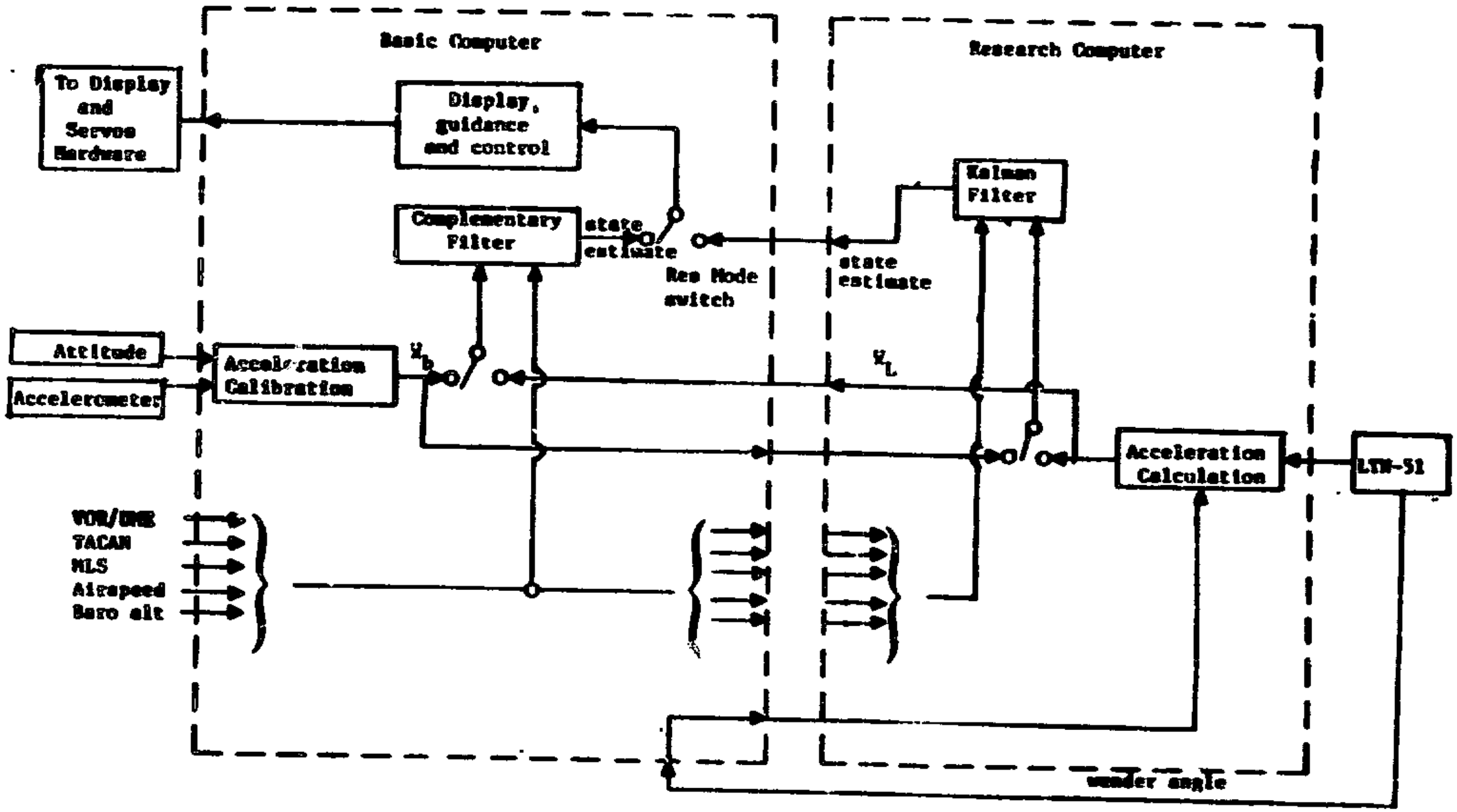


Figure 14. Navigation Systems Implementation in V/STOLAND

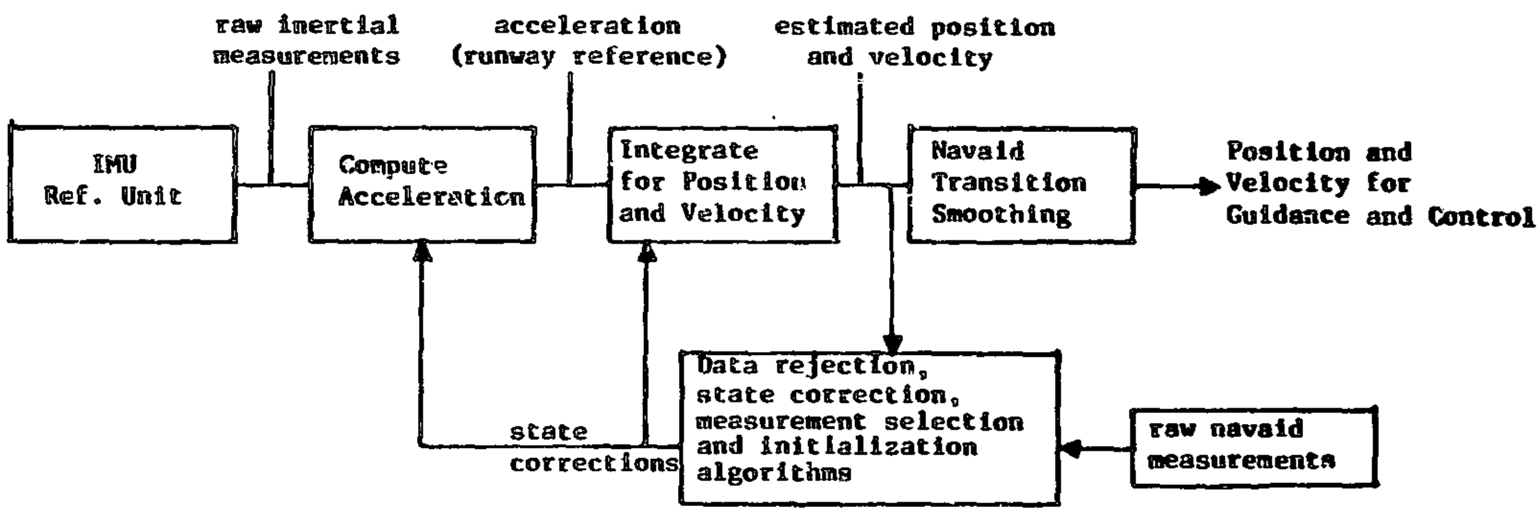


Figure 15. Block Diagram of Navigation Systems

The vertical channel is handled independently of the level channels in the systems described. The vertical channel is started using the raw barometric altitude reading for the vertical position at the initialization time point, and zero initial value is placed on the vertical velocity.

For the level channel, x-y position initialization is performed using MLS range and azimuth if available; otherwise, the less accurate TACAN range and bearing measurements are used. Airspeed and aircraft heading measurements are used to initialize the level components of velocity.

Initialization is done when the pilot selects a valid navaid for the first time. The filter velocities are initialized to the velocity components relative to the air mass ($\dot{X}_A$, $\dot{Y}_A$), assuming negligible wind components. At 200 milliseconds after navaid selection, the filter position is initialized to the navaid computed position and the velocity loop is opened.

The initial and continuous validation of the range and azimuth data is done as follows:

- MLS azimuth data is valid if both of the following conditions are satisfied:
  1. $|(\psi_c)_n - (\psi_c)_{n-1}| \leq 2$ degrees for 10 seconds where ψ_c = conical azimuth angle.
  2. MLS azimuth is valid for any 5-second interval of the previous 10 seconds.
- MLS range data is valid if both of the following conditions are satisfied:
  1. $|(R)_n - (R)_{n-1}| \leq$ 457m (1500ft) for 10 seconds where R = MLS range.
  2. MLS range is valid for any 5-second interval in the previous 10 seconds.

At the end of the initial validation and if the initial validation is satisfied, the MLS navigation pushbutton is illuminated amber enabling either manual or automatic navigation selection of MLS.

The continuous validation check for MLS navigation becomes invalid (after initial validation) if any of the following conditions are met.

1) $|\psi_c - \hat{\psi}_c| > 2$ degrees for 10 seconds

2) Localizer valid becomes invalid for 5 seconds.

3) $|R - \hat{R}| >$ 457m (1500ft) for 10 seconds.

4) Range valid becomes invalid for 5 seconds.

The automatic measurements selection algorithm for the level channels will use MLS range and azimuth if available; otherwise, TACAN measurements are used. If neither source of data is available, a dead-reckoning mode involving either inertial information only or inertial information and airspeed measurements is used.

The dead-reckoning mode goes into effect when the selected navaid has remained invalid for a period of 5 seconds. In this mode the velocity loop is closed and the position loop is open. The last values of filtered position, X_R and Y_R, are updated with position changes derived from the air mass velocity components and the last (just prior to switching to dead reckoning) computed values of wind velocity components.

The position update accuracy in this mode deteriorates with time, especially with changing wind conditions, and hence dead reckoning is limited to a period of 2 minutes.

6.2 Complementary Filters

The complementary filters which are used in the flight tests with the V/STOLAND avionics system were initially developed by Sperry Flight Systems [2]. The availability of some new data sources (MLS and INS accelerometer data) and information gleaned from flight test results have led to a number of modifications. The complementary filter as currently mechanized in the Sperry 1819B basic computer is summarized in this section.

Figure 16 is a block diagram of the complementary filter used in the V/STOLAND system. The MLS range, azimuth, and elevation, the TACAN range and bearing and the VOR/DME range and bearing measurements are fed through first-order pre-filters. In order to prevent lags caused by the pre-filter time constants, the estimated rates for each of the measurements based on the current state estimate are also fed to the pre-filter. Reference selection logic, either manually through push buttons or automatically (if the auto nav mode is selected), determines which pre-filter navaid data are used for the raw x-y calculations. The raw x-y data and the acceleration in the runway reference frame as calculated from the raw inertial data are fed to the two third-order x-y navigation filters. The acceleration input source may be either the strapped-down IMU or the LTN-51, as was shown in Figure 14.

In the vertical channel the pre-filtered MLS elevation data and raw barometric altitude data are fed to the reference selection logic. The reference selection logic is fully automatic for the vertical channel. The barometric altitude is used until MLS elevation data are valid. This is followed by a blending period where MLS elevation and estimated x-y coordinates are used to calculate one source of the altitude and the barometric altitude is the second source. The raw altitude used for the filter is a linear combination of the two altitude sources where the weight shifts with time from all barometric data to all MLS altitude data. The total time for the blend is 60 seconds. The raw altitude and the vertical acceleration are fed to a third order navigation filter for the altitude channel.

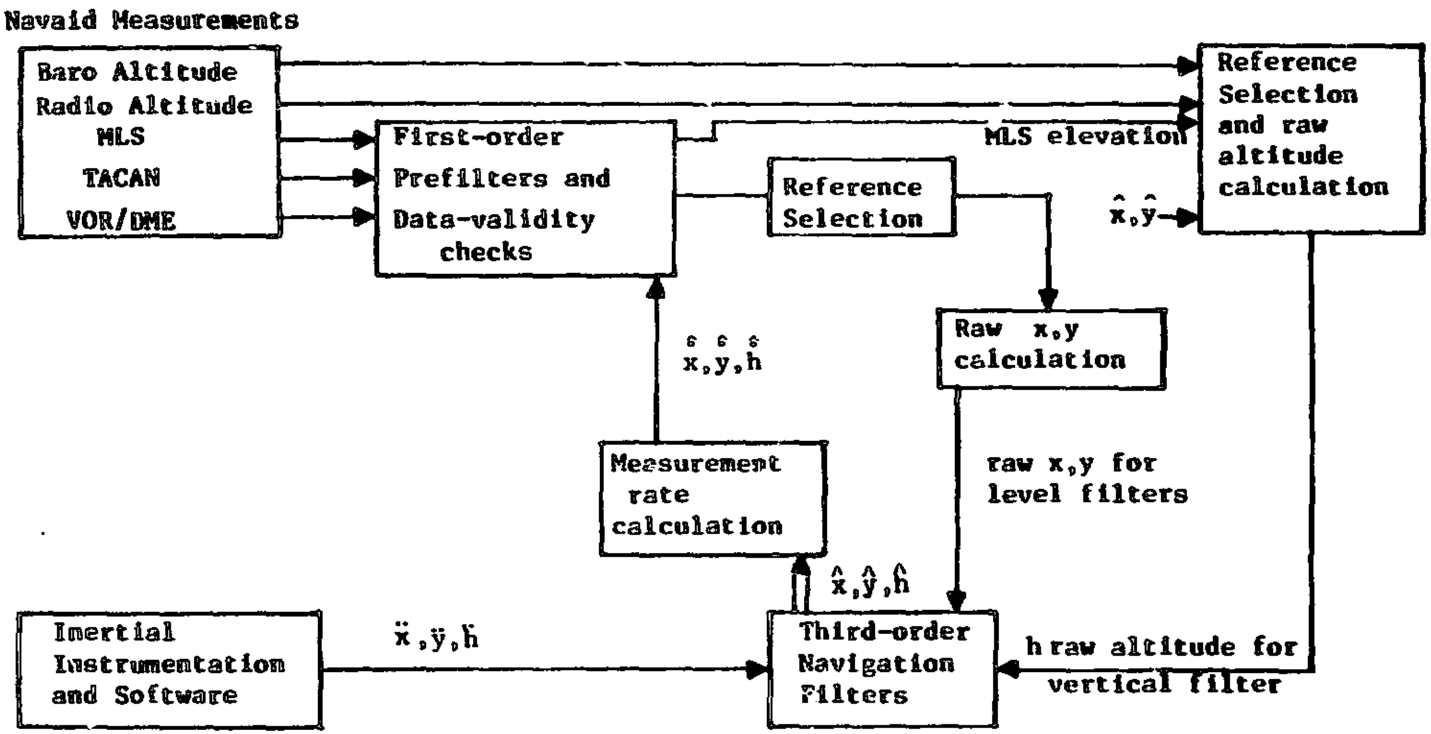


Figure 16. Block Diagram of Complementary Filters

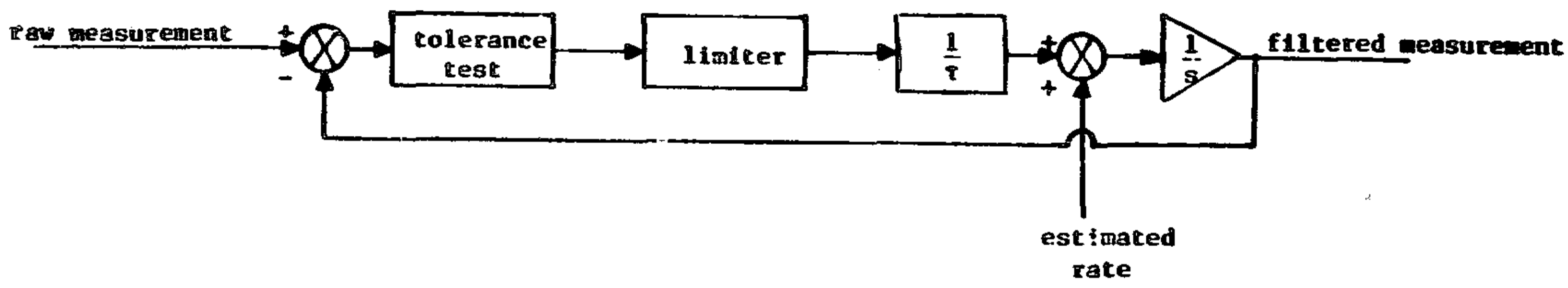
Figure 17 is a block diagram of the pre-filters used in the complementary filter. The filtered measurement is subtracted from the raw measurement and the difference sent to a tolerance test. If the tolerance is exceeded, the raw measurement is rejected. If the tolerance test is passed, then the error signal is limited before being multiplied by the reciprocal of the time constant and integrated. The estimated rate for the measurement is fed directly to the integrator for the filtered measurement. The table on Fig. 17 gives the tolerance, limit level, and time constants used for the pre-filters in the V/STOLAND complementary navigation filters.

Figure 18 shows the third-order navigation filter for the x channel of the complementary filter. The y channel is identical in structure and filter gains. The switches in the figure are shown in the normal "navigation valid" operation of the system. In this mode of operation the estimated position $\hat{x}$ is subtracted from the pre-filtered raw position x and the difference used as feedback through gains K_{1x}, K_{2x}, and K_{3x} into the three integrators of the filter. The measured acceleration from the selected source feeds the integrator whose output is estimated groundspeed $\hat{\dot{x}}$. In this mode of operation the values of the filter gains depend on the source of the navaid-derived position.

The time constant in the pre-filters for TACAN and VOR was chosen at 7.45 seconds to filter the high frequency components of the bearing and range signals. The high frequency components of the MLS signals are less than either TACAN or VOR which resulted in the pre-filter time constant chosen at 2 seconds. With a shorter time constant, the MLS pre-filters are more responsive to bearing and range changes than the TACAN or VOR pre-filters. The third order complementary filter for MLS contains lower filter gains than TACAN or VOR to prevent oscillations introduced by the coupling between the first order pre-filter and the third order complementary filter. The coupling between the two filters exists because ground speed, calculated from the complementary filter, is part of the estimated rate input to the pre-filters. Since ground speed is composed of x and y, the x filter and y filter are coupled. Further, the complexity of the x filter and y filter is now eighth in order due to coupling between the pre-filter and complementary filter instead of fourth order.

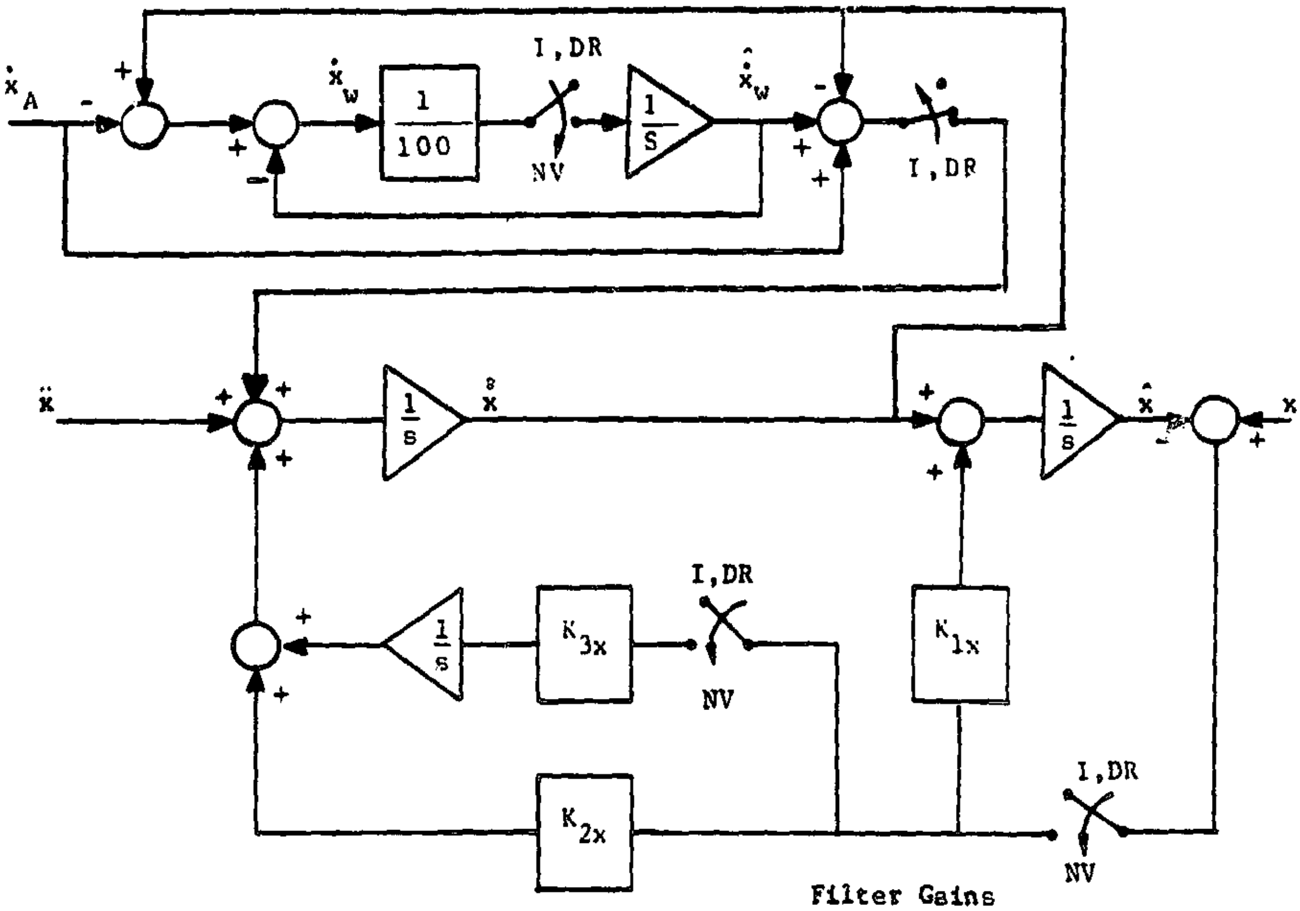
It should be noted that the pre-filter time constants shown in Fig. 17 also depend on the source of the navaid-derived position. The combination of the filter gains and the pre-filter time constants were selected so that, when MLS is in use, the overall complementary filter is more responsive in tracking the navaid-derived position than when TACAN or VOR/DME is in use. It should be mentioned that the pre-filters used in the V/STOLAND navigation system cause coupling to exist among all the channels.

In the normal mode of operation the components of wind are estimated in a runway referenced coordinate frame. This is achieved by sending the difference between measured airspeed $\dot{x}_A$ and estimated ground speed $\hat{\dot{x}}$ into a first order filter with a 100 second time constant.



Measurement Type	Tolerance	Limit Level	Time Constant
TACAN Bearing	± 5 deg	± 10 deg	7.45 sec
TACAN Range	± 457m (± 1500 ft)	± 122m (± 400 ft)	"
VOR Bearing	± 5 deg	± 10 deg	"
VOR Range	± 457m (± 1500 ft)	± 122m (± 400 ft)	"
MLS Elevation	± 5 deg	± 10 deg	2 sec
MLS Azimuth	± 2 deg	± 10 deg	"
MLS Range	± 457m (± 1500 ft)	± 122m (± 400 ft)	"

Figure 17. Block Diagram and Parameters of the Prefilters



Filter Gains

Gain	MLS	TAC/VOR	UNITS
K_{1x}	.298	.735	1/sec
K_{2x}	.03	.0375	$1/sec^2$
K_{3x}	.00153	.000743	$1/sec^3$

Notes:

$\ddot{x}$ = acceleration from IMU

x = navaid-derived position from prefilter

$\hat{\dot{x}}$ = estimated ground-speed

$\dot{x}_A$ = A/C velocity relative to airmass (x-component)

$\dot{x}_w$ = raw wind velocity (x-component)

$\hat{\dot{x}}_w$ = wind velocity (x-component) estimate

DR = dead reckoning mode

I = initialization

NV = navigation valid

Figure 18. Third Order Navigation Filter for x Channel

In initialization the groundspeed components $(\dot{x},\dot{y})$ are initialized to the airspeed components $(\dot{x}_A, \dot{y}_A)$. Acceleration component $\ddot{x}$ allows a complementary filter implementation.

In dead reckoning, the last filtered wind estimate is frozen. A new reference groundspeed $\dot{x}_{DR}$ is computed as sum of the present airspeed and the last frozen wind estimate. The filtered groundspeed estimate $\hat{\dot{x}}$ is subtracted from the new groundspeed estimate $\dot{x}_{DR}$ and the error is input to the complementary filter. The wind estimate is not used for any other function.

Figure 19 shows the third-order navigation filter for the altitude channel. In this instance the configuration and gains are not dependent on the source of altitude data.

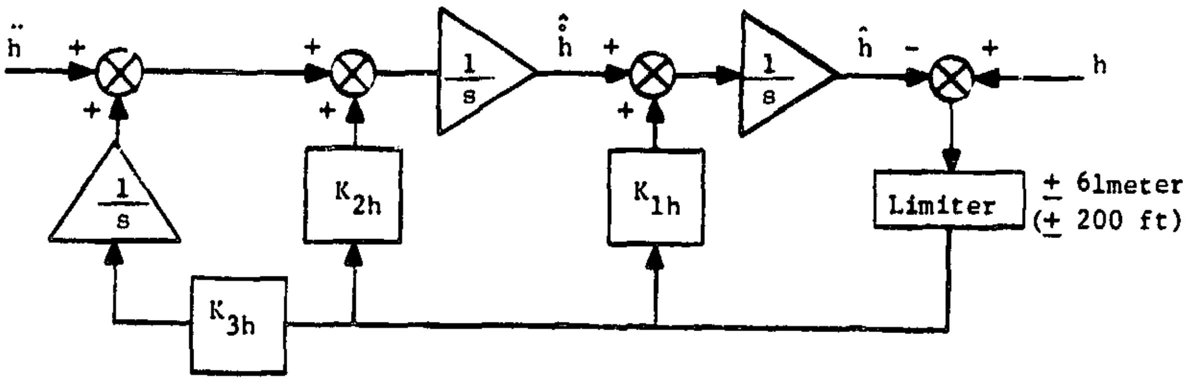
The complexity of the vertical filter is due to the coupling between the pre-filter and complementary filter. The coupling is due to $\hat{h}$ from the complementary filter being used as part of the estimated rate input to the pre-filter. Further, ground-speed (computed from the x and y channel) is used as another part of the estimated rate input to the pre-filter. The vertical filter uses MLS data for all three approaches except for the start of the U-turn approach which starts outside MLS coverage. At the start of the U-turn approach, barometric altitude is used until MLS elevation becomes valid. During the transition from barometric altitude to MLS derived altitude, the dynamics of the vertical filter changes, due to the 60 second blend from barometric altitude to MLS derived altitude.

Comments on the V/STOLAND Complementary Filter

The V/STOLAND complementary filters navigation system has some undesirable characteristics which should be removed in an operational design.

1. There is no provision for providing smooth transition from one navaid source to another source. If the aircraft is in the automatic navigation mode, undesirable steering transients occur when navigation aids are changed (for example, a transient occurs when switching from TACAN to MLS).

2. The pre-filters used in the V/STOLAND system introduce much unnecessary complexity without providing any improvements in performance. The complexity occurs due to the coupling between the pre-filter and complementary filter and the coupling between the x filter and y filter. The structure of the x channel and y channel is now an eighth order filter. With lower filter gains for the MLS complementary filter (to prevent oscillations from occurring), the navigation filter is less responsive to bearing and range changes and results in navigation errors.



Notes

$\ddot{h}$ = altitude component of acceleration from IMU

$\hat{\dot{h}}$ = estimated altitude rate

$\hat{h}$ = estimated altitude

h = raw altitude from measurement selection logic

Gains

K_{1h} = .24 sec^{-1}

K_{2h} = .024 sec^{-2}

K_{3h} = .001 sec^{-3}

Figure 19. Third-Order Navigation Filter for Altitude Channel

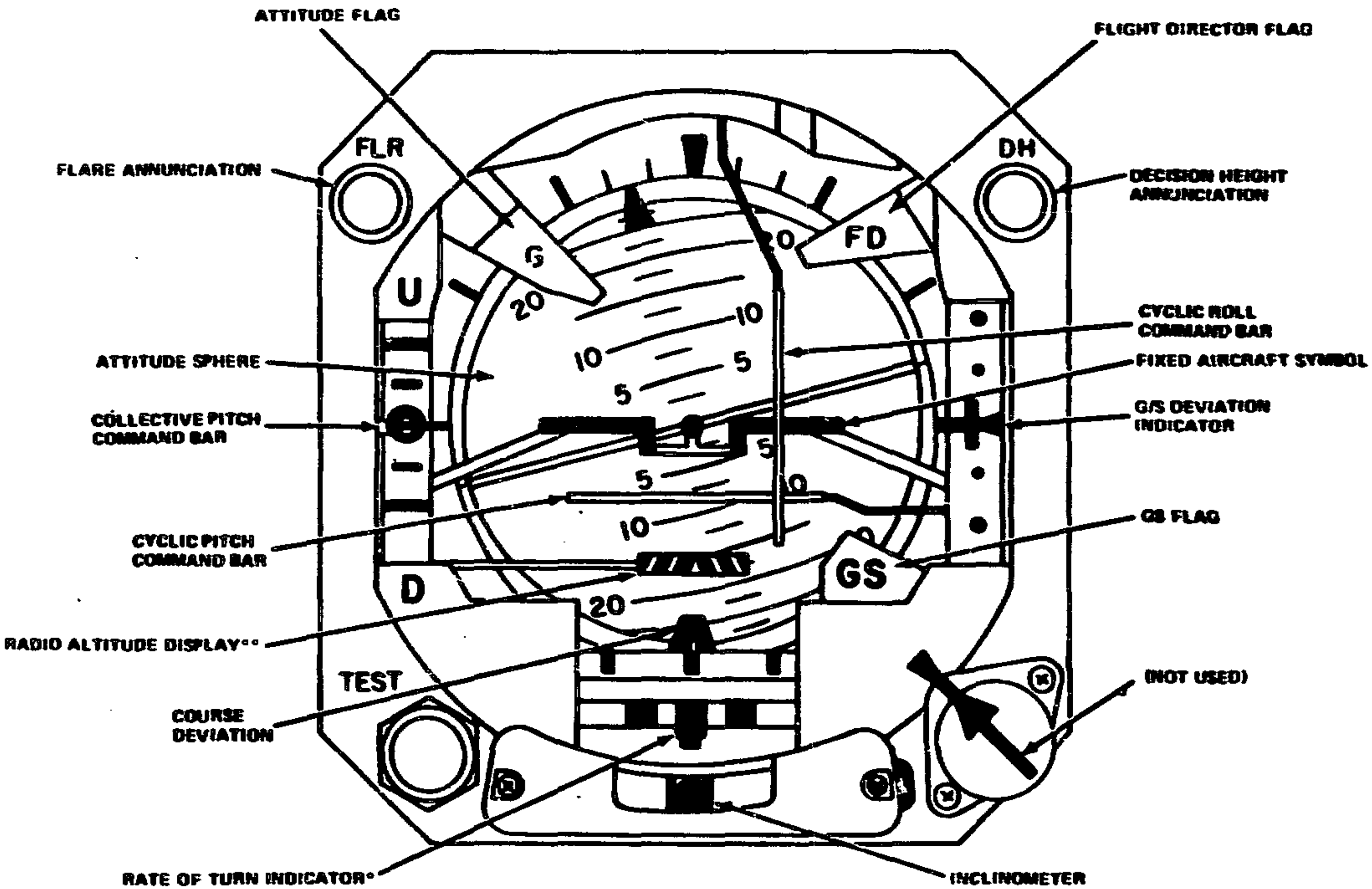
7. GUIDANCE SYSTEM

The manual mode of the V/STOLAND System was used during the NASA/FAA flight test program. In this configuration the pilot must fly the aircraft using the standard controls (i.e. cyclic control stick, collective lever and pedals) acting through the mechanical linkages. Two guidance modes are provided to the pilot to fly the U-turn, S-turn and Straight-In reference flight paths: (1) raw data without flight director, and (2) raw data with flight director.

