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DEVELOPMENT OF THE NASA VALT DIGITAL NAVIGATION SYSTEM

by

Walter J. McConnell Jr.
Edmund R. Skutecki
Alfonso J. Calzado

PREPARED UNDER CONTRACT NO. NAS1-12365 by

SPERRY FLIGHT SYSTEMS
PHOENIX, AZ.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SPERRY FLIGHT SYSTEMS IS A DIVISION OF SPERRY RAND CORPORATION

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SUMMARY

Sperry Flight Systems was awarded Contract NAS1-12365 in June of 1973 by the NASA Langley Research Center. The purpose of this contract was to develop and fabricate a terminal area navigation system for use in the NASA VTOL Approach and Landing Technology (VALT) program. This report presents the results of that effort through contract modification number seven.

The navigation system developed and fabricated was based on a general purpose airborne digital computer. A set of flight hardware units was fabricated to create the necessary analog, digital and human interface with the computer. A comprehensive package of software was created to implement the control and guidance laws required for automatic and flight director approaches that are curved in two planes.

A technique was developed that enables the generation of randomly shaped lateral paths from simple input data. The lateral path concept combines straight line and elliptical-curved segments to fit a continuous curved path to the data points.

A simple, fixed base simulation was put together to assist in developing and evaluating the system. The simulation was used to obtain system performance data during simulated curved-path approaches.

INTRODUCTION

On 6 June 1973, NASA/LaRC, Hampton, Virginia awarded Contract NAS1-12365 to Sperry Flight Systems for the design and fabrication of a Digital Navigation System to be used in conjunction with a modified CH-47B helicopter. Subsequent modifications to the contract were issued in October 1973, March 1974, and December 1974 to expand the capabilities of the system through additional hardware and software. The work performed under this contract is a part of the ARMY/NASA VTOL Approach and Landing Technology (VALT) program designed to determine the operating envelope and piloting procedures for VTOL aircraft in the terminal area.

This report describes the design, fabrication, and initial performance evaluation of a digital navigation system. The principal output from this project was a set of flight system hardware, a set of ground support hardware and a digital computer software package that together were used to implement the desired control laws and navigation equations.

The objective of this project was to produce a digital navigation system that could be used to generate and track arbitrary curved path approaches, altitude profiles, and speed profiles. The system was to be a flexible research tool suitable for the evaluation of various control, display, and guidance concepts related to VTOL Approach and Landing problems. The system was to be configured such that complex approaches could be made in either a fully automatic mode or by a pilot through the use of various cockpit displays. The project was divided into the following two main tasks:

Task 1 - Systems Analysis and Definition

An installation survey was made to determine the detailed electrical and mechanical interface with the CH-47B helicopter. NASA/LaRC defined a baseline system built around a TR-48 analog computer, a set of aircraft sensors, a modified GSN-5 radar, and a digital telemetry link. These items of equipment were to be combined with a general purpose digital computer and the necessary interface units to form the integrated system. The digital computer was to perform all computations except for the inner loop rate damping in the pitch, roll and yaw axes. NASA LaRC provided a model of the characteristics of the CH-47B with the NASA inner loops closed. This model was used in a simulation to determine the control laws necessary to obtain acceptable tracking of the lateral curved paths. A technique was developed using elliptical and straight line path segments to approximate an arbitrary lateral curved path with a minimum number of data points. A format for the entry of path data was developed together with a limited number of restrictions on the use of the curved path technique. Detailed performance requirements for the flight system interface hardware were developed and used as a basis for the design of the flight system hardware. A set of Ground Support Equipment hardware was designed and fabricated in order to facilitate the generation of the system software.

Task 2 - Fabricate Hardware, Generate Software and Measure System Performance

A set of flight hardware was fabricated and tested. Software to implement the desired control law and navigation equations was written. The software and hardware were integrated and interfaced with the simulation to verify the design in a dynamic situation. Data runs were taken to document the closed loop system performance and navigational capabilities. A programmers manual was developed to document the software in detail and to serve as a basis for future system software modifications. The flight system and ground support system components were delivered to NASA/LaRC for installation and system checkout. A training course was developed and presented to NASA personnel as an aid to building an 1819A programming capability at LaRC.

As part of one of the contract modifications, additional software was generated to provide digital inner loop stabilization and control, in addition to the analog capability.

SYMBOLS

Values are given in both SI and U.S. Customary Units.

a_y	lateral accelerometer output, m/sec^2 (ft/sec^2)
a_{ZI}	vertical accelerometer output, compensated for gravity, m/sec^2 (ft/sec^2)
a_{XI}	longitudinal accelerometer output, compensated for gravity, m/sec^2 (ft/sec^2)
p	body axis roll rate, deg/sec
q	body axis pitch rate, deg/sec
r	body axis yaw rate, deg/sec
x	positional error parallel to aircraft longitudinal axis, m (ft)
y	positional error parallel to aircraft lateral axis, m (ft)
U	airspeed, m/sec (ft/sec)
V	groundspeed, m/sec (ft/sec)
XYZ	aircraft position, west, north, up, m (ft)
h	barometric altitude, m (ft)
θ	pitch attitude, positive nose up, deg
ϕ	roll attitude, positive right wing down, deg
ψ	magnetic heading, deg
δ_θ	pitch actuator position, percent of full travel from center
δ_ϕ	roll actuator position, percent of full travel from center
δ_T	collective actuator position, percent of full travel from center
δ_ψ	yaw actuator position, percent of full travel from center
ϵ	crosstrack error, m (ft)

Subscripts

c	commanded parameters
e	error
m	model output
p	pilot originated
ref	reference parameter
T	tangential to reference angle
h	derived by hover augmentation system computation
u	change in longitudinal body axis velocity, positive forward, m/sec (ft/sec)
v	change in lateral body axis velocity, positive right, m/sec (ft/sec)
w	change in vertical body axis velocity, positive down, m/sec (ft/sec)

SYSTEM DESCRIPTION

The VALT Digital Navigation System is an integrated hardware and software package designed to provide a tool for investigating the problems associated with the terminal area operations of VTOL aircraft. The system has been configured for integration into a NASA CH-47B research aircraft and as such is designed to interface with the sensors, control system, and data link that will be installed in that aircraft. The hardware and software created for this system are designed to provide a tradeoff in favor of flexibility and cost as opposed to minimum size, weight, power, or memory requirements.

System Components

As presently configured, the total NASA VALT Research System is a hybrid combination of analog and digital components. The analog elements of the system include the sensors, the actuation system, and the inner loop stabilization and control portion of the control system. The digital elements of the system include the digital navigation system and the air/ground telemetry data system. Software has been generated to permit digital computation of the inner loop control laws. The initial flight tests will be accomplished using the hybrid digital-analog system. A block diagram of the VALT research system is shown in Figure 1. This report pertains to the VALT Digital Navigation System and the associated Ground Support Equipment (GSE) only.

Hardware.- The navigation system hardware consists of a general purpose digital computer, a pair of control and display units, an analog-to-digital and digital-to-analog conversion unit, a telemetry data system interface unit, a flight hardware mounting pallet and electrical junction box, and the necessary interconnecting cables and wiring.

Digital Computer: The primary hardware component in the Digital Navigation System is the Sperry Flight Systems 1819A Digital Computer. This general purpose computer is designed for airborne applications. The computer configuration used for the Digital Navigation System consists of 16,384 words of 18-bit, magnetic core memory, 1024 words of 18-bit, solid-state, read only memory, seven input/output channels, and a built-in test routine. This computer performs all of the computations, data formatting, and logic decision making for the navigation system. In addition, the computer controls and directs the flow of digital data to and from the remaining hardware elements of the system.

Analog Interface: The interface between the 1819A navigation computer and the analog sensors, displays and actuation components is provided by the Digital Interface Unit (DIU). The DIU is configured to provide 30 channels of analog-to-digital conversion and 30 channels of digital-to-analog conversion. In addition, the DIU provides the capability to input 12 discretes into the computer and to accept 12 discretes from the computer. The DIU will convert analog signals within the range from -10 volt dc to +10 volt dc into 12-bit digital words. Conversely, the DIU will convert 12-bit digital words into signals within the range from -10 volt dc to +10 volt dc.

Control and Display: The man/machine interface function within the navigation system is provided by two Navigation Guidance Control Panels (Nav/Guidance). The two panels are identical in both appearance and operation and allow simultaneous interrogation of the computer by either the cockpit personnel or the flight test engineer. The primary functions of the Nav/guidance panel are mode selection and indication, parameter insertion, and in-flight programming of the digital computer.

Data Link: The primary navigational position information for the VALT Digital Navigation System is generated by a ground radar system and is transmitted to the aircraft via a data link. The interface between the Transponder Data System (TDS) and the 1819A computer is provided by the Transponder Data System Interface Unit (TIU). The TIU provides the level shifting, logic sequencing, and memory buffering required to accept uplink data from the TDS and transmit it to the computer. It also accepts data from the computer and transmits it to the TDS for further transmission to the ground via the downlink. Uplink data consists of up to 16 proportional data words of 10 bits each, and up to 64 single-bit, discrete signals. Downlink data consists of up to 48 proportional data words of 10 bits each and up to 64 single-bit, discrete signals.

Support Equipment: A set of Ground Support Equipment (GSE) provides the means to modify existing software or to generate new software for the digital computer. The GSE consists of a set of peripheral devices, a control electronics unit, power supplies, and the necessary interconnecting wiring and cables. The GSE provides the capability for interactive communication between the programmer and the computer as well as the capability to read in or punch out paper tapes. A portable item of ground support equipment was also fabricated to enable the computer memory to be updated when the aircraft is away from the GSE. This unit, the Carry-On Load/Dump (COLD) box, provides the capability to load the computer memory from a magnetic tape cassette and to output the contents of the computer memory onto a magnetic tape cassette.

Software.- Because of the flexible nature of the hardware configuration, the particular characteristics of the navigation system are primarily determined by the software that is input to the computer. The software developed for this particular project is comprised of two major parts: Ground Support Utility Software and Flight System Software.

Ground Support Software: The ground support utility package consists of five major programs and is the primary tool for the system programmer. This software package, when used in conjunction with the ground support equipment, provides the programmer with the capability to write, debug, edit, and assemble programs for the 1819A computer.

Flight Software: The flight software consists of a group of special purpose subroutine modules, each of which performs a specific computational or logic task. Control of the subroutines is maintained by a master logic executive routine that decides which subroutines should be used. This decision is based on data that is entered into the system through either of the Nav/guidance control panels.

Modes and Indicators.- The two Nav/guidance control panels provide the primary means to control the Digital Navigation System during flight. In the normal system configuration, Nav/guidance panels will be located in the aircraft cockpit and at the engineer's station in the aircraft cabin. These two panels are identical and provide both stations with the capability to (1) select and monitor system modes of operation, (2) alter and verify system parameters stored in the digital computer, and (3) inspect, change, and verify computer programs stored in the digital computer. The panel controls are shown in Figure 2.

Operational Modes: The Digital Navigation System modes of operation are divided into three major categories: Hold Modes, Approach Modes, and Convenience Modes. The Hold Modes are Heading Hold/Heading Select, Altitude Hold/ Altitude Select, and Speed Hold/Speed Select. The Approach Modes are Manual Approach, Automatic Approach, Go-Around, and Land. The Convenience Modes are the On-Line and Test Modes.

Heading Hold/Heading Select - This mode provides automatic magnetic heading hold through either the roll axis or the yaw axis. The switch from yaw axis control at hover or low airspeed to roll axis control at higher airspeeds is a software function based on airspeed. The current magnetic heading is used for the heading reference whenever this mode is engaged. Once the mode is engaged, however, the desired reference heading can be changed (Heading Select) by means of the keyboard on the Nav/guidance control panel. A transition from one heading reference to another is indicated by a blinking heading-hold indicator.

Altitude Hold/Altitude Select - When this mode is selected, the system will generate collective axis commands to hold automatically the current barometric altitude. Whenever this mode is engaged, the reference altitude can be changed by means of the keyboard on either of the Nav/guidance panels. Transitions from one reference to another are indicated by a blinking altitude-hold indicator.

Speed Hold/Speed Select - This mode provides automatic airspeed hold through the pitch axis. The current airspeed is used as the reference when the mode is first engaged; however, the reference airspeed can be changed by means of the keyboard on the Nav/guidance panel. As in the case of the other hold modes, transitions between speed references are indicated by a blinking mode indicator.

Manual Approach - This mode provides pitch, roll, and collective commands to the flight director command bars, in order to provide guidance information to the pilot relative to the selected deceleration profile, lateral path, or altitude profile. This mode is inhibited whenever ground position information is not being received via the data link. When the manual approach mode is engaged, the heading hold, altitude hold or speed hold mode buttons can be used to provide a split axis control configuration. Under these conditions, engaging the heading hold mode, for example, will result in automatic tracking of the ground track profile without automatic tracking of the velocity or altitude profiles. Any of the various combinations of automatic and manual split axis control of the pitch, roll and collective axes are allowed; however, automatic control of the yaw axis is provided regardless of which combination of automatic or manual operation is selected for the other three axes.

Automatic Approach - This mode generates the pitch, roll, yaw, and collective commands necessary to provide automatic tracking of the selected deceleration profile, lateral path, or altitude profile. Like the manual approach, this mode is inhibited whenever ground position information is not being received via the data link. The automatic approach mode provides output signals to the flight director command bars to enable the pilot to monitor system performance.

Go-Around - This mode was implemented to allow the pilot to quickly select and automatically capture a preset heading, altitude and airspeed reference.

Land - The land mode initiates a vertical descent and a landing sequence in conjunction with either the manual approach or automatic approach modes. This mode is inhibited if one of the approach modes has not been selected. The land mode is enabled only when certain programmable restrictions on aircraft position and velocity have been satisfied. This enabled condition is indicated by blinking land-mode indicator on the Nav/guidance control panels.

On-Line - This mode is provided primarily as a convenience to the flight test engineer in order to minimize computer faults during airborne programming operations. With the on-line mode disengaged, the computer is executing a minimal program that performs initialization and filtering computations only. This short cycle routine allows the flight test engineer to make data or instruction changes to the software stored in the computer, without the need to plan the changes, in such a way as to avoid faulting the computer. The on-line mode must be engaged before any hold or approach mode can be engaged.

Test - The test mode is used to generate up to 30 analog output voltages from the computer memory and to read in up to 30 analog input voltages into the computer memory. These voltages can be interfaced with the analog inner loop to create a static or dynamic test of the navigation system. The test mode is inhibited by any other mode selection and, in turn, inhibits the selection of any other mode.

Displays and Indicators: The displays and indicators on the Nav/guidance control panels are the primary source of navigation system data for the pilot and the flight test engineer.

Mode Indication - System mode status is displayed by illuminated legends built into the mode select pushbuttons.

Data Displays - Two numerical readouts are provided for the presentation of digital data. The current data readout displays the current value of the parameter selected by the Nav/guidance panel rotary switch position. The keyboard readout displays the data to be entered into the computer from the keyboard.

Parameter Selection and Alteration: The first ten positions of the nav/guidance panel rotary selector switch enable the panel user to monitor the following parameters:

- Lateral track profile to be used.

- Altitude profile to be used.

- Deceleration profile to be used. Up to five lateral, five altitude and five deceleration profiles may be stored in the computer. Selection of a different profile is accomplished by changing the appropriate profile number with the keyboard. Selection of a baseline configuration for all three profiles may be obtained by using the baseline mode switch.

- Vertical Velocity Control System (VVCS) configuration to be used. Up to five VVCS configurations may be stored in the computer. The keyboard is used to enter the desired configuration number. The variable VVCS configuration feature is enabled only in conjunction with one of the approach modes.

- Path distance to go, in feet, along the approach path.

- Slant range, in feet, from the present aircraft position to the origin of the approach coordinate system.

- Altitude, in feet. The altitude that is displayed is either barometric or radar-derived, depending on the particular VVCS configuration in use.

- Speed reference, in knots, for use with the speed hold mode. This reference clamps when the speed hold mode is engaged and can then be changed through the keyboard. When either of the approach modes is engaged, this display presents the desired ground speed reference as determined by the velocity profile.

- Altitude reference, in feet, for use with the altitude hold mode. This reference clamps when the altitude hold mode is engaged and can then be changed through the keyboard. When an approach mode is engaged, this display presents the desired radar-derived altitude reference.

- Heading reference, in degrees, for use with the heading hold mode. This reference clamps when the heading hold mode is engaged and can then be changed through the keyboard. With either approach mode engaged, this display presents the computed tangential heading along the approach path.

In-Flight Computer Programming.- The last two rotary switch positions on the nav/guidance panels enable the user to inspect and change the contents of the digital computer memory. Input and output data can be in either decimal or octal format as indicated by the rotary switch position. The software that is required to implement this programming capability is located in the protected memory section of the computer and, therefore, cannot be destroyed or altered due to an operator error.

Inspection of the Computer Memory: When the selector is rotated to either the decimal or octal position, the left hand display will show all zeros and the right hand display will be blank. The desired memory address is then entered into the left hand display with the keyboard switches. Momentarily depressing the ENT button will cause the contents of the selected memory location to be presented in the right hand display. The selected memory address can be incremented or decremented by momentarily depressing the "+" switch or the "-" switch respectively. The contents of the new memory location will be presented in the right hand display in the correct format. Selection of a different memory address by use of one of the other keyboard switches will cause the right hand display to be blanked out again until the ENT button is momentarily depressed.

Changing the Computer Memory: The contents of a computer memory location can be changed by first inspecting the desired location and then momentarily depressing the Memory Access Switch (MEM). This will cause the memory access switch indicator light to be lighted, indicating that the contents of the selected location may be changed. In addition, the right hand display will be activated and will show all zeros. The new contents are then entered via the keyboard. These contents will appear right justified in the right hand display. Momentarily depressing the ENT button will cause the current data to be entered into the selected memory location. At this time, the right hand display will blank out for approximately 1 second and then return. In addition, the memory access indicator light will go out, indicating the return to the normal memory inspection mode. Momentarily depressing the memory access switch when the indicator light is on will cause the control panel to revert to the inspection mode without altering the selected memory location contents. The "-" switch is used to enter negative numbers into memory when the decimal format display has been selected. The "+" switch does not need to be utilized since data will be entered as positive numbers unless the "-" switch has been depressed.

Fault Recovery: The ability to recover in flight, from a computer fault due to an invalid instruction, is built into the system. When such a fault is detected by the computer, the operating program is interrupted and a fault recovery subroutine is executed. This subroutine is located in the protected portion of the computer memory. The fault recovery routine will cause the message FFFFFF to appear in the current data display. Rotating the nav/guidance rotary switch to the octal position and then momentarily depressing the ENT button will cause the address where the fault occurred to appear in the keyboard data display. The contents of the fault location will be displayed in the current data display. Changing the contents of the fault location to a valid instruction will clear the fault and restart the operating program.

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CONTROL LAWS

The VALT research vehicle is a CH 47B helicopter which has undergone extensive electrical and mechanical modifications. The mechanical linkages between the right-hand set of pilot controls and the basic aircraft have been replaced by full authority, electrohydraulic actuators in the pitch, roll, yaw, and collective axes. These actuators are driven by the inner loop control system which provides the aircraft with high-gain stability augmentation. In addition, the inner loop accepts reference commands generated by the outer loop control system in response to automatic navigation commands.

Inner Loop Control Laws

The pitch and roll inner loops are configured identically and are shown in Figure 3. This implementation yields a second-order attitude response to outer loop commands, and pilot inputs. The VALT Digital Navigation System is currently configured such that the pitch and roll inner loop control laws may be implemented in either digital or analog fashion. In the digital inner loop configuration, the 1819A computes both outer and inner loop control laws and produces actuator-position commands which are fed to an analog servo loop via the Digital Interface Unit (DIU). In the analog inner loop configuration, only the outer loop control laws are computed by the 1819A.

The yaw axis inner loop yields a first-order response to yaw rate commands. The implementation may be either digital or analog. A block diagram of the digital version, which is similar to the analog version in the AUTO mode, is shown in Figure 4.

The collective axis inner loop, the Vertical Velocity Control System (VVCS), shown in Figure 5, has a first-order response to altitude-rate commands. The VVCS is currently implemented in a digital configuration only.

Outer Loop Control Laws

Roll Axis.- The roll axis outer loop control laws produce an attitude command which in turn is fed to the roll inner loop. A block diagram of the roll axis controller is shown in Figure 6.

The most basic roll outer loop is Heading Hold/Select, which is implemented through roll at speeds above 35 knots.

Current heading is summed against a heading reference and scaled by a gain constant equal to the desired gain at 60 knots. The result is then gain programmed with velocity to produce a roll-angle command. One percent integral control is employed to compensate for any nulls in the system. The integrator is clamped whenever the heading error magnitude exceeds 10 degrees in order to prevent large overshoots when a new heading is selected.

During a high speed approach, crosstrack error is controlled through the roll axis alone. Error rate generates a bank-angle command which in turn causes the aircraft to yaw (yaw axis is in turn coordination mode) thereby producing a ground speed vector in a direction opposite to the crosstrack rate. Crosstrack error is scaled and fed into the velocity loop as a crosstrack rate reference. The rate command is limited in such a way as to provide a maximum capture angle of 30 degrees.

During the low-speed portion of an approach the control technique used is similar to the high-speed implementation with the exception that velocity is commanded by direct lateral translation (yaw axis is independent of roll). In addition, that portion of ground speed which is directly controllable by lateral translation is fed into the velocity loop. This provides the control necessary to follow a prescribed ground track while performing independent yaw maneuvers. The rate and position gains are the same in the high and low speed modes, but have been implemented separately in order to provide the capability to investigate the two modes independently. In addition, integral control is employed to compensate for the aircraft's lateral drag.

Pitch Axis.- Pitch axis outerloop control is implemented in three basic modes: Airspeed Hold/Select, High-Speed Approach, and Low-Speed Approach. A block diagram of pitch axis controller is shown in Figure 7. In the airspeed hold/select mode, airspeed is summed against a reference and gain scaled to produce a pitch-attitude command. This command is limited to a ±5-degree change from trim. A trim reference is provided by an integrator which is initialized at the moment of engagement and which is also used to provide integral control. The integral control gain was selected to compensate for aircraft longitudinal drag in the 70 to 90 knot region.

During a high speed approach, ground speed is controlled by pitch-attitude commands only. The groundspeed reference generated by the velocity profile calculation is summed against groundspeed and gain scaled to provide a pitch-attitude command above trim. The command is limited and integral control is employed as in the airspeed hold case. In addition, a pitch-attitude lead term provides the pitch-attitude command necessary to hold the deceleration commanded by a changing velocity reference.

The technique employed during low speed approach is similar to the high speed case except only that portion of the groundspeed reference which is directly controllable by pitch is used for a reference. In addition, only the groundspeed along the aircraft longitudinal axis is used as the feedback term rather than total groundspeed. Furthermore, that portion of crosstrack error parallel to the aircraft longitudinal axis is gain scaled and used to augment the velocity control loop. An implementation of this nature provides a natural transition to hover control, and also provides the control necessary to follow prescribed groundtrack in the presence of independent yaw maneuvers.

Yaw Axis.- The yaw axis outer loop operates in two modes; heading hold and turn coordination. A block diagram is shown in Figure 8. In the turn coordination mode the automatic bank-angle command is gain scaled with either airspeed or groundspeed and a yaw-rate command is generated which, in the steady-state, balances the equation

$$g\phi = U\,r$$

Additional feedback is provided by lateral acceleration.

In the heading hold mode, heading error is gain scaled to provide a yaw rate command. A yaw rate lead term is employed during low speed approaches to augment the system during curved path maneuvers.

Collective Axis.- Altitude select and altitude path control is provided by the collective outer loop controller shown in Figure 9. The VVCS inner loop controller holds the aircraft at an altitude equal to its model reference, Z_m. In the altitude select mode, Z_m is subtracted from the selected altitude, and the result is gain scaled to provide a commanded altitude rate. This command feeds the input to the VVCS model integrator ($\dot{Z}_m$). In the approach mode, a $\dot{Z}$ lead term is added to control the aircraft along various glideslope segments.

Hover Augmentation System

The Hover Augmentation System (HAS) is a selectable outer loop mode which provides the aircraft with short-term acceleration and velocity damping. The routine also shapes stick inputs in such a way as to provide the pilot with a velocity command system. The pitch and roll HAS implementations are identical and only the pitch axis will be considered here.

Figure 10 is a block diagram of the pitch axis HAS. Gravity compensated acceleration is processed through a pseudo integrator producing a short term velocity signal, U_h. The term is then fed back through another integrator producing long term washout on both the acceleration and velocity signals. The derived velocity and acceleration signals are gain scaled and fed to the inner loop as θ_c. Washed-out stick position is summed against the original acceleration signal while lagged stick is summed against the total feedback signal. A configuration of this type provides a short-term velocity response and a long-term attitude response.

When HAS is engaged, the inner loop uses a special set of damping and frequency parameters which allow a higher gain HAS configuration (ζ = .9, ω = 2.5).

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PATH GEOMETRY

The selection of the geometry to be used for generation of the lateral curved path, involved a tradeoff between versatility and reasonable programming requirements. Ideally, the ability to synthesize any arbitrary path in the horizontal and vertical planes, with no reprogramming, is desired. However, this flexibility is limited by certain practical constraints. The path geometry must be expressible in a mathematical form suitable for numeric computation techniques. Also, aircraft position, with respect to the desired position on the path, must be definable such that error signals can be generated. In addition, the engineering work load in generating the input parameters for the computer to specify paths and path variations must be reasonable.

The horizontal (X - Y) plane path consist of a series of straight line and elliptical path segments. This approach has the following advantages: first, good approximations of crosstrack error, distance to go, and desired heading can be calculated; second, since the circle is a special case of the ellipse, circular segments are inherently included in the horizontal path geometry; and third, the specification of the path is relatively simple, requiring only a series of data points consisting of an X-coordinate, a Y-coordinate, and a desired heading.

The altitude and speed profiles consist of a series of straight-line segments in the "altitude (or speed) versus distance to go along the path" plane. This provides the capability to approximate any arbitrary single-valued function. The profiles are specified as a table of "altitude (or speed) versus distance to go" data points.

Lateral Path

The general purpose lateral path consists of a series of (X, Y) data points, connected by either straight lines or elliptical sections, to form a continuous flight path. In addition to the (X, Y) data, a desired heading at each point is required to specify the path. The path generated passes over each data point.

Straight Line Segment.- Consider the line segment defined by X_1, Y_1, and X_2, Y_2, and the point off the segment, X_A, Y_A shown in Figure 11(a). If the segment and the point are rotated and translated to a coordinate system as shown in Figure 11(b), then:

$$X_1' = 0$$

$$Y_1' = 0$$

$$X_2' = 0$$

$$Y_2' = (Y_2 - Y_1) \sin \theta - (X_2 - X_1) \cos \theta$$

$$X_A' = (X_A - X_1) \cos \theta + (Y_2 - Y_1) \sin \theta$$

$$Y_A' = (Y_A - Y_1) \cos \theta - (X_A - X_1) \sin \theta$$

The perpendicular distance from the point to the line (crosstrack error) is X_A'. The length of the segment is Y_2'. The projection of the point on the segment is $(0, Y_A')$ and the length remaining on the segment past the projection point is $Y_2' - Y_A'$.

Elliptical Segment.- The curved sections of the lateral path are generated by fitting an elliptical segment between two data points. The selection of the elliptical segment to be used is always determined in a coordinate system where one of the data points is located at the origin and the entry or exit heading for that point is along the Y axis. Data points are translated to this new coordinate system prior to determination of the ellipse. The elliptical section used is defined such that the origin of the coordinate system is always a point of maximum or minimum curvature on the ellipse and the length of the segment is equal to or less than one-quarter of the length of the perimeter of the ellipse.

Selecting the elliptical section: Consider the section of the ellipse and the coordinate system shown in Figure 12. The equation for the ellipse shown is:

$$\frac{(x - a)^2}{a^2} + \frac{y^2}{b^2} = 1$$

The slope, m, of this ellipse at point (x, y) is:

$$m = - \frac{(x - a)}{a^2} \cdot \frac{b^2}{y}$$

If this slope and point (x, y) are given, then a and b are determined:

$$a = \frac{yx - mx^2}{y - 2\ xm}$$

$$b^2 = \frac{ma^2 y}{a - x}$$

For the elliptical section shown in Figure 12, $a > 0$. To satisfy this condition, the following inequality must hold:

$$\frac{y}{x} > 2m$$

Similarly, for the case in which $a < 0$, the inequality that must hold is:

$$\frac{y}{x} < 2m$$

The restrictions $y/x > 2m$ for $a > 0$ and $y/x < 2m$ for $a < 0$ may appear too limiting at first glance. It should be noted, however, that for a given set of data points, the restriction encountered by placing the origin of the coordinate system on one of the points is not present if the origin is placed on the other data point. This is illustrated in Figures 13 and 14. The elimination of these path restrictions in this manner leaves only one major restriction remaining. For a given set of data points connected by an elliptical segment, the slope of the path at the exit point must be greater than the slope of a straight line joining the points for $a < 0$. For $a > 0$, the slope of the path at the exit point must be less than the slope of a straight line joining the points. This is illustrated in Figure 15. This restriction precludes the introduction of a point of inflection in the curved path unless the inflection point is specified as a data point.

For a given pair of data points defined by X_1, Y_1, M_1, and X_2, Y_2, M_2, it is possible to determine the equation of the ellipse that contains the two data points, if the segment restrictions are satisfied, by appropriate rotation and translation of the coordinate system. Given the ability to determine an appropriate elliptical segment, it is then possible to fit a smooth, continuous path to a set of x, y data points using a combination of elliptical and straight line segments. An example of such a path is shown in Figure 16. Note that if two data points are to be connected with a straight line segment, the slopes at the two data points are determined and only the x, y position is required to specify these points. If a data point is the junction of two elliptical segments however, then it is necessary to specify the slope of the path at that data point in addition to the x, y position data.

Determination of crosstrack error: In order to determine the crosstrack error while flying along an elliptical section, it is necessary to determine the perpendicular distance from a given point to the ellipse. Consider the ellipse shown in Figure 17:

$$\frac{(x - a)^2}{a^2} + \frac{y^2}{b^2} = 1$$

and a point A near the ellipse defined by:

$$x = X_A$$

$$y = Y_A$$

The center of the ellipse is located at (a, 0) and the distance from the center of the ellipse to the two foci is given by:

$$c = \sqrt{a^2 - b^2}$$

The coordinates of the foci are then given as:

$$F_1 = (a - c), 0$$

$$F_2 = (a + c), 0$$

If X_A, Y_A were located on the ellipse, then the normal (perpendicular) to the ellipse at that point is the bisection of the angle defined as $F_1 AF_2$.

Let: θ = bisection of angle $F_1 AF_2$.

The angle from A to F_1 is defined by:

$$\theta_1 = \tan^{-1} \frac{Y_{F_1} - Y_A}{X_{F_1} - X_A}$$ where X_{F_1} and Y_{F_1} are coordinates of focus F_1.

for the orientation shown, $Y_{F_1} = 0$

$$\theta_1 = \tan^{-1} \frac{-Y_A}{X_{F_1} - X_A}$$

Similarly:

$$\theta_2 = \tan^{-1} \frac{-Y_A}{X_{F_2} - X_A}$$

θ is given as:

$$\theta = \frac{\theta_1 + \theta_2}{2}$$

Consider an ellipse of the same form as described, except that $b > a$. For this case, shown in Figure 18, the distance from the center of the ellipse to the foci is given by:

$$c = \sqrt{b^2 - a^2}$$

and the coordinates of the focal points are:

$$F_1 = a, c$$

$$F_2 = a, -c$$

In a manner similar to that previously presented, the angle θ is determined to be

$$\theta = \frac{\theta_1 + \theta_2}{2}$$

where

$$\theta_1 = \mathrm{Tan}^{-1} \frac{c - Y_A}{a - X_A}$$

$$\theta_2 = \mathrm{Tan}^{-1} \frac{-c - Y_A}{a - X_A}$$

For small deviations of (X_A, Y_A) off the ellipse, assume θ still defines the normal to the ellipse. Then the projection (X_E, Y_E) of (X_A, Y_A) onto the ellipse is defined by θ. The slope of (X_E, Y_E) is the slope of a line perpendicular to the normal:

$$M_E = \mathrm{Tan}\ (\theta + 90°)$$

The equations for the ellipse and the slope of a point on the ellipse can be solved to yield X_E and Y_E in terms of a, b, and M_E:

$$X_E = a \pm \frac{a^2 M_E}{\sqrt{b^2 + a^2 M_E^2}}$$

$$Y_E = \frac{b^2}{\sqrt{b^2 + a^2 M_E^2}}$$

Given the capability to determine the projection of the aircraft position onto a specified elliptical section, it is then possible to compute the magnitude of the crosstrack error as:

$$\text{XTRACK} = \left| \sqrt{(X_A - X_E)^2 + (Y_A - Y_E)^2} \right|$$

Where X_A, Y_A is the actual aircraft position and X_E, Y_E is the projection of this position onto the ellipse. The direction of the error is given by θ as previously defined.

Determination of path distance: In order to determine the distance to go from any point on the lateral path it is necessary to determine the length of an elliptical segment. Determination of this length involves the use of elliptical integrals for which there are no explicit solutions. For this reason, a piecewise linear approximation of the elliptical segment is used to calculate distance data. Consider the approximation shown in Figure 19 where:

$$S = \sum_{i=1}^{n} \Delta S_i$$

and

$$\Delta S_1 = \sqrt{(y_i - y_{i-1})^2 + (X_i - X_{i-1})^2}$$

If the X axis is divided into n equal segments then:

$$(X_n - X_{n-1}) = \frac{X_T}{n}$$

where X_T = X coordinate where the elliptical segments ends.

$$S = \sum_{i=1}^{n} \left[(y_i - y_{i-1})^2 + \frac{X_T{}^2}{n2} \right]^{1/2} \quad \text{for } 0 \leqslant X \leqslant X_T$$

where:

$$y_i = \left[b^2 - \frac{b^2}{a^2} (X_i - a)^2 \right]^{1/2}$$

If the speed of the aircraft is known, the bank angle required as it traverses an elliptical segment can be determined from the following equation:

$$\phi = \mathrm{TAN}^{-1} \frac{V^2}{RG}$$

where

ϕ = Bank Angle

V = Speed

R = Radius of Curvature

G = Acceleration due to Gravity

The radius of curvature of a curve Y = F(X) at any point (X, Y) is given by:

$$R = \frac{(1 + Y')^{3/2}}{|Y''|}$$

For an ellipse, this radius is given by

$$R = \frac{[Y^2 (a^2 - b^2) + b^4]^{3/2}}{ab^4}$$

Form of data entry: Data to describe the flight path is entered in the form of X position and Y position information for each point. In addition, a third entry is used to indicate whether a straight line or an elliptical section should be used to join a data point to the next data point. Provision for up to 50 data points is incorporated into the program. Storage is provided for 5 different sets of data points. X position and Y position data are entered in feet in signed decimal format. The coordinate system used is shown in Figure 20. Data points to describe the flight path are entered, in order, starting at the desired hover position and working backwards. A termination code (77777) is entered last to indicate the point where the flight path should start. The selection of a straight line or an elliptical section to join a pair of data points is indicated by the third entry for each data point. If two data points are to be joined by a straight line, then a flag code (77776) is inserted along with the X, Y data for these points. If a data point is the junction of a straight line and an elliptical section, then the same flag code is inserted. If a data point is the junction of two elliptical sections, then the third entry to be supplied is the magnetic heading, in degrees, that the aircraft should have as it passes over that data point. The form of the data entry for a sample path is shown as Table 1 and the path described is shown as Figure 21.

TABLE 1

LATERAL PATH DATA

2	5ØØØ	ØØ	ØØØØ	Ø	X_1	Data Point 1
2	5ØØ1	ØØ	ØØØØ	Ø	Y_1	
2	5ØØ2	22	772Ø	77776	Straight Line Flag	
2	5ØØ3	ØØ	ØØØØ	Ø		
2	5ØØ4	77	21Ø7	- 3ØØØ		
2	5ØØ5	22	772Ø	77776		
2	5ØØ6	77	6647	- 6ØØ		
2	5ØØ7	76	7ØØ7	- 46ØØ		
2	5Ø1Ø	22	772Ø	77776		
2	5Ø11	77	4Ø57	- 2ØØØ		
2	5Ø12	76	4217	- 6ØØØ		
2	5Ø13	22	772Ø	77776		
2	5Ø14	77	21Ø7	- 3ØØØ	X_5	Data Point 5
2	5Ø15	76	Ø277	- 8ØØØ	Y_5	
2	5Ø16	ØØ	ØØØØ	Ø	Desired Heading	
2	5Ø17	77	4Ø57	- 2ØØØ		
2	5Ø2Ø	75	4357	- 1ØØØØ		
2	5Ø21	22	772Ø	77776		
2	5Ø22	ØØ	ØØØØ	Ø		
2	5Ø23	75	Ø437	- 12ØØØ		
2	5Ø24	22	772Ø	77776		
2	5Ø25	ØØ	372Ø	2ØØØ		
2	5Ø26	74	6467	- 13ØØØ		
2	5Ø27	22	772Ø	77776		
2	5Ø3Ø	ØØ	764Ø	4ØØØ		
2	5Ø31	74	6467	- 13ØØØ		
2	5Ø32	22	772Ø	77776		
2	5Ø33	Ø1	356Ø	6ØØØ		
2	5Ø34	74	Ø577	- 16ØØØ		
2	5Ø35	ØØ	ØØØØ	Ø		
2	5Ø36	ØØ	567Ø	3ØØØ		
2	5Ø37	73	Ø737	- 2ØØØØ		
2	5Ø4Ø	ØØ	Ø132	9Ø		
2	5Ø41	ØØ	175Ø	1ØØØ		
2	5Ø42	73	27Ø7	- 19ØØØ		
2	5Ø43	22	772Ø	77776		
2	5Ø44	77	6647	- 6ØØ		
2	5Ø45	73	6ØØ7	- 174ØØ		
2	5Ø46	22	772Ø	77776		
2	5Ø47	77	Ø757	- 36ØØ		

TABLE 1 (cont)

LATERAL PATH DATA

2	5Ø5Ø	73	6ØØ7	-	174ØØ	
2	5Ø51	ØØ	ØØ55		45	
2	5Ø52	77	Ø757	-	36ØØ	
2	5Ø53	73	Ø117	-	2Ø4ØØ	
2	5Ø54	77	7722	-	45	
2	5Ø55	77	6647	-	6ØØ	
2	5Ø55	73	Ø117	-	2Ø4ØØ	
2	5Ø57	77	757Ø	-	135	
2	5Ø6Ø	77	6647	-	6ØØ	
2	5Ø61	73	6ØØ7	-	174ØØ	
2	5Ø62	ØØ	Ø2Ø7		135	
2	5Ø63	77	Ø757	-	36ØØ	
2	5Ø64	73	6ØØ7	-	174ØØ	
2	5Ø65	ØØ	ØØ55		45	
2	5Ø66	77	Ø757	-	36ØØ	
2	5Ø67	73	Ø117	-	2Ø4ØØ	
2	5Ø7Ø	77	7722	-	45	
2	5Ø71	77	6647	-	6ØØ	
2	5Ø72	73	Ø117	-	2Ø4ØØ	
2	5Ø73	77	757Ø	-	135	
2	5Ø74	77	6647	-	6ØØ	
2	5Ø75	73	6ØØ7	-	174ØØ	
2	5Ø76	22	772Ø		77776	
2	5Ø77	77	Ø137	-	4ØØØ	
2	51ØØ	74	4517	-	14ØØØ	
2	51Ø1	22	772Ø		77776	
2	51Ø2	22	7721		77777	—— End of Path Flag

Path restrictions: In order to simplify the geometry and the logic decisions necessary to generate the lateral path, some restrictions on the data used to specify the path are necessary:

- The path cannot have two consecutive straight line segments.
- A single elliptical section cannot be used to change the flight plan heading by an angle greater than 90 degrees.
- Two consecutive data points cannot describe a path that contains an inflection point. At least three data points are required in this case. The program will flag this as an input data fault and will advise the user.
- The data points used cannot require a heading change in a distance so short as to require the aircraft to exceed the nominal bank angle limit. The program will flag this as an input data fault and will advise the user. The nominal bank angle limit for a given set of data is selected by the user.
- A velocity profile must be stored in the computer in order to determine the aircraft bank angles. The profile must be defined in terms of along-track-distance to go in the $Z = \phi$ plane.

Initial Path Capture Maneuver.- Whenever the lateral path is initialized, it is necessary to compute a flight path from the present aircraft position to the starting point of the path selected. The initialization will insure that the aircraft enters the lateral path with the correct heading, as well as the correct speed and altitude, for the speed and altitude profiles.

Capture Conditions: Consider the path capture situation shown in Figure 22. The point P_N denotes the first point of the desired lateral path. The objective is to arrive at point P_N with a heading in the same direction as the vector from P_N to P_{N-1}. This can be achieved by extending the vector $\overline{P_N P_{N-1}}$ and capturing it prior to reaching P_N. Assume, however, that the maximum allowable capture angle of a straight line is β, as shown in Figure 22. If ΔP is equal to zero, any capture attempt initiated from outside the capture cone would fail to capture the line prior to reaching P_N. Next, consider the worst case condition in which the initial aircraft position is on the outer boundary of the capture region and in which the initial aircraft heading is along the boundary and away from the path. The minimum aircraft turning radius is:

$$R = \frac{V_o^{\,2}}{g \sin \phi_{max}}$$

where V_o is the desired speed at start of horizontal path, and ϕ_{max} is the maximum allowable bank angle. If a capture is attempted from this worst case condition, the aircraft will parallel the shaded region boundary at a distance 2R. The cone vertex must therefore be moved along the heading vector a distance of $X = 2R/\sin\beta$ away from P_N to insure that any capture attempt from within the cone will be successful.

Path Capture Outside the Cone: Figure 23 depicts the techniques for capture used when the initial aircraft position (X_A, Y_A) is outside the cone. Two circles are constructed so as to be tangent to each other at the apex of the cone (X_o, Y_o). The radius of each circle is:

$$R_o = \frac{V_o^{\,2}}{g \sin \phi_{nom}}$$

where ϕ_{nom} is the nominal bank angle. The center of circle 1 is:

$$X_R = X_o + R_o \cos \psi_c$$

$$Y_R = Y_o - R_o \sin \psi_c$$

where ψ_c is the initial path magnetic heading. The center of circle 2 is:

$$X_R = X_o - R_o \cos \psi_c$$

$$Y_R = Y_o + R_o \sin \psi_c$$

The circle used in the capture is the circle that lies on the same side of the extended vector $\overline{P_N, P_{N-1}}$ as the initial aircraft position.

As long as the distance from the aircraft to the circle center is greater than twice the circle radius, the aircraft is commanded to fly toward the circle center. This is accomplished by making the desired heading

$$\psi_{desired} = \mathrm{TAN}^{-1} \frac{X_A - X_R}{Y_A - Y_R}$$

where X_A, Y_A is the present aircraft position. When the aircraft gets within a distance $2R_o$ from the circle center, the aircraft is commanded to capture the circle. The desired heading becomes the heading tangential to the circle:

$$\psi_{desired} = \text{TAN}^{-1} \frac{X_A - X_R}{Y_A - Y_R} + 90° \qquad \text{for circle 1}$$

$$\psi_{desired} = \text{TAN}^{-1} \frac{X_A - X_R}{Y_A - Y_R} - 90° \qquad \text{for circle 2}$$

The crosstrack error from the circle is:

$$E = R_o - \sqrt{(X_A - X_R)^2 + (Y_A - Y_R)^2} \qquad \text{for circle 1}$$

$$E = \sqrt{(X_A - X_R)^2 + (Y_A - Y_R)^2} - R_o \qquad \text{for circle 2}$$

Crosstrack error is negative if the aircraft position is to the left of the path.

The decision whether to continue on the circle, or head for the start of path, is made when the aircraft passes the cone apex. The aircraft is allowed to exit the circle if the speed, altitude and heading are within the tolerance limits allowed for the start of the lateral path. If these limits are not satisfied, the aircraft is commanded to fly around the circle one more time.

Altitude Profile

The altitude path is specified by a series of data points. Each data point consists of a distance to go along the flight path and a desired altitude at that distance. The altitude change between two data points is a linear function of the distance difference between those points.

Consider a portion of the altitude profile as shown in Figure 24. Between data point $3(S_3, H_3)$ and data point $2(S_2, H_2)$ the change in altitude as a function of distance is:

$$\Delta H = \frac{H_3 - H_2}{S_3 - S_2} \cdot \Delta S$$

and the altitude for any S ($S_2 \leqslant S \leqslant S_3$) is:

$$H = H + \frac{(H_3 - H_2)}{(S_3 - S_2)} \cdot (S - S_2)$$

Since the slope of the path has discontinuities at the data points, a transition procedure is required to provide a smooth flight path. The transition can be accomplished by switching to a new segment prior to completion of the present segment. For any any S between S_3 and S_A the desired altitude reference is given as:

$$H = H_2 + \frac{(H_3 - H_2)}{(S_3 - S_2)} \cdot (S - S_2)$$

At the switch point $S = S_A$, a switch to the segment defined by S_1 H_1 and S_2, H_2 is made thus producing an artifical error H_e:

$$H_e = \left[H_1 + \frac{(H_2 - H_1)}{(S_2 - S_1)} \cdot (S_A - S_1)\right] - \left[H_2 + \frac{(H_3 - H_2)}{(S_3 - S_2)} \cdot (S_A - S_2)\right]$$

and a desired vertical speed change from:

$$\dot{H}_{32} = -\dot{S}\,\frac{(H_3 - H_2)}{(S_3 - S_2)} \qquad \text{Where } \dot{S} = \text{Ground speed along the path.}$$

to:

$$\dot{H}_{21} = -\dot{S}\,\frac{(H_2 - H_1)}{(S_2 - S_1)}$$

For a smooth transition, the net change in vertical speed at S_A should be zero. For this condition:

$$0 = \dot{H}_{32} - \dot{H}_{21} - KH_e$$

where the system gain, K, is given as:

$$K = \frac{-\dot{H}}{H_e} \qquad \text{or} \qquad \dot{H} = -KH_e$$

Since:

$$0 = -\dot{S}\,\frac{(H_3 - H_2)}{(S_3 - S_2)} + \dot{S}\,\frac{(H_2 - H_1)}{(S_2 - S_1)} - K\left[H_1 + \frac{(H_2 - H_1)}{(S_2 - S_1)} \cdot (S_A - S_1)\right]$$

$$+ K\left[H_2 + \frac{(H_3 - H_2)}{(S_3 - S_2)} \cdot (S_A - S_2)\right]$$

Then:

$$KS_A\left[\frac{H_2 - H_1}{S_2 - S_1} - \frac{H_3 - H_2}{S_3 - S_2}\right] = K\left[H_2 - H_1 + S_1\,\frac{(H_2 - H_1)}{(S_2 - S_1)} - S\,\frac{(H_3 - H_2)}{(S_3 - S_2)}\right]$$

$$+ \dot{S}\left[\frac{H_2 - H_1}{S_2 - S_1} - \frac{H_3 - H_2}{S_3 - S_2}\right]$$

Note that:

$$H_2 - H_1 = \frac{(H_2 - H_1)}{(S_2 - S_1)} \cdot (S_2 - S_1) = S_2\,\frac{(H_2 - H_1)}{(S_2 - S_1)} - S_1\,\frac{(H_2 - H_1)}{(S_2 - S_1)}$$

$$\therefore KS_A\left[\frac{H_2 - H_1}{S_2 - S_1} - \frac{H_3 - H_2}{S_3 - S_2}\right] = \left[\frac{H_2 - H_1}{S_2 - S_1} - \frac{H_3 - H_2}{S_3 - S_1}\right] \cdot \left[KS_2 + \dot{S}\right]$$

or

$$S_A = S_2 + \frac{\dot{S}}{K}$$

It should be noted that while this technique provides a smooth transition between segments, it does not provide the correct value of altitude reference for data-recording purposes during the transitions.

