NASA Technical Memorandum 74061

A DESCRIPTION OF THE SOFTWARE ANALYSIS FROM

FLIGHT AND SIMULATION DATA OF THE COURSE CUT LIMITER

IN THE TCV B-737 AREA NAVIGATION COMPUTER

(NASA-TM-74061) A DESCRIPTION OF THE SOFTWARE ANALYSIS FROM FLIGHT AND SIMULATION DATA OF THE COURSE CUT LIMITER IN THE TCV B-737 AREA NAVIGATION COMPUTER (NASA) 21 p HC A02/MF A01 CSCL 17G G3/04

N77-31125

Unclas 47836

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August 1977

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National Aeronautics and
Space Administration

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A DESCRIPTION OF THE SOFTWARE ANALYSIS FROM FLIGHT AND SIMULATION DATA OF THE COURSE CUT LIMITER IN THE TCV B-737 AREA NAVIGATION COMPUTER

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SUMMARY

During automatic horizontal path captures, the TCV B-737 airplane maintained smaller than designed path intercept angles and experienced a sawtooth bank angle oscillation during its turn towards the path. From flight data, it was determined that these anomalies were caused by the improper output of the course cut limiter in the horizontal path control law. The output from the course cut limiter did not obtain its full value and it was calculated stepwise discontinuously.

The automatic horizontal path captures were then conducted on the TCV B-737 airplane real-time simulation. The path intercept angles were maintained properly and no bank angle oscillation was encountered. Data showed that the course cut limiter was calculated at its full value in a continuous manner.

Though the navigation software in the airplane's computer and in the real-time simulation are written from the same control law algorithms, software organization is different. In addition, the airplane's navigation computer's word length is 24 bits compared to the real-time simulation's word length of 64 bits. Since more significant figures can be maintained in the real-time simulation because of its longer word length, it was believed that the calculations in the airplane's navigation computer may have been truncated such that the final output of the course cut limiter was adversely affected.

The intermediate calculations of the course cut limiter in the airplane's navigation computer were rewritten and rescaled in such a manner that truncation errors could be minimized. The horizontal path capture tests were then reflown. The airplane maintained the proper path intercept angle and no bank angle oscillations occurred on any of the tests. Hence, it was concluded that the reduced path intercept angles and bank angle oscillations were caused by truncation errors in the airplane's navigation computer.

INTRODUCTION

The NASA Terminal Configured Vehicle (TCV) Program was conceived to examine the compatibility of aircraft, advanced navigation and flight systems, and operational procedures for an advanced air traffic control system. The broad objectives of the TCV program include improving terminal area capacity and efficiency, improving approach and landing capability in adverse weather, and reducing noise through operational flight techniques. The program will accomplish these objectives through analysis, simulation, and flight research.

To accomplish the flight research in a realistic manner, the NASA acquired a twin-jet, commercial type transport airplane. This airplane is equipped with a separate, full-scale sized research flight deck, a digital guidance and control system, a digital navigation system, an advanced electronic display system, and an extensive data recording system.

A sophisticated real-time simulation of the research airplane was also acquired so that research activities and advanced flight concepts could be tested before flight. The simulator duplicates the features and operation of the research cockpit in the airplane. Nonlinear effects such as engine lag, varying stability functions, and control surface servo models are included in the simulation for realism.

To effectively utilize the airplane and its research systems during flight testing, it is essential that the airplane and the experimental systems' operational characteristics and effects on the flight experiments be known. During flights conducted to document the navigation, guidance, and automatic control systems characteristics, it was found that during horizontal path captures, the airplane flew towards the horizontal path at an intercept angle smaller than programed. It was also found that certain combinations of cross track error and track angle error would cause the airplane to develop a sawtooth bank angle oscillation during path captures.

The purpose of this report is to describe the software corrections and analysis for the anomolies encountered in the horizontal path capture documentation tests.

SYMBOLS

CRT	cathode ray tube
DME	distance measuring equipment
EADI	electronic attitude director indicator
EHSI	electronic horizontal situation indicator
g	acceleration of gravity constant, 9.81 meters/second
INS	inertial navigation system
K_Y, $K_{\dot{Y}}$	horizontal guidance control law gains
PADS	piloted aircraft data system
TKF	track angle error (see figure 5), degrees

TR	turn radius ($TR = VGS^2/g \tan 20^\circ$), meters
VGS	groundspeed, meters per second
XTK	cross track error (see figure 5), meters
4D	four dimensional flight (time referenced)
ϕ	bank angle, degrees

DESCRIPTION OF AIRPLANE AND EXPERIMENTAL SYSTEMS

General

The test airplane is a twin jet, commercial transport type aircraft shown in figure 1. Although the airplane is used as an experimental vehicle, all normal flight systems (flight control, navigation, pressurization, etc.) and conventional cockpit have been retained in a normal, functional state. This allows changes to occur to the experimental systems without effecting the operational safety of the airplane.

The experimental systems consist of a digital guidance and control system, a digital navigation system, and an electronic CRT display system integrated into a separate research cockpit. The research cockpit is full-sized (figure 2) and is located in the airplane cabin just forward of the wing. The research cockpit is configured for two-man crew flight operations. All of the airplane's primary flight control surfaces (pitch, roll, and yaw axes) may be operated directly from the research cockpit through the experimental flight control systems. Throttle, thrust reversers, flaps, and the radios may also be operated from the research cockpit. Speed brakes, auto brakes, and the landing gear position settings may be signaled from the research flight deck to the airplane's safety pilots in the conventional flight deck. The safety pilots must then engage these systems.

The airplane may be flown from the research cockpit manually, through two fly-by-wire control modes or with various degrees of automatic flight through the autopilot control mode panel shown in figure 3. Autopilot flight options range from track angle select, flight path angle select, and altitude hold options selectable through the control mode panel to fully automatic, preprogramed, 4-D flight. Autothrottle modes, based on either calibrated airspeed or programed groundspeed, may also be selected by the research pilots.

Each of the research pilots have three CRT displays for airplane attitude and navigation information and for addressing the navigation computer. The electronic attitude director indicator (EADI) display shows the pilot basic airplane attitude, flight path angle, potential flight path angle, and, at the pilot's discretion, flight director and navigation situation information. The electronic horizontal situation indicator (EHSI) display gives the pilot an electronically drawn map of pertinent navigation information (routes, nav-aids, etc.) relative to the airplane's position. The pilot may display other information such as other airports, obstacles, route altitudes and ground speeds, a time box for 4-D navigation, and airplane horizontal path prediction information. The third CRT display is used by the research pilots as an input/output display unit used to address the navigation computer.

Horizontal Guidance System

Figure 4 shows a simplified functional block diagram of the experimental navigation, guidance, and control systems on the airplane. Various navigation sensors (including DME, VOR, INS, etc.) are input to the navigation computer (a general purpose digital processor) which generates horizontal guidance commands based on its estimate of the airplane's position, velocity, and tracking errors from the programed path. Path tracking errors include cross track error (XTK) and track angle error (TKE) as shown in figure 5. The horizontal guidance commands are computed and transferred to the flight control computer system, which commands the flight control surface servos, 20 times per second.

Figure 6 is a functional block diagram of the horizontal guidance control law. The horizontal guidance control law was designed considering the airplane to be a simple, point mass, second order system (reference 2). Cross track error, track angle error, and groundspeed are combined to give a lateral acceleration command proportional to the horizontal guidance errors. During curved path segments, the nominal bank angle required to track the curved path with no wind and no lateral path error at the airplane's present groundspeed is added to the acceleration command.