7.1 Raw Data Display

Raw data in the form of estimated lateral and vertical deviations from the reference flight path are displayed on the Attitude Director Indicator (ADI) and Horizontal Situation Indicator (HSI). The Attitude Director Indicator (ADI) displays attitude, flight director commands, vertical deviation (glideslope), course deviation (localizer), radio altitude and rate of turn. A front view of the ADI is shown in Figure 20. The ADI also has Decision Height (DH) and Flare (FLR) annunciation lights, and failure warning flags for the vertical deviation (GS) and the flight director (FD).

The Horizontal Situation Indicator (HSI) is shown in Figure 21. Lateral deviations are displayed by the movement of the localizer bar with respect to a course deviation scale. Vertical deviation is displayed on the right vertical scale. The lateral and vertical deviations as displayed on the ADI/HSI are scaled as a function of the along track distance to go from the azimuth and elevation antennas, respectively. The scaling functions used in the NASA/FAA flight test program are shown in Figure 22 for the lateral course deviation and Figure 23 for the vertical deviation. Note that although the course deviation scaling function remains the same for any reference glideslope γ_{ref}, the vertical deviation scaling function parameters x_{AWF} and VDHGN are different for $\gamma_{ref} = 3°, 6°, 9°$ and $12°$ as shown in Table 11.



NOTES: ° INPUT FROM ROLL/YAW RATE GYRO ASSEMBLY
°° INPUT FROM RADIO ALTIMETER

716-36-7

Figure 20. ADI (HZ-6P), Front View

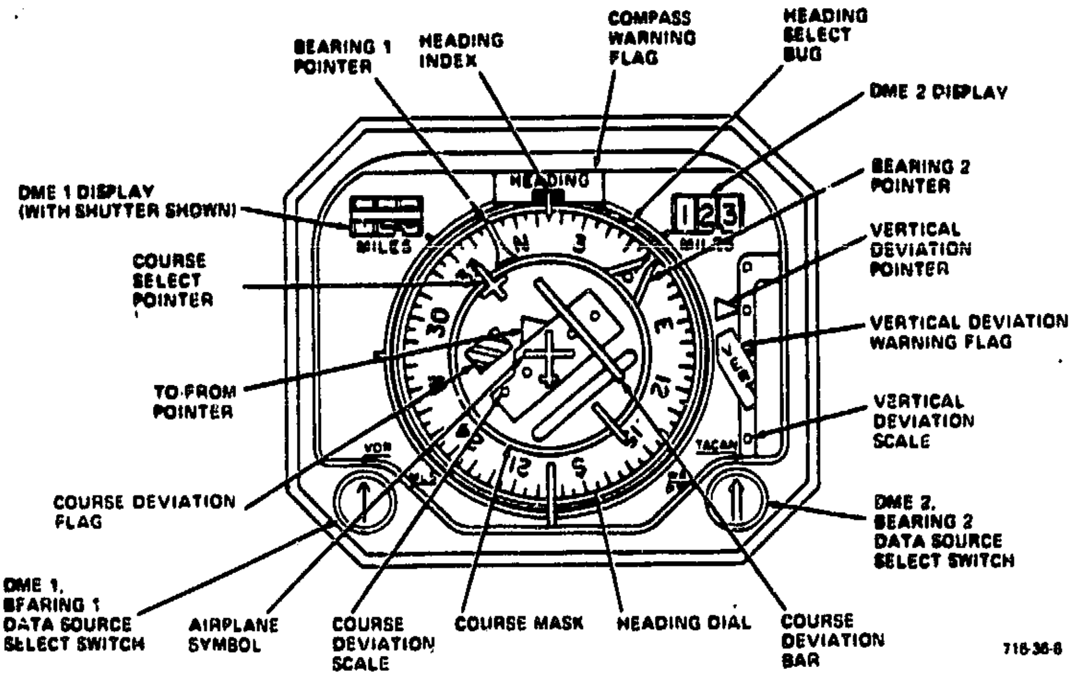


Figure 21. HSI (RD-202), Front View

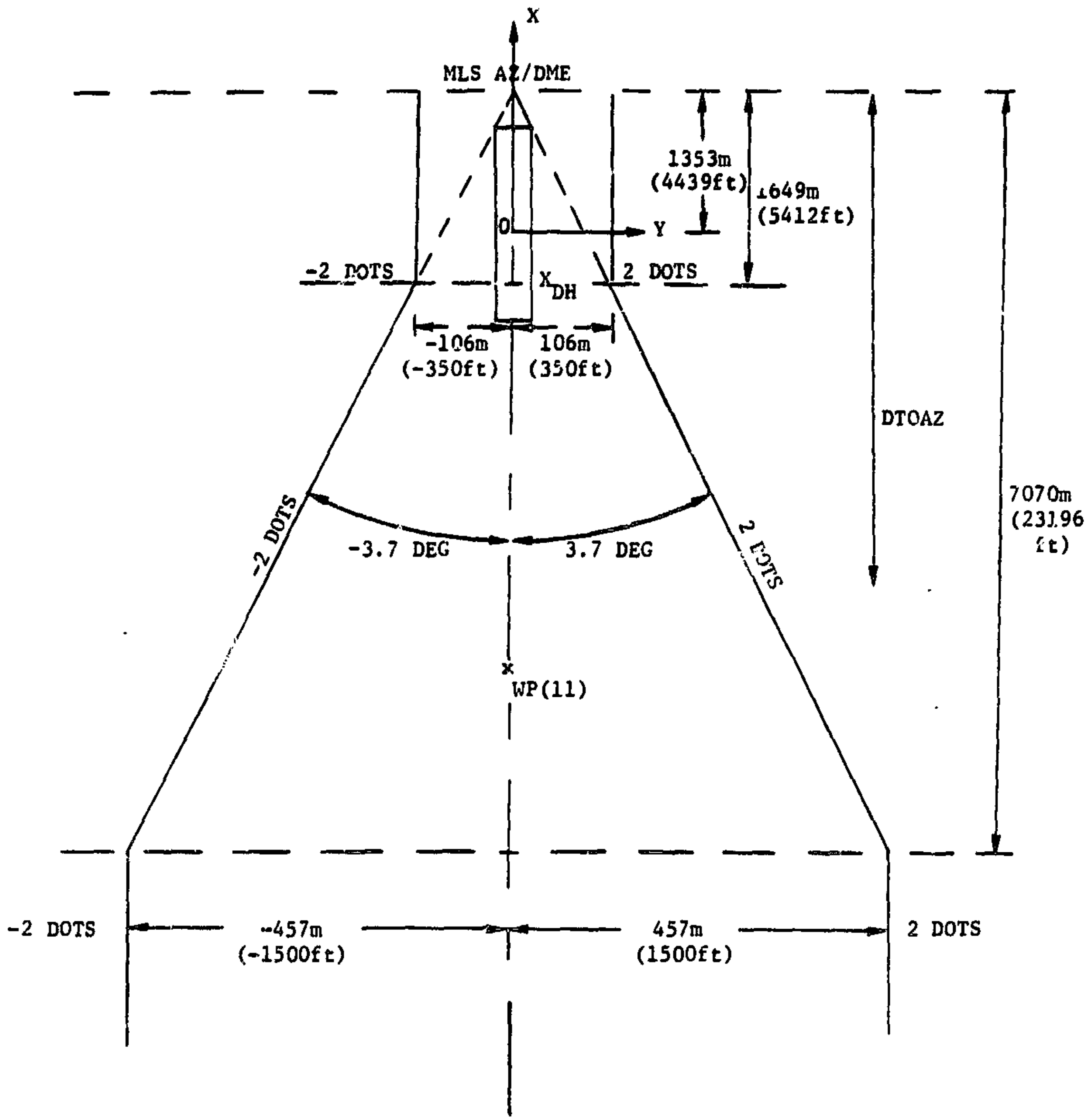


Figure 22. Scaling Function for Course (Lateral) Deviation Display

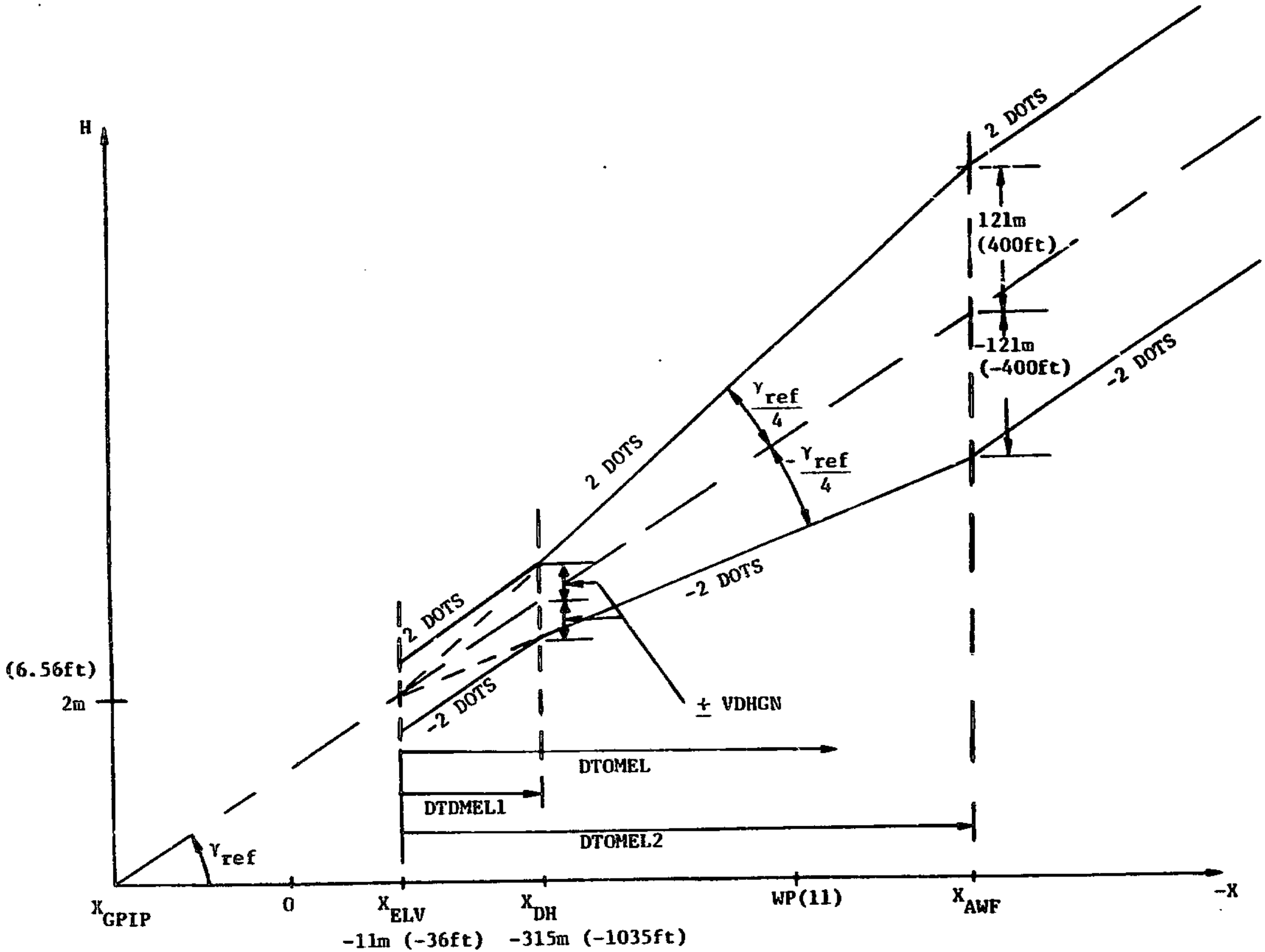


Figure 23. Scaling Function for Glideslope (Vertical) Deviation Displav.

Table 11. Vertical Deviation Scaling Function Parameters

G/S γ_{REF}	XGPIP	x_{AWF}	VDHGN
3°	35 m (116 ft)	-9,312 m (-30,551 ft)	4 m 13 ft
6°	12 m (40 ft)	-4,641 m (-15,227 ft)	8 m 26 ft
9°	5 m (16 ft)	-3,076 m (-10,091 ft)	12 m 40 ft
12°	0 m (0 ft)	-2,287 m (-7,503 ft)	16 m 53 ft

The parameter VDHGN in Figure 23 defines the 2 dot or full scale constant vertical deviation in meters (feet) in the last 305 m (1000 ft) starting at approximately the decision height and terminating at the GPIP.

7.2 Flight Director Guidance

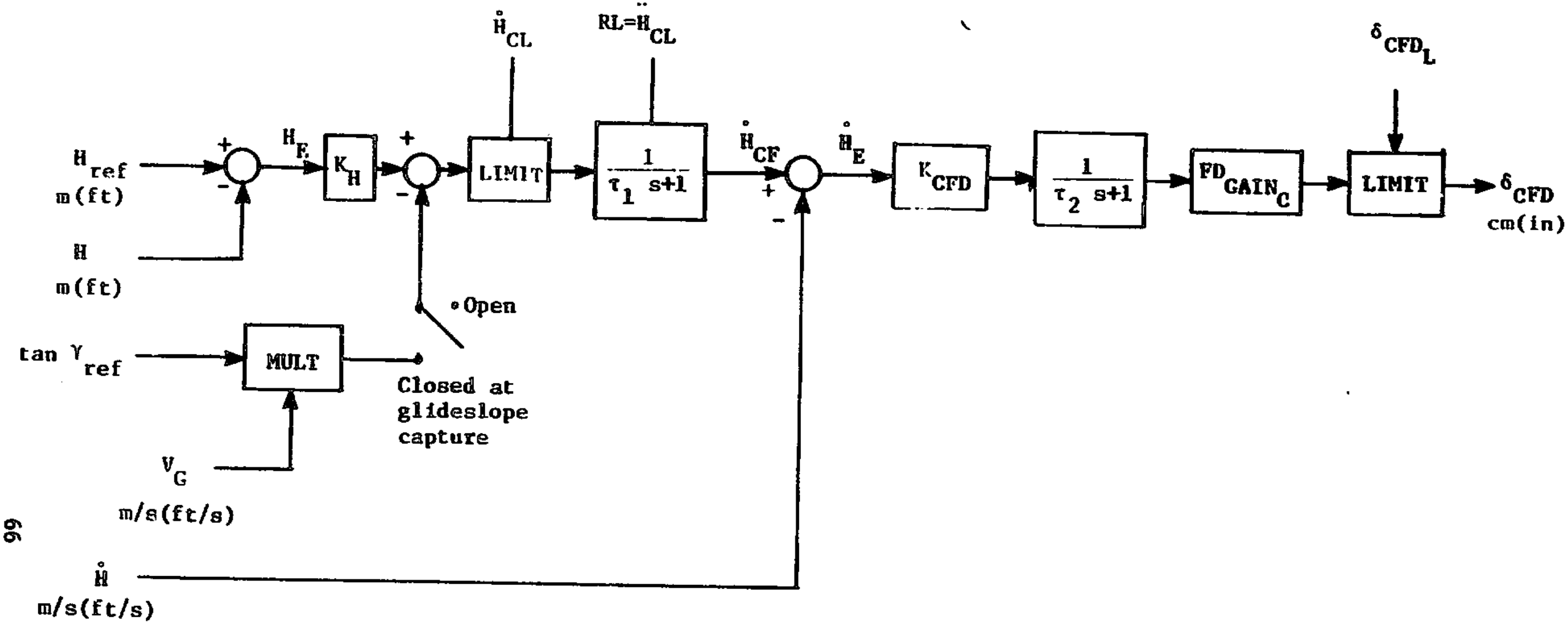
A 3-cue flight director was used in the NASA/FAA flight test program. Flight director commands are displayed on the ADI. The pitch and roll command bars display the pitch and roll flight director commands to the pilot. The collective command bar displays the altitude rate command to the pilot.

The piloting task is to null the command bars by applying the proper cyclic and collective stick inputs. For a pitch-up command, the pitch command bar moves above the aircraft symbol, and the pilot has to pull back (positive) on the cyclic stick gradually until the bar is centered. For all roll-right command, the roll command bar moves right, and the pilot gradually moves the cyclic stick to the right (positive) until the bar is centered. The collective flight director can be displayed on either a "fly to" or "fly from" format. For a positive-up altitude rate command, the collective command bar moves towards the marking U in the "fly to" mode (marking D in the "fly from" mode), and the pilot pulls up (positive) gradually on the collective stick until the indicator is centered. The reverse is true for a positive-down altitude rate command.

Maximum travel of the command bars is:

Pitch command bar = $\pm$ 1.24cm ($\pm$ .490in) = $\pm$ 7 degrees
Roll command bar = $\pm$ 2.3cm ($\pm$ .9in) = $\pm$ 60 degrees
Collective command bar = U to D = $\pm$ 1.27cm ($\pm$ 0.5in) = $\pm$ 6.1m/s ($\pm$ 20ft/s)

The following sections describe the guidance laws for the 3-cue flight director implemented for the NASA/FAA MLS flight test program [4].



K_H	$= .025 - .1875 \frac{1}{s}$ gain scheduled (see fig 25)	FD_{GAIN_C}	= 100%
$\dot{H}_{CL}$	= 10.16 m/s (33.33 ft/s)	K_{CFD}	$= .21 \frac{cm}{m/s}$ $(.025 \frac{in}{ft/s})$
$\ddot{H}_{CL}$	= 0.686 m/s^2 (2.25 ft/s^2)	τ_1	= 0.5 sec
δ_{CFD_L}	= 1.27 cm (0.5 in)	τ_2	= .067 sec

Figure 24. Collective Flight Director Block Diagram (Engineering Units)

7.2.1 Collective Flight Director

The collective flight director provides the command signal which the pilot must follow in order to maintain the aircraft on the desired vertical (i.e. altitude) reference trajectory. Figure 24 shows a block diagram of the collective flight director. The control command to the collective flight director bar

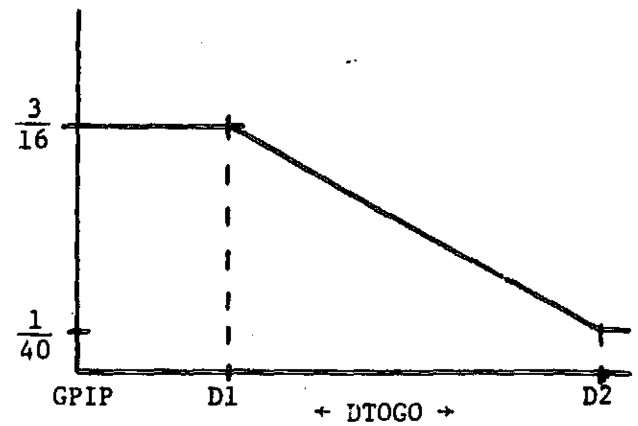
$$\dot{H}_E = \dot{H}_{CF} - \dot{H}$$

where $\dot{H}_{CF} \simeq K_H (H_{ref} - H) + V_g \tan \gamma_{ref}$

The flight director signal

$$\delta_{CFD} = \frac{1}{\tau_2 s+1} K_{CFD} \dot{H}_E$$

The parameters K_H and K_{CFD} determine the sensitivity of the collective flight director display command to errors H_E and $\dot{H}_E$ in following reference altitude H_{ref} and commanded altitude rate $\dot{H}_{CF}$, respectively. The gain K_H is scheduled to change with distance to go from the glide path intercept point (GPIP) as shown in Figure 25. The parameters D2 and D1 vary with the reference glideslope γ_{ref} and correspond to the parameters DTOMEL2 and DTOMEL1 in Figure 23 used to schedule the vertical deviation display scale during



Parameter / G/S γ_{ref}	D1	D2
3°	350m (1151ft)	9347m (30667ft)
6°	327m (1075ft)	4653m (15267ft)
9°	320m (1051ft)	3080m (10107ft)
12°	315m (1035ft)	2286m (7503ft)

Figure 25. Scaling Function for K_H

these experiments. Thus, a full scale deflection on the vertical flight director corresponds to an altitude error (assuming zero vertical velocity error) that varies with distance to go DTOGO from the GPIP, as follows:

CONDITION	Altitude Error Corresponding to Full Scale Deflection m/s ($\pm$ 20 ft/s)
DTOGO $\geq$ D2	$\pm$ 244 m ($\pm$ 800 ft)
DTOGO $\leq$ D1	$\pm$ 33 m ($\pm$ 107 ft)
D1 $\leq$ DTOGO $\leq$ D2	Linearly Interpolated Value Between $\pm$ 244m ($\pm$ 800 ft) and $\pm$ 33 m ($\pm$ 107 ft)

The gain scheduling shown in Figure 25 was chosen to satisfy the NASA research pilots during actual flight tests with MLS curved descending approaches.

The collective flight director block diagram of Figure 24 shows a switch for introducing the feedforward vertical sink rate $V_G \tan \gamma_{ref}$ after glideslope capture. Figure 26 shows a block diagram of the glideslope capture law that was implemented during the NASA/FAA MLS flight test program.

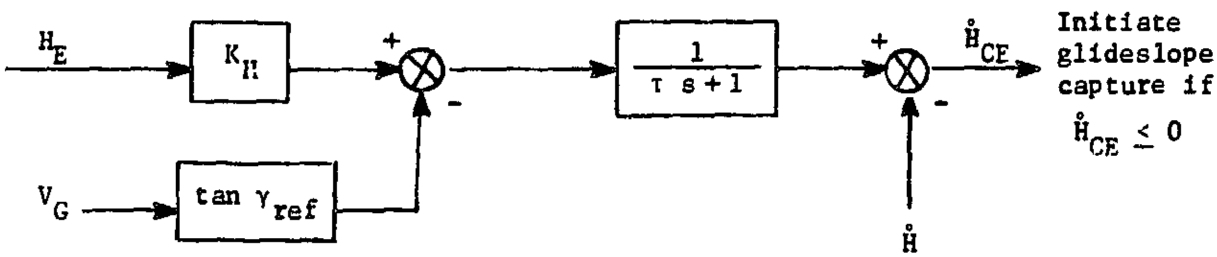


Figure 26. Glideslope Capture Law

Glideslope capture is initiated when $\mathring{H}_{CE} \leq 0$ for the first time following lateral capture. This capture law prevents any up command from occuring during glideslope capture and also gives an earlier and more gradual transition to the reference glideslope trajectory. The switch for $V_G \tan \gamma_{ref}$ is closed following capture and the γ_{ref} glideslope reference trajectory is inserted into the H_{ref} command input.

7.2.2 Pitch Flight Director

A block diagram of the pitch flight director is shown in Figure 27 and the complementary filtered indicated airspeed is shown in Figure 28. The pitch flight director provides the pitch attitude command that the pilot must follow in order to maintain the desired reference airspeed. The pitch flight director command

$$\delta_{\theta FD} \doteq \frac{1}{\tau_2 s+1} K_{\theta FD} (\theta_c - \theta_{wo})$$

where

$$\theta_{wo} = \frac{\tau_3 s}{\tau_3 s+1} \theta$$

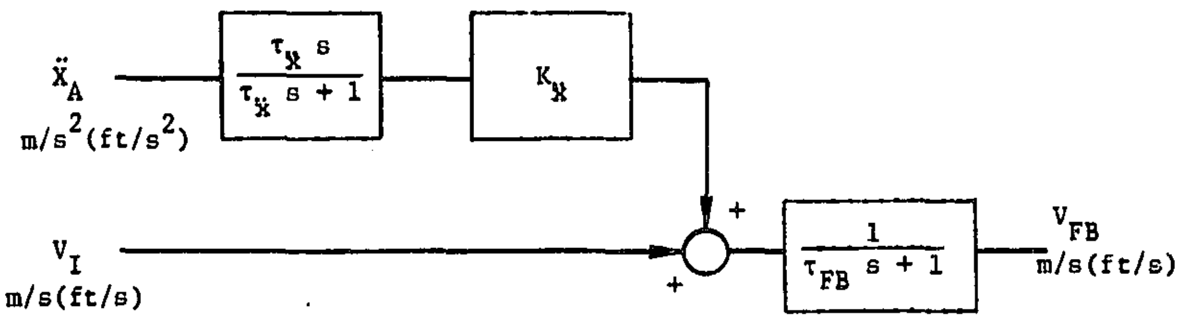
$\theta_c \doteq K_{\theta c1} (V_c - V_{FB})$

V_c = reference airspeed

V_{FB} = feedback indicated airspeed (complementary filtered)

θ in degrees and

$\delta_{\theta FD}$ in cm (inches) (1 cm $\stackrel{\Delta}{=}$ 6 deg)

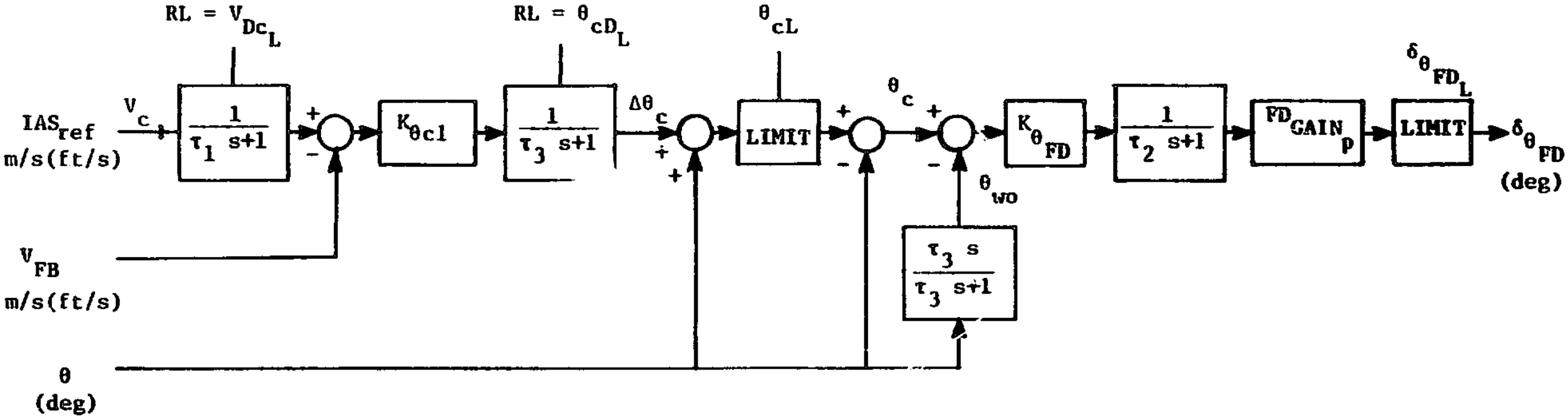


$K_{\ddot{X}}$ = 1 sec

$\tau_{\ddot{X}}$ = 15 sec

τ_{FB} = 1 sec

Figure 28. Feedback Velocity for Pitch Flight Director



V_{Dc_L} = .46 m/s^2 (1.5 ft/s^2)

$K_{\theta c1}$ = −0.82 deg/m/s (−.25 deg/ft/s)

θ_{cD_L} = 5 deg/s

θ_{c_L} = 20 deg

$K_{\theta_{FD}}$ = 1 deg/deg

FD_{GAIN_p} = 100%

$\delta_{\theta_{FD_L}}$ = 15 deg

τ_1 = 0.5 sec

τ_2 = .067 sec

τ_3 = 25 sec

Figure 27. Pitch Flight Director Block Diagram (Engineering Units)

The pitch flight director is the least significant task of the 3-flight director commands since the reference airspeed is held constant throughout the flight task. The actual airspeed flown by the pilot can be slightly different and varying from the reference value without degrading pilot performance on the overall approach and landing task.

7.2.3. Roll Flight Director

A block diagram of the roll flight director is shown in Figure 29 The director can operate in one of two modes: a reference flight path land mode and a heading hold mode. The former mode is used during the MLS curved descending approaches, while the latter mode is primarily used during reference flight path capture and the go-around maneuvers. The roll flight director signal

$$\delta_{\phi FD} \cong \frac{1}{\tau_3 s + 1} K_{\phi FD} (\phi_{CF} - \phi)$$

where ϕ = aircraft roll attitude (deg)

$\phi_{CF} \cong K_{DY} (\tau_D \dot{y}_e + y_e) + \phi_{Tc}$: Ref. Flight Path Land Mode

$= \frac{V_T}{200} (\psi_{ref} - \psi)$: Heading Hold Mode

$\phi_{Tc} = \left(\frac{1}{4 s + 1}\right) \tan^{-1} \left[\frac{V_g^2}{g R}\right]$

y_e = lateral deviation error (m or ft)

$\dot{y}_e$ = lateral deviation error rate (m/s or ft/s)

ψ_{ref} = reference heading (deg)

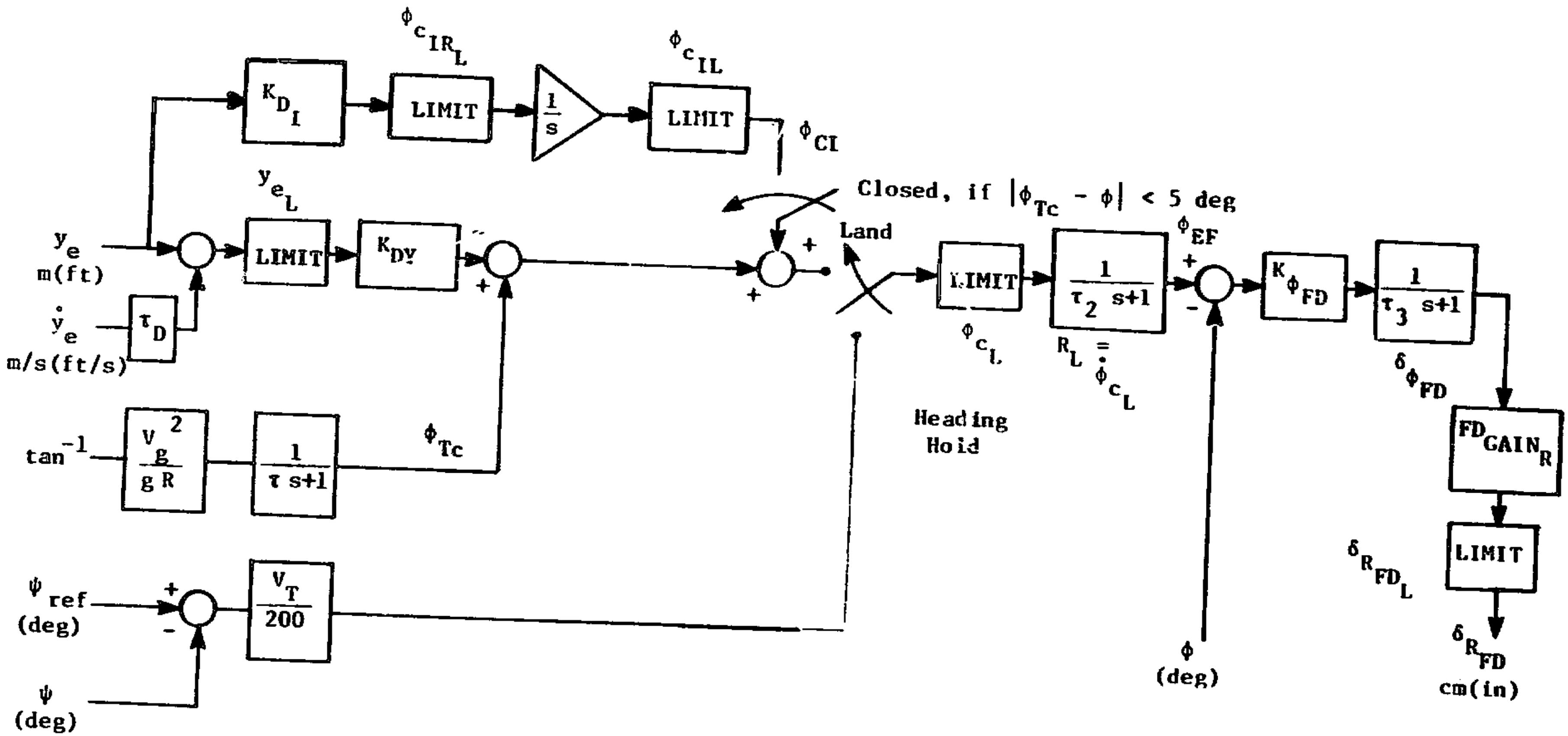
ψ = aircraft heading (deg)

V_T = aircraft airspeed (m/s or ft/s)

V_g = aircraft ground speed (m/s or ft/s)

R = radius of turn segment (m or ft)

g = gravity acceleration. (m/s^2 or ft/s^2)



τ_D = 10 sec

y_{eL} = 610 m (2000 ft)

K_{DY} = 0.16 deg/m (.049 $\frac{deg}{ft}$)

K_D = .00003 $\frac{deg/s}{ft}$

ϕ_{c_L} = 25 deg

$\dot{\phi}_{c_L}$ = .5 deg/s

$K_{\phi_{FD}}$ = .04 $\frac{cm}{deg}$ (.015 $\frac{in}{deg}$), gain scheduled (see figure 29)

τ_2 = .5 sec

τ_3 = .091 sec

$\phi_{c_{IR_L}}$ = .1 deg/s

FD_{GAIN_R} = 100%
= f(DTOGO)

Figure 29. Roll Flight Director Block Diagram (Engineering Units)

The gain parameters K_{DY} and $K_{\phi FD}$ determine the flight director signal sensitivity to lateral deviation error predicted τ_D seconds in the future, and roll attitude command following error, respectively. During the NASA/FAA flight tests, the display gain $K_{\phi FD}$ was scheduled to vary with distance to go DTOGO from the GPIP as shown in Figure 30. The gain scheduling occurs linearly over the straight in segment connecting way points 11 and 12, with the gain $K_{\phi FD}$ varying from its nominal value of 0.038cm/deg (.015in/deg) near Way Point 11 to 0.0476 (.01875in/deg) around decision height.