Data to describe the altitude profile is entered in the form of distance-to-go and desired altitude at that distance for each data point. Up to 25 data points may be used to define an altitude profile. Storage is provided for five different sets of data points in the computer. Distance-to-go and altitude are entered in feet using a decimal data format. Data points to describe the altitude profile are entered, in order, starting at the hover position and working backwards. A termination code (77777) is entered last to indicate the data point where the profile should start. The form of the data entry for a sample path is shown in Table 2.

TABLE 2

DATA FOR SAMPLE ALTITUDE PROFILE

Input	Data Point	Entry
1	1	0 Distance to go, in Feet
2		0 Desired Altitude, in Feet
3	2	200
4		25
5	3	300
6		35
7	4	1000
8		200
9	5	5000
10		1000
11	6	77,777 Termination Code

Speed Profile

The speed profile is specified by a series of data points. Each data point consists of a distance to go along the flight path and a desired velocity at that distance. The velocity change between two data points is a linear function of the distance difference between those points.

Consider a portion of the velocity profile as shown in Figure 25. Between data point $3(S_3, V_3)$ and data point $2(S_2, V_2)$ the change in velocity as a function of distance is:

$$\Delta V = \frac{V_3 - V_2}{S_3 - S_2} \cdot \Delta S$$

and the velocity for any S $(S_2 \leqslant S \leqslant S_3)$ is:

$$V = V_2 + \frac{(V_3 - V_2)}{(S_3 - S_2)} \cdot (S - S_2)$$

A lead term corresponding to deceleration is generated by processing predicted future velocity through a washout routine as shown in Figure 26. This lead term is applied to the pitch axis control system in order to initiate required pitch angle changes prior to the break in the velocity profile. The predicted velocity term, $V_{(t + a)}$, is computed by first assuming that the present actual velocity will remain constant for the next "a" seconds and then multiplying the actual velocity by "a" to generate a lead distance. This lead distance is then subtracted from the present distance-to-go along the path to provide an approximate distance-to-go after "a" seconds. This approximate distance is then entered into the velocity profile program to compute an estimate of the desired velocity after "a" seconds. A block diagram of this implementation is shown in Figure 27.

Data to describe the speed profile is entered in the form of distance-to-go and desired velocity at that distance for each data point. Up to 25 data points may be used to define a velocity profile. Storage is provided for five different sets of data points in the computer. Distance-to-go is entered in feet and desired velocity is entered in feet-per-second using a decimal data format. Data points to describe the speed profile are entered, in order, starting at the hover position and working backwards. A termination code (77777) is entered last to indicate the data point where the profile should start. The form of the data entry for a sample path is shown in Table 3.

TABLE 3

DATA FOR SAMPLE VELOCITY PROFILE

Input	Data Point	Entry
1	1	0 Distance to go, in Feet
2		0 Desired Velocity in Feet-Per-Second
3	2	500
4		10
5	3	1000
6		25
7	4	2500
8		50
9	5	6000
10		60
11	6	10,000
12		60
13	7	77,000 Termination Code

HARDWARE

The VALT Digital Navigation System is built around the Sperry Flight Systems 1819A Digital Computer. This computer was combined with a set of analog, digital, and human interface devices to form the VALT hardware set. All of the interface hardware devices were specifically designed and fabricated for this project.

1819A Digital Computer

The 1819A Digital Computer (Figure 28) is a medium scale, general-purpose computer specifically designed for airborne applications. The particular 1819A configuration used for the VALT Digital Navigation System consists of 16,384 words of 18-bit core memory, 1096 words of 18-bit solid-state-read-only memory and seven input/output channels.

Physical Characteristics.- The 1819A is contained in a single cast-aluminum chassis which measures .194 meters high, .257 meters wide and .498 meters long in accordance with ARINC full ATR long form factor. The computer chassis is divided laterally into two card bays. One card bay contains digital circuit components and the internal power supply while the second bay contains digital circuit components and the core memory. All digital circuits are mounted on plug-in printed circuit board assemblies. The entire chassis assembly is indirectly forced-air-cooled by blowing external air through heat exchangers built into the outside walls. Card interconnection is provided by blade and fork connectors with wire-wrap terminations on a back plane.

The computer, as configured for the VALT system, weights 24.5 kilograms and requires approximately 250 watts of power. The unit is mounted on a tray plenum and receives cooling air from an external blower.

Control Section.- The control section contains circuitry necessary to procure, modify, and execute the instructions of a program stored in the memory of the computer. It controls parallel transfers of instructions and data. Direct and indirect addressing capabilities and automatic address and operand modification are directed by the control section. This section controls all arithmetic, logical, and sequential operations of the computer except those assigned to the input/output section. It has facilities to permit an interruption of the running program when certain events require such interventions.

Arithmetic Section.- The arithmetic section performs all the 1's complement arithmetic, shifting, and logical operations for the computer under the direction of the function code translation in the Control Section. The Arithmetic Logic Unit (ALU) is used in conjunction with the two holding registers X and D to perform addition and logical operations. Shifting operations are performed using the X and W registers in combination with the AL and AU registers. The K register is used to hold the shift count for both the shifting operations, and the multiply or divide operations. The B register is used for holding the current index value. The detection of an overflow condition is also accomplished in the arithmetic section.

Core Memory.- The computer core memory internal to the unit contains 16,384 18-bit words of addressable storage locations. Several of these locations are special purpose and provide for the distinct functions shown in Table 4.

TABLE 4

CORE MEMORY ADDRESS LOCATION

Memory Address (octal)	Assignment
DRO Memory	
00000	Fault Interrupt Entrance Register
00001 → 00010	Index Registers
00011	Spare
00012	Power Fail Interrupt Entrance Register
00013	Spare
00014	Overflow Interrupt Entrance Register
00015	Spare
00016	Real-Time Clock Interrupt Entrance Register
00017	Scale Factor Shift Count Register
00020 and 00021	Spares
00022 → 00037	External Function Buffer Control Registers for Channels 1 - 7
00040 and 00041	Spares
00042 → 00057	Output Buffer Control Registers for Channels 1 - 7
00060 and 00061	Spares
00062 → 00077	Input Buffer Control Registers for Channels 1 - 7
00100	Spare

TABLE 4 (cont)

CORE MEMORY ADDRESS LOCATION

Memory Address (octal)	Assignment
00101 → 00117	External Interrupt Entrance Registers for Channels 1 - 7
00120 → 00141	Spares
00142 → 00157	Output Monitor Interrupt Entrance Registers for Channels 1 - 7
00160 and 00161	Spares
00162 → 00177	Input Monitor Interrupt Entrance Registers for Channels 1 - 7
00200	Power Up Entrance Address
00202	Self-Test Program Return
00201, 00203 → 37777	Instruction Word and Data Storage

A write protect feature for 2048 consecutive storage locations is also provided. The write protect circuitry in memory control will not allow memory locations 34000 through 37777 (octal) to be written into unless the protect function is disabled. This function may be disabled via a switch on the computer control panel.

Nondestructive Readout Memory.- A solid-state read only memory is also provided with the computer. The 1024 18-bit words of Nondestructive Readout (NDRO) memory are used to contain a self-test program an a paper tape load program (Bootstrap). The computer has provisions for an additional 3072 words of NDRO memory available in 1024-word increments. The 1024 words provided with the computer are storage locations 70000 through 71777 (octal). The following table lists the address assignments for NDRO memory.

TABLE 5

NDRO MEMORY ADDRESS LOCATION

Memory Address (octal)	Assignment
70000	BITE Interrupt Entrance Register
70001 → 71722	Self-Test Program Storage
71723 → 71777	Bootstrap

Program Interrupts.- The computer has provisions for the interruption of a running program by an event which may occur asynchronously with that program. An interrupt suspends the normal program sequence and causes the execution of the instruction located in a permanently assigned interrupt entrance address in the memory. There are eight levels of interrupts in the computer with the five lowest levels controllable via an interrupt lockout mask that is contained in the Interrupt Lockout Register (ILR). The following is a list of the program interrupts in descending order of priority:

(1) Power Fail

(2) BITE (Built-in-Test)

(3) Fault

(4) Overflow

(5) Real-Time Clock

(6) External Interrupt

(7) Input Monitor

(8) Output Monitor

The three lowest levels (external interrupt, input monitor, output monitor) are input/output functions and, as such, they are processed by the input/output section. These levels are given priority according to the input/output channel involved with the channel priority taking precedence over the function priority. That is, if an output monitor interrupt on channel 2 occurs simultaneously with an input monitor interrupt on channel 3, the output monitor interrupt will be honored first since channel 2 has a higher priority assignment than channel 3.

Input/Output Section.- The Input/Output (I/O) section includes those data paths and control circuits used by the computer for communicating with external equipment. Communication with the computer is carried on in either an 18-bit or 36-bit parallel mode. The interface uses a full party-line data transmission system with a single set of 36 twisted pairs for both transmitting and receiving all data. The system is organized as one 36-bit parallel channel and six 18-bit channels. Each channel has its own set of control lines using 8 twisted pairs per channel. All references to input or output are made from the standpoint of the computer; that is, "input" is always input to the computer, and "output" is always output from the computer. The I/O section has access to the total 16,384 words of core memory.

I/O Buffering: The computer has the capability for communicating with peripheral equipment on any and all I/O channels concurrently with the execution of the program. Buffering operations, once initiated by the programmed instruction, proceed to termination asynchronously with the program. The buffer instruction selects the I/O channel, channel mode (input, output, external function), and designates the area of computer memory to be used by the channel for storing incoming data or dispatching outgoing data.

I/O Channel Priority: The input and output channels are numbered 1 through 7 with the highest priority being given to the lowest numbered channel in the case of simultaneous requests for the same type of operation.

I/O Memory Addresses: The I/O section uses the assigned memory addresses (buffer control words) which dictate the memory area affected by an input or output operation. The other memory addresses that are used by the I/O section are allocated for I/O interrupts. The I/O section generates the addresses required to reference memory for all I/O requirements as well as for all interrupts. These special addresses are held in the special address register for utilization in referencing memory.

Control Lines: Inputs to the computer and outputs from the computer are controlled using eight control lines. The control lines are the external interrupt, input data request, input data enable, input data acknowledge, external function request, external function acknowledge, output data request, and output data acknowledge. These signals are listed in Table 6.

TABLE 6

CONTROL SIGNALS USED FOR INPUT/OUTPUT

	Signal Name	Origin	Meaning
Input Channel	Input Data Request (IDR)	Peripheral Equipment	Peripheral equipment has a data word on the input lines ready for the computer to accept.
	Input Data Enable (IDE)	Computer	Computer is ready to sample input lines and peripheral equipment must enable its line drivers.
	Input Data Acknowledge (IDA)	Computer	Computer has sampled the word on the input lines.
	External Interrupt (EI)	Peripheral Equipment	Peripheral Equipment has an Interrupt Code Word on the input lines ready for the computer to accept.
Output Channel	Output Data Request (ODR)	Peripheral Equipment	Peripheral Equipment is in a condition to accept a word of data from the computer.
	Output Data Acknowledge (ODA)	Computer	Computer has put a data word on the output lines for the Peripheral Equipment to sample.
	External Function Request (EFR)	Peripheral	Peripheral Equipment is in a condition to accept an External Function message from the computer.
	External Function Acknowledge (EFA)	Computer	Computer has put an External Function message on the output lines for the Peripheral Equipment to sample.

I/O Function Priority: The I/O function priority circuits provide automatic selection of the higher priority operation when two or more operations are requested by peripheral equipment or by the computer at the same time. Some real-time events, as well as certain information transfers, require special handling or main program intervention. These operations or interrupts are processed by the I/O section according to a prearranged priority scheme. The following is a list of the operating modes in descending order of priority:

(1) External Function Request

(2) Input Request

(3) Output Request

(4) External Interrupt

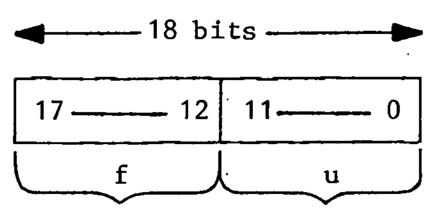
(5) Internal Interrupt from "Input Transfer with Monitor"

(6) Internal Interrupt from "Output Transfer with Monitor"

The above functions are given the listed priority according to the channel involved, with the channel priority taking precedence over the function priority.

Instructions.- Two basic instruction word formats are used by the computer, the first of which is shown below.

FORMAT I INSTRUCTIONS

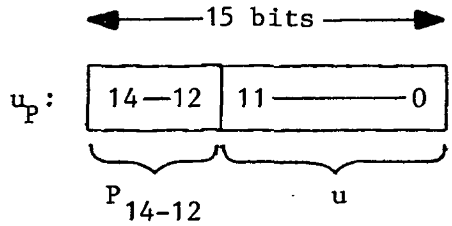


f is defined as the function code
u is defined as the twelve low order bits.

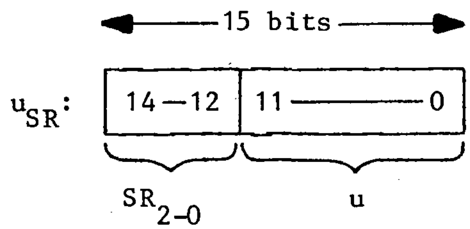
The definition and usage of u are determined by the function code utilizing u in two distinct manners:

(1) As a constant. For this case, u itself is the operand and requires no further memory reference; however, u is "extended" to 18-bits. (Refer to List of Instructions.)

(2) As an address. For this case, u is used as the lower order 12-bits of the base address referring to a memory cell. The base address is 15-bits, designated as u_P or u_{SR}, and is described below:



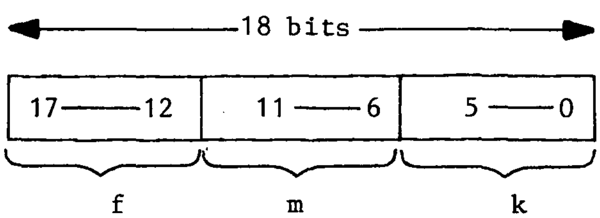
u_P is defined as a 15-bit address whose 3 high order bits consist of the 3 high order bits of P and whose 12 low order bits are u.



u_{SR} is defined as a 15-bit address whose 3 high order bits consist of the 3 low order bits of SR and whose 12 low order bits are u.

Certain Format I instructions allow the use of either u_P or u_{SR} as the operand address; for these instructions u_{SR} is used if SR is ACTIVE and u_P is used whenever SR is INACTIVE. (Refer to List of Instructions.)

FORMAT II INSTRUCTIONS



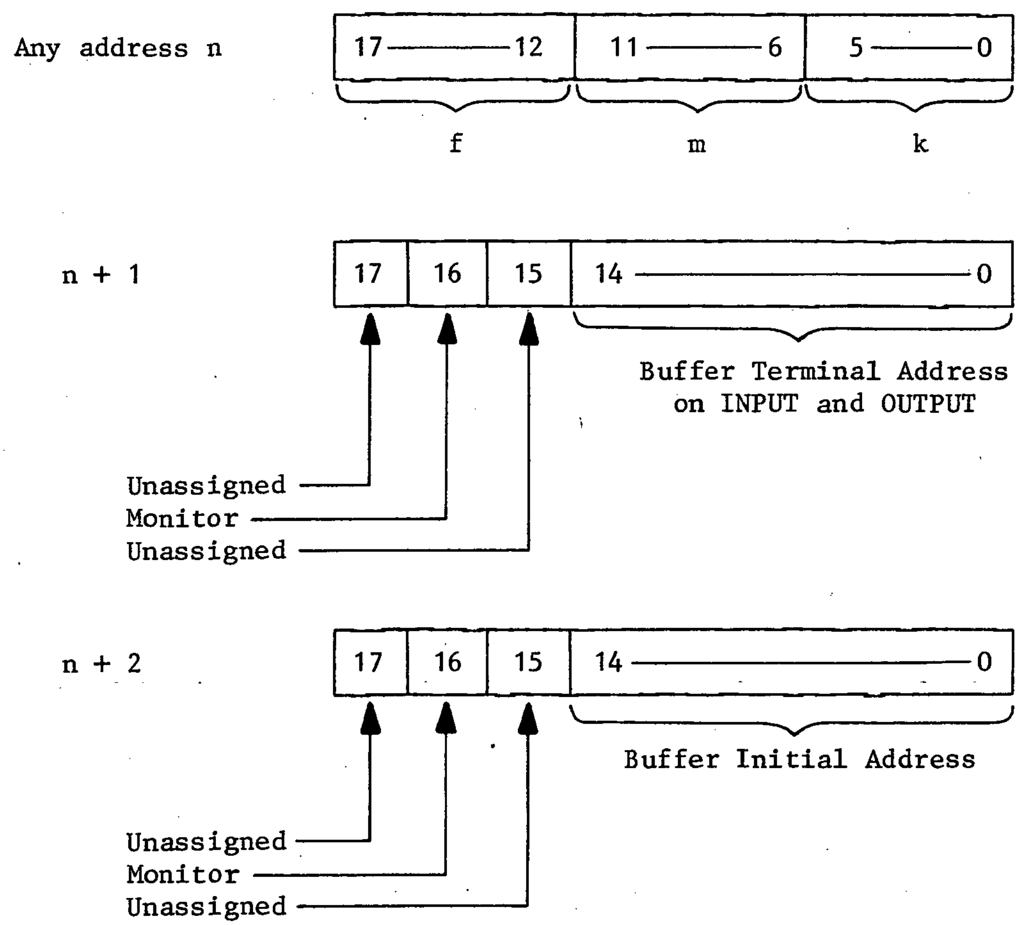
f is defined as the six-bit function code (always equal to octal 50)
m is defined as the six-bit minor function code
k is defined as the six low order bits

Format II instructions perform a variety of operations and can be classified in three instruction categories:

(1) No memory address needed. For this case, the information existing in the computer's arithmetic or control registers and the value k are sufficient to perform the specified operation.

(2) 36-bit enter/store. For this case, the memory cell immediately following the instruction is used to contain the memory address of Y. This address must be even.

(3) Initiate input/output buffer. For this case, the two memory cells immediately following the instruction are used to contain the buffer control words. The complete instruction, therefore, must occupy three sequential memory cells; the format is as follows:



Bit 16 (Monitor): If set to one, the monitor interrupt occurs upon successful completion of the last transfer; if set to zero, no monitor interrupt will occur.

NOTE: Normal buffer termination occurs when the incremented buffer initial address word is equal to the buffer terminal address word. Therefore, bit 16 must be set to the same respective value for both buffer control words. Bits 15 and 14 will be set to values according to the maximum size of memory in the computer.

For all buffer control words, all bits above the most significant bit of the terminal address must be exactly the same in both control words.

A complete repertoire of instructions is given in Table 7.

Registers.- The 1819A has both addressable and non-addressable registers.

ADDRESSABLE REGISTERS

- AU - Upper accumulator, 18-bit arithmetic register
- AL - Lower accumulator, 18-bit arithmetic register
- A - AU and AL are linked together to form one 36-bit arithmetic register
- B - One of eight index registers. Each register is an 18-bit dedicated memory location. The contents of the currently active register are also contained in a hardware register in the control section.
- ICR - A 4-bit index control register which contains the identity of the index register currently active.
- P - A 15-bit program address register which contains the address of the instruction currently being entered for execution.
- SR - A 4-bit special register through which the program can control which of the 4096-word banks in core memory is to be referenced.
- ILR - A 6-bit interrupt lockout register which contains the interrupt lockout mask.

NON-ADDRESSABLE REGISTERS

- DO and DE - Two 18-bit output buffer registers in the I/O section for transferring data or instruction words (external function) to external devices. The DO register is the buffer register for the odd-numbered channels (1, 3, 5, and 7) and the DE register is the buffer for the even-numbered channels (2, 4, and 6).
- W - An 18-bit holding register used in the arithmetic section during arithmetic, shifting, and logical operations.
- D - An 18-bit register used in the arithmetic section during arithmetic and logical operations, and as a temporary operand address register.
- X - An 18-bit register used in the arithmetic section during arithmetic, shifting, and logical operations.
- F - A 7-bit function register that holds the function code of the instruction being executed.
- K - A 6-bit register that receives the shift count.
- S - A 15-bit register that receives and holds the address of a main memory location during a memory cycle.
- Z - An 18-bit memory buffer register for all transfers to and from memory.
- SAR - A 7-bit special address register in the I/O section that is used for holding the special-purpose memory addresses.
- BCW - A 16-bit buffer control word register in the I/O section used in all input and output transfers.

1819A Control Panel

The 1819A Control Panel (Figure 29) is a special purpose peripheral device used to facilitate software and computer hardware troubleshooting. The unit provides direct visual inspection of the computer accumlators, instruction register, and address register through indicator lights located on the panel. These indicator lights also contain integral pushbutton switches which allow the computer operator to preload the appropriate register. In addition, selective skip and stop keys are provided together with indicator lights that display I/O activity, overflows, faults, and interrupts. The 1819A Control Panel is configured to allow operation of the computer in either the normal run mode or in a step mode. In the step mode, instructions are executed one at a time under manual control.

TABLE 7

1819-A REPERTOIRE OF INSTRUCTIONS

INSTRUCTION WORD — FORMAT I: | 17 - f - 12 | 11 - u - 0 | — FORMAT II: | 17 - f - 12 | 11 - m - 6 | 5 - k - 0 |

	f m	SYMBOL	INSTRUCTION	DESCRIPTION	EXEC TIME
ENTER	= 10*	ENTAU	ENTER AU WITH (Y)	(Y)→AU	4
	= 12*	ENTAL	ENTER AL WITH (Y)	(Y)→AL	4
	= 32*	ENTB	ENTER B WITH (Y)	(Y)→B	4
	36	ENTBK	ENTER B WITH CONSTANT	Y→B 1	2
	70	ENTALK	ENTER AL WITH CONSTANT	Y→AL 1	2
	50 04*	ENTA	ENTER A WITH (Y + 1, Y)	(Y)→AL, (Y + 1)→AU, Y = (P + 1)	8
	50 72	ENTICR	ENTER INDEX CONTROL REGISTER	(B)→(ICR), k_{0-2}→ICR, (k_{0-2})→B	6
	50 73	ENTSR	ENTER SPECIAL REGISTER	k_{0-3}→SR	2
STORE	= 40*	STRZ	STORE ZERO IN Y	0→Y	4
	= 42*	STRB	STORE (B) IN Y	(B)→Y	4
	= 44*	STRAL	STORE (AL) IN Y	(AL)→Y	4
	= 46*	STRAU	STORE (AU) IN Y	(AU)→Y	4
	72	STRICR	STORE (ICR) IN Y_{0-5}	(ICR)→Y_{0-5}	4
	74	STRADR	STORE (AL) IN Y_{0-11}	(AL)→Y_{0-11}	4
	75	STRSR	STORE (SR) IN Y_{0-5}	(SR)→Y_{0-5}, 0→SR_{0-3}	4
	50 06*	STRA	STORE (A) IN Y + 1, Y	(AL)→Y, (AU)→Y + 1, Y = (P + 1)	8
ARITHMETIC	= 14*	ADDAL	ADD (Y) TO (AL)	(AL) + (Y)→AL	4
	= 16*	SUBAL	SUBTRACT (Y) FROM (AL)	(AL) − (Y)→AL	4
	= 20*	ADDA	ADD (Y + 1, Y) TO (A)	(A) + (Y + 1, Y)→A	6
	= 22*	SUBA	SUBTRACT (Y + 1, Y) FROM (A)	(A) − (Y + 1, Y)→A	6
	= 24*	MULAL	MULTIPLY (AL) BY (Y)	(AL) * (Y)→A	24
	= 26*	DIVA	DIVIDE (A) BY (Y)	(A) ÷ (Y)→AL, REMAINDER→AU	24
	37	ENTBKB	ADD CONSTANT TO (B)	(B) + Y→B 1	2
	71	ADDALK	ADD CONSTANT TO (AL)	(AL) + Y→AL 1	2
INDEXING	56	BSK	B SKIP	IF B = (Y); P + 2→P IF B ≠ (Y); (B) + 1→B & P + 1→P	4
	57	ISK	INDEX SKIP	IF (Y) = 0; P + 2→P IF (Y) ≠ 0; (Y) − 1→Y & P + 1→P	6
	73	BJP	B JUMP	IF B ≠ 0; (B) − 1→B & Y→P IF B = 0; P + 1→P	2
REG TRANS	50 70	XFRBL	TRANSFER (B) TO AL	(B)→AL	2
	50 71	XFRLB	TRANSFER (AL) TO B	(AL)→B	2
	50 74	XFRLU	TRANSFER (AL) TO AU	(AL)→AU	2
	50 75	XFRUL	TRANSFER (AU) TO AL	(AU)→AL	2
TRANSFER ADDRESS — UNCOND	30*	IRJP	INDIRECT RETURN JUMP	P + 1→(Y); (Y) + 1→P 2	6
	34*	JP	UNCONDITIONAL JUMP	Y→P	2
	54	IJPEI	INDIRECT JUMP AND ENABLE INTERRUPTS	(Y)→P AND ENABLE INTERRUPTS	4
	55	IJP	INDIRECT JUMP	(Y)→P	4
	76	RJP	RETURN JUMP	P + 1→Y, Y + 1→P 2	4

TRANSFER ADDRESS — CONDITIONAL f m	COMPARE NOT SET		COMPARE SET		DESCRIPTION	EXEC TIME
60	JPAUZ	JUMP (AU) = 0	JPEQ	JUMP M = (AL)	Y→P TEST CONDITION MET	2
61	JPALZ	JUMP (AL) = 0	JPEQ	JUMP M = (AL)	Y→P TEST CONDITION MET	2
62	JPAUNZ	JUMP (AU) ≠ 0	JPNOT	JUMP M ≠ (AL)	Y→P TEST CONDITION MET	2
63	JPALNZ	JUMP (AL) ≠ 0	JPNOT	JUMP M ≠ (AL)	Y→P TEST CONDITION MET	2
64	JPAUP	JUMP (AU) ⩾ + 0	JPMLEQ	JUMP M ⩽ (AL)	Y→P TEST CONDITION MET	2
65	JPALP	JUMP (AL) ⩾ + 0	JPMLEQ	JUMP M ⩽ (AL)	Y→P TEST CONDITION MET	2
66	JPAUNG	JUMP (AU) ⩽ − 0	JPMGR	JUMP M > (AL)	Y→P TEST CONDITION MET	2
67	JPALNG	JUMP (AL) ⩽ − 0	JPMGR	JUMP M > (AL)	Y→P TEST CONDITION MET	2

NOTE: $Y = P_{12-14} + u_{0-11}$
= SR SENSITIVE $Y_{12-14} = SR_{0-2}$, $Y_{0-11} = u_{0-11}$ IF SR SET
* B MODIFICATION OF "Y" POSSIBLE; ADD SUFFIX B TO SYMBOL AND ADD 1 TO f-CODE, $Y = u_{0-11} + B_{0-17}$

NOTE: IF SR SET AND B MODIFICATION REQUESTED, $Y_{12-17} = SR_{0-2} + B_{12-17}$; $Y_{0-11} = u_{0-11} + B_{0-11}$
1 Y = u SIGN EXTENDED TO 18 BITS
2 EXECUTED FROM INTERRUPT ENTRANCE REGISTER, STORE P

TABLE 7 (cont)

1819-A REPERTOIRE OF INSTRUCTIONS (cont)

		f m	SYMBOL	INSTRUCTION	DESCRIPTION	EXEC TIME
LOGICAL		= 02*	CMAL	COMPARE AND SET DESIG.	(AL): (Y)	4
		= 06*	CMSK	COMPARE WITH MASK AND SET DESIG.	L (AL) (AU): L (Y) (AU)	4
		= 04*	SLSU	SELECTIVE SUBSTITUTE	L (AL) $\overline{(AU)}$ + L (Y) (AU) → AL	4
		51	SLSET	SELECTIVE SET (INCLUSIVE OR)	L (AL) + (Y) → AL; SET $(AL)_N$ FOR $(Y)_N = 1$	4
		52	SLCL	SELECTIVE CLEAR (LOGICAL AND)	L (AL) (Y) → AL; CLEAR $(AL)_N$ FOR $(Y)_N = 0$	4
		53	SLCP	SELECTIVE COMPLEMENT (EXCLUSIVE OR)	L (AL) ⊕ (Y) → AL; COMPLEMENT $(AL)_N$ FOR $(Y)_N = 1$	4
		50 61	CPAL	COMPLEMENT (AL)	$\overline{(AL)}$ → AL	2
		50 62	CPAU	COMPLEMENT (AU)	$\overline{(AU)}$ → AU	2
		50 63	CPA	COMPLEMENT (A)	$\overline{(A)}$ → A	2
SHIFT		50 41	RSHAU	RIGHT SHIFT (AU)	SHIFT RIGHT k BIT	2 + k
		50 42	RSHAL	RIGHT SHIFT (AL)	POSITIONS END OFF AND FILL	OR
		50 43	RSHA	RIGHT SHIFT (A)	UPPER k BITS WITH ORIGINAL SIGN	2 + k + 1
		50 44	SF	SCALE FACTOR ROTATE	LEFT ROTATE A UNTIL $A_{35} \neq A_{34}$ OR K – SHIFT COUNT = 0, THEN k – SHIFT COUNT → 00017	4 + k OR 4 + k + 1
		50 45	LRTAU	LEFT ROTATE (AU)	LEFT ROTATE k BIT	2 + k
		50 46	LRTAL	LEFT ROTATE (AL)	POSITIONS	OR
		50 47	LRTA	LEFT ROTATE (A)		2 + k + 1
SKIP	ARITH	50 51	SKPNFL	SKIP ON NO FLAG	P + 2 → P IF FLAG NOT SET	2
		50 52	SKPOV	SKIP ON OVERFLOW	P + 2 → P IF OVERFLOW SET	2
		50 53	SKPNOV	SKIP ON NO OVERFLOW	P + 2 → P IF OVERFLOW NOT SET	2
		50 54	SKPODD	SKIP ON ODD PARITY	P + 2 → P IF SUM OF ONES IN A IS ODD	2
		50 55	SKPEVN	SKIP ON EVEN PARITY	P + 2 → P IF SUM OF ONES IN A IS EVEN	2
	I/O	50 21	SKPIIN	SKIP ON INPUT INACTIVE	P + 2 → P IF CHANNEL k INPUT IS INACTIVE	2
		50 22	SKPOIN	SKIP ON OUTPUT INACTIVE	P + 2 → P IF CHANNEL k OUTPUT IS INACTIVE	2
		50 23	SKPEIN	SKIP ON EXF INACTIVE	P + 2 → P IF CHANNEL k EXF IS INACTIVE	2
		50 50	SKP	SKP ON KEY SETTING	P + 2 → P IF k = CONSOLE KEY SETTING	2
INPUT/OUTPUT		50 11	IN	INPUT TRANSFER	(P + 1) → 60 + 2k, (P + 2) → 61 + 2k SET INPUT CH k ACTIVE	10
		50 12	OUT	OUTPUT TRANSFER	(P + 1) → 40 + 2k, (P + 2) → 41 + 2k SET OUTPUT CH k ACTIVE	10
		50 13	EXF	EXTERNAL FUNCTION TRANSFER	SET EXTERNAL FUNCTION CH k ACTIVE	2
		50 14	IOSTP	TERMINATE INPUT/OUTPUT	CLEAR ACTIVES ALL CH AND SET ALL LOCKOUTS EXCEPT MASTER	2
		50 15	INSTP	TERMINATE INPUT	CLEAR INPUT ACTIVE CH k	2
		50 16	OUTSTP	TERMINATE OUTPUT	CLEAR OUTPUT ACTIVE CH k	2
		50 17	EXFSTP	TERMINATE EXTERNAL FUNCTION	CLEAR EXTERNAL FUNCTION ACTIVE CH k	2
		50 26	OUTOV	OUTPUT OVERRIDE	SET OUTPUT REQUEST CH k	2
		50 27	EXFOV	EXTERNAL FUNCTION OVERRIDE	SET EXTERNAL FUNCTION REQUEST CH k	2
INTER-RUPTS		50 30	RIL	REMOVE INTERRUPT LOCKOUT	ENABLE ALL INTERRUPTS (IGNORE k)	2
		50 34	SIL	SET INTERRUPT LOCKOUTS	TRANSFER k TO INTERRUPT MASK (1) AND ENABLE ALL INTERRUPTS	2
		50 24	WTFI	WAIT FOR INTERRUPT	HOLD SEQUENCE UNTIL INTERRUPT	2
STOP		50 56	STOP	STOP ON KEY SETTING	STOP IF k = CONSOLE KEY SETTING	2
NO-OP		50 20	NO OP	NO OPERATION		2
		50 40	NO OP	NO OPERATION		2
		50 60	NO OP	NO OPERATION		2
FLAGS		50 64	CLRFL	CLEAR FLAG		2
		50 65	SETFL	SET FLAG		2
		50 66	CLROVF	CLEAR OVERFLOW		2
		50 67	SETOVF	SET OVERFLOW		2
FAULT		00,01,77 5000,5077	FAULT		GO TO FAULT INTERRUPT REGISTER	2

ASSIGNED CORE MEMORY LOCATION

000	FAULT INTERRUPT	042 - 057	OUTPUT BUFFER CONTROL WORDS
001 - 010	INDEX REGISTERS	062 - 077	INPUT BUFFER CONTROL WORDS
012	POWER FAIL INTERRUPT	102 - 117	EXTERNAL INTERRUPT
014	OVERFLOW INTERRUPT	142 - 157	OUTPUT MONITOR INTERRUPT
016	REAL TIME CLOCK INTERRUPT	162 - 177	INPUT MONITOR INTERRUPT
017	SCALE FACTOR SHIFT COUNT	200	POWER ON ENTRANCE
022 - 037	EXF BUFFER CONTROL WORDS	70000	BITE INTERRUPT

(1) INTERRUPT MASK: BIT 5 - MASTER; BIT 4 - OVERFLOW; BIT 3 - OUTPUT MONITOR; BIT 2 - INPUT MONITOR; BIT 1 - EXTERNAL INTERRUPT; BIT 0 - REAL TIME CLOCK

The 1819A Control Panel is housed in a stand-along cabinet which measures .279 meters high, .442 meters wide and .241 meters long. The unit weights approximately 4.082 kilograms.

Digital Interface Unit

The Digital Interface Unit (DIU) provides the capability to convert analog signals into digital data and to convert digital data into analog signals. The DIU is shown in Figure 30.

Physical Characteristics.- The DIU is contained in an aluminum chassis which measures .194 meters high, .124 meters wide and .562 meters long. The unit weighs 7.25 kilograms and uses approximately 90 watts of power. The chassis is divided into three card bays with each bay containing five card assemblies. The card interconnection wiring is provided by plug-in connectors and conventional harness wiring attached to a connector plate.

Input Section.- The DIU input section consists of 30 analog buffer amplifiers, a 32-channel analog multiplexer, a sample-and-hold amplifier, and a high-speed, 12-bit A/D converter. The A/D converter is time-shared by the multiplexer which is controlled by the DIU control logic section. A block diagram of the input section is provided in Figure 31.

The analog buffer amplifiers provide overvoltage protection for the DIU multiplexer and converter circuits as well as providing the voltage gains necessary to transform all analog input signals to a ±10 volts dc full scale level.

The 32-channel multiplexer is implemented with series field effect transistor switches. The particular analog channel that is being selected at any one time is determined by a counter in the DIU logic section.

The A/D converter is a high-speed, 12-bit, successive-approximation converter with a conversion time of less than 30 microseconds. The 12-bit converter provides an effective analog resolution of .0049 volt dc at ±10 volts dc input scaling. A sample and hold amplifier is used to provide a relatively constant input signal to the A/D converter during the conversion process.

The A/D conversion cycle is initiated by a start-convert command generated by the control logic section. This command triggers a 20-microsecond monostable multivibrator, which commands the sample-and-hold circuit to sample the selected analog input. At the completion of the sample period, the transition of the monostable sets the convert logic command through 3-microsecond delay, which allows the sample-and-hold output to settle out before conversion begins. The converter completes the conversion under control of its internal clock and generates an end-of-convert command which is sent to the control section. The digital data is held on the output data lines until the input acknowledge is received from the 1819A. The acknowledge command is also used to step the sequential counter in the control logic section, thus starting the conversion cycle again.

Discrete input signals are transmitted to the 1819A computer through a digital multiplexer when the DIU logic counter output equals 31. A total of 12 input discretes are provided.

Output Section.- The 30 analog output voltages are generated by 30 separate Digital-to-Analog (D/A) converters. Each of these converters provides a continuous output voltage that is a function of the 12-bit digital code that is applied. A block diagram of the DIU output section is shown as Figure 32. Each converter is connected to a 12-bit digital data storage register that provides a fixed digital code to the converter between data updates from the 1819A computer. The storage registers are updated by sequentially generating a series of strobe-and-latch commands such that the appropriate storage register takes data from the data bus at the proper time. Strobe generation is accomplished in the logic section and is a function of the I/O transfer rate between the DIU and the 1819A computer. In this manner, the correct strobe is generated for each computer-output word transferred to the DIU. The use of 12-bit D/A converters provides a full scale output voltage range of -10 volts dc to +10 volts dc with a resolution of .0049 volt dc.

The output of D/A converter number 30 is used to provide a test voltage to the input section of the DIU. This signal provides a continuous end-around test of the DIU input section, I/O transfers, sequence logic, and output section strobe logic. The test signal is reconverted into digital form and transmitted back to the 1819A computer where a test subroutine compares the returned digital data with the original digital data. A DIU test error message is transmitted to the navigation/guidance control panel if the difference between these two values exceeds a selectable tolerance.

In addition to the analog output voltages, the DIF output section also provides 12 discrete outputs. The discretes are generated in the 1819A computer and are latched into a storage register in the DIU in the same manner as the D/A converter codes.

Logic Section.- The logic section provides the counting and timing functions necessary to sequence and control data transfers between the DIU and the 1819A computer. The DIU logic controls the I/O such that input data transfers are alternated with output data transfers so that the same counter and sequence logic can be used for A/D and D/A conversions. A block diagram of the logic section is shown in Figure 33.

A DIU transfer sequence is initiated by the 1819A computer under control of the system software. The computer transmits a forced External Function Acknowledge (EFA) with a code word to the DIU to reset all the DIU control logic and preset the counter to one of four starting positions. The DIU then initiates an A/D conversion sequence and also transmits an Output Data Request (ODR) to the computer, to indicate that the DIU is ready to accept the first output data word. Output data is then transmitted to the DIU by the 1819A, together with an Output Data Acknowledge (ODA). The DIU uses the ODA to latch the data into the correct storage register in the output section. When the DIU receives the ODA, and the A/D conversion sequence previously initiated has been completed, the DIU places the converted data on the data lines and transmits an Input Data Request (IDR) to the computer. Once the computer accepts the input data, an Input Data Acknowledge (IDA) is transmitted back to the DIU which advances the DIU counter and repeats the sequence. The total number of I/O transfers is controlled by the 1819A under software control. A DIU logic section timing diagram is shown in Figure 34.

Navigation/Guidance Control Panel

The navigation/guidance control panel is a general-purpose computer interface unit that provides a method of gaining access to the 1819A computer program during flight test. The panel electronics converts commands manually entered through the front panel controls into the voltage levels and word format necessary for transmission to the computer. In addition, output information from the computer is decoded and displayed in various forms on the front panel.

Physical Characteristics.- The navigation/guidance panel (Figure 35) is configured as a panel-mounted unit [as per MS25212 (ASG)] intended for mounting in an aircraft panel rack. The unit measures .229 meters high, .146 meters wide and .188 meters long and weighs 3.7 kilograms. The panel contains three printed circuit board assemblies and two hand-wired circuit board assemblies. The circuit board interconnection wiring uses plug-in circuit board connectors and a conventional wiring harness attached to a connector plate.

Output Section.- Data is transmitted from the 1819A computer by four twisted wire pairs. Differential line receivers are used to provide the necessary interface to the TTL logic levels used in the navigation/guidance panel. Data interface is identical to that used in the DIU. Incoming data is sequentially multiplexed into data storage registers by a counter in the control panel logic section. The contents of the storage registers are displayed on the front panel in two forms. Numerical data such as the contents of a memory location is presented on a numerical readout display. The readouts are planar gas tube indicators using a 7-segment character format. A total of 11 digits of display is provided in one 6-digit group and one 5-digit group. The necessary BCD-to-7-segment decoders are contained within the navigation/guidance panel so that display information can be output directly from the digital computer memory without additional software processing. Display blanking is under program control.

Mode status and flag information from the storage registers is displayed in the form of lighted legends on the front panel pushbuttons. Selection and control of these indicators are completely determined by the software. One data bit is required to be set for each indicator. All necessary lamp-driving circuits are contained in the unit. Indicator lamps operate from the aircraft 28 volts dc system. A block diagram of the output section is shown as Figure 36.

Input Section.- Information is input to the navigation/guidance panel by one of three types of front panel controls: a numerical keyboard, a rotary selector switch, or 1 of 14 momentary pushbuttons. Maximum flexibility is obtained by making all input device functions a matter of software implementation.

A sequential counter in the control section multiplexes each input device onto the data lines for transmission to the 1819A computer. Differential line drivers are used to drive the twisted pair data lines. A block diagram of the input section is shown in Figure 37.

Pressing one of the keyboard or indicator pushbuttons sets a unique bit in the transfer word sequence as long as the button is held down. Decoding of the bit and subsequent action within the 1819A are determined entirely by software.

Selection of a particular rotary switch position sets one bit in one of four words associated with the rotary switch. As in the case of the pushbuttons, the decoding of the switch position and the subsequent action taken is determined by the software.

Control Section.- The navigation/guidance control section provides the timing and counting circuits necessary to sequence and control data transfer between the navigation/guidance panel and the 1819A computer. The operation of the logic section is similar to the logic section used in the DIU.

TDS Interface Unit

The TDS Interface Unit (TIU) is a digital data buffer unit placed between the 1819A computer and the Transponder Data System (TDS). The TDS serves as the data link between the aircraft and the ground facilities. Both uplink and downlink data are transmitted through the Transponder Data System and the TIU.

Physical Characteristics.- The TIU (Figure 38) uses the same chassis and general construction as the DIU. The unit contains four printed circuit board assemblies and six hand-wired circuit board assemblies.

Uplink Section.- The TIU is organized into two major sections: the uplink section and the downlink section. The uplink section provides the logic and counting circuits necessary for transmission of data from the TDS uplink receiver to the 1819A computer. The TIU uplink section contains a 32-word, solid-state, memory which acts as a buffer between the TDS and the computer. The buffer memory is loaded by the TDS at a high update rate and then read into the 1819A core memory at a lower rate. Transfers of data from the TDS to the TIU are initiated by the TDS. Transfers of data from the TIU to the 1819A are initiated by the 1819A. A block diagram of the uplink section is shown in Figure 39.

Uplink data from the TDS is in the form of 16 proportional data words and 16 groups of four discrete signals. Proportional data words are ten bits in length, but double precision capability is provided through software manipulation in the 1819A computer and in the ground computer.

Data transfers between the TDS and the TIU can be in either block mode or single-word transfer mode. In the block mode, a block of uplink data is transferred to the TIU in a high-speed sequential operation at the end of each TDS transmission frame. In the single-word mode, each piece of uplink data is transferred from the TDS to the TIU as it is received by the TDS.

Downlink Section.- The downlink section provides the logic and counting circuits necessary for transmission of data from the 1819A computer to the TDS. The downlink section contains a 64-word, solid-state, memory which acts as a buffer between the 1819A and the TDS. The buffer memory is loaded by the 1819A at a rate determined by the software and is read into the TDS at a higher rate. Transfers of data from the 1819A to the TIU are initiated by the 1819A. Transfers of data from the TIU to the TDS are initiated by the TDS. A block diagram of the downlink section is shown in Figure 40.

Downlink data transmitted to the TDS is in the form of 48 proportional data words and 16 groups of 4 discrete signals. Proportional-data words are 10 bits in length, but double precision capability is provided through software manipulation in the 1819A and in the ground computer.

Data transfers between the TIU and the TDS can be in either block mode or single-word transfer mode. In the block mode, the entire contents of the TIU buffer memory are transmitted to the TDS in response to a TDS demand. In the single-word mode, a single proportional data word or a single group of four discrete signals is transmitted from the TIU to the TDS in response to a TDS demand.

Flight Equipment Pallet

The flight equipment pallet provides the mounting tray and cooling air plenum chamber for the 1819A computer when the navigation system is installed in the CH-47B helicopter. In addition, the pallet contains the mounting tray for the digital interface unit, the electrical junction box, the system interconnecting wiring, and the interface connectors for the ground support equipment.

Ground Support Equipment

A set of Ground Support Equipment (GSE) was specifically designed for the digital navigation system in order to provide a means to both program the 1819A computer and to isolate malfunctions in either the system hardware or software. The GSE is shown in Figure 41. The GSE contains a paper-tape reader, a paper-tape punch, a keyboard printer, a peripheral-device control unit, and the necessary interconnecting wiring and cables. In addition, the GSE contains a blower and mounting tray with a plenum chamber for the 1819A computer, as well as an interface for a high-speed line printer.