The horizontal guidance acceleration command from the navigation computer is in the form of a bank angle command. Lateral acceleration is approximately equal to $g \tan(\phi)$ assuming coordinated turns.

The horizontal guidance control law gains, K_Y and $K_{\dot{Y}}$ are related as $K_Y = K_{\dot{Y}}^2/7.12$ to obtain a damping ratio of 1.0. A damping ratio of 1.0 causes the airplane to capture the path asymptotically. K_Y AND $K_{\dot{Y}}$ were held constant at 0.00275 and 0.14, respectively, through out the simulation and flight tests.

Though the same control law gains are used during both capture and tracking maneuvers, various limits have been added to the horizontal guidance control law to eliminate the possibility of one error signal masking another error signal. The final command transferred to the flight control computers is always limited to $\pm 25^{\circ}$ bank angle.

When large cross track errors are present the cross track error component of the final command signal would be so large it would mask the track angle error component and command the airplane to fly in a circle (never capturing the path). The course cut limiter restricts the cross track error component of the final command signal so that the airplane will capture a horizontal path according to the[1] intercept angle schedule shown in figure 7. The course cut limiter restricts the cross track error component by using the smaller of either the course cut limit or K_y times the cross track error. This causes the airplane to intercept the programed path on a 90° intercept angle if its cross track error is greater than 3.0 turn radii (TR). The path intercept angle is decreased linearly from 90° to 30° between cross track errors of 3.0 and 1.5 TR. The airplane will maintain the 30° intercept angle until the cross track error signal becomes less than the course cut limit, at which time an asymptotic capture is started. The turn radius is calculated 20 times per second and is a function of the airplane's present groundspeed and a 20° bank angle ($TR = VGS^2/g\tan\phi$).

Data Acquisition System

Data were recorded onboard the airplane on a wide-band magnetic tape recorder at 40 samples per second using Langley's Piloted Aircraft Data System. This data included ninety-three parameters describing the airplane's configuration, attitude, and control surface activity and an additional thirty-two separate parameters from the navigation computer. In addition, video recordings of the EADI and the EHSI displays were made throughout the flight.

Computer simulation data were recorded continuously on magnetic tape and strip charts. Thirteen parameters describing the airplane's attitude, position, and pertinent horizontal path control law variables were recorded.

DISCUSSION AND RESULTS

Flight Tests

To test the horizontal path control law, including the course cut limiter throughout its entire range, the horizontal path mode was engaged when the airplane's cross track error was greater than 4.0 TR and track angle error was approximately 179° towards the path (the airplane flying almost parallel to the path, but in the opposite direction). The expected initial airplane response was a turn to a 90° intercept angle towards the path. Then the airplane should follow the path intercept angle schedule shown in figure 7.

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1) Path intercept angle and track angle error are synonymous. However, path intercept angle is used when referring to the angle at which the airplane is to be flown to the path. Track angle error is used when referring to an error signal in the horizontal control law.

Figure 8 shows the flight test data for the horizontal path capture test conducted at approximately 300 knots groundspeed. In this case the initial conditions were a cross track error of 4.24 TR (27,379 meters), a track angle error of 179°, and an initial groundspeed of 295 knots. After the horizontal path mode was selected, the airplane rolled to a 25° bank angle turning the airplane towards a 90° intercept angle to the path as defined by the path intercept angle schedule (figure 7). However, bank angle rollout was not started until the track angle error was 93°. This resulted in the airplane rolling to an almost wings level attitude on a course intercept of 79° instead of 90°. As the cross track error decreased though 3.0 TR, the airplane started to decrease its course intercept angle from 79°. The data shows that the airplane rolled to a wings level attitude to maintain a 27° intercept angle instead of the expected 30° angle. The 27° intercept angle was held until an asymptotic capture was started. Figure 9 shows a comparison between the actual path intercept angle flown in the flight test and the programed path intercept angle.

Additional horizontal path capture flight tests at both 300 knots and 160 knots groundspeed resulted in the airplane consistently intercepting the path with an initial path intercept angle of approximately 78° rather than the designed intercept angle of 90° and a final intercept of 27° instead of the expected 30°.

During these flights, additional parameters in the horizontal path capture law, particularly those concerned with the course cut limiter, were recorded. It was found that the magnitude of the course cut limiter being calculated in the navigation computer was approximately 85% of its designed value. This caused the airplane to fly intercept angles less than the programed schedule.

The second anomaly encountered during the test flight was a sawtooth bank angle oscillation as the airplane decreased its intercept angle from 90° to 30° (figure 8). Flight data (figure 10) showed the course cut limit was being calculated step-wise discontinuously when the cross track error was between 3.0 TR and 1.5 TR for no apparent reason. This caused the navigation computer to command a roll oscillation since the magnitude of the course cut limiter was less than the cross track error signal and the sum of the bank angle command components due to cross track error and track angle error was 25°, or less.

Figure 10 shows a path capture where the first two discontinuous steps of the course cut limiter were masked by the lower values of the cross track error signals. Thus bank angle command was smooth. However, the last two discontinuous steps of the course cut limiter caused the bank angle command to produce two sawtooth spikes. The course cut limit was not constant for a cross track error great than 3.0 TR since the limit is a function of groundspeed which varied slightly during thetest because of wind and autothrottle fluctuations.

Simulator Tests

A simulation study was conducted to determine if the problems encountered during the horizontal path captures were caused by control law design errors or by software implementation. Since the simulation used the same control law algorithms, but not the same software implementation, a duplication of the roll oscillation and reduced path intercept angle during a path capture would indicate that a problem existed in the control law design. If the errors were not encountered in the simulation, then software implementation could be the source of error.

The initial conditions (cross track error, track angle error, and groundspeed) used in the path captures tests conducted in the simulator were approximately the same as those used in flight. Additional tests, at different groundspeeds, were also conducted. Path intercepts were flown from both sides of the path.

Figure 11 show the results of a typical simulator path capture. The initial conditions were a cross track error of 4.73 TR (23,208 meters), a track angle error of 179°, and a groundspeed of 257 knots. When the horizontal path capture was started, the simulated airplane rolled into a 25° bank turning towards the path. At a track angle error of 113°, the simulated airplane started to decrease its bank angle to a wings level attitude. A wings level attitude was obtained with a track angle intercept of approximately 90°. This intercept angle was maintained until the cross track error was 3.0 TR (14,720 meters). At 3.0 TR, the simulated airplane turned to decrease its path intercept angle. The airplane rolled to a wings level attitude at a cross track error of 1.5 TR (7359 meters) and a path intercept angle of 30°. This intercept angle was maintained until the asymptotic capture was started at 0.72 TR (3529 meters).

The data from this path capture shows that the control law functions as designed. Additional path captures at other groundspeeds with the simulated airplane yielded similar results. At no time did a roll oscillation occur during the captures. The airplane always maintained the appropriate programed intercept angle. Hence, it was concluded that the roll oscillation and the improper path intercept angles were caused by software implementation in the airplane rather than improper control law design.

Software Analysis and Verification Flight Test

The software concerning the calculation of the course cut limiter and its intermediate calculations in the navigation computer were determined to be mathematically correct. However, word length in the airplane's navigation computer is only 24 bits which can result in the truncation of significant digits when manipulating large or small numbers. This problem did not occur in the real-time simulation where the computer word length is 64 bits.