Note that the reference flight path land mode includes an integral lateral deviation error component driving the commanded roll attitude. This feed forward integral roll command ϕ_{cI} is position and rate limited, and operates only for roll tracking errors $|\phi - \phi_{Tc}| \leq 5$ degrees. Inclusion of the integral command provides for anticipation of turns and a smoother entry into the circular flight path segments.

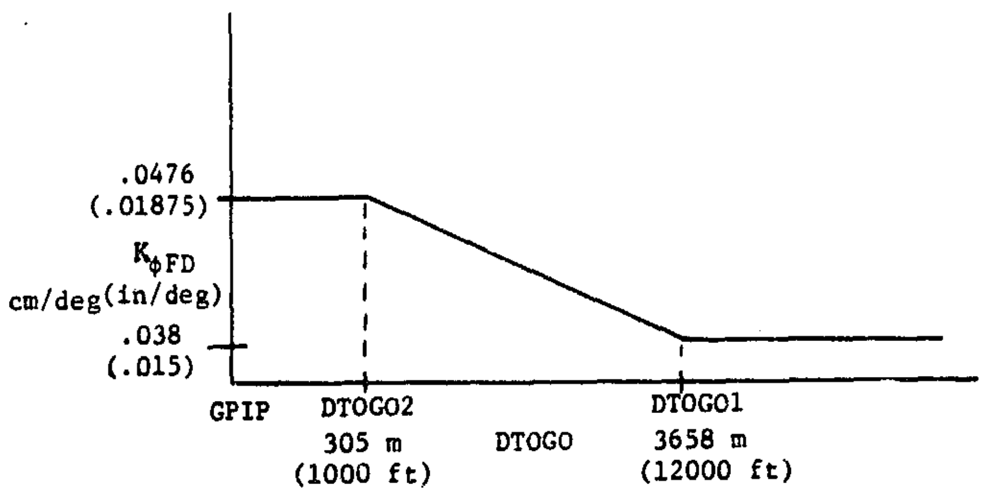


Figure 30. Gain Schedule Used for $K_{\phi FD}$

8. FLIGHT TEST EVALUATION OF MLS FLIGHT DIRECTOR PERFORMANCE

An operational evaluation of the MLS flight director guidance and navigation system was performed through a comprehensive flight test program. A total of eighteen (18) evaluation pilots from various segments of the helicopter community (commercial, corporate, industry, NASA, DOD, FAA and DFVLR-West Germany) participated. Each pilot flew a total of twelve (12) hooded approaches consisting of two U-turns and two S-turn approaches at 6° and 9° glideslopes, and two Straight-in approaches at 9° and 12° angles. These approaches were under IFR until the decision height (i.e., commanded altitude at decision range of 305 m or 1000 ft) followed by either a VFR deceleration to a hover over the GPIP, or a missed approach maneuver at a runway heading of 353° to an altitude of 305m (1000 ft) above sea level. A NASA safety pilot performed all the computer interface functions (e.g. keyboard entry etc.) and flew the helicopter from takeoff until it was established on the IP segment (as indicated on the MFD) at which point he handed over control to the evaluation pilot on the left seat and initiated recording of the flight data. Details on the operational aspects of the flight test program may be found in reference 5.

One of the objectives of the NASA/FAA MLS flight test program was to obtain data on the pilot's ability to perform a variety of lateral and vertical capture maneuvers using a 3-cue flight director. Lateral capture approaches at 30°, 40°, 60° or 90° intercept angles were selected (IP segments 1-6 in Fig. 11-13). Vertical capture was initiated: (1) just prior to the turn on the 6° U-turn approach, (2) just after the turn on the 9° U-turn approach, (3) immediately after lateral capture and prior to the first turn in the 6° S-turn approach, (4) at the completion of the first turn in the 9° S-turn approach, and (5) just after lateral capture in the 9° and 12° Straight-in approaches.

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8.1. Flight Test Data

Although time history data for a large number (total of 144) of variables was recorded during the evaluation flight tests, only a few of these variables are relevent for assessing pilot performance during curved and descending instrument approaches with MLS flight director guidance. A total of seventeen (17) plots (three sets of five each for the vertical, pitch and roll control axes, respectively, plus one plot each for horizontal and vertical flight path trajectories) for each of the six test flight profiles is adequate for evaluating the flight director performance. Specifically, the seventeen variables listed below are plotted against along-track distance to go from the GPIP (except for "Y Ground Track" which is plotted against the "X Ground Track" variable):

a. Y Ground Track
b. Altitude z
c. Altitude Error
d. HDOT Command
e. HDOT
f. Collective Flight Director Command
g. Collective Stick
h. Lateral Error
i. Roll Command
j. Roll Attitude
k. Roll Flight Director Command
l. Lateral Cyclic Stick
m. Airspeed Error
n. Pitch Command
o. Pitch Attitude
p. Pitch Flight Director Command
q. Longitudinal Cyclic Stick

Figures 31-36 show the actual response histories of these variables for the six flight-director approaches corresponding to the $6^{\circ}/9^{\circ}$ U-turn, the $6^{\circ}/9^{\circ}$ S-turn, and the $9^{\circ}/12^{\circ}$ Straight-in reference flight

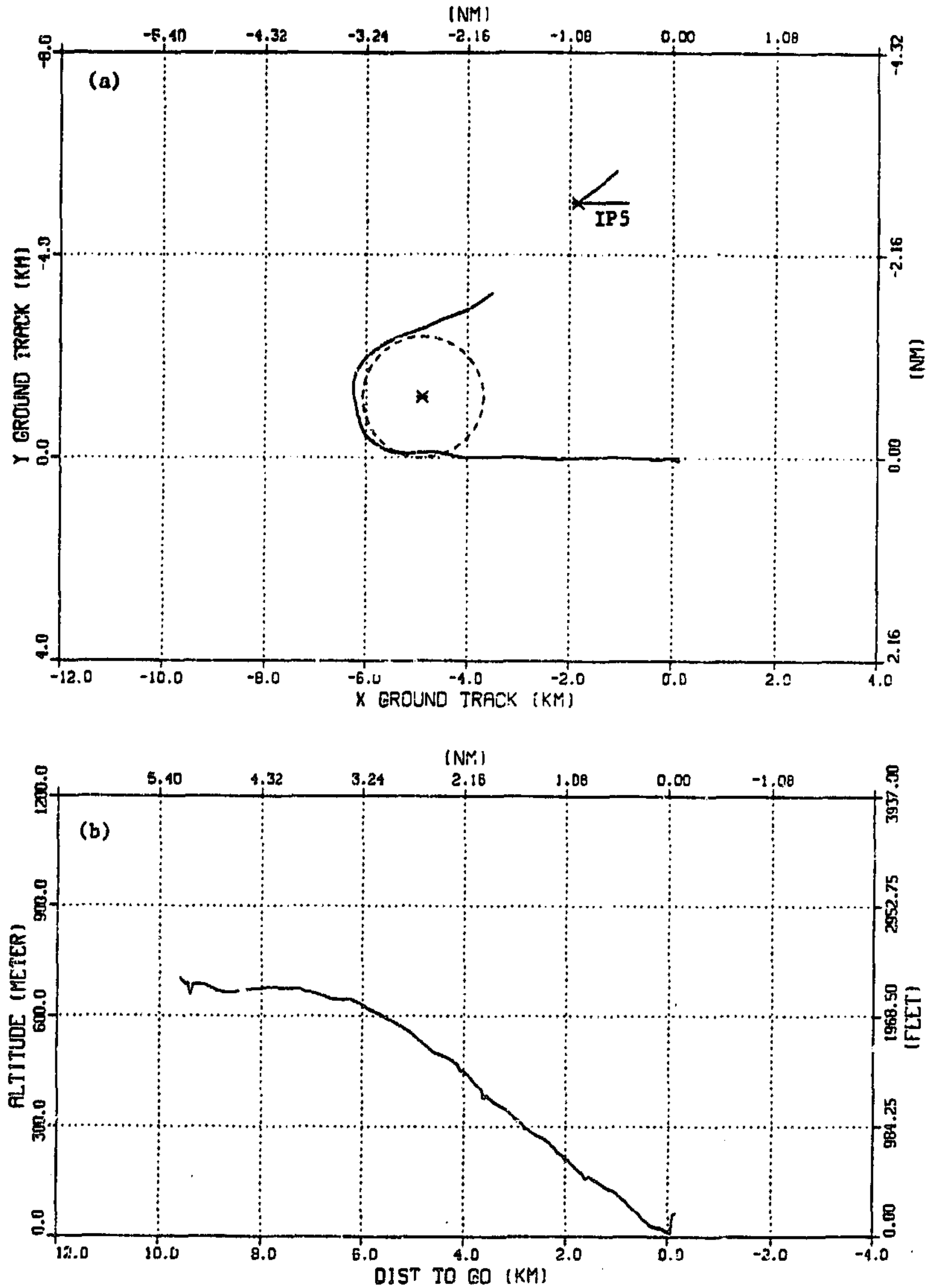


Figure 31. U-Turn: 6 Degrees Glide Slope Data

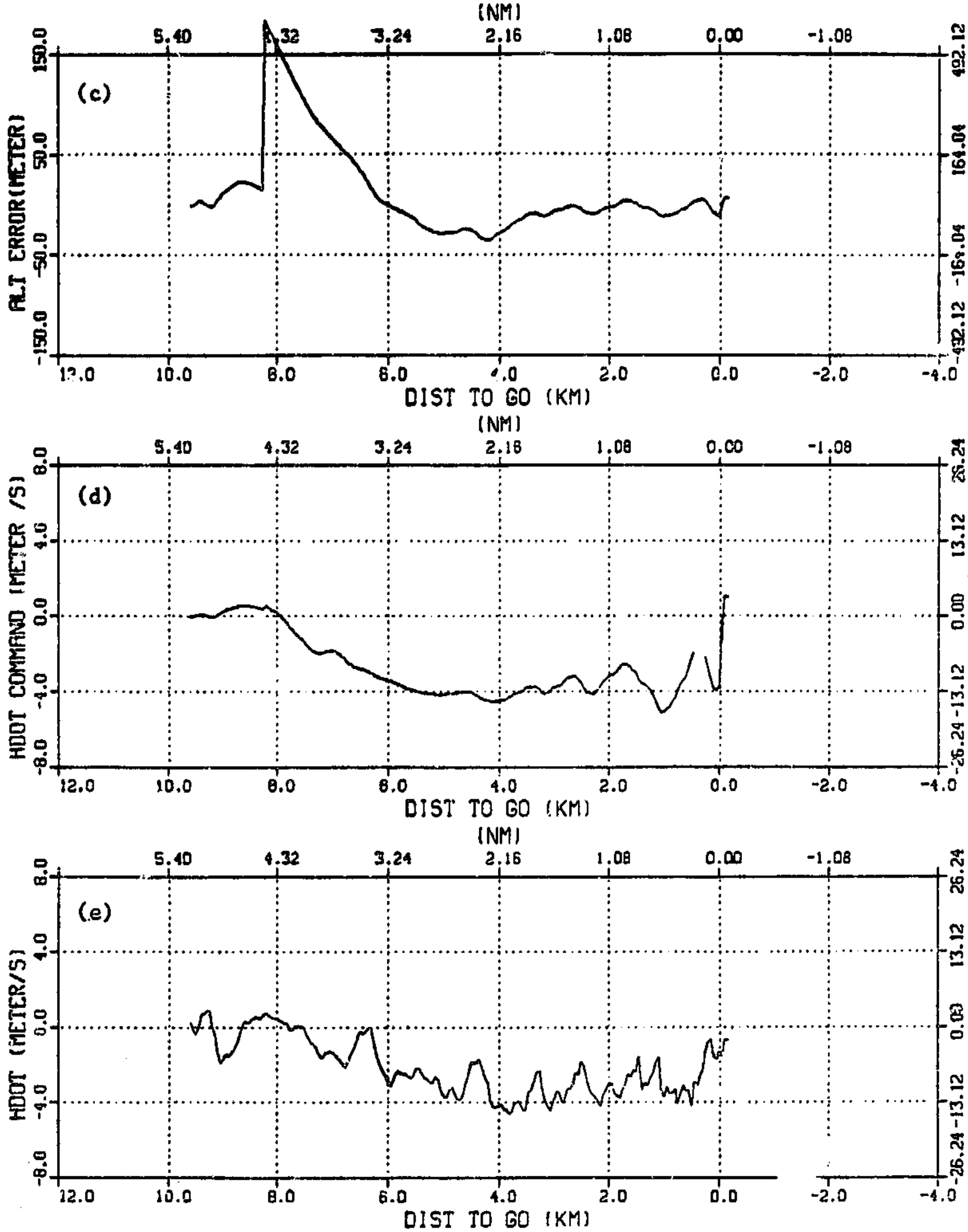


Figure 31. U-Turn: 6 Degrees Glide Slope Data (Continued)

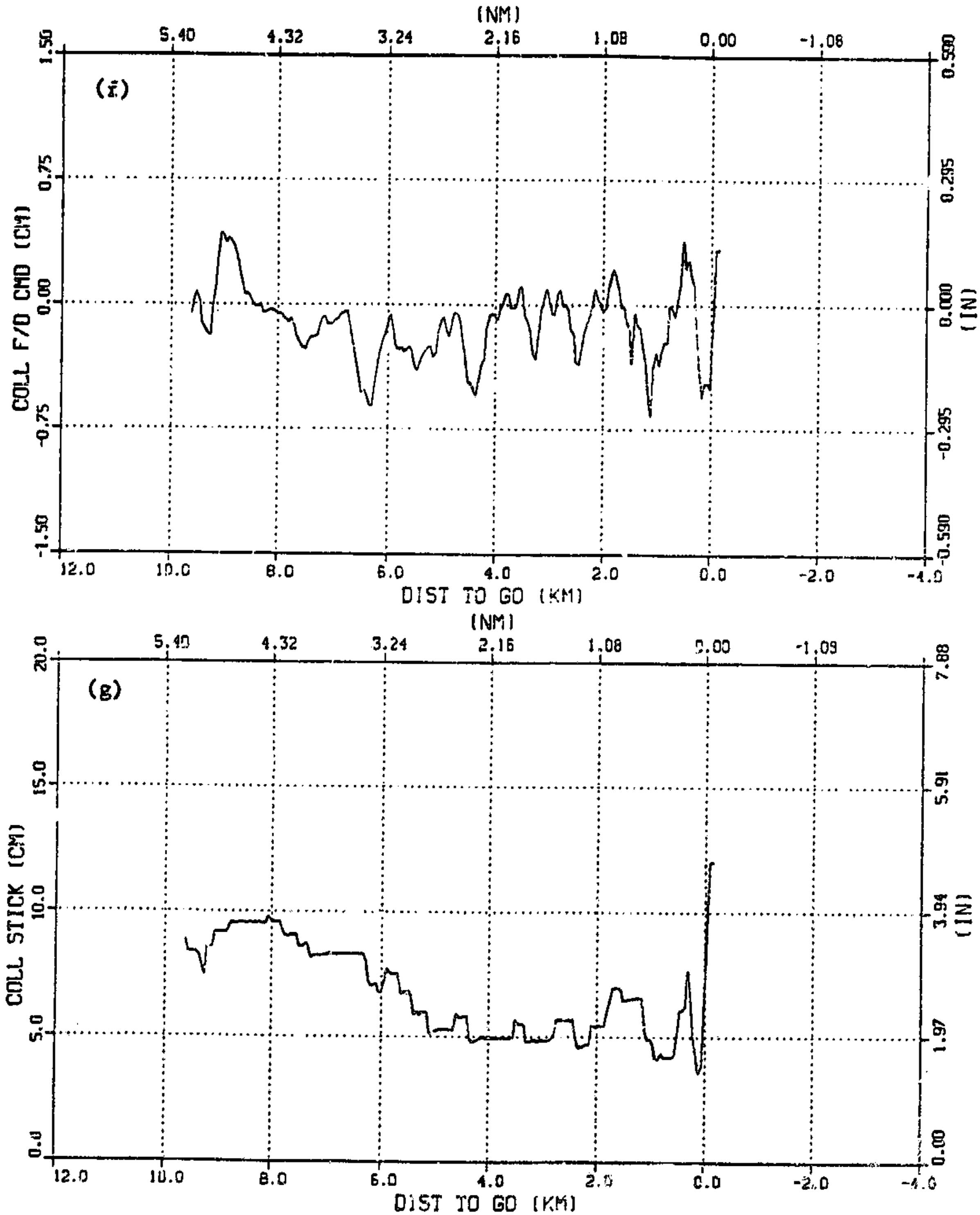


Figure 31. U-Turn: 6 Degrees Glide Slope Data (Continued)

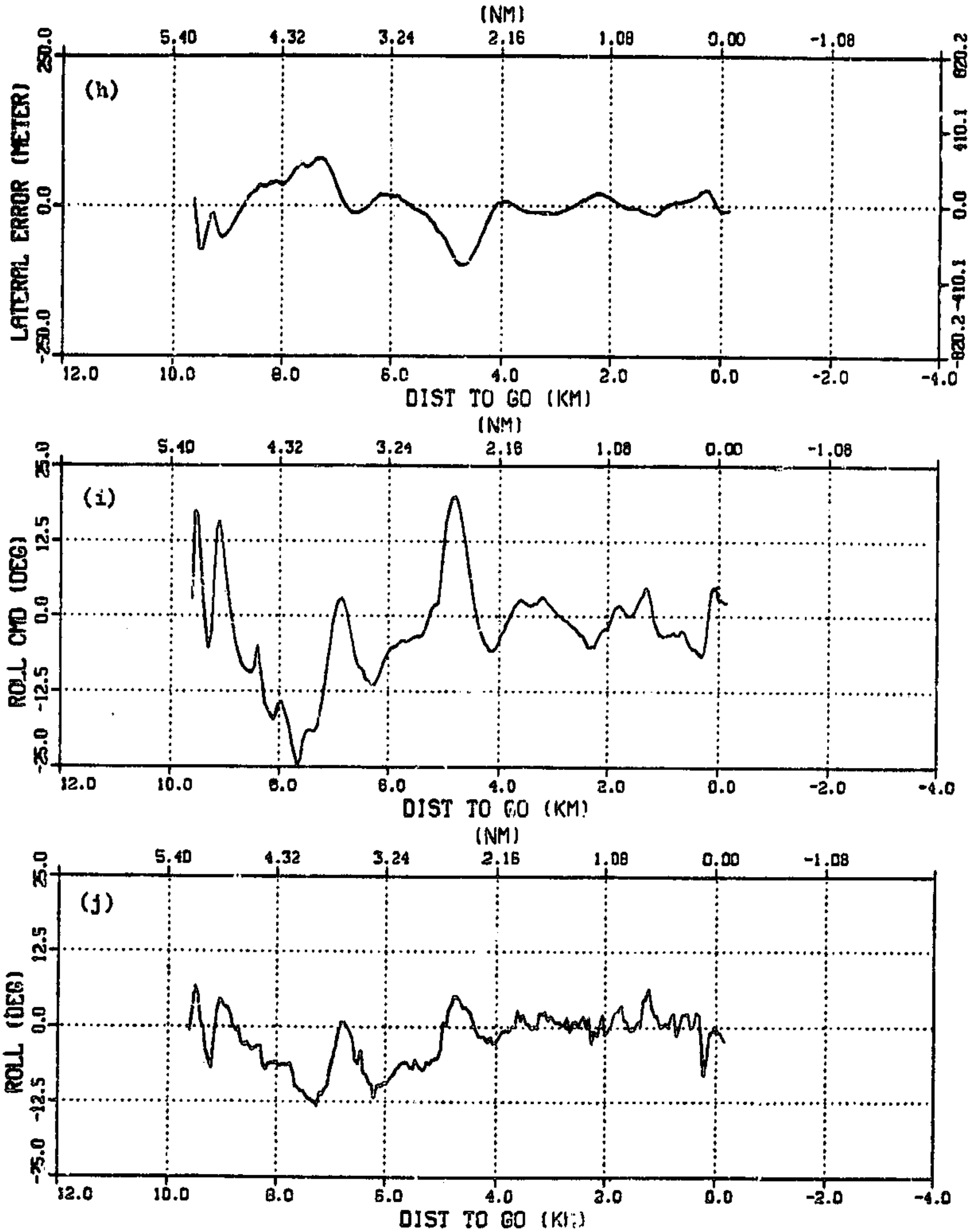
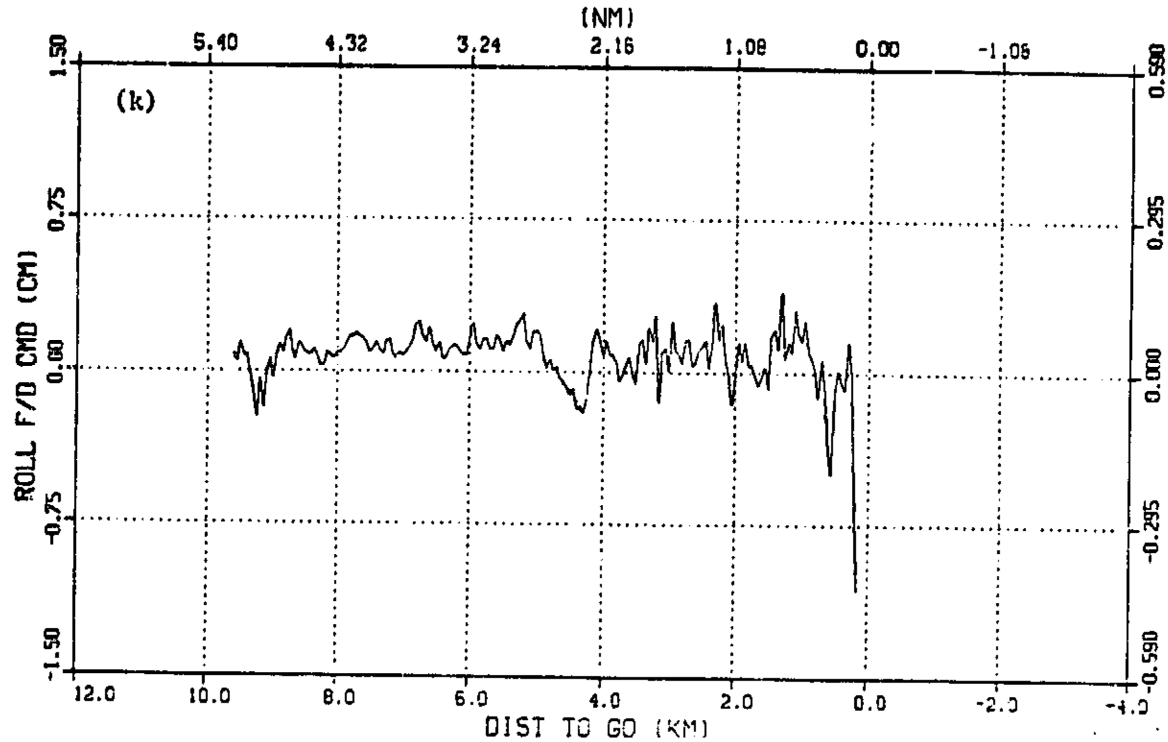
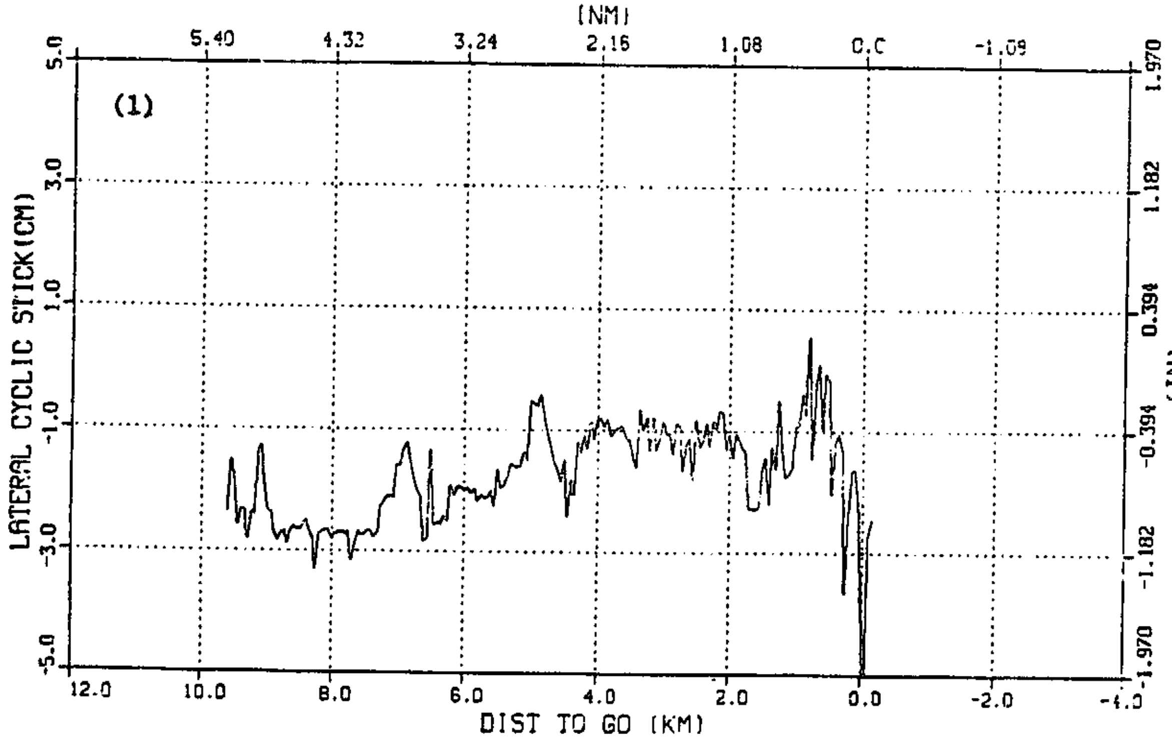


Figure 31. U-Turn: 6 Degrees Glide Slope Data (Continued)





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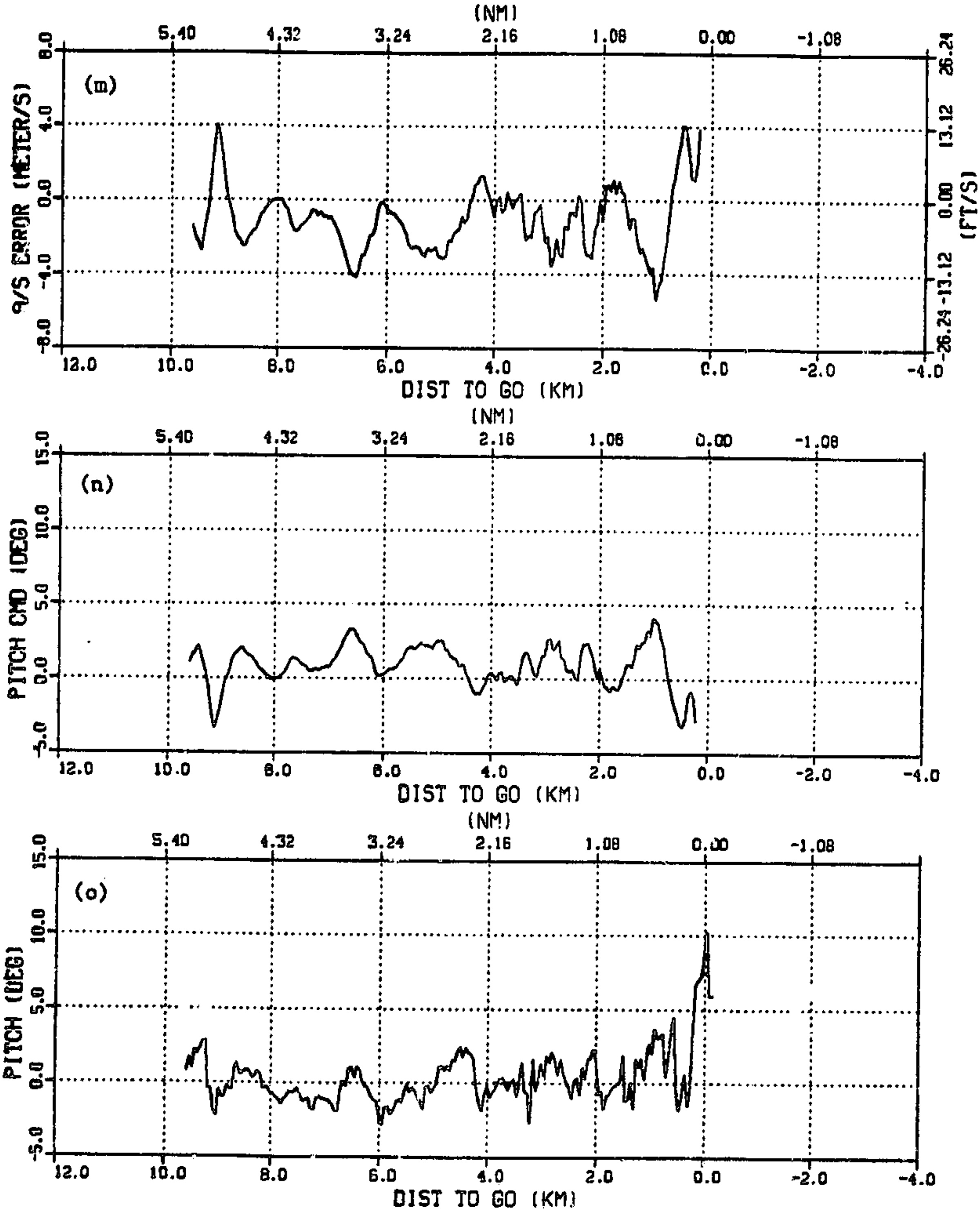
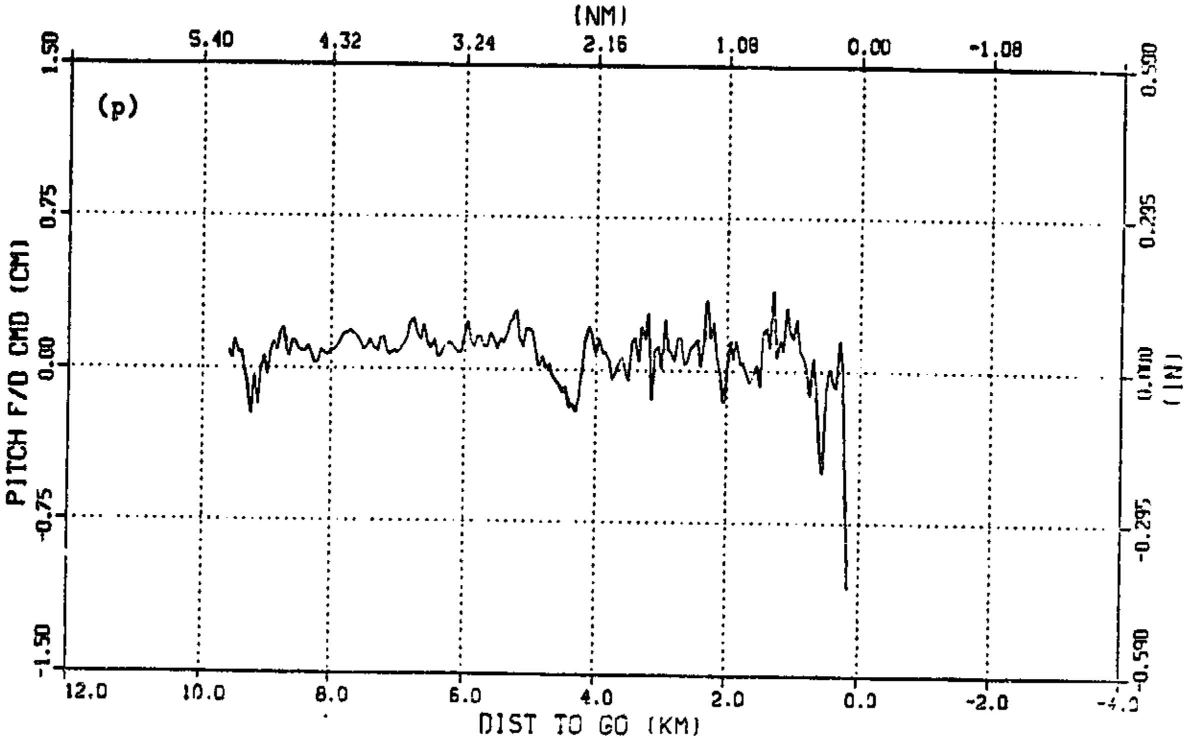