The GSE is designed to operate in one of two configurations. When used in conjunction with the 1819A computer and the 1819A control panel, the GSE can be operated in a stand-alone mode to provide the interface between the 1819A computer and the system programmer. The GSE is used in this mode to write, check, edit, and assemble programs for the computer. To facilitate a complete checkout of the system software, the GSE contains the interconnecting wiring and cables necessary to operate all the system hardware components independent of the flight equipment pallet or the CH-47B aircraft.

The GSE can also be configured to operate as a system support tool for the flight equipment pallet.

In this configuration the GSE is connected directly to the pallet with four test cables while the pallet and the system hardware components are installed in the aircraft. When used in this manner, the GSE provides the capability to monitor and change the system software while the system is in operation.

Carry-On Load/Dump Unit

A portable Carry-On Load/Dump (COLD) unit was designed to provide limited ground support for the flight system in those cases where the primary GSE is not available. The COLD unit provides the capability to load the 1819A memory from a magnetic tape cassette and to store the contents of the 1819A memory on the cassette. The COLD unit connects directly to the pallet through the same cable set that is used with the GSE. In addition to the read-and-store capability, the COLD unit allows the operator to start and stop the 1819A, and to select the program start location. With this capability, the operator can perform a bootstrap load into the computer. The COLD unit is shown in Figure 42, and the front panel of the COLD unit is shown in Figure 43.

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SOFTWARE

The software supplied with the VALT system can be classified as either flight software or ground utility software. The flight system software consists of a set of specialized subroutines, one of which is a checkout routine and the rest of which form the in-flight running program. The ground support utility package consists of programs that can be used to modify old software or create new software for the 1819A computer.

The software can be used in one of three configurations. In flight, only the running program is used. On the ground, the running program can be used in conjunction with a utility routine and the lateral path checkout routine to test or troubleshoot the flight software. In the third configuration, which is again a ground configuration, only the utility programs are used.

For the first two configurations described above, the computer memory is organized in the following manner: Bank Ø contains the majority of the running program; Bank 1 is reserved for a utility routine; Bank 2 contains the lateral path program and the lateral path checkout program; Bank 3 contains the program variables, arithmetic routines and, in protected memory, the routines which service the navigation/guidance control panels.

Flight System Software

The flight system software is organized as a group of specialized subroutines. The lateral path plot routine is a ground checkout routine while the remaining routines form the flight system running program.

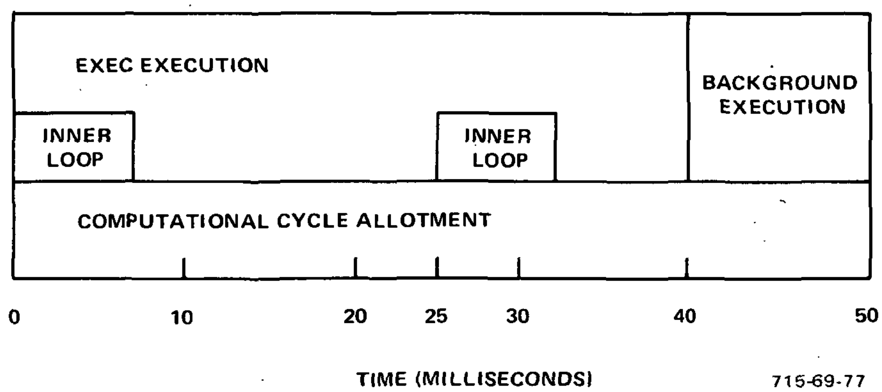
Flight System Running Program.- When ac power is applied to the 1819A, the program register is set to ØØ2ØØ once the power supply voltages are within designated tolerances. If the 1819A control panel is not connected, the instruction in ØØ2ØØ is immediately executed. The VALT flight system software contains a SIL'77 in location ØØ2ØØ which disables all interrupts. The next instruction is a jump to the power up routine which performs the following functions:

- Resets all real-time integrators to zero
- Sets all mode flags to off status
- Clears all control panel storage locations
- Restores all critical interrupt locations

Upon completion of the above functions, the real-time clock interrupt is enabled and program control is transferred to the background routine. This routine is executed during the time left over in the real-time cycle loop once the running program has been executed. Nonreal time programs such as curved path initialization are executed in background.

A Real-Time Clock (RTC) interrupt is generated by the 1819A every millisecond. If the RTC interrupt has not been masked out, normal program execution is suspended and the instruction located in ØØØ16 is executed. Location ØØØ16 in the VALT flight system software contains a jump to a routine called MASTER. The MASTER routine controls the real-time loop and enables time sharing between this loop and the background program.

The Executive (EXEC) routine is the primary real-time loop sequencer. It is called by the MASTER routine every 50 milliseconds. The EXEC routine executes inner loop control laws immediately upon being called and then proceeds with normal real-time programs. Twenty-five milliseconds into the computational cycle allotment time, MASTER interrupts EXEC, re-executes the inner loop, and then returns to normal EXEC operation. A typical computational cycle is shown below.



In the above case the computational cycle allotment is 50 milliseconds. The EXEC routine execution time is 40 milliseconds (including two executions of the inner loop) leaving 10 milliseconds for background computations. Since the background routine is typically 20 milliseconds long, it will take two cycles (100 milliseconds) to completely execute background. Similarly, if the EXEC time is less than 30 milliseconds, the background program may be executed more than once within the computational cycle.

Initially, the EXEC routine executes the following sequence:

(1) Performs 25-millisecond integrations

(2) Scales high frequency inputs from the DIU

(3) Processes TDS inputs

(4) Executes inner loop control laws

(5) Performs low frequency integrations and filters

(6) Executes hover augmentation control laws

EXEC then calls the proper outer loop subroutines in order to implement the desired flight mode. If neither approach mode has been engaged, EXEC checks to see if any or all of the hold modes are engaged. If the heading hold mode is engaged, EXEC calls HDGHLD. If the altitude hold mode is engaged, ALTHLD is called. With the speed hold mode engaged, EXEC calls SPDHLD. With all control law functions complete, EXEC then services the navigation/guidance control panels. Mode indicators on the panels correspond to several of the software mode "flags" which are used by EXEC. These flags are created by EXEC based on navigation/guidance panel inputs and flight conditions.

Major Flight System Subroutines.-

Arithmetic and Convenience Routines: These routines include square root, sine, cosine, arctangent, arcsine, BCD-to-Octal and Octal-to-BCD conversion. In addition, a general-purpose time integration routine using trapezoidal approximation is provided for use with the filter and control law routines.

Control Panel Routines: These routines service the navigation/guidance panel to determine which buttons have been pushed, what the rotary switch position is and what should be displayed. A utility routine is included which allows the user to inspect and change computer memory locations, thus providing the capability to program the computer through the panel. In addition, a fault recovery routine allows the user to locate and correct invalid instructions in the program.

Control Law Routines: These routines implement automatic pitch, roll, yaw, and collective pitch axis control. Specific control laws employed are a function of flight conditions and mode(s) engaged.

Vertical Velocity Command System (VVCS): A VVCS using control laws provided by NASA is implemented. Nine gains define the VVCS configuration. Five configurations may be stored in the computer at one time.

Service Routines: These routines initiate the I/O sequences to the navigation/guidance panel, the digital interface unit, and the TIU.

Flight Director Control Laws: These routines generate the outputs that are to be sent to the flight director command cues. The flight director routines are independent of the routines that generate the automatic commands.

Path Geometry Routines: These routines generate the references for flying the lateral path and the vertical and speed profiles. The initialization routines check the path data for errors, fit the curved path to the data points and generate the data required to maneuver the aircraft to the start of the path. The lateral path routine calculates crosstrack error, desired heading, and raw distance-to-go. This raw distance-to-go is filtered with ground speed to obtain a smoothed output. The vertical profile routine generates an altitude reference and a vertical rate reference. The speed profile routine generates a speed reference and a predicted speed reference two seconds ahead.

Terminal Area Navigation System (TANS) Routine: This routine implements four second order complementary filters to generate smoothed XYZ radar position and barometric altitude.

Lateral Path Plot Routine: This routine generates a plot of the path data stored in the computer and is used as a ground check on the validity of the path. The plot is generated by placing a simulated point mass aircraft on the starting data point of the path, displacing the simulated aircraft some distance along the tangent to the path at that point, projecting the new aircraft position back onto the path to obtain a new path position, and then repeating the above procedure until the end of the path is reached.

Ground Support Utility Software

The ground support utility package is the primary software tool for the system programmer. This package, when used in conjunction with the ground support equipment, provides the programmer with the capability to write, edit, assemble, and debug programs for the 1819A Digital Computer. The utility package consists of five programs: The 75-code loader, the manual utility, the extended utility, the text editor, and the assembler.

75-Code Loader.- The 75-code loader is used to load relocatable formatted tapes. The loader itself is loaded using the bootstrap routine which resides in the 1819A read-only memory. The 75-code loader is used in conjunction with the paper-tape reader.

Manual Utility.- The manual utility is a collection of routines designed to assist the programmer in loading programs into the 1819A computer and to assist in debugging these programs. The utility performs the operations of loading absolute and relocatable paper tapes, inspecting and changing memory locations, searching a block of memory for masked data, storing a constant in a block of memory, moving a block of memory, and punching an absolute-format paper tape.

Extended Utility.- The extended utility is the primary utility routine used by the programmer to enter, operate, and debug programs. This utility performs more functions than the manual utility and has the added versatility of operating in a conversational manner from the teletype. The extended utility performs the functions of inspecting and changing memory locations, executing subroutines, executing programs starting at a specified location, loading absolute and relocatable paper tapes, punching absolute tapes, outputting to the line printer, outputting to the teletype printer, moving a block of memory, searching a block of memory for masked data, writing into consecutive memory locations in a specified format, storing a constant in a block of memory, and tracing a program. This last function provides a listing of every instruction executed in the program being traced. In addition, if specified, the listing will include the contents of the accumulators and special registers when the contents change.

Text Editor.- The text editor is used to edit and create source program tapes. The editor uses four peripheral devices: a teletype reader, a teletype printer, a paper-tape reader, and a paper-tape punch. The editing process consists of reading or typing a page of text into a buffer storage area; listing or printing this text if desired; changing, deleting, or inserting any additional text from the teletype keyboard; and finally, generating a new source tape of the edited copy.

Assembler.- The assembler accepts a source program expressed symbolically, absolutely, or any combination thereof and converts it into an ordered set of machine instructions suitable for loading via the utility routines. The assembler is a 2-pass assembler and requires the use of a paper-tape reader, a paper-tape punch, and a console typewriter.

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INITIAL SIMULATION RESULTS

A hybrid analog and digital simulation was developed and used to checkout the hardware, debug the software, and to integrate and evaluate the entire system. The system performance during simulated test flights is documented in this section.

Longitudinal/Vertical Performance

Data depicting longitudinal/vertical axis performance was obtained by using the VALT flight system hardware and software in conjunction with the hybrid simulation. Various disturbances were introduced into the system by commanding mode and reference changes with the navigation/guidance control panel.

Longitudinal Axis Data.-

Speed Select: Figure 44 shows the system response to a commanded increase of 2.57 meters per second (5 knots) in the reference velocity. Initial velocity for the case is 30.9 meters per second (60 knots). System dynamics are masked slightly by the fact that commanded velocity reference changes are lagged and rate limited prior to being introduced into the control laws. The effect of this reference smoothing technique is best shown in Figure 45 in which the aircraft is commanded from a hover to 46.3 meters per second (90 knots). An initial pitch attitude change of .075 radians is smoothly commanded. The attitude then increases to compensate for changing trim demands as the aircraft accelerates at .76 meter per second (2.5 feet per second^2). At no time does the velocity error (V_e) exceed 1.83 meters per second (6 feet per second).

Automatic Approach: Automatic transition from forward flight to a hover is shown in Figure 46. The NASA "1.5 degrees" deceleration profile is used. This profile approximates a constant attitude deceleration in which the pitch attitude demanded is 1.5 degrees above the hover trim attitude. The velocity error during the transition does not exceed .91 meter per second (3 feet per second) and the transition to the hover control laws does not require any abrupt pitch attitude changes. The NASA "Concave Downward" altitude profile was used for this data run.

Vertical Axis Data.-

VVCS: The NASA Vertical Velocity Control System (VVCS) is a high gain collective pitch axis inner loop which has been implemented digitally within the VALT software. The response of the system, shown in Figure 47, was obtained by inserting a step model attitude change of 1.52 meters (5 feet). Figure 48 shows the normal VVCS performance when a 2.54 centimeter (1 inch) step of collective command is applied. This data was taken with a VVCS configuration having a rate model lag time constant of 2 seconds.

Altitude Select: Vertical axis response to commanded altitude reference changes is shown in Figure 49. During the first part of the run the altitude reference is changed from 0 to 305 meters (1000 feet). The 5.18 meters per second (17 feet per second) vertical velocity limit is achieved within 10 seconds ("g" limiting is used) and is held until the new reference is approached. During the second part of the trace the altitude reference is switched to zero. The vertical velocity limit is automatically decreased as the aircraft nears the ground in the interest of safety and pilot acceptability.

Automatic Approach: Vertical performance during an automatic approach is shown in Figure 50. The NASA "Concave Downward" altitude profile is used for this case. This profile approximates a constant vertical speed of 2.44 meters per second (8 feet per second) with an automatic flare to 15.2 meters (50 feet). The discontinuities in the h_e and h_{REF} traces are caused by the altitude error/altitude rate cancelling technique used to assymptotically transition between various altitude profile segments. The "1.5 degree" deceleration profile was used for this data run.

Lateral/Directional Performance

Data depicting lateral/directional axes performance was obtained by using the VALT flight system hardware and software in conjunction with the hybrid simulation. Various disturbances were introduced into the system by commanding mode and reference changes with the navigation/guidance control panel.

Lateral/Directional Axes Data.-

Heading Select: Heading Select performance for cruise flight velocities above 20.5 meters per second (40 knots) is shown in Figures 51 and 52. In Figure 51 the heading reference is changed by 10 degrees, while in Figure 52 the reference is changed by 180 degrees. The effect of bank angle and roll rate limiting is readily apparent in these figures. For both of these cases a velocity of 30.5 meters per second (100 feet per second) was used. The heading gain is programmed to be directly proportional with velocity to provide a heading response which is virtually independent of airspeed. Hover performance for similar reference changes is shown in Figures 53 and 54. The yaw rate command is both magnitude and rate limited to provide a smooth response.

Automatic Approach: Crosstrack capture performance for an airspeed of 30.5 meters per second (100 feet per second) with position deviations of 30.5 meters (100 feet) and 305 meters (1000 feet) is shown in Figures 55 and 56 respectively. In the latter case, the effect of a 30 degree cut angle limit is apparent. Maximum overshoot for this case is approximately 15.2 meters (50 feet).

The ability of the VALT system to track a curved path is shown in Figure 57 for an airspeed of 30.5 meters per second (100 feet per second) and in Figure 58 for an airspeed of 10.4 meters per second (34 feet per second). In the higher speed case, a 180 degree turn is commanded by flying a semicircle of radius 609.6 meters (2000 feet) connected by straight-line segments at entry and exit. Crosstrack deviations during the maneuver are less than 13.7 meters (45 feet). The low-speed case employs a semicircle of radius of 61 meters (400 feet) and crosstrack error is less than 12.2 meters (40 feet). It should be noted, that in the low-speed case, crosstrack error is corrected by direct lateral translation commands. The yaw axis is in a heading mode which forces the aircraft heading to be tangential to the path.

Digital Inner Loop Performance.- In addition to the previously described digital outer loop, provisions have been made to implement the pitch, roll, and yaw inner loops within the 1819A.

The pitch and roll inner loops yield a second-order attitude response to outer loop commands and manual inputs. The undamped natural frequency and damping ratio of the response model are explicitly available as variables within the inner loop software and can be readily changed. Figure 59 depicts system response at a hover to 4-degree step change in commanded pitch attitude. An inner loop frequency of 1.414 radians per second and damping ratio of .707 were used for this run. The capability to independently vary the model damping ratio is shown in Figure 60. In this run, 3-degree step commands were applied for model damping ratios of 1.5, .707, and .25 while the model frequency was held constant at 1.414 radians per second. Model frequency versatility is shown in Figure 61. For a constant damping ratio of .707, 4-degree steps were applied to models of frequency .5, 1.5, and 3 radians per second.

The yaw inner loop yields a first-order response to yaw rate input commands. In addition, outer loop functions are used to augment aircraft performance. At low speeds, heading is automatically held through yaw until the evaluation pilot depresses either pedal more than .098 centimeter (.25 inch). The loop then goes into followup, while a yaw rate proportional to pedal deflection is commanded. Figure 62 shows the yaw response at a hover to a pedal step of 2.54 centimeters (1 inch). The first-order yaw rate response is apparent. When the step is removed, the heading reference is clamped. Heading overshoot is less than 2 degrees.

At higher speeds automatic turn coordination is provided. The pilot may, however, force a sideslip by depressing the pedals. Aircraft response to a 2.54 centimeter (1 inch) pedal pulse at an airspeed of 45.7 meters per second (150 feet per second) is depicted in Figure 63. Figure 64 shows the aircraft response at the same airspeed to a 10 degree step of bank-angle command. Sideslip and lateral acceleration excursions are minimal during the maneuver.

Hover Augmentation System (HAS).- When the pitch and roll inner loops are implemented within the 1819A, the pilot may select the HAS mode to further augment aircraft response and stability. HAS provides short term acceleration and velocity damping, thus making the aircraft less susceptible to gusts. Figure 65 shows the effect of these feedbacks when a 5 degree step-input command is applied to the pitch inner loop model in parallel with the HAS. The magnitude of the step command is shown as the dashed line on the θ trace in order to emphasize the effect of the HAS feedback. The long-term washout of the HAS feedback is apparent in the U and θ traces.

A short-term velocity response to pilot inputs is achieved by various combinations of stick position signal shaping. Figure 66 shows aircraft response to a 2.54 centimeter (1 inch) pilot input using a "1 second" HAS (i.e., a velocity command system with a 1 second time constant). Figure 67 shows the response of the nominal system (2 seconds) described in Figure 10. A four-second system is shown in Figure 68. By rearranging the stick signal shaping configuration slightly, an aircraft response similar to the original inner-loop-only system may be achieved. The response of such a configuration is shown in Figure 69.

Lateral Path Performance

A curved path supplied by NASA was used to demonstrate the performance of the general purpose lateral path program. Twenty two data points were entered into the computer to set up the desired path. The data points used are given in Table 8.

Path Plot.- The path plotting routine (LPPLOT) was used to generate an X-Y plot of the lateral path in order to verify that the path data was correct and that the resulting path was continuous. The plotting routine also calculated the maximum nominal bank angle required to fly each segment of the path and compared this bank angle with a preset bank angle limit. The maximum bank angle requirement for this path was 17 degrees and occurred at the end of Segment 8. The path plot is shown in Figure 70.

Simulated Test Flight.- The VALT simulation was used in conjunction with the Digital Interface Unit, Navigation/Guidance Control Panel, 1819A Digital Computer, and the GSE to fly the lateral path. The resulting flight path is shown in Figure 71. This path was flown with a 1.5 degree constant attitude speed profile and a concave downward altitude profile as supplied by NASA.

TABLE 8

LATERAL PATH DATA

2	5000	00	0000	0
2	5001	00	0000	0
2	5002	37	7776	131070
2	5003	00	0000	0
2	5004	77	2107	- 3000
2	5005	37	7775	131070
2	5006	77	6647	- 600
2	5007	76	7007	- 4600
2	5010	37	7776	131070
2	5011	77	4057	- 2000
2	5012	76	4217	- 6000
2	5013	37	7776	131070
2	5014	77	2107	- 3000
2	5015	76	0277	- 8000
2	5016	00	0000	0
2	5017	77	4057	- 2000
2	5020	75	4357	- 10000
2	5021	37	7776	131070
2	5022	00	0000	0
2	5023	75	0437	- 12000
2	5024	37	7776	131070
2	5025	00	3720	2000
2	5026	74	6467	- 13000
2	5027	37	7776	131070
2	5030	00	7640	4000
2	5031	74	6467	- 13000
2	5032	37	7776	131070
2	5033	01	3560	6000
2	5034	74	0577	- 16000
2	5035	00	0000	0
2	5036	00	5670	3000
2	5037	73	0737	- 20000
2	5040	00	0132	90
2	5041	00	1750	1000
2	5042	73	2707	- 19000
2	5043	37	7776	131070
2	5044	77	6647	- 600
2	5045	73	6007	- 17400
2	5046	37	7776	131070
2	5047	77	0757	- 3600

TABLE 8 (cont)

LATERAL PATH DATA

2	5Ø4Ø	ØØ	Ø132	9Ø
2	5Ø41	ØØ	175Ø	1ØØØ
2	5Ø42	73	27Ø7	- 19ØØØ
2	5Ø43	37	7776	131Ø7Ø
2	5Ø44	77	6647	- 6ØØ
2	5Ø45	73	6ØØ7	- 174ØØ
2	5Ø46	37	7776	131Ø7Ø
2	5Ø47	77	Ø757	- 36ØØ
2	5Ø5Ø	73	6ØØ7	- 174ØØ
2	5Ø51	ØØ	ØØ55	45
2	5Ø52	77	Ø757	- 36ØØ
2	5Ø53	73	Ø117	- 2Ø4ØØ
2	5Ø54	77	7722	- 45
2	5Ø55	77	6647	- 6ØØ
2	5Ø56	73	Ø117	- 2Ø4ØØ
2	5Ø57	77	757Ø	- 135
2	5Ø6Ø	77	6647	- 6ØØ
2	5Ø61	73	6ØØ7	- 174ØØ
2	5Ø62	ØØ	Ø2Ø7	135
2	5Ø63	77	Ø757	- 36ØØ
2	5Ø64	73	6ØØ7	- 174ØØ
2	5Ø65	ØØ	ØØ55	45
2	5Ø66	77	Ø757	- 36ØØ
2	5Ø67	73	Ø117	- 2Ø4ØØ
2	5Ø7Ø	77	7722	- 45
2	5Ø71	77	6647	- 6ØØ
2	5Ø72	73	Ø117	- 2Ø4ØØ
2	5Ø73	77	757Ø	- 135
2	5Ø74	77	6647	- 6ØØ
2	5Ø75	73	6ØØ7	- 174ØØ
2	5Ø76	37	7776	131Ø7Ø
2	5Ø77	77	Ø137	- 4ØØØ
2	51ØØ	74	4517	- 14ØØØ
2	51Ø1	37	7776	131Ø7Ø
2	51Ø2	22	7721	77777

Data taken during the simulated flight is shown in Figure 72. This data includes actual roll angle, crosstrack error, sine of the actual magnetic heading, actual altitude, and actual velocity. In addition, a segment counter output was recorded to assist in correlating the data with points on the lateral path. The lateral path and the speed and altitude profiles used brought the aircraft to a hover with an altitude of 15.2 meters (50 feet). The land mode was then engaged to demonstrate this function.

The maximum crosstrack error recorded was 22.86 meters (75 feet) and occurred at the point on the path where the aircraft bank angle requirements changed from 17 degrees to 0 degree as the path changed from a small radius curved segment to a straight line segment. This point serves as a good illustration of the problem that can result when a curved section is connected to a straight line section. The curved section in this case has a radius of curvature at its end point that requires a 17 degree nominal roll angle at the velocity specified. This curve is abruptly terminated and followed by a straight line segment. Consequently, an instantaneous bank angle change of 17 degrees is required. This particular example is further complicated by the fact that the curved segment was one that had a decreasing radius of curvature. This decreasing radius of curvature requires an increasing roll angle as the segment is traversed, thus causing an adverse roll rate to be in existence at the moment that the path segment is changed. The path tracking can be improved for such cases as this, by altering the path slightly to provide for a better transition between curved and straight line segments.

Path Initialization and Go-Around.- A second simulated flight was made to illustrate the automatic path initialization and the go-around mode. This flight path is shown in Figure 73. Upon completion of the flight, the go-around mode was engaged, with the aircraft in a hover at 50 feet. The preset go-around conditions used for this flight were 180 degrees for magnetic heading, 500 feet for altitude and 55 knots for speed.

Path Capture Maneuvers.- The initial path capture maneuvers for three different starting points are shown in Figure 74. For both path one and path two, the path initialization occurred within the cone capture limits. Path three shows an initilization outside the cone capture limits.

Altitude Profile Data

Figure 75 shows the simulated radar-derived altitude versus path distance-to-go for a concave downward and a constant glideslope angle altitude profile. The data to define the concave downward profile is given in Table 9. These profiles were obtained while the simulated aircraft was flying a straight-in approach. Both of the profiles shown include a flare to a hover at 15.2 meters (50 feet).

Speed Profile Data

Figure 76 shows the simulated radar-derived groundspeed versus path distance-to-go for three different velocity profiles. These profiles produce decelerations that require a constant pitch attitude above trim. The profiles shown are for 1 degree, 1.5 degree, and 2 degree attitudes. The data to define the 2 degree attitude profile is given in Table 10. All three of the speed profiles shown were flown in conjunction with a straight-in approach.

TABLE 9

ALTITUDE PROFILE DATA

2	6563	ØØ	ØØØØ	Ø
2	6564	ØØ	ØØ62	5Ø
2	6565	ØØ	ØØ62	5Ø
2	6566	ØØ	ØØ62	5Ø
2	6567	ØØ	Ø454	3ØØ
2	657Ø	ØØ	Ø226	15Ø
2	6571	ØØ	1Ø46	55Ø
2	6572	ØØ	Ø327	215
2	6573	ØØ	144Ø	8ØØ
2	6574	ØØ	Ø411	265
2	6575	ØØ	2Ø32	1Ø5Ø
2	6576	ØØ	Ø461	3Ø5
2	6577	ØØ	2621	1425
2	66ØØ	ØØ	Ø536	35Ø
2	66Ø1	ØØ	36Ø5	1925
2	66Ø2	ØØ	Ø62Ø	4ØØ
2	66Ø3	ØØ	4766	255Ø
2	66Ø4	ØØ	Ø7Ø7	455
2	66Ø5	Ø1	4431	6425
2	66Ø6	ØØ	1356	75Ø
2	66Ø7	22	7721	77777

TABLE 10

SPEED PROFILE DATA

2	7163	ØØ	ØØØØ	Ø
2	7164	ØØ	ØØØØ	Ø
2	7165	ØØ	ØØ74	6Ø
2	7166	ØØ	ØØ1Ø	8
2	7167	ØØ	Ø144	1ØØ
2	717Ø	ØØ	ØØ14	12
2	7171	ØØ	Ø31Ø	2ØØ
2	7172	ØØ	ØØ24	2Ø
2	7173	ØØ	Ø62Ø	4ØØ
2	7174	ØØ	ØØ4Ø	32
2	7175	ØØ	113Ø	6ØØ
2	7176	ØØ	ØØ51	41
2	7177	ØØ	144Ø	8ØØ
2	72ØØ	ØØ	ØØ62	5Ø
2	72Ø1	ØØ	2Ø32	1Ø5Ø
2	72Ø2	ØØ	ØØ74	6Ø
2	72Ø3	ØØ	2455	1325
2	72Ø4	ØØ	Ø1Ø6	7Ø
2	72Ø5	ØØ	31ØØ	16ØØ
2	72Ø6	ØØ	Ø12Ø	8Ø
2	72Ø7	ØØ	3516	187Ø
2	721Ø	ØØ	Ø132	9Ø
2	7211	ØØ	4172	217Ø
2	7212	ØØ	Ø144	1ØØ
2	7213	ØØ	4456	235Ø
2	7214	ØØ	Ø151	1Ø5
2	7215	ØØ	47Ø4	25ØØ
2	7216	ØØ	Ø154	1Ø8
2	7217	ØØ	5214	27ØØ
2	722Ø	ØØ	Ø156	11Ø
2	7221	22	7721	77777

CONCLUDING REMARKS

This section presents a brief summary of the major results of the contract efforts and some recommendations for increasing the capability of the system.

Results

General Purpose Lateral Path.- A technique was developed, using straight line and elliptical segments, that can generate randomly shaped, curved paths and that can provide data necessary to fly such a path. The technique involves the use of stored data points that define the position and heading which the aircraft is to have as it traverses the path.

Hardware.- A set of flight system hardware which provides navigation computation and analog, digital, and human interface with the system was developed and fabricated. The flight system hardware was built around the 1819A Digital Computer. A set of ground support equipment was also fabricated to facilitate programming of the 1819A computer and to check out other hardware components.

Software.- A set of utility programs was created to facilitate the writing, editing, assembly, and checkout of computer programs for the 1819A. A flight system program containing a split cycle, real-time, executive routine, and a series of specialized subroutines was created to implement the control laws and the navigation geometry calculations. A programming manual was written as a guide to system understanding and use.

Software Validation Facility.- An analog computer was interfaced with the 1819A Digital Computer and the other flight system hardware to simulate the CH-47B aircraft. This hybrid combination was connected to a helicopter cockpit simulator to provide the capability to verify and improve the system hardware and software. The validation facility was used to conduct simulated test flights in order to obtain data on system performance.

Recommendations

The evaluation of the techniques that have been developed during this contract must await the integration of the system into the NASA research aircraft and the subsequent flight tests. Preliminary evaluation of the system using the Sperry fixed based simulator, however, shows two areas that should be considered for further development.

Lateral Path Technique.- The technique that combines a straight line and elliptical segments into continuous flight paths results in a path that does not contain heading discontinuities. However, the junction between an elliptical segment and a straight line segment generally results in a bank angle discontinuity. The curve fitting technique should be expanded to incorporate some form of transitional curve in addition to the elliptical and straight segments. Such a transitional curve would provide smoother turn entry and turn exit performance and should reduce crosstrack error at these points.

Information Display.- Simulated data flights undertaken in the Sperry fixed base simulation have indicated that it will be necessary to provide more situation information to the pilot during curved approaches that incorporate steep, decelerating descents. Graphical displays that present the computed flight path in relation to the terminal area surroundings should be considered.

ILLUSTRATIONS

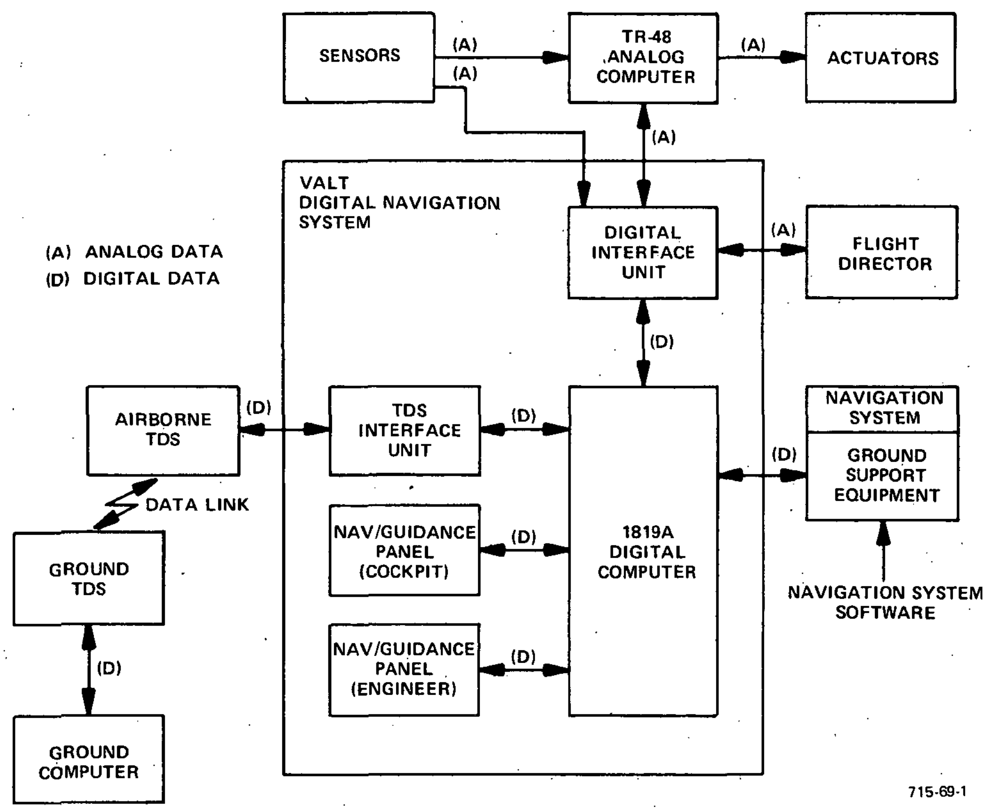


Figure 1
VALT Research System

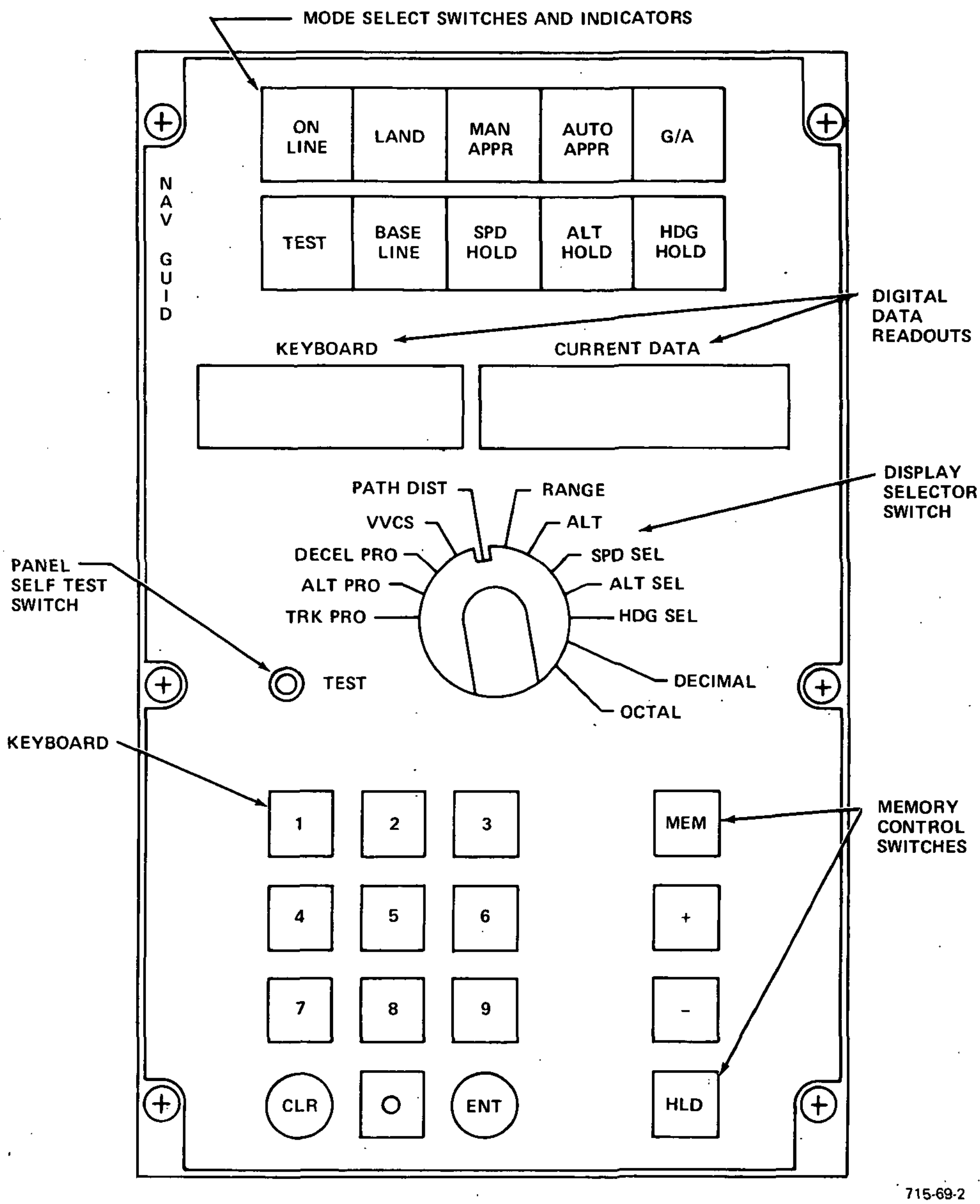
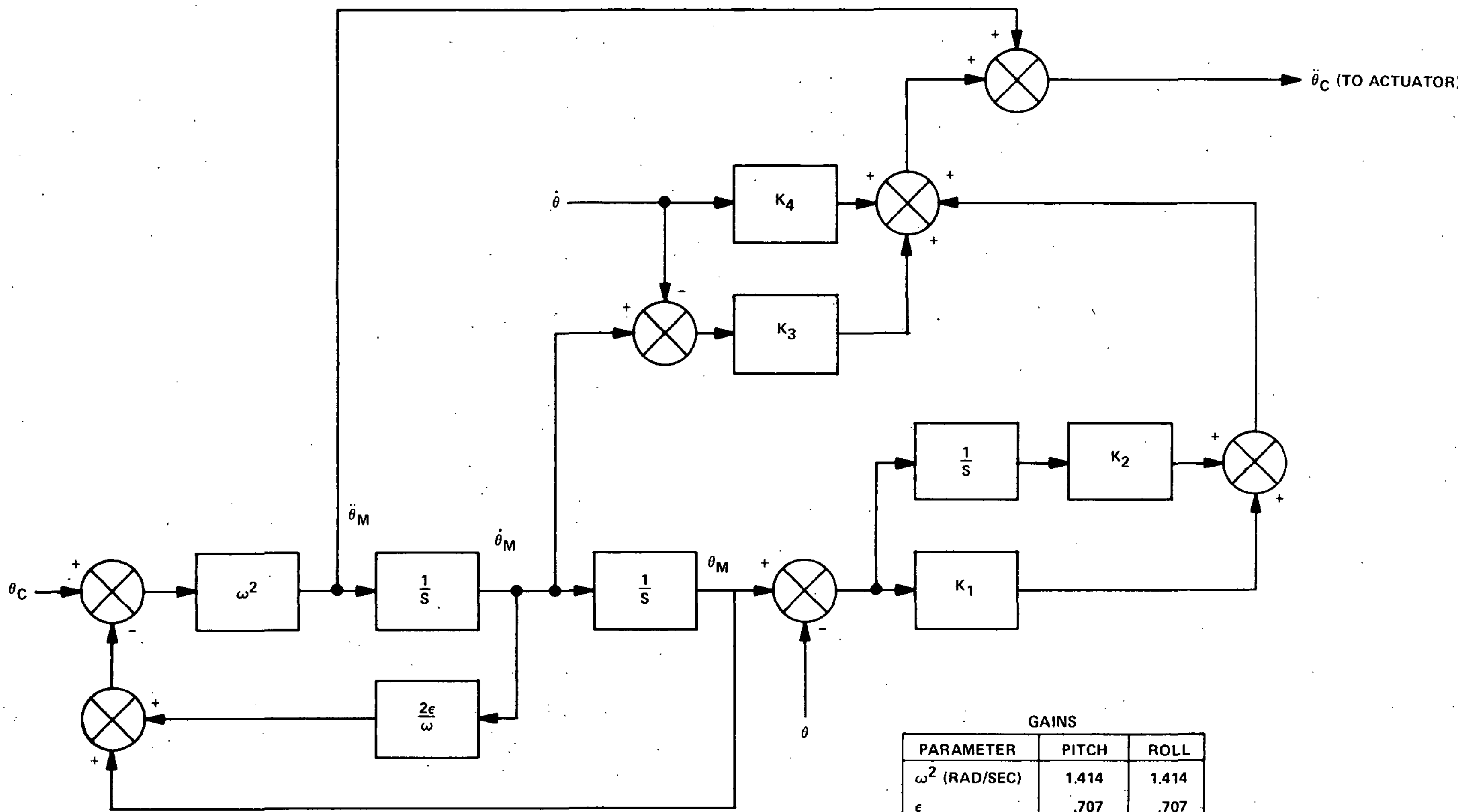


Figure 2
Nav/Guidance Displays and Indicators



NOTES:
1. ROLL IMPLEMENTATION IS IDENTICAL EXCEPT FOR GAINS.
2. K_4 IS A POSITIVE FEEDBACK PATH GAIN USED TO YIELD NEUTRALLY STABLE BASIC AIRCRAFT DYNAMICS.

GAINS

PARAMETER	PITCH	ROLL
ω^2 (RAD/SEC)	1.414	1.414
ϵ	.707	.707
K_1 (SEC^{-2})	3.32	5.46
K_2 (SEC^{-3})	2.32	2.10
K_3 (SEC^{-1})	5.42	5.74
K_4 (SEC^{-1})	1.2	.7

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Figure 3
Pitch Inner Loop Block Diagram

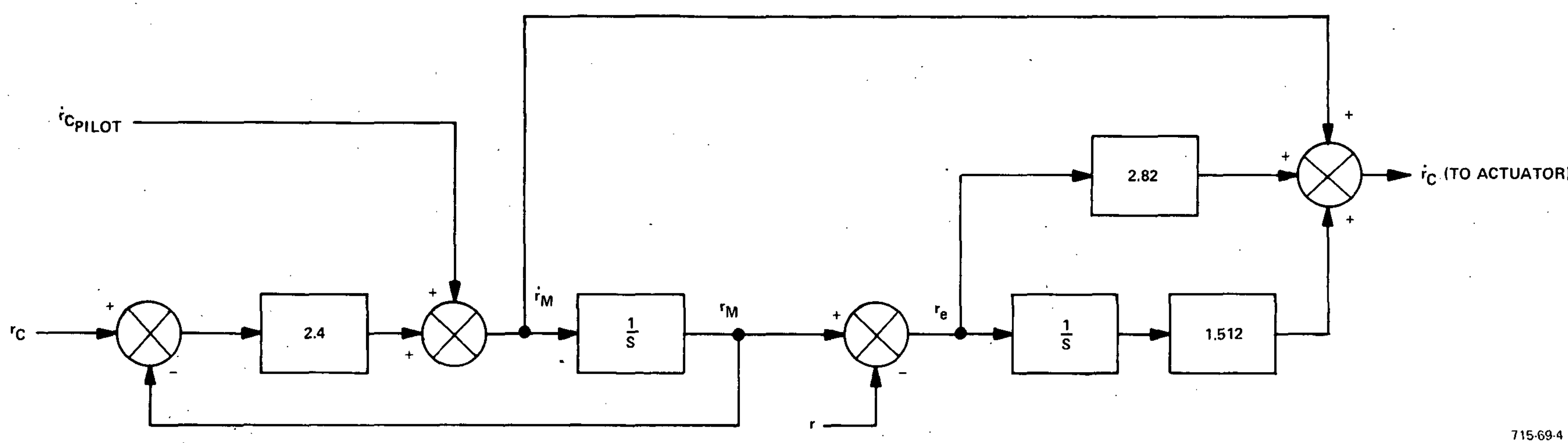
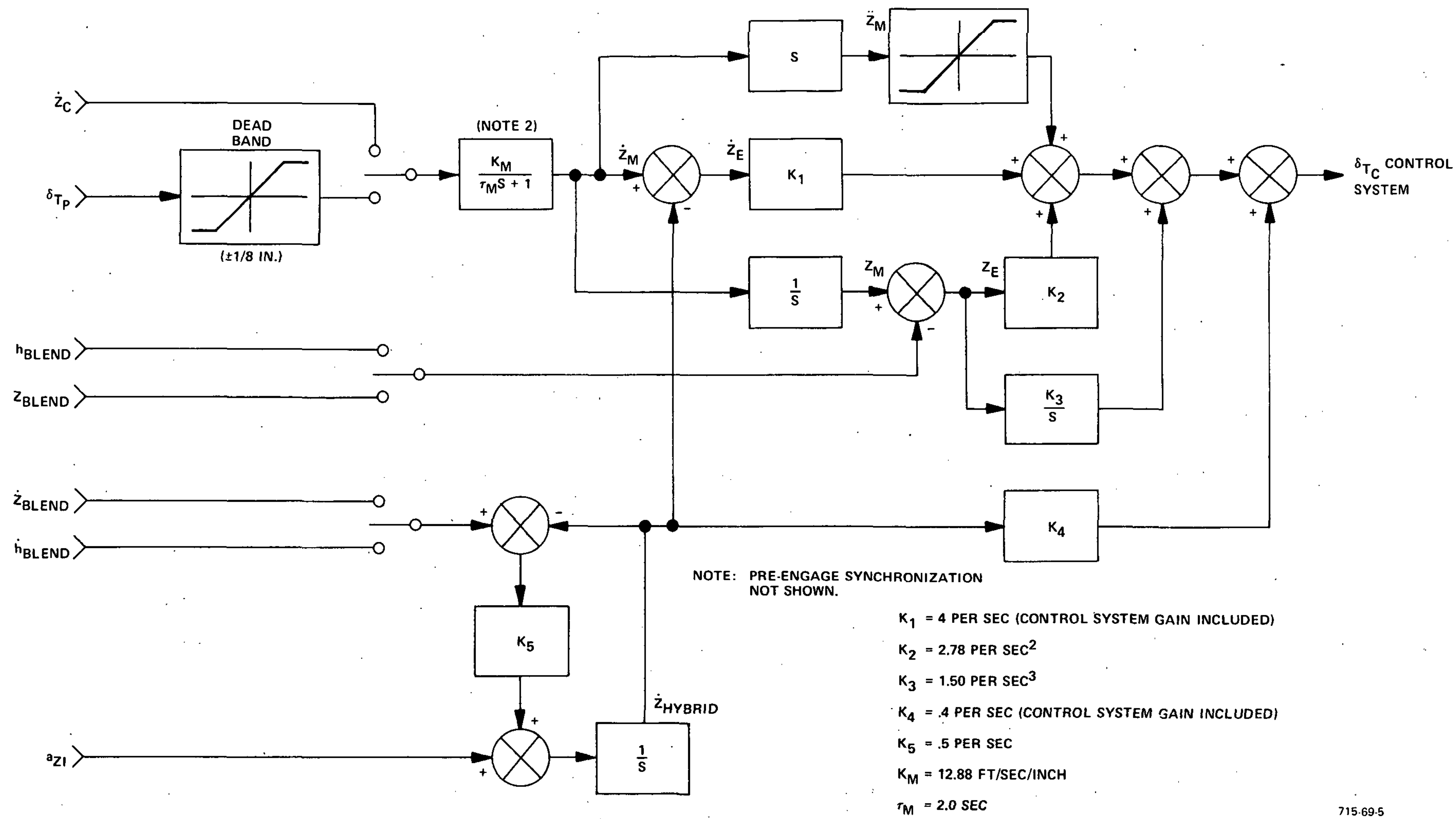


Figure 4
Yaw Inner Loop Block Diagram



NOTE: PRE-ENGAGE SYNCHRONIZATION NOT SHOWN.