The airplane's navigation computer software was reprogramed with particular attention given to equation manipulations so that truncation errors would be minimized. This was accomplished by appropriately scaling numbers and solving the course cut limiter equation such that very large or very small intermediate values which could cause round-off errors would be eliminated. The horizontal path capture tests were then reflown to test the revised software.

Figure 12 shows the results of a horizontal path capture flight test with the revised software. The initial conditions were a cross track error of 4.06 TR (44,196 meters), a track angle error of 176°, and a groundspeed of 383 knots. The airplane rolled to a 25° bank angle towards the path when the horizontal path capture was started. The airplane turned towards the path and rolled to a wings level attitude on a 90° path intercept angle. When the cross track error was reduced to 3.0 TR (26,216 meters), a turn was started and the intercept angle was reduced to 30°. The 30° path intercept angle was held until the asymptotic capture was started.

The airplane intercepted the horizontal path according to the path intercept angle schedule (figure 7) on all subsequent path capture flight tests. In addition, no bank angle oscillations occurred. Hence, it can be concluded that the bank angle oscillations and the reduced path intercept angles encountered during path captures were caused by truncation errors in the airplane's navigation computer.

CONCLUDING REMARKS

Truncation errors generated during intermediate manipulations in the area navigation computer, particularly when combining relatively large numbers with small numbers, can adversely affect the results of the final calculation. This paper illustrates the importance of the order of intermediate calculations and number scaling. Particular attention must be addressed to this problem during software implementation.

REFERENCES

1. McKinstry, R. G.: Guidance Algorithms and Non-Critical Control Laws for ADEDS and the AGCS. D6-41565, The Boeing Company, 1974.