Figure 31. U-Turn: 6 Degrees Glide Slope Data (Continued)



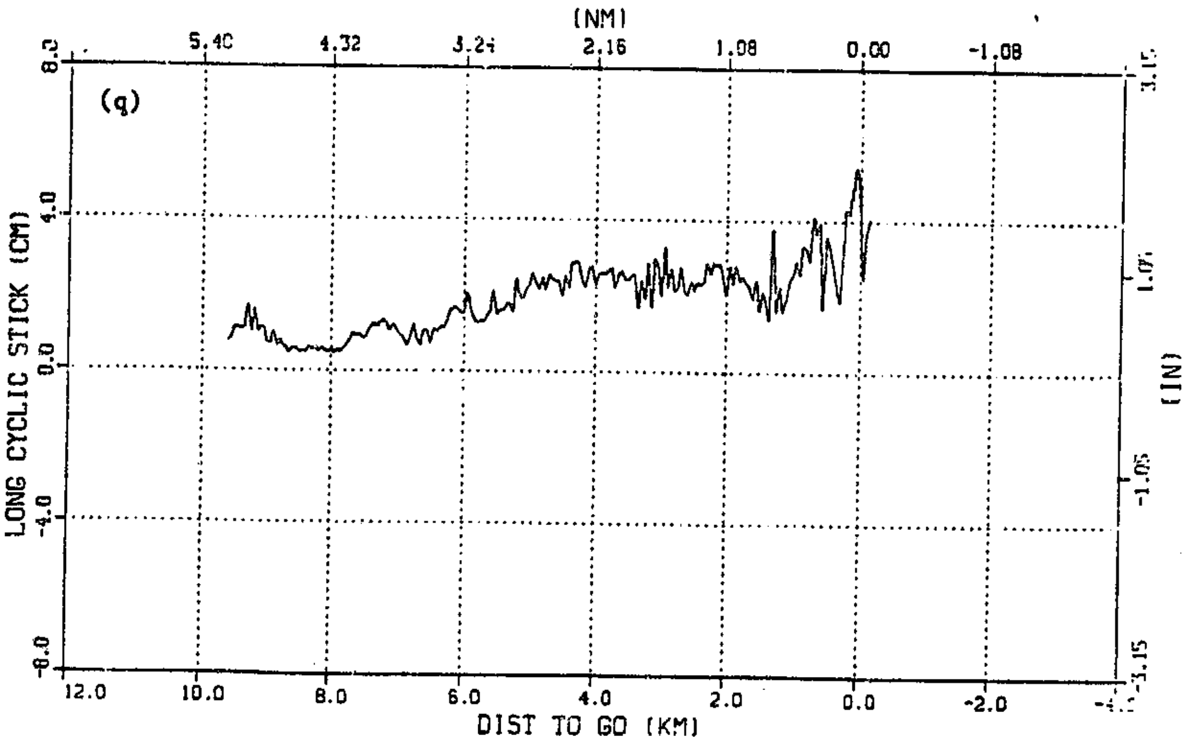


Figure 31. U-Turn: 6 Degrees Glide Slope Data (Continued)

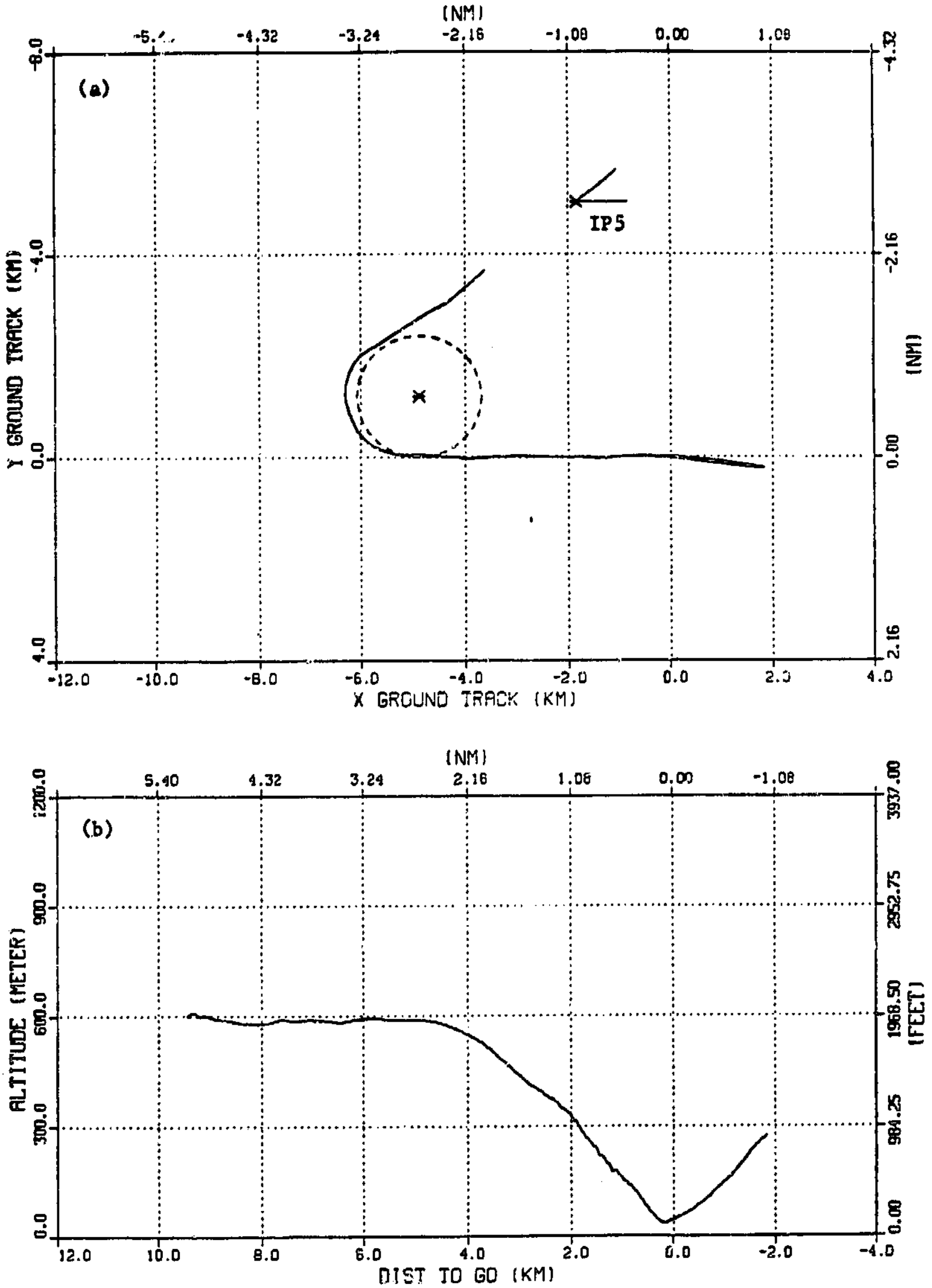
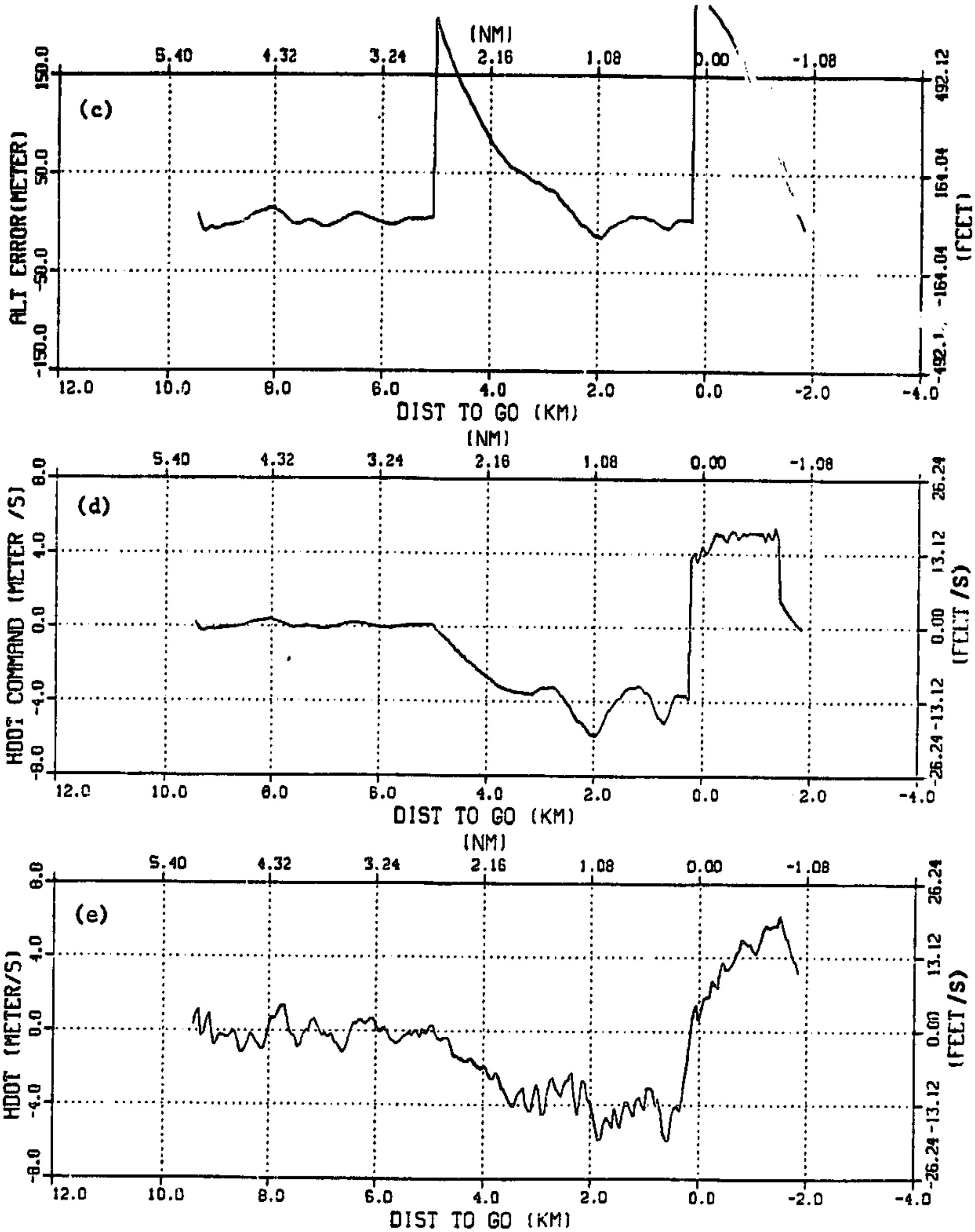


Figure 32. U-Turn: 9 Degrees Glide Slope Data



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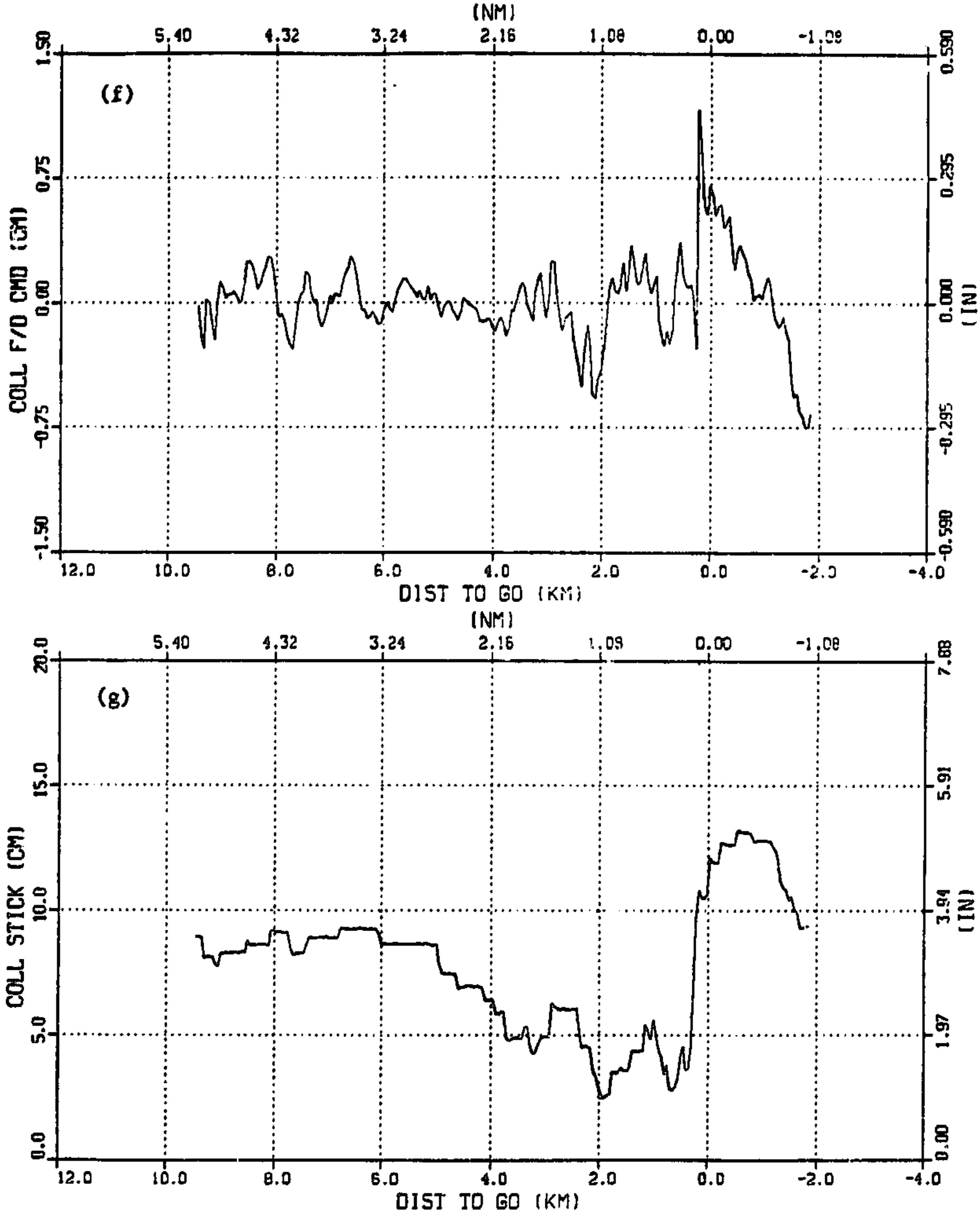

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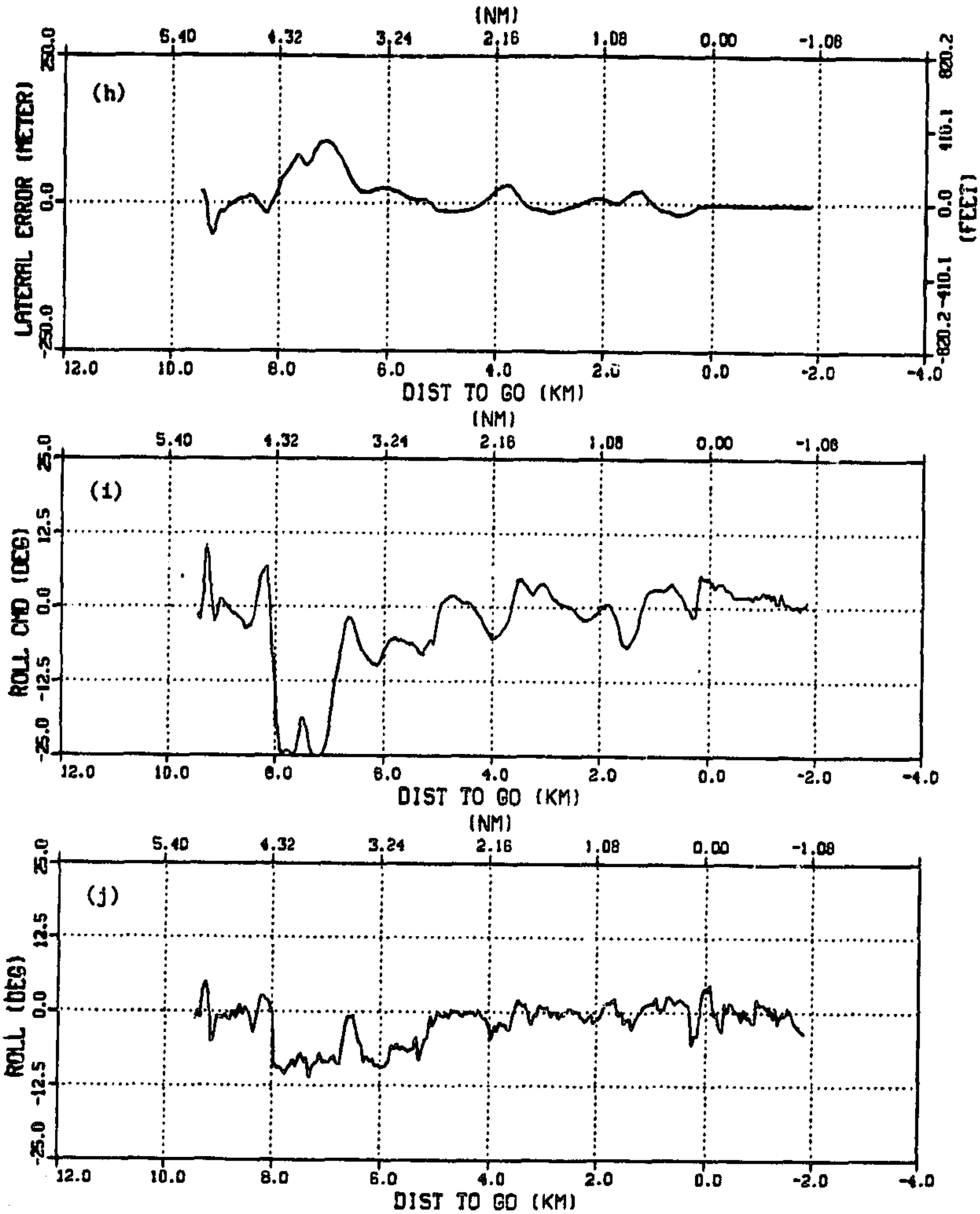

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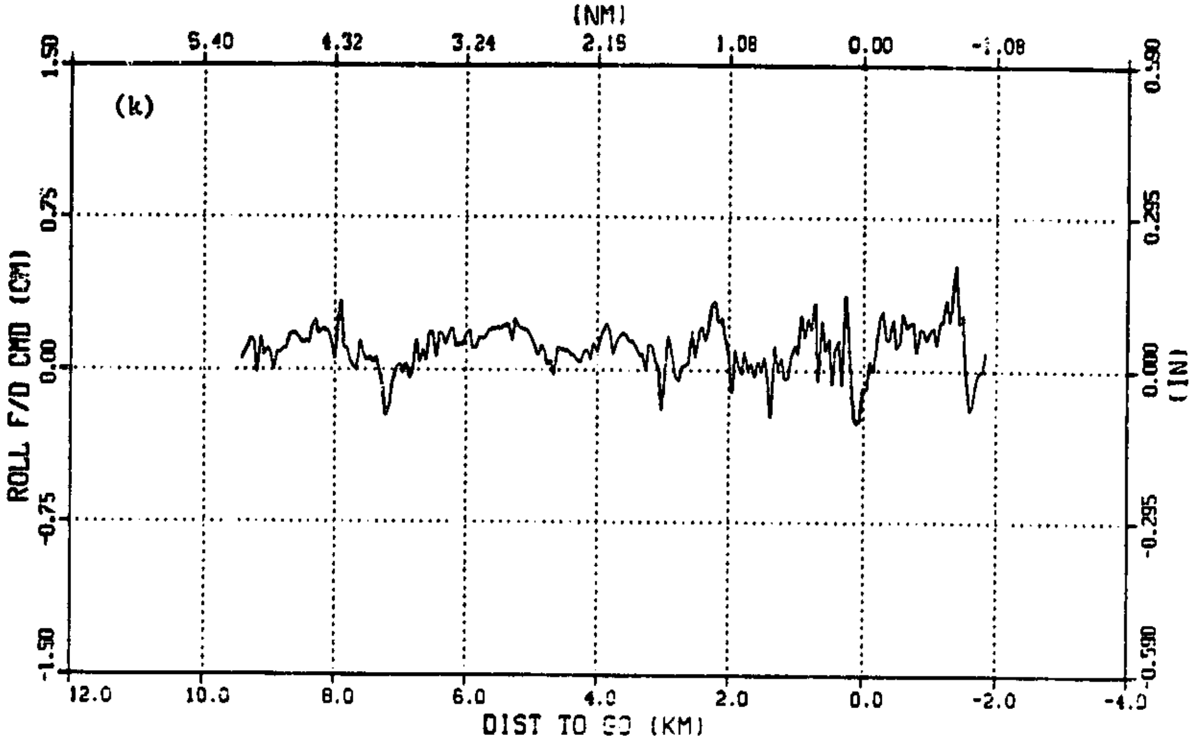

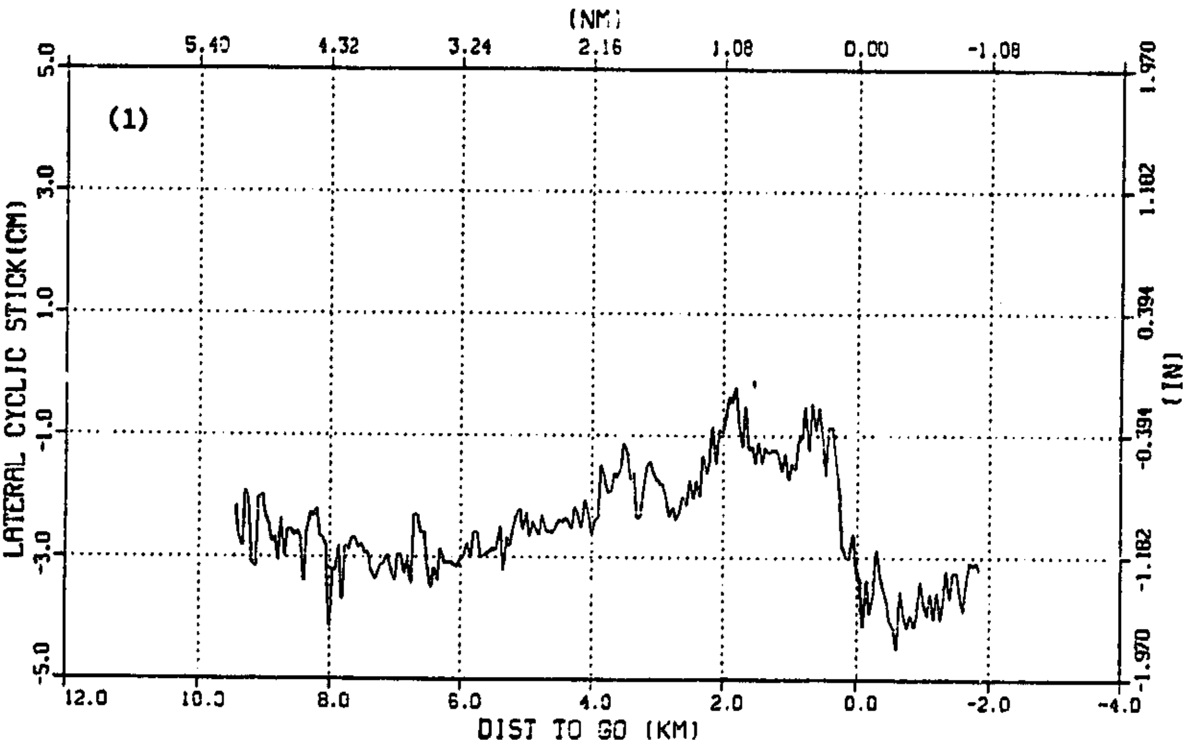

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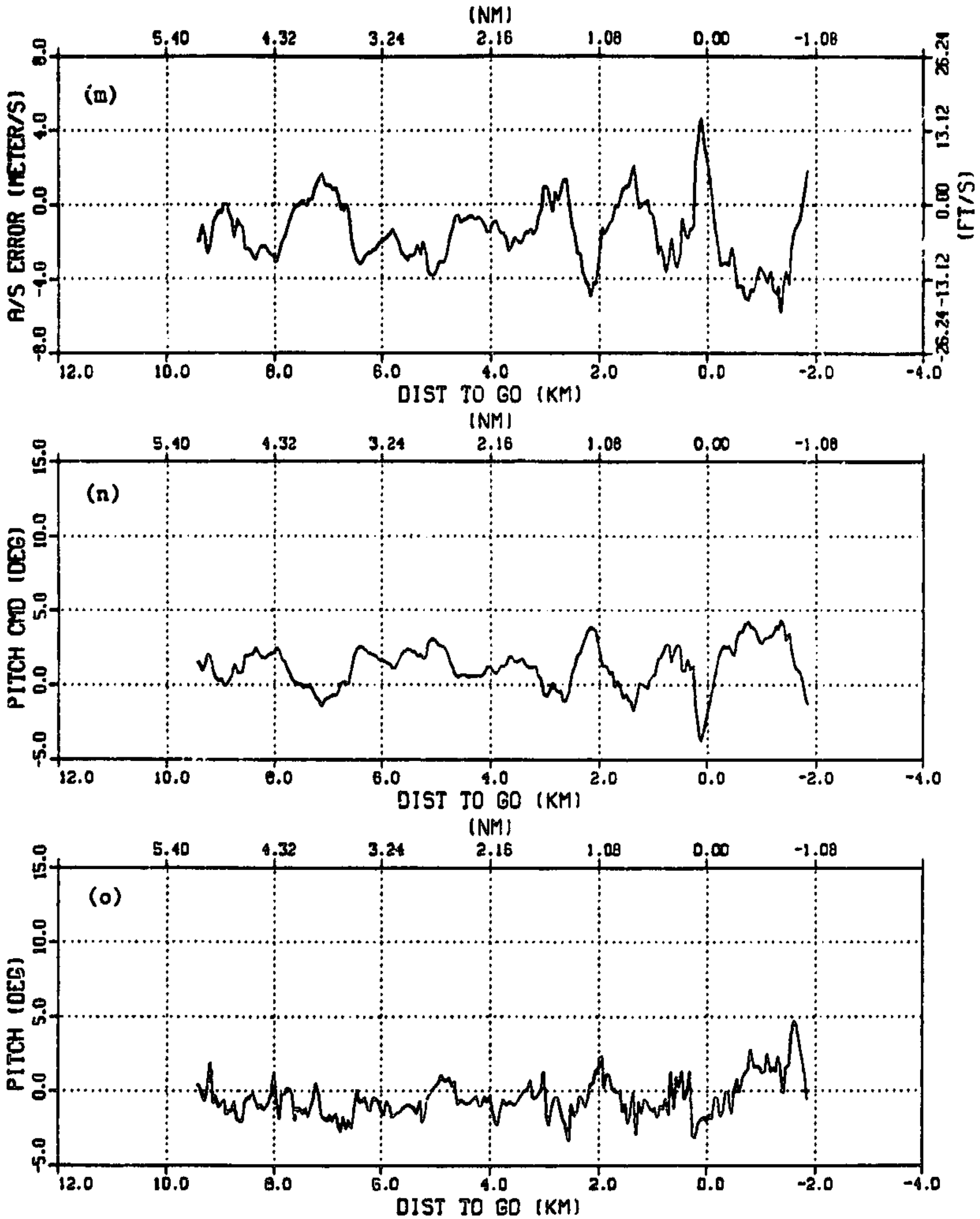