K_1 = 4 PER SEC (CONTROL SYSTEM GAIN INCLUDED)
K_2 = 2.78 PER SEC^2
K_3 = 1.50 PER SEC^3
K_4 = .4 PER SEC (CONTROL SYSTEM GAIN INCLUDED)
K_5 = .5 PER SEC
K_M = 12.88 FT/SEC/INCH
τ_M = 2.0 SEC

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Figure 5
Vertical Velocity Command System

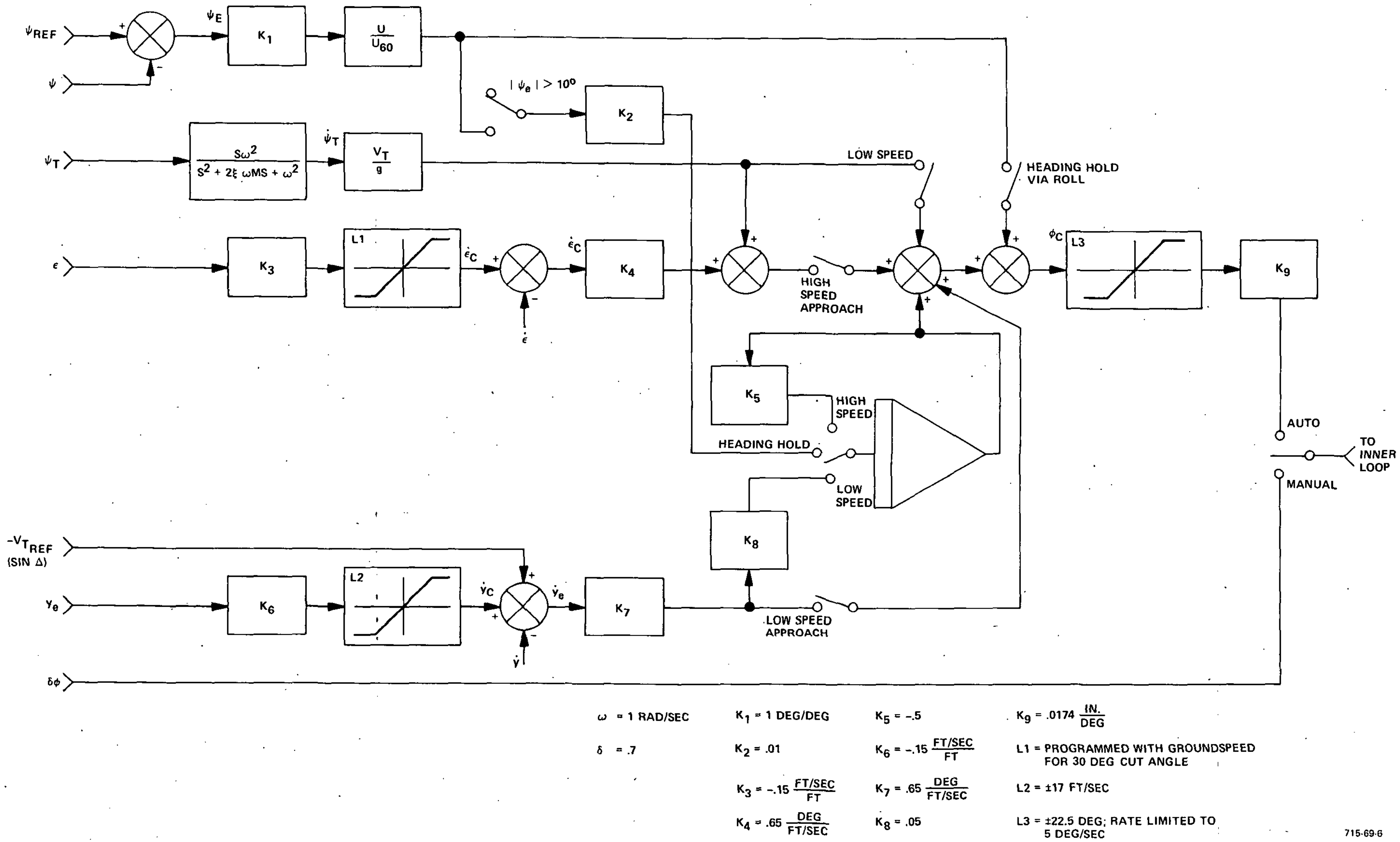
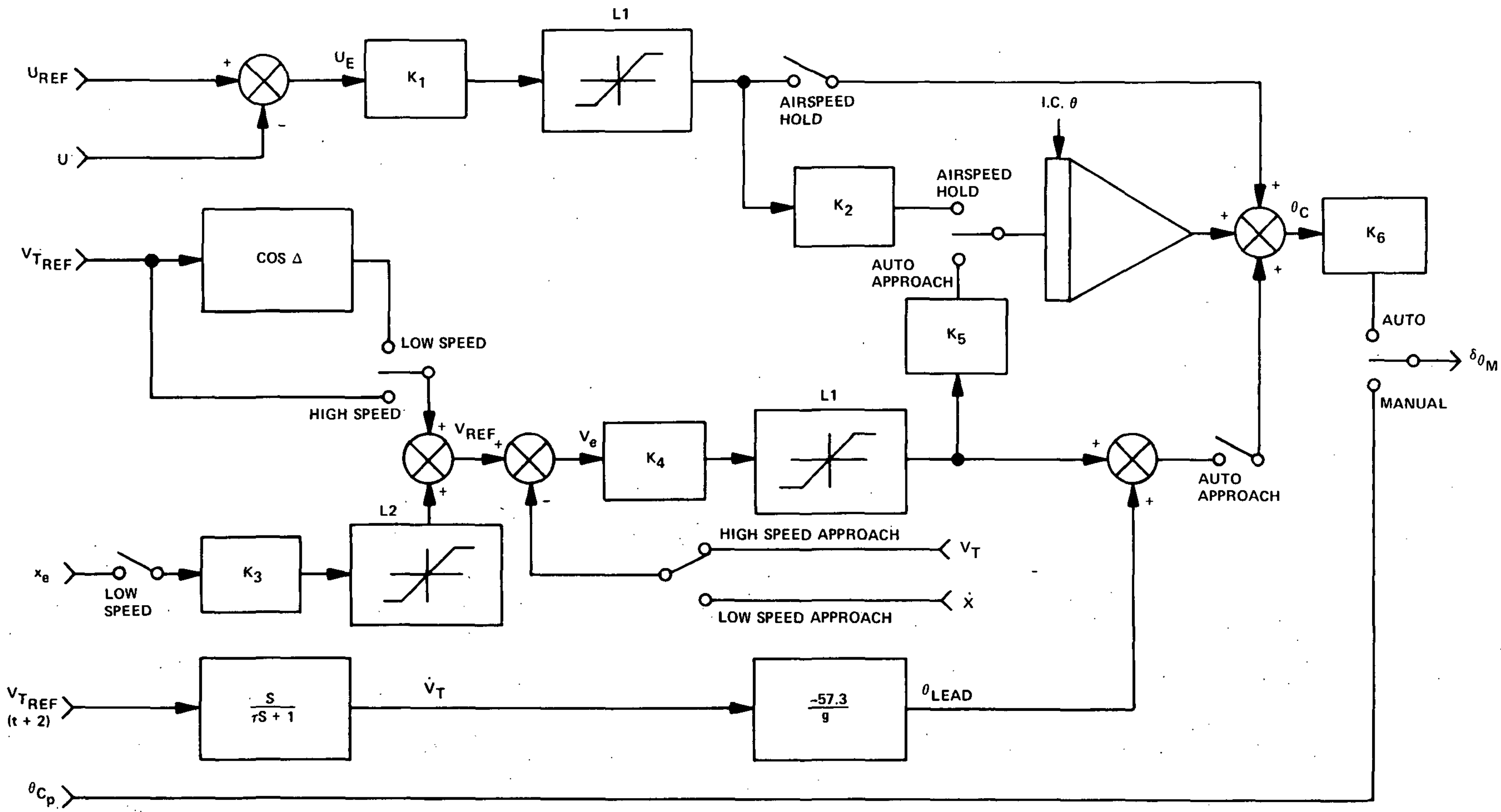


Figure 6
Roll Axis Control System



L1 = ±5 DEG

L2 = ±17 FT/SEC

τ = 1 SEC

$K_1 = -.65 \frac{DEG}{FT/SEC}$

$K_2 = .03$

$\Delta = \psi - \psi_T$

$K_3 = -.15 \frac{FT/SEC}{FT}$

$K_4 = -.65 \frac{DEG}{FT/SEC}$

$K_5 = .02$

$K_6 = .0174 \frac{IN.}{DEG}$

715-69-7

Figure 7
Pitch Axis Control System

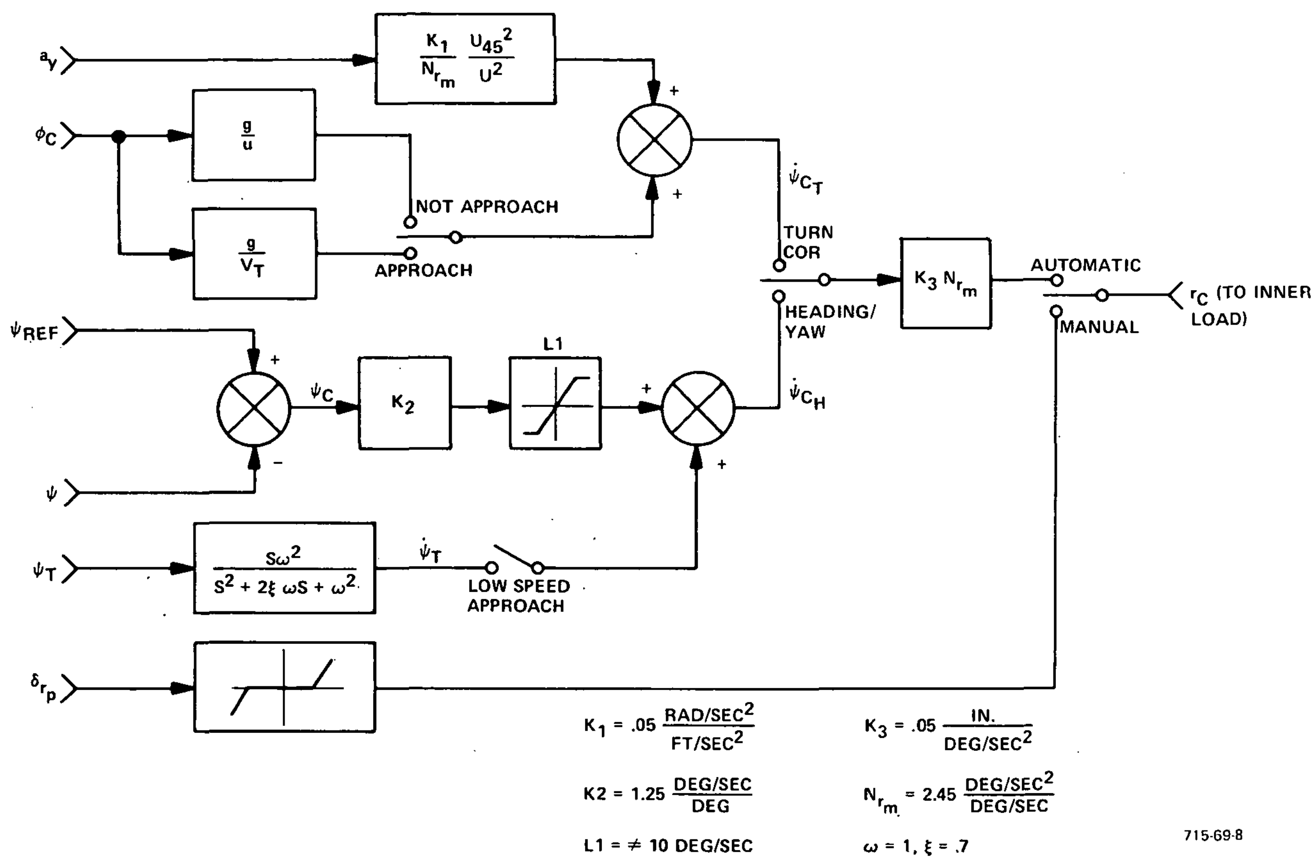


Figure 8
Yaw Axis Control System

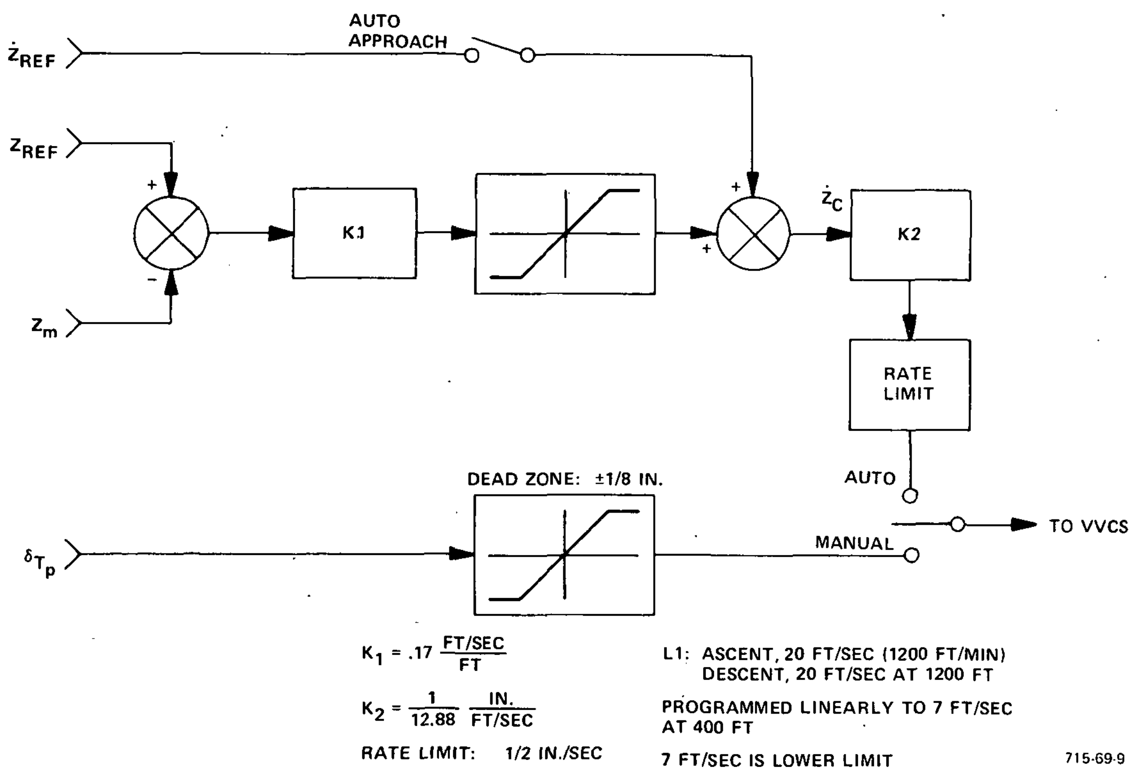


Figure 9
Collective Axis Control System

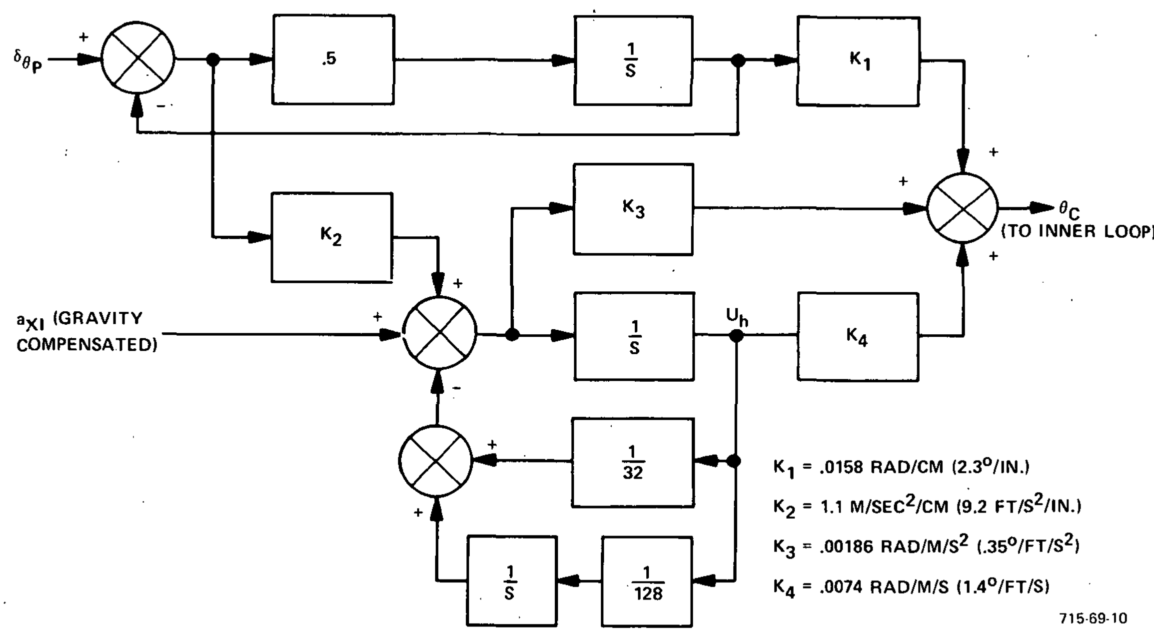


Figure 10
Pitch HAS Block Diagram

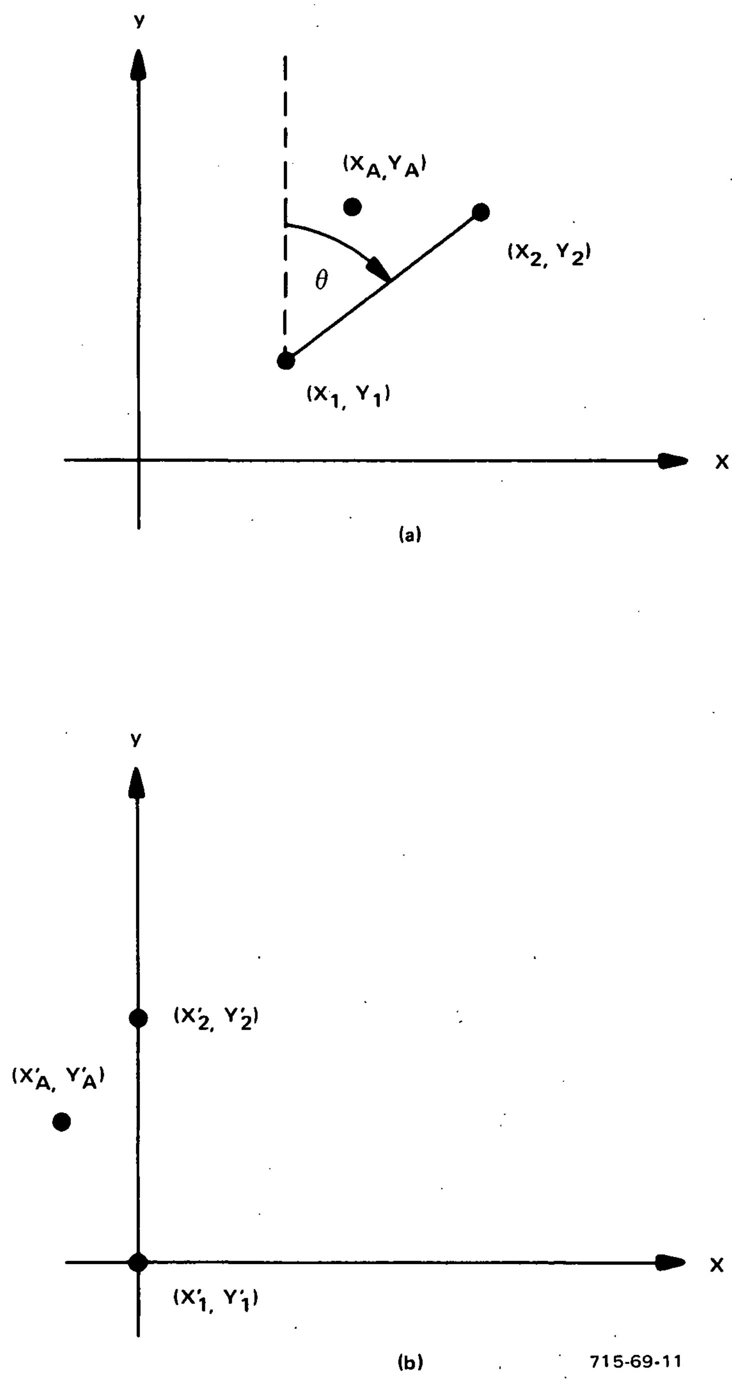


Figure 11
Rotation of the Coordinate System

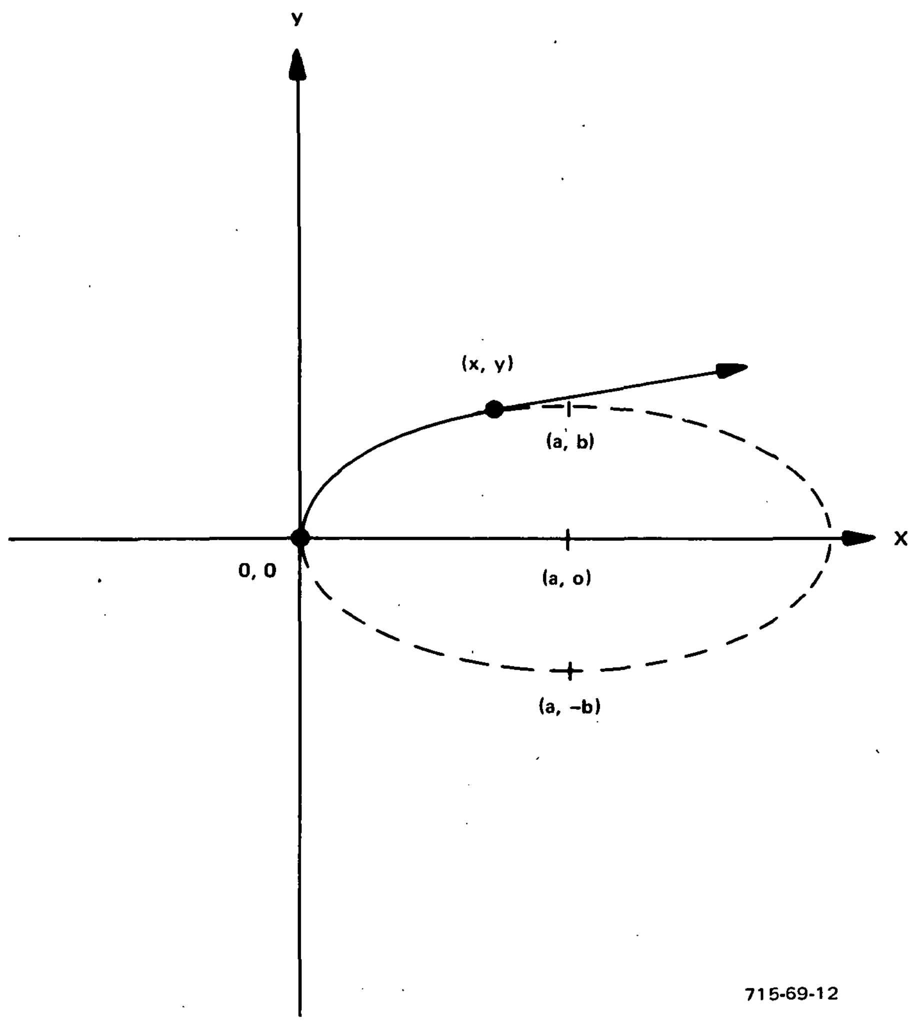


Figure 12
Elliptical Segment Coordinate System

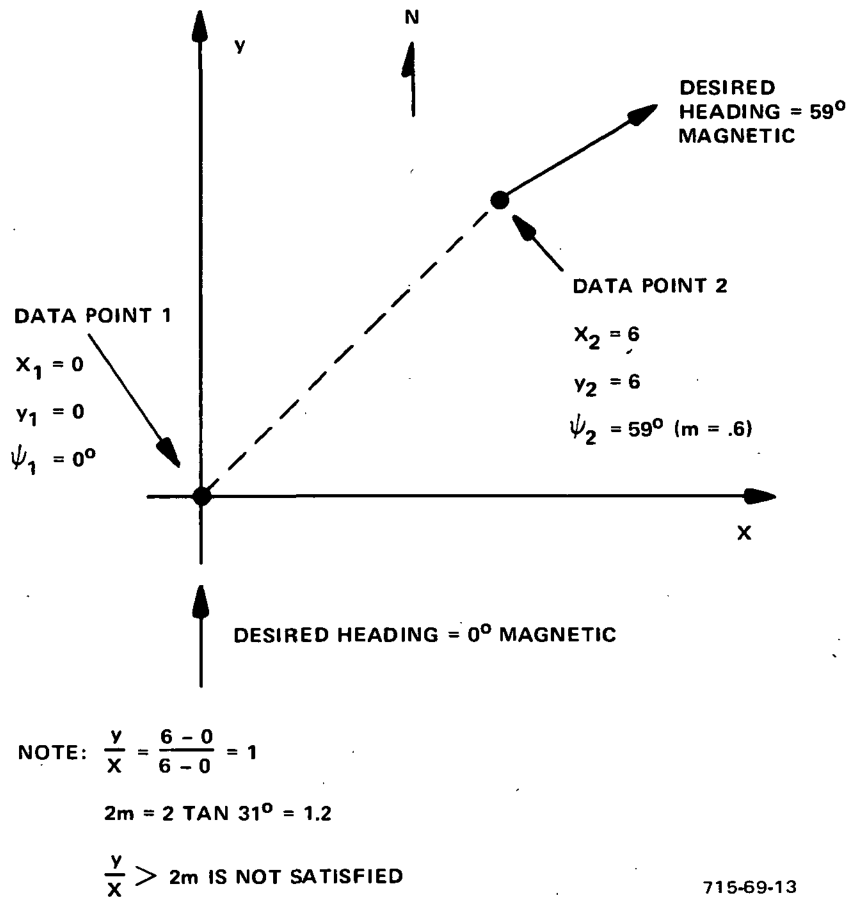
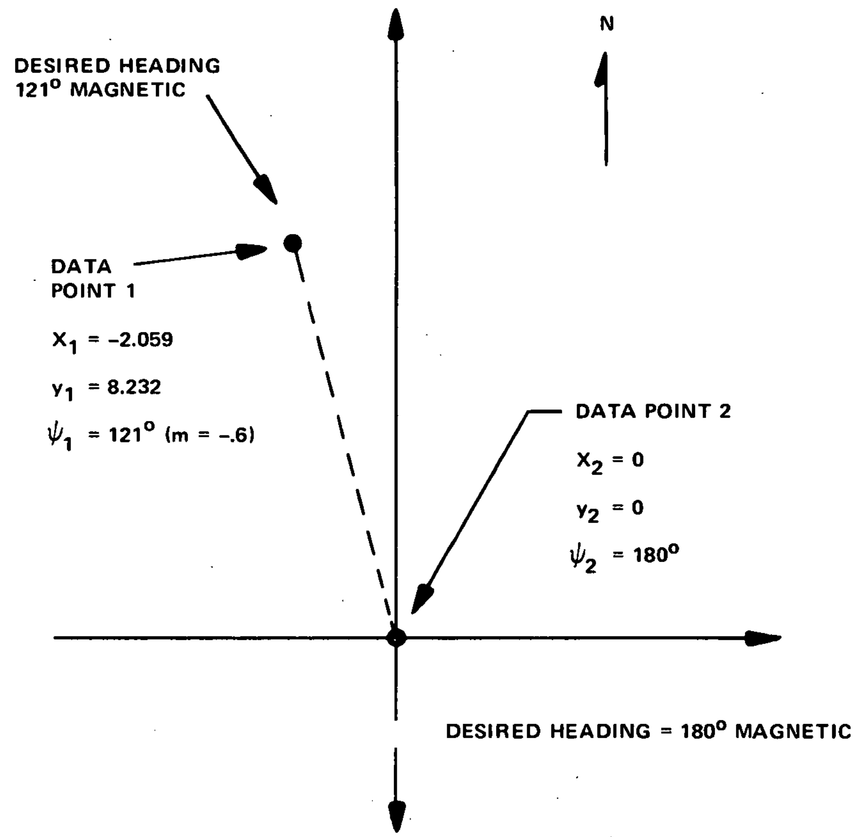