FIGURE 1-TWIN JET, COMMERCIAL TYPE TRANSPORT TEST AIRPLANE

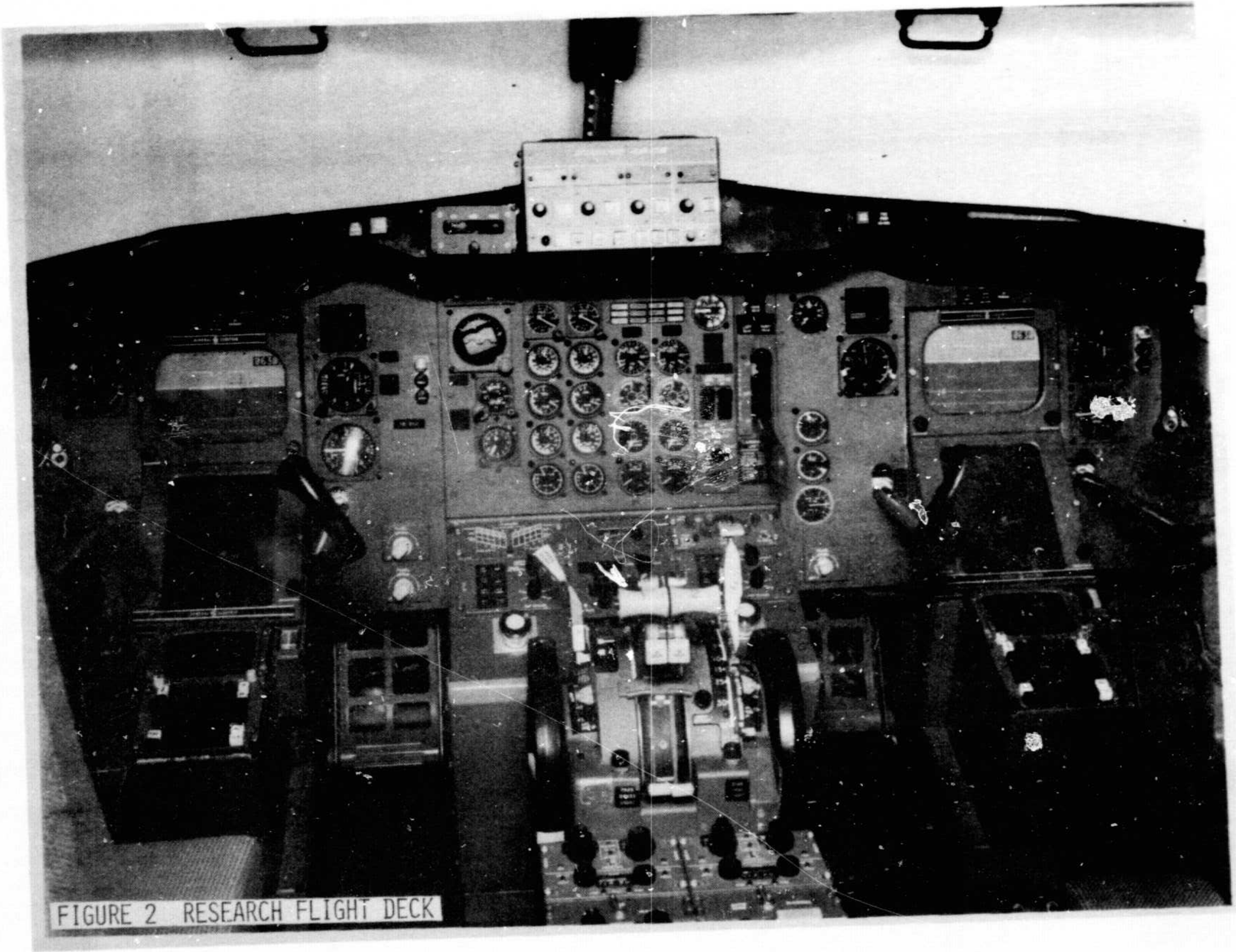


FIGURE 2 RESEARCH FLIGHT DECK

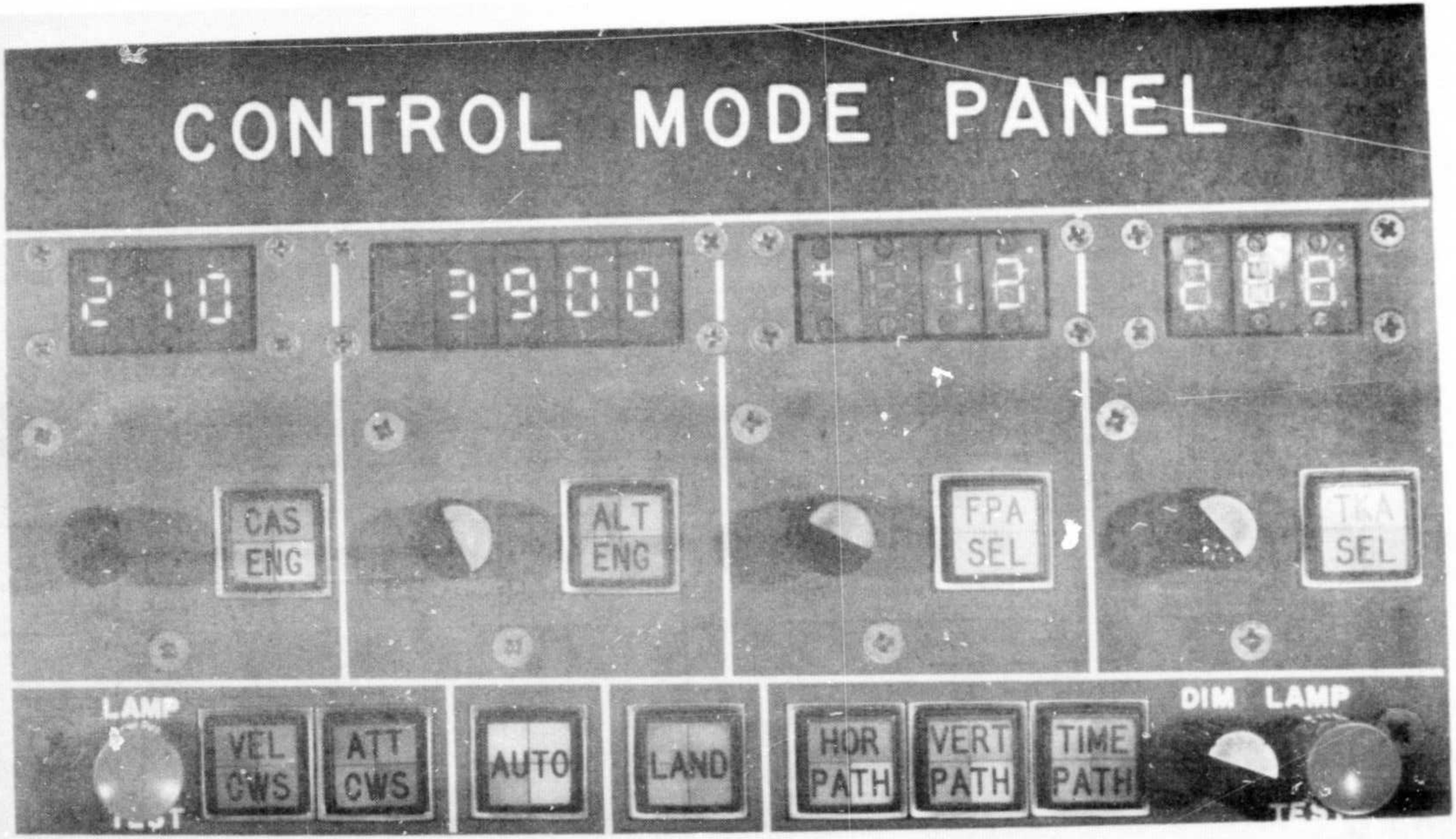


FIGURE 3 AUTOPILOT CONTROL MODE PANEL

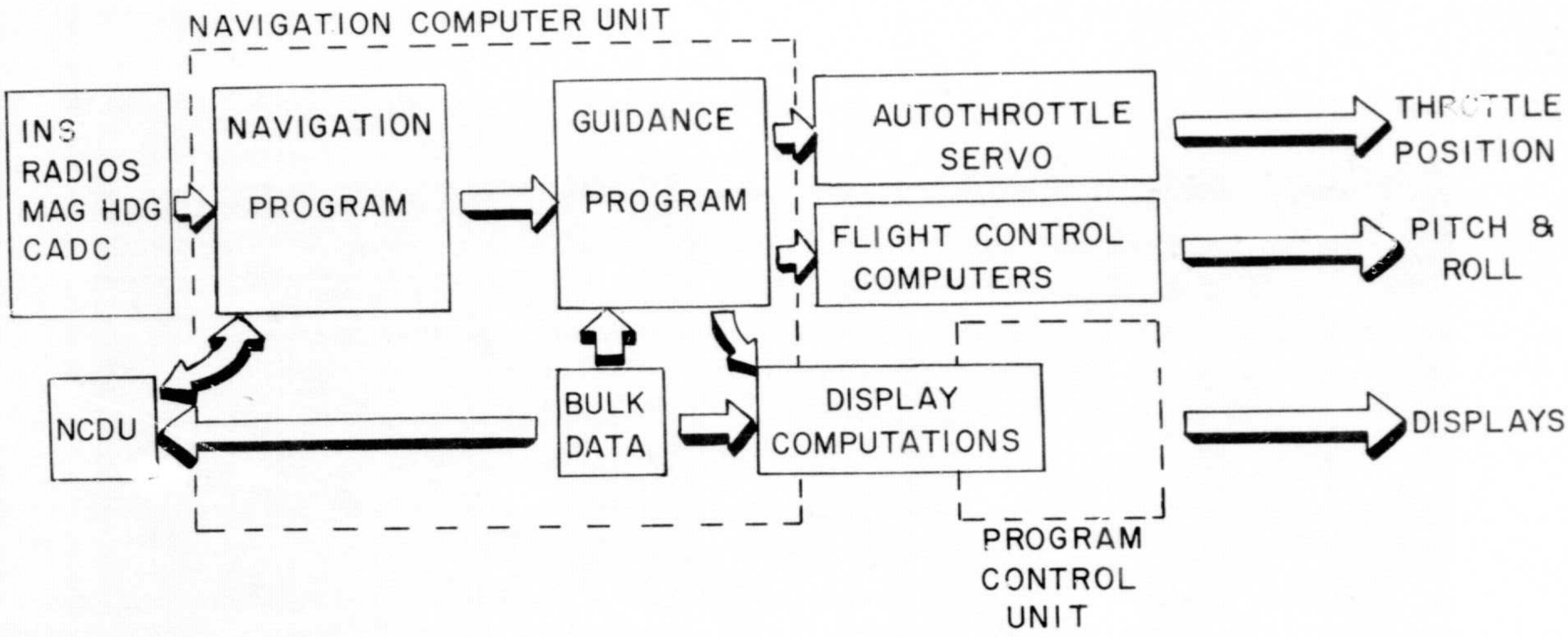
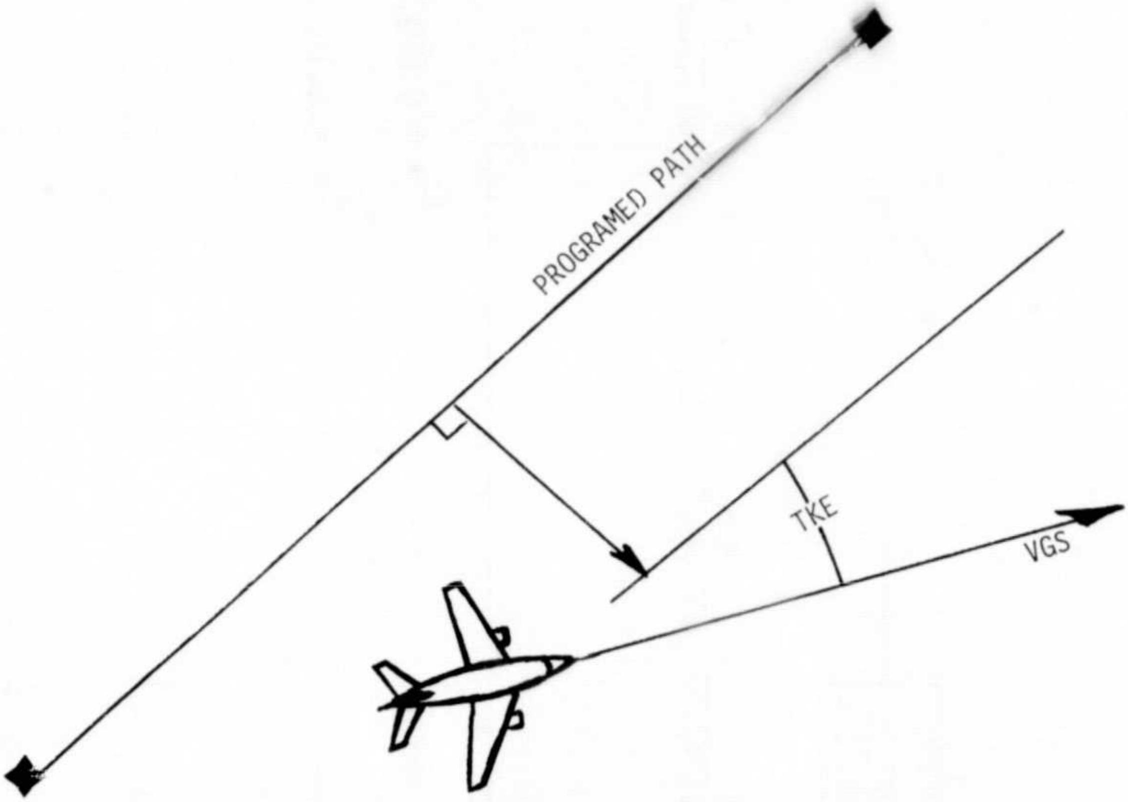