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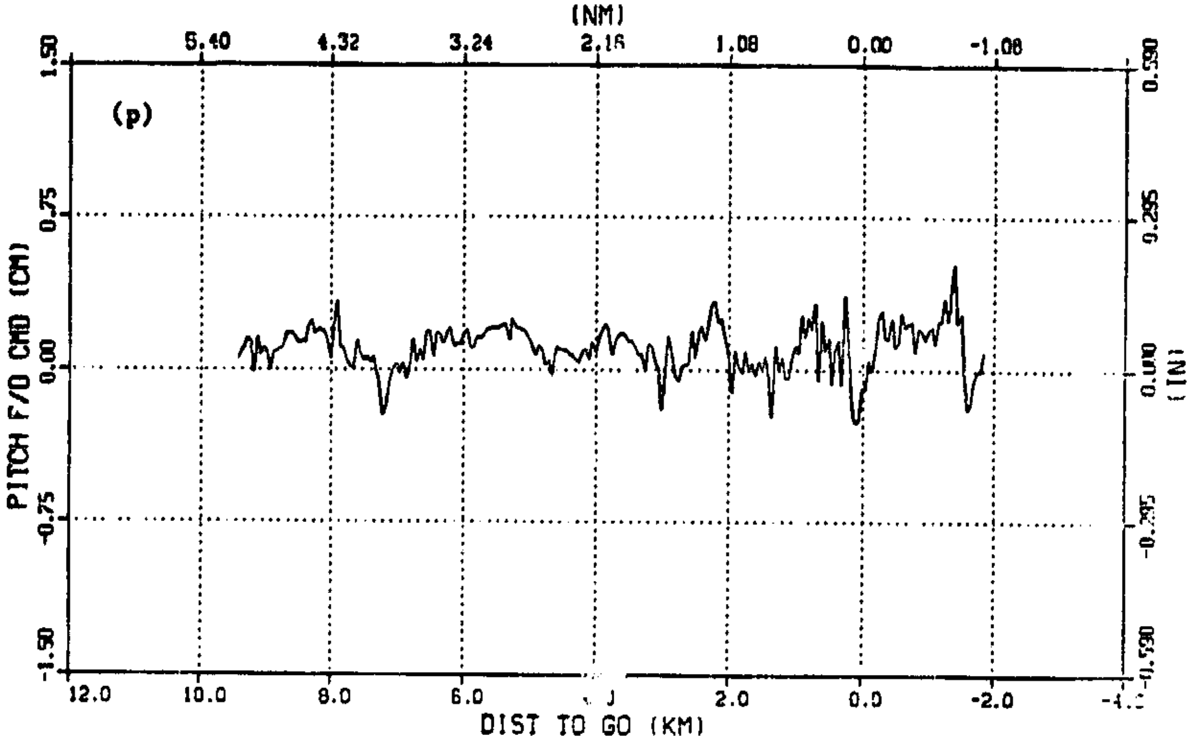

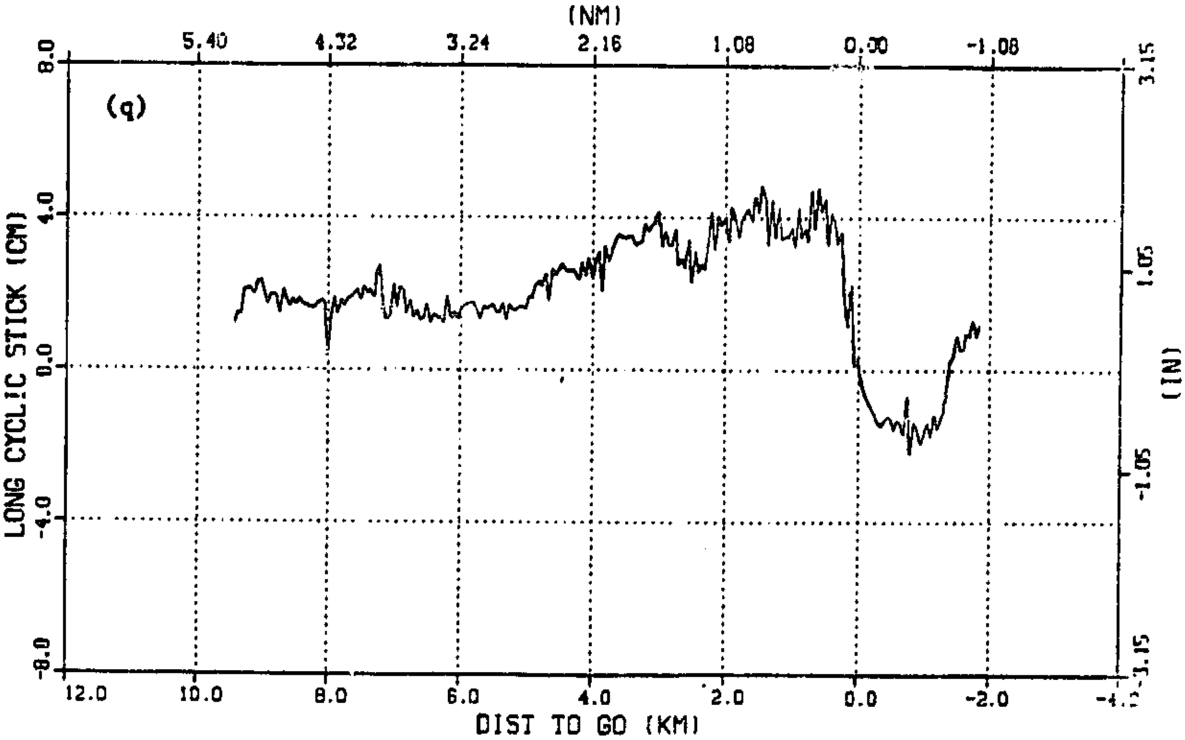

Figure 32. U-Turn: 9 Degrees Glide Slope Data (Continued)

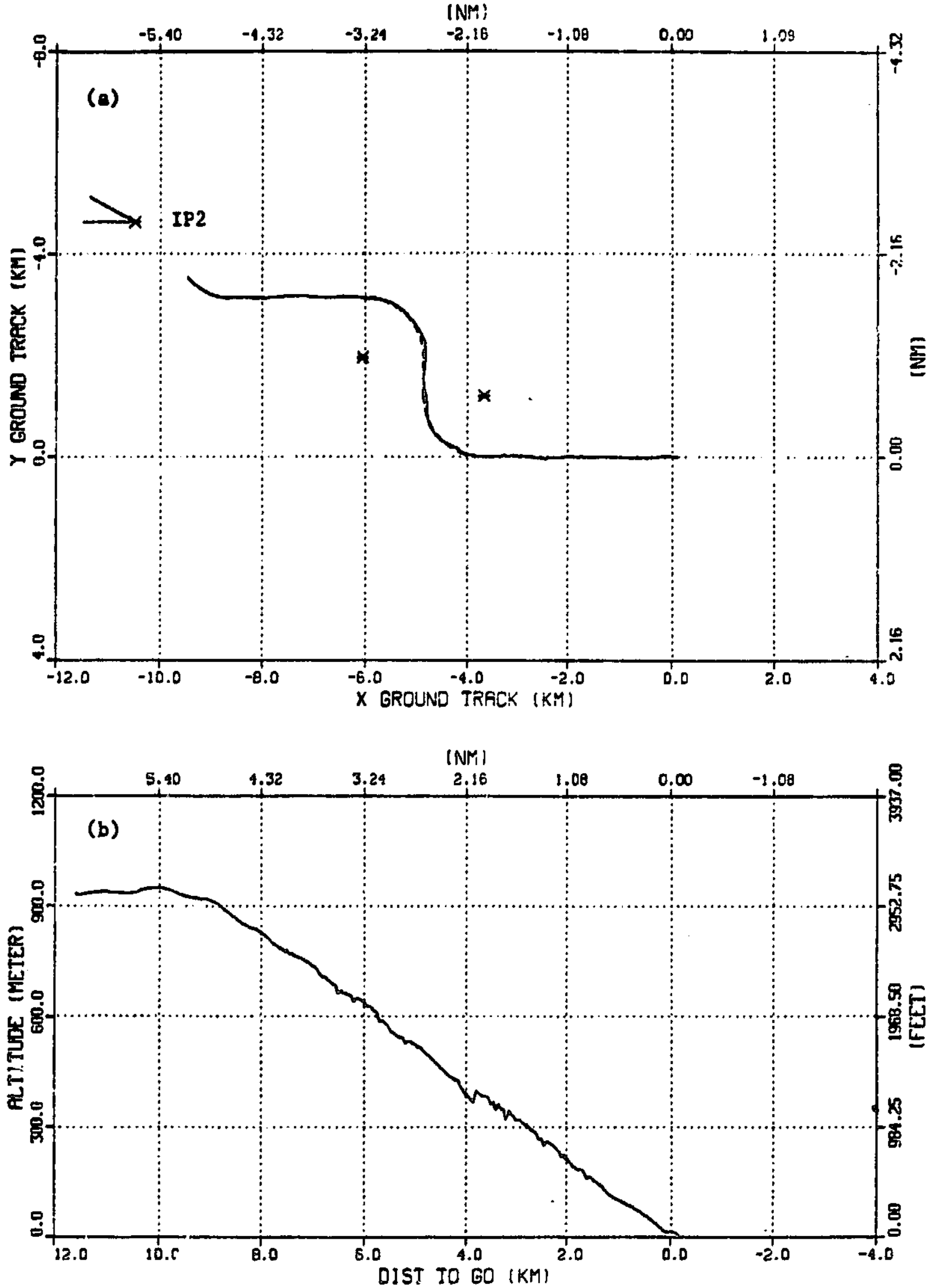

Figure 33. S-Turn: 6 Degrees Glide Slope Data

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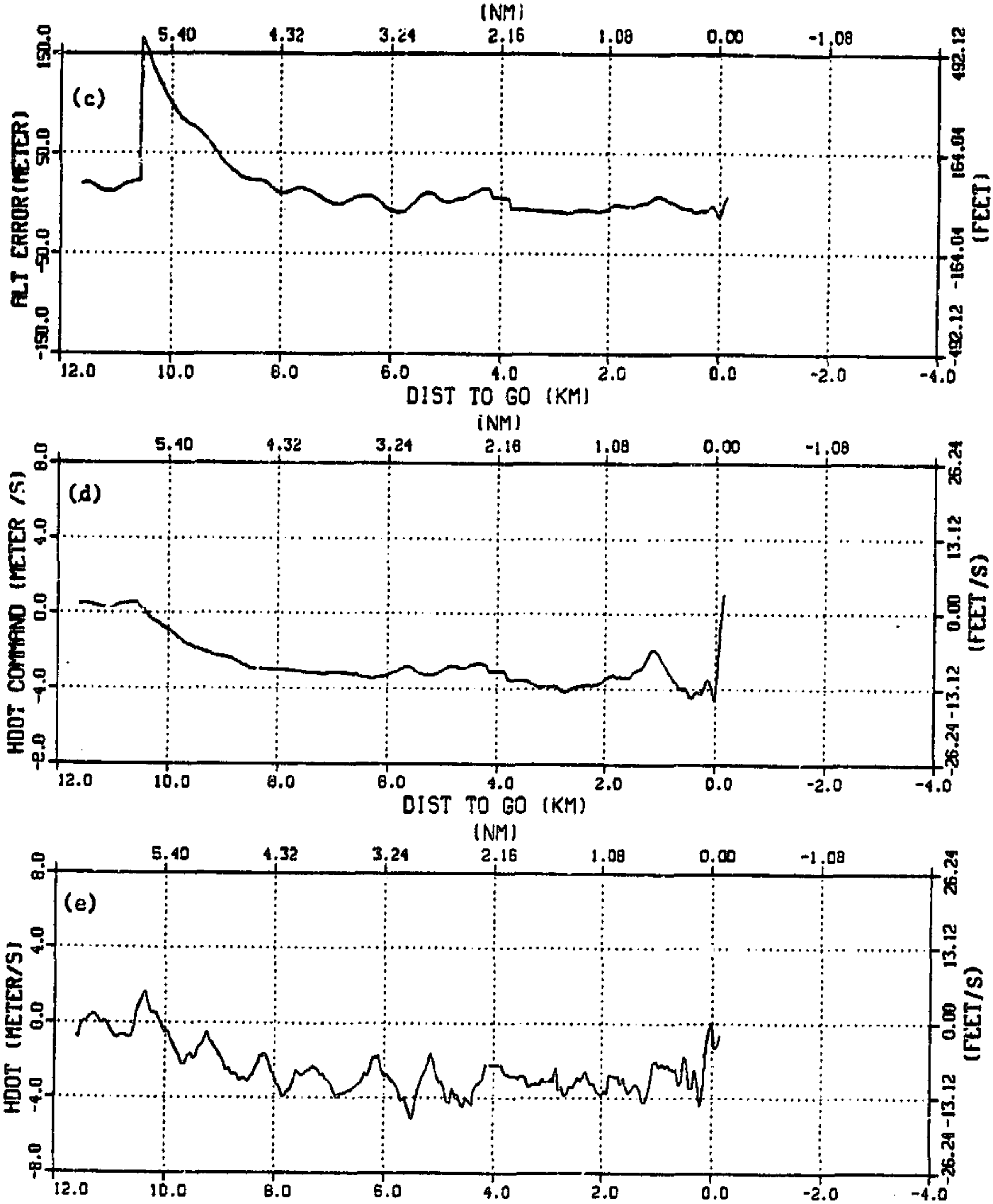

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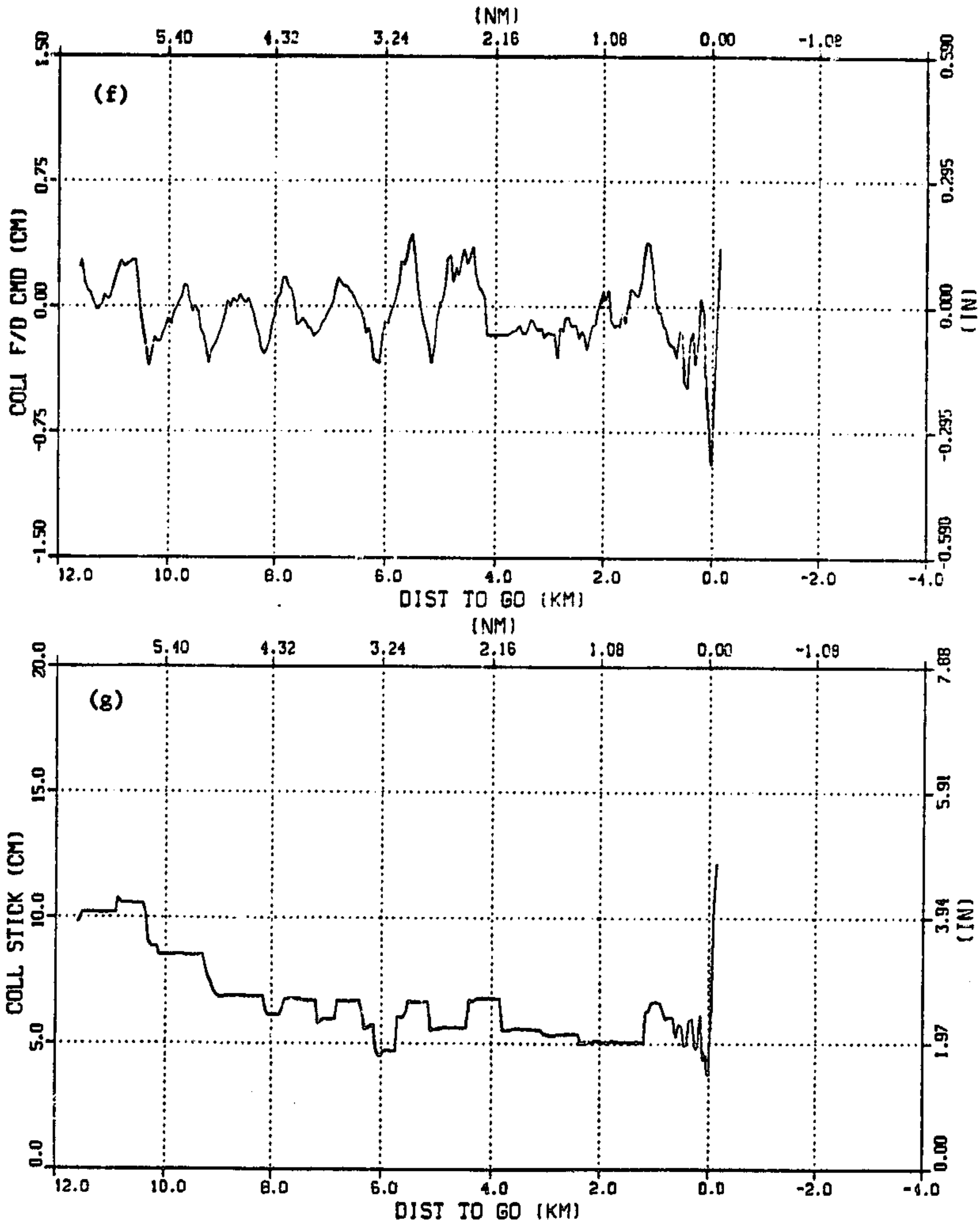

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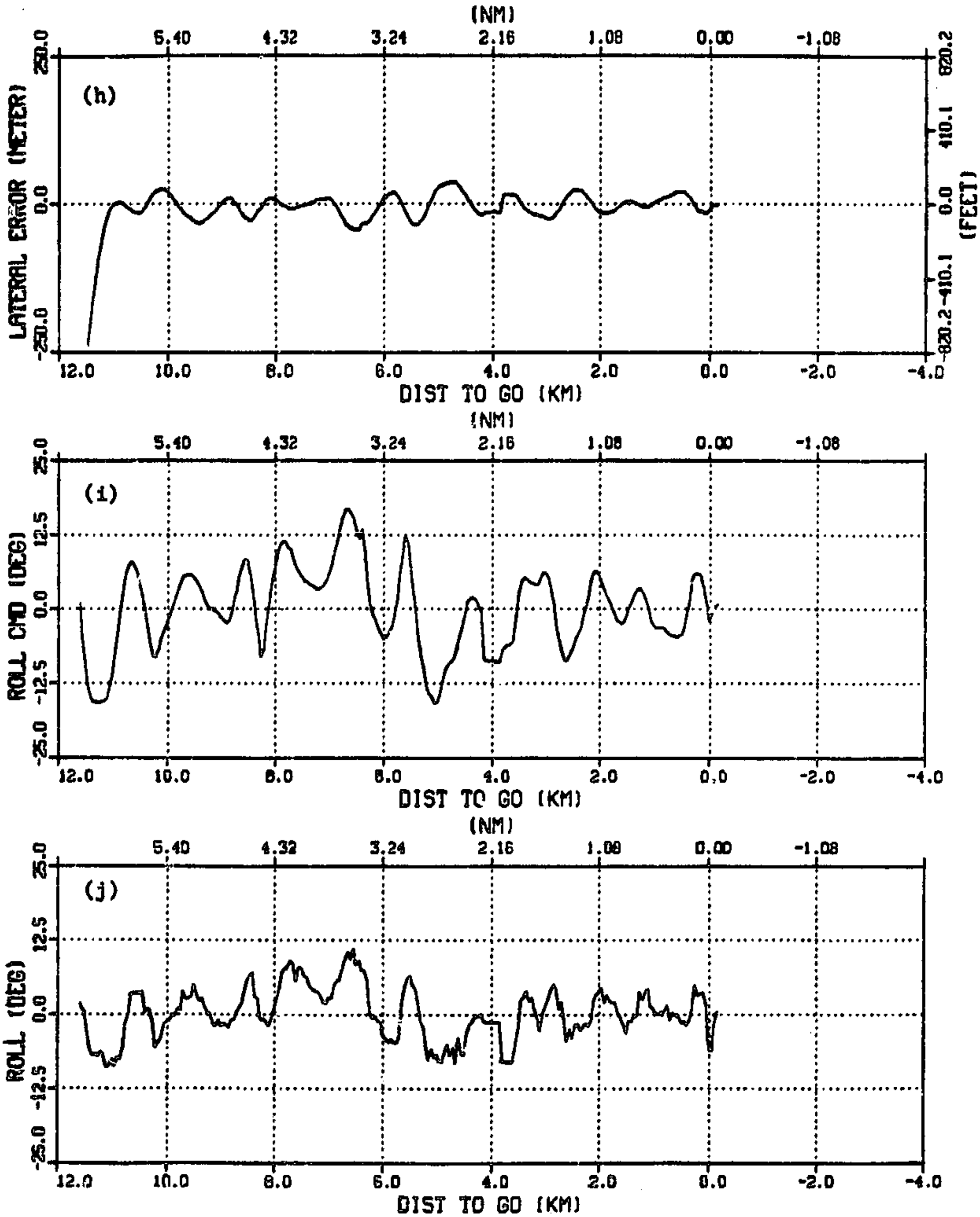
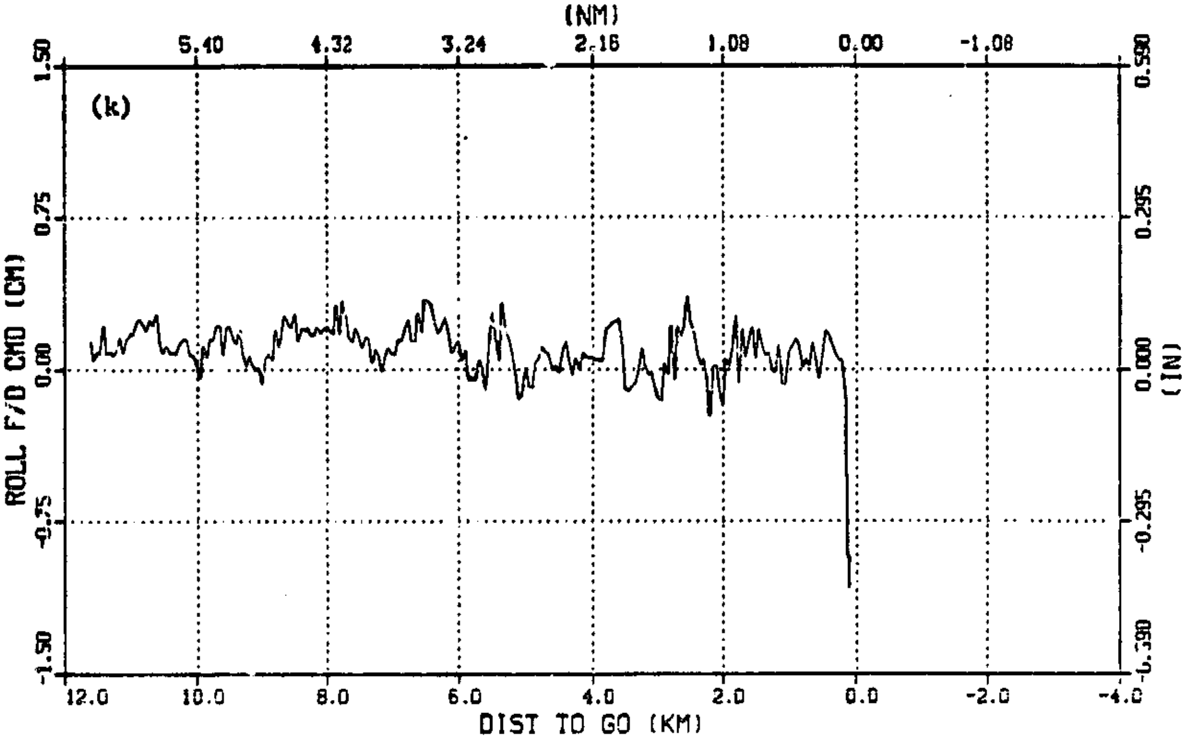


Figure 33. S-Turn: 6 Degrees Glide Slope Data (Continued)



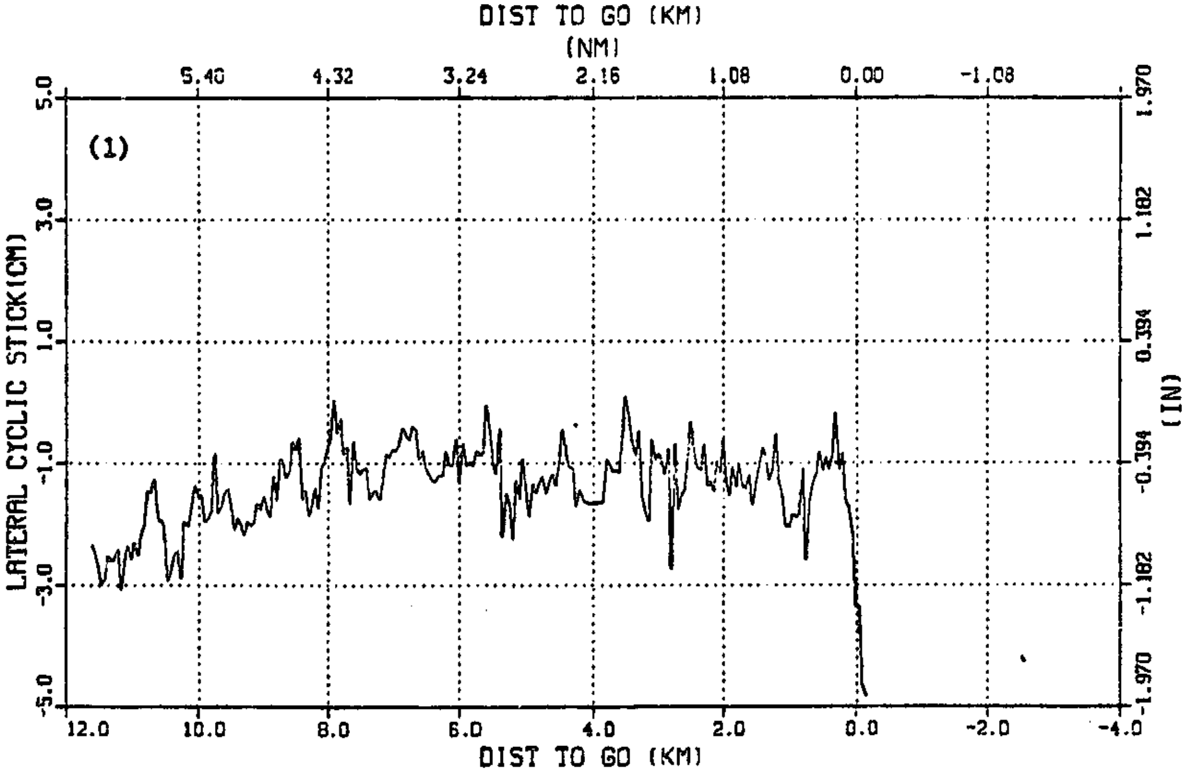
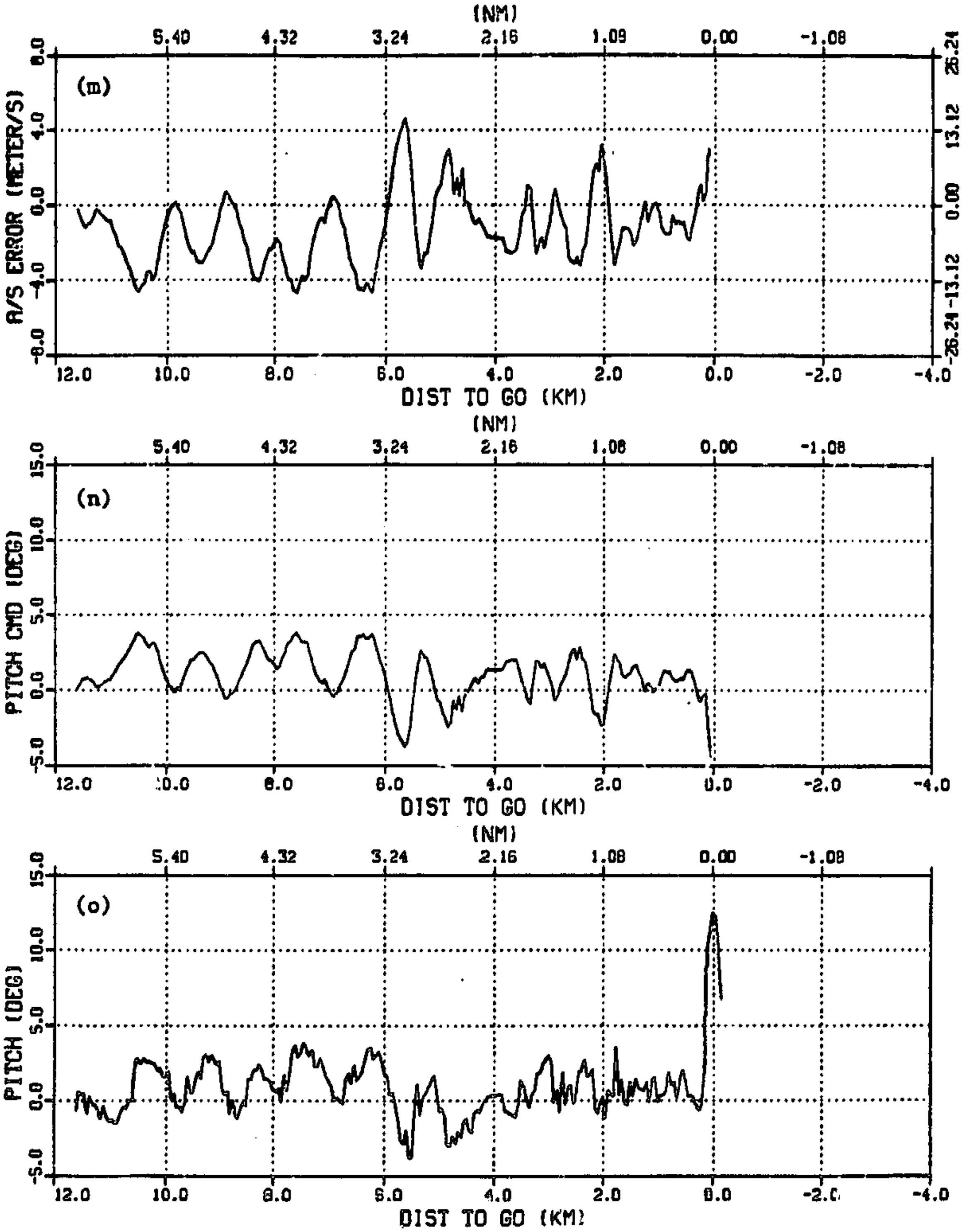


Figure 33. S-Turn: 6 Degrees Glide Slope Data (Continued)



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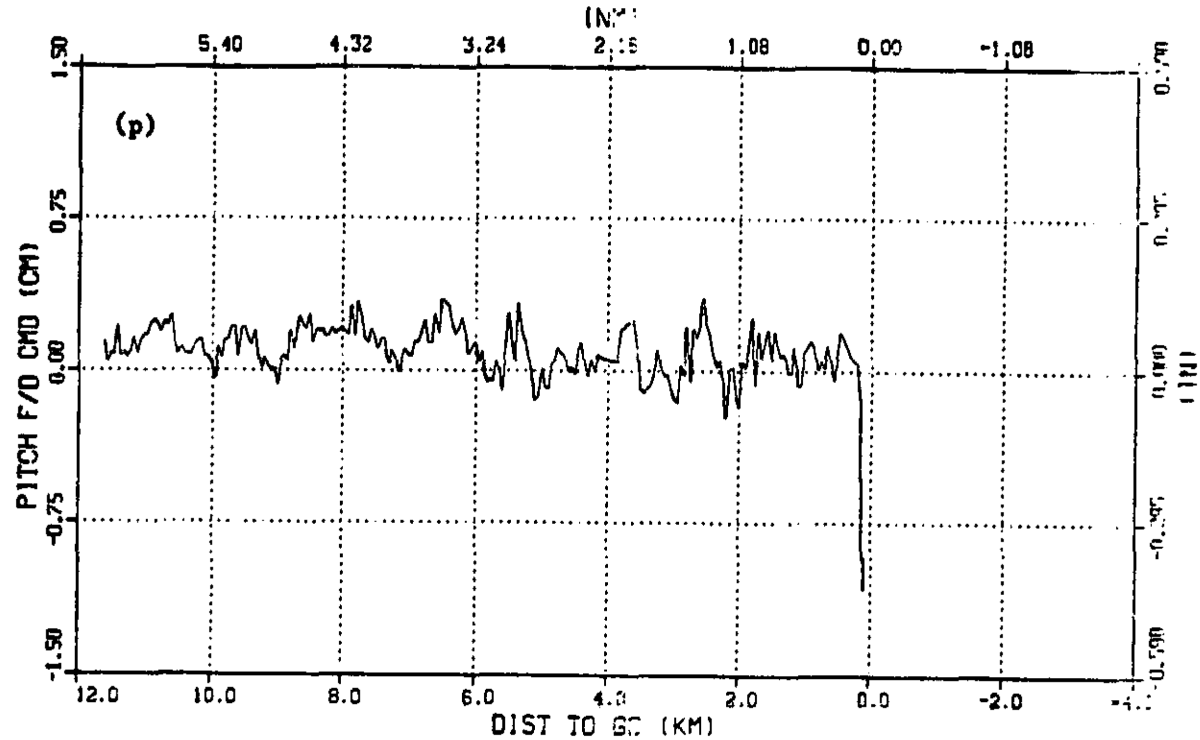