Figure 13
Elliptical Segment Path Restriction



NOTE: $\frac{y}{X} = \frac{8.232 - 0}{-2.059 - 0} = -3.998$

$2m = 2 \text{ TAN } (-31^\circ) = -1.2$

$\frac{y}{X} < 2m$ IS SATISFIED

715-69-14

Figure 14
Elliptical Segment Path Restriction

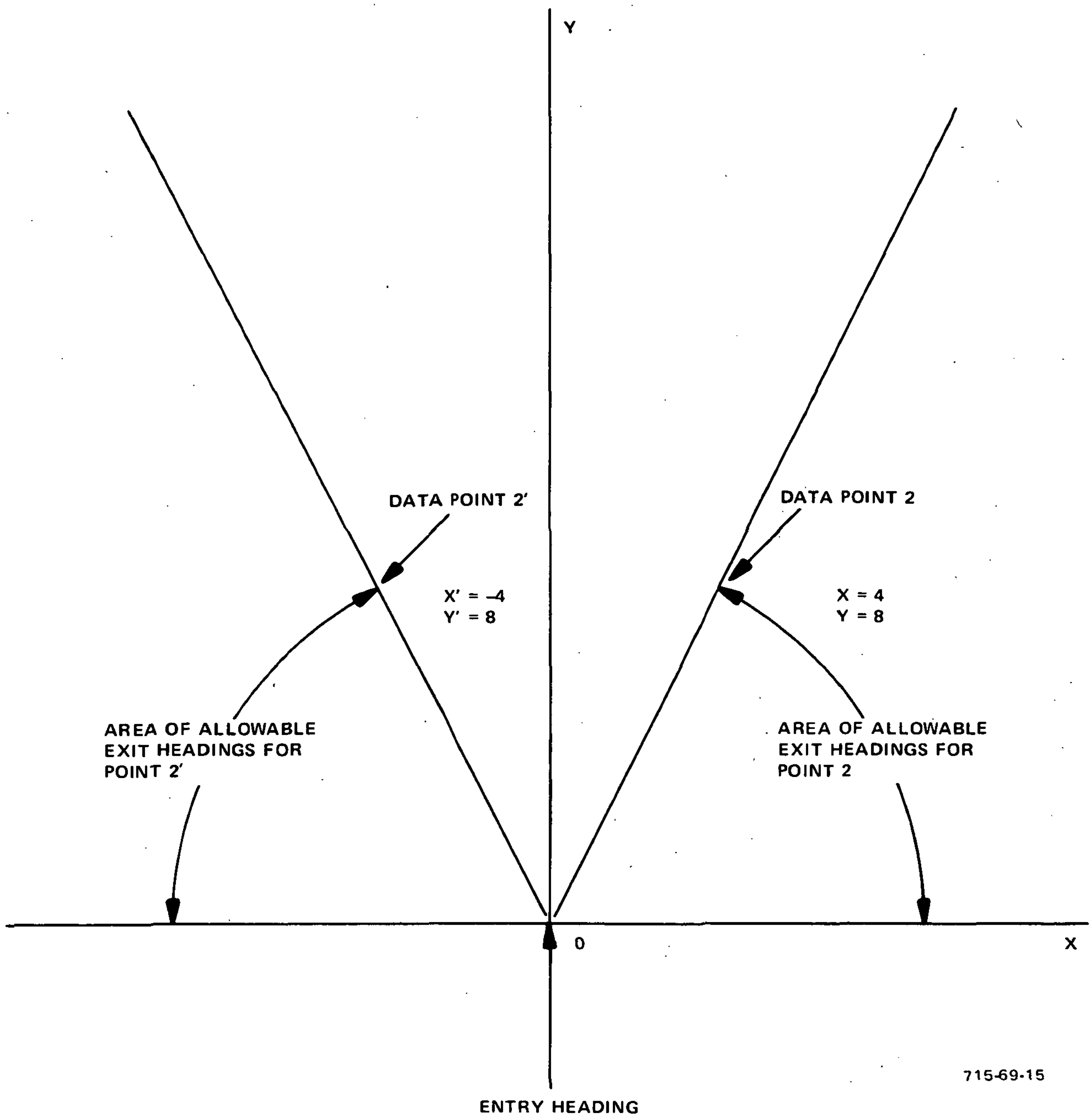


Figure 15
Area of Allowable Heading Changes

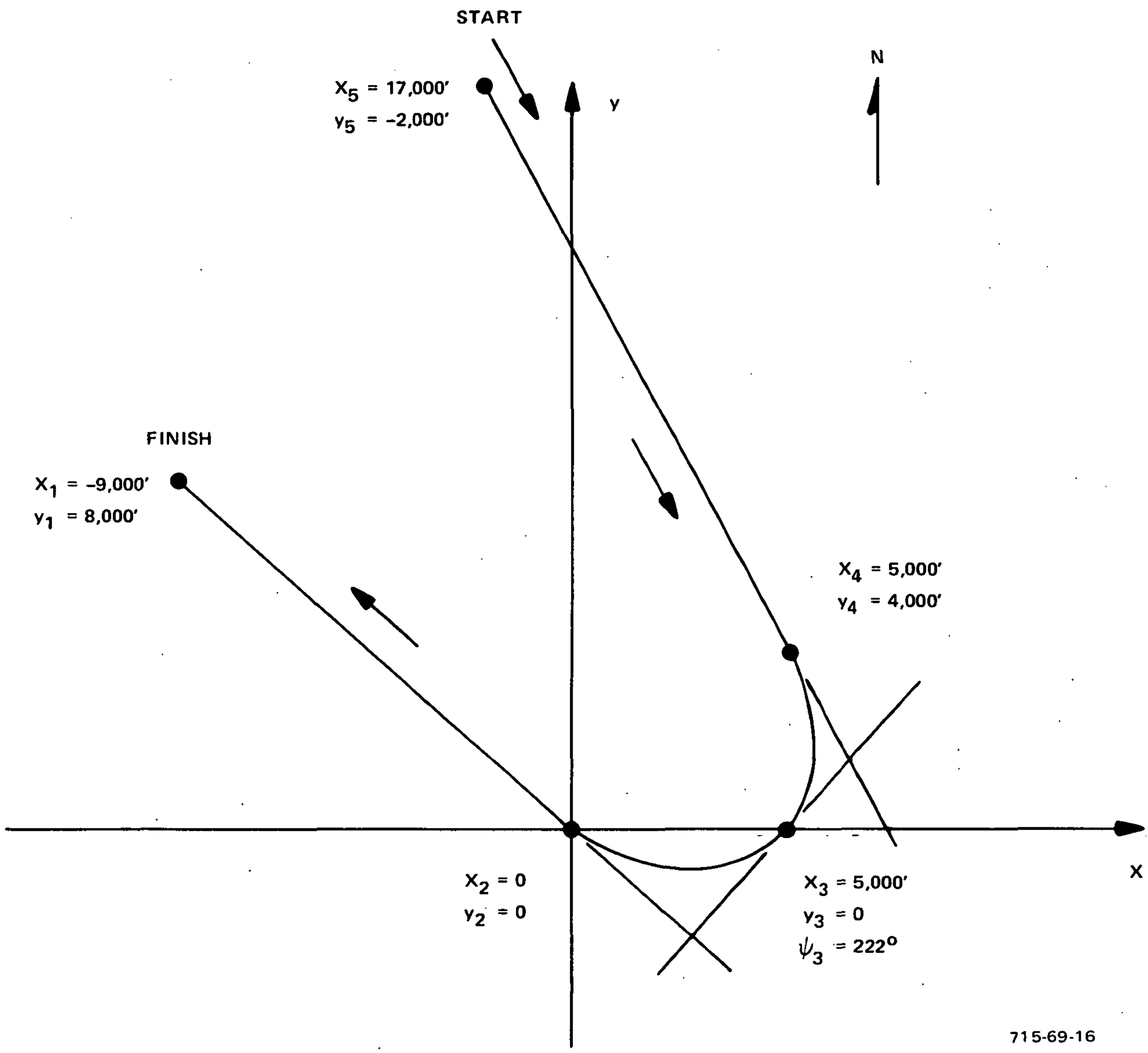


Figure 16
Simple Curved Path

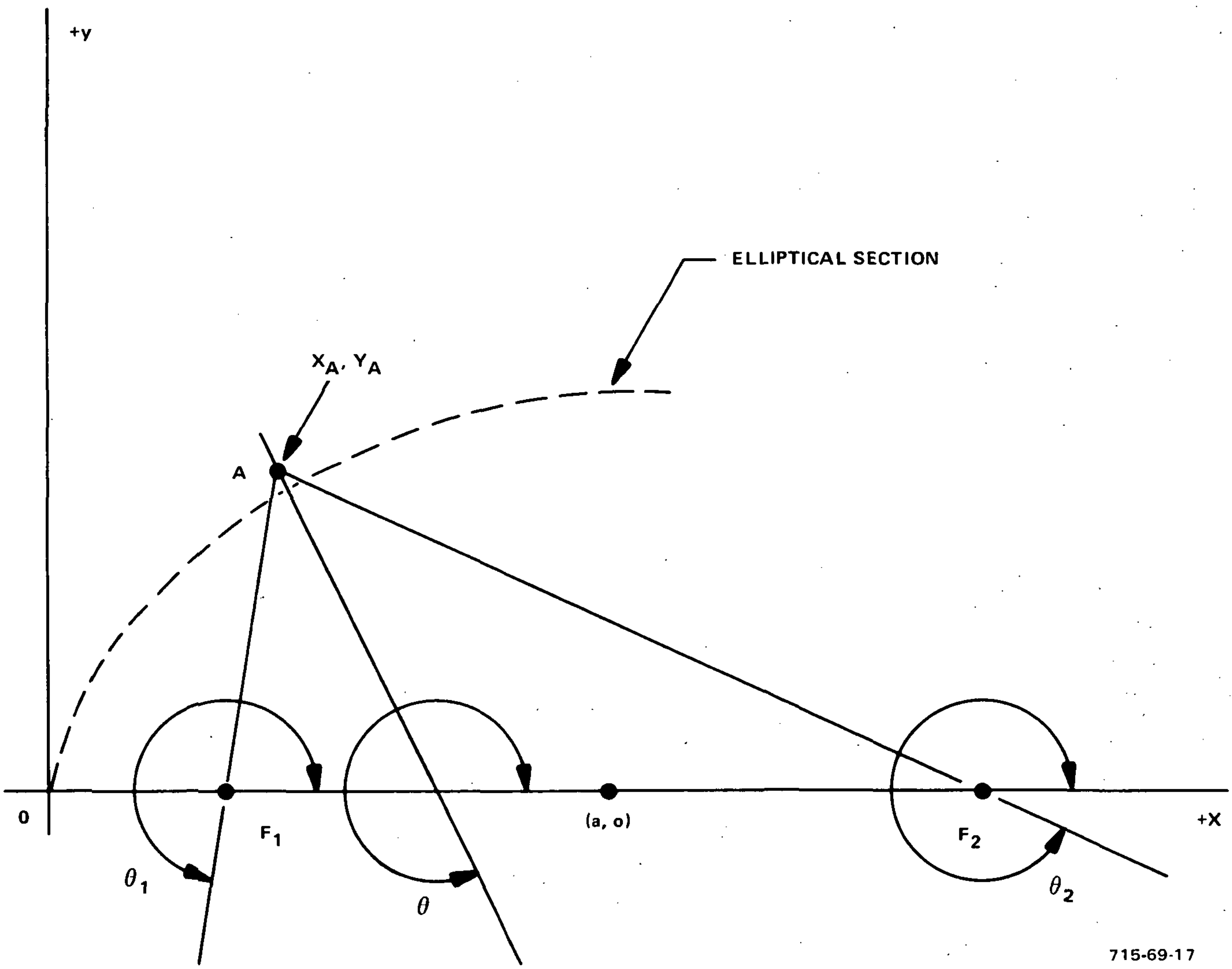


Figure 17
Normal Projection for a > b

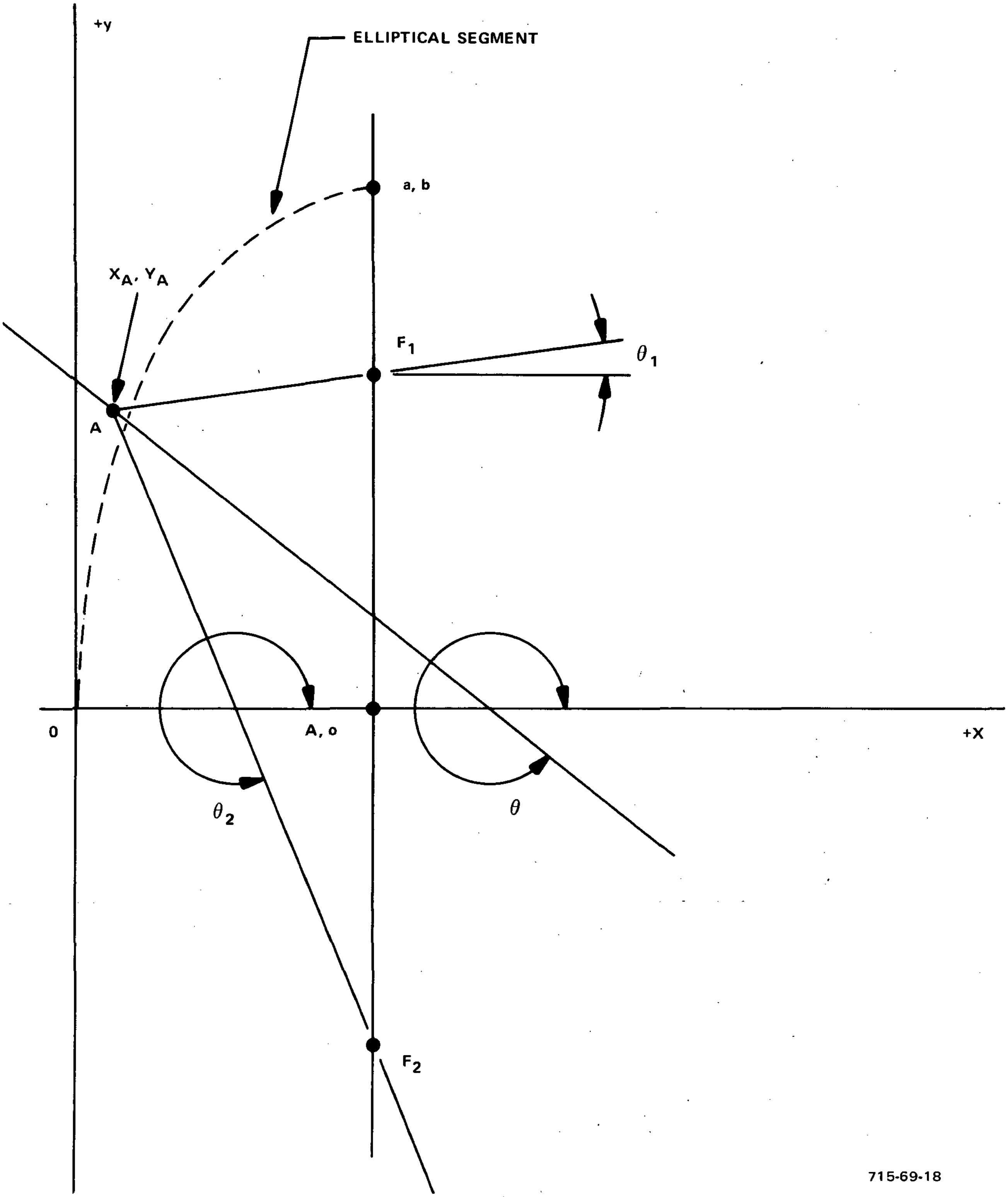


Figure 18
Normal Projection for b > a

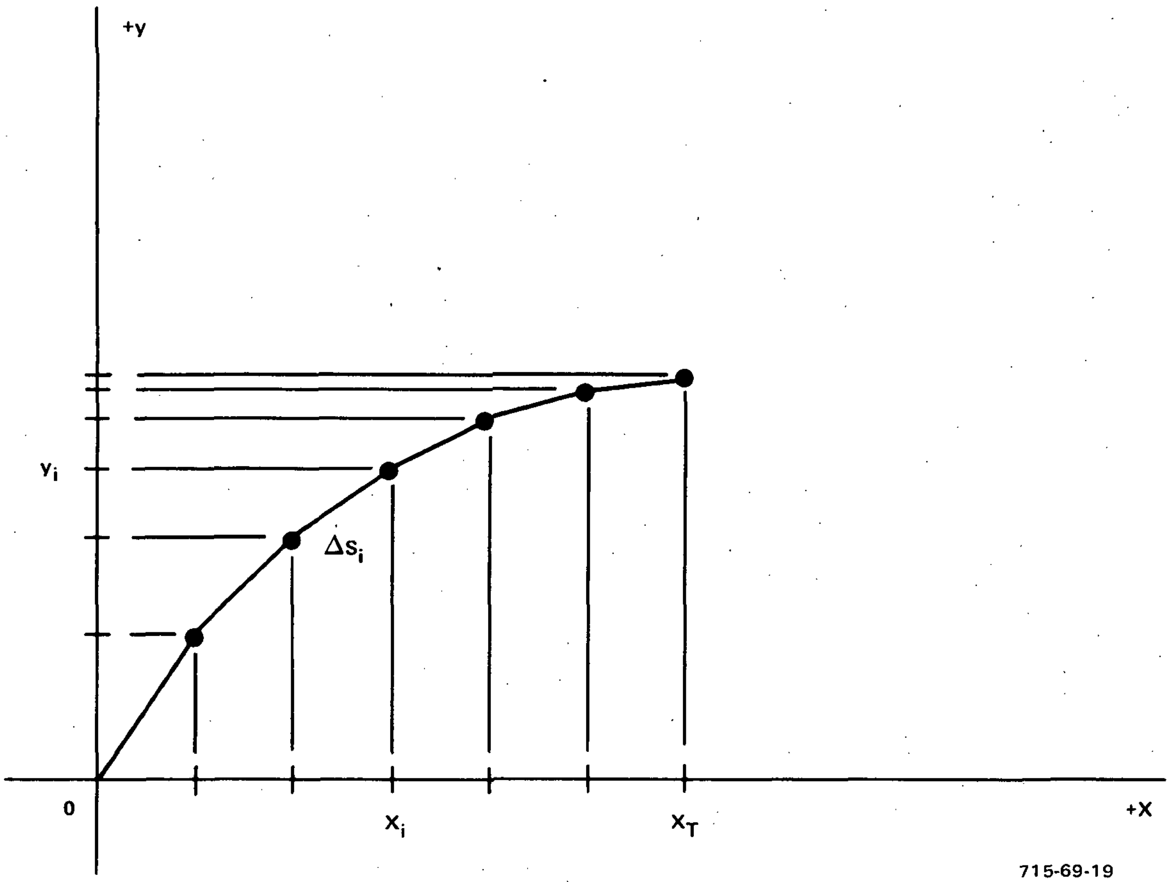


Figure 19
Path Length Approximation

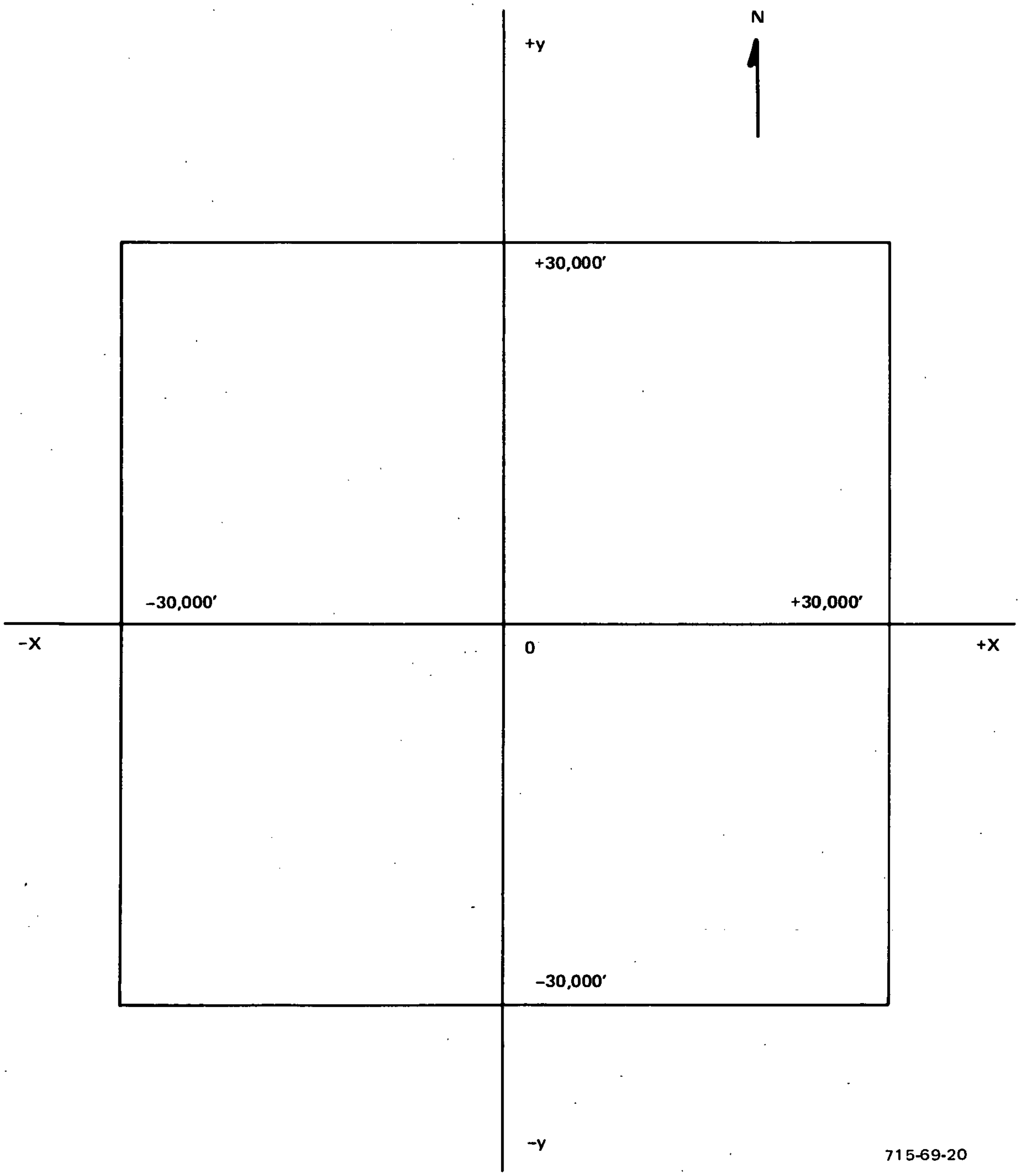


Figure 20
Lateral Path Coordinate System

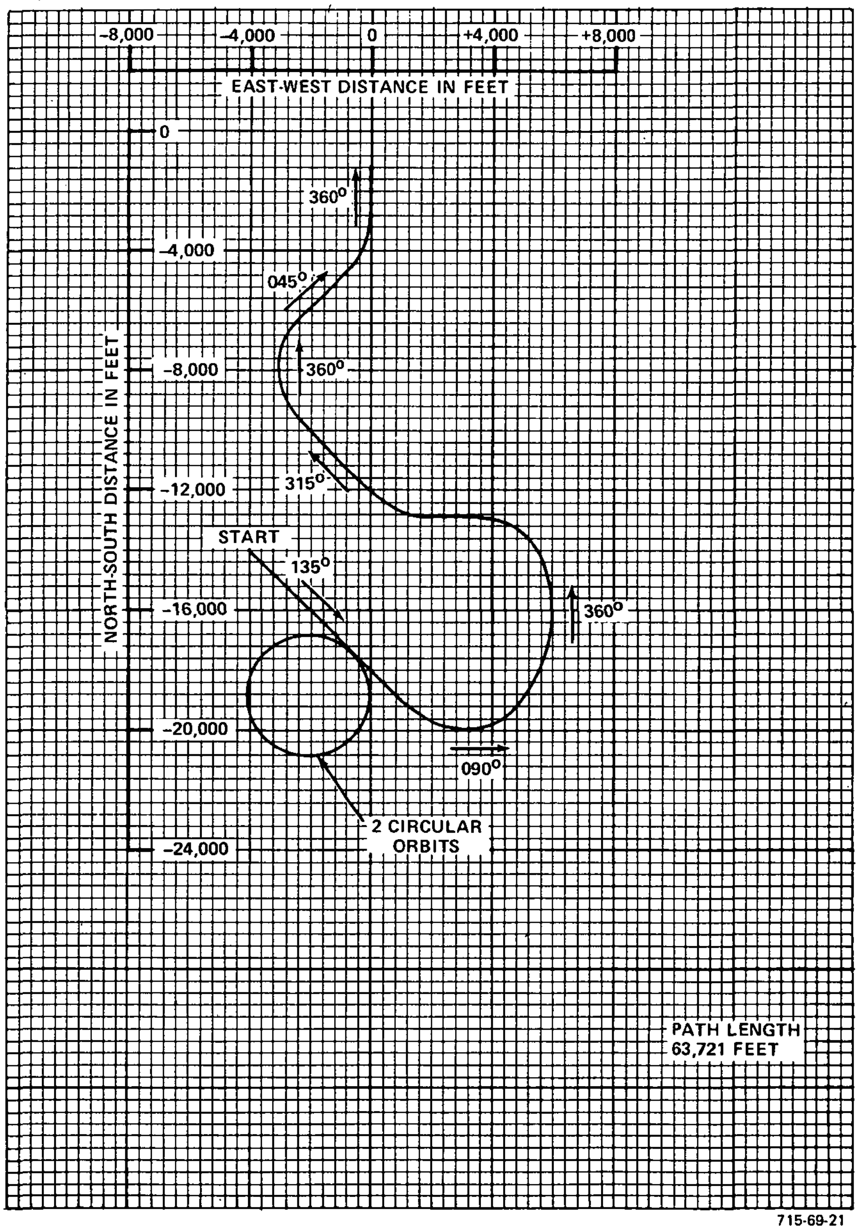


Figure 21
NASA VALT Baseline Path

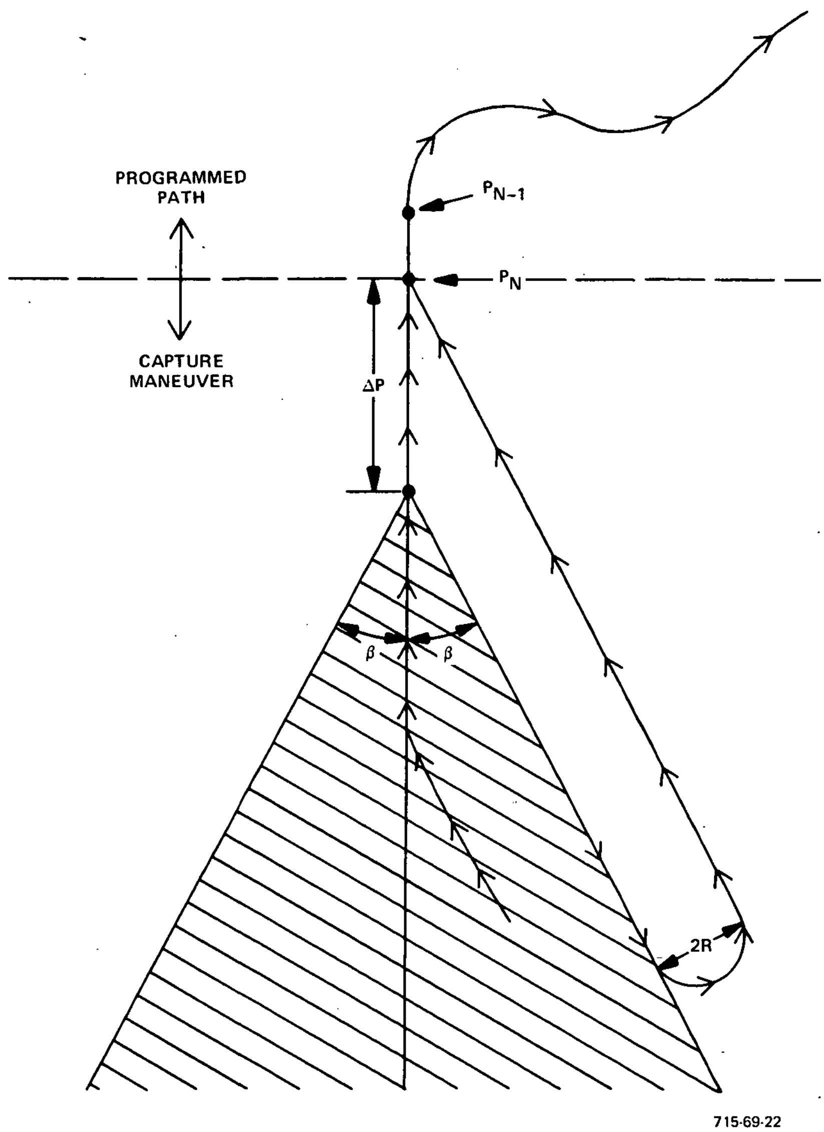


Figure 22
Path Capture Geometry

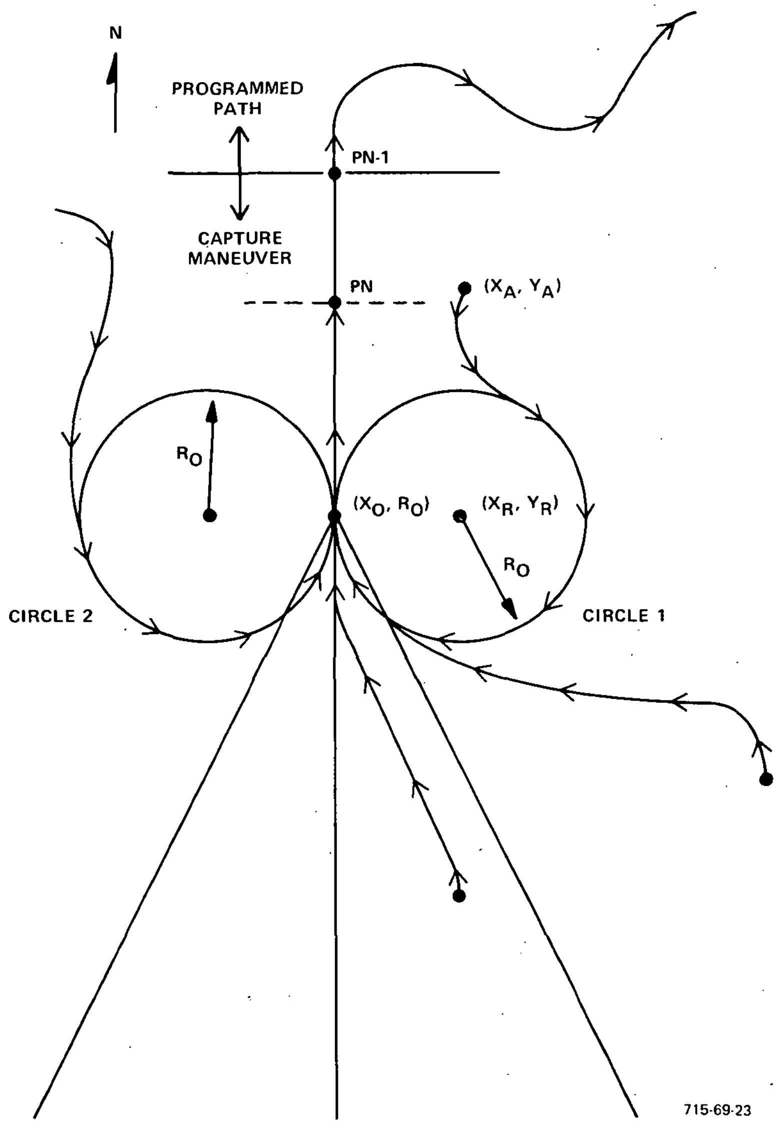


Figure 23
Path Capture Outside the Cone

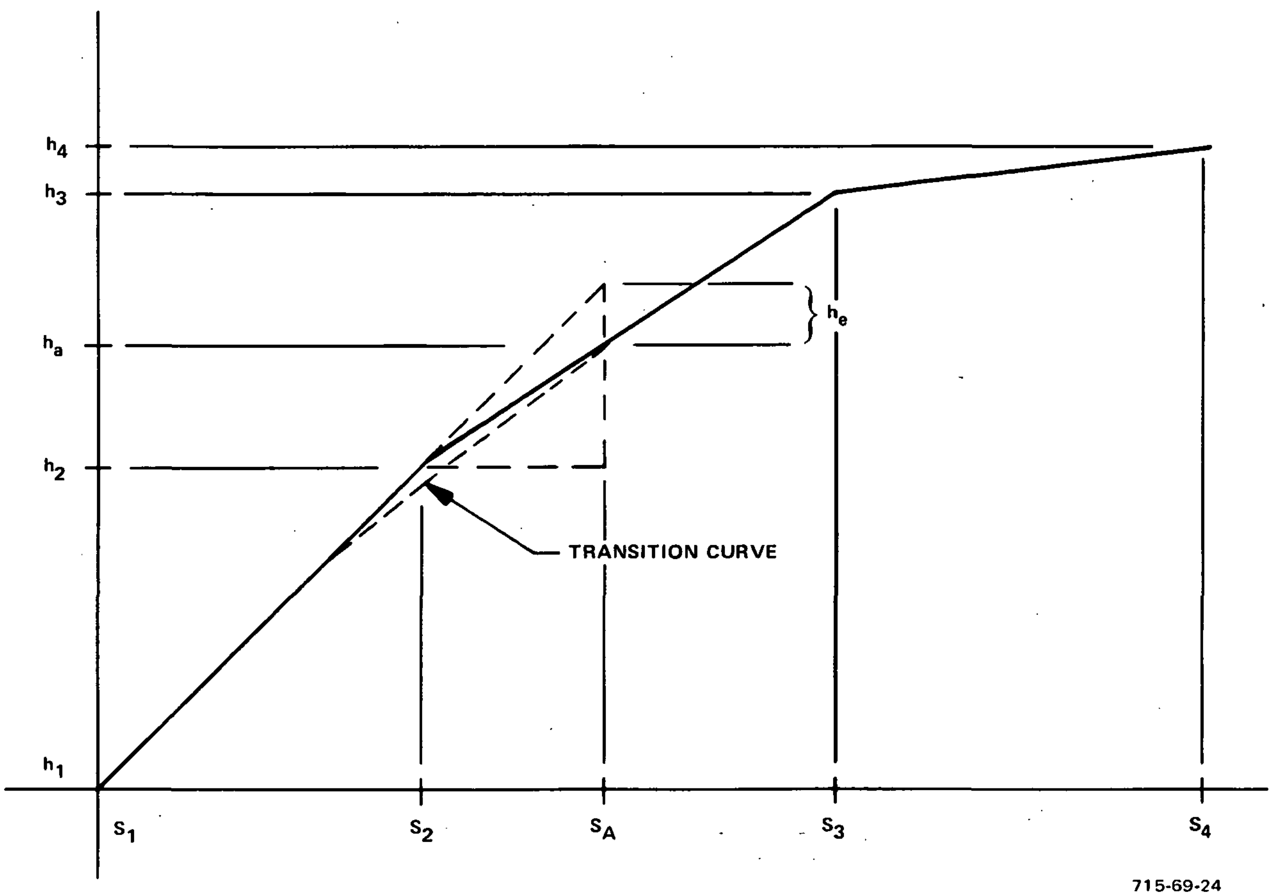


Figure 24
Altitude Profile Geometry

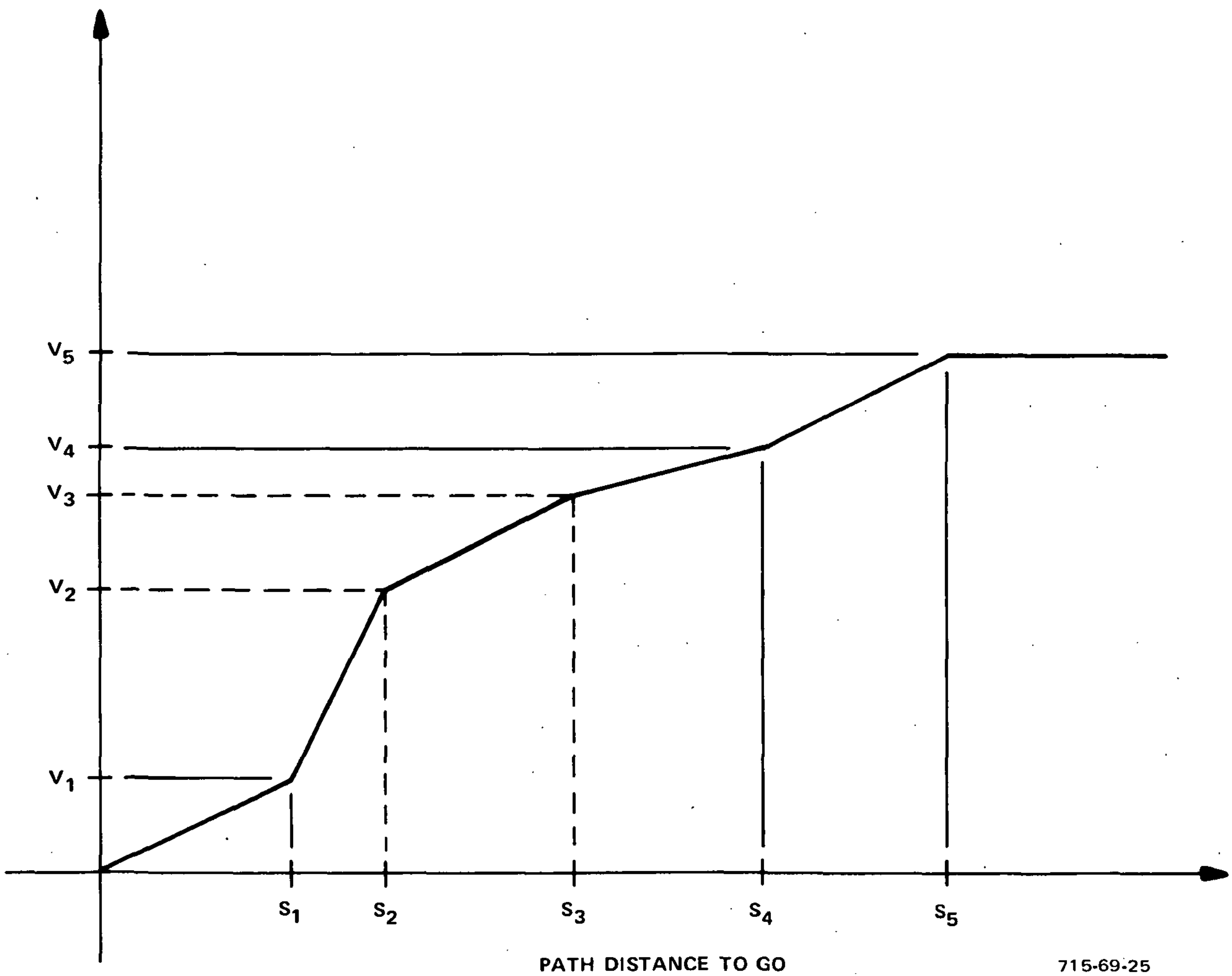


Figure 25
Speed Profile Geometry

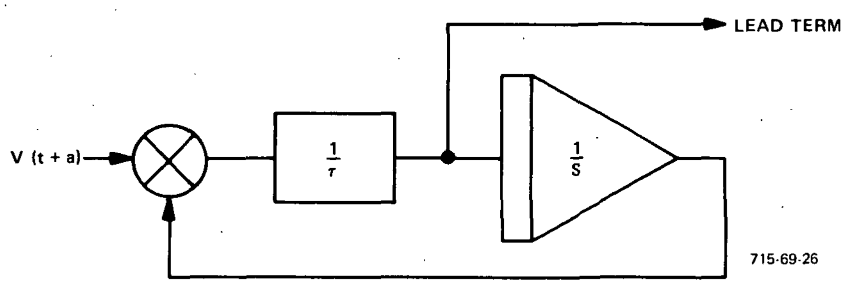


Figure 26
Velocity Washout

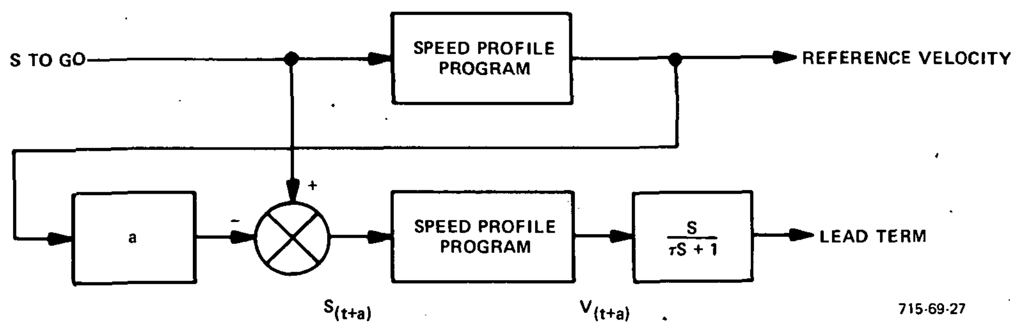


Figure 27
Velocity Lead Term Generation

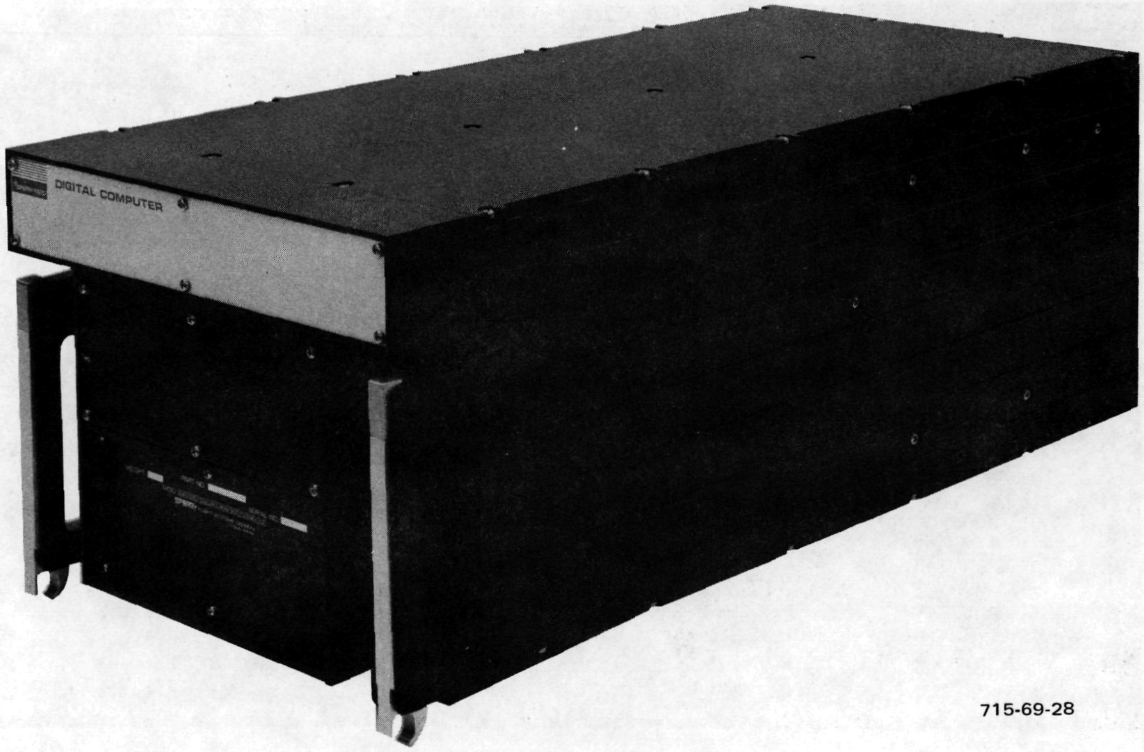


Figure 28
1819A Computer

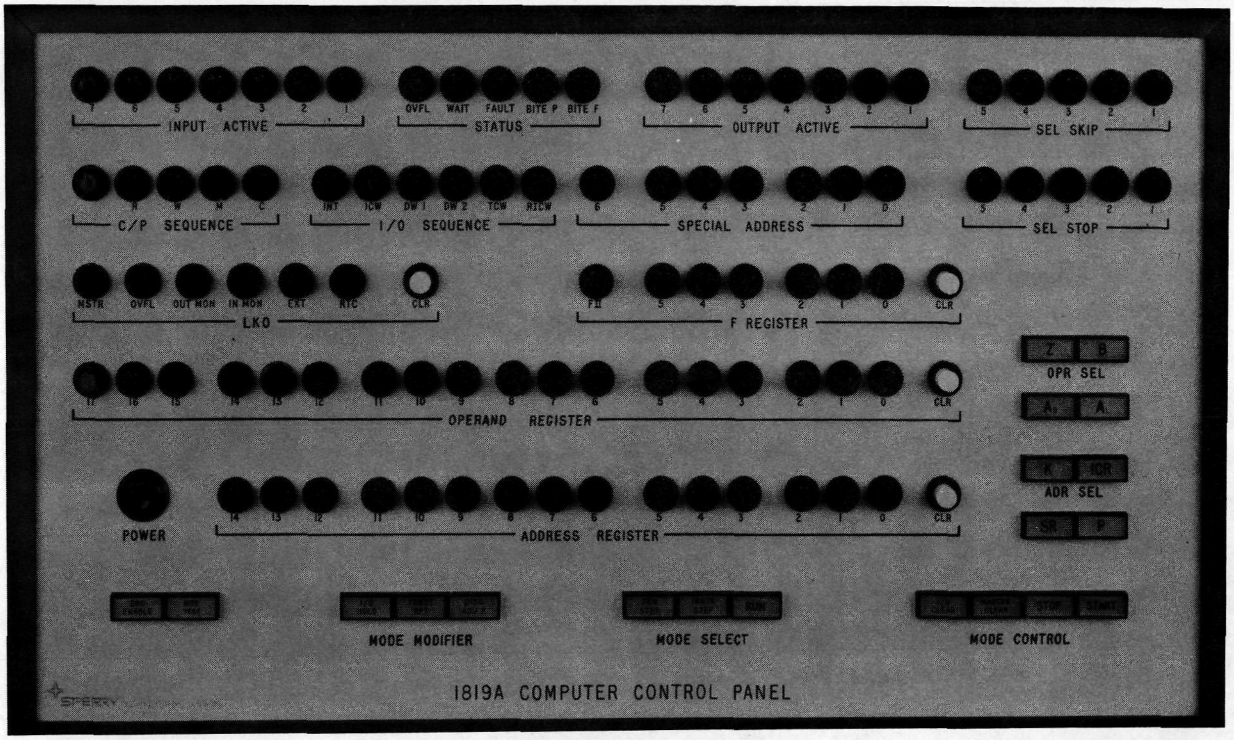


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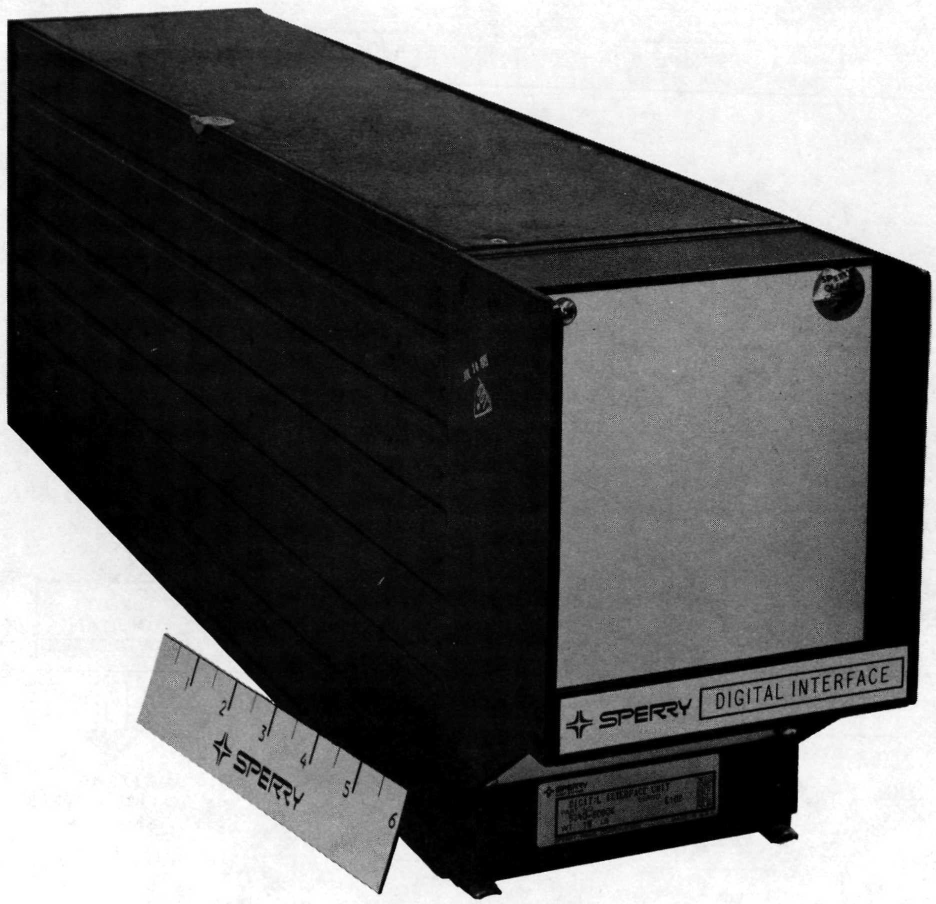
Figure 29
1819A Control Panel



715-69-30

Figure 30
Digital Interface Unit

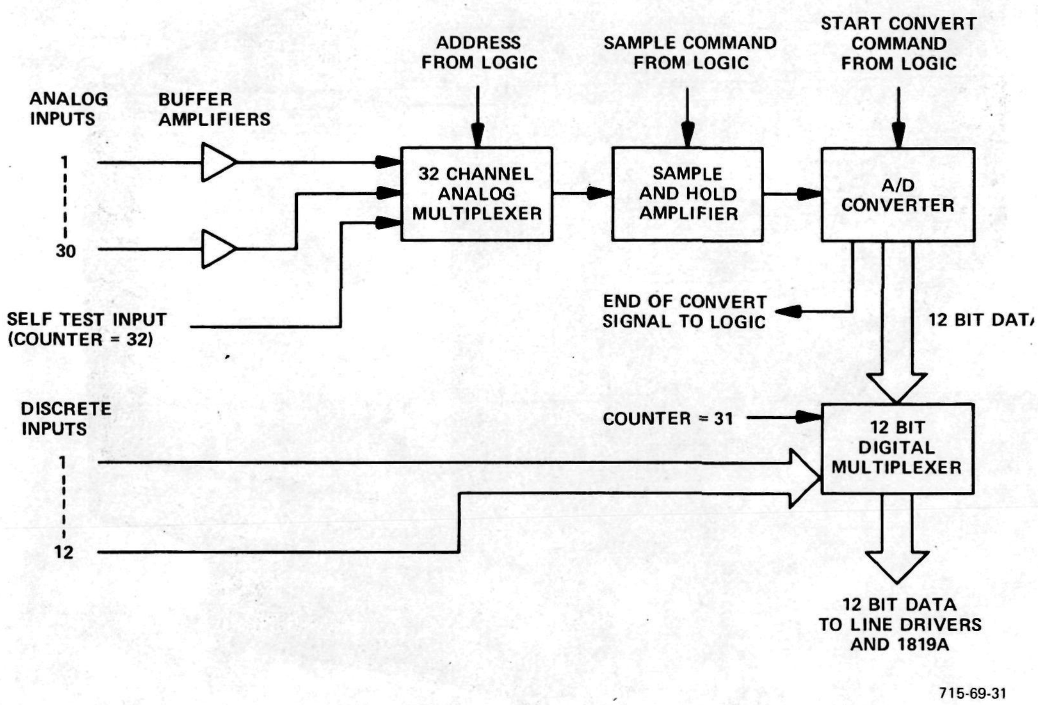


Figure 31
DIU Input Section Block Diagram

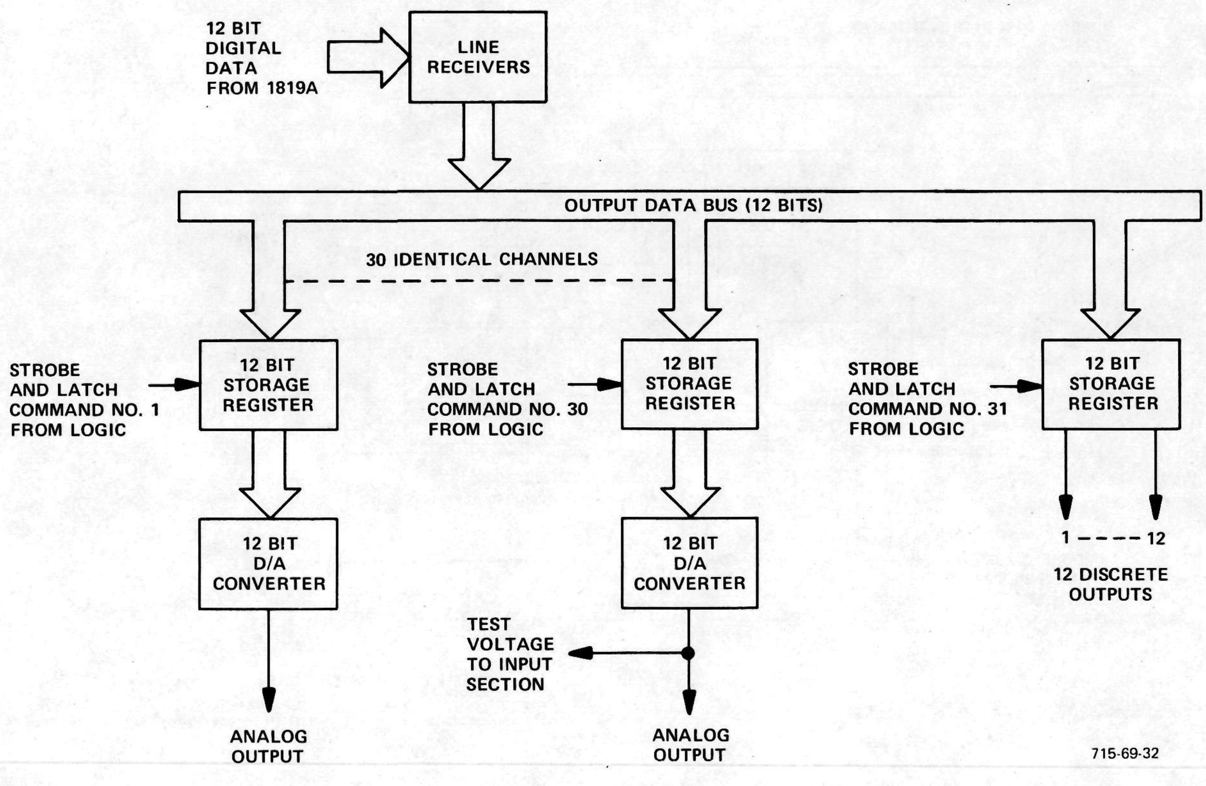


Figure 32
DIU Output Section Block Diagram

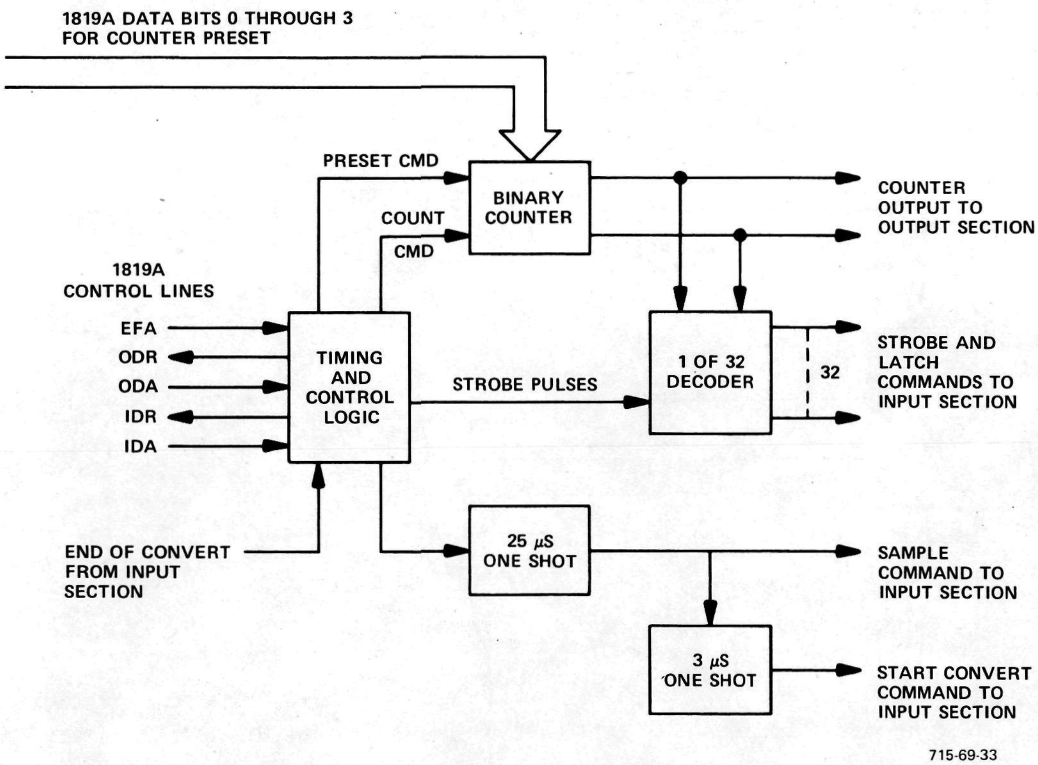


Figure 33
DIU Logic Section Block Diagram

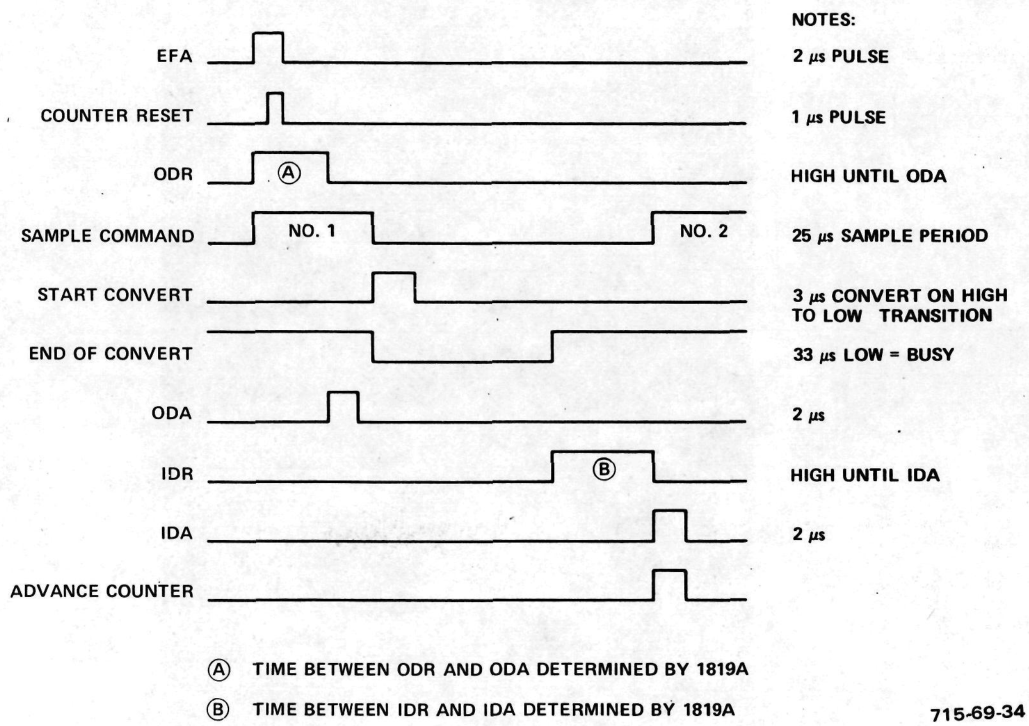
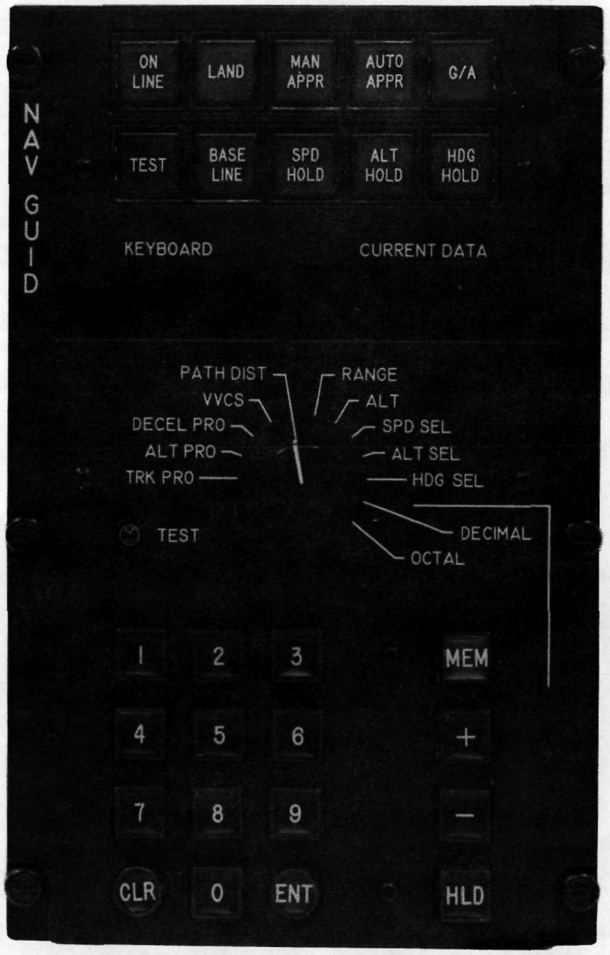