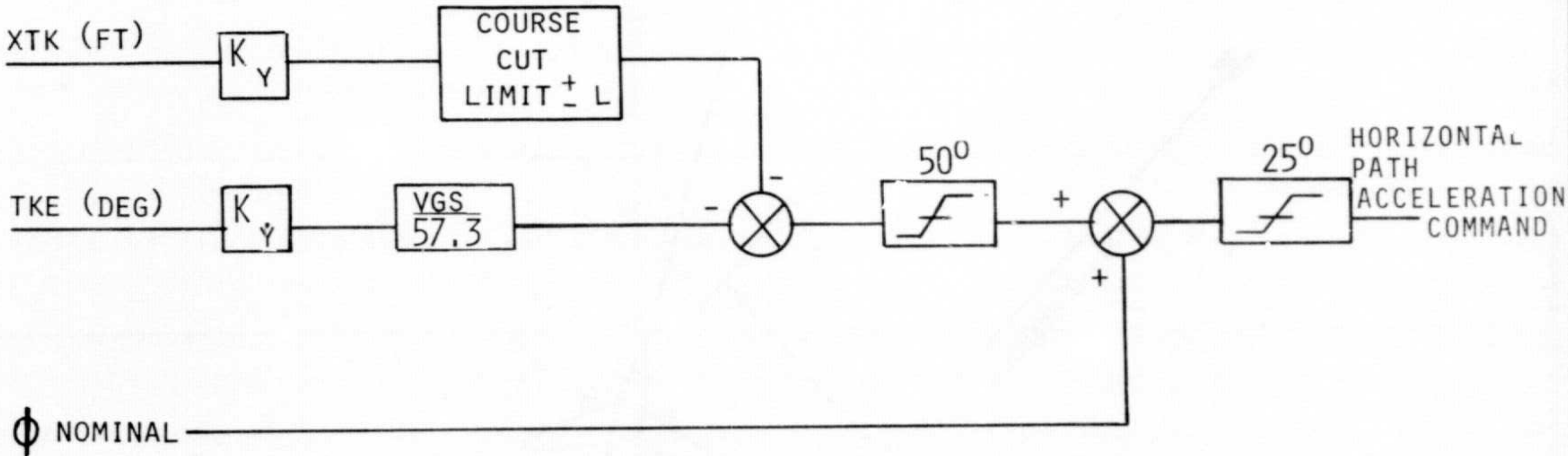
FIGURE 4 NAVIGATION, GUIDANCE AND CONTROL SYSTEMS



XTK CROSS TRACK ERROR
TKE TRACK ANGLE ERROR

ERRORS ARE POSITIVE AS SHOWN

FIGURE 5
PATH TRACKING ERRORS



$L = \frac{VGS\ K_{\dot{Y}}}{57.3}\ \psi_I$ IN WHICH

$$\psi_I = \begin{cases} 30^0 & \text{FOR } X < 30^0 \\ 90^0 & \text{FOR } X > 90^0 \\ X & \text{OTHERWISE} \end{cases}$$