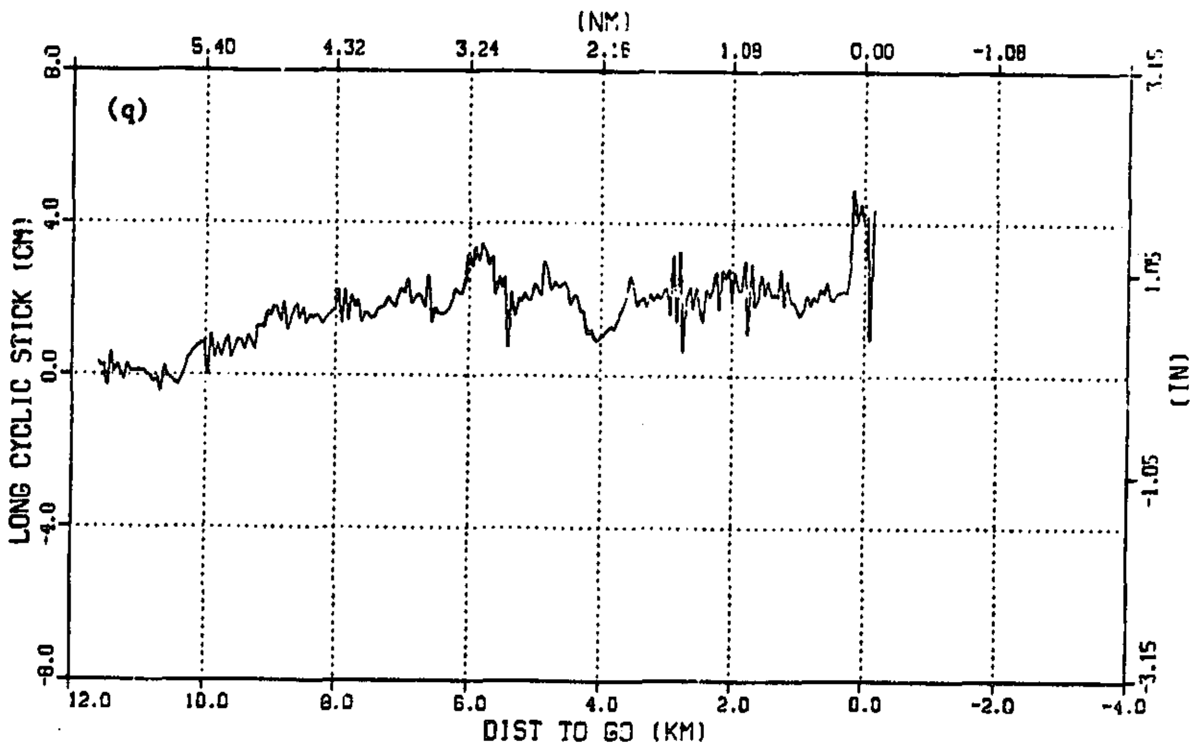
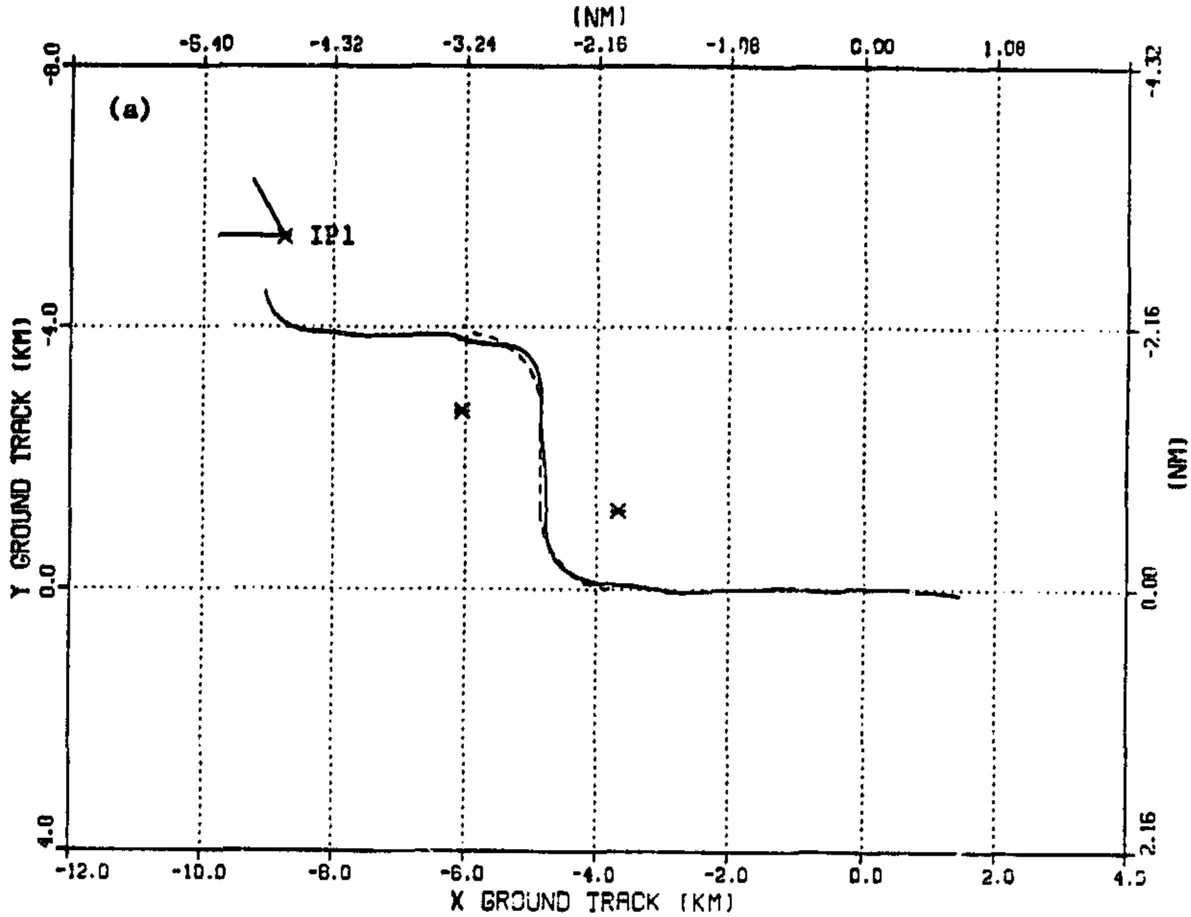


Figure 33. S-Turn: 6 Degrees Glide Slope Data (Continued)



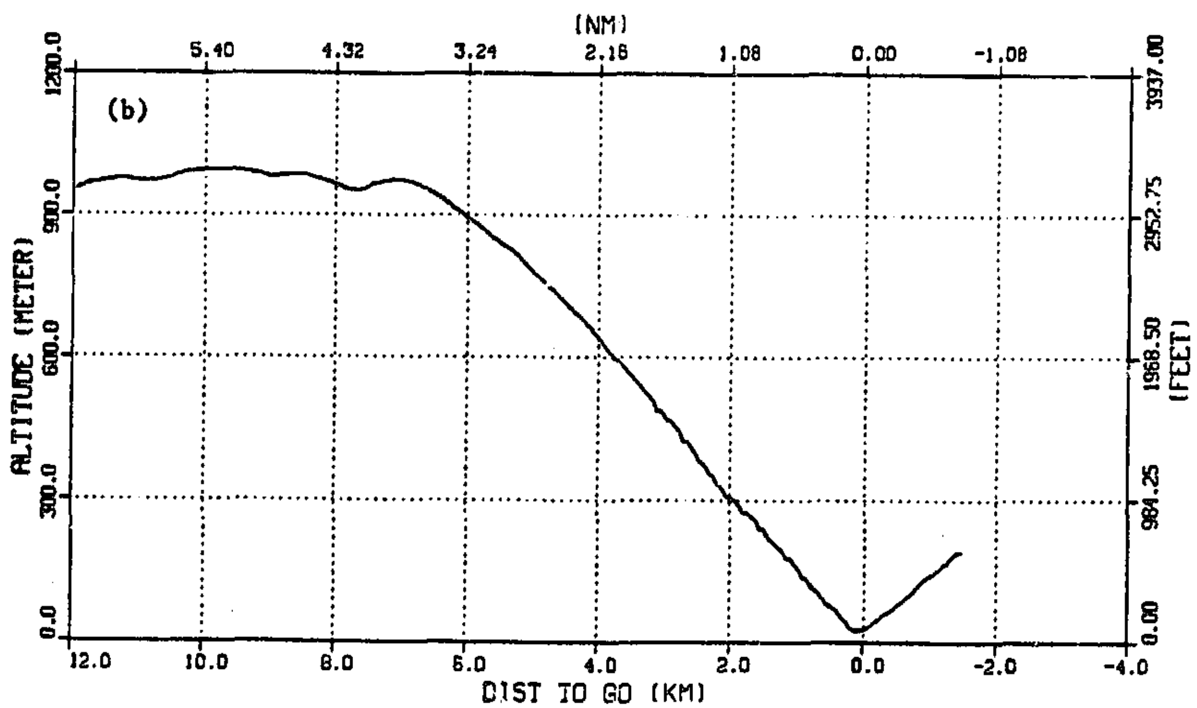
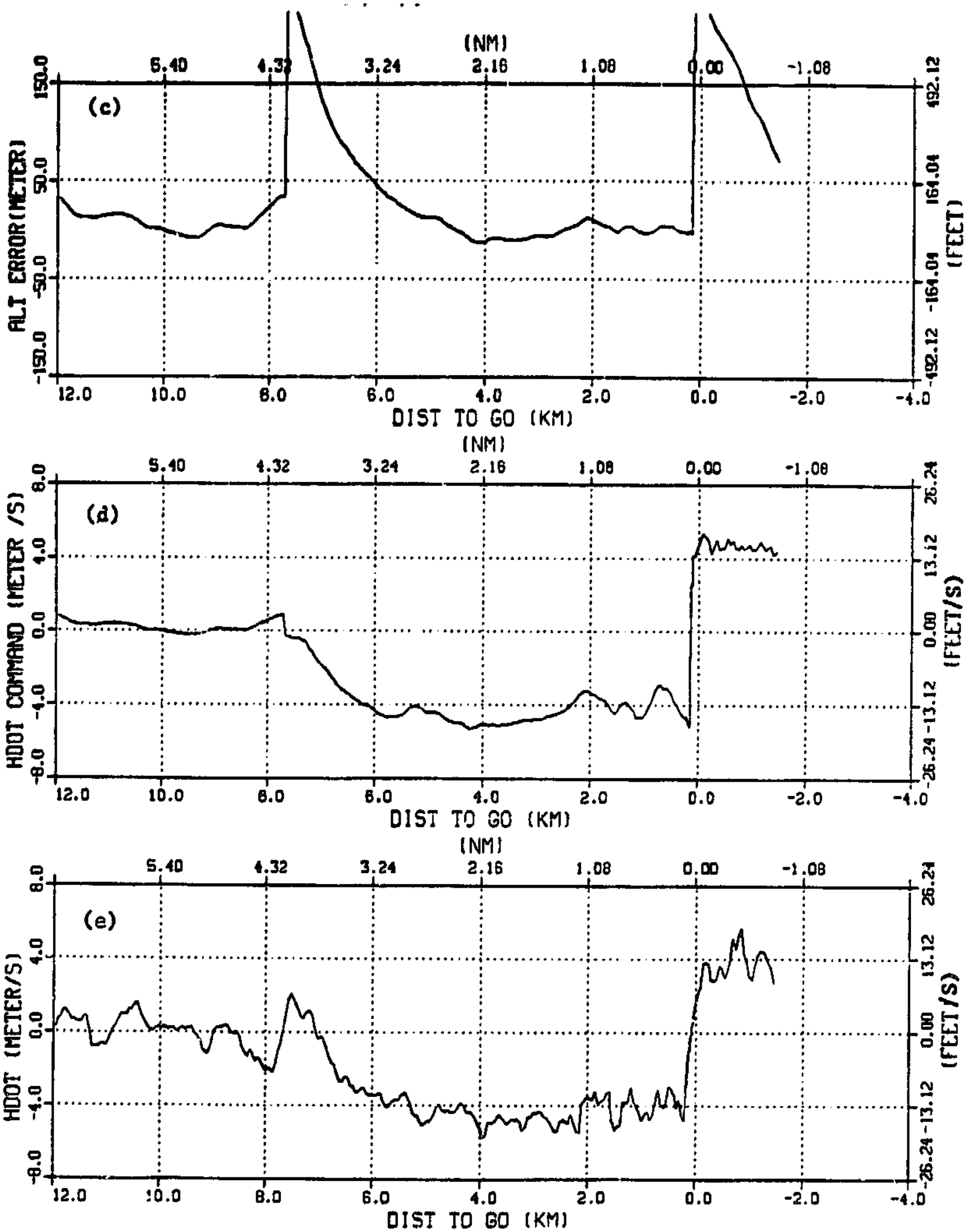


Figure 34. S-Turn: 9 Degrees Glide Slope Data



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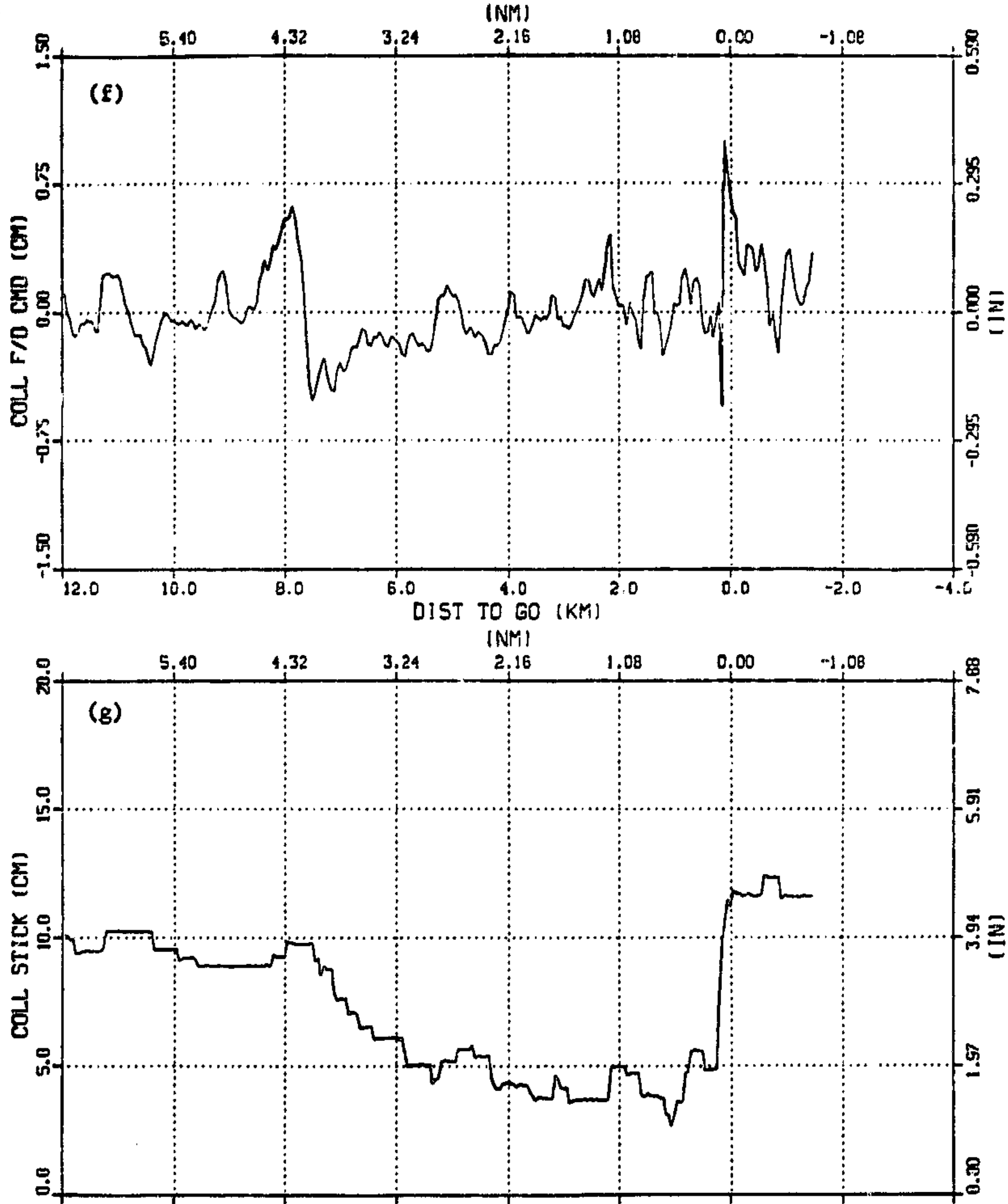

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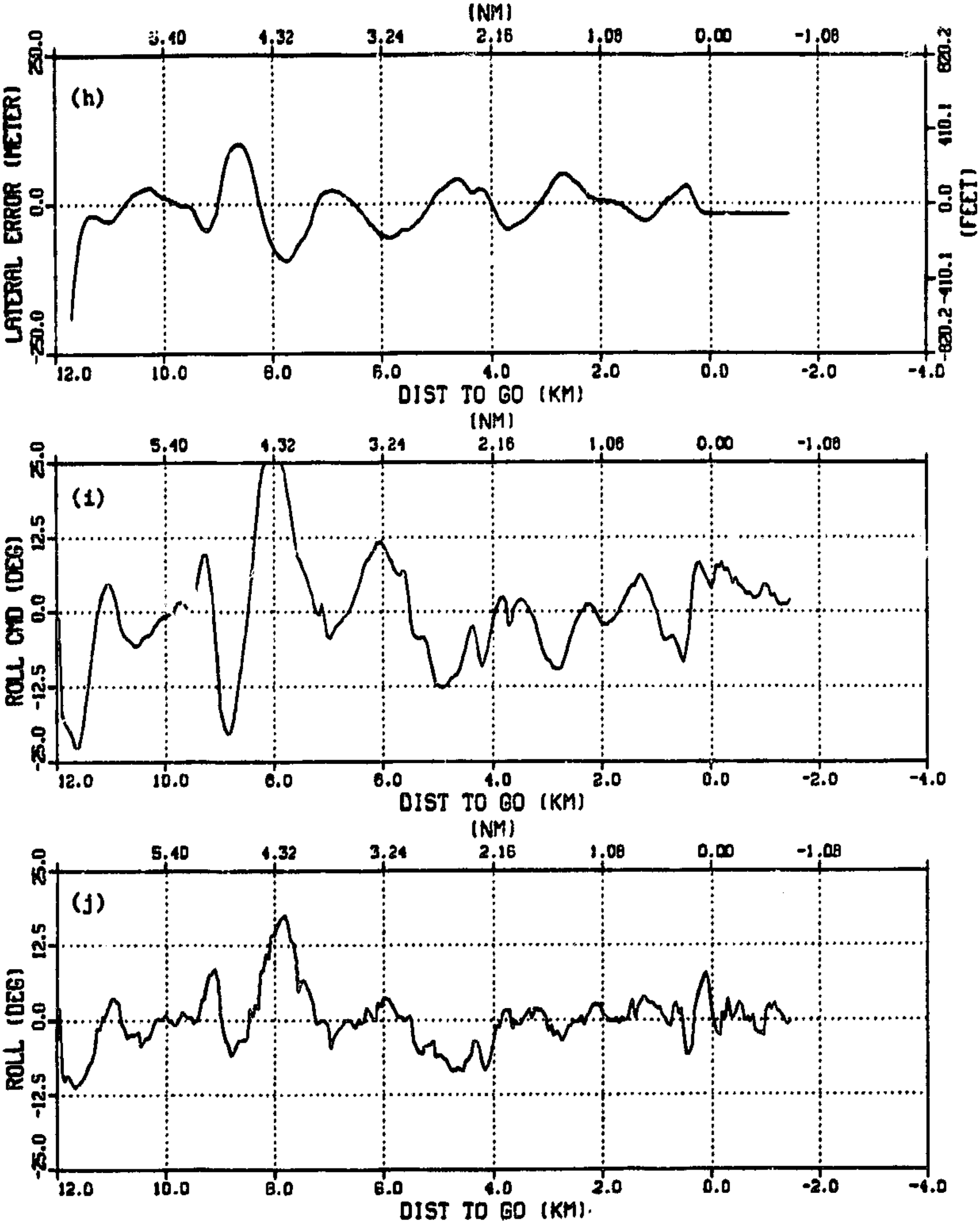

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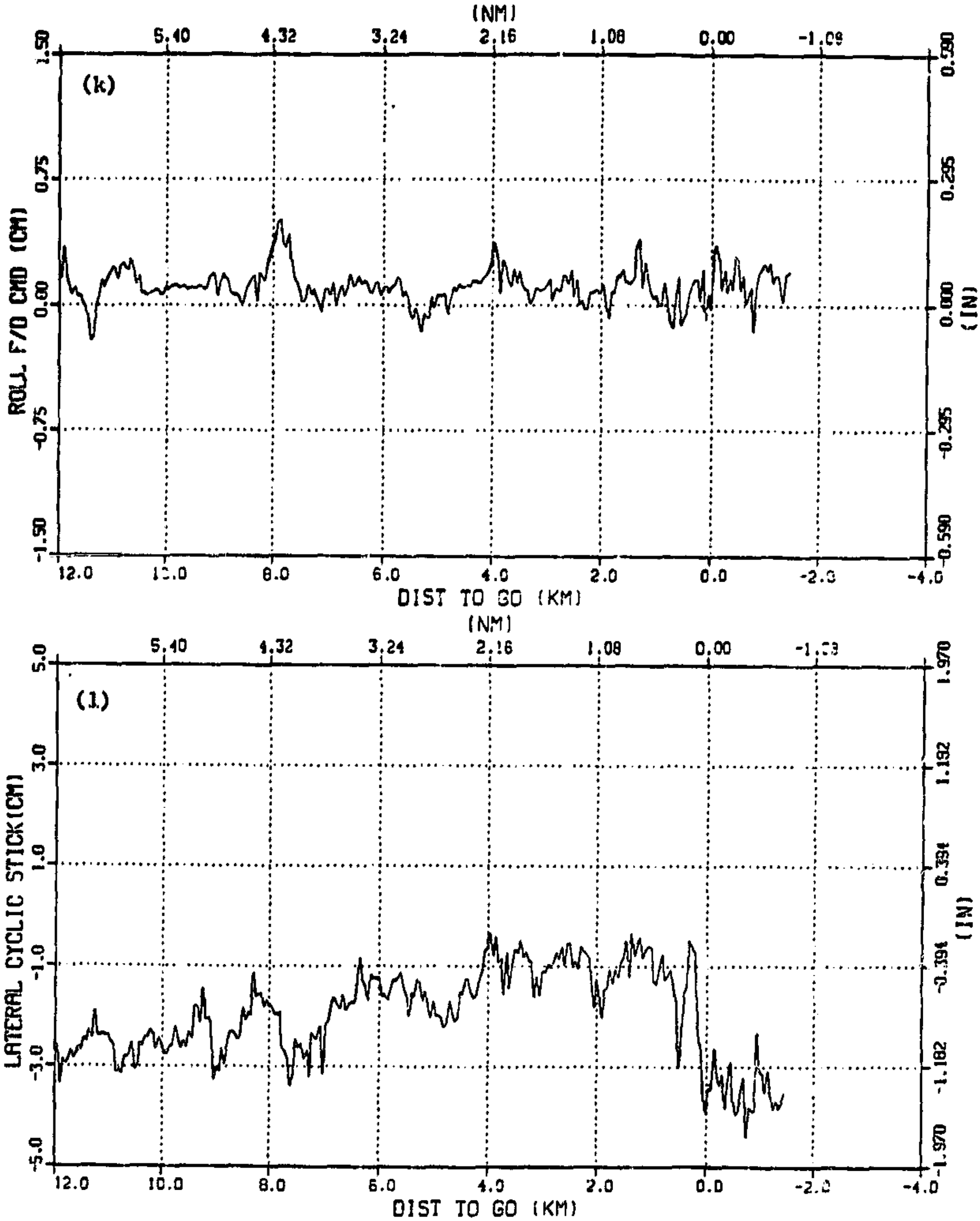

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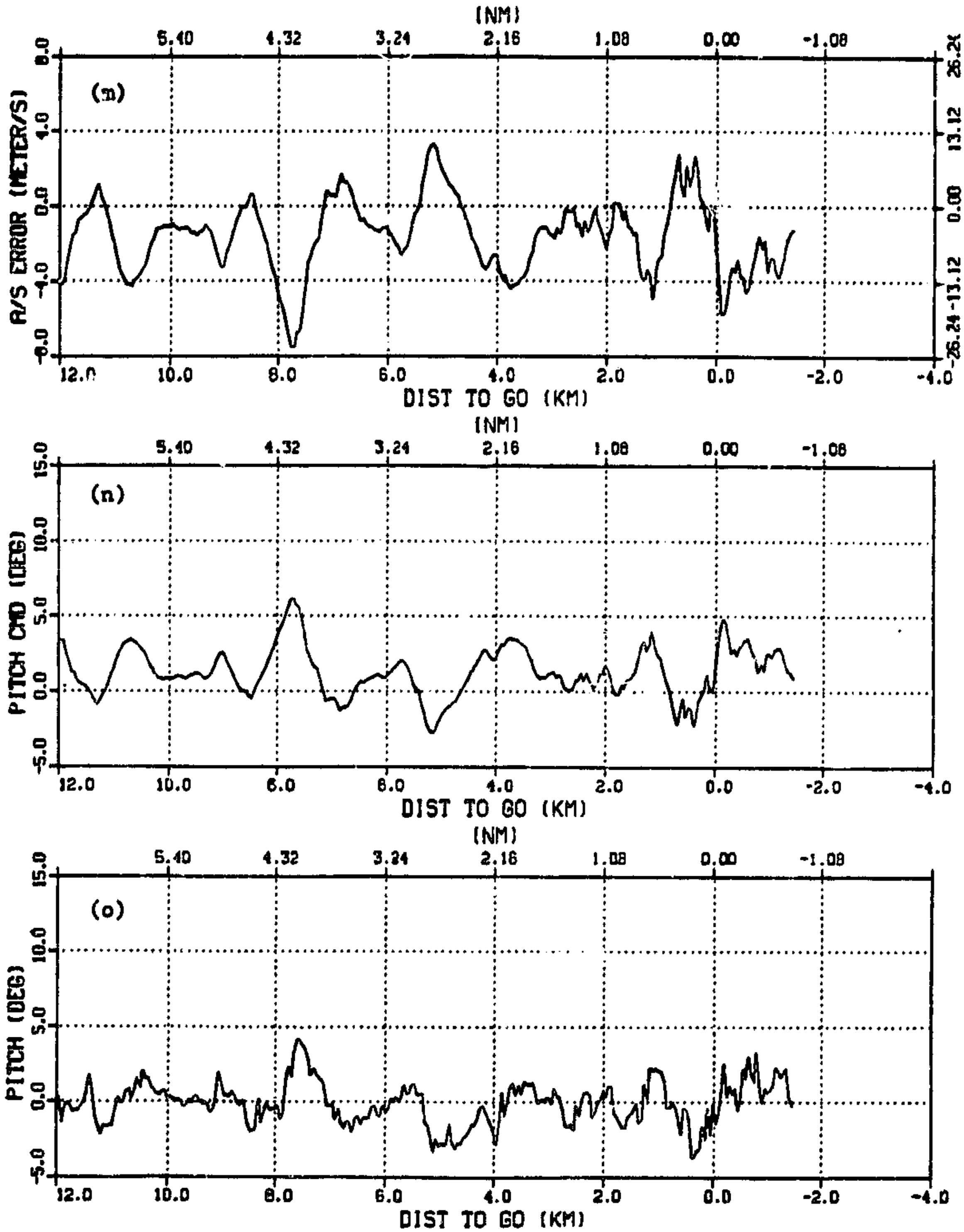

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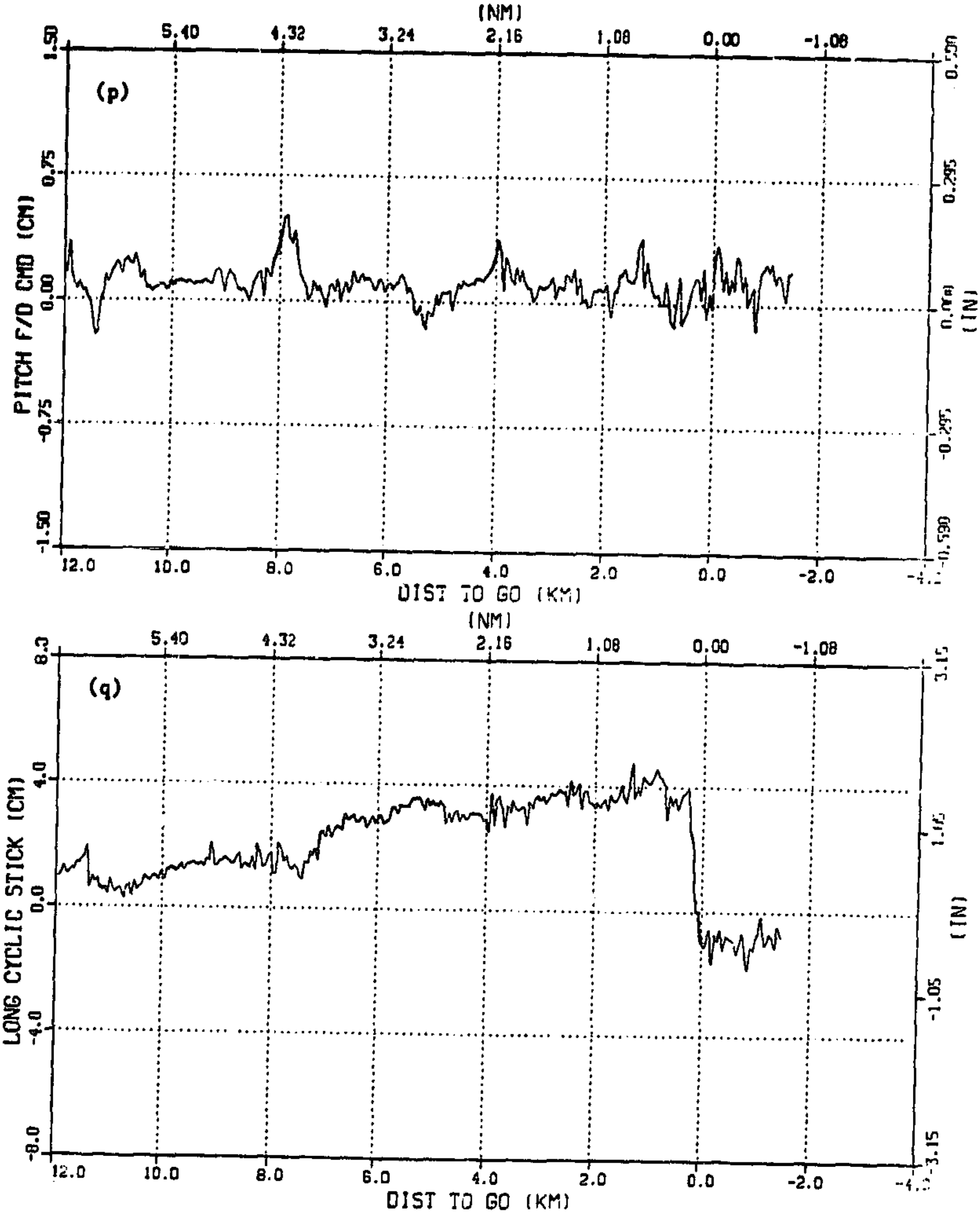