Figure 34
DIU Logic Section Timing



715-69-35

Figure 35
Navigation/Guidance Control Panel

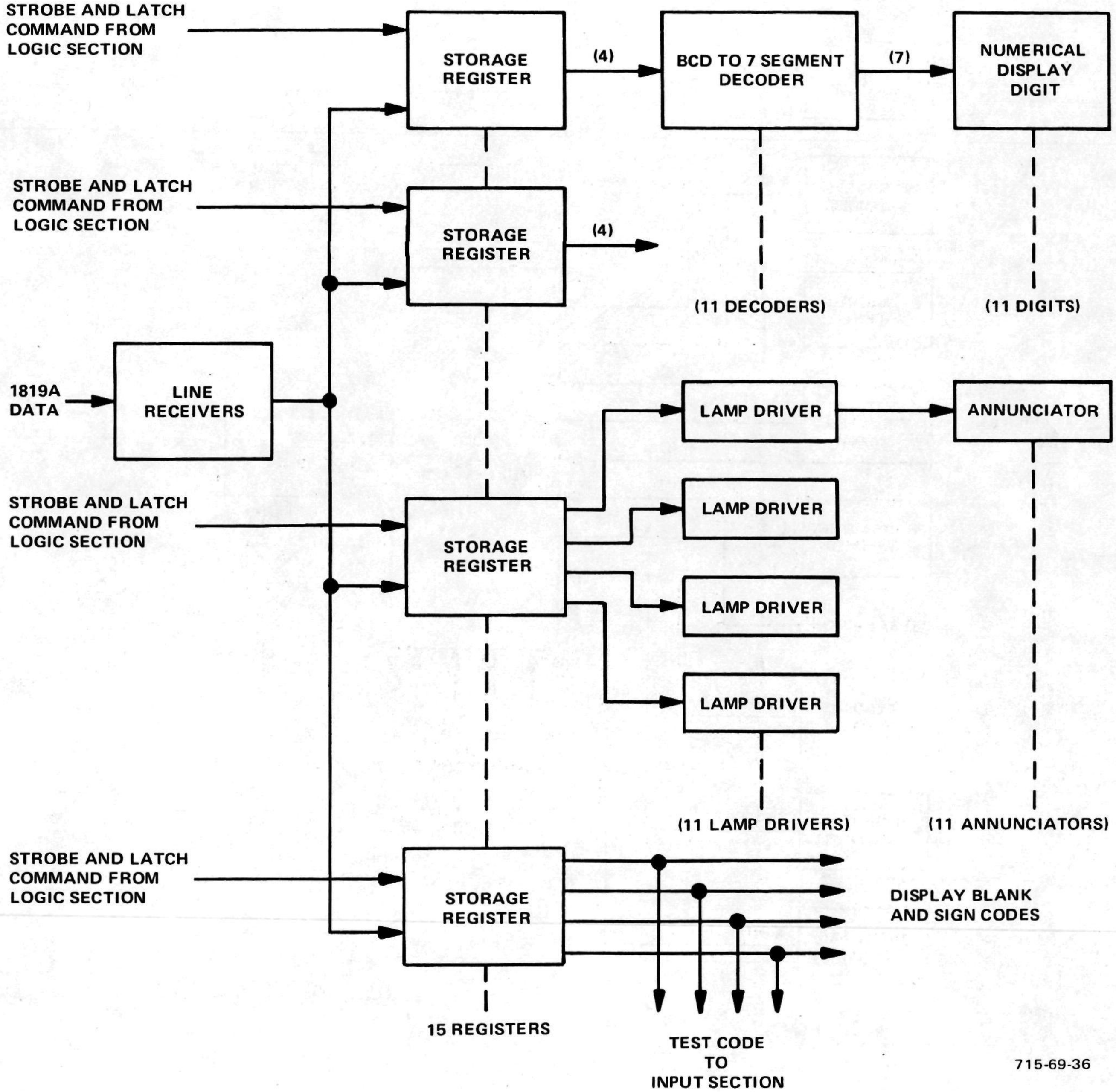


Figure 36
Navigation/Guidance Control Panel Output Section Block Diagram

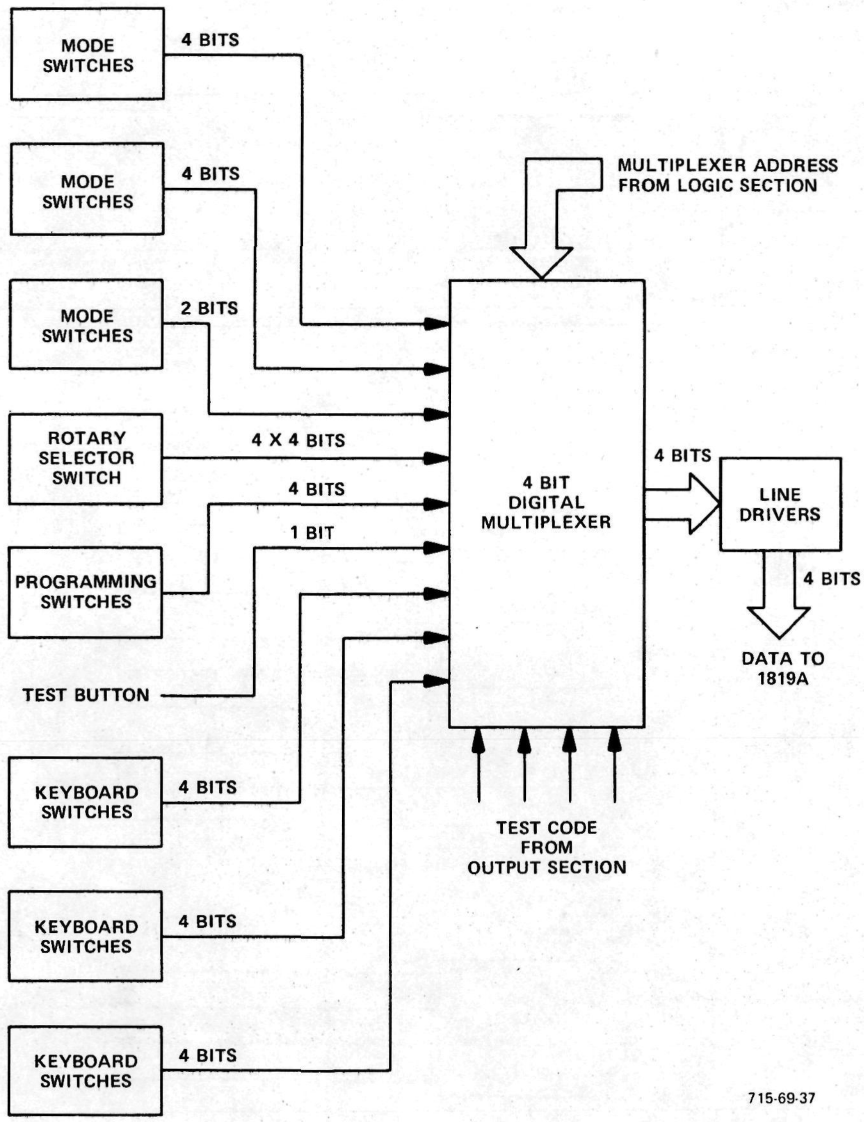


Figure 37
Navigation/Guidance Control Panel Input Section Block Diagram

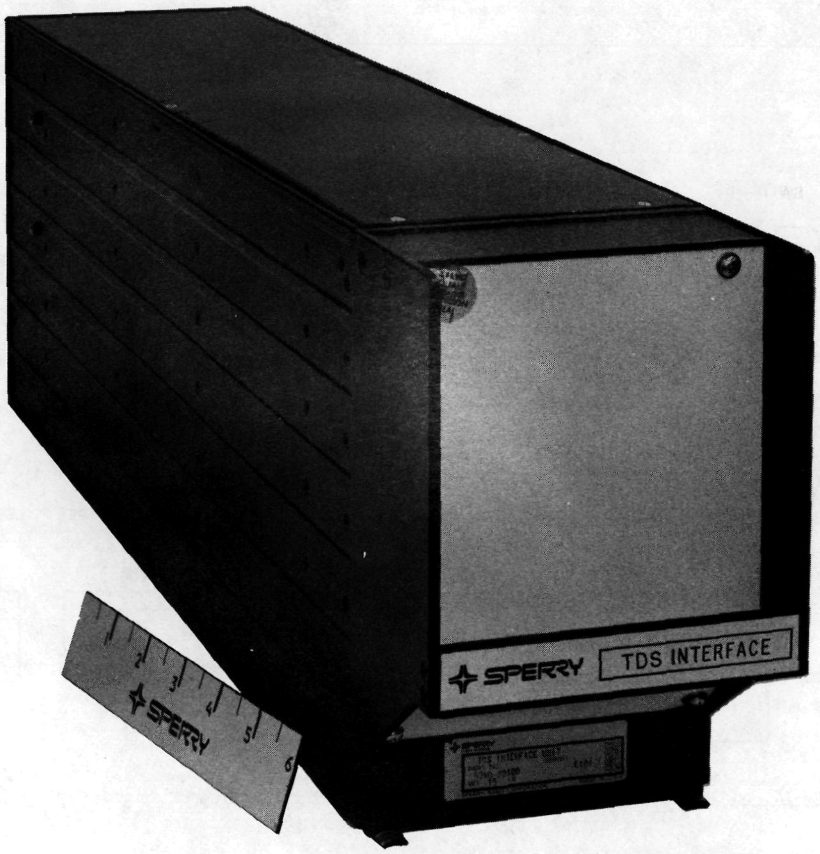


Figure 38
Transponder Data System Interface Unit

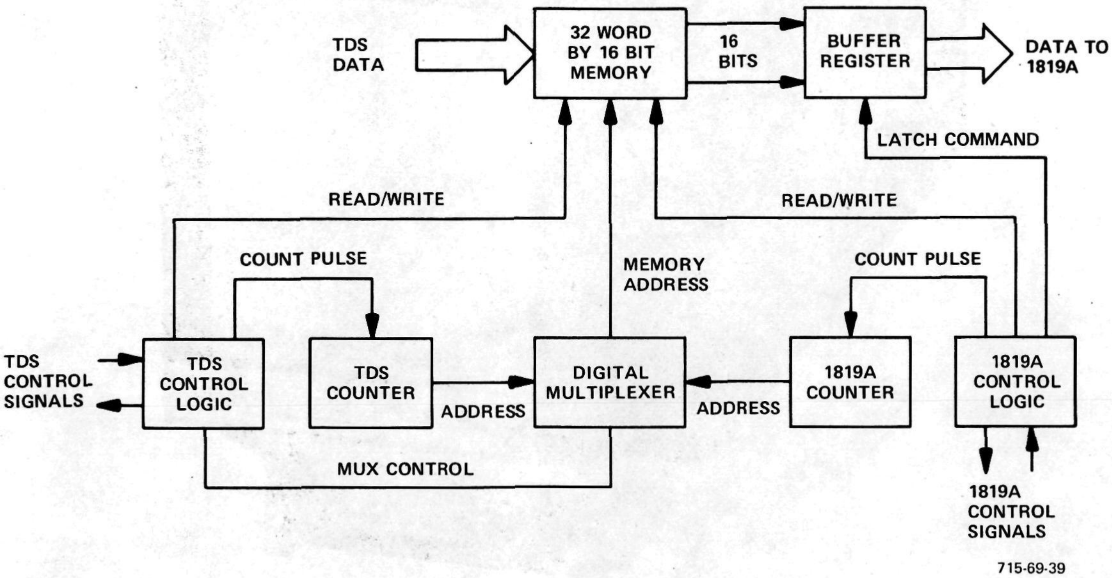


Figure 39
TIF Uplink Memory Section

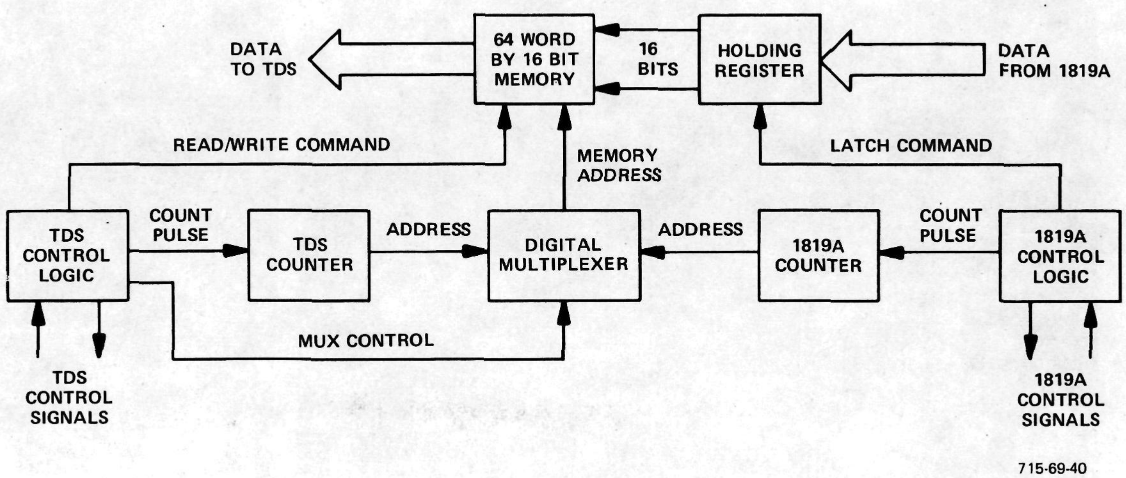
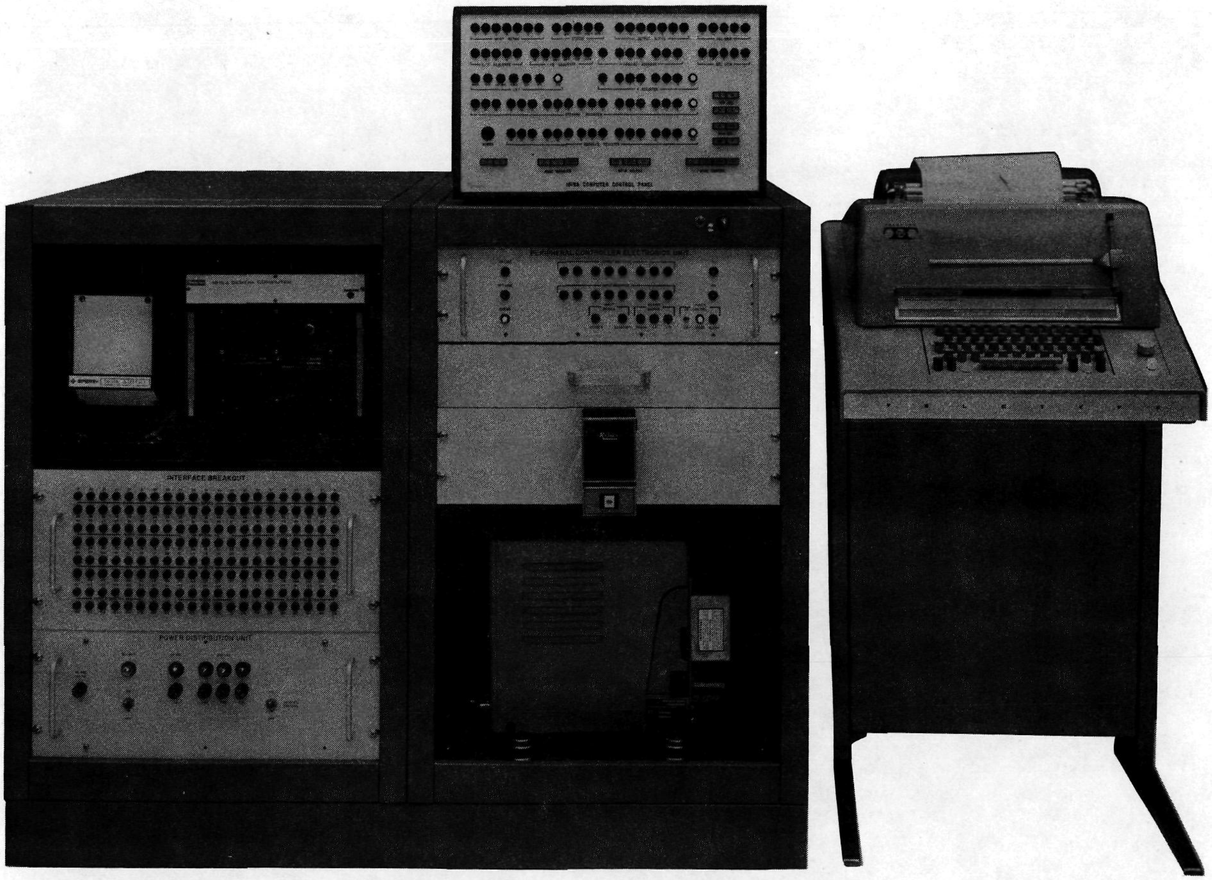