$$X = \frac{470\,|XTK|}{(VGS)^2} - 30$$

$K_Y = 0.00275$

$K_{\dot{Y}} = 0.14$

FIGURE 6

HORIZONTAL CONTROL LAW BLOCK DIAGRAM

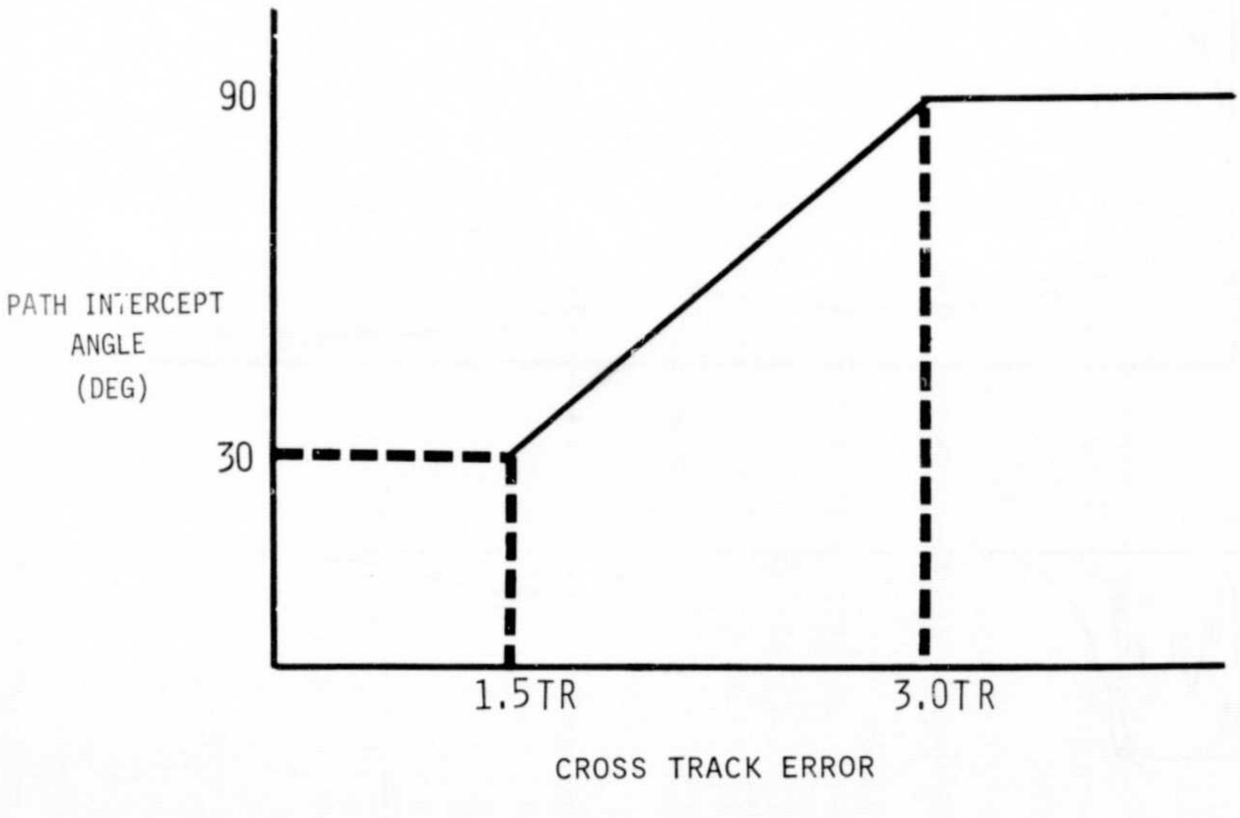


FIGURE 7
COURSE INTERCEPT LIMIT SCHEDULE

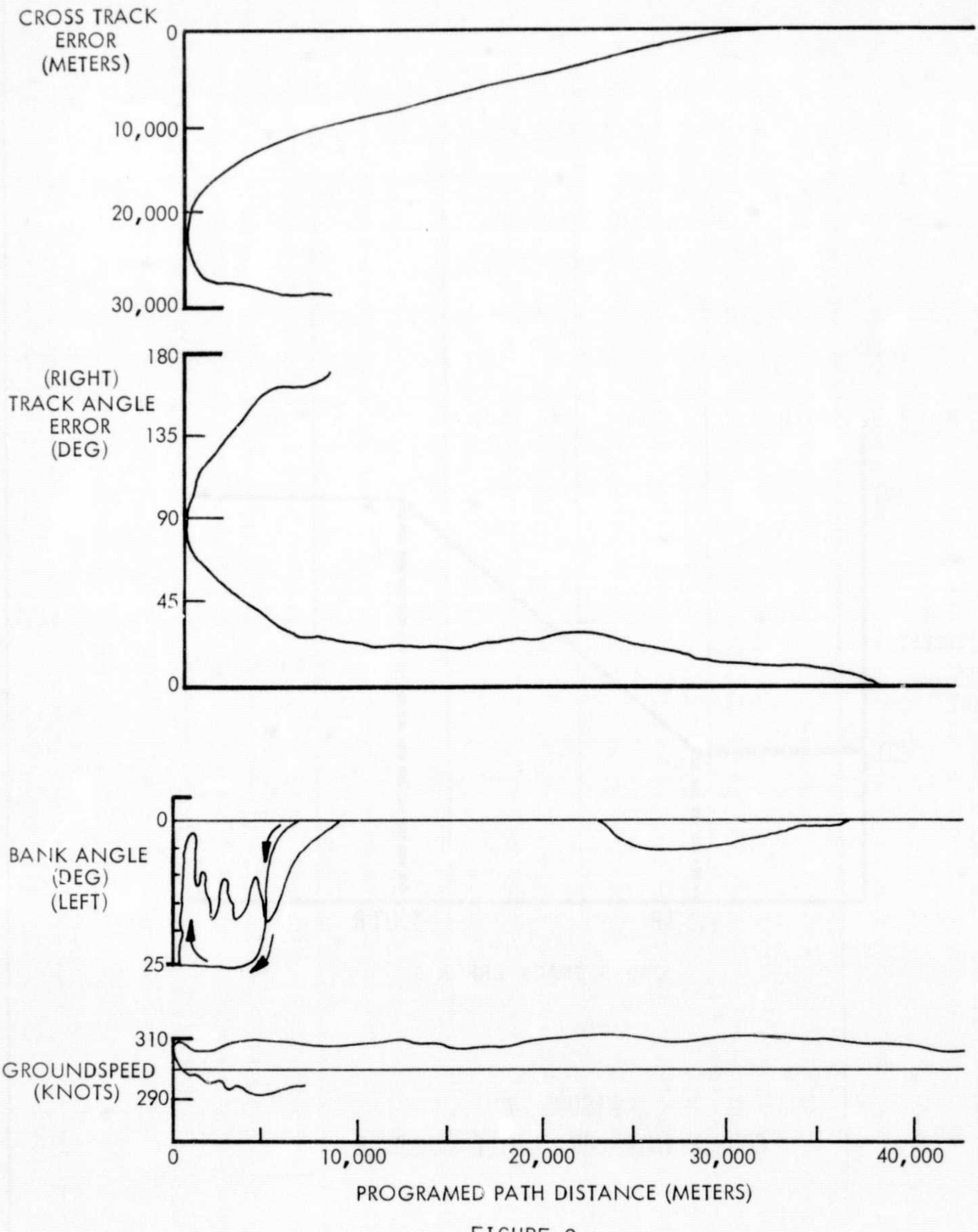


FIGURE 8

HORIZONTAL PATH CAPTURE TEST - AIRPLANE

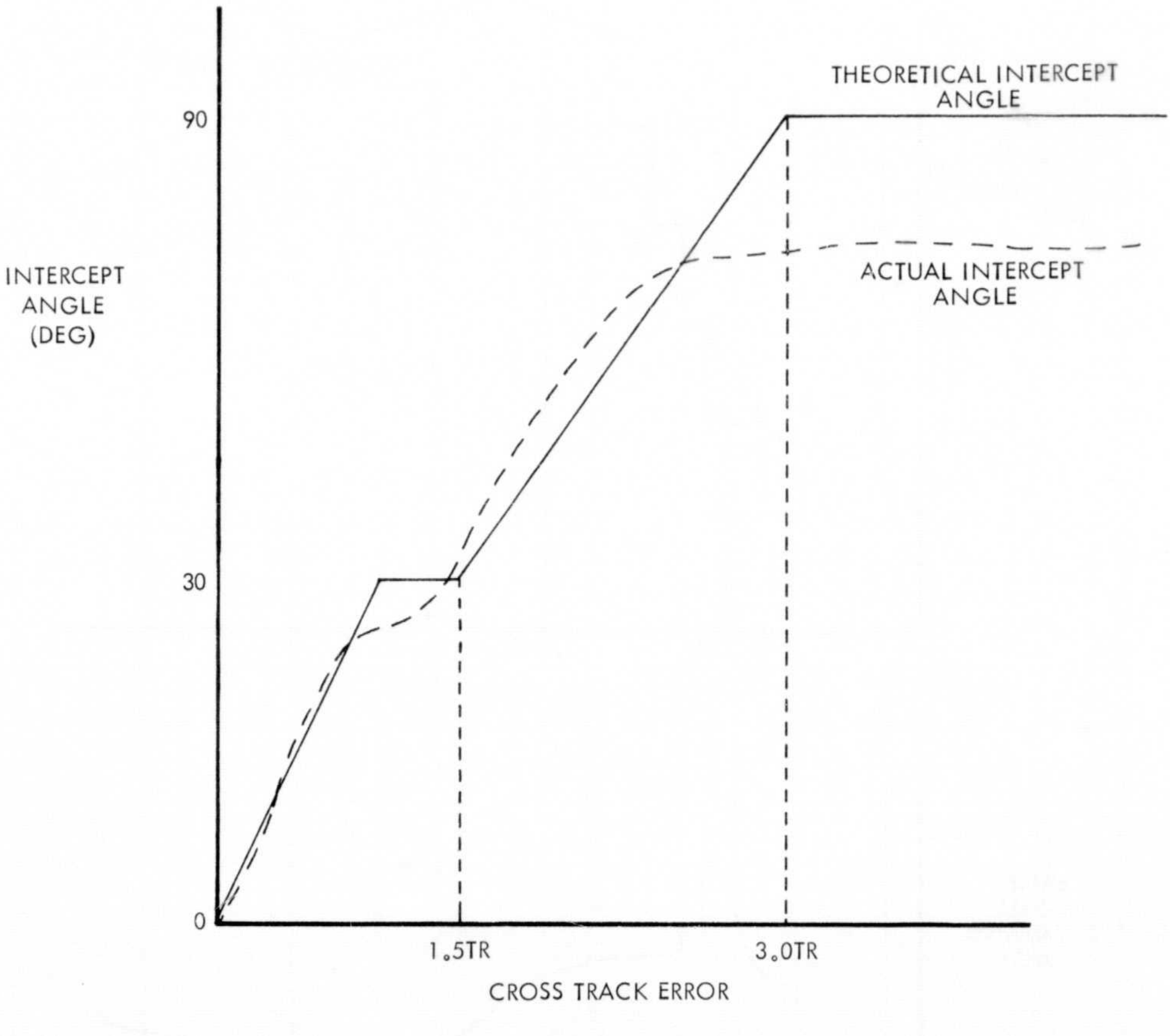


FIGURE 9

THEORETICAL INTERCEPT ANGLE AND ACTUAL INTERCEPT ANGLE DURING A HORIZONTAL PATH CAPTURE - AIRPLANE

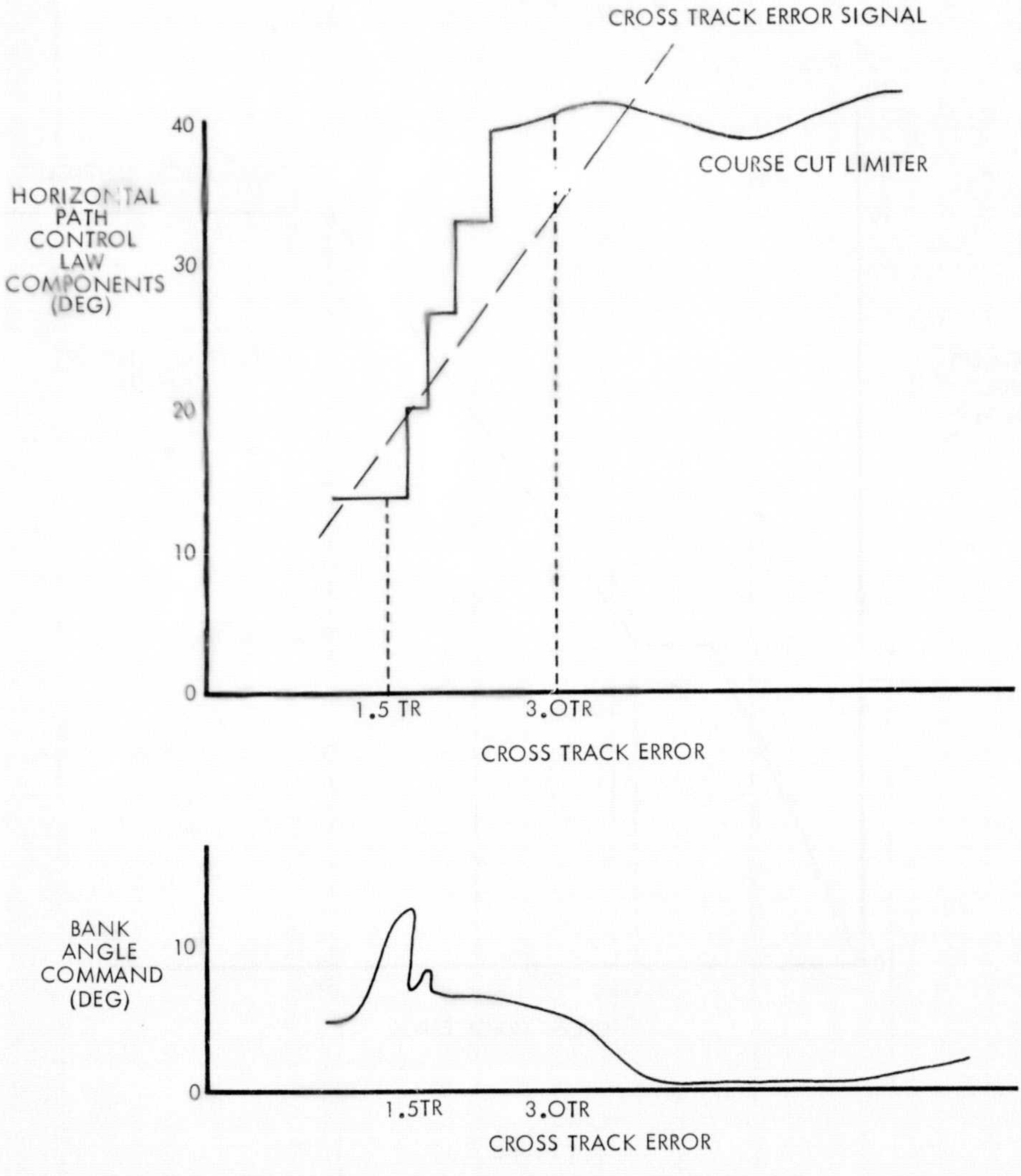


FIGURE 10
MASKING OF THE STEP-WISE DISCONTINUOUS COURSE CUT LIMITER BY THE CROSS TRACK ERROR SIGNAL

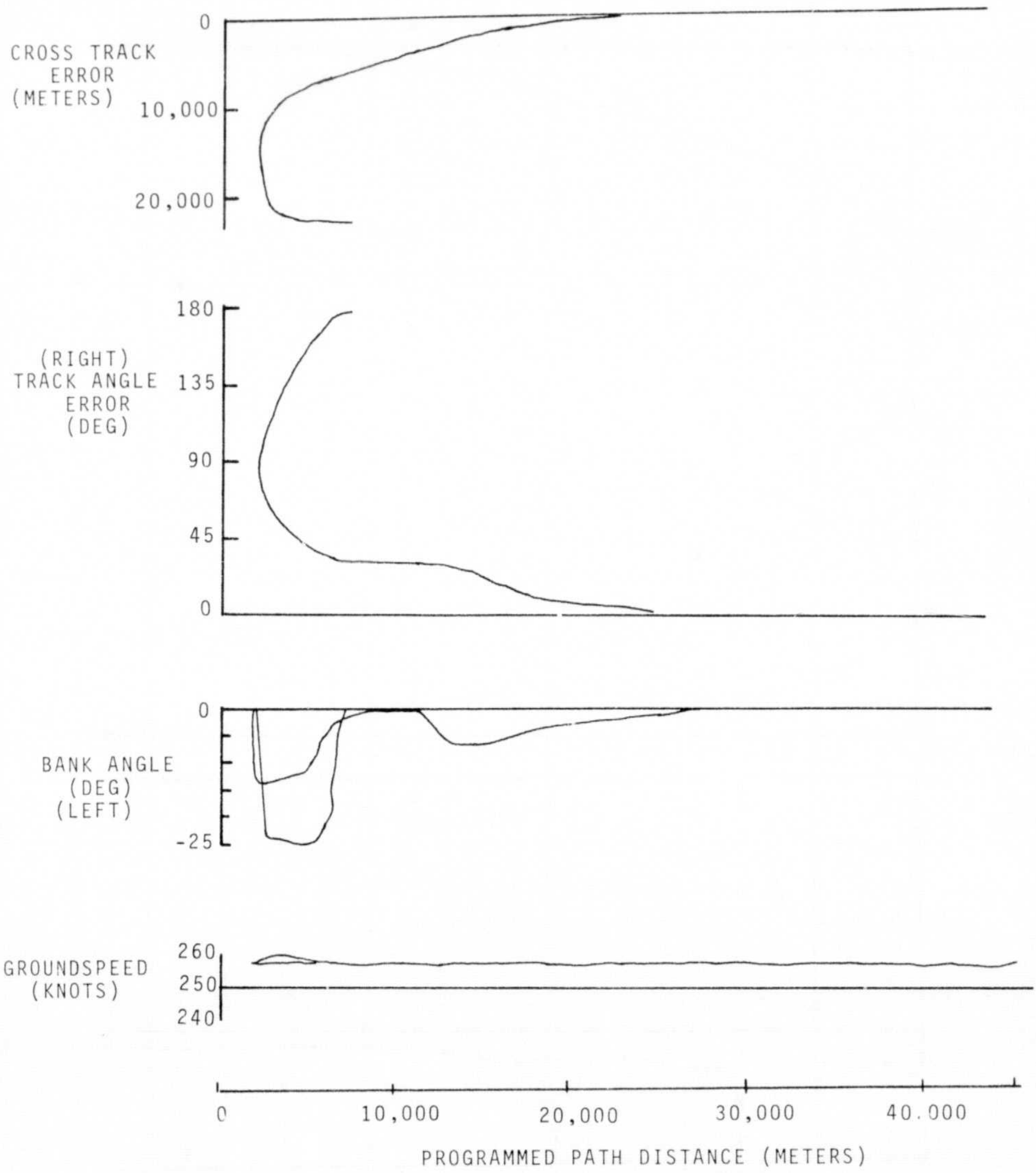


FIGURE 11-HORIZONTAL PATH CAPTURE TEST IN THE SIMULATOR

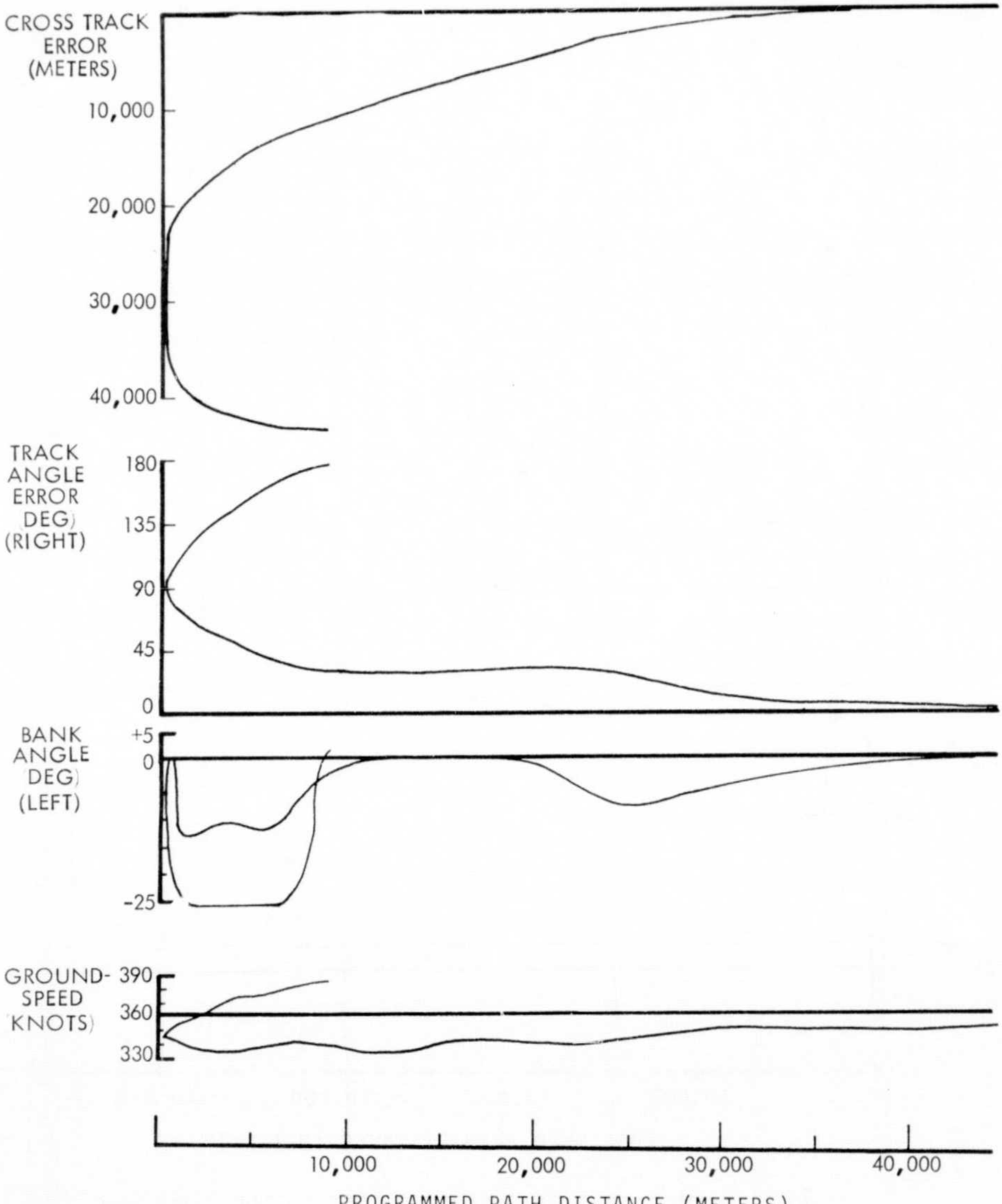


FIGURE 12 - HORIZONTAL PATH CAPTURE TEST WITH REVISED SOFTWARE - AIRPLANE

1. Report No. NASA TM 74061	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