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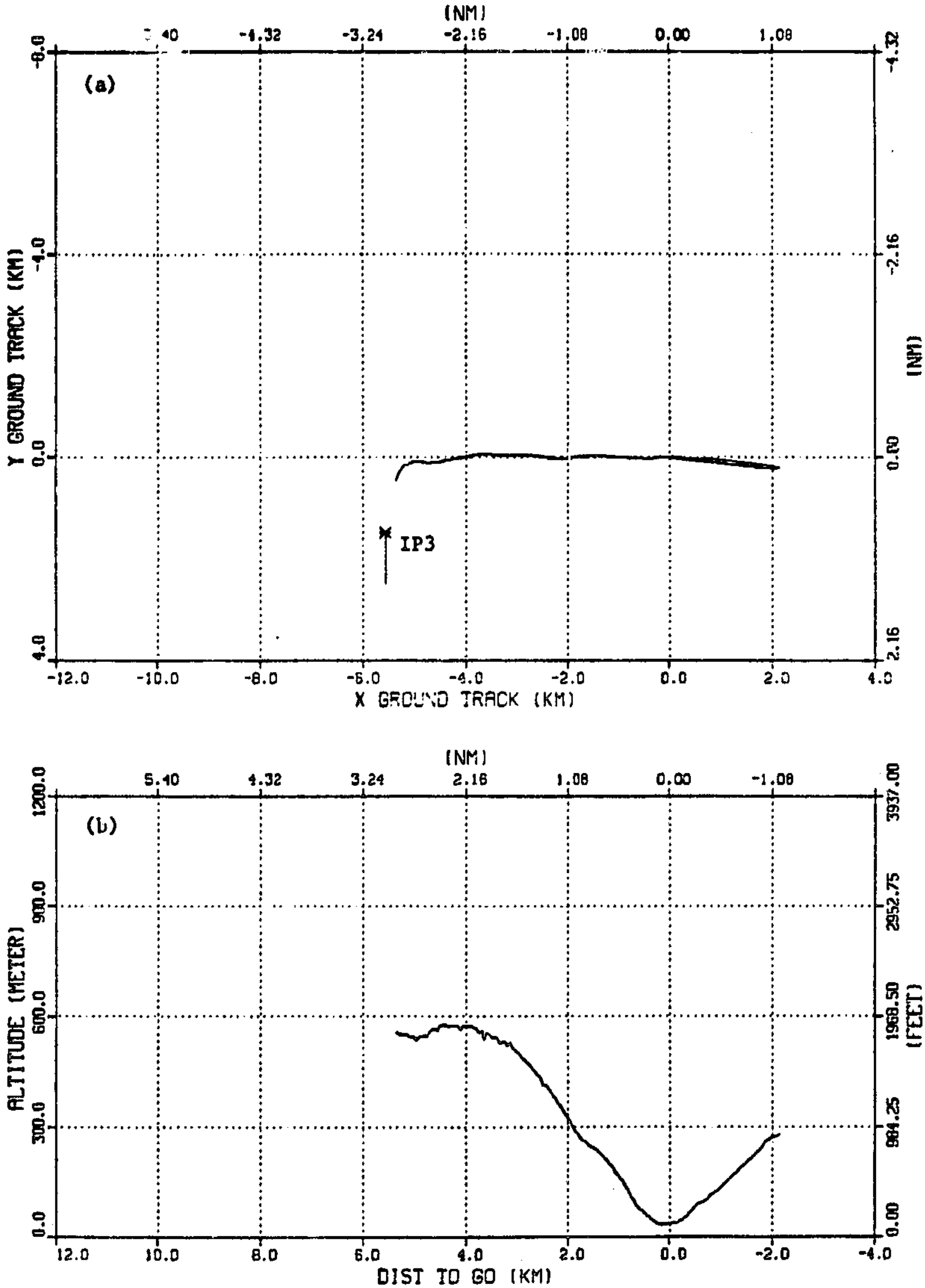


Figure 35. Straight-In: 9 Degrees Glide Slope Data

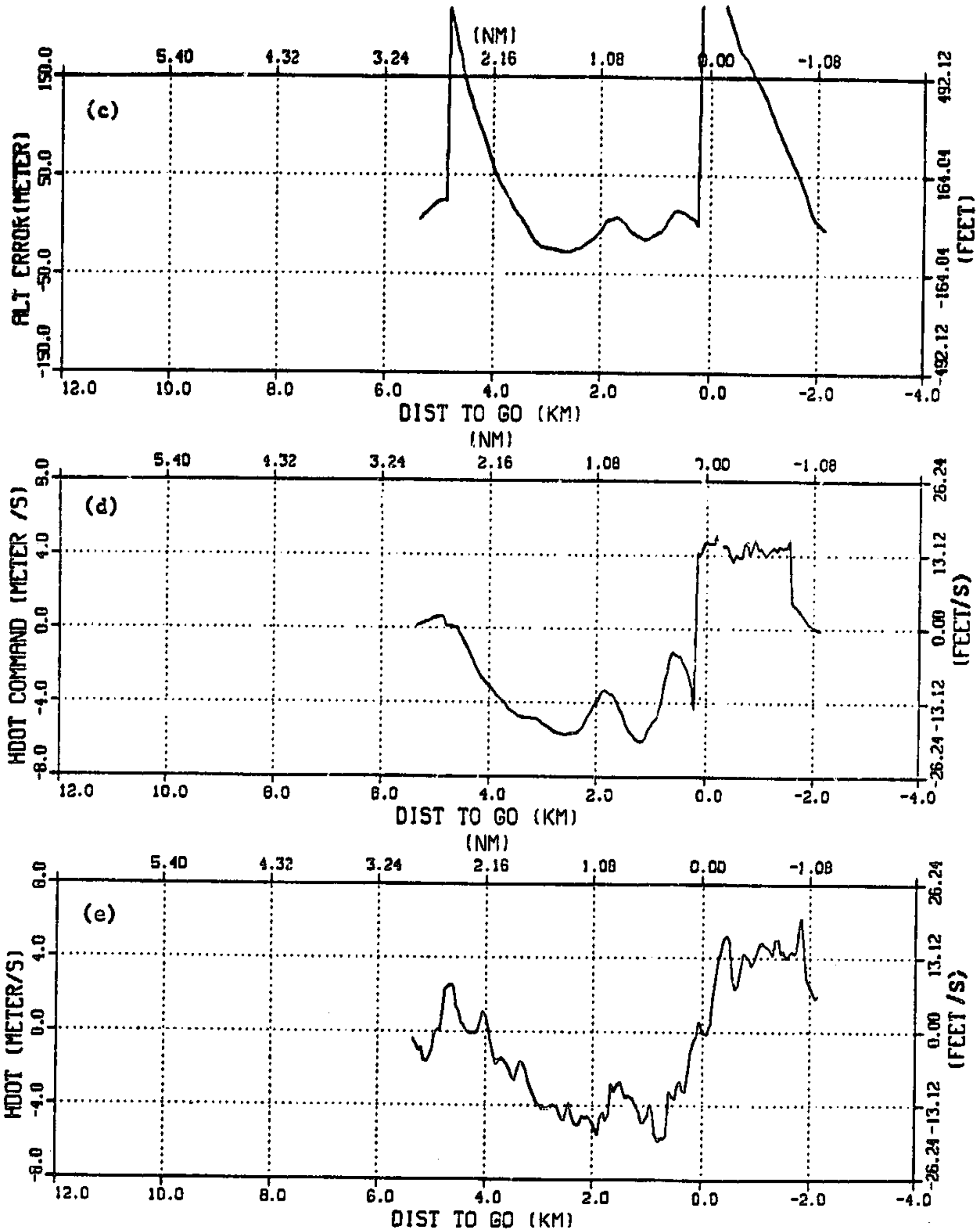
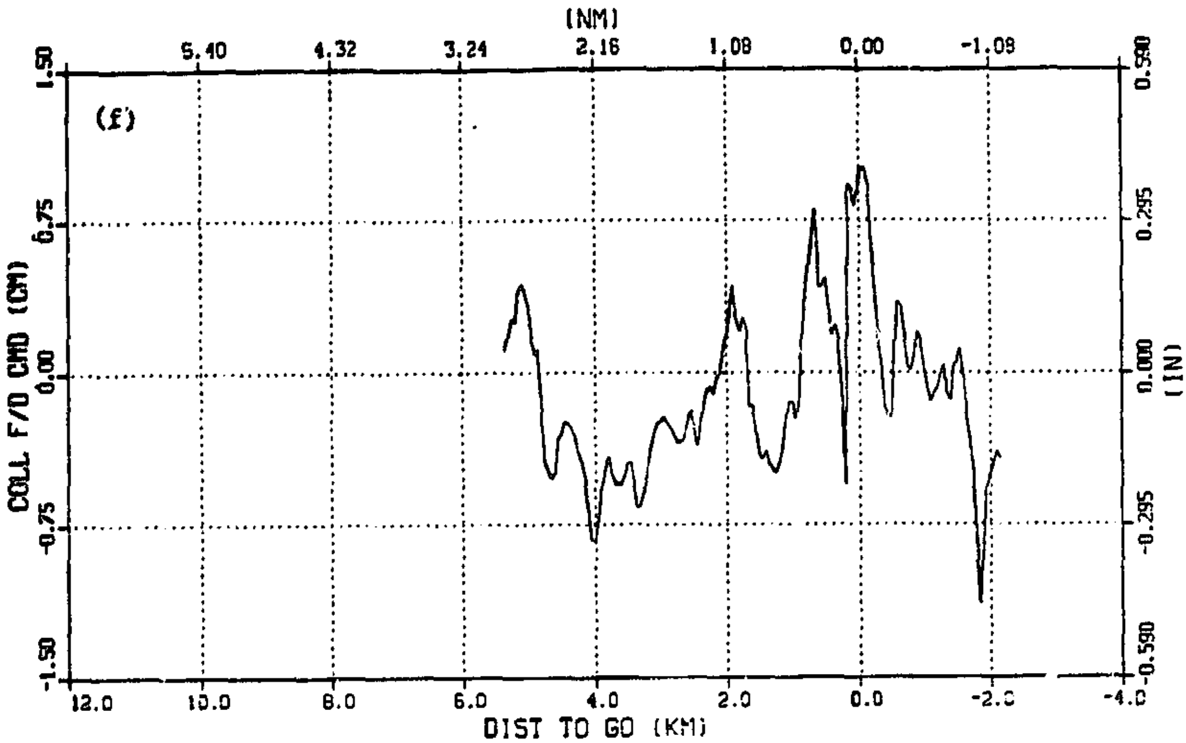
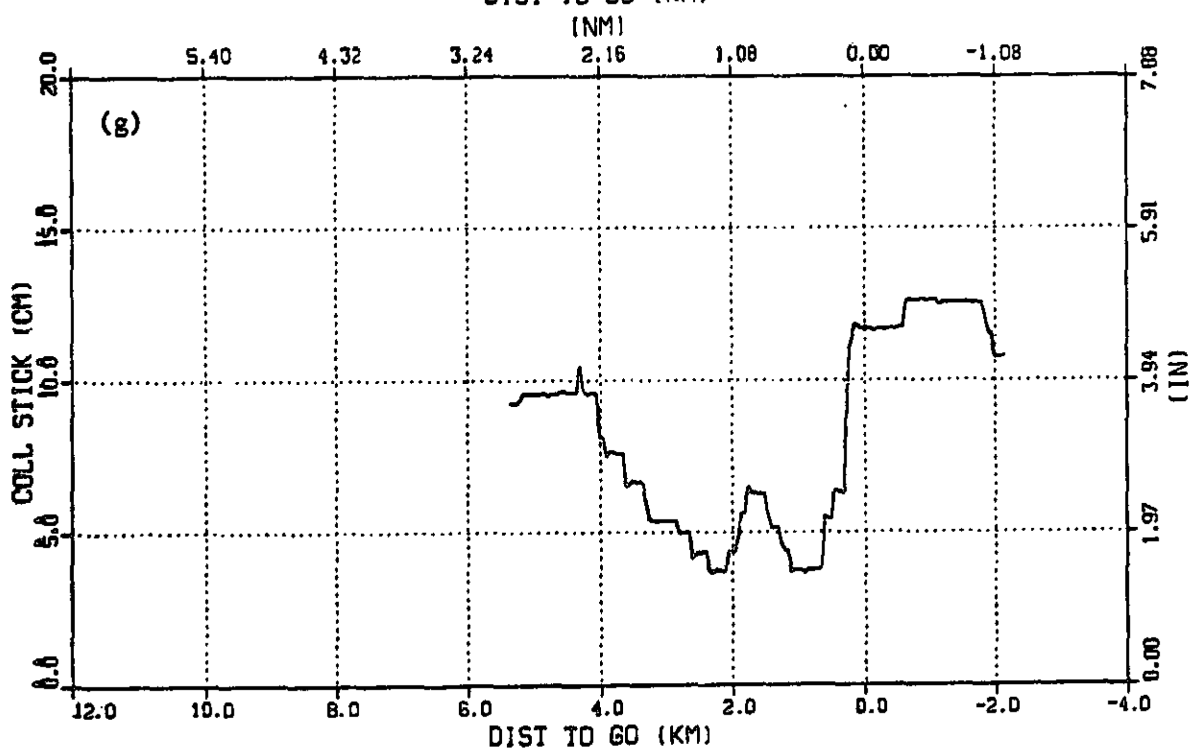


Figure 35. Straight-In: 9 Degrees Glide Slope Data (Continued)





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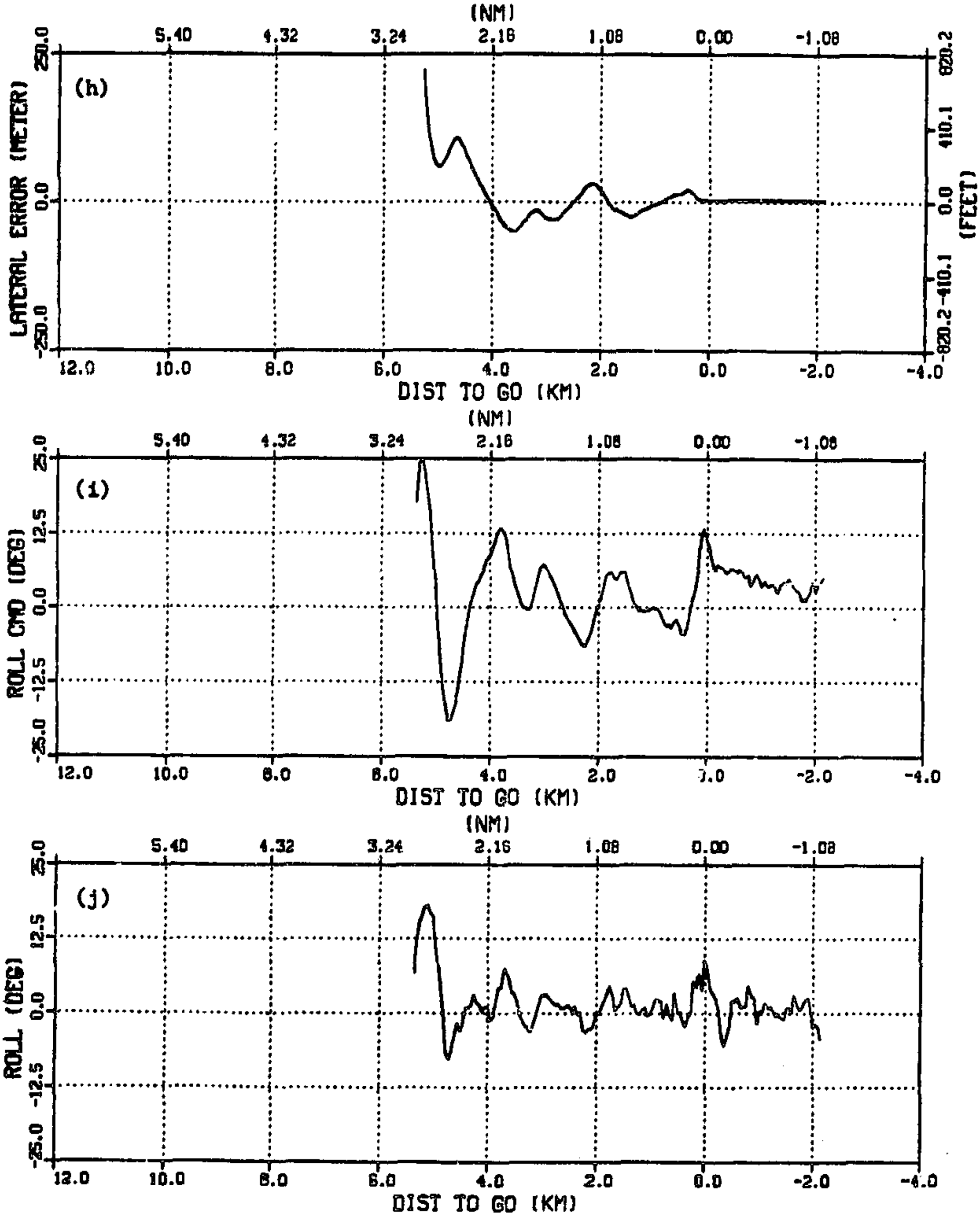

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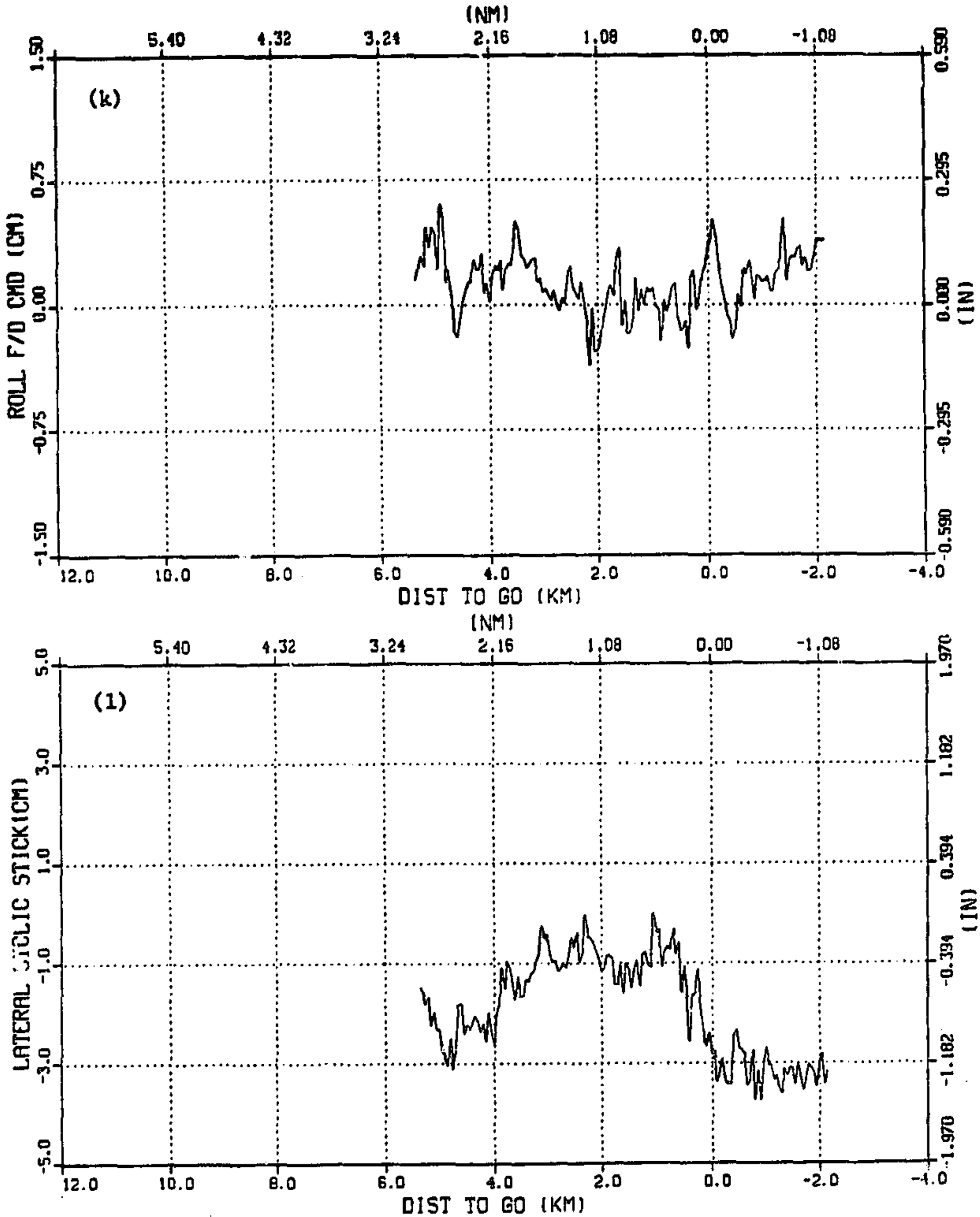

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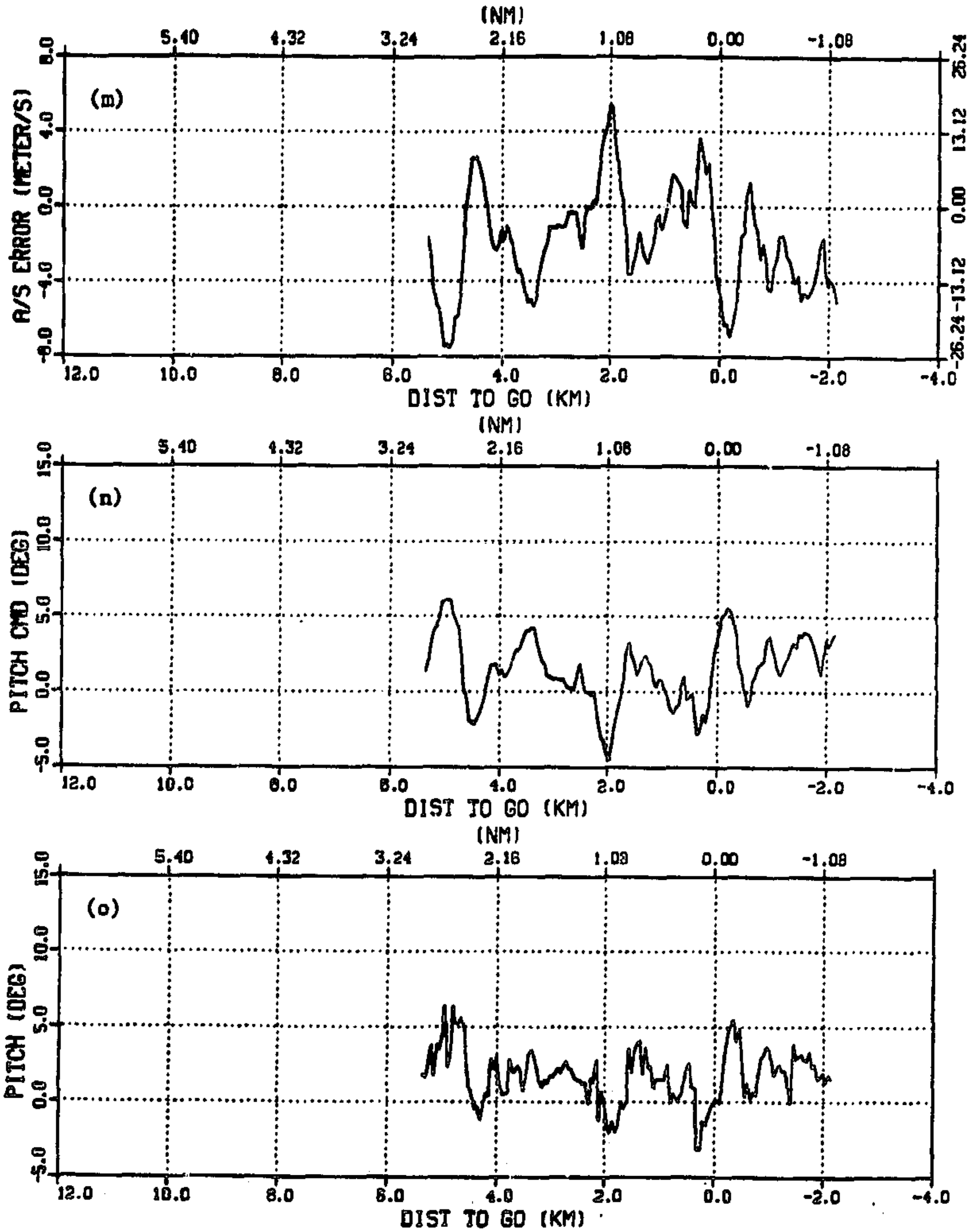

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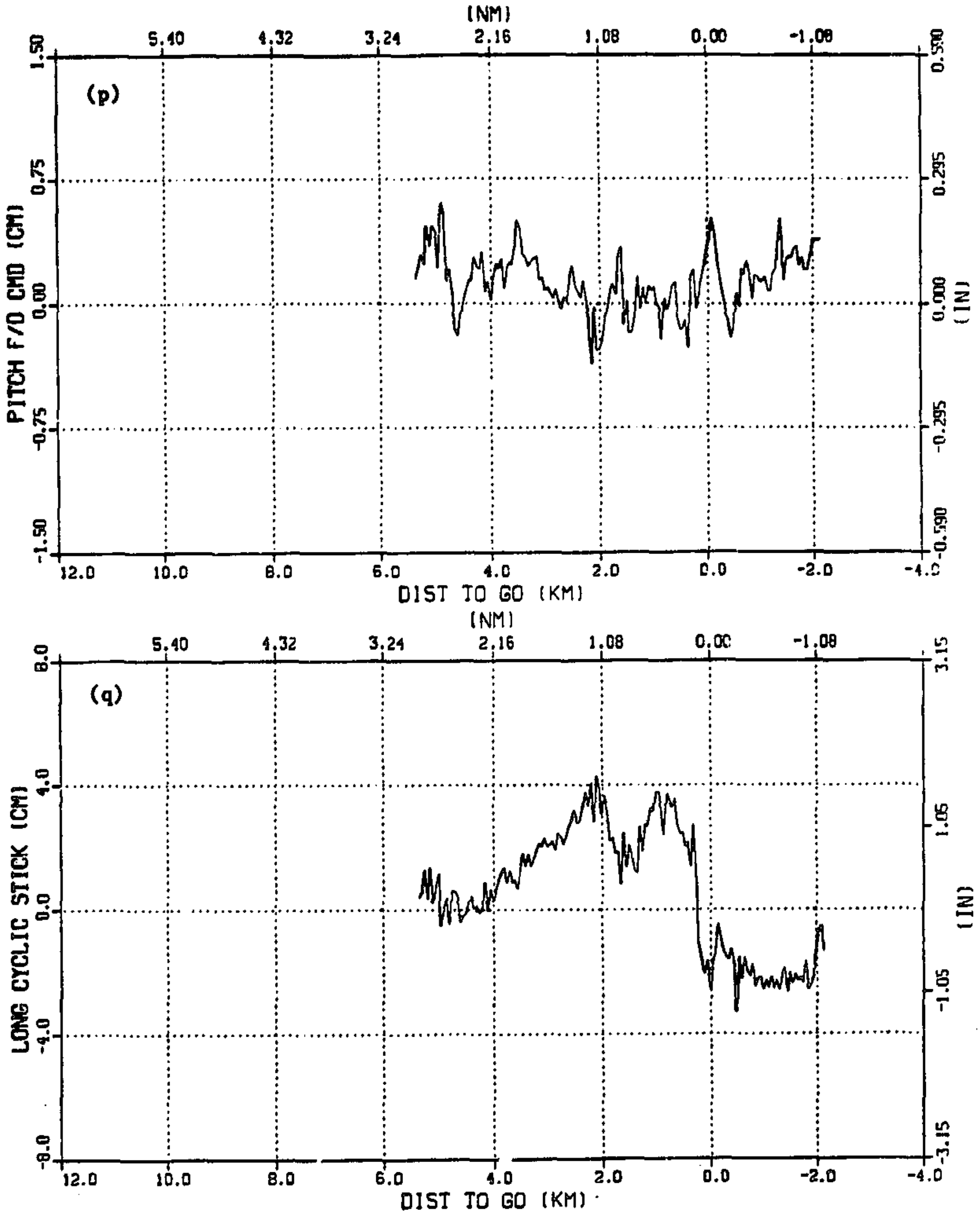