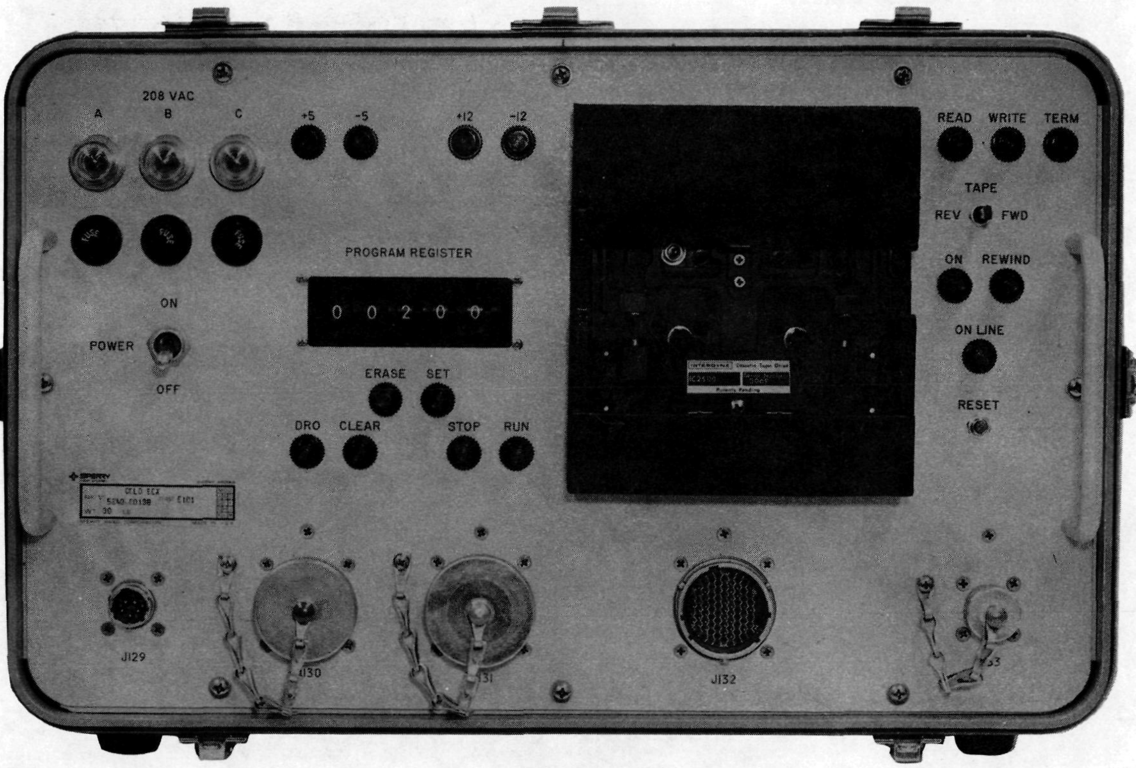
Figure 40
TIF Downlink Memory Section



715-69-41

Figure 41
Ground Support Equipment

Figure 42
Carry-On Load/Dump Unit



715-69-43

Figure 43
Front Panel Carry-On Load/Dump Unit

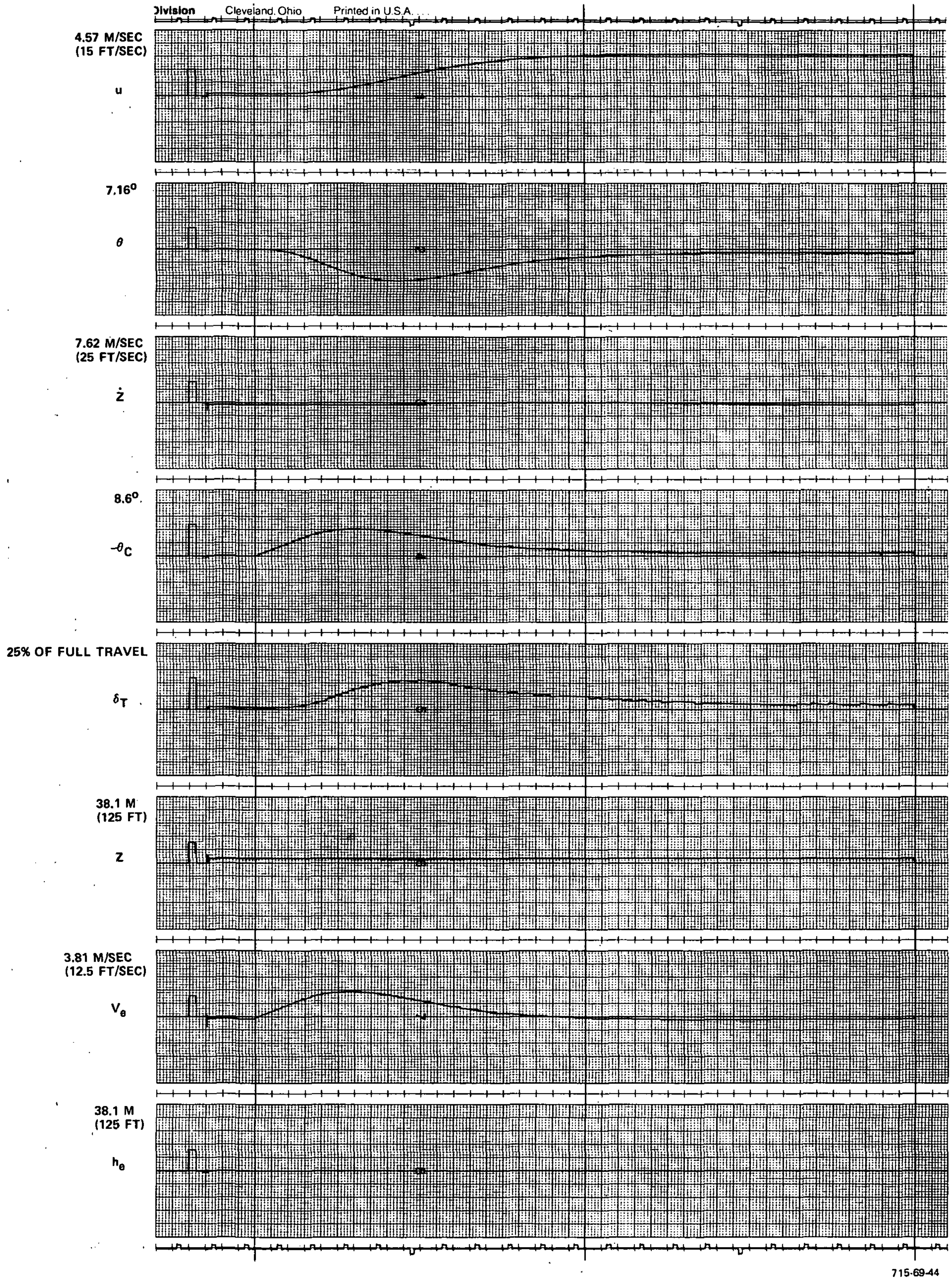


Figure 44
Commanded Speed Increase

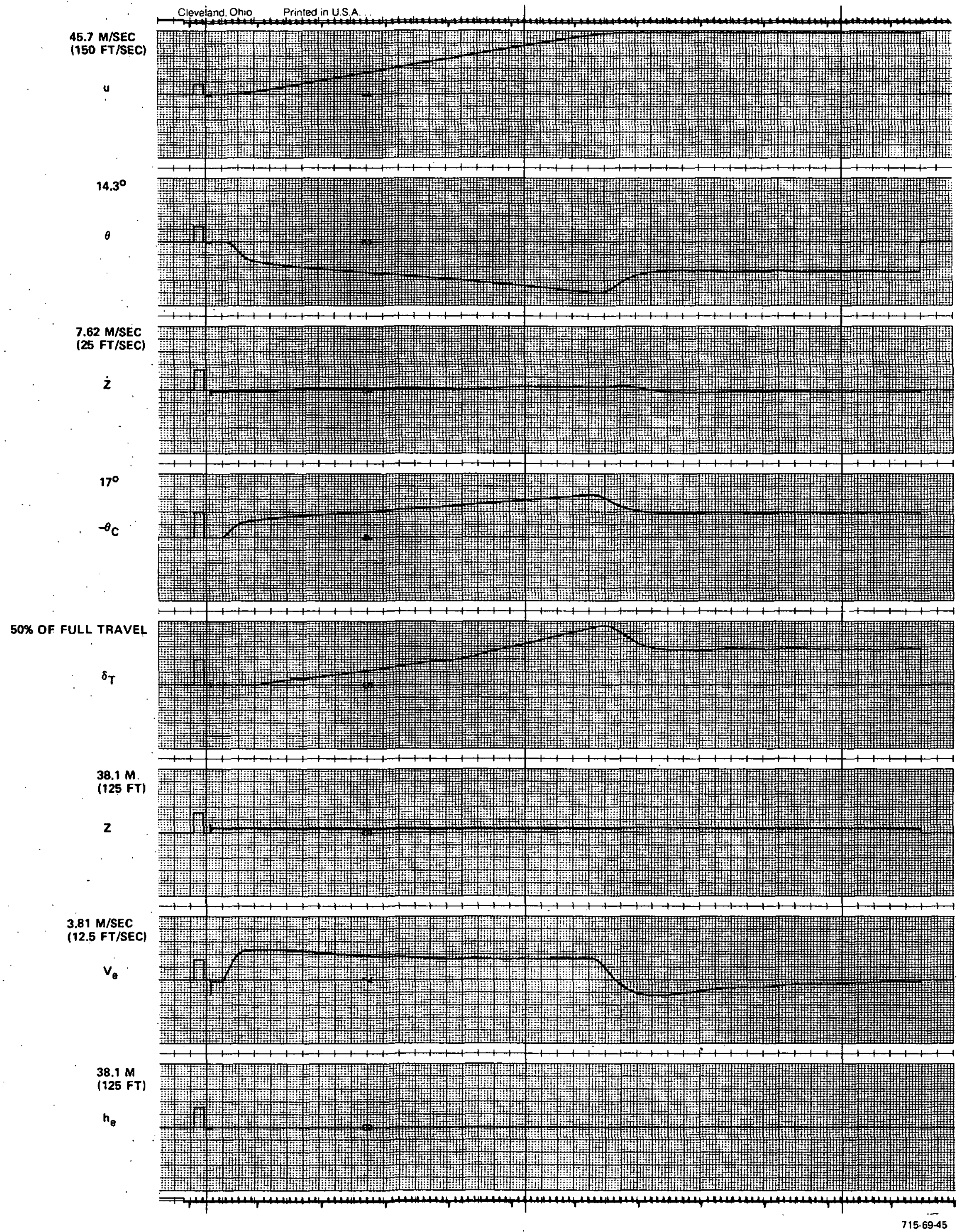


Figure 45
Commanded Speed Decrease

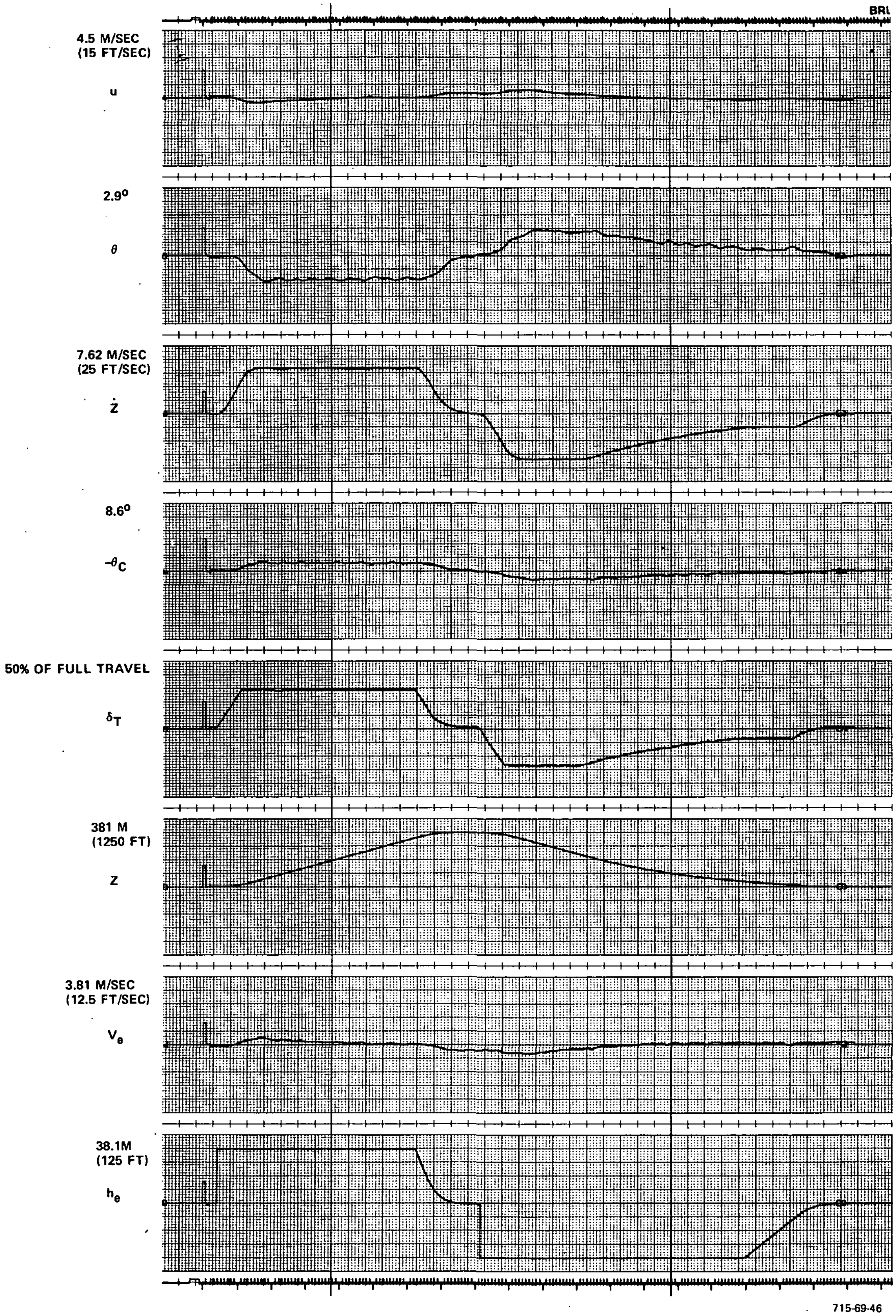


Figure 46
Transition to Hover Data

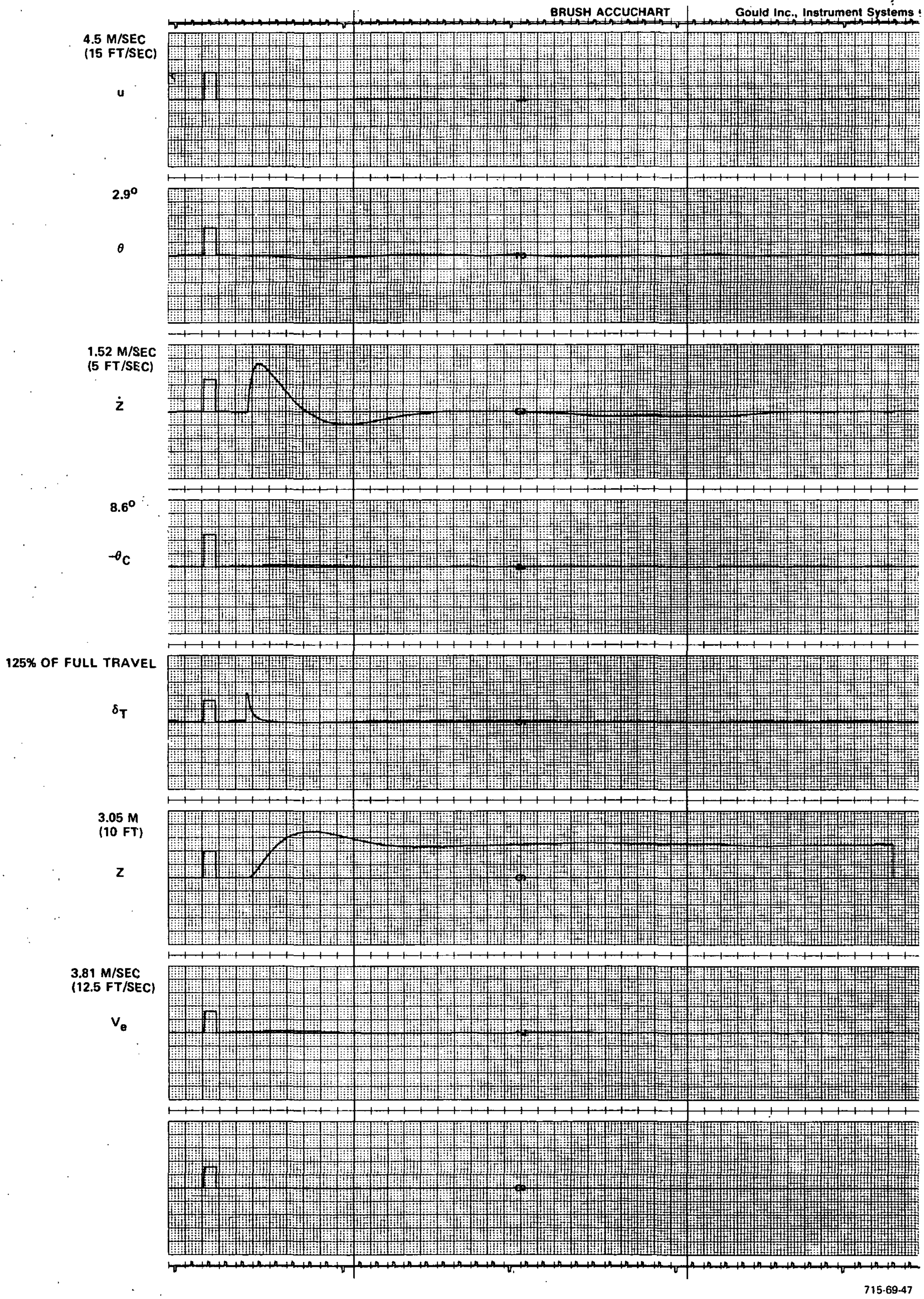


Figure 47
VVCS Response to Altitude Change

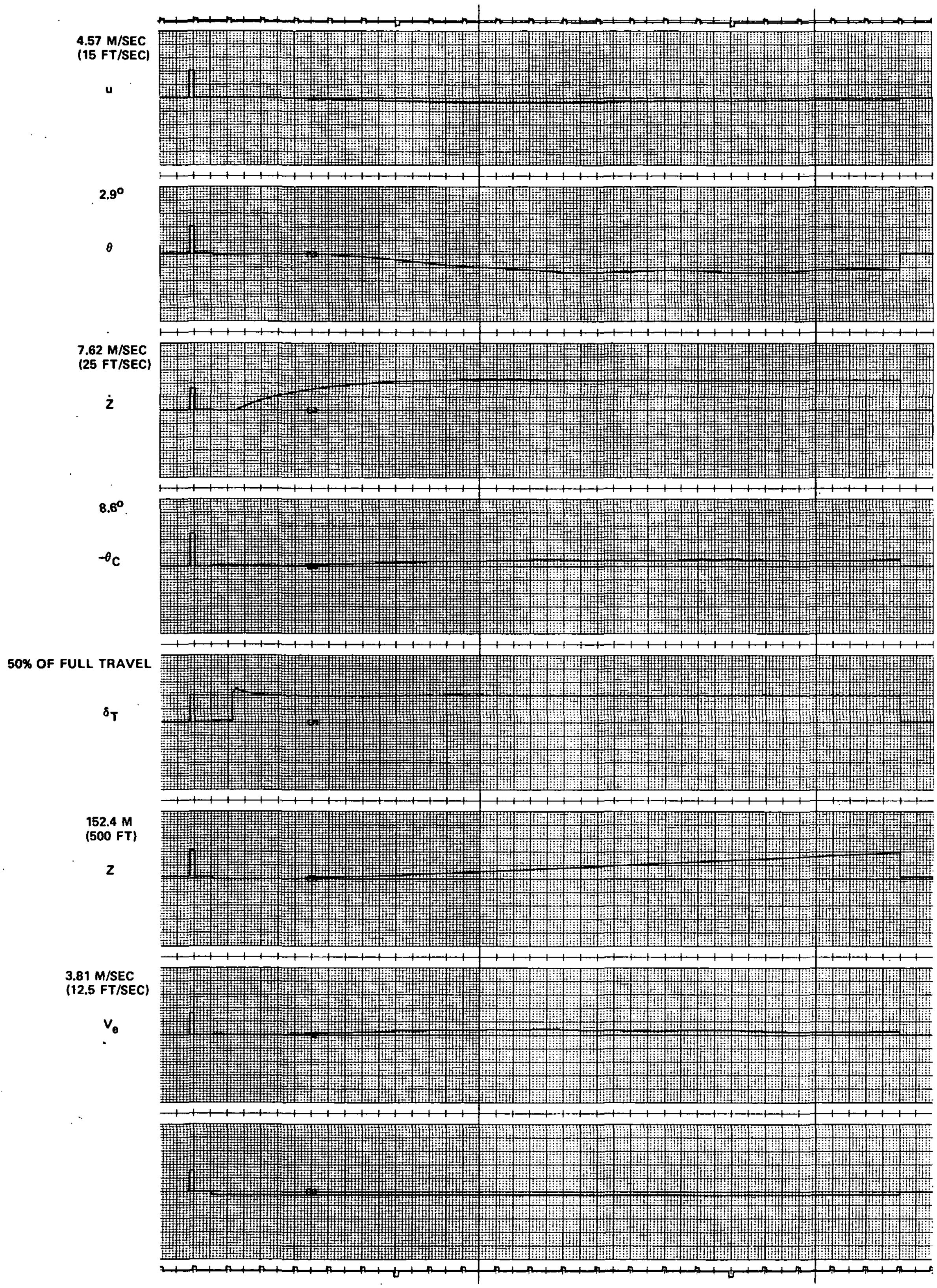


Figure 48
VVCS Response to Collective Command

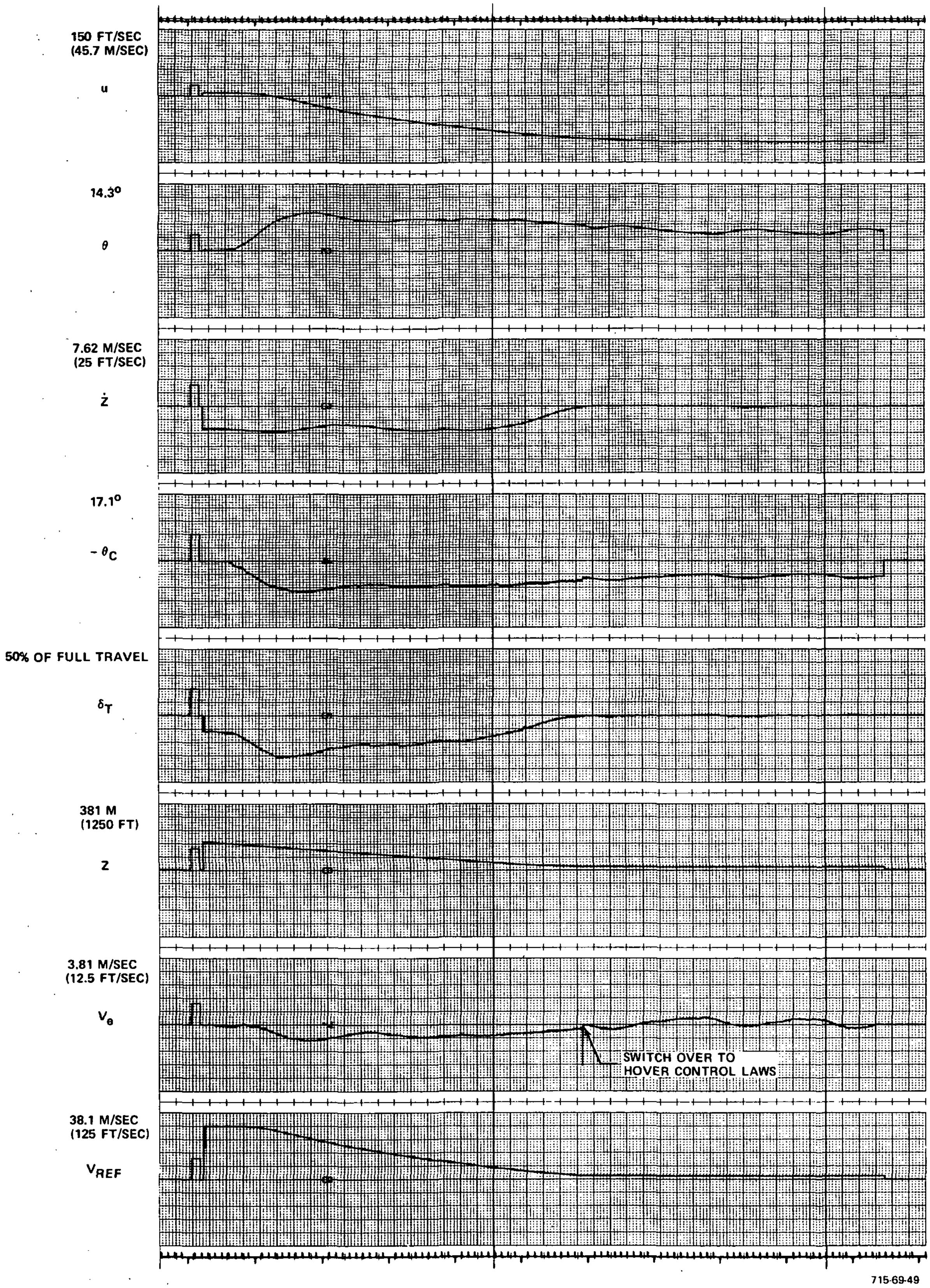


Figure 49
Commanded Altitude Change

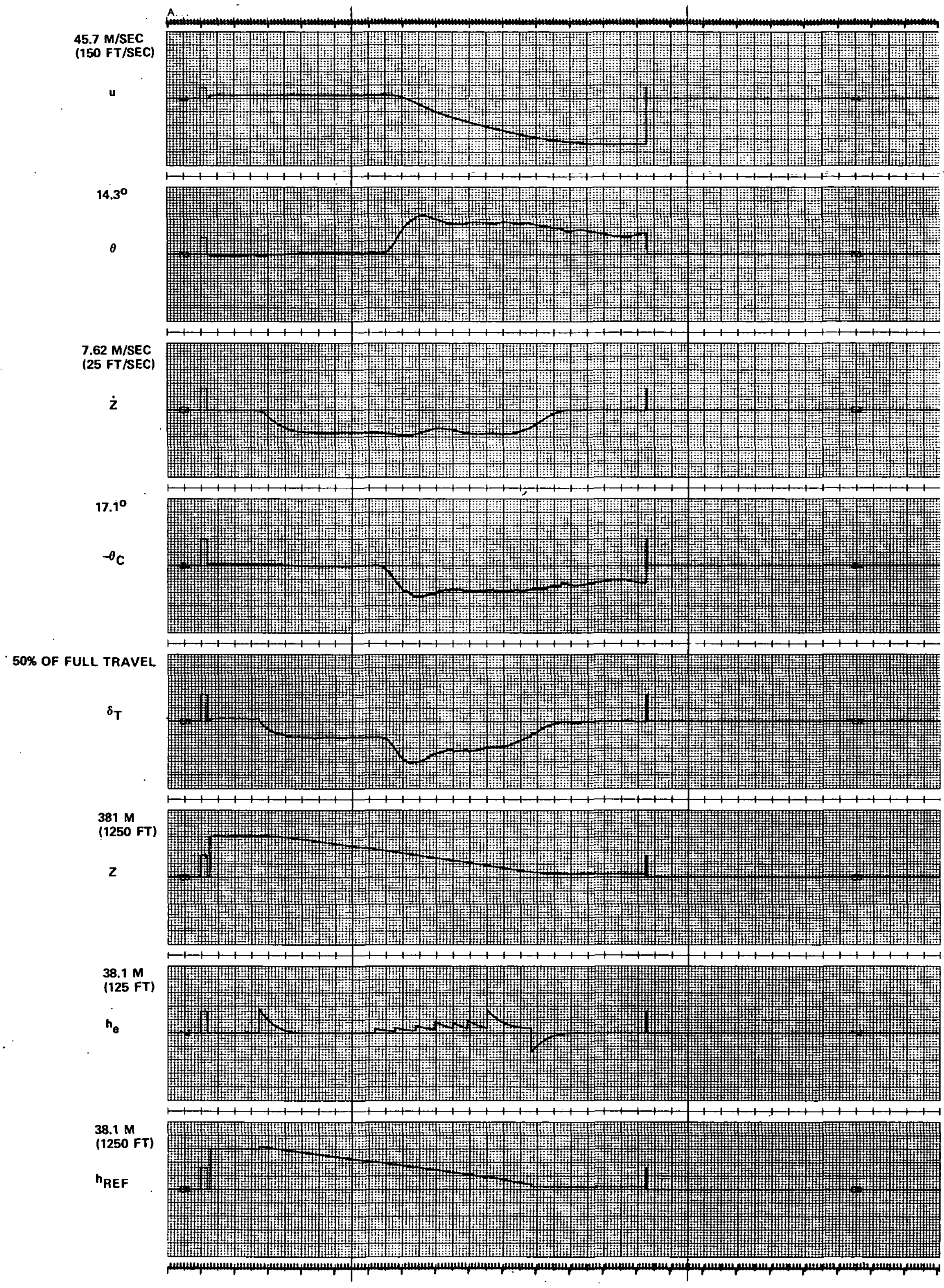


Figure 50
Automatic Descent

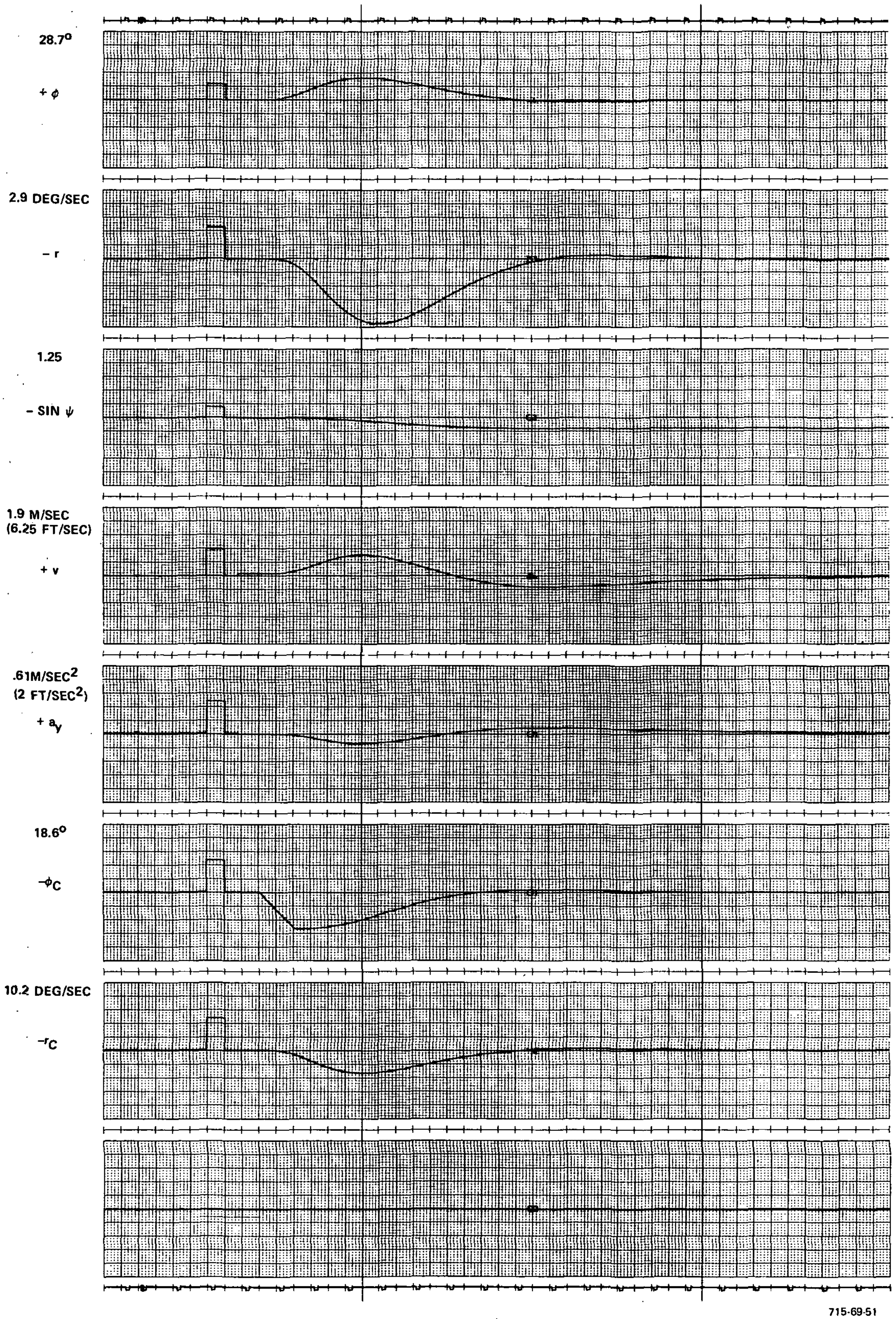


Figure 51
Commanded 10 Degree Heading Change

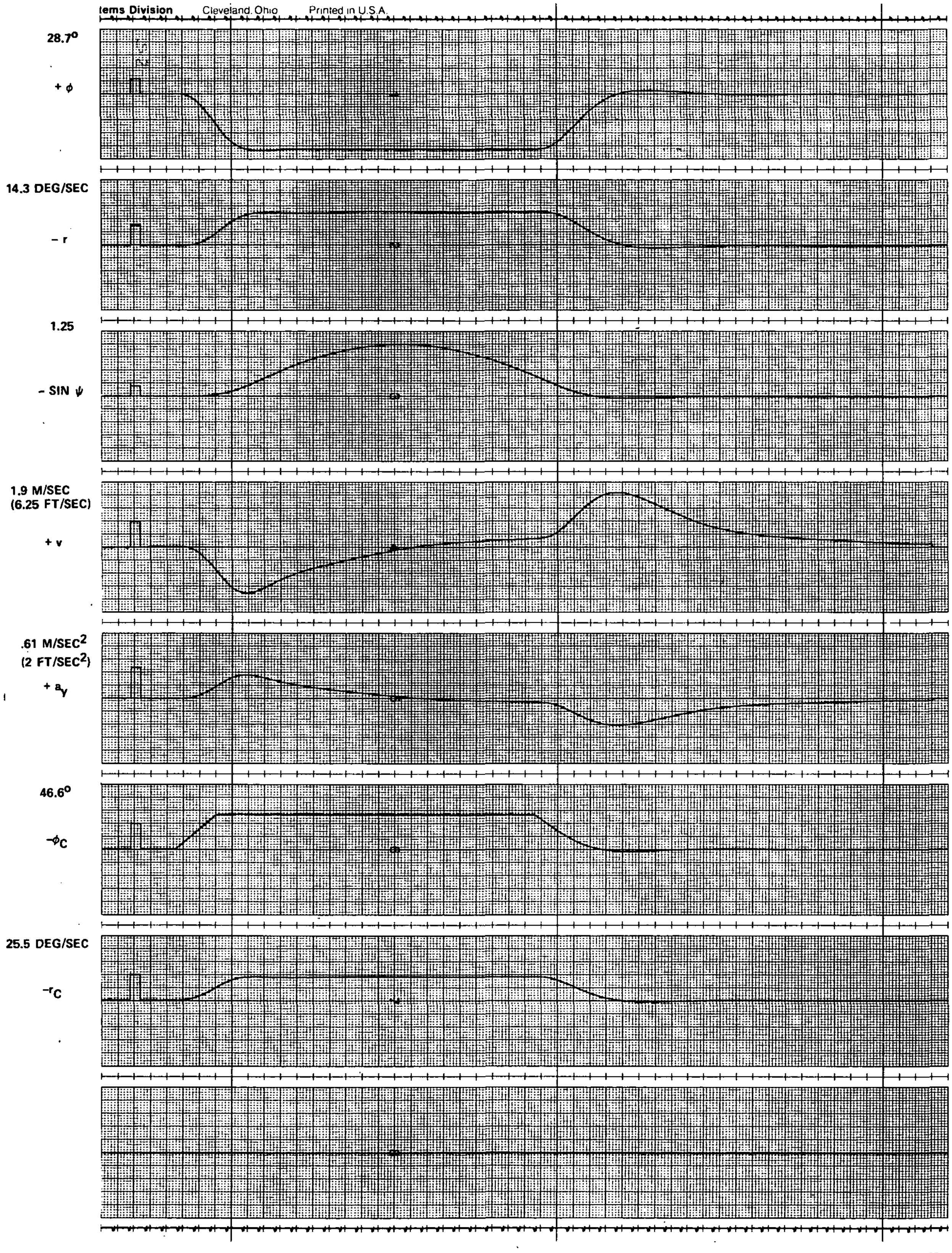


Figure 52
Commanded 180 Degree Heading Change

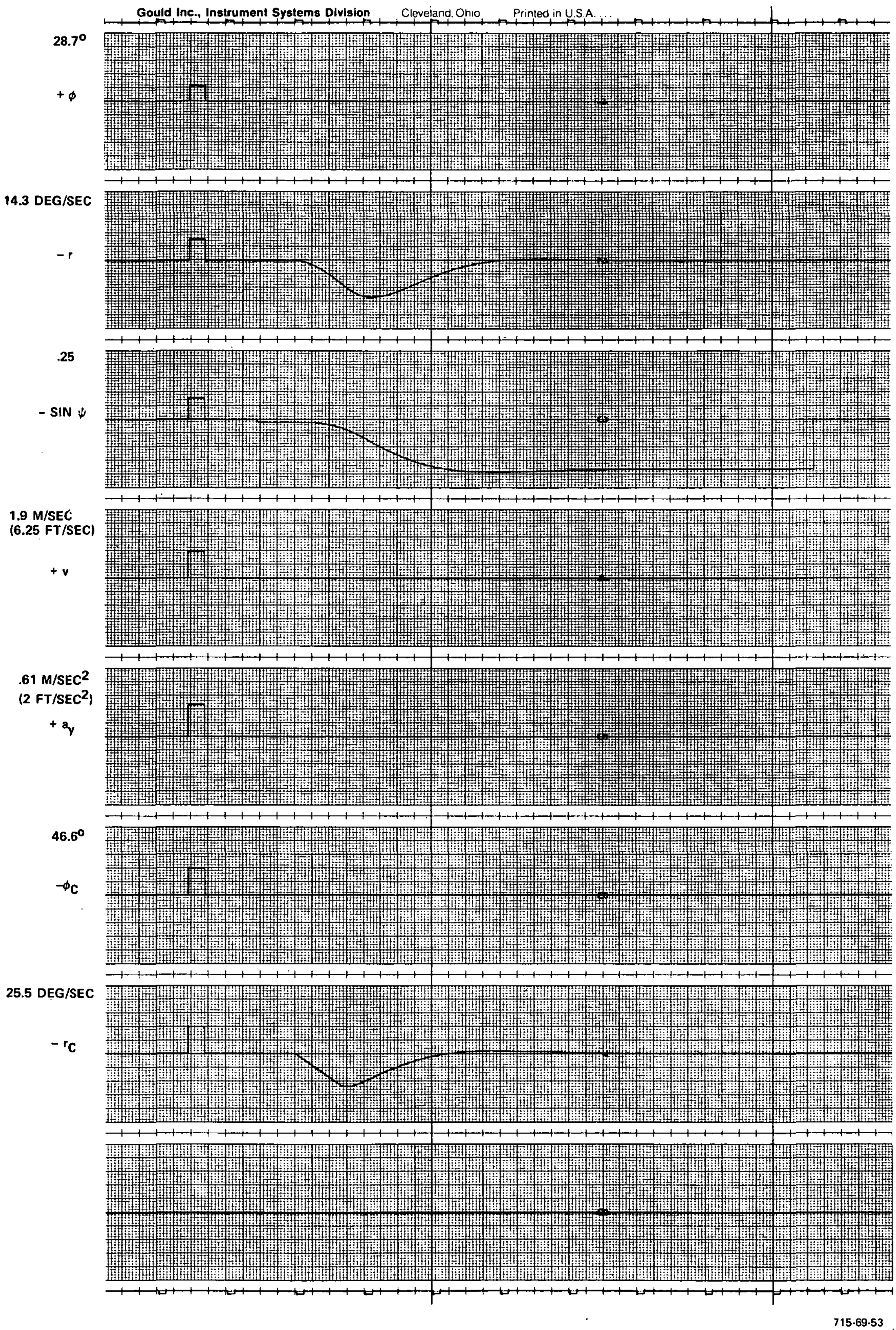


Figure 53
Commanded 10 Degree Heading Change at Hover

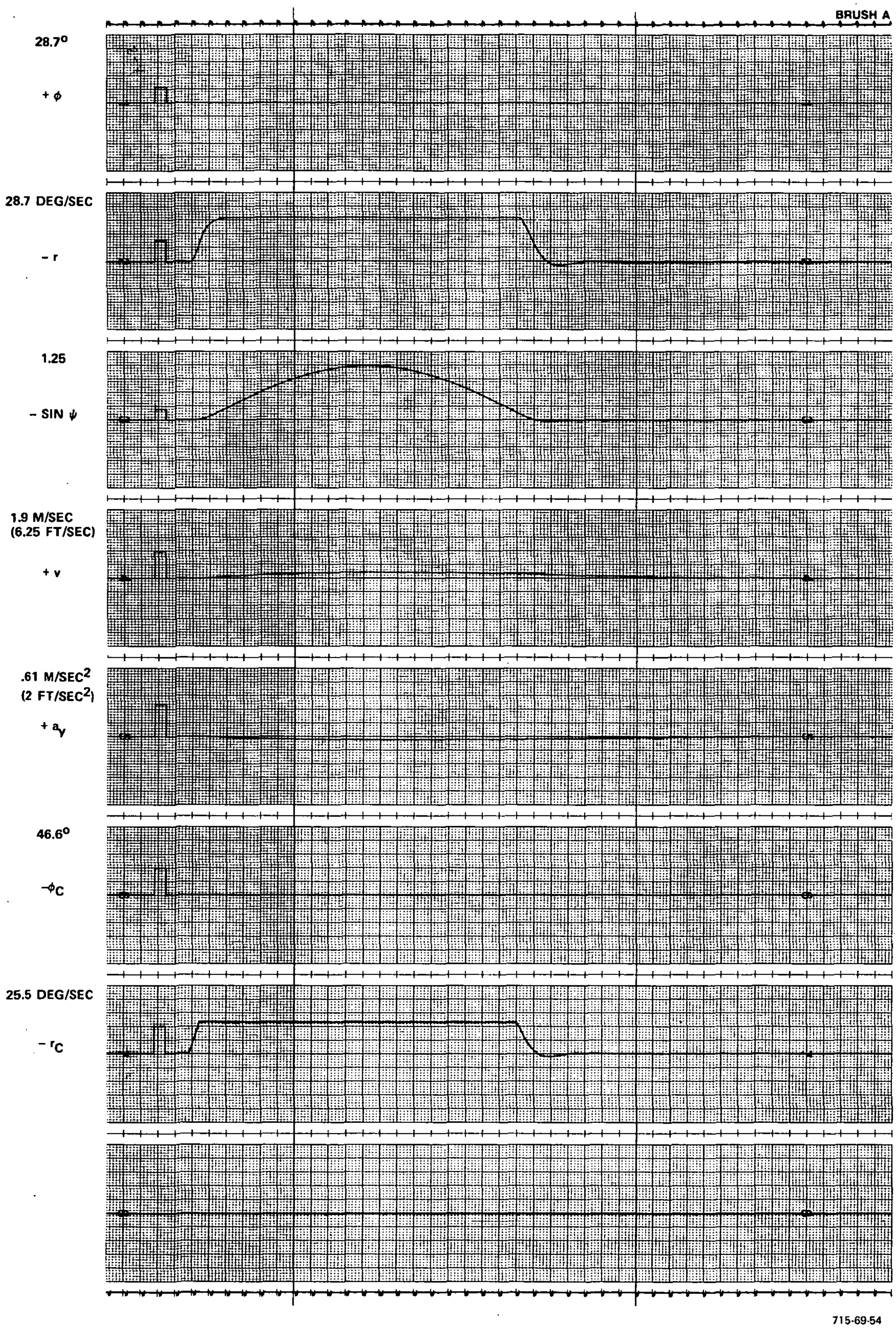


Figure 54
Commanded 180 Degree Heading Change at Hover

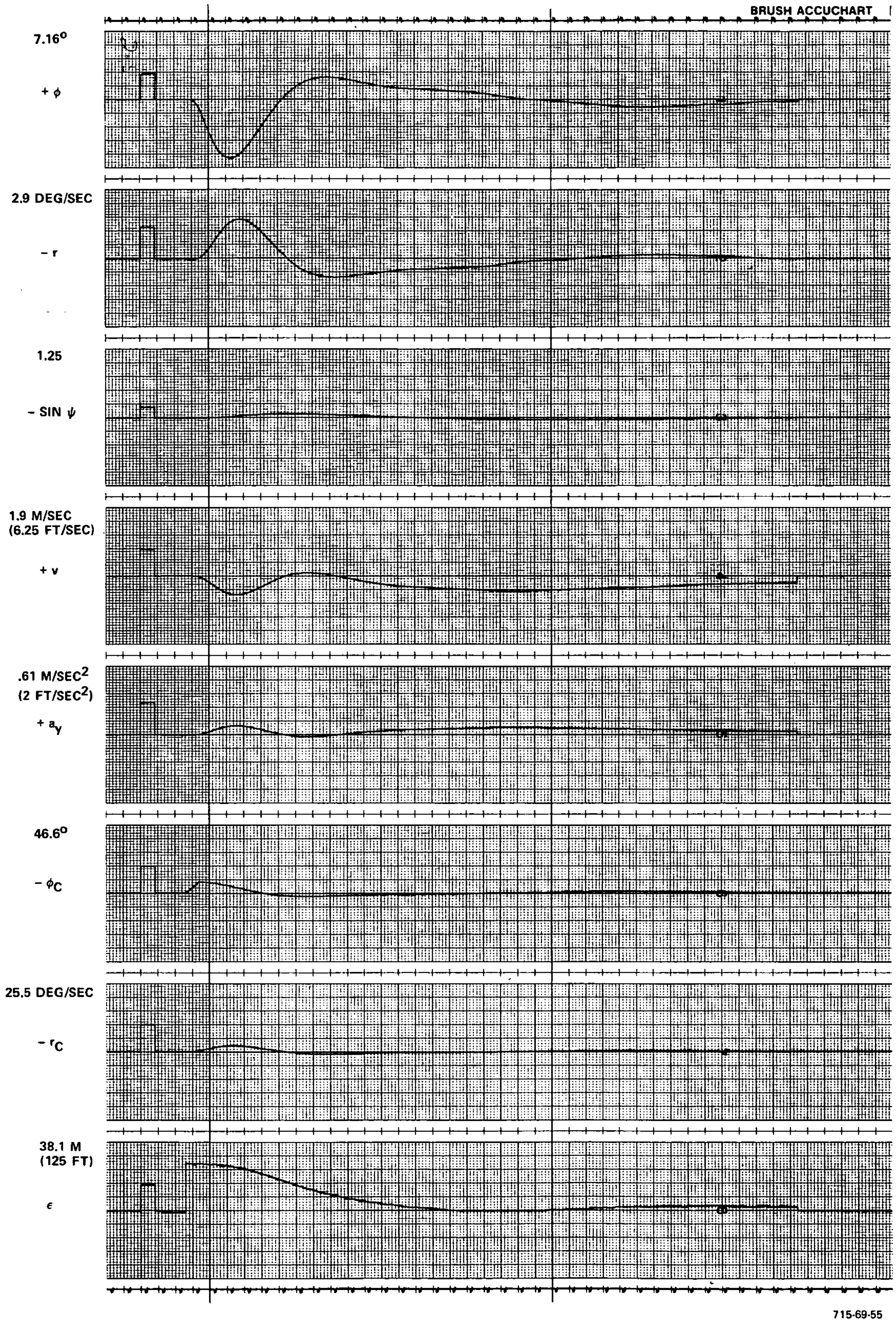


Figure 55
Crosstrack Capture

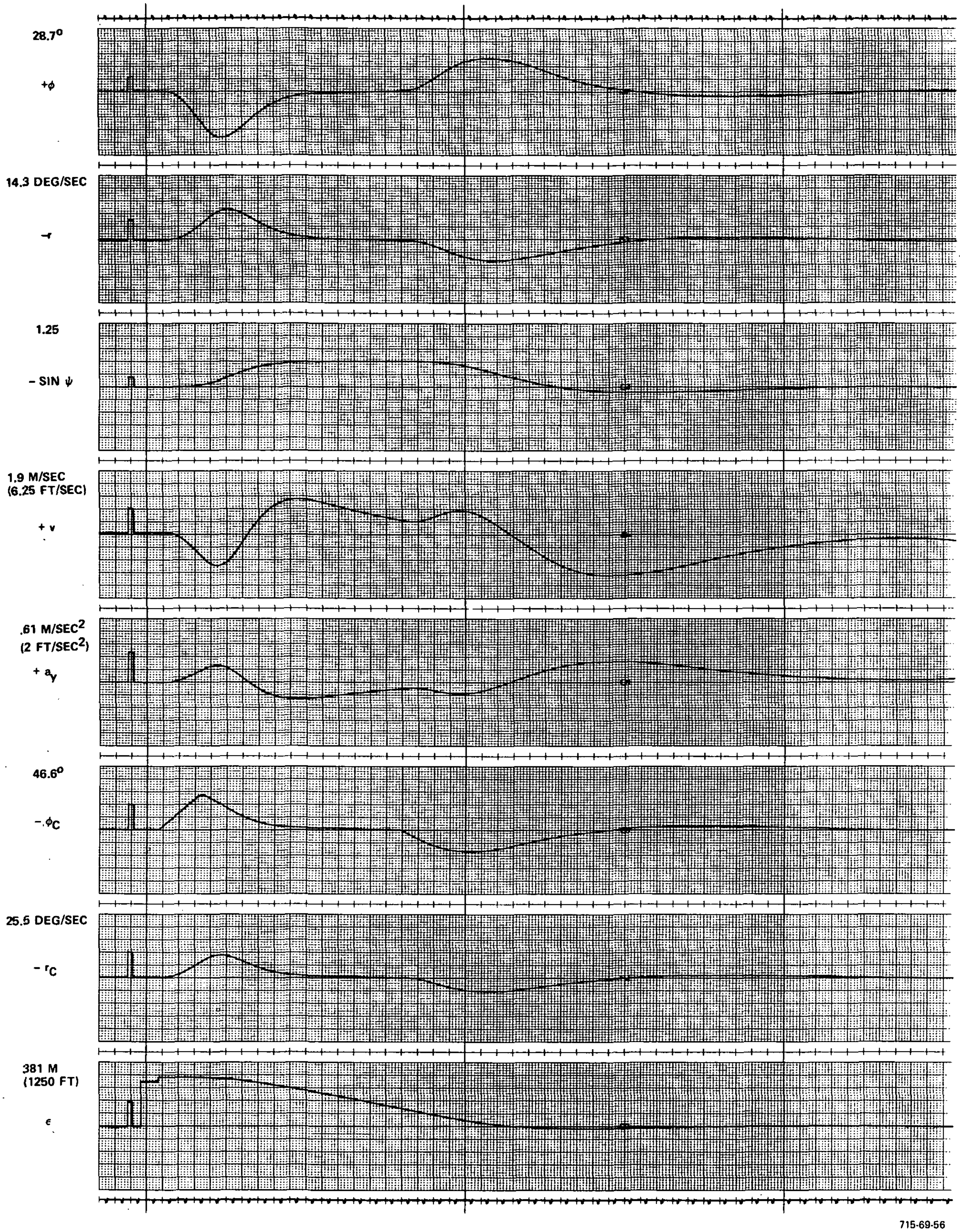


Figure 56
Large Error Crosstrack Capture

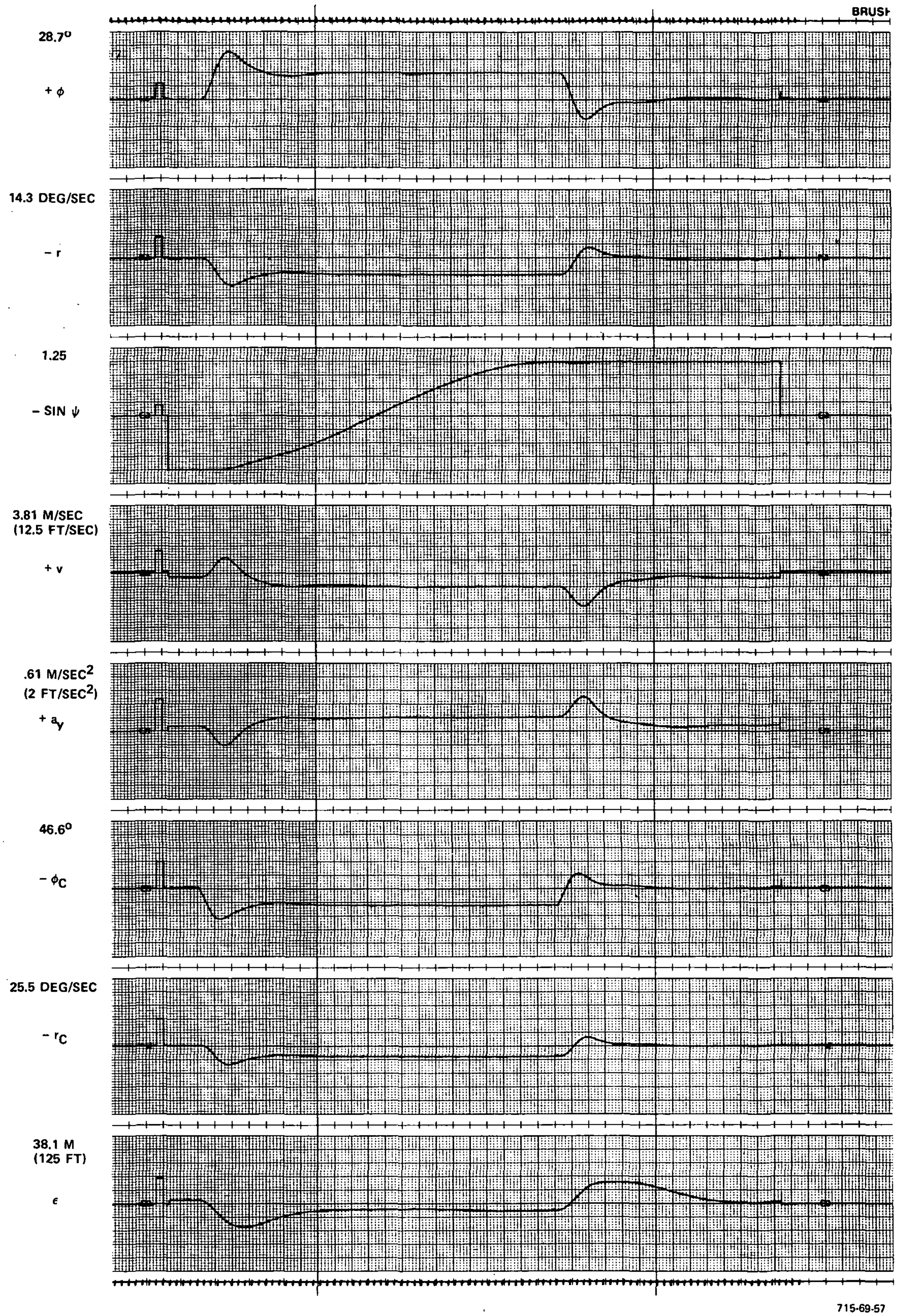


Figure 57
High Speed Curved Path Tracking

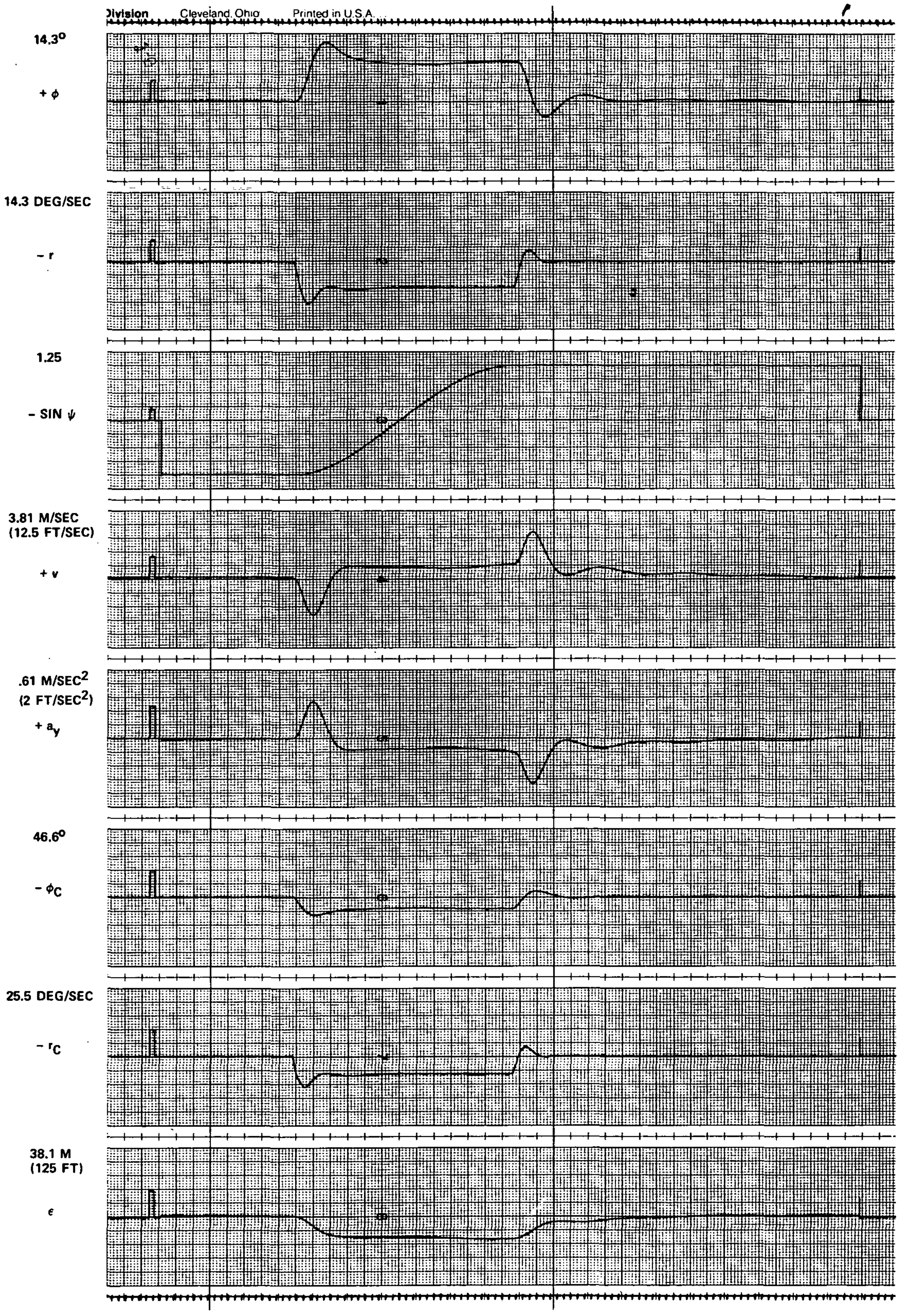


Figure 58
Low Speed Curved Path Tracking

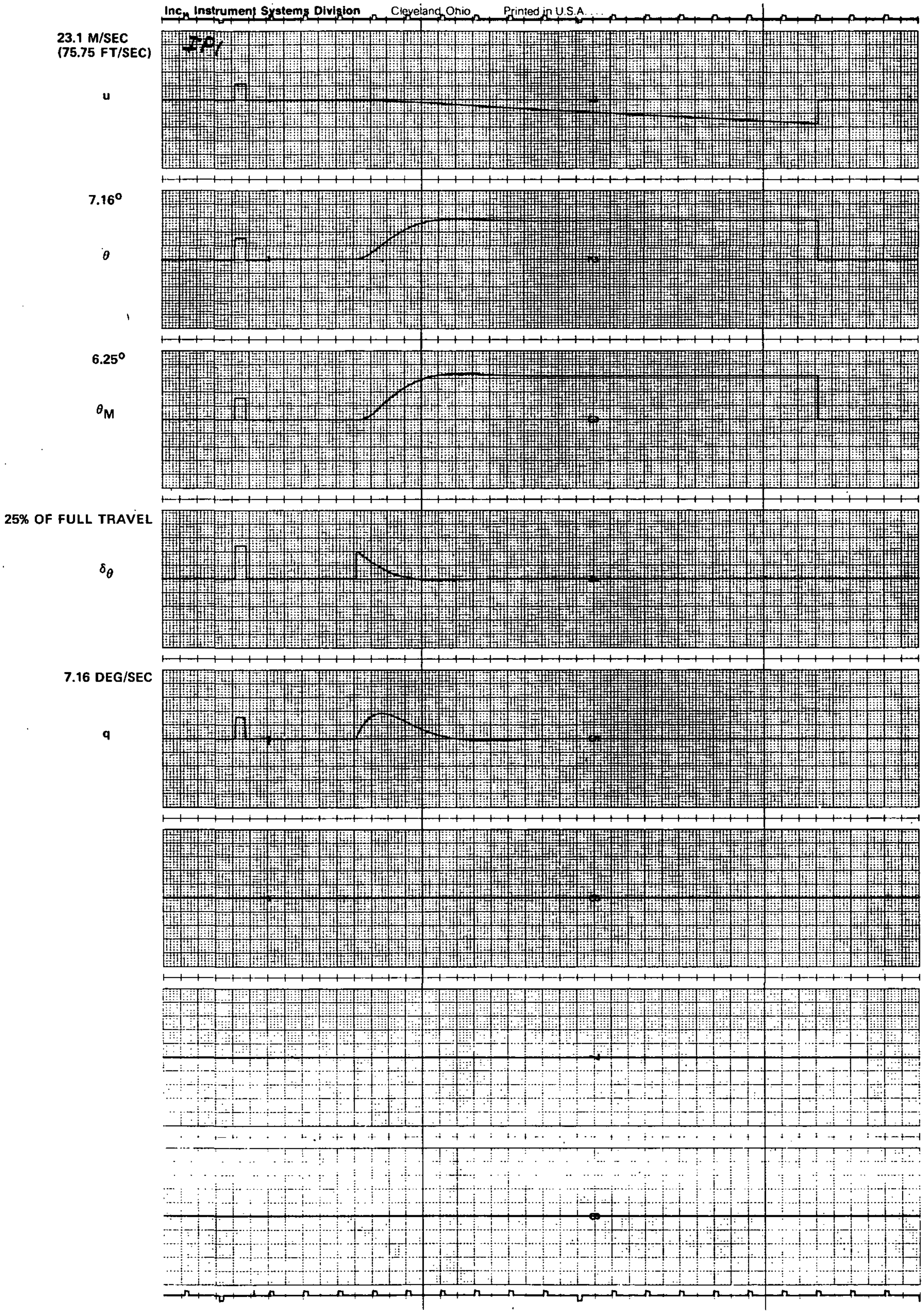


Figure 59
Inner Loop Response

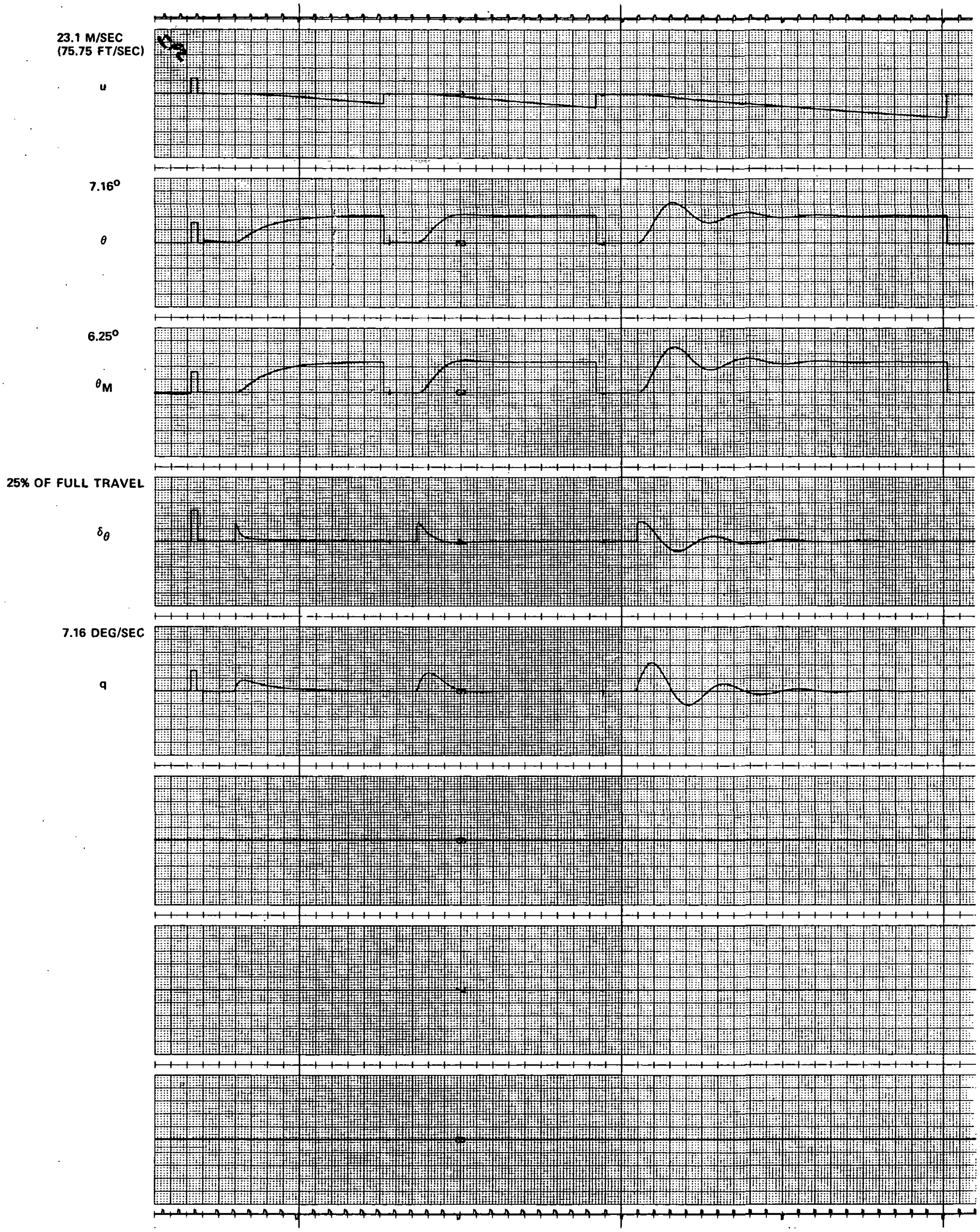


Figure 60
Variable Inner Loop Damping

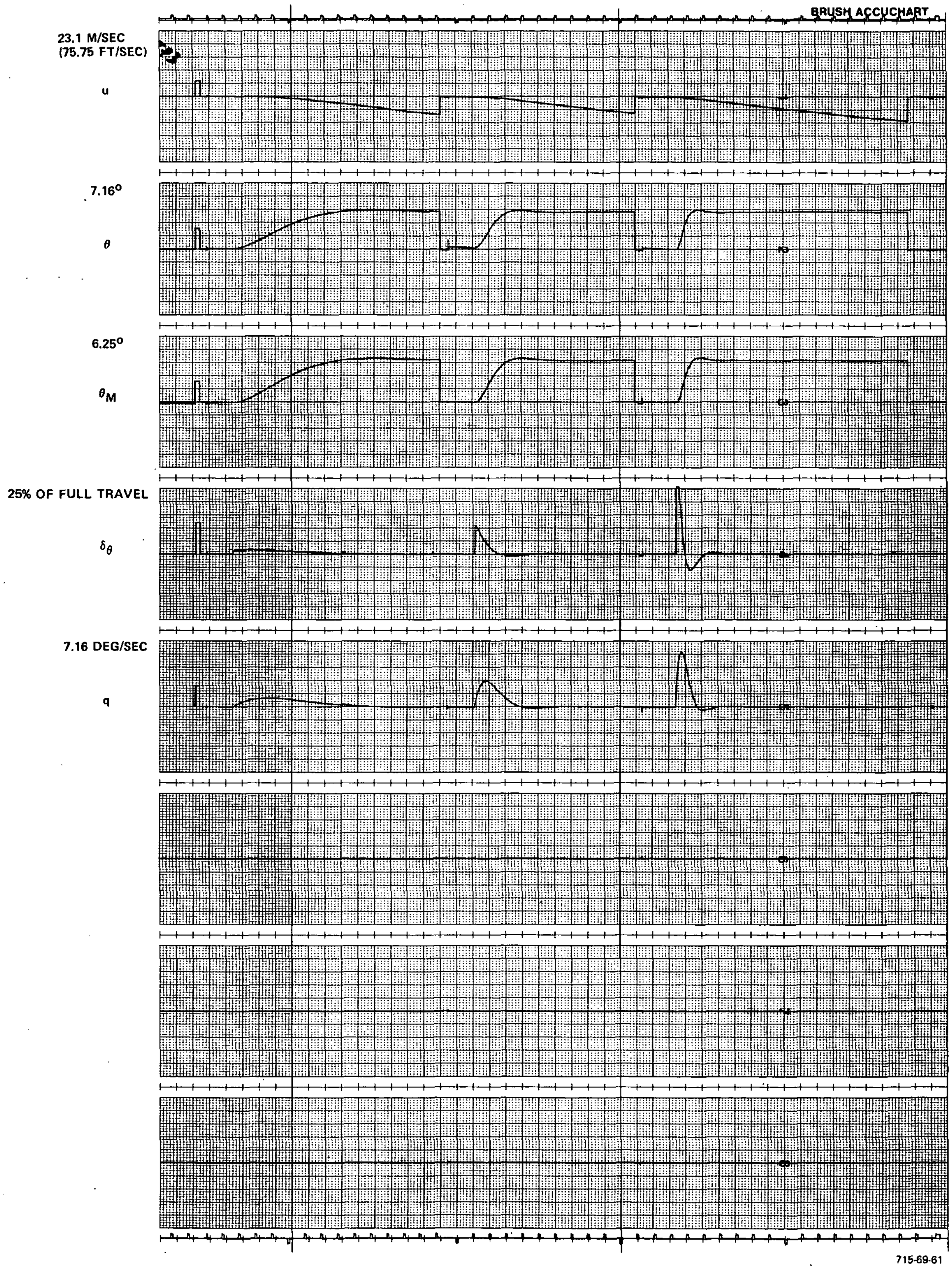


Figure 61
Variable Inner Loop Frequency

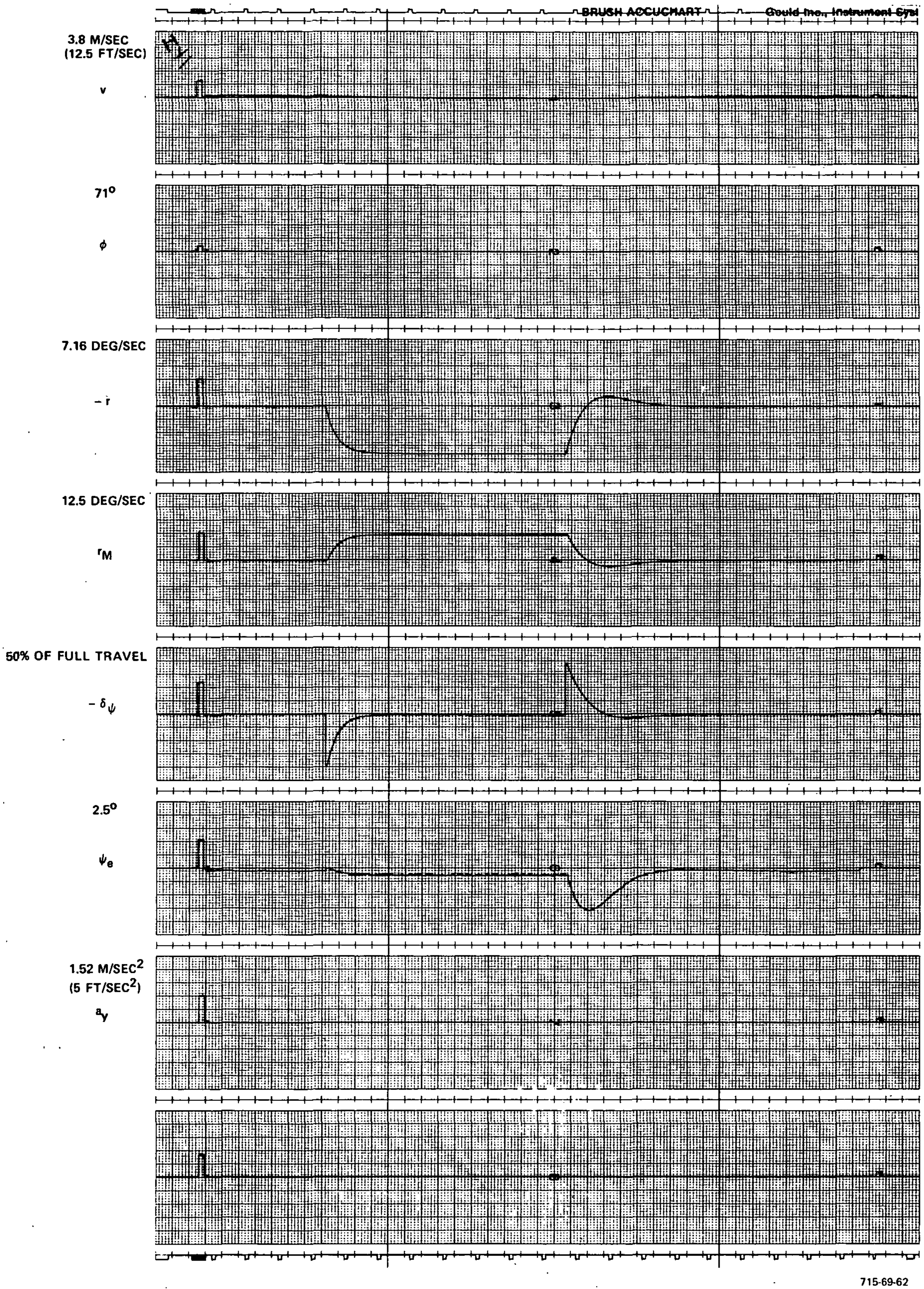


Figure 62
Yaw Inner Loop Response

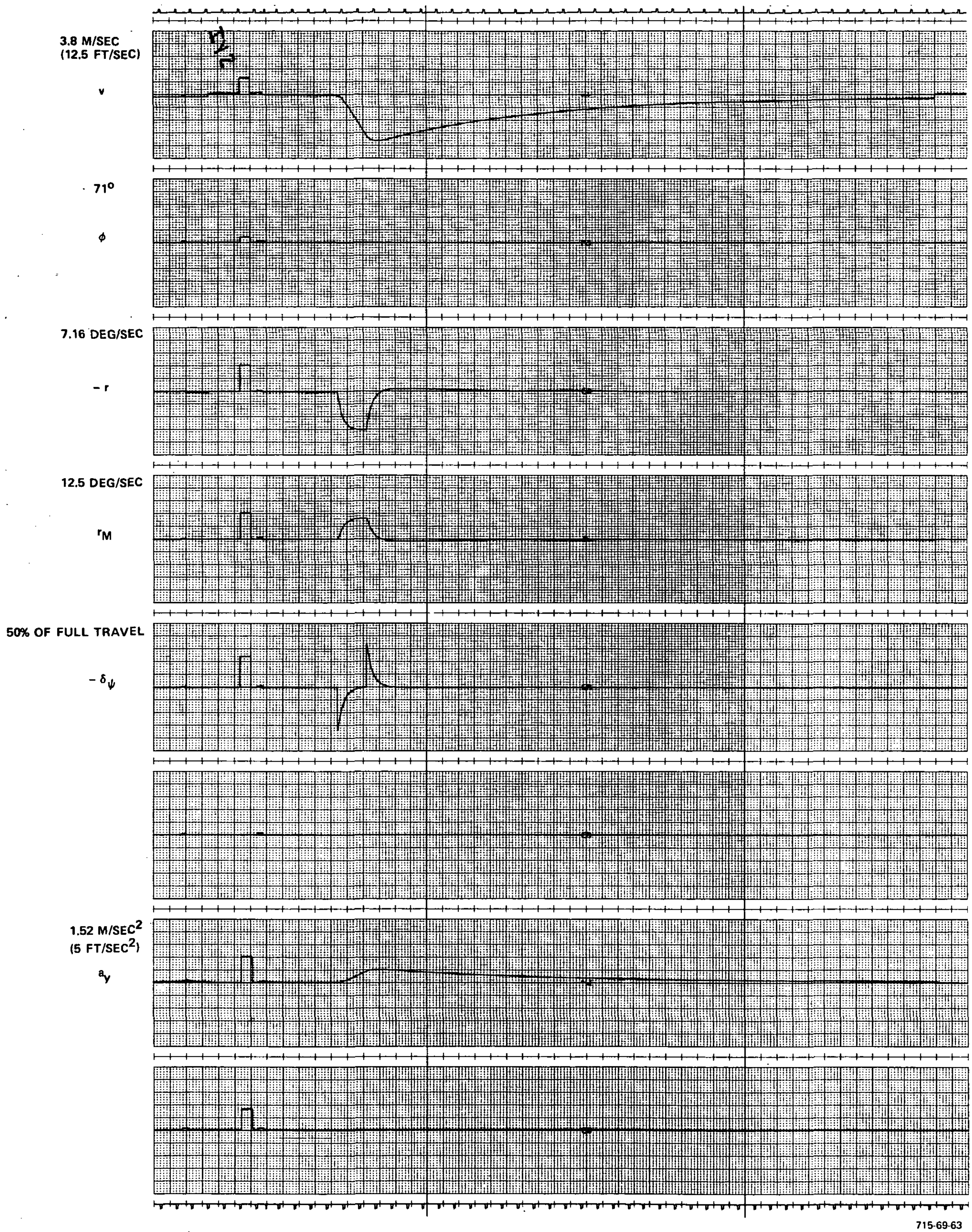


Figure 63
Yaw Inner Loop Pedal Command

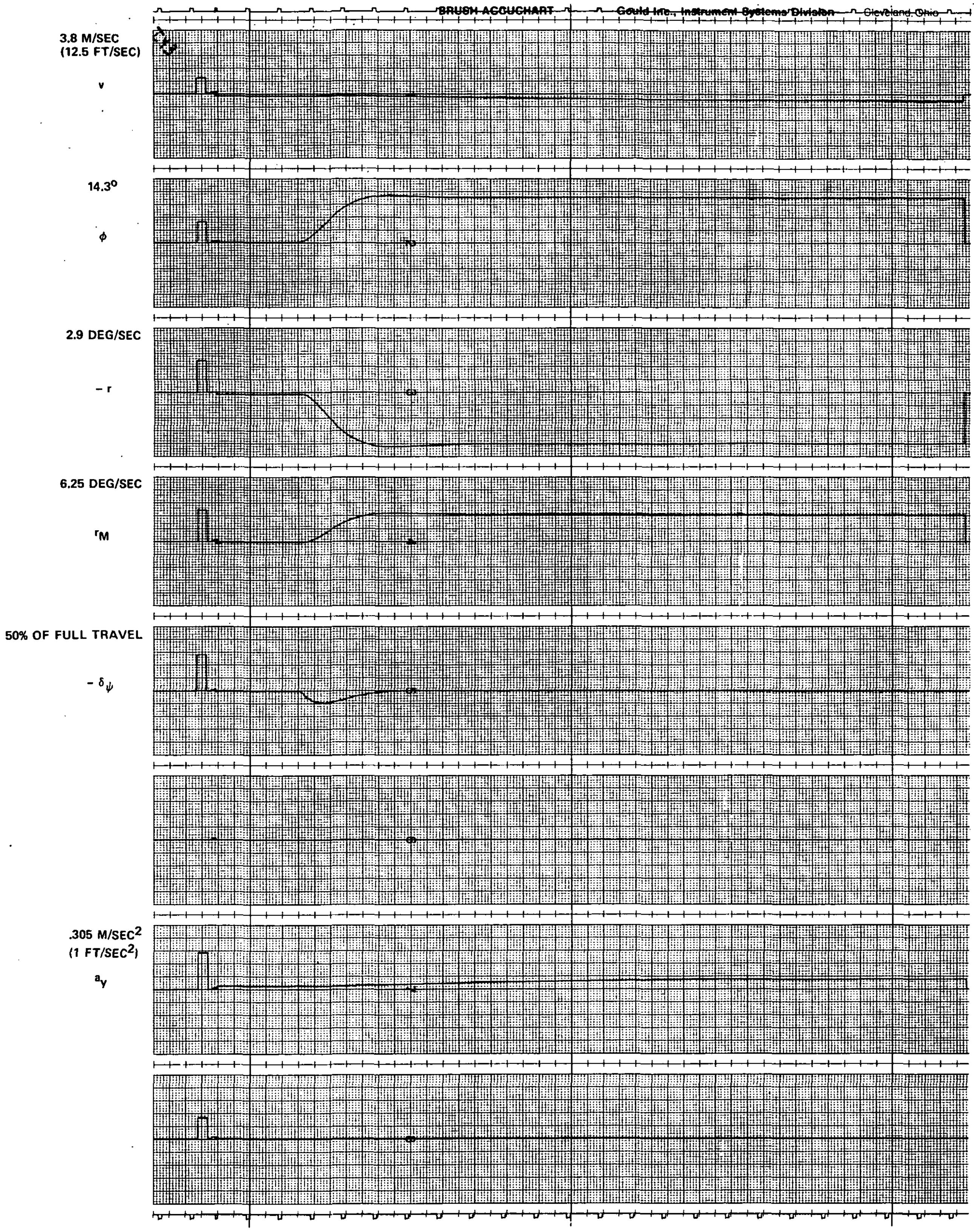


Figure 64
Yaw Inner Loop Bank Command

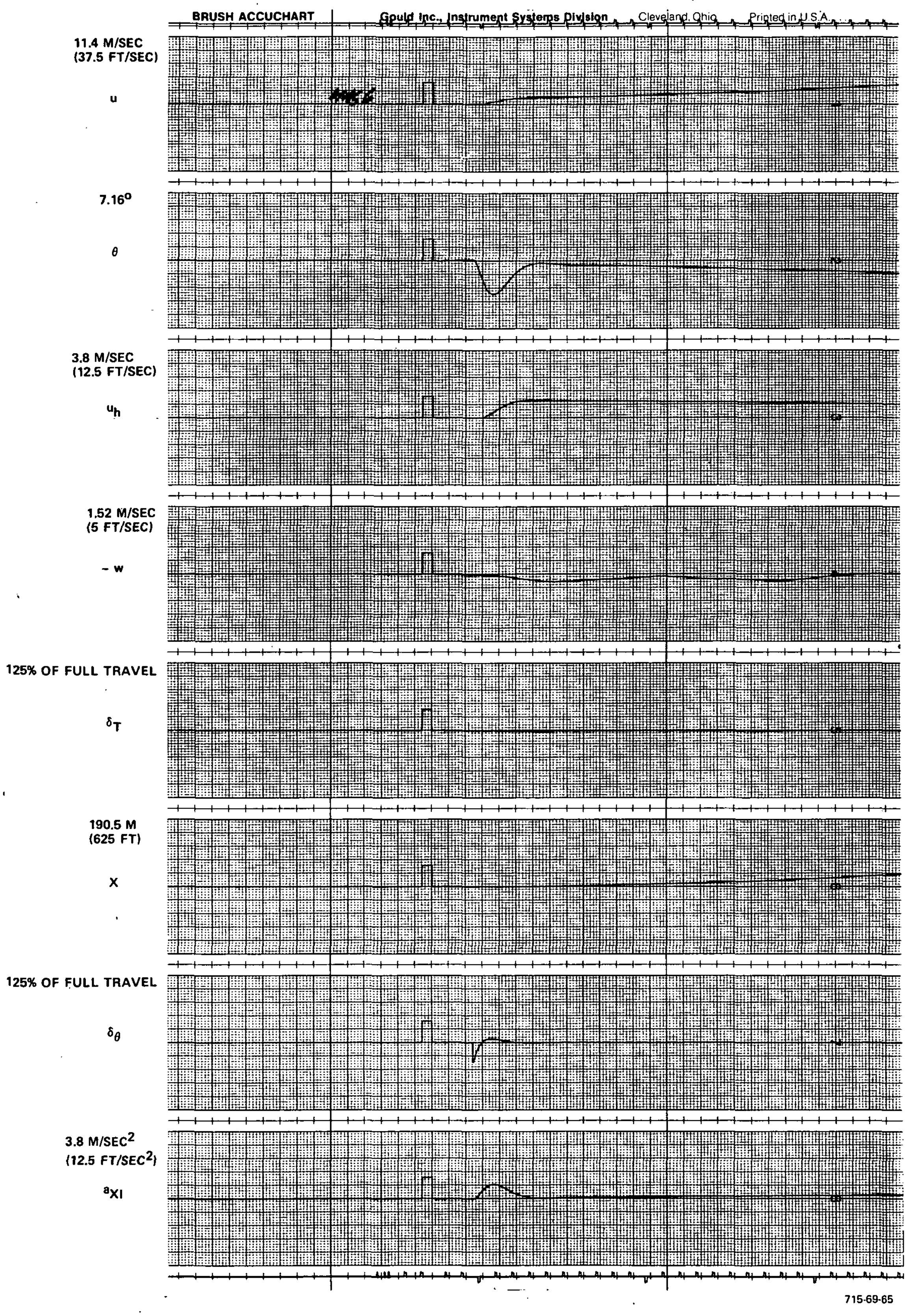


Figure 65
HAS Response

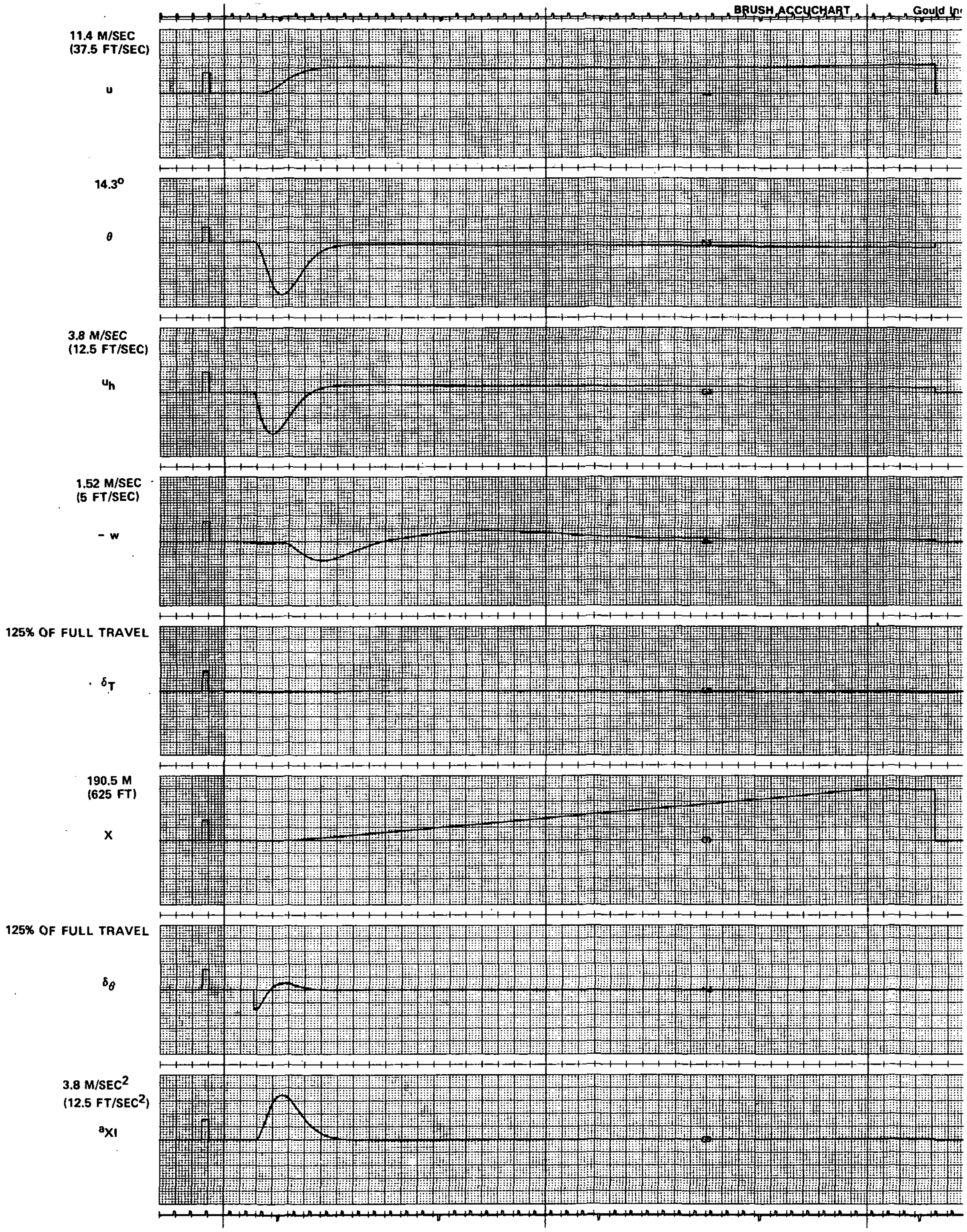


Figure 66
HAS 1 Second Velocity Response

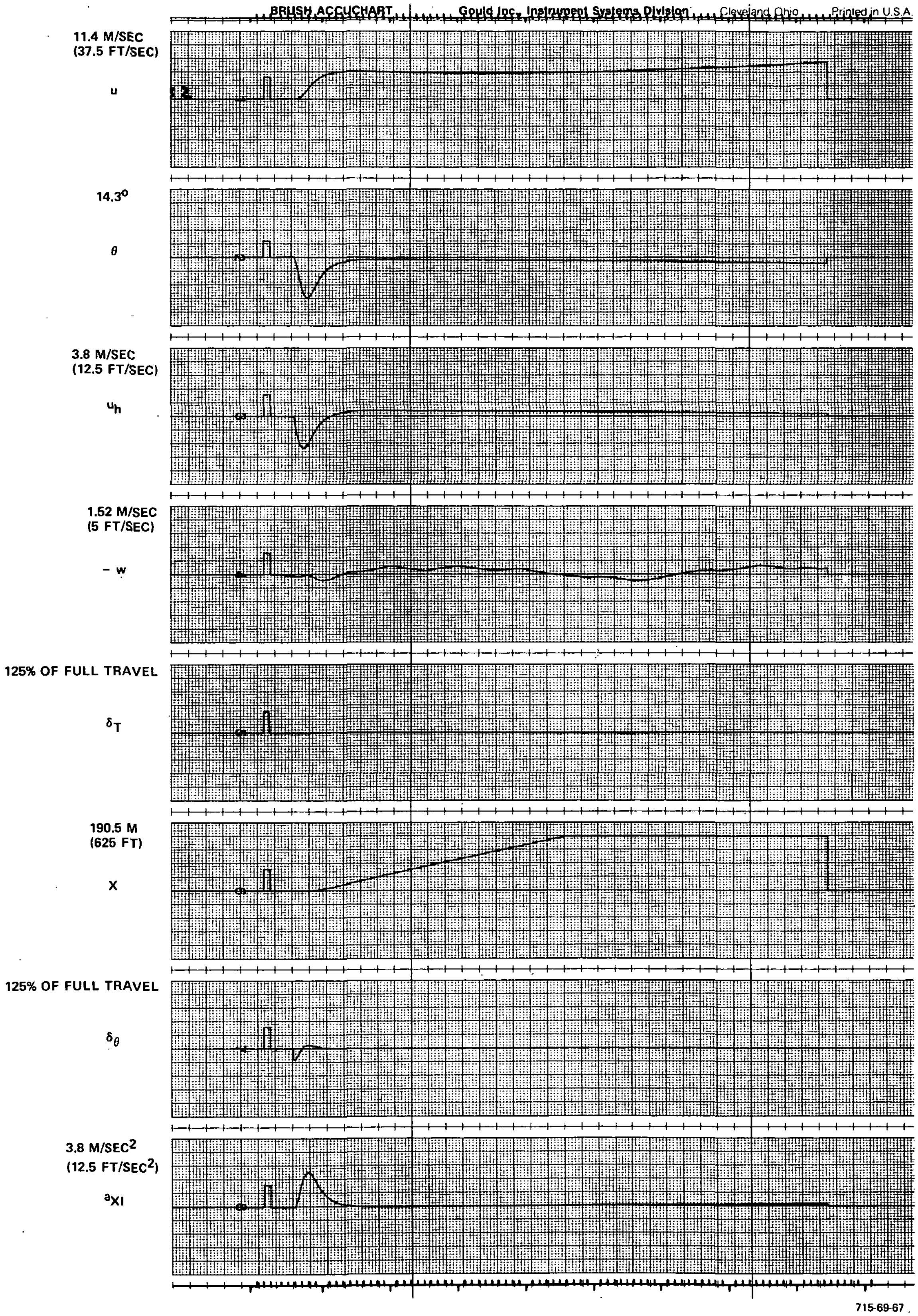


Figure 67
HAS 2 Second Velocity Response

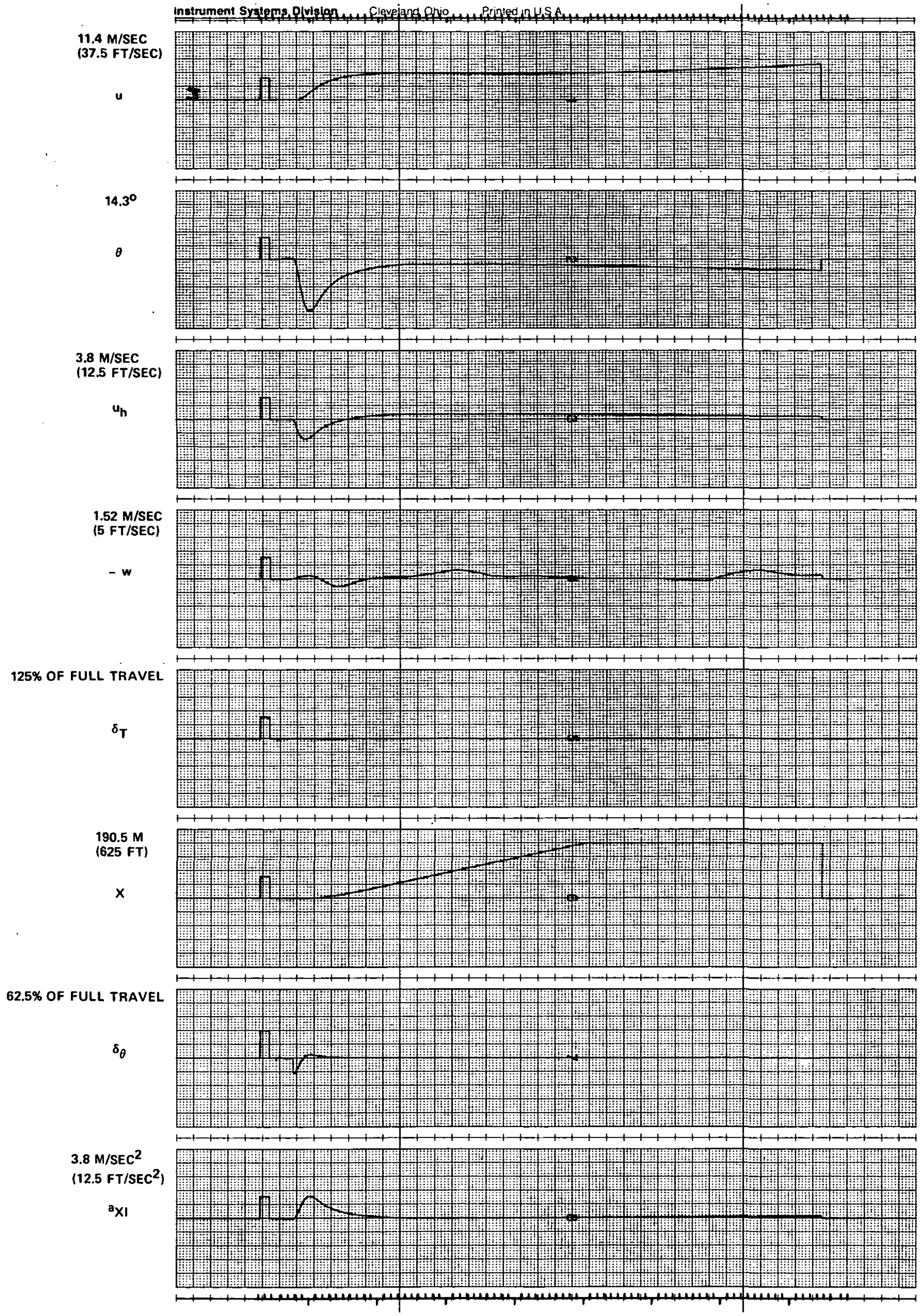


Figure 68
HAS 4 Second Velocity Response

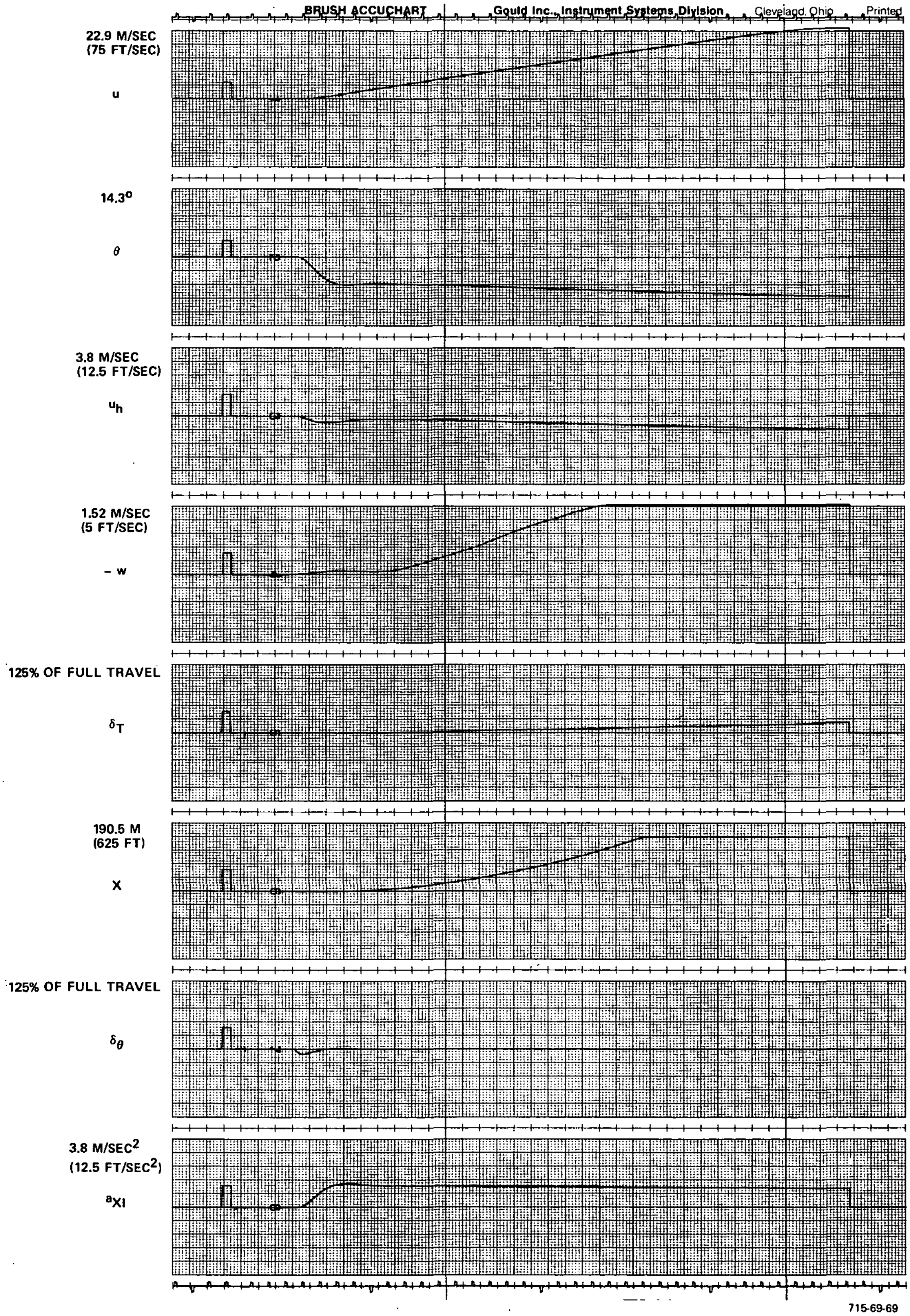


Figure 69
HAS With Attitude Response

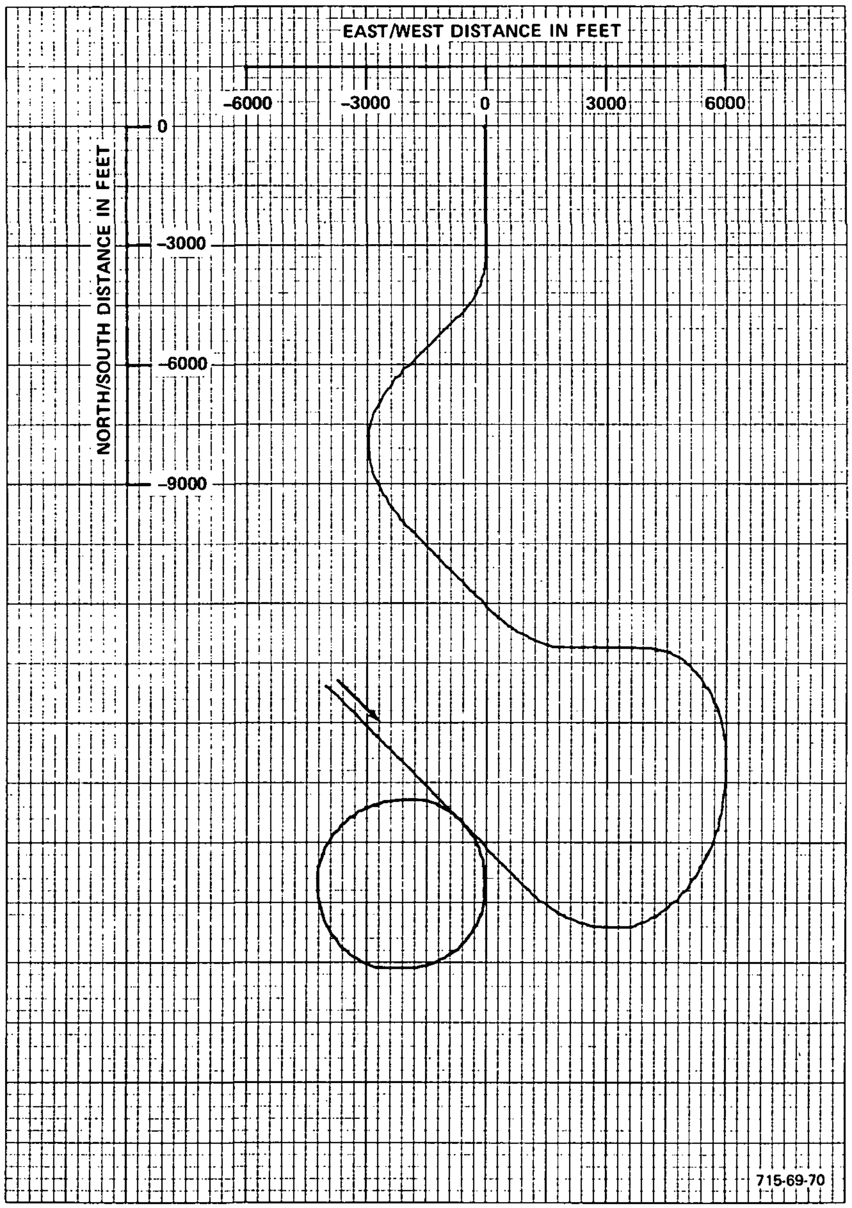


Figure 70
Path Plot Using LPPLOT Routine

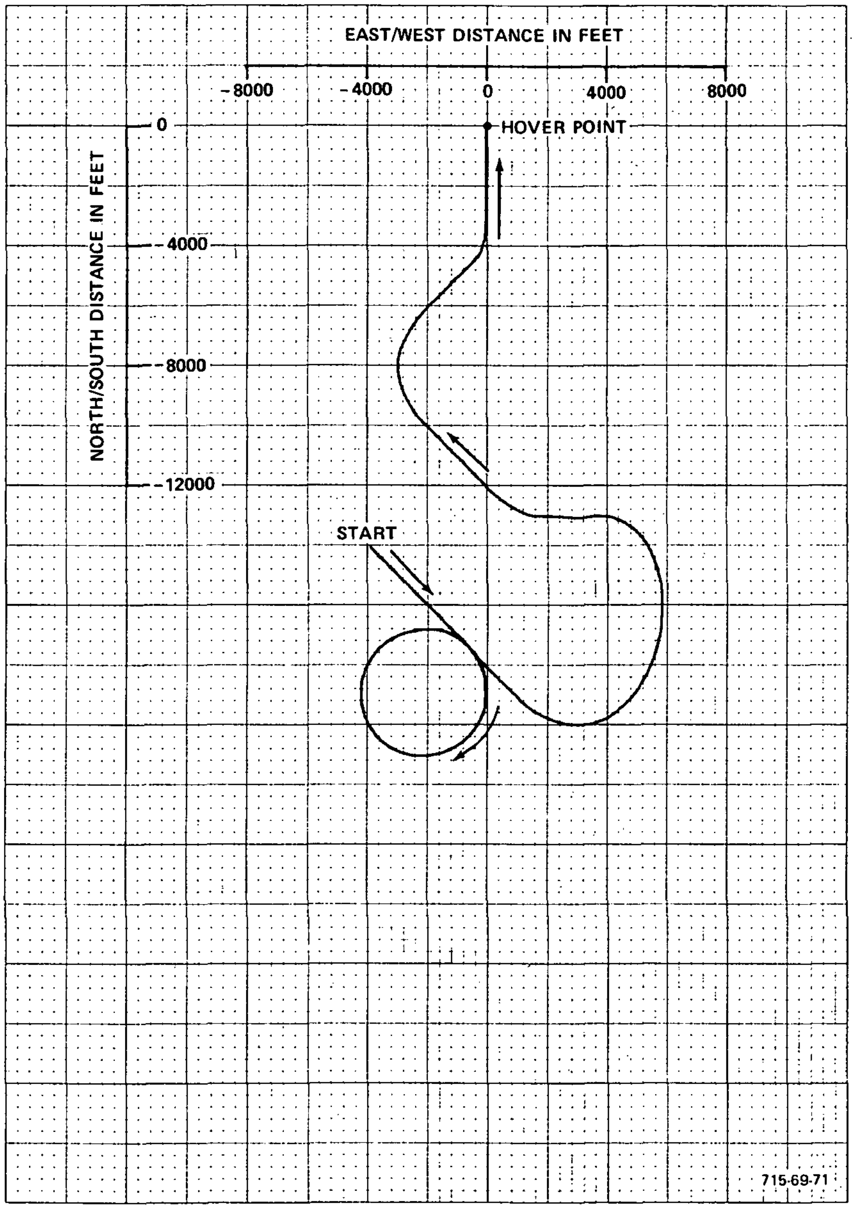


Figure 71
Simulated Flight Track

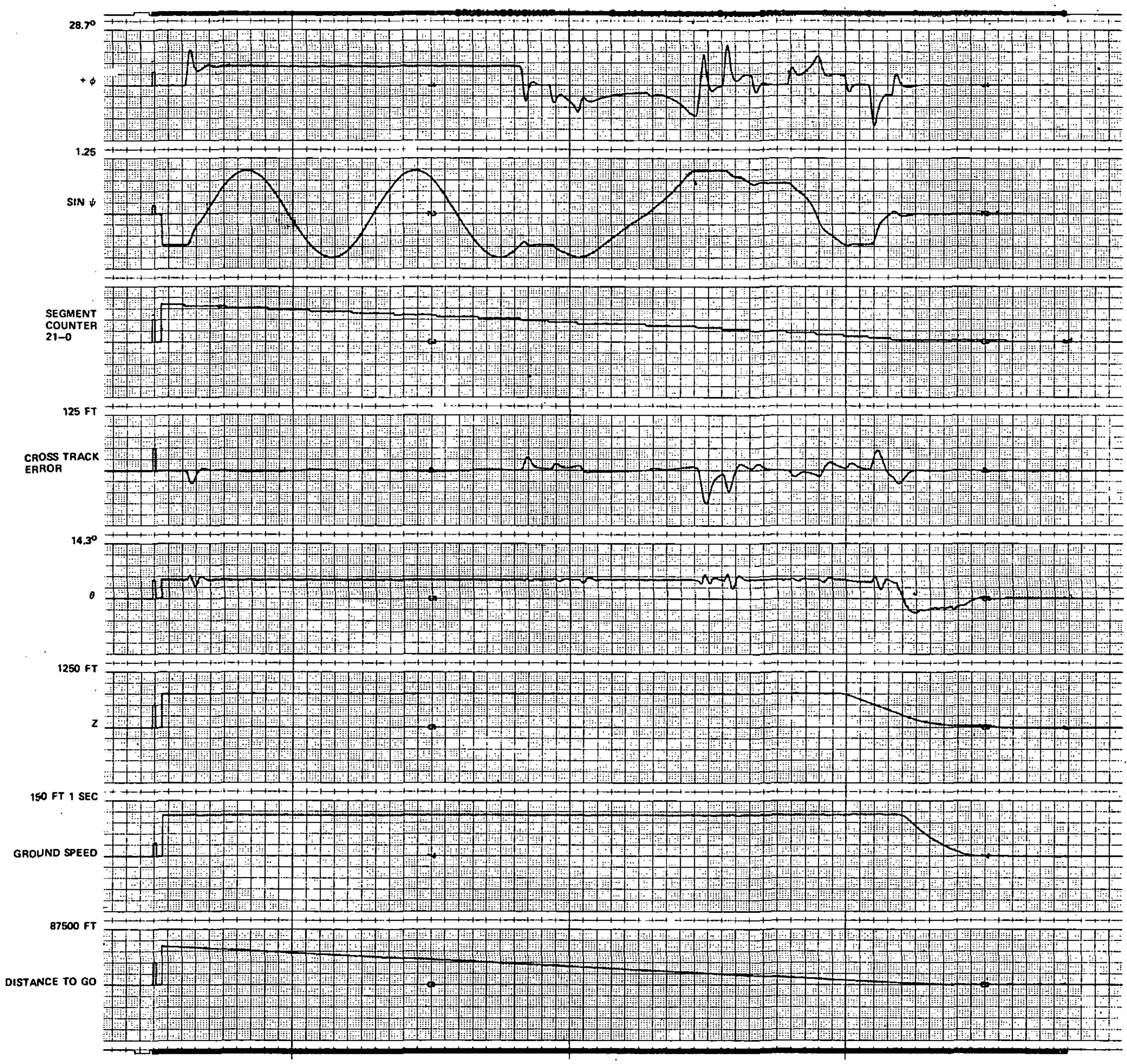


Figure 72
Simulated Flight Data

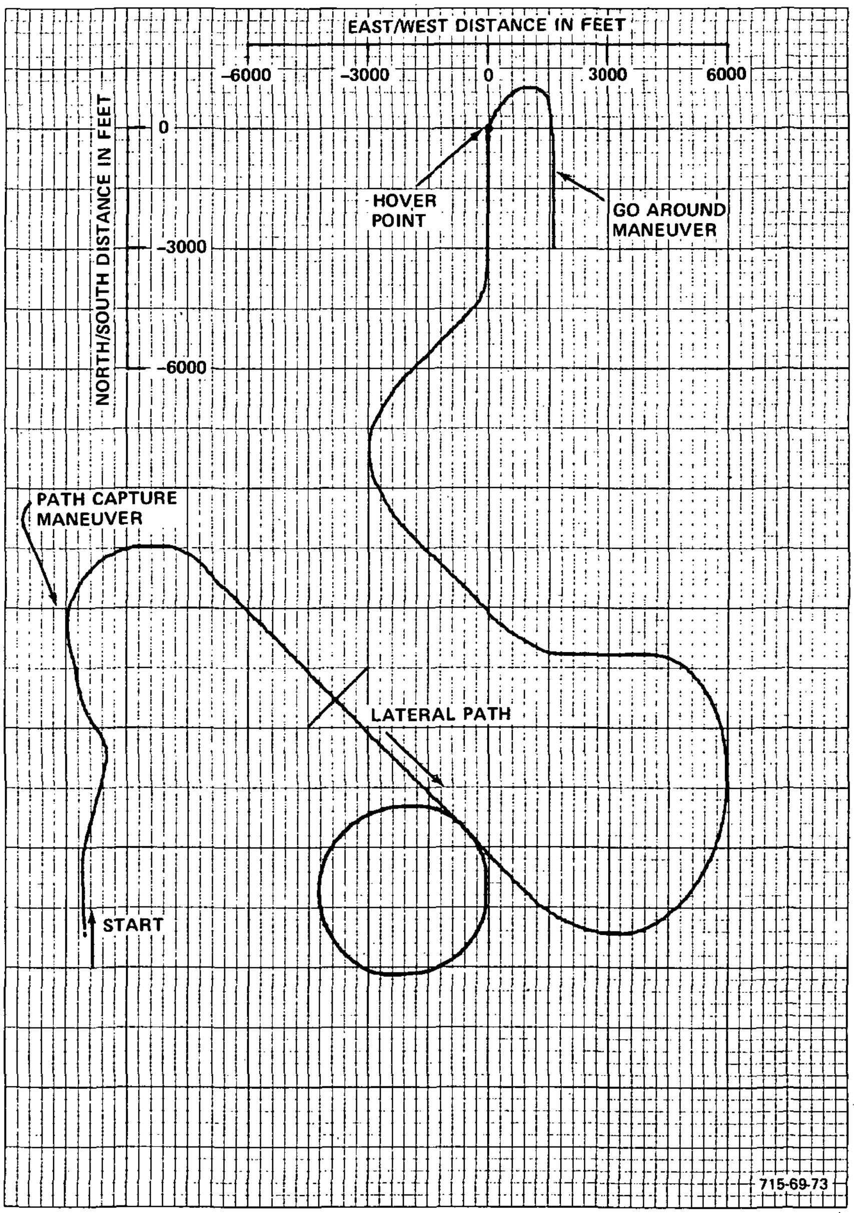


Figure 73
Path Initialization and Go-Around

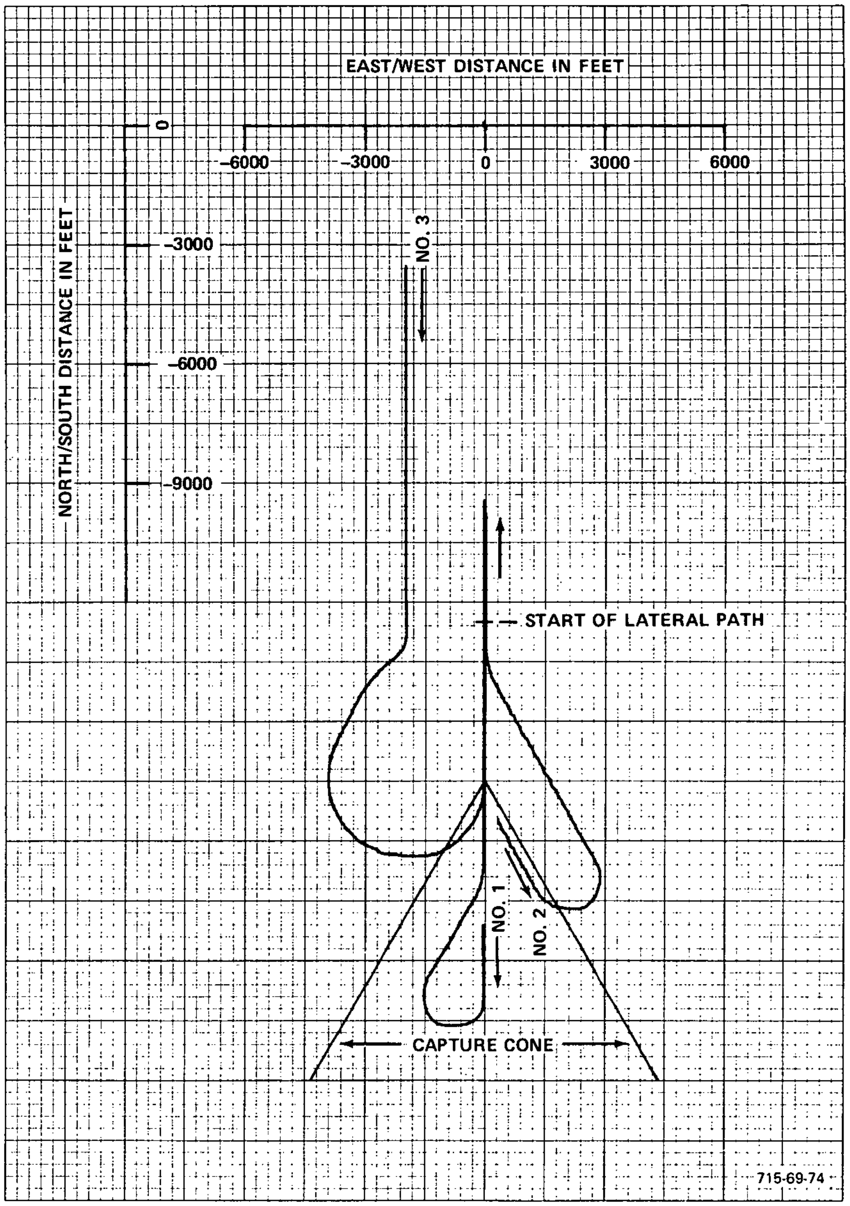


Figure 74
Path Capture

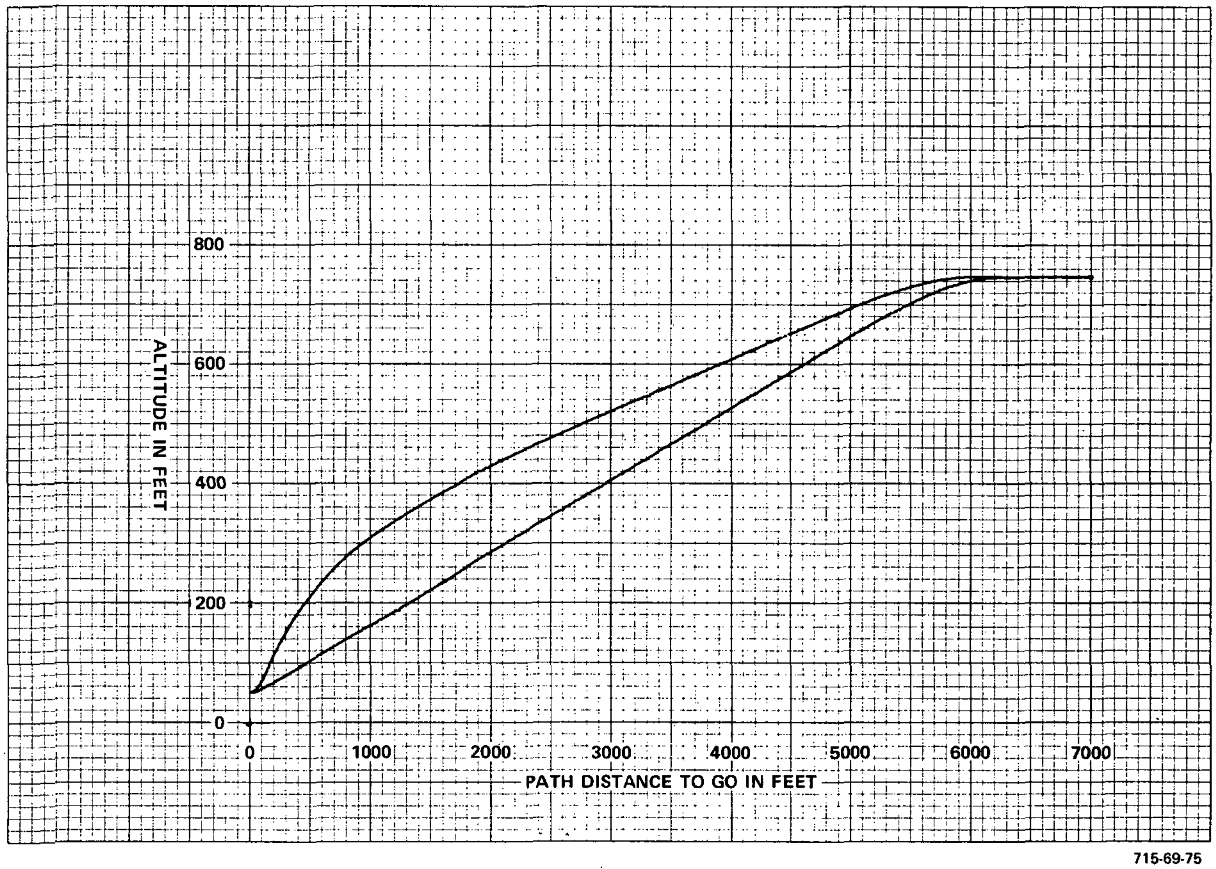


Figure 75
Altitude Profiles

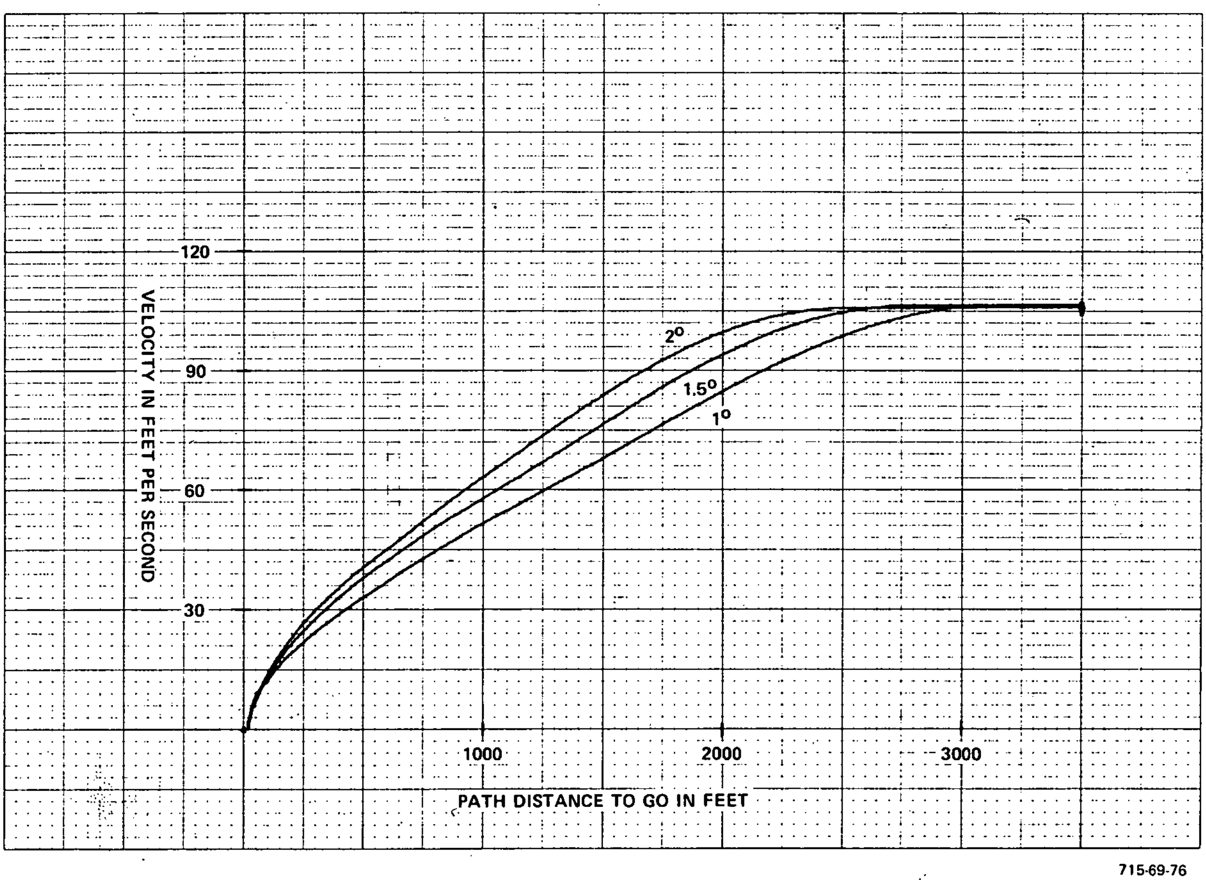


Figure 76
Velocity Profiles