A DESCRIPTION OF THE SOFTWARE ANALYSIS FROM FLIGHT AND SIMULATION DATA OF THE COURSE CUT LIMITER IN THE TCV B-737 AREA NAVIGATION COMPUTER

5. Report Date
August 16, 1977

6. Performing Organization Code
36.100

7. Author(s)
Charles E. Knox and David A. Hinton

8. Performing Organization Report No.
NASA TM 74061

9. Performing Organization Name and Address
NASA Langley Research Center
Hampton, VA 23665

10. Work Unit No.
513-52-01-16

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Memorandum

14. Sponsoring Agency Code

15. Supplementary Notes
This is the final release of special information not suitable for formal publication which serves the following need: Documents the requirements of proper scaling and bit significance when working with very small or large numbers in an airborne area navigation computer.

16. Abstract

During automatic horizontal path captures, the TCV B-737 airplane maintained smaller than designed path intercept angles and experienced a sawtooth bank angle oscillation during its turn towards the path. From flight data and real-time simulation analysis, it was determined that the calculation of the course cut limiter in the horizontal path control law was written such that truncation errors adversely effected the airplane's path capture performance.

The course cut limiter intermediate calculations were rewritten and scaled such that truncation errors would be minimized. The path capture tests were then reflown satisfactorily.

17. Key Words (Suggested by Author(s))
Area Navigation Computers
Flight Testing
Control Law Development

18. Distribution Statement
Unlimited - Unclassified

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	20	$3.50

* For sale by the National Technical Information Service, Springfield, Virginia 22161