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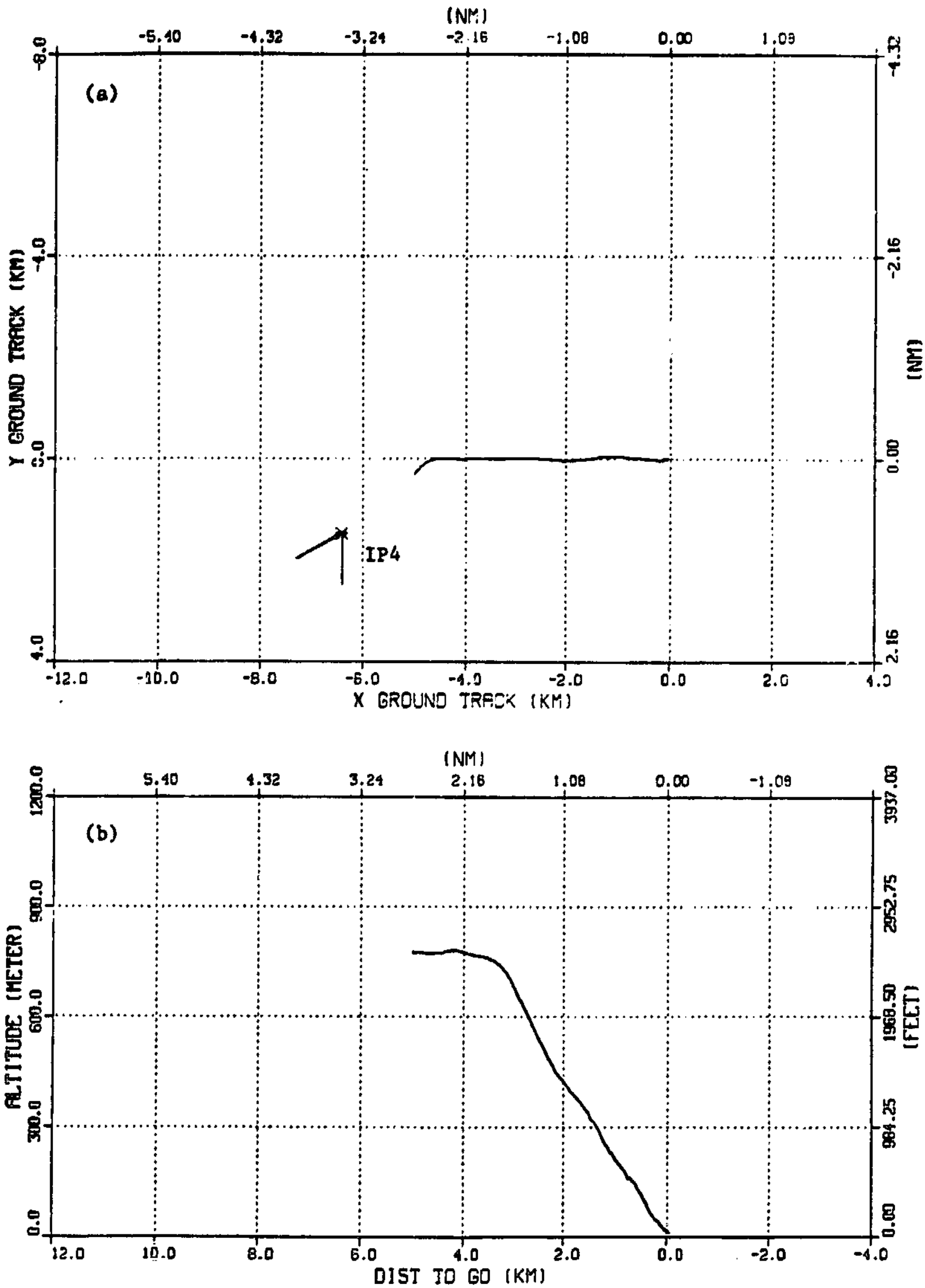
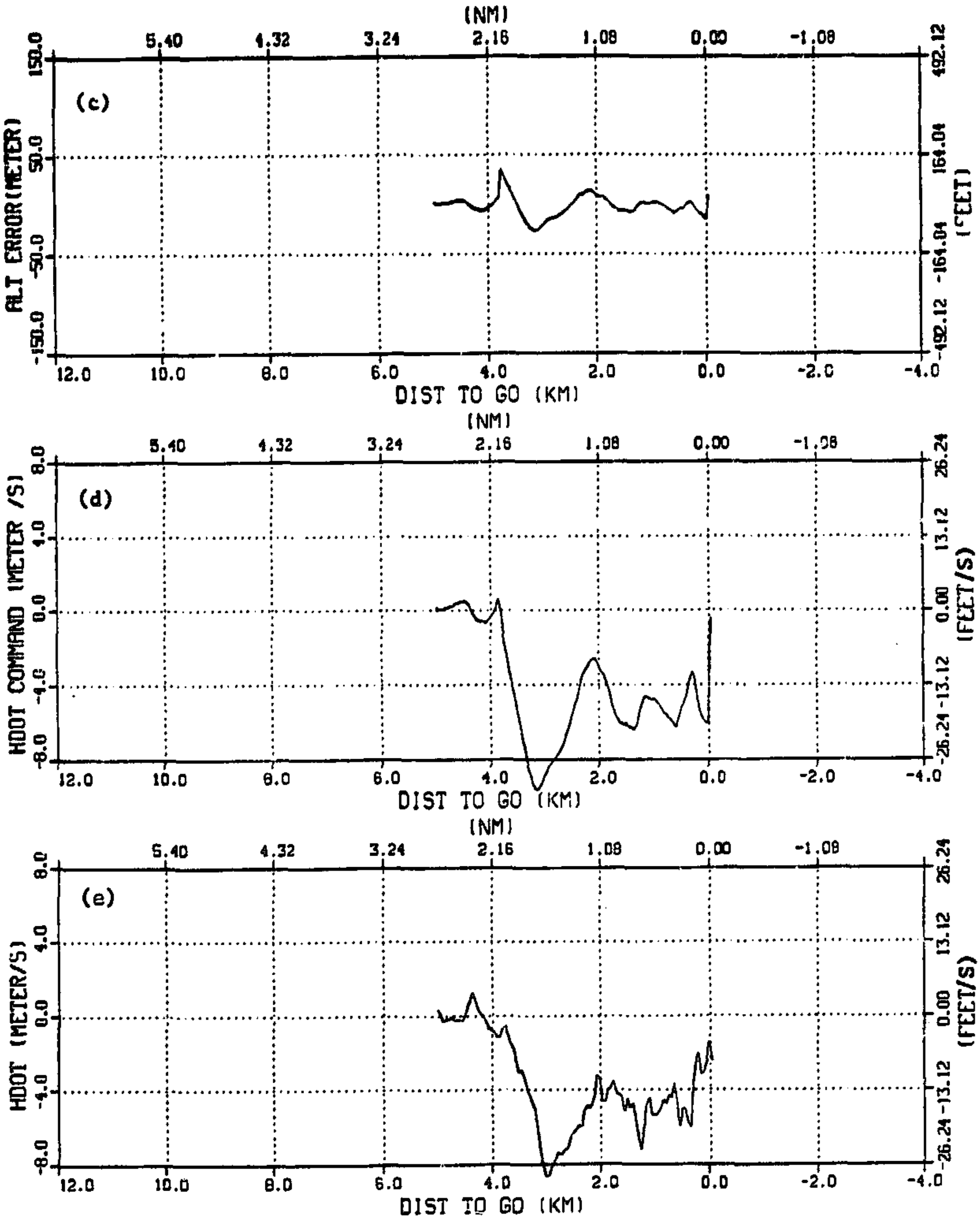


Figure 36. Straight-In: 12 Degrees Glide Slope Data



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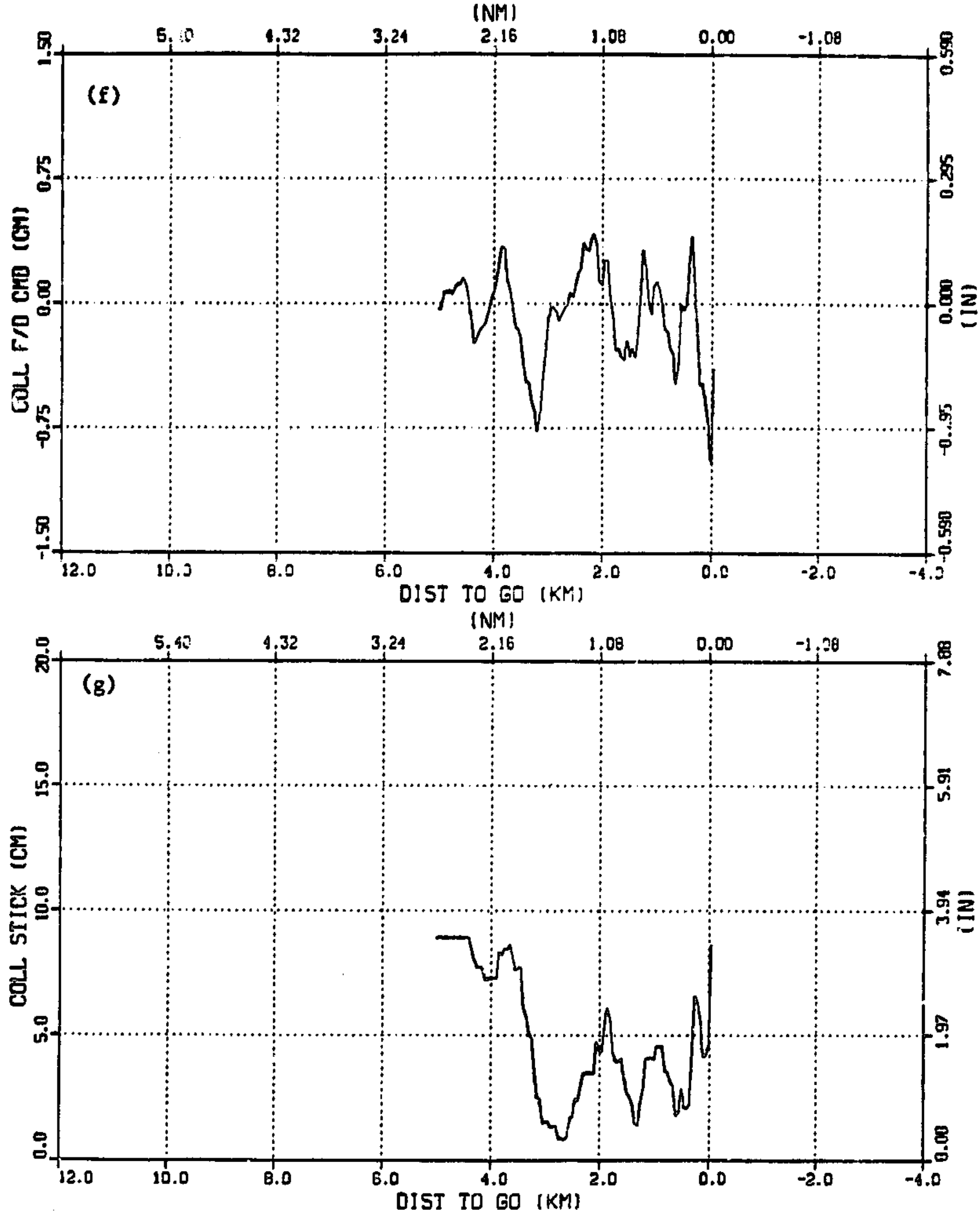

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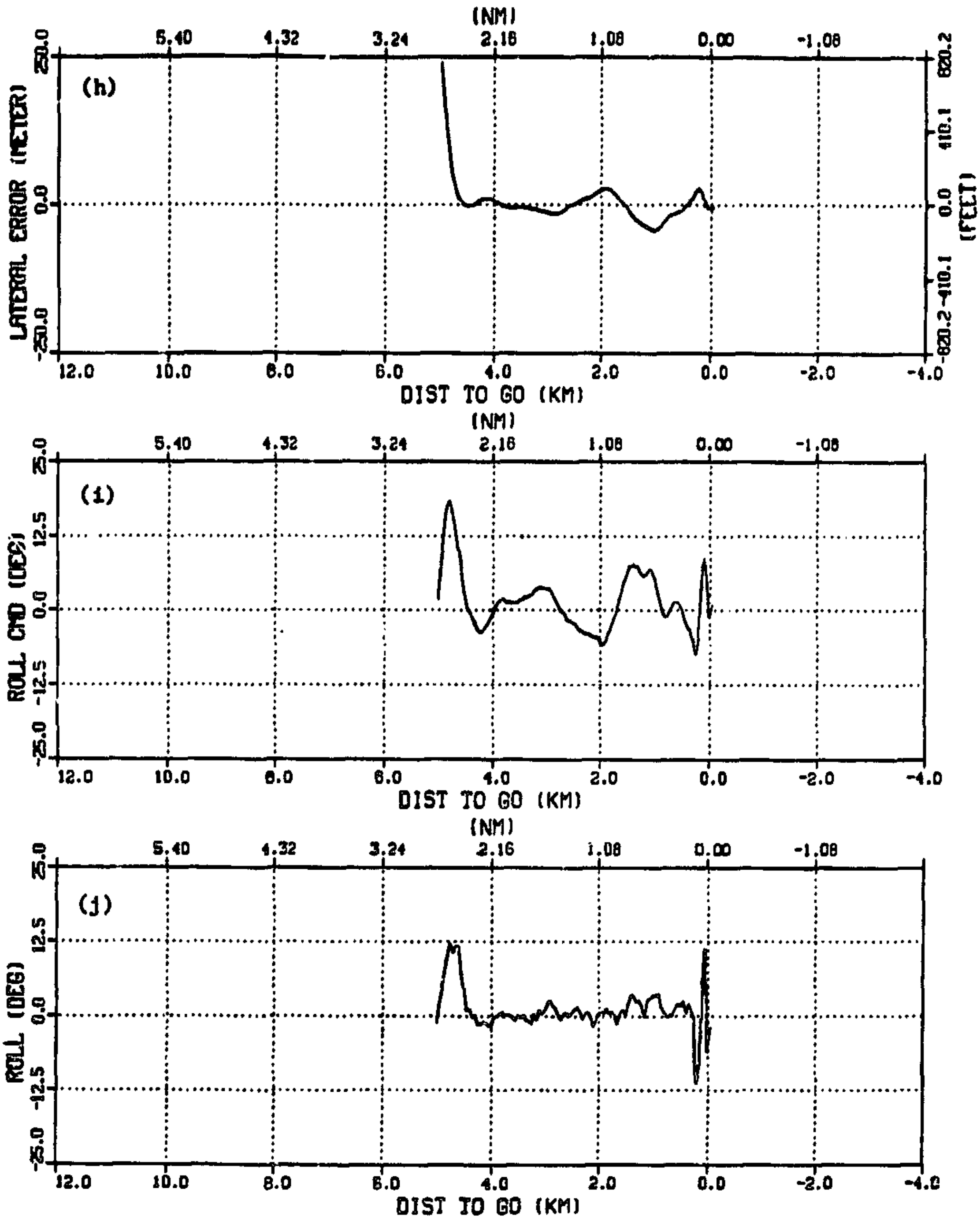

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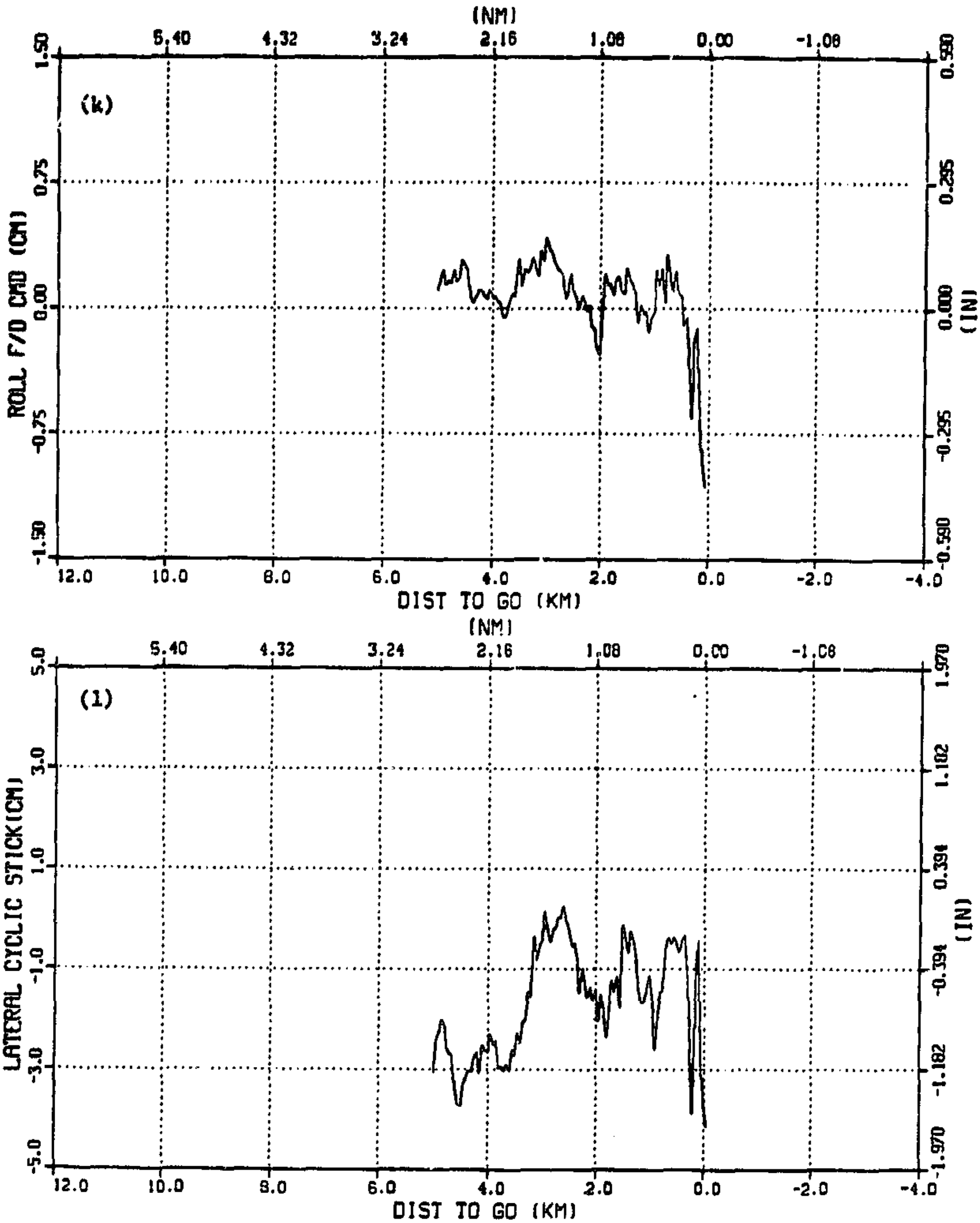

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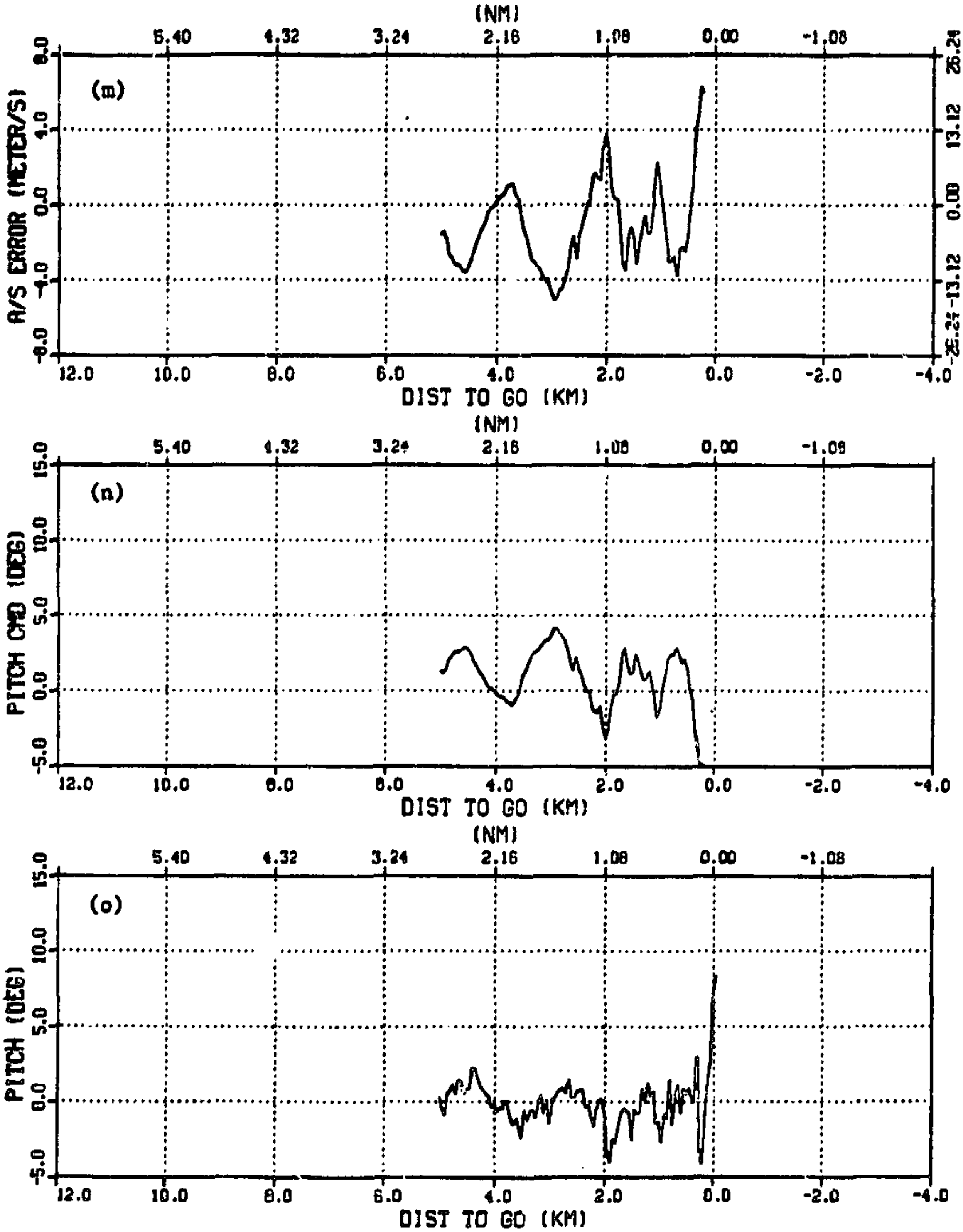

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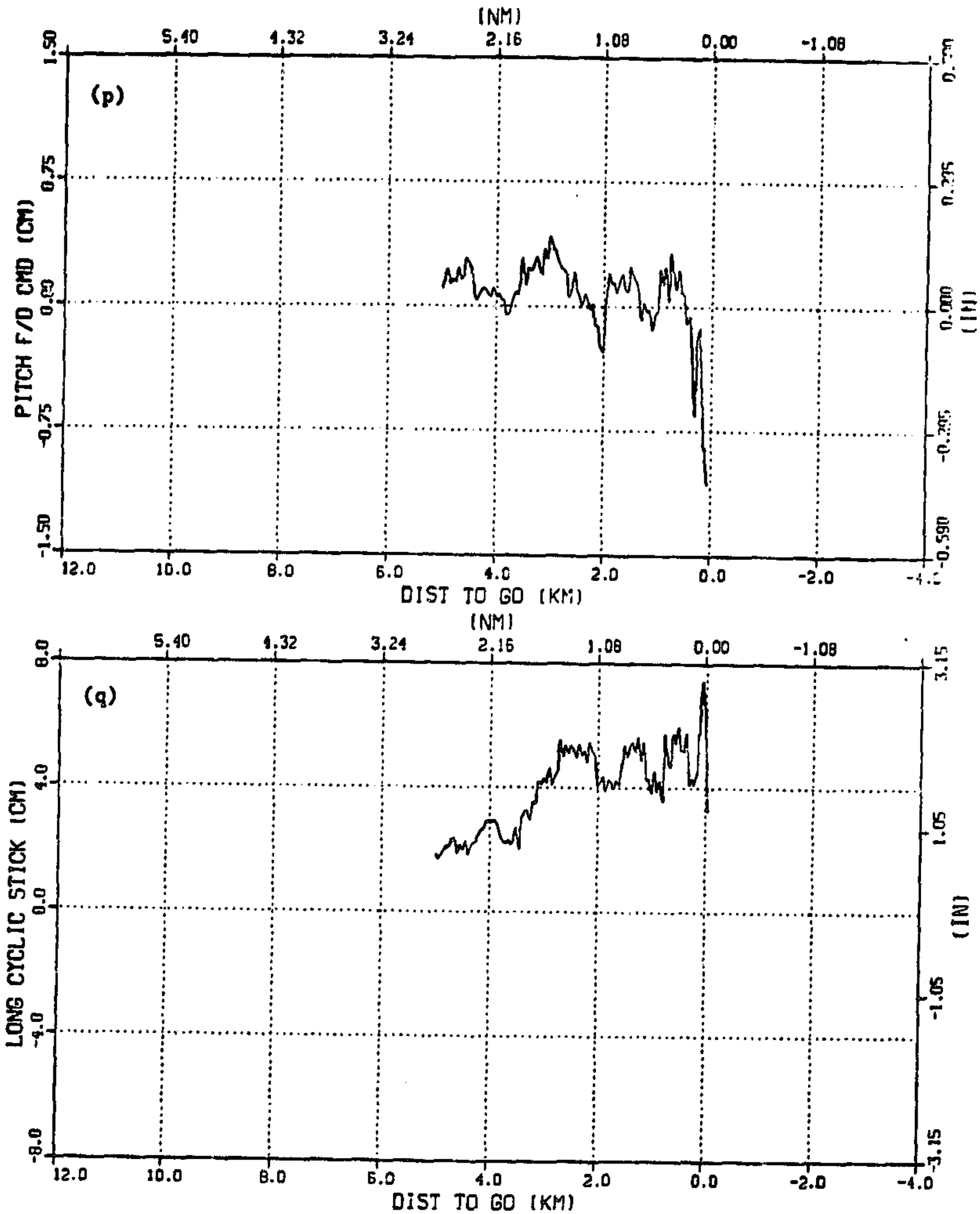

Figure 36. Straight-In: 12 Degrees Glide Slope Data (Continued)

path geometries. Composite (i.e., all plots surperimposed onto one) and statistical (i.e., mean $\pm$ standard deviation) plots using data from all 18 pilots are not shown because of the lack of homogeneity of the data sample, evident by the large degree of variability in the individual response time histories. This results in fuzzy composite plots and gross smoothing in the statistical plots during the transient or time varying flight segments (e.g., localizer/glide slope capture, S-turns, U-turns and descents). However, the data shown in Figures 31-36 is representative of the response behavior of the more experienced (flight-director and IFR) pilots. Note that, for almost all the flight paths, the test pilots were able to perform all the phases of the approach task, including the required deceleration to a hover or missed approach procedure, in a "satisfactory" (opinion rating of 1-4 on a modified Cooper-Harper rating scale) manner. Only the 12° glide slope accounted for some of the pilot's ratings in the "requires improvement" (4-6) range.

8.2. Performance Analysis

The task of flying the UH-1H helicopter (with stabilizer bar only and no SAS) along curved path and steep glide slope approach profiles is difficult because of the existence of strong aerodynamic coupling between the four control axes. As a result, a sudden decrease (increase) in the collective stick input to initiate a descent (climb) results in a yaw left (right) and pitch down (up) moment upon the aircraft. If uncorrected, this results in the aircraft diverging to the left (right) of the reference flight path with increasing airspeed. An experienced pilot can anticipate the adverse effects of such cross coupling and may compensate by simultaneously applying a yaw right (left) pedal, a roll right (left) lateral cyclic, and a pitch up (down) longitudinal cyclic. In response the aircraft should start descending without departing significantly from the reference flight path and airspeed. Unfortunately, even the most skilled and experienced pilots are generally not capable of determining and executing the four control inputs precisely or synchronously.

Consequently, the pilot must track the flight director guidance commands and apply the control inputs necessary to follow the reference flight profile and airspeed within reasonable error bounds.

This task is made even more complicated for reference paths where the pilot is required to execute more than one descrete maneuver (e.g., initiate descent and begin U-turn) in a given flight segment. Typically, pilot's prefer a minimum of 25 to 30 seconds separation between any two discrete maneuvers. This interval gives sufficient time for the transients to decay and for the pilot to stabilize the aircraft before executing a second maneuver.

The two factors discussed above, namely (i) the highly coupled aircraft dynamics, and (ii) the number of simultaneous discrete command maneuvers required of a pilot, have a significant impact on the pilot's performance/workload and hence opinion rating. The NASA/FAA MLS flight tests were conducted with a UH-1H helicopter, and reducing the cross-coupling with a stability augmentation system was not considered. However, the reference flight paths geometries were chosen with the goal that no more than one discrete pilot command maneuver would be required during any given path segment.

The following observations on the pilot's control strategy and performance during curved and descending instrument approaches using MLS flight director guidance are pertinent (see Figures 31-36).

- Initial altitudes prior to lateral capture were chosen so as to provide sufficient time (distance to go) for the pilot to perform the curved and descending approach. The 12° Straight-in approach was chosen to show the feasibility of performing steep approaches in the presence of gust turbulence and wind shear.

. The nominal airspeeds for the approaches were chosen to give a sink rate around 305 m/min (1000 ft/min) during the glide slope tracking segment. Typical airspeeds observed were 75, 65 and 60 knots for the 6°, 9° and 12° approaches, respectively. However, these slow airspeeds required large crab angles (up to 30° - 40°) to follow the reference profiles in the presence of 10 - 15 knot winds.

The presence of cross winds during the go-around mode using constant heading (353°) guidance, resulted in a ground track that diverges to the right of the runway center line (also 353°). Therefore, wind estimates must be used in computing the heading reference in the constant heading go around guidance.

. Glide slope capture is a transient maneuver involving a transition of the aircraft trim state (i.e., attitudes, control deflections, etc) from one flight condition (namely, constant altitude/airspeed flight path) to another (namely, constant glide slope/airspeed descent).

The strong coupling between the vertical, pitch and roll axes can be observed by analyzing the effects of step collective stick inputs during glide slope capture (plot g) on (a) lateral error (plot h), roll command (plot i), roll flight director command (plot k), lateral cyclic stick (plot l), and (b) airspeed error (plot m), pitch command (plot n), pitch flight director (plot p), longitudinal cyclic stick (plot q).

The data shows that the pilot drops the collective stick input to its new trim position in a series of small but discrete steps. In between the collective inputs, the pilot continually adjusts the longitudinal and lateral cyclic stick positions to compensate for the adverse effects on airspeed and lateral errors. The net result is a large amount of control activity throughout the approach task.

- The lateral errors (plot h) during the curved flight segments of the U-turn and S-turn profiles (Figures 31-34) following lateral capture are less than ± 106m (± 350 ft) throughout the approach profile. However, although these errors appear large, they are within the ± 2 DOTS scale (see Figure 22) at decision height, and are therefore acceptable. Note that the roll axis activity is fairly busy.

- Even though the 9° glide slope capture for the U-turn and the Straight-in profiles is initiated at the same point (2.75 nmi from GPIP), the vertical flight path profiles (Figures 32b, 35b) and the collective stick inputs (Figures 32g, 35g) for the two cases are quite different. During the 9° Straight-in approach the pilot has very little time (distance) between completion of lateral capture and initiation of glide slope descent. This results in delays in initiating descent and subsequent large overshoot above the reference glide slope which must be corrected by a sudden and large drop in the collective stick position to its steady state trim position. In contrast data for the 9° U-turn profile shows that a vertical descent is begun soon after the simulation of the glide slope capture by a small drop in the collective stick. Glide slope capture is achieved from below the reference trajectory by using a series of small step decreases in the collective input.

In summary, the results from these flight tests show that the evaluation pilots were able to fly the U-turn, S-turn, and Straight-in trajectories using a 3-cue flight director with acceptable tracking performance.

9. CONCLUDING REMARKS

Navigation and flight-director guidance for the NASA/FAA MLS flight test program have been described. Test results show that the evaluation pilots were able to perform all the phases of the approach, including visual deceleration to a hover or a missed approach, in a satisfactory manner. As a result, a data base to aid the FAA in establishing Terminal Instrument Procedures (TERPS) for helicopter MLS Instrument Flight Rules (IFR) approaches has been established.

The flight director and raw data guidance laws developed during this test program provide a baseline for further experimentation and improvements. In particular, modifications to the missed approach guidance law are needed to include a capability for maintaining a constant heading ground track profile during steady cross winds or shear.

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15. Supplementary Notes

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16. Abstract

This report describes the navigation and flight director guidance systems implemented in the NASA/FAA helicopter microwave landing system (MLS) curved approach flight test program. Flight test were conducted at the U.S. Navy's Crows Landing facility, using the NASA Ames UH-1H helicopter equipped with the V/STOLAND avionics system. The purpose of these tests was to investigate the feasibility of flying complex, curved and descending approaches to a landing using MLS flight director guidance. The report provides a description of the navigation aids used, the avionics system, cockpit instrumentation and on-board navigation equipment used for the flight test. Three generic reference flight paths were developed and flown during the test. They were as follows: U-Turn, S-turn and Straight-In flight profiles. These profiles and their geometries are described in detail. A 3-cue flight director was implemented on the helicopter. A description of the formulation and implementation of the flight director laws is also presented. Performance data and analysis is presented for one pilot conducting the flight director approaches.